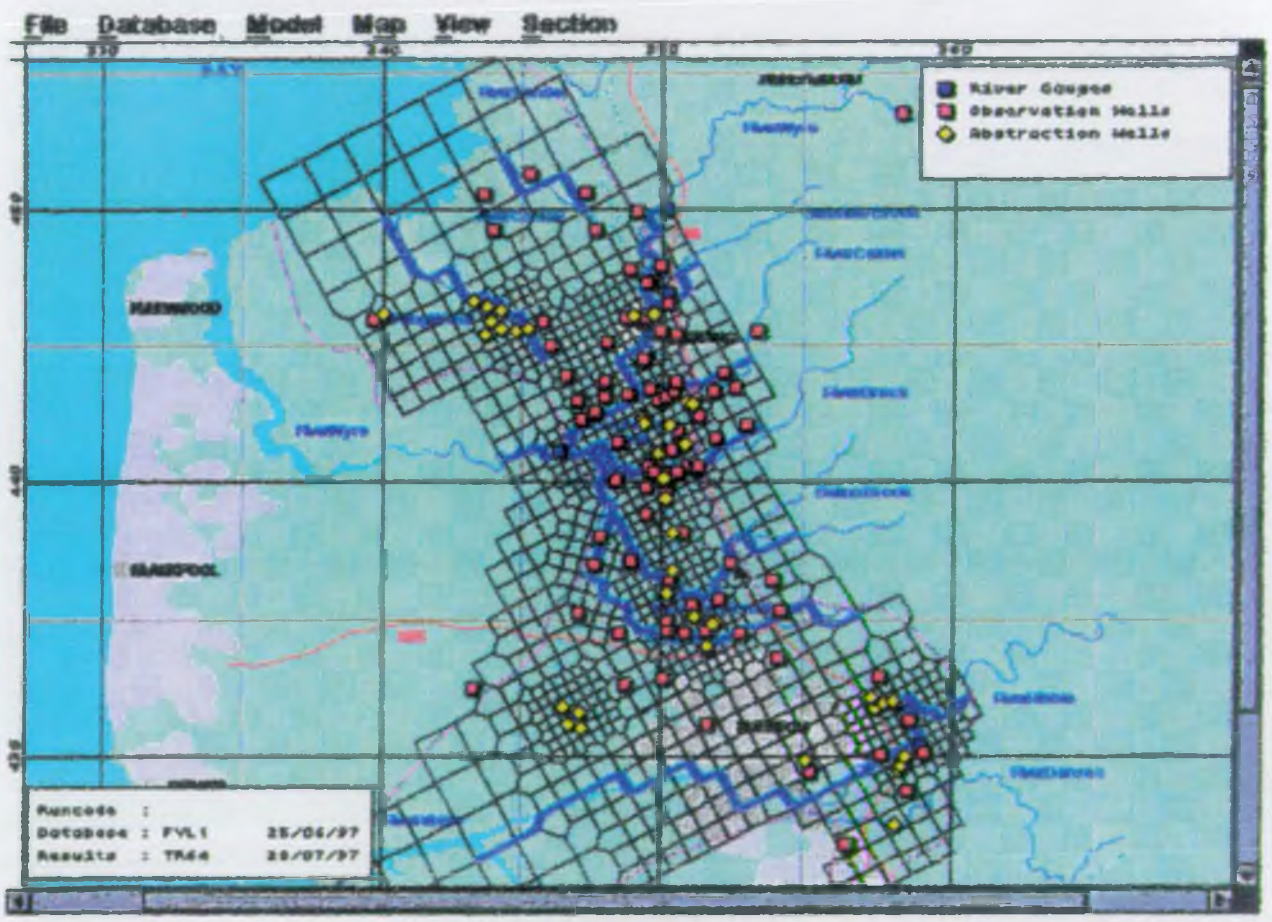
FYLDE AQUIFER/WYRE CATCHMENT WATER RESOURCES STUDY



Final Report

August 1997

ENVIRONMENT AGENCY

Mott MacDonald

FYLDE AQUIFER/WYRE CATCHMENT WATER RESOURCES STUDY

Final Report

carried out for the Environment Agency (North West Region),
in conjunction with North West Water Ltd,
by Mott MacDonald

August 1997

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Acknowledgements

The Authors and Project Board would like to thank the following for their valuable assistance during the course of the Study and the preparation of this report:

- Environment Agency - Area Water Resources staff
  Regional Groundwater and Hydrology colleagues

- Prof K R Rushton
- North West Water Ltd
- Rod Ireland
- British Geological Survey
- Aquatic Pollution & Management Ltd. (APEM)
- British Nuclear Fuels
- ICI
- Whitbread

and all other companies, organisations and individuals who provided data, access to records or otherwise contributed to the Study

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EXECUTIVE SUMMARY

FYLDE AQUIFER/WYRE CATCHMENT
WATER RESOURCES STUDY

EXECUTIVE SUMMARY

S1 Study Area

S1.1 The Fylde Aquifer/Wyre Catchment Study Area stretches from the headwaters of the River Wyre in the east to its estuary in the west, and from the River Ribble in the south to Morecambe Bay in the north. The River Wyre and its tributaries originate on the complex and highly faulted and folded Carboniferous strata of the Bowland Forest. They then flow predominantly westwards across the Permo-Triassic Sherwood Sandstone and extensive Superficial deposits of the Fylde Plain to meet just east of St Michaels on Wyre.

S1.2 The Sherwood Sandstone in this area constitutes the Fylde aquifer. It is an important source of water for North West Water (NWW), forming a component of their Lancashire Conjunctive Use Scheme (LCUS). In addition the Fylde aquifer is used by a number of industrial and private abstractors, most notably ICI Ltd in the north and British Nuclear Fuels Limited (BNFL) and Whitbreads in the south, near Preston. The current (1997) licensed groundwater abstractions are as follows:

Licence Owner	Annual Licence (Ml/annum)
North West Water Ltd	28 059
British Nuclear Fuels	2 982
ICI Ltd	5 455
Whitbreads	3 273
Other private licensed abstractions	597
Total	40 366

S1.3 The Fylde aquifer system is also the source of natural baseflow to the Wyre and Ribble river systems with discharge occurring to the rivers via the overlying Drift. Low river flows in a number of the surface water courses are partly mitigated by river augmentation undertaken by NWW, as specified in individual site licence conditions.

S2 Study Objectives

S2.1 Concerns had been expressed over a number of years about the long-term reliability of water supply from the Fylde aquifer, and depleted summer flows in the Wyre and its tributaries. When LCUS was licensed, environmental protection was not a primary issue. However the Environment Agency now has a duty to balance the needs of water supply and the environment. Recent droughts have brought environmental issues of the Fylde aquifer system into focus, particularly because the NWW LCUS groundwater sources have not been used at their full licensed rates.

S2.2 As a result of these concerns the Environmental Agency instigated this study to:

- examine historical and possible future conditions in the Fylde aquifer and the Wyre surface water catchment;
- assess whether there are adequate water resources available within the Fylde aquifer/Wyre catchment to meet the needs of existing (and possibly additional) abstractors without causing environmental damage or derogation of existing users;
- investigate the low flow problems in the River Wyre and its tributaries and assess how these can be alleviated;
- develop a clear management policy for the sustainable use of groundwater and surface water resources in the area.

S2.3 The specific objectives of the study were to :

- review the response of the Fylde aquifer to 20 years of operational use of the LCUS;
- develop an integrated numerical model capable of representing **both** the groundwater and surface water environments (particularly during low flow conditions) which can be used as a tool for resource management and decision-making;
- assess the validity of assumptions which were used in the formulation of the LCUS licence conditions (in particular licensed quantities), taking account of new geological, hydrogeological and hydrological information;
- investigate a series of abstraction/climatic scenarios to assess the impact of existing and possible additional licences on groundwater sources, resources, surface waters and groundwater dependent features.

S3 Hydrology and Hydrogeology of the Fylde Aquifer/Wyre Catchment

S3.1 Annual rainfall is less than 1000 mm on the Fylde plain, but increases substantially with altitude and on moving inland to a maximum of around 1800 mm. The driest year during the study period was 1995, with rainfall on the Fylde Plain down to 760 mm.

S3.2 River flows are monitored continuously at six gauging stations on the Wyre and its tributaries and intermittently at over 30 spot gauging sites located on the River Wyre and its tributaries. Data collected during 1994, 1995 and 1996 indicate that a reduction in river flow occurred along a number of reaches:

- near Garstang which might relate to abstraction from NWW sources W and Z (refer to figure 2.11);
- from the River Wyre downstream of the confluence with the River Calder (located about 1 km

from NWW source M);

- along the River Calder at Calder Bridge and Calder Weir;
- along the river Brock (upstream of Roe Bridge and downstream of New Bridge);
- at various locations along Barton and Woodplumpton Brooks and the New Draught.

S3.3 The geology of the study area consists of three main domains:

- Carboniferous rocks, consisting of mudstones, shales and sandstones, form the eastern boundary of the Fylde Plain. The Carboniferous rocks are faulted against the Sherwood sandstones resulting in different degrees of contact between the Fylde aquifer and the Carboniferous rocks.
- Permo-Triassic Sherwood Sandstones consist of fine to medium grained sandstone with interbedded 'marl' (mudstone) beds. This aquifer dips westwards from the outcrop at the Carboniferous boundary to depths in excess of 500 m. The sandstone is downthrown at the Woodsfold Fault by up to 600 m, west of which is overlain by Mercia Mudstone.
- Quaternary Drift which overlie the Fylde aquifer. Three distinct units are recognised within the Drift: poorly consolidated, often sandy, boulder clay; sands & gravels; and, stiff, firm boulder clay. Sands & gravels directly overlie the sandstone aquifer in a limited area in the central part of the Fylde plain, roughly coincident with the NWW abstraction sources.

S3.4 During development and calibration of the groundwater model it became apparent that there was insufficient data to accurately define the geological structure of the Fylde aquifer in many areas, particularly in the south of the study area around Barton and Woodplumpton Brooks and the River Ribble. The Agency, therefore, commissioned the British Geological Survey to reinterprate geophysical and lithological data of the Fylde aquifer system and drilled two exploratory boreholes to establish the base of the sandstone aquifer. The results of these investigations have both improved the understanding of the geological structure of the Fylde aquifer system and confirmed the parameters adapted in the calibrated groundwater model.

S3.5 Hydrogeologically the Carboniferous rocks are classed as a "minor aquifer" and are relatively unexploited. There are very few data on the aquifer properties of the of the Carboniferous. The Bowland Shales are considered to be impermeable, while local sandstones within the Millstone Grit Group form localised aquifers near Garstang and Preston. During the original field studies of the Fylde aquifer, and subsequent modelling by WRc in the 1970's, it was postulated that, since the Permian Manchester Marl (which forms an effectively impermeable barrier between the Carboniferous and Sherwood Sandstone) was generally absent along the boundary, hydraulic continuity exists between the Fylde aquifer and the Carboniferous. The WRC model then allowed substantial inflows from the Carboniferous as the major recharge source to the Sherwood Sandstone, with abstractions from the aquifer being balanced by inflows from the Carboniferous. On the contrary, evidence from piezometric responses across the boundary suggests that inflow from the Carboniferous is small and does not significantly contribute to sandstone recharge in the Wyre catchment. In addition reanalysis of the geology indicated that there is very little direct contact between the permeable sandstones of the Carboniferous and the Sherwood Sandstone.

S3.6 The Sherwood Sandstone Group forms a thick aquifer bounded at the base by mudstones of the Permian Manchester Marl. In the study area, the top of the sandstone aquifer is generally confined by clayey beds (boulder clay) within the overlying Drift. The confining boulder clay layer is locally absent, potentially allowing flow between rivers, the sands & gravel deposits within the Drift and the sandstone aquifer; these 'windows' providing pathways for a significant component of recharge and river/groundwater interaction.

Unconfined aquifer conditions occur in the sandstone in the central part of the Fylde during the seasonal intensive pumping from NWW boreholes.

Although the sandstone aquifer thickens westwards from the Carboniferous contact, to over 1000m, active groundwater flow is probably restricted to the upper 200m However, since boreholes seldom penetrate more than the upper 120m of the aquifer, the deep groundwater system is little known.

There are no obvious patterns to the transmissivity distribution, with the mean section permeability ranging from 0.2 to 3.0 m/d over the 200 m active flow zone. Data from the NWW abstraction boreholes, which extend along a north-south line 1 to 2 km west of the boundary with the Carboniferous, indicate the presence of high transmissivities; significantly, the majority are located on N-S faults. Piezometric evidence suggest that flow may locally be restricted across to the faults.

Vertical permeability within the sandstone is controlled by 'marl' (mudstone) beds, typically thin (0.6m) and occurring more frequently in the basal part of the aqiuifer; during model development it was found necessary to represent the aquifer as two layers.

S3.7 The Drift is a heterogeneous mixture of boulder clay and sands & gravels, between 5 and 30 m thick. An aquifer is developed within sands & gravels of the Drift, but almost no data is available on the Drift properties, in particular the horizontal and vertical permeabilities of boulder clay and sands & gravel.

The occurrence and position of the sands & gravel aquifer, is a major control on recharge to the sandstone aquifer. These controls on recharge derive from:

- the overall proportion of boulder clay within the Drift sequence, which controls both the vertical permeability of the Driftand hence the leakage (or recharge) to the top of the sandstone aquifer or to river baseflows;
- the lateral continuity between sand lenses, which controls the horizontal permeability of the Drift.

The distribution and vertical permeability of boulder clay is therefore highly significant in controlling recharge to the Sherwood Sandstone; values in the range of 10^{-5} to 10^{-1} m/d are likely. The horizontal permeability of sands & gravel depends on composition and degree of sorting; values are expected to be in the range of 5 to 25 m/d.

S3.8 Water level data for 150 observation boreholes were used in the study: good cover exists in the central area of the Fylde Plain but limited data are available in both the north west and south west of the study area.

S4 Model Development and Calibration

S4.1 The integrated surface water and groundwater model used in this study is called the Integrated Catchment Management Model (ICMM) and is based on the integrated finite difference method. The model represents flow in multi-layered aquifer systems simulating horizontal flow within aquifers and vertical flow between aquifer layers: all other water balance components of the Fylde aquifer system (such as recharge, discharge and flows between rivers and the aquifer system) are calculated. The model is capable of simulating the temporal and spatial distribution of groundwater heads and river flows in a network of variable sized grid cells covering the model area. The river systems are fully integrated within the model.

S4.2 A four layer model was designed:

- two layers representing the Sherwood Sandstone separated by a "low permeability leakage interface" representing the marl bands within the sandstone;
- a sands & gravels layer, where this directly overlies the sandstone (which acts as an additional storage reservoir);
- undifferentiated drift comprising varying proportions of sands & gravels and boulder clay.

S4.3 All the major rivers were incorporated in the model as additional elements, where the interaction of the river with the sandstone aquifer is dependent upon the Drift coverage at the river. In areas where significant thickness of boulder clay exists beneath the river (>15 m), no exchange of water between river and the sandstone was simulated. At the other extreme, there are areas where boulder clay is absent beneath the river (such as the River Wyre just upstream of St Michaels, where the river valley cuts through the Drift deposits). In these circumstances the river is in "direct" contact with the sandstone and significant leakage between river and sandstone is simulated, with the river effectively acting as a "recharge barrier".

River flows are simulated in the model as the resultant flow balance of the river-aquifer interaction, river abstractions and augmentations and lateral inflows from overland flow (where simulated Drift water levels are at ground surface and any incoming water is rejected).

S4.4 The *potential* recharge (representing the rate of vertical flow through the base of the root zone) was evaluated using the Penman-Grindley recharge model. Not all this recharge percolates through the Drift to the sandstone due to limitations in the capacity of the Drift: the majority is rejected and is routed to the river system; a proportion flows within the Drift and discharges as baseflow to the river system; and a proportion is stored within the Drift (and in particular the sands & gravels) and is then slowly released into the sandstone aquifer when groundwater is being abstracted from the sandstone aquifer.

The recharge/leakage mechanism between ground surface and the sandstone aquifer is highly complex. The leakage mechanism used in the model simplifies the processes. However, detailed modelling of the Drift recharge/leakage mechanism was carried out in order to confirm the validity of thie simplified mechanism.

S4.5 The model was calibrated over the period 1969 to 1996 using monthly timesteps. The geological structure, aquifer and river parameters were adjusted until an acceptable match between observed and simulated data was achieved.

Prior to model calibration the model the model was considered a good representation of the Fylde aquifer system when the model simulated:

- the observed piezometry for selected time periods, representative of different climatic and abstraction conditions;
- the observed hydrographs over the whole of the study area;
- the observed river flows at the six major gauging stations currently monitoring river flows of the Wyre catchment;
- the observed river losses and gains.

S5 Conclusions From Model Calibration

S5.1 The developed model accurately simulates the integrated groundwater and surface water system of theFylde. The observed piezometry, groundwater level hydrographs, river flow hydrographs and river losses and gains have all been accurately simulated by the model under all climatic conditions between 1969 and 1996.

S5.2 The model results highlight one very significant feature of the Fylde aquifer: groundwater abstractions are primarily derived from vertical leakage of rainfall recharge through the overlying Drift deposits and from leakage through river beds. The water balance components for the Fylde aquifer are shown in Table S-1. This is very different from the mechanism of flow adopted in the WRc model (1972), where groundwater abstraction volumes were primarily derived from the inflow of water from the Carboniferous deposits to the east. This has an important bearing on the resource availability and the licensing of groundwater abstractions. In the WRc model, the impacts of groundwater abstractions on the environment are minimised since the Carboniferous system is considered as a reservoir with infinite storage. In the current, revised model, groundwater abstractions are limited by the vertical conductance of the Drift deposits. A deficit in vertical flow through the Drift is compensated by the inducement of leakage from the surrounding rivers system. The impacts of groundwater abstractions on the environment are therefore more pronounced and more accurately represented in the current model. Furthermore, the current model extends south

TABLE S1

Simulated Water Balance Components for the Sandstone Aquifer

Flow Component (Ml/d)	Average 1972 - 96	September 1995 - Low Recharge/High Abstraction	April 1987 - Low Abstractions
Inflows			
Leakage from Drift	50.1	75.0	38.9
Carboniferous Inflow	5.8	5.6	5.2
Leakage from Rivers	4.2	12.2	0.0
Storage Release	0.8	46.3	1.3
Total Inflows	60.9	139.1	45.4
Outflows			
Abstraction	-35.9	-121.6	-13.9
Outflow to Morecambe Bay	-4.2	-2.1	-5.0
Outflow to Ribble Estuary	-4.3	-3.5	-4.5
Groundwater flow to Rivers	-16.5	-11.9	-22.0
Storage Gain	0.0	0.0	0.0
Total Outflows	-60.9	-139.3	-45.4
Model Imbalance	0.0	-0.2	0.0

to encompass the Ribble while the WRc model terminated on the northern outskirts of Preston.

S5.3 In relation to the north west of the study area (around Morecambe Bay) the follwoing conclusions are made:

- Abstractions from ICI sources, and to a lesser extent from NWW sources W and Z (near Garstang to the south east), caused a reversal from the historical upward leakage at the Winmarleigh Mosses SSSI, which may have resulted in a reduction of surface water levels/discharges around the SSSI.
- ICI abstractions reduce outflow to Morecambe Bay. This could potentially lead to a deterioration in groundwater quality in the north west of the Fylde as a result of saline intrusion.

S5.4 For the Garstang area the conclusions are:

- NWW sources W and Z cause a loss of flow in the River Wyre .
- Under non-pumping conditions, there is only a limited inflow of water from the sandstone formations of the Carboniferous along the eastern boundary, while NWW's abstraction only induce small additional inflows.

S5.5 For the central part of the Fylde plain, the conclusions are:

- Abstractions from the central NWW sources (Franklaw 'A' & 'B' and Broughton 'B' boreholes) induce losses from all the rivers at different locations.
- The sands & gravels which directly overlie the sandstone aquifer in this area act as an important storage reservoir for NWW abstractions. Without this additional storage, abstractions would result in higher river losses during summer.
- Groundwater abstractions do not induce additional flow from the Carboniferous boundary because very low permeability Manchester Marls separate the Carboniferous from the Sherwood Sandstone aquifer.

S5.6 For the area in and around Preston the conclusions are:

- There is marked horizontal anisotropy in aquifer permeability (caused by faulting) to the west of NWW Broughton 'A' sources (sites B, C and D) limiting the east-west groundwater flow in this area.
- The main 'trough' of aquifer exploited by NWW's boreholes is effectively hydraulically isolated by structural controls from the upstream end of the Ribble valley - the 'Red Scar Basin', in which the Whitbreads and the former Courtaulds boreholes are situated.
- Sands & gravels in the west of the area, at the Woodsfold Fault, act as a conduit linking Woodplumpton and Barton Brooks with the sandstone aquifer, resulting in river flow losses during abstractions from the central area and NWW's B, C and D sites.

S5.7 In the extreme south east of the Fylde plain at the River Ribble the conclusuins are:

- Groundwater levels within the upstream end of the Ribble catchment (i.e. the 'Red Scar basin', around Whitbreads and the former Courtaulds sites) are controlled by the river valley and inflows from the Carboniferous.

S6 Model Predictions

S6.1 A total of 16 prediction runs were carried out using the calibrated model. These predictions were used to investigate:

- the impact of the current licenses on groundwater levels and river flows;
- the effectiveness of the licensed river augmentation system;
- the impact of various licence applications/enquiries received by the Agency over the last three years and in particular the licence application by Emmitt Denim in Preston.

S6.2 From these runs it is concluded:

- if licences were operated at full capacity there would be a large reduction in sandstone piezometry to such an extent that the level at borehole T74 would fall below the constraining level once in every three years on average and there would be a further increase in losses from the river system;
- that licensed augmentations are insufficient to maintain river flows at the gauging stations above the prescribed limits;
- with an additional licensed abstraction of 900 Ml/annum in the Preston area, groundwater levels would decline in Preston by a maximum of 1.8 m and the influence would extend as far north as the River Calder;.

S7 Study Conclusions

S7.1 The main conclusions from this study are the following:

- The study has greatly enhanced our understanding of the geological structure of the Fylde aquifer system;
- The study has shown that groundwater abstractions are not balanced by inflow from the Carboniferous system to the east as was originally assumed during the licensing of the NWW LCUS sources. Recharge to the sandstone aquifer is restricted by the low vertical conductance of the Drift Deposits. A deficit in vertical flow through the Drift caused by historical public supply and industrial abstractions is made up in part by induced leakage from the surrounding river system. The impacts of groundwater abstractions are therefore more pronounced than previously assumed when the LCUS license was granted. This has an important bearing on the sustainability of currently licensed groundwater abstractions and the effectiveness of the existing licence conditions to adequately protect the aquatic environment.
- If all existing licensed sources were operated at full licensed rates there would be a serious impact upon the environment: river flows would be substantially reduced in summer and some river reaches would dry up and wetland features such as the Winmarleigh Mosses (a SSSI) would be adversely affected.
- New licenses in Preston if granted would cause a large decline in groundwater levels in Preston affecting the Whitbreads and NWW Broughton sources as well as affecting levels at the

constraining observation borehole (T74).

- Therefore, the aquifer cannot support additional/increased groundwater abstraction beoyond the present licensed rates without derogating existing protected rights and/or exacerbating the adverse effect on the surface aquatic environment.

S8 Recommendations

S8.1 The model developed for this study should be regularly updated with hydrometric, climatic and abstraction data so that the calibration can be checked and updates to the calibration be made. This will ensure that decisions made derived form model predictions are based on the most up to date data. In addition, confidence in the model results would continuously improve.

S8.2 To further increase confidence in the model calibration, additional observation boreholes should be constructed in the Preston area. In addition, observation boreholes within the Drift would aid the understanding of the Drift leakage mechanism. These Drift boreholes should be situated in Preston, around T74, in the central Fylde around the main NWW abstraction sources and in or adjacent to the Winmarleigh Moss.

S8.3 It is important that a water management plan for the Fylde aquifer is developed. This plan should balance the needs of existing abstractors with the needs for protecting the water environment. Before such a plan can be developed it will be necessary to obtain further information on environmental constraints; studies into the environmental impact of groundwater abstractions, source reliable output and the feasibility/effect of any change to current abstraction/augmentation arrangements. This will require:

- definition of the acceptable minimum flows at different sections of the rivers and at different times;
- monitoring of Drift groundwater levels at environmentally sensitive areas, such as the Winmarleigh Moss;
- investigating the criteria for the control of groundwater abstractions from observed groundwater levels (as is carried out with the T74 control borehole (SD43/19);
- enhanced understanding of the aquifer flow and recharge mechanisms.

CHAPTER 1

INTRODUCTION

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1.1 Extent of Study Area

The Fylde Aquifer/Wyre Catchment Study Area is shown in Figure 1.1. The area stretches from the headwaters of the River Wyre in the east to its estuary in the west, and from the River Ribble in the south to Morecambe Bay in the north. The River Wyre and its tributaries (most notably the River Calder, the River Brock and the Grizedale, Barton and Woodplumpton Brooks) originate on the complex and highly faulted and folded Carboniferous strata of the Bowland Forest. They then flow predominantly westwards across the Permo-Triassic Sherwood Sandstone and extensive Superficial deposits of the Fylde Plain to meet just east of St Michaels on Wyre. The River Wyre continues to travel west across Triassic Mercia Mudstone before turning north and entering Morecambe Bay near Fleetwood.

The Sherwood Sandstone in this area constitutes the Fylde aquifer. It is an important source of water for North West Water (NWW), forming a component of their Lancashire Conjunctive Use Scheme (LCUS). In addition the Fylde aquifer is used by a number of industrial and private abstractors, most notably ICI Ltd in the north and British Nuclear Fuels Limited (BNFL) and Whitbreads in the south, near Preston.

The Fylde aquifer system is also the source of natural baseflow to the Wyre and Ribble river systems with discharge occurring to the river via the overlying Drift. Low river flows in a number of the surface water courses are partly mitigated by river augmentation undertaken by NWW, as specified in individual site licence conditions.

1.2 Background/Need

Concerns had been expressed over a number of years about the long-term reliability of water supply from the Fylde aquifer, and depleted summer flows in the Wyre and its tributaries.

When the LCUS was licensed environmental protection was not a primary issue. However, the National Rivers Authority (NRA) and now the Environment Agency (Agency)[1] have duties to promote sustainable management and to protect and enhance the environment. It's aim is to achieve a balance between the needs of water supply and the environment, on all timescales.

NWW have never used their Fylde groundwater sources up to their full licensed rates because of distribution constraints. However, recent droughts, particularly the 1995/96 drought have focused attention on potentially under used licensed resources such as the Fylde. This has highlighted concern over possible impacts if increasing demands were to be placed on the aquifer.

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1 The NRA became part of the Environment Agency (referred to in this report as 'the Agency') on 1.4.1996

One of the options considered by the NRA's 'National Strategy for Water Resources' (1994) was the partial redeployment of water from Vyrnwy in North Wales. At present the majority of water is used to supply Liverpool. Water would be diverted to regulate the Severn, for possible onward transfer to the Thames basin. If this plan were to go ahead, NWW and the Agency would need to be satisfied that sufficient supplies are available within the region to meet projected future demand in a sustainable manner. Diversion of Vyrnwy water would increase the pressure to fully utilise the Fylde licences.

Furthermore, there has been considerable interest in additional development of the groundwater resources of the Fylde aquifer, particularly for industrial and commercial use around Preston.

1.3 Aims & Objectives

As a result of these concerns, in 1994 the NRA (supported by NWW) instigated the Fylde Aquifer/Wyre Catchment Water Resources Study. The overall aims were to:

- examine historical and possible future conditions in the Fylde aquifer and the Wyre surface water catchment;
- assess whether there are adequate water resources available within the Fylde aquifer/Wyre catchment to meet the needs of existing (and possibly additional) abstractors without causing environmental damage or derogation of existing users;
- investigate the low flow problems in the River Wyre and its tributaries and assess how these can be alleviated;
- develop a clear management policy for the sustainable use of groundwater and surface water resources in the area.

The specific objectives of the study were to :

- review the response of the Fylde aquifer to 20 years of operational use of the LCUS;
- develop an integrated numerical model capable of representing both the groundwater and surface water environments (particularly during low flow conditions) which can be used as a tool for resource management and decision-making;
- assess the validity of assumptions which were used in the formulation of the LCUS licence conditions (in particular licensed quantities), taking account of new geological, hydrogeological and hydrological information;
- investigate a series of abstraction/climatic scenarios to assess the impact of existing and possible additional licences on groundwater sources, resources, surface waters and groundwater dependent features.

1.4 Catchment Description

The River Wyre and its principal tributaries, Grizedale Brook, the River Calder, the River Brock and the Barton and Woodplumpton Brooks, originate in the Bowland Fells and in rolling hills to the east of the Fylde plain. The tributaries converge on the eastern side of the plain and join the River Wyre flowing from the north of the catchment in major confluences between Garstang and St Michael's on Wyre (Figure 1.1). Downstream of St Michaels the river runs west then north to discharge into Morecambe Bay. Extensive flood defence and land drainage works have been carried out in the lower reaches of the river, including channel straightening, bank reformation work and construction of two flood basins.

The northern part of the project area is drained by two other minor surface water systems, the River Cocker and the Pilling Water; both originate within the Fylde plain. The southern limit of the Fylde plain is bounded by the catchment of the River Ribble.

A distinct contrast, in geology and landform, exists across the area. The Fylde Plain is a low lying area of elevation typically less than 50m AOD, which is underlain by Permo-Triassic sandstones and marls; the area is mantled with glacial drift deposits, with sporadic peats and alluvium; to the north west the plain merges into tidal sands fringing Morecambe Bay. Within the Fylde Plain, peats have accumulated within low lying areas with poor drainage, locally termed 'mosses'.

Eastwards, beyond the line of the M6 motorway , upland hills and moorland, the Bowland and Longridge Fells, are developed upon resistant Carboniferous sandstones, with intervening valleys based upon softer Carboniferous shales. The fells reach 400m AOD within the study area, in the Wyre headwater area.

Much of the Fylde plain is pasture land used for dairying, with some scattered woodland; some arable crops, mainly potatoes and other vegetables, are grown in the north west towards Morecambe Bay. Peaty areas formerly subject to flooding (the mosses), have largely been drained.

By contrast, the fells to the east support open moorland used mainly for shooting and rough grazing.

1.5 Development of Water Supplies

The earliest developments for public water supply in the study area were surface water abstractions from the Upper Wyre (Tarnbrook Wyre) using catchwaters and stream intakes. A reservoir (Abbeystead) was built to supply compensation to mills on the River Wyre which had lost supplies with the construction of the stream intakes. These compensation rights were bought out in the 1920's, although a small flow is released from the reservoir in addition to a fish pass. Barnacre reservoirs were built in the late 1800's, with intakes similarly taking the whole flow of the River Calder and Grizedale Brook with no compensation or bypass at low/medium flows.

There is a further intake on the River Calder, which can take the whole flow, without compensation for the

Lancaster canal.

Groundwater has been abstracted from the northern part of the Fylde aquifer since the 1890's, although the rest of the aquifer was virtually unexploited until investigations in the late 1950's by Fylde Water Board in the area between Garstang and Preston.

The idea of conjunctive use of water resources in the Fylde area was first implemented in 1954. The principle of conjunctive use is that by operating the surface and groundwater systems as a single unit, greater yields and average supplies can be obtained than from the separate components. The first scheme used up to 27 Ml/d of borehole water to augment supplies from Stocks Reservoir (east of the study area, near the Vale of Chipping). The area was considered suitable for this type of integrated scheme because of its good geographical location and existing infrastructure.

The interim report of the Northern Technical Working Party (1967) identified future shortages in Lancashire during the 1970's. In 1969 the Lancashire River Authority proposed a scheme with conjunctive use of surface water reservoirs and the rivers Ribble, Wyre and Lune.

In 1971 the North Working Group II recommended a scheme which included an enlarged Stocks Reservoir, the Fylde aquifer, and abstractions from the rivers Lune and Wyre.

Investigations of the aquifer started in the late 1950's with trial boreholes to prove the existence of the aquifer and to determine its possible yield. The quantities available for supplies were limited by statute, later by licences. The historical development of groundwater licences is indicated below:

Year	Maximum Daily Licence (Ml/d)	Maximum Annual Licence (Ml/annum)
1960	9	1932
1961	54.5	12424
1974	73	14356 (subject to conditions)
1996	135.3	40585 (subject to conditions)

In the early 1970's, the first extensive pumping tests of the aquifer were undertaken by the former Fylde Water Board and Lancashire River Authority. The data collected during these tests were used in the development of a groundwater model of the Fylde aquifer (Water Research Centre(WRC), 1975). This model was used to guide the design of the Lancashire Conjunctive Use Scheme (LCUS) and also to determine licence quantities and conditions governing groundwater abstraction. LCUS consists of a number of diverse sources, both within and outside the Wyre catchment as shown in Figure 1.2.

Through LCUS the surface water resources of the Lune and Wyre catchment are managed in conjunction with Stocks reservoir and the groundwater resources of the Fylde aquifer. The groundwater is used to supplement the surface water supplies, generally in the period from April to October, and to augment flows in the River Wyre and tributaries in periods of low flow. Water is abstracted from the River Lune and transferred to the River Wyre at Abbeystead with abstraction for public water supply at Garstang.

1.6 Previous Studies

There are a large number of existing reports, papers and university theses on the geology and hydrogeology of the Fylde aquifer as well as on the operation of the LCUS. They can be roughly categorised as follows:

- BGS Memoirs on the geology of the area and reports on the Wyresdale Tunnel giving the stratigraphy and structure of the Carboniferous;
- internal NRA and NWW reports and a number of published papers on aquifer properties;
- papers and theses concerned with the hydrochemistry of the Fylde aquifer;
- papers and theses on geophysical investigations of the Fylde aquifer;
- WRB and WRC reports on the LCUS groundwater model;
- papers and theses describing the background to the development of the LCUS and its operation.

A full list of references is given at the end of this report while the key findings from the previous hydrogeological reports are summarised below.

Hydrogeological/Modelling Studies

During the period from 1971 to 1973, extensive field investigations and testing were undertaken by the Fylde Water Board and Lancashire River Authority in conjunction with the Water Resources Board (WRB); modelling activities were transferred to the Water Research Centre (WRC) following the reorganisation of the Water Industry on 1 April 1974.

Long term pumping tests were undertaken during 1971 and 1972 to determine aquifer response to groundwater abstraction from the Fylde aquifer and assist in establishing limitations on pumping, to protect other abstractions, low river flows and the aquifer itself from over-abstraction.

WRB postulated that since impermeable Permian Marls are not present everywhere along the boundary with the Carboniferous, hydraulic continuity existed between the Fylde aquifer and the Carboniferous.

WRB also recognised that the Drift was an important hydrogeological component of the aquifer system. Forty six exploratory observation boreholes were completed in the superficial deposits to assess lithology and groundwater conditions.

WRB further identified extensive sand & gravel deposits directly overlying the sandstone aquifer which enhance the transmissivity of the aquifer. Boulder clay was believed to cover most of the area although boulder clay free areas of limited extent were identified. Lower boulder clay horizons between the sand & gravel and the sandstone were believed to be of localised occurrence. Boulder clay was found to be missing northeast of Garstang and in the east part of the River Brock valley.

Recharge to the sandstone aquifer was assumed to occur by inflow from the Carboniferous and downward leakage through the Drift; leakage was assumed to be predominantly through small windows of boulder clay free Drift and to a lesser extent through Drift where this contains less than 10 m of boulder clay. No leakage was assumed where total boulder clay thickness was greater than 10 m.

The study recognised that river gains and losses are largely controlled by water table conditions in the Drift and that the influence of abstraction on Drift water levels would control the impacts on river flows. Losses were observed during the pumping test trials along sections of the Rivers Wyre and Brock, where boulder clay free Drift occurs. It was recognised that losses along these river sections could occur naturally but that losses were enhanced by pumping.

WRB concluded from their investigations that three times more recharge to the sandstone aquifer was derived from inflow from the Carboniferous deposits in the east, than through leakage from the overlying Drift deposits and surface water system.

Using this hydrogeological analysis, a modelling study was instigated by WRC to check what effect increased groundwater abstraction for public water supply would have on rivers and on industrial groundwater users, such as ICI, and to determine whether the increased abstraction would be sustainable in the long term.

In the WRC model, recharge under non-pumping conditions was allowed only in the form of inflow across the Carboniferous boundary. Abstraction from the aquifer was balanced by increased inflow from the Carboniferous and by a reduction of outflow to rivers and in some cases river water contributing to the aquifer. Both calibration and model predictions showed a significant increase in inflow from the Carboniferous during pumping.

From the results of these field investigations and groundwater modelling, the licence conditions and rates for the groundwater components of LCUS were defined. The main licence conditions are summarised in Table 1.1

TABLE 1.1

LCUS - Fylde Aquifer Licence Conditions

Objective:	Controls/Operating Principle:
abstraction less than recharge	annual & 'rolling' 3 year totals
distributed abstraction throughout the aquifer	conjunctive limits on borehole groups
develop unconfined storage	seasonal abstraction
protect existing abstractors (Courtaulds[1] & BNFL)	'hands off level' conditions on observation boreholes (T68[1] & T 74 respectively)
acceptable impact on surface waters	river augmentation[2]
maintain positive gradients at aquifer boundaries[3]	quality/level monitoring[3]

Notes: (1) Courtaulds licence now revoked; T68 constraint removed from NWW licence.
(2) at specified sites; rates & durations related to pumping rate & river flows.
(3) to avoid saline intrusion from Morecambe Bay and from beneath Mercia Mudstones.

Studies into Aquifer Properties

The flow mechanisms within the sandstone aquifer were originally studied in some detail by Worthington (1977). He used both field and laboratory measurements of permeability to investigate the relative importance of intergranular and fissure flow. Previously two possible mechanisms of groundwater flow had been suggested:

- mainly fissure flow with variations in transmissivity resulting from different degrees of fissure development and with relatively uniform horizontal intergranular permeability;

- mainly intergranular flow with variations in transmissivity resulting from pronounced lateral variations in horizontal intergranular permeability. Localised development of fissures could enhance transmissivity, but was not considered to be the primary control.

Worthington investigated the two theories by comparing histograms of specific capacity for 150 mm diameter boreholes. The first histogram plotted specific capacity of the aquifer for different basal Drift cover and the second looked at specific capacity related to different degrees of consolidation of the sandstone. Generally boreholes with sands & gravels directly overlying the aquifer were shown to have a higher specific yield than those where clay is in contact with the sandstone. Boreholes in loosely cemented sandstone were found to be more productive than those in strongly cemented sandstone. Worthington concluded that both findings indicated that intergranular flow, including flow in sands &

gravels where they directly overlie the aquifer, is more important than fissure flow.

This hypothesis was tested further by comparing permeability measured in the laboratory with permeability calculated from pumping test data; the former should only reflect intergranular permeabilities where aquifer test results should give a total value reflecting both intergranular permeability and permeabilities of fissures. The laboratory and field measurements were of similar magnitude confirming the predominance of intergranular flow.

More recently, short hydrogeological reports have been produced by both NRA and NWW which contain data on investigations of public water supply sources and industrial borehole sources, together with Groundwater Protection Zone (GPZ) studies and data pertinent to abstraction licence applications. These data provided useful estimates of aquifer transmissivity; they are discussed elsewhere, in the section on hydrogeological parameters.

Hydrochemical Investigations

Hydrochemistry, and bicarbonate concentration in particular, has been used to establish groundwater flow paths and help assess the recharge contribution to the aquifer from the Drift. This work is described in detail by Sage and Lloyd (1978) and in Sage's MSc thesis (1976).

Although the distribution of bicarbonate concentration in the Sherwood Sandstone is complex, it is generally found that areas of low concentration (< 250 mg/l) correlate with areas of glacial sands and river alluvium but with little boulder clay, suggesting indirect recharge of soft water from rivers. High concentrations (> 350 mg/l) were associated with inflows from the Carboniferous rocks. These areas are of limited extent indicating to the authors that the sand transmitted recharge is at least as important as the contribution from the Carboniferous. High concentrations were also found to occur where there are large thicknesses of Boulder Clay.

Sodium bicarbonate waters produced by ion exchange predominate towards Morecambe Bay and were attributed to a lack of significant outflow in the area. Discharge from the system was thought to take place into the Wyre valley, Pilling Water and the River Cocker.

High iodine concentrations in the groundwater close to the coast were attributed to long residence times in the aquifer rather than to recent saline intrusion. This was consistent with the postulated low groundwater flow in coastal areas resulting from the presence of thick marine clays in Morecambe Bay.

1.7 Study Structure

The Fylde Aquifer/Wyre Catchment Water Resources study was originally split into four phases, as follows:

Phase I	- Data Collation and Formulation of Conceptual Model of the Aquifer System
Phase II	- Model Development and Calibration
Phase III	- Modelling of Resource Options
Phase IV	- Training in Model Operation of the Agency and NWW staff, and User Support

Phase I was carried out between November 1994 and April 1995, with the report issued in April 1995. There were three main components of this phase:

- Data collection and processing of all hydrological and hydrogeological data relevant to the study area.

- Hydrological and hydrogeological analysis of the data.

- Development of the conceptual model of the Fylde aquifer and Wyre surface water system which would be adopted in the formulation of the integrated groundwater and surface water model.

Phase II was carried out between May 1995 and December 1995, with the Phase II report issued in January 1996. Phase II concentrated on the construction and calibration of the integrated groundwater and surface water model of the Fylde aquifer/Wyre catchment.

Phase III was carried out during December 1995/January 1996, where seven different water resource scenarios were tested in the model.

Training and model handover (Phase IV) took place at the Environment Agency offices during March 1996.

At the end of the study, the Agency, along with their external advisor, Professor K Rushton of Birmingham University, thought that the reports produced for the original four phases did not present the integrated picture of conditions in the Fylde aquifer/Wyre catchment. Therefore, Mott MacDonald were requested to produce a Final Report summarising the activities and results of the full study in one report.

During the original study, the lack of geological and hydrogeological data for the area to the south of Woodplumpton Brook was recognised as a constraint to the confidence that could be placed on the model in that region. This area is critical to future water resource strategies as it includes Preston, where there has been considerable interest over the last three years in developing new groundwater-sources. Consequently, the Agency has instigated further investigations; the drilling of two new exploratory boreholes and commissioning the British Geological Survey (BGS) to remap the geological structure of the Sherwood Sandstone using geophysical data.

In addition, during the drought conditions of 1995/96, groundwater levels in the Fylde aquifer declined to the lowest levels recorded in some areas, with no signs of recovery. As a result, the response of the Fylde Aquifer to drought conditions became a key concern of both the Agency and NWW. However the model had only been calibrated to the end of 1994 and the Agency, therefore, requested that Mott MacDonald update the model calibration to include 1995 historical data and incorporate the findings of the new geological data collected.

The calibration was updated further in 1997 to include 1996 historical data. At the same time, Mott MacDonald carried out detailed modelling of the mechanisms of leakage through the Drift Deposits to the sandstone aquifer in order to increase confidence in the leakage mechanisms adopted within the regional model.

As a result of this additional work, some of the sections in the Phase I and II reports of the original study have been superseded, as follows:

Phase I Report

- Geological data availability and interpretation (Section 2.3) does not include references to new BGS mapping of the sandstone structure or the new exploratory borehole drilled south of Woodplumpton Brook.

- All transient data (rainfall, evapotranspiration, river flow, abstractions) has since been updated to the end of 1995.

Phase II Report

- Model calibration processes (Chapter 3) does not include any of the additional work carried out since March 1996 (update to end 1995 or revisions to geological structure) and therefore calibration presented in Chapter 4 should be treated as a "Preliminary Calibration".

- Model sensitivity (Chapter 5) has been superseded by the sensitivity analysis carried out for this report.

- Conclusions (Chapter 6) should be read in the context of the preliminary calibration. These have been replaced with the conclusions on the model defined in Chapter 4 of this report.

1.8 Organisations Contributing Data

The organisations contributing data to the study are listed in Table 1.1.

TABLE 1.2

Summary of Data Collected

Data Category	Type of Data	Source
Geological[1]	1:50 000 geology maps	BGS, Phd Thesis
	lithological logs	NRA[2], BGS
Hydrogeological	groundwater levels	NRA
	groundwater abstraction licences	NRA
	actual groundwater abstractions	NRA, NWW
	hydrochemistry	NRA, MSc thesis by R Sage
	aquifer properties	NRA, BGS
Hydrological	rainfall	NRA
	evapotranspiration	NRA project by R Manley, Independent consultant
	river flows	NRA
	river augmentation	NRA
	Lune-Wyre transfer	NRA, NWW
	river abstraction at Garstang	NRA, NWW
	River Calder to Lancaster canal transfer	British Waterways Board
		NRA
Other	river cross sections	
	Digital Terrain Model data (surface	NRA
	topography)	NRA
	Environmental Surveys	
		APEM[5]

Notes (1) Geological information and lithological logs were obtained either from the NRA or from the British Geological Survey (BGS). In some areas, modelling difficulties suggested that the geological system was imperfectly known. As a result, the NRA contracted the BGS to carry out a remapping of the Permo-Trias basin under the Fylde, based on interpretation of geophysical data.

(2) Project initiated by former NRA; transferred to Environment Agency (Agency) on 1.4.96

(3) Details of data collected for the study can be found in the Phase I Report.

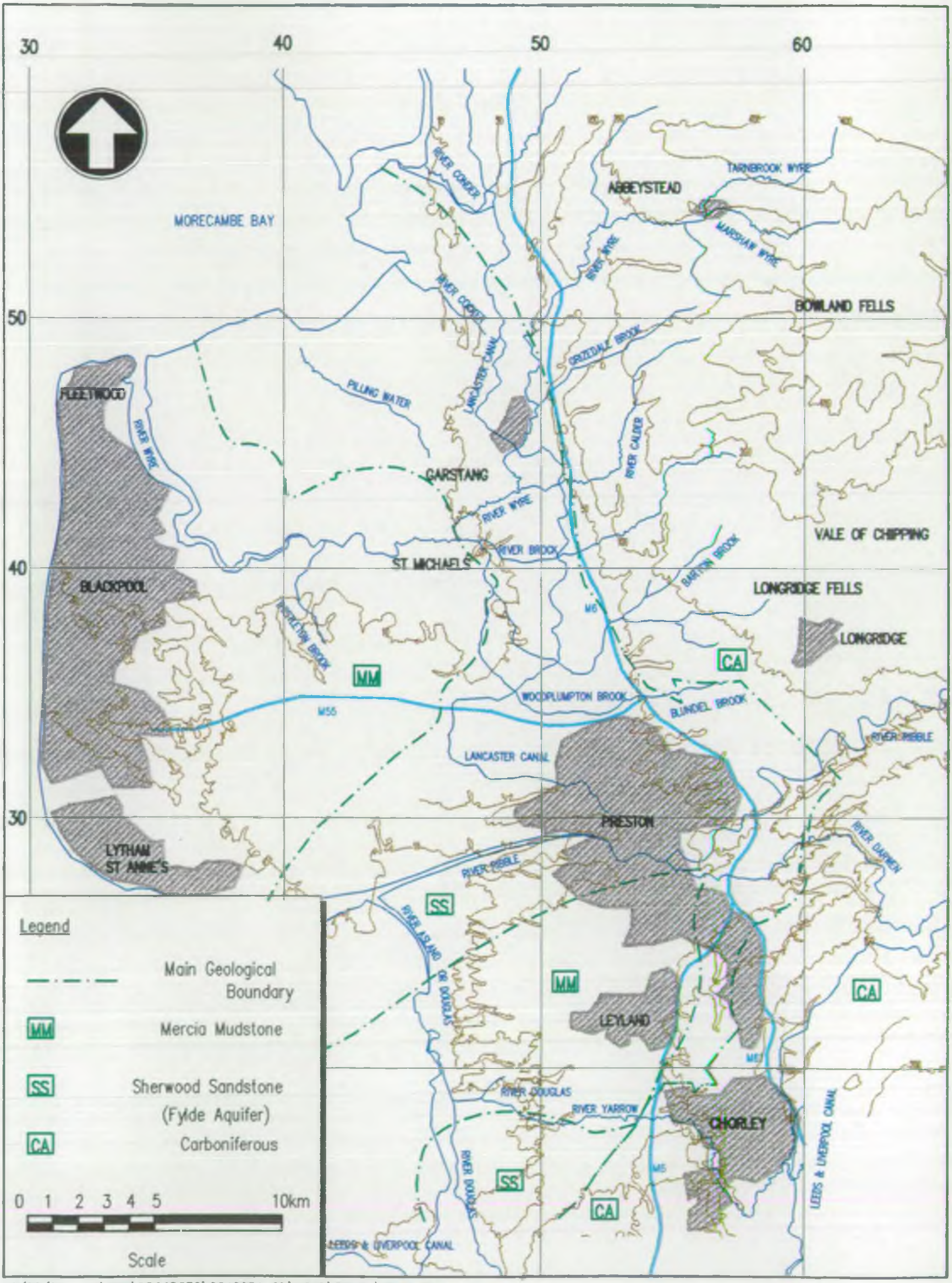
(4) All hydrogeological data related to boreholes was entered into a central database, with four main database files containing the following information on each well:

- the well number, coordinates, location and elevation, information on the type of well (observation/abstraction/lithology) and the source of the data;
- borehole lithology;
- daily abstraction volumes;
- groundwater levels.

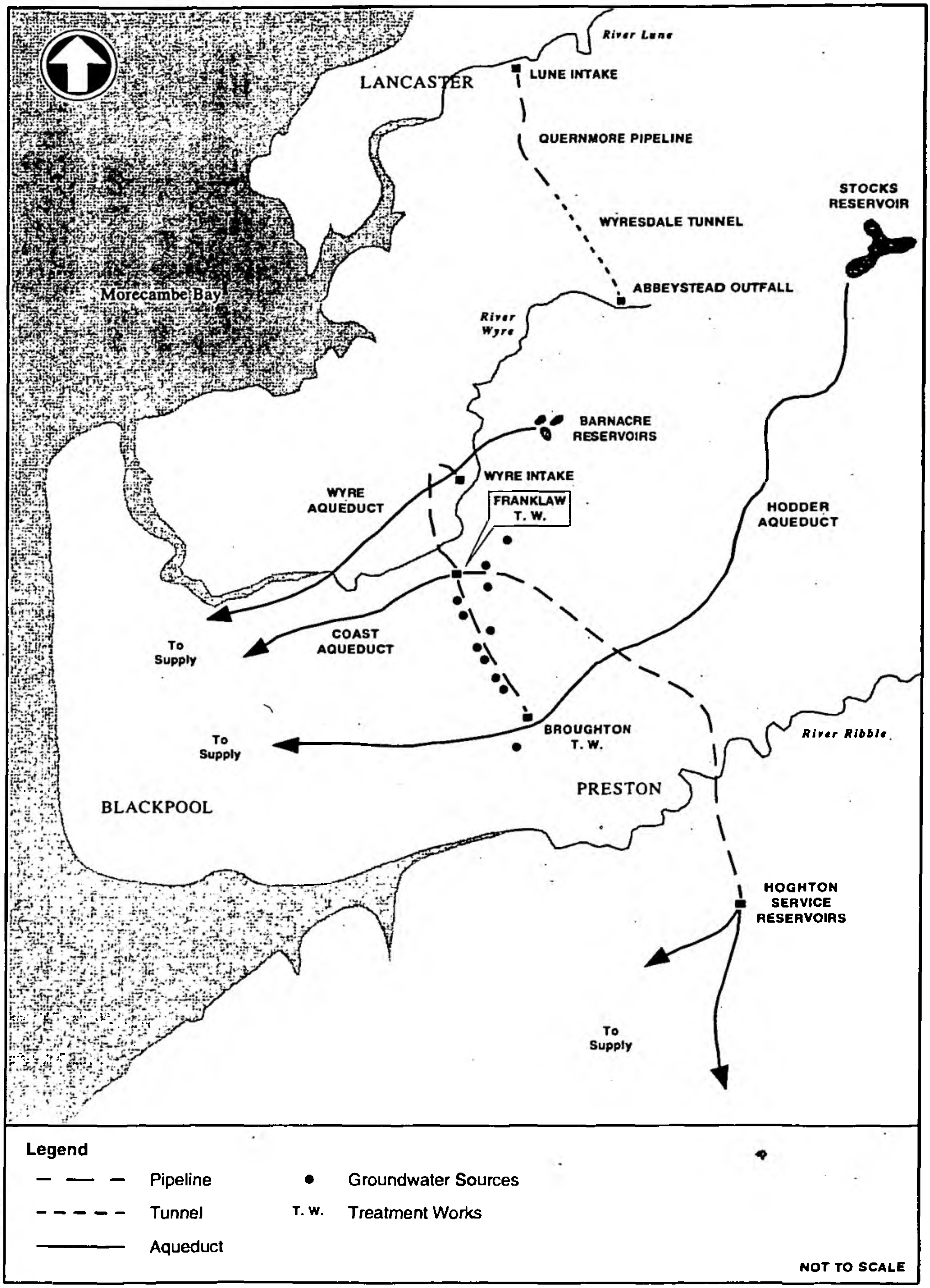
(5) Environmental Report by Aquatic Pollution and Environmental Management "Review of the Ecological Effects of Low Flow in the Fylde Area ", Draft Report March 1996 - a study commissioned by the Agency during the course of these studies.

Figure 1.1

Location Map



Layout of Lancaster Conjuctive Use Scheme



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CHAPTER 2

HYDROLOGY AND HYDROGEOLOGY

CHAPTER 2

HYDROLOGY AND HYDROGEOLOGY

2.1 Hydrology and Land Use

The hydrometric network is shown in Figure 2.1. This shows the rainfall stations, river gauging stations and spot gauging network set up as part of these studies by the Agency.

2.1.1 Rainfall

Extensive rainfall records of good quality were provided by the Agency; the majority consisted of daily data, but some of the upland gauges were limited to monthly data. For hydrological analysis and modelling, 14 of these gauges with largely complete records were selected to give a representative coverage of the area (Table 2.1).

Average annual rainfall is less than 1000 mm on the Fylde plain, but increases substantially with altitude and on moving inland to a maximum of around 1800 mm. The annual rainfall totals do not show any clear trend. However there was particularly wet period between 1980 and 1983, peaking in 1980 at 2075 mm at Abbeystead and 1293 mm in the Fylde plain (St Michael's). The driest year (since 1961) was 1995, with rainfall on the Fylde plain down as low as 760 mm (St Michael's).

The average monthly rainfall measured at St Michaels gauge (representative of the Fylde Plain) varies from a maximum of 110mm in October to 59 mm in February.

2.1.2 Evapotranspiration

Evapotranspiration was derived from a program developed by R Manley for the Agency (1995), called PET-CALC, which requires input of latitude, longitude and altitude, and outputs monthly estimates of potential evapotranspiration for the period 1918 to 1991. For each of the main tributories shown in Figure 2.1, an average altitude was estimated and entered together with the latitude and longitude of the approximate centre of the catchment.

Average annual potential evapotranspiration for the catchments is shown in Table 2.2; it can be seen that there is little difference in potential evapotranspiration for upland and lowland areas.

TABLE 2.1

Summary of Rainfall Records Used for Preliminary Hydrological Modelling

Name	Station number	Period of record	% complete	Mean annual rainfall (mm)
Brennand	573695 M	1974-94	98	1792
Chipping	574005	1972-94	100	1416
Longridge	575662	1961-94	98	1188
Haighton Reservoir	573352	1961-94	95	1114
Haresyke	577658 M	1974-94	100	1821
Abbeystead	577793	1961-94	100	1369
Highcross Moor	577880 M	1974-94	100	1336
Damas Gill Reservoir	577881	1961-94	98	1224
Barnacre Reservoir	578008	1961-94	100	1243
Barnsfold Reservoir	578378	1974-94	100	1274
St Michael's	578682	1961-94	100	987
Hambleton	578978	1973-94	100	956
Pilling	579149/ 579155	1973-94	100	968
Nateby	579215	1968-94	99	918

Notes:
1. M indicates a monthly raingauge. In addition, some daily gauges have occasional periods with only monthly values.
2. The mean annual rainfall is derived from infilled series for the period 1961-94.

TABLE 2.2

Annual Potential Evapotranspiration (PE)

Catchment	PE (mm)	Catchment	PE (mm)
Abbeystead	531	Barton Brook	552
Grizedale	544	Scorton	543
Calder	545	Garstang	556
Brock	546	St Michael's	563

Note: The named catchments refer to incremental areas ie excluding any upstream catchment which is listed separately.

Check comparisons between the PET-CALC derived values and monthly values derived from MORECS grid squares 91 and 97 which cover the study area, indicated a reasonable agreement for an overlapping period of 159 months. Overall, average values from PET-CALC are about 3% lower than MORECS for square 91 and about 7% higher for square 97.

2.1.3 River Flows

Daily river flow data for eight gauging stations were used in the study (Table 2.3).

TABLE 2.3
Gauging Station Records

Catchment	Station Reference	Period for Calculation of Mean Flow	Mean Flow (m^3/s)	BFI Calcu-lated	BFI Published
Wyre at Abbeystead	720101	1969 to 1995	2.085	0.22	
Grizedale Brook	720103	1972 to 1980	0.152	0.36	
River Calder	720210	1970 to 1981	0.435	0.30	
River Brock upstream of the A6	720215	1979 to 1995	0.905	0.34	0.32
Barton Brook at Hollowforth	720212	1985 to 1995	0.643	0.27	
Wyre at Scorton	720102	1977 to 1995	3.260	0.35	0.36
Wyre at Garstang	720107	1977 to 1995	3.521	0.32	0.31
Wyre at St Michael's	720517	1977 to 1995	7.018	0.33	0.32

Since a number of these gauge stations lie very close to the geological boundary between the Carboniferous formations and the Fylde plain, they were of value in defining the runoff characteristics of the upper Wyre catchment, developed upon Carboniferous rocks.

The flow series have been analysed using the procedures recommended in the Low Flow Studies report (Institute of Hydrology, 1980) to separate the baseflow and runoff and to calculate the baseflow indices (BFI, defined as the ratio of total baseflow volume to total volume of flow) for each catchment; missing data were infilled.

Since it was expected that runoff from the Fylde plain would be lower relative to natural baseflow than from the uplands of the Carboniferous, the highest value for BFI was expected at St Michael's, the gauging station furthest downstream on the river system. This is not so and BFI's are broadly similar across the area; it was therefore assumed that a reduction in baseflow on the plain, resulting from groundwater abstraction, produces a significant reduction in baseflow index for St Michael's.

A preliminary estimate of the influence of groundwater abstractions on river baseflow was made by comparing daily river flows with groundwater abstraction rates. Although there was a slight tendency for low baseflow to be associated with high abstractions, the data does not indicate a clear relationship. Furthermore, any relationship between these two variables does not necessarily imply that baseflow is directly influenced by the level of abstractions; comparison with rainfall data for the upper catchments suggests that low abstraction tends to occur in wet years (when surface water availability is above average), and high abstraction in dry years when baseflows may be lower anyway.

During 1994 the Agency set up a number of sites for spot gauging to be carried out on a regular basis. These were as far as possible similar to sites set up in the 1972/73 tests. Locations of these sites are shown in Figure 2.1. Data from 1994, 1995 and 1996 indicate that a reduction in river flow occurred along a number of reaches:

- near Garstang which might relate to abstraction from NWW sources W and Z (refer to figure 2.11);
- from the River Wyre downstream of the confluence with the River Calder (located about 1 km from NWW source M);
- along the River Calder at Calder Bridge and Calder Weir;
- along the river Brock (upstream of Roe Bridge and downstream of New Bridge);
- at various locations along Barton and Woodplumpton Brooks and the New Draught.

The later gaugings confirm that not only similar stretches to those identified during the original LCUS investigations were being affected, the effects were more widespread.

The locations of these loss reaches are shown in Figure 2.1.

No gauging data are available for the Pilling, Cocker and Ribble and knowledge of losing and gaining sections is not available.

2.1.4 Surface Water Transfers and Abstractions

River flows are significantly modified by several surface water transfer, abstraction and augmentation schemes, as follows:

- The Lune-Wyre transfer scheme which modifies river flows in the Wyre.
- Abstraction from the River Calder to feed the Lancaster canal.
- Other surface water abstractions feeding reservoirs, notably from the River Calder and Grizedale Brook.

- Augmentation of river flows in the Fylde Plain in low flow periods, using water abstracted from the Fylde aquifer.

In the Lune-Wyre scheme, Lune water is discharged to the Wyre just downstream of Abbeystead Reservoir, with abstraction at Garstang. The licence allows abstraction of the transferred 'Lune' water plus certain proportions of 'Wyre' water when available above specified threshold flows. Daily values of the transfer from the Lune and the net abstraction from the Wyre (ie actual abstraction at Garstang less the transfer from the Lune) were available for the period from 1980 to 1995. On average 23 Ml/d were added at Abbeystead in this period whilst 33 Ml/d were abstracted at Garstang. The maximum rates of transfer and abstraction were both about 200 Ml/d with high rates generally sustained over only one or two days.

For the Calder-Lancaster Canal transfer, daily transfer to the canal averaged 2.5 Ml/d from 1974 to 1991 with a maximum rate of 36 Ml/d. High rates of transfer only occur over periods of a few days. In wet conditions, surplus water in the canal overflows to the River Calder and the Woodplumpton Brook, both tributaries of the Wyre. Although these natural overflows are unrecorded, this is not considered significant since low flows are the primary concern of this study.

Some surface water abstractions, notably from the River Calder, Grizedale Brook and tributaries of the Tarnbrook Wyre upstream of Abbeystead, feed reservoirs. These abstractions were designed to divert all the flow in the river channel at the abstraction point for flows up to about mean flow; detailed records of these abstractions were not available.

Augmentation of river flows during low flow periods with groundwater, takes place on the River Wyre at Wyre Lane, on the River Brock just downstream of the Lancaster canal, on the River Calder at Stubbins Brook and on Mill Brook at Hollowforth. Augmentation ranged from zero in 1987 and 1988 to 590 Ml in 1992, with an average of 220 Ml/year; there was no augmentation prior to 1987.

2.1.5 Hydrological Modelling

The main objective of hydrological modelling was to simulate river flows originating in the upper reaches of the Wyre catchment underlain by formations of Carboniferous age. These models could then be used to derive river inflows to the groundwater model at the Carboniferous boundary.

The lumped parameter model, HYSIM (developed by Manley, 1993) was used for this purpose. Six upstream catchments models were developed and calibrated: Abbeystead, Scorton, Grizedale Brook, River Calder, River Brock and Barton Brook. In addition, models of the Garstang and St Michaels subcatchments were also developed and calibrated with inflows provided from the upstream catchments in order to check the overall hydrological model calibrations.

The model uses rainfall and potential evapotranspiration data, together with any surface or groundwater abstractions or augmentation, to generate the simulated river flows. These are then compared with available recorded data, and hydrological model parameters adjusted to achieve a reasonable fit.

2.1.6 River Geometry

Accurate river channel survey data was needed to establish channel width, the relative elevation of the river bed and the surrounding land for reasonable representation of surface water/groundwater interaction in the groundwater model.

River channel survey data was acquired from the Agency (Preston area office). River cross sections are available for the River Wyre from Cartford Bridge (near the confluence of Thistleton Brook and the River Wyre) to Dolphinholme (just upstream of the M6 motorway). Cross sections are also available for parts of the River Brock, the River Calder, Thistleton Brook, Woodplumpton Brook and the River Ribble. These sections extend over much of the area underlain by Sherwood Sandstone in the Fylde plain. They were augmented by new survey for the River Wyre tributaries on the Fylde plain as far east as the contact with the Carboniferous and for the River Cocker and Pilling Water in the north.

2.1.7 Land Use

For the purposes of recharge simulation, land use in the area was simplified to three major land use types:

- Much of the Fylde plain is pasture, with scattered woodland; some arable crops, mainly potatoes and other vegetables, are grown in the north west towards Morecambe Bay.
- The fells to the east comprise mainly rough pasture and open moorland.
- Areas within the Fylde Plain, called 'mosses'; a major example is Winmarleigh Moss. These are peaty areas with historically poor drainage associated with groundwater discharge where the drift cover is thin.

2.2 Geology

2.2.1 Geological Setting

The geology of the Study area consists of the following elements:

- A deep basement of deformed Lower-Paleozoic rocks; deeply buried and without outcrop in the study area.

- A folded sequence of rocks of Carboniferous age, lying unconformably upon the lower Paleozoic rocks, whose outcrop is expressed as hill and fell country which defines the eastern margin of the Fylde plain.

- Rocks of Permian to Triassic age, unconformably overlying the Carboniferous rocks and occurring as thick accumulations under the Fylde and westwards, in fault bounded basins or troughs.

- Quaternary glacial and post-glacial sediments (termed the Drift) which mantle the Permo-Trias rocks across the Fylde, and locally cover Carboniferous outcrop.

The geological succession is summarised in Table 2.4. Figure 2.2A reproduces the geology of the Study area as depicted on the published 1:50,000 geological sheets 67 (Garstang) and 75 (Preston). However, the extent of the Fylde aquifer and the position of major faults has been revised during the Study (Figure 2.2B) - see Section 2.2.2.2 and Chapter 5.

A NE-SW cross section of the deep geological structure of the area and an E-W section of the drift geology along the M55 motorway are shown on Figures 2.3 & 2.4 respectively (after BGS).

TABLE 2.4

Summary of Geological Succession

Period	Lithology/Formation	Thickness
Quaternary	Drift: Peat Alluvium River Terrace Deposits Head Glacial Lake Deposits Glacial Sand & gravel Till, boulder clay	up to 60 m
Triassic	Mercia Mudstone Group Sherwood Sandstone Group	up to 500 m up to 1100 m
Permian	Manchester Marls	up 110 m
Carboniferous: -Namurian -Dinantian	 Millstone Grit Group upper Bowland Shale group Bowland Shale Group Worston Shale Group Chatburn Limestone Group	 up to 1000 m up to 500 m up to 3000 m up 130 m

2.2.2 Solid Geology

2.2.2.1 Lithostratigraphy

Carboniferous:

Dinantian rocks underlie the whole area and outcrop within the Vale of Chipping as the core of a NE trending denuded anticline. Much of the Dinantian succession consists of mudstones or siltstones and shales with minor sandstone beds; significant limestones, generally argillaceous but with reef development, occur in the section.

Namurian rocks outcrop in elevated hill masses flanking the Vale of Chipping, to the north in the Bowland Fells and to the south, forming Longridge Fell. The Namurian, represented by the Millstone Grit Group, is a sequence of sandstones and grits with mudstones; the grit members forming prominent features where they outcrop in the fells.

The Namurian sandstones are variable from thick bedded, medium to coarse turbiditic sandstones to thin bedded flaggy laminated sandstones.

Permo-Triassic:

The marine Permian section, termed the Manchester Marl, consists of a reddish-brown mudstones of maximum thickness 28m in the study area. The bed does not appear to be continuous in the east; it has been proved in shallow boreholes below drift cover, between Garstang and Fulwood and is encountered at a number of locations along the faulted boundary between the Carboniferous and Permo-Triassic rocks in the area between Barton Brook and Woodplumpton Brook.(Figure 2.2A)

The Triassic Sherwood Sandstone Group, (which forms the Fylde aquifer), is a product of mixed aqueous and aeolian deposition under desert conditions; precise correlation of beds within the sequence is difficult because it is unfossiliferous. It is typically a red to red-brown, fine to medium grained sandstone, with sporadic layers of coarse sand, clastic marl[1] flakes and thin beds of red silty mudstone; the sandstone has intergranular porosity but is locally fissured. Within the sandstone, individual 'marl' (mudstone) beds are typically thin (0.6m) and are more common in the basal part of the sequence. This has required the sandstone aquifer to be modelled as a two layer system (Section 2.5.2, Chapters 3&4).

Both hydraulic performance of the aquifer and the recent geophysical reinterpretation of the Fylde aquifer by the BGS have suggested the presence of relatively persistent marls within the Sherwood Sandstone Group (referred to in the latter report as the 'Intra-Sherwood Sandstone Marls' - see Section 2.2.2.2).

The younger Mercia Mudstone, which occur to the west of the Woodsfold fault comprises fine grained, laminated mudstones and siltstones, deposited mainly in shallow marine conditions

2.2.2.2 Structure

Carboniferous:

Carboniferous rocks outcrop in the Bowland and Longridge Fells. These rocks have been folded into a series of anticlines and synclines of NE axial trend, and have been faulted along a general NW trend.

Permo-Triassic:

The Permian and Triassic rocks of the Fylde Plain overlie the Carboniferous basement in a marked angular unconformity. They dip west from outcrop, to depths of over 500m close to the Woodsfold fault where the Sherwood Sandstone is downthrown by up to 600m and is overlain by the Mercia Mudstone.

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1 although the mudstones in the Permo-Triassic sequence of the Fylde are referred to as 'marls', both in this report and in general terminology, they are not true marls since they are non-calcareous.

Further west, in the Kirkham Basin the Permo-Triassic sequence reaches thicknesses well in excess of 1500m.

As Permo-Triassic sediments accumulated upon a deeply eroded Carboniferous surface, concurrent N-S oriented rifting produced fault bounded depositional basins in the region which have exerted a strong control upon the present thickness of Permo-Trias rocks. The Permo-Trias rocks are little folded, but are faulted along N-NE trends which are well established on geophysical evidence. The major faults cutting the Permo-Trias are shown in Figure 2.2B and Figure 2.5.

Figure 2.5 also shows the elevation of the base of the Sherwood Sandstone Group as inferred by BGS from seismic and gravity data (BGS, 1995). This work was commissioned by the Agency because of uncertainty over the geological structure in the southern half of the Fylde aquifer and modelling difficulties which arose during the Study. It has subsequently been complemented by the sinking of two exploratory/observation boreholes, one to the north west of Preston and the other north east of Preston centre.

The key differences in structure, compared with the published geological maps are:

- the dominant N-S fault trend;
- the Woodsfold Fault veers N-S, west of Garstang, rather than running NE onto the Carboniferous margin of the aquifer;
- termination of the western subcrop of the Sherwood Sandstone by faulting;
- the presence of a set of relatively minor parallel faults east of the Woodsfold fault, north west of Preston (in an area referred to as the' Woodplumpton Terrace');
- the presence of a raised 'Horst' block between the LCUS NWW Broughton A sources and the Whitbread sources in the south east of the model, where the sandstone thickness reduces to less than 100 m;
- a deep basin south of the River Ribble, east of Preston, the northern limit of which is defined by a major E-W fault;
- the Catterall Fault defined in the former posotion of the Woddfold fault in the north east.

The BGS's refinement of the structure in the western half of the Study area (around the Woodsfold Fault and into the Kirkham basin) can be viewed with a high level of confidence because of the abundance of seismic lines on which the reinterpretation was based, as well as it tying in with new borehole information, hydrogeological responses and model output (Chapter 4).

However, this is not the case around and to the east of Preston where there is a paucity of seismic data. Historical borehole logs in this area had reportedly encountered red mudstone at relatively shallow depth, previously interpreted as being either basal Manchester Marl or underlying Carboniferous strata (BGS-Garstang Memoir, 1990 and in this study, Phase II report, Chapter 3). This implied dramatic variations in aquifer thickness and a 'horst and graben' structure was postulated early in the Study. By contrast, the BGS's geophysical reinterpretation inferred gradual thickening of the aquifer south westwards from its eastern margin. Therefore, a 190m deep fully cored borehole was drilled for the Agency in December 1996 in Moor Park, on the northern side of Preston. This encountered Carboniferous strata (sandstones and mudstones/shales) below a depth of 107m whereas the Sherwood Sandstone was unbottemed at 320m depth in one of the former Courtaulds boreholes 2.5 km to the east. This confirms that there are considerable variations in aquifer thickness in the south east of the Study area. Re-examination of borehole logs, piezometry and geophysical data (seismic, gravity and electro-magnetic) has enabled further revision of the structure of the aquifer; Figure 2.2B shows the current understanding.

This aspect of the Study has been of fundamental importance in model development, particularly regarding the concept of hydrogeological compartmentalisation.

Carboniferous Boundary:

In the east of the area, the Carboniferous/Permo-Triassic junction appears to be part faulted and part unconformity at depositional overlap. Locations of these contacts are shown in Figure 2.6, a section through the Carboniferous along its contact with the Permo-Triassic. The three main types of types of contacts are delineated :

- ***Faulted Contact***; where a hydraulic contact between the water bearing formations of the Carboniferous (eg Ellel Crag, Wellington Crag and Park Wood sandstones and Pendle Grit) exists and therefore the transfer of water between Triassic Sandstone and Carboniferous is considered to be highest along the contact. This contact exists to the north west and west of Garstang and at the upstream end of the River Ribble.

- ***Manchester Marl Unconformity***; where Manchester Marl separates Carboniferous water bearing formations and the Triassic. Here the transfer between the two units is considered to be very low as a result of the low permeability of the Manchester Marls.

- ***Unconformity*** where the Sherwood Sandstone directly overlies the Carboniferous (Manchester Marls thin, absent or overlapped).

The nature of the contact between the Carboniferous and Permo-Triassic has a very important bearing on the flow of water between the two units.

Rockhead Topography:

Figure 2.7 shows the elevation of the top of the Sherwood Sandstone as derived from borehole logs which fully penetrate the overlying Drift. The geophysical work by Worthington (1972) has been used to infill data in the Garstang area. The definition of the top of the sandstone is poor in the south western part of the Ribble estuary due to limited data availability.

Drift filled channels, which occur in the sandstone surface, were probably cut by glacial meltwater systems draining off the Bowland Fells. They are referred to in the BGS report on the 'Geology of the Country around Garstang' (1992) and can be identified in the figure. One of these channels is associated with the current course of the Pilling Water and the River Wyre near St Michaels. Other less pronounced valleys can be identified, all extending from the Carboniferous in a southwesterly and westerly direction.

2.2.3 Drift Geology

The Quaternary Drift mantles the Triassic rocks and in some places also extends over the Carboniferous; it consists of glacial and post-glacial deposits. The glacial deposits comprise boulder clays (till) which mantles all but the most prominent bedrock features and glacial sand and gravel; the latter are found as channel-fills over bedrock, stratified spreads in and beneath the till and as eskers and kames. The till can be up to 50 m thick and is generally an ill sorted mixture of rock fragments in an clayey matrix. Figure 2.4 illustrates the Drift geology along the line of the M55 motorway. Early post-glacial deposits include peat accumulations and head deposits (weathered near surface bedrock/Drift, moved down slope by solifluction). Later deposits comprise marine or estuarine silts and clays.

The variability of the drift makes impossible any correlation of individual sub-layers within the Drift. However, since the representation of the Drift in terms the overall proportion of clay within the Drift sequence and the lateral continuity between sand lenses has an important bearing on groundwater modelling, its distribution and lithology is described in some detail below.

In the Blackpool area, early geologists (Binney, 1852, and De Rance, 1875) made a threefold subdivision of the Drift and these original subdivisions, Lower boulder clay, Middle Sand and Upper boulder clay, have been retained in the current memoir (BGS, 1990). Examination of the borehole logs collected during the course of this study has shown that although this sub-division can sometimes be recognised, the patterns are often more complicated, with very little lateral continuity between beds.

Three distinct units can however be recognised within the Drift:

- a poorly consolidated, sometimes sandy, boulder clay;
- sand and gravel;
- a stiff, firm boulder clay;

The two types of boulder clay could not be distinguished in all of the borehole logs as full descriptions are not always in the drillers logs.

The distribution and lithology of the Drift was analysed using contour plots, boulder clay thickness maps and cross sections based on the boreholes logs collected during the course of the study.

Figure 2.8 shows the total thickness of the Drift. In the Garstang area, Drift thickness is part controlled by the occurrence of buried channels in the top surface of the Sherwood Sandstone; greatest thicknesses are found along the River Pilling, in the valleys of the Rivers Wyre and Calder, and in the eastern part of the River Brock. To the south of the Barton Brook, Drift thickness increases to over 20 m.

Relatively thin Drift (< 15 m) occurs in the central part of the Fylde plain and also in the Morecambe Bay area; an extensive area with less than 5 m Drift thickness between Garstang and Morecambe Bay, located around Winmarleigh Moss. In historical times, this was an area of natural discharge from the Fylde aquifer.

Figure 2.9 shows the total thickness of boulder clay within the Drift. This boulder clay is a low permeability material which if reasonably thick and laterally continuous can have a very significant effect in reducing recharge to the sandstone aquifer. Boulder clay free Drift only occurs in a few areas, notably along the River Wyre to the north of Garstang, in isolated locations in the central Fylde plain and locally in the Preston area.

The Drift composition appears to be very variable. The continuity of boulder clay over the region, acting as a blanket cover with interbedded lenses of sand & gravel, is uncertain. The geological section along the M55 motorway (Figure 2.4) shows lateral continuity of boulder clay in the upper part of the Drift, but this also coincides with significant total thickness of Drift and boulder clay. Although correlation between individual boreholes is difficult, the available data indicate that boulder clay is generally laterally continuous across the study area.

The evidence also suggests a reasonable continuity of sand & gravel layers throughout the Fylde plain.

The occurrence of sand & gravel directly over sandstone, appears to be limited to the central part of the Fylde plain and in the central/eastern part of the Ribble valley. The significance of sand & gravel over sandstone relates in particular to areas where seasonal abstraction relies on the releases of groundwater from unconfined storage.

2.3 The Aquifer System

2.3.1 Carboniferous

The Carboniferous rocks to the east of the Fylde are classed as 'minor aquifer' and are relatively unexploited, except for limited agricultural/domestic use. Consequently there is a lack of borehole data, in particular water levels and test data giving aquifer properties; the few available values of transmissivity vary from 6 m^2/d to 337 m^2/d for the sandstone units.

The Carboniferous consists of the Bowland Shale Group, which is likely to be effectively impermeable, and a Namurian sandstone-grit-shale sequence, the Millstone Grit Group. Within the Millstone Grit Group, the sandstone units will act as localised aquifers separated by shales/mudstones, with groundwater movement being predominantly by fissure flow. The thicker sandstone/grits (eg Pendle Grit and Warley Wise Grit) have extensive outcrops on the uplands of the Bowland Fells and Longridge Fell. However, they tend to be displaced by faulting, potentially creating isolated aquifer units.

These beds are brought into contact with Sherwood Sandstone in places along the Bilsborrow fault (Figures 2.2B & 2.6), in particular between to the north and west of Garstang and also south of the Ribble where the Manchester Marls are thin or absent; in these locations, flows from Carboniferous sandstone aquifers to the Sherwood Sandstone may occur.

Some evidence for this process has been given by Sage and Lloyd (1978) and in Sage's MSc thesis (1976). In a hydrochemical study of the Fylde aquifer, they associate high bicarbonate concentrations (> 350 mg/l) with inflows from the Carboniferous rocks, although these areas are of limited extent north of the River Ribble.

During the original field studies of the Fylde aquifer (principally within the Wyre catchment), and subsequent modelling by WRC, it was postulated that, since the basal Permian Manchester Marl was generally absent along the boundary, hydraulic continuity exists between the Fylde aquifer and the Carboniferous. The WRC model then allowed substantial inflows from the Carboniferous as the major **recharge source** to the Sherwood Sandstone, with abstractions from the aquifer being balanced by inflows from the Carboniferous.

On the contrary, evidence from piezometric responses across the boundary suggests that inflow from the Carboniferous is small and does not significantly contribute to sandstone recharge in the Wyre catchment. In particular, hydraulic gradients in the Carboniferous do not show significant changes between pumping and non-pumping years. This is particularly significant when considering the abstractions from NWW sources P, Q and R which are located near the boundary where inflow from the Carboniferous is anticipated. The evidence is further discussed in the section on piezometry (Section 2.4.2).

2.3.2 Sherwood Sandstone

The Sherwood Sandstone Group forms a thick aquifer bounded at the base by mudstones of the Permian Manchester Marl. In the study area, the top of the sandstone aquifer is generally confined by clayey beds (boulder clay) within the overlying Drift. The drift-sandstone boundary may be irregular since drift filled glacial channels occur within the top surface of the sandstone (Section 2.2.2.2 & Figure 2.7). Further, the confining boulder clay layer is locally absent, potentially allowing groundwater flows between river beds, the sand and gravel deposits within drift and the sandstone aquifer; these 'windows' providing pathways for a significant component of recharge and river/groundwater interaction.

Westwards, the sandstone is confined as it dips beneath the Mercia Mudstones within the Kirkham syncline (Figure 2.2B). Although the host sandstone thickens from the Carboniferous contact zone, westwards to over 1000m, active groundwater flow is probably restricted to the upper 200m, although since boreholes seldom penetrate more than 120m of section, the deep groundwater system is little known.

The Sherwood Sandstone aquifer is a fine to medium grained sandstone, generally with intergranular porosity but locally with fissures. Mean section permeability values (Figure 2.10) were estimated from step test data and specific capcity data from the original LCUS investigation using the Logan approximation (which is considered to underestimate the actual permeability).

There are no obvious patterns to the transmissivity distribution. High values do not appear to be associated with river valleys. Data from the NWW abstraction boreholes, which extend along a north-south line 1 to 2 km west of the boundary with the Carboniferous, indicate the presence of high transmissivities; significantly, the majority are located on N-S faults, according to the recent BGS remapping (Figure 2.5). This area also corresponds with a reduction in piezometric gradient, which tends to confirm the presence of high aquifer transmissivity. Many of the NWW abstraction boreholes are also located in areas where Drift sand and gravel directly overlies the sandstone aquifer; the derived transmissivities may therefore be the combined value for the sand & gravel and the sandstone.

Transmissivities are generally lower in the area towards Morecambe Bay; low groundwater flows in this area are confirmed by the high content of total dissolved solids in the groundwater, an indicator of long residence times.

Horizontal permeability in the sandstone may locally be restricted perpendicular to faults. On geophysical evidence, BGS interpret a high density fault zone on N-S axes, in the area of Woodplumpton Terrace, north west of Preston (Figure 2.5); this interpretation is consistent with the observed slow/limited response of piezometers in the area to major abstraction from NWW's sources further to the east.

Vertical permeability within the sandstone is restricted by 'marl' (mudstone) beds, typically thin (0.6m) and occurring more frequently in the basal part of the sequence; during model development it was found necessary to represent the aquifer as two layers.

Unconfined aquifer conditions occur in the sandstone during the seasonal intensive pumping from NWW boreholes. During the earlier LCUS investigations, WRC assumed a value of 9% for the unconfined aquifer storage coefficient. This value seems high and probably represents an upper limit; values in the range of 3-9% were tested during model calibration, with a final value of 6% adopted..

Recharge to the aquifer appears to be mainly by vertical transfer through river bed material and through the permeable drift aquifer, to the sandstone, in areas where boulder clay is absent; evidence from drift piezometers shows that sandstone abstraction is met partly from increased flows from the Drift. Recharge flows across the Carboniferous boundary, from permeable members of the Millstone Grit Group, is generally insignificant; Carboniferous piezometers generally fail to respond to sandstone abstractions.

Discharge from the sandstone aquifer occurs as follows:

- Vertical discharge to diffuse seepage in the coastal zone around Morecambe Bay and to the SW about the estuary of the River Ribble.
- Discharge as river baseflows, in stretches of river where boulder clay is absent and there is continuity between river bed and permeable Drift. Discharge to baseflow, controlled by head differences between the Drift water levels and river level, is considered to be the major aquifer discharge path.
- Flows into the Kirkham Basin, where the sandstone becomes deeply buried beneath Mercia Mudstone, which is considered to be relatively insignificant.

2.3.3 The Drift

The Drift is a heterogeneous mixture of boulder clay and sands and gravels, between 5-30m thick, whose individual layers are laterally impersistent and locally absent. An aquifer is developed within sands and gravels of the Drift, but almost no data exist on the Drift properties, in particular the horizontal and vertical permeabilities of boulder clay and sand & gravel.

The occurrence and position of the Drift sand and gravel aquifer, is a major control on recharge to the Sherwood Sandstone aquifer. These controls on the aquifer derive from:

- the overall proportion of boulder clay within the Drift sequence, which controls both the Drift vertical permeability and hence the leakage (or recharge) to the top of the Fylde aquifer or to river baseflows;
- the lateral continuity between sand lenses, which controls the horizontal permeability of the Drift.

The distribution and vertical permeability of boulder clay is therefore highly significant in controlling recharge to the Sherwood Sandstone; values in the range of 10^{-4} to 10^{-3} m/d are likely. The horizontal permeability of sand & gravel depends on composition and degree of sorting; high values are expected to be in the range of 5 to 25 m/d.

Where sand & gravel directly overlies the Sherwood Sandstone, the effective thickness of the aquifer is increased, leading to higher transmissivities. At these sites, intensive pumping of LCUS abstraction boreholes draws water from storage in the sand & gravel aquifer.

2.3.4 Mercia Mudstone

To the east of the Woodsfold fault zone, Mercia Mudstone is absent beneath the Drift but westwards, the Permo-Trias section thickens into a deep depositional basin about Kirkham, where the Sherwood Sandstone becomes confined beneath Mercia Mudstone at over 300m depth. Here, the Mercia Mudstone is a confining layer of low permeability; piezometry suggests that groundwater flows through the sandstone aquifer in this deep confined area are very small.

2.4 Groundwater

2.4.1 Groundwater Abstraction

The Fylde aquifer is extensively used for water supply. A large number of boreholes were sunk between 1956 and 1971 by the former Fylde Water Board; abstractions are now managed by North West Water (NWW). There are a number of industrial users, namely ICI, BNFL, Whitbreads and North Country Poultry. Courtaulds also held a licence until 1980. The locations of all abstraction boreholes are shown in Figure 2.11, while the historical increase in groundwater licensed quantities is presented in Section 1.2.

The NWW sources consist of groups of up to 6 boreholes at each site. The daily licences are generally specified for individual sites but annual licences are specified for groups of sites. In some cases there is also a limitation on the aggregate abstraction over a three year period and on conjunctive use at combined sites. A summary of licensed abstraction boreholes is given an Appendix B.

The annual abstractions for NWW and other abstractors are shown in Figure 2.12.

2.4.2 Piezometry

Sandstone

Water level data for 150 observation boreholes was used to study the piezometry of the Sherwood Sandstone aquifer.

Figure 2.13 shows the distribution of observation boreholes; good cover exists in the central area of the Fylde plain but little data is available in both the north west and south west of the study area.

Figure 2.14 shows the piezometry of the sandstone aquifer for two periods: April 1987, when abstraction was at its lowest and the piezometry is relatively high; and for August 1976 following a period of relatively high abstraction rates and low rainfall representing minimum piezometric conditions.

In April 1987, groundwater flows broadly westwards from the Carboniferous boundary; flow then divides, with groundwater south of the River Brock flowing south west towards the River Ribble and its estuary, and groundwater north of the River Brock flowing north west to Morecambe Bay. Piezometric gradients are steepest close to the Carboniferous boundary (of the order of 0.005) and shallowest in the west (of the order of 0.001).

In August 1976 the piezometry indicates that most of the westward flow from the Carboniferous boundary are intercepted by the NWW wells. During this period of intensive pumping a linear trough in the groundwater piezometry is created in the central part of the Fylde plain, between the River Wyre and the Woodplumpton Brook. This produces a reversal in the groundwater flow to the north west of Preston.

September 1995 also follows a period of relatively high groundwater abstractions (particularly north of Barton Brook) and very low rainfall. Groundwater levels around NWW sources L and M are considerable lower in September 1995 than in August 1984 (when groundwater abstractions were at a similar level, but followed a period of average rainfall). The lower groundwater levels in 1995 are therefore a result of the lower rainfall indicating that rainfall has a significant impact on groundwater resources. This was not considered important in the WRB/WRC studies in the early 70's, where the leakage of rainfall through the Drift deposits was considered a relatively minor component of the groundwater resource system.

Individual observed groundwater level hydrographs are described in Chapter 4 along with model simulations.

Drift

Although some Drift piezometry is available for 27 boreholes, data are only available for limited periods and the data is insufficient to derive regional piezometry. The analysis is complicated for a variety of reasons, including:

- The boreholes penetrate a considerable and variable thickness of Drift. Consequently, with different screen setting depths between boreholes in the Drift it is not possible to relate groundwater level measurements between boreholes due to the highly heterogeneous nature of the Drift deposits.

- The extent to which monitored Drift water levels are affected by the Drift geology and the connection of sand & gravel layers with the underlying sandstone.

  For example if the Drift borehole penetrates a sand & gravel layer which directly overlies the sandstone, the measured Drift water level is likely to be closely associated with the sandstone water level. If boulder clay overlies this sand & gravel layer the phreatic surface may well remain close to ground surface.

In many cases, the Drift water level is close to ground surface during the winter and only 0.5 to 1 m above the sandstone water level. During the summer, the Drift and sandstone water levels differ by some 1 to 1.5 m, although this difference increases during years of major abstraction, thereby increasing the hydraulic gradient and hence potentially allowing increased downward leakage.

Many Drift observation boreholes show a clear response to Sandstone piezometric variations, both in the long and the short term. Seasonal fluctuations range from about 3 m during pumping years to less than 1 m during years of low pumping.

In some Drift boreholes, particularly at Barton Brook, a continuous decline of up to 3 m between 1973 and 1977 was observed, with very little recovery since.

Carboniferous

Few water levels are available for the Carboniferous and most of these are located to the east of the M6 between the Rivers Calder and Brock. The data is important as it provides a means of confirming hydraulic connection between the sandstone aquifer and the Carboniferous, a process which was earlier assumed on geological evidence. There is very little influence of abstractions observed in these boreholes. The only influence that may take place is to the east of NWW sources P, Q and R.

2.4.3 Hydrochemistry

Bicarbonate

To give some indication of the origin of the sandstone groundwater, Agency hydrochemical data, which included analyses of major cations and anions and overall electrical conductivity, were used to derive a map of the distribution of bicarbonate (Figure 2.15). This gives a bicarbonate ion distribution broadly similar to that presented by Sage and Lloyd (1978). Deductions are as follows:

High bicarbonate concentrations:

- Around Woodplumpton Brook and near the Carboniferous boundary north of Preston:

  These correspond with areas of thick boulder clay cover which may limit recharge through the Drift and hence indicate long residence times. Inflow of high bicarbonate groundwater from the Carboniferous (sandstones, limestones and shales), either from the higher ground to the east and/or upflow from depth .

- West of Garstang and south of Morecambe Bay:

  The area coincides roughly with a piezometric ridge which forms when pumping from sources W and Z occurs. Low permeabilities in the sandstone indicate that this area may form a partial barrier to groundwater flow in a westerly direction. The consequence is high residence time in the aquifer, as a result of low flows.

An alternative mechanism/explanation is upflow from the Carboniferous basement along major faults.

Lower bicarbonate concentrations:

- Along the River Brock and between the River Wyre and River Calder:

  These may result from a zone of low groundwater contribution from the Carboniferous groundwater, as Permian Marls occur at the contact with the Carboniferous.

  The recharge contribution through the Drift may also be high as the Drift is both thinner and contains a high proportion of sand & gravel.

  Contribution of river water via the Drift to the aquifer induced by groundwater abstraction, would also be expected to result in low bicarbonate concentrations; the low bicarbonate concentrations in boreholes located along the river valleys indicate that leakage from the rivers is likely to be significant.

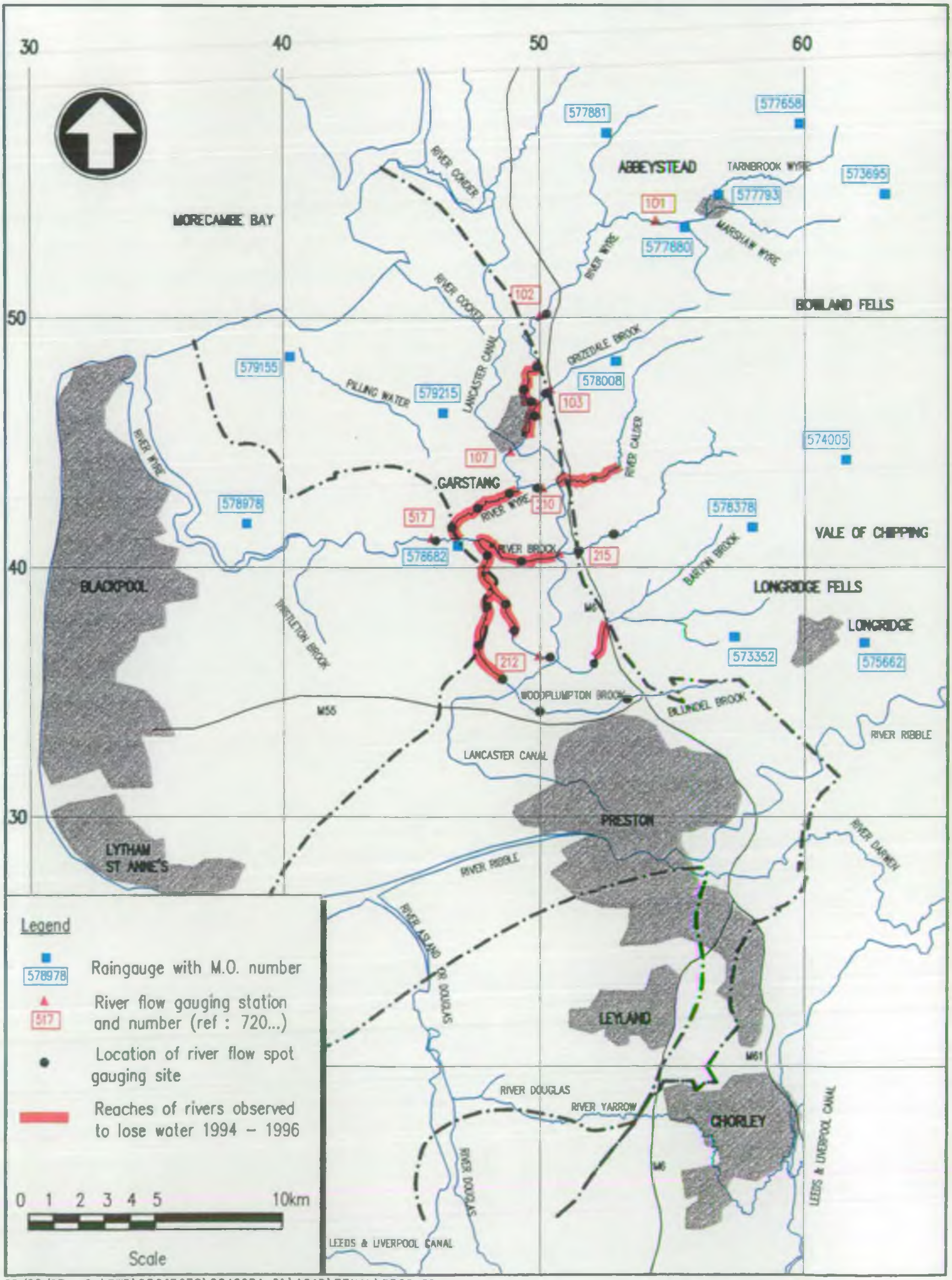
Chloride

Chloride concentrations within the Fylde sandstone have a fairly uniform distribution with typical values around 20 mg/l, except in two areas:

- Chloride concentrations between 170-1360 mg/l occur in the vicinity of Morecambe Bay corresponding with the area of low flow and extended residence times.
- Chloride concentrations between 60-140 mg/l in sandstones within the Kirkham basin; in this case too, low groundwater flows and extended residence times are likely, as well as the influence of poor quality (saline) groundwater associated with evaporites within the Mercia Mudstone Group and younger Triassic sequence.

Figure 2.1

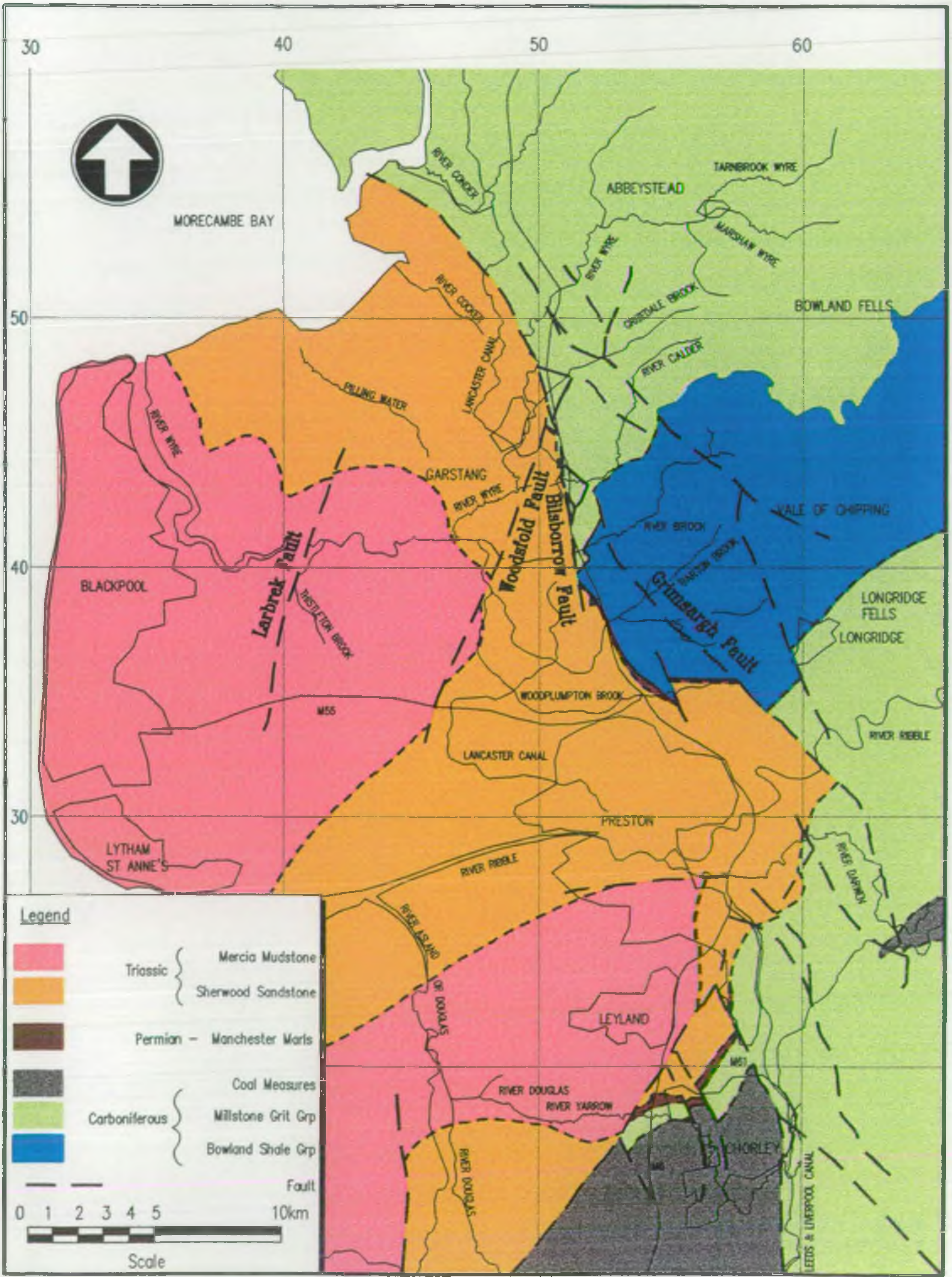
Rainfall and River Gauging Stations



20/02/97 Q: \EWR\PROJECTS\38436BA. 01\ACAD\FINAL\FIG2-01

Figure 2.2A

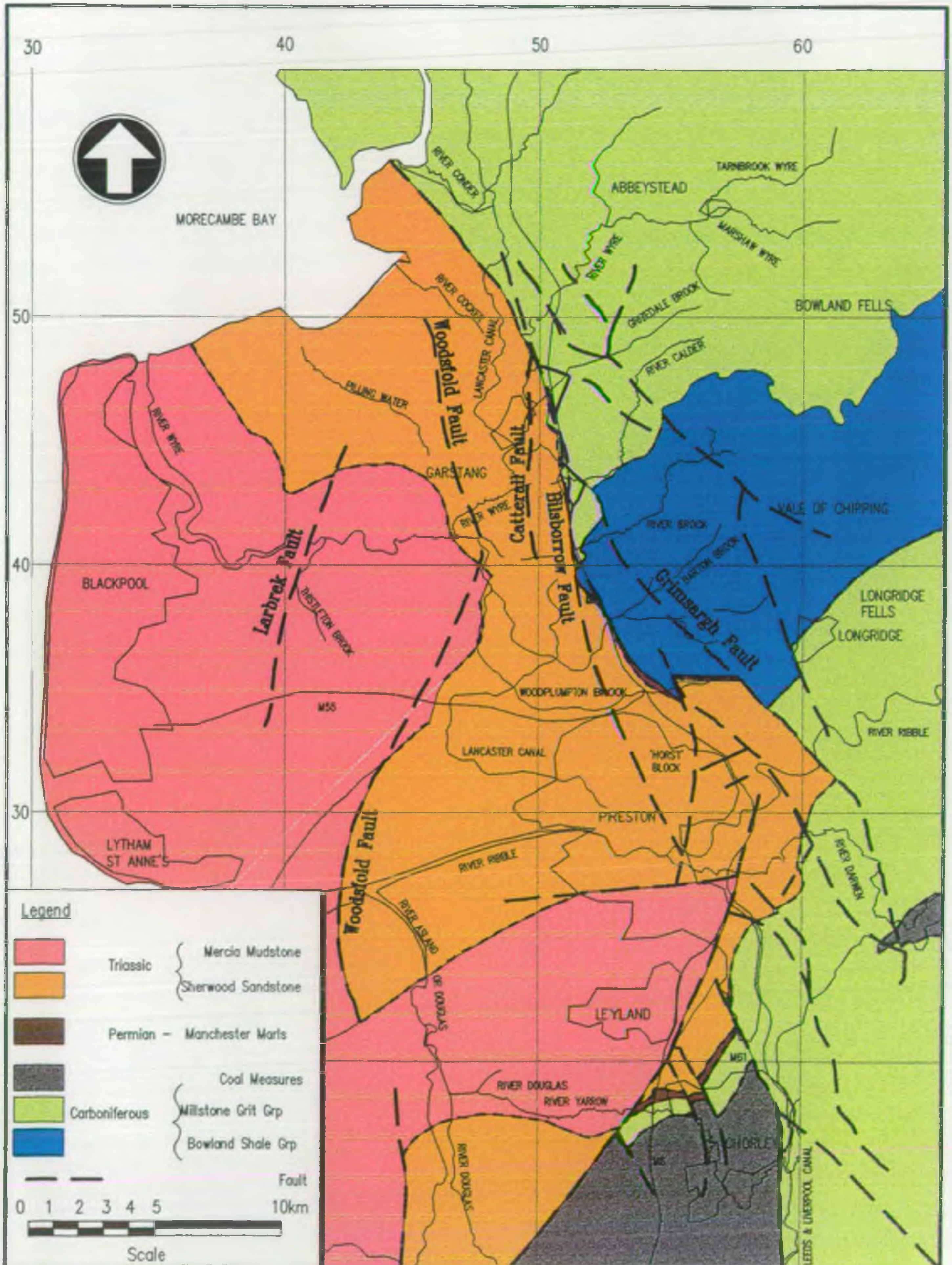
Regional Geological Map (Based on Published BGS Maps)



18/02/97 Q: \EWR\PROJECTS\38436BA.01\ACAD\FINAL\FIG2-02A

Figure 2.2B

Revised Regional Geological Map



31/07/97 Q:\EWR\PROJECTS\38436BA.01\ACAD\FINAL\FIG2-02C

Figure 2.3

Cross Section Showing Deep Structure

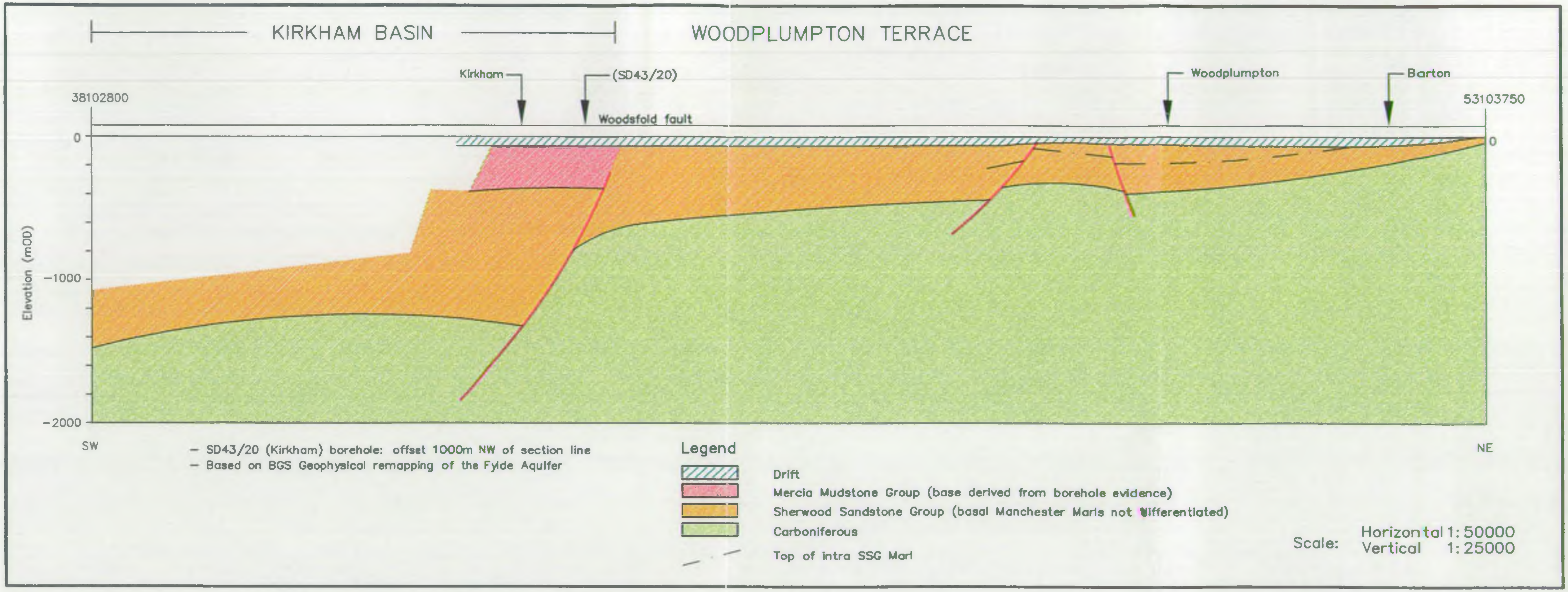
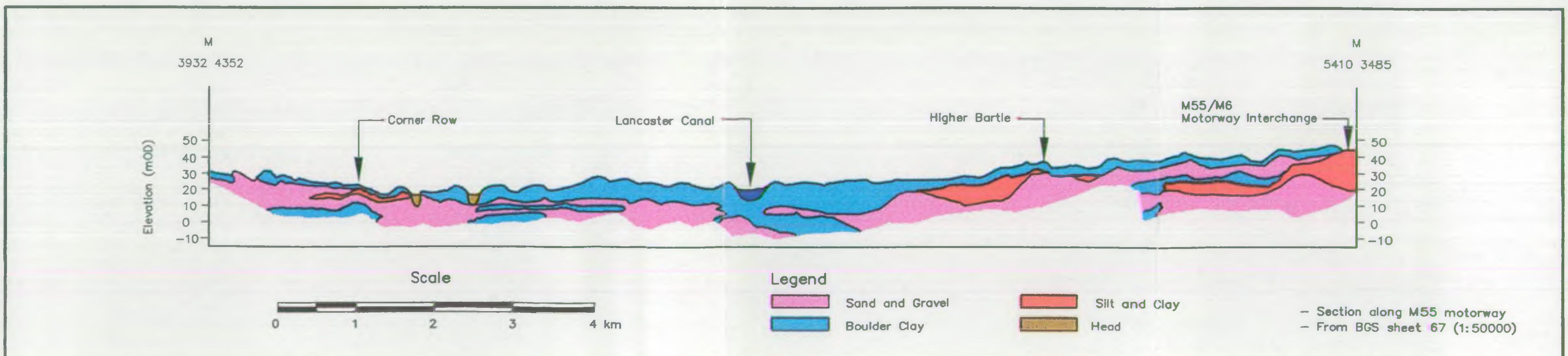


Figure 2.4

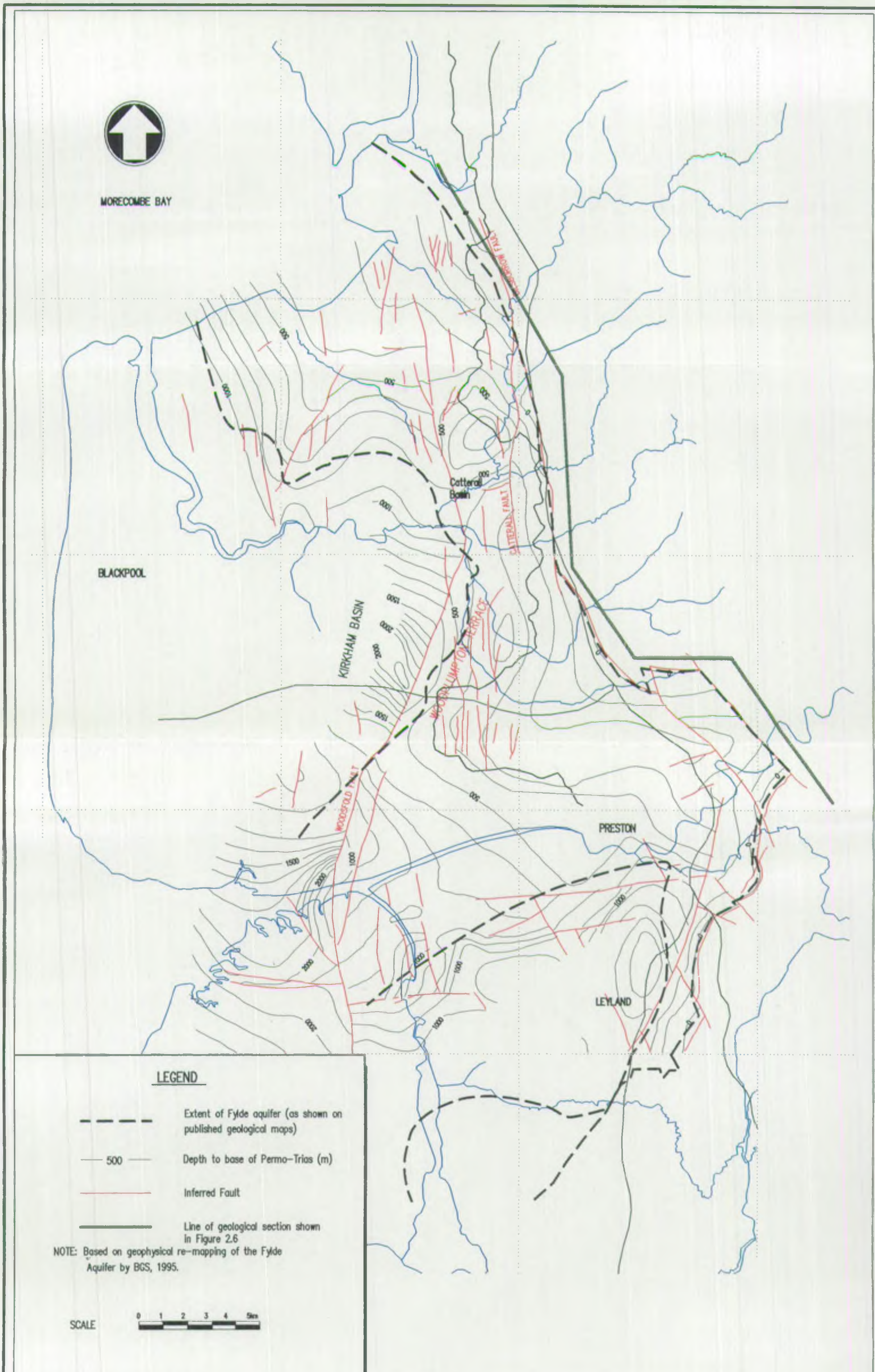
Cross Section Showing Drift Geology



18/02/97 Q:\EWR\PROJECTS\38436BA.01\ACAD\FINAL\FIG2-03

Figure 2.5

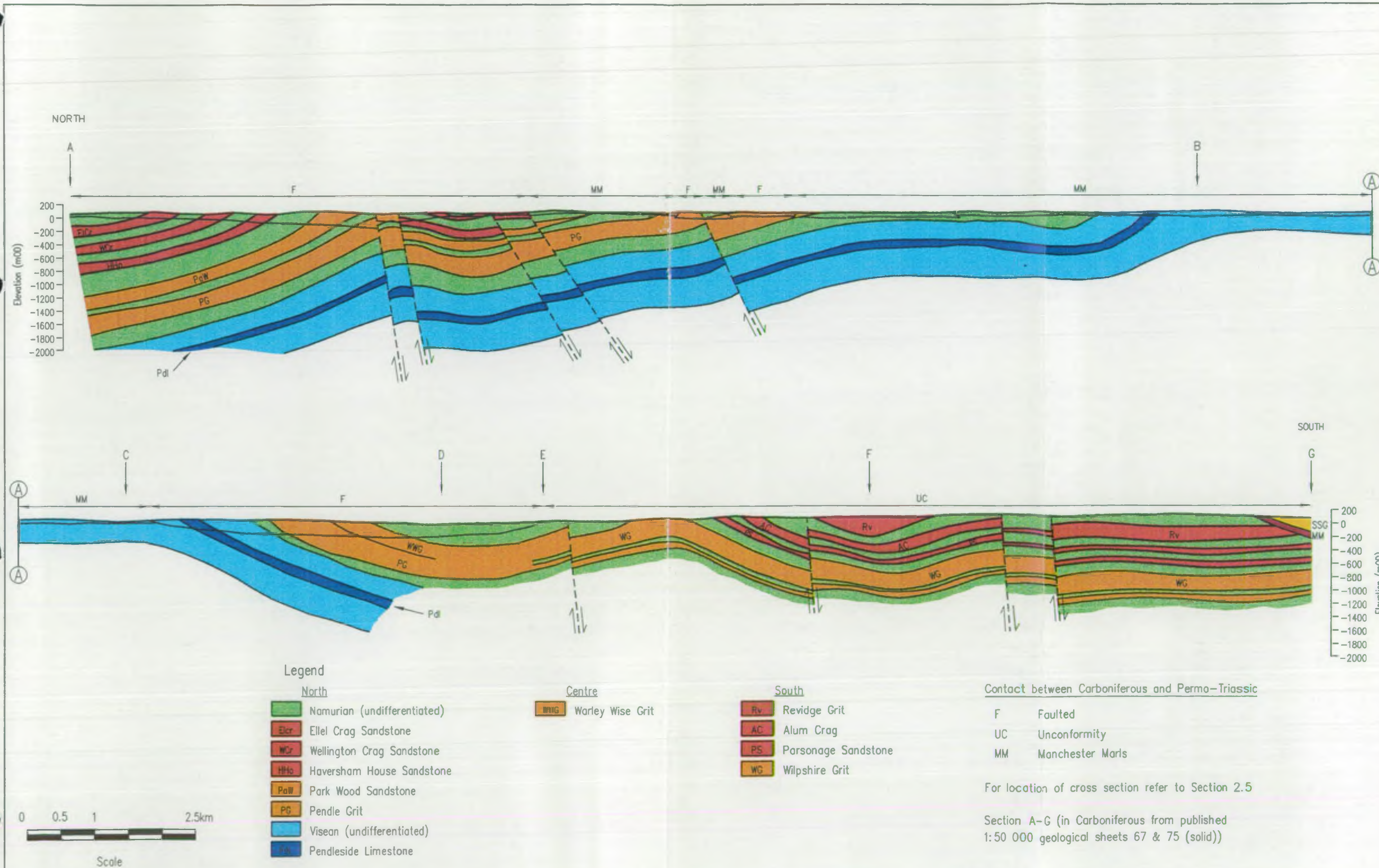
Base of Sherwood Sandstone



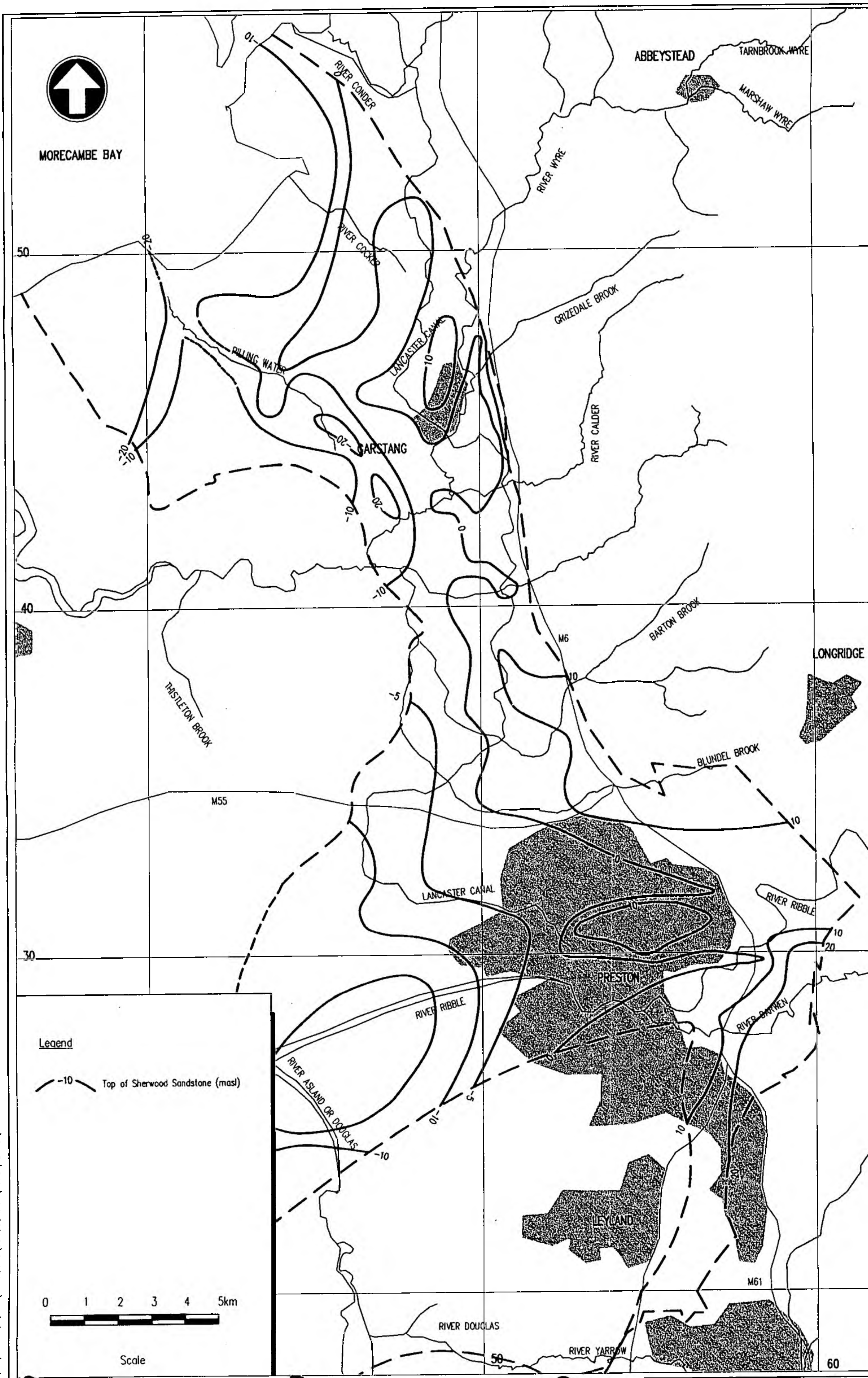
31/07/97 Q:\EWR\PROJECTS\38436BA.01\ACAD\FINAL\FIG2-05m

Figure 2.6

Structure of Carboniferous / Permo-Triassic Contact

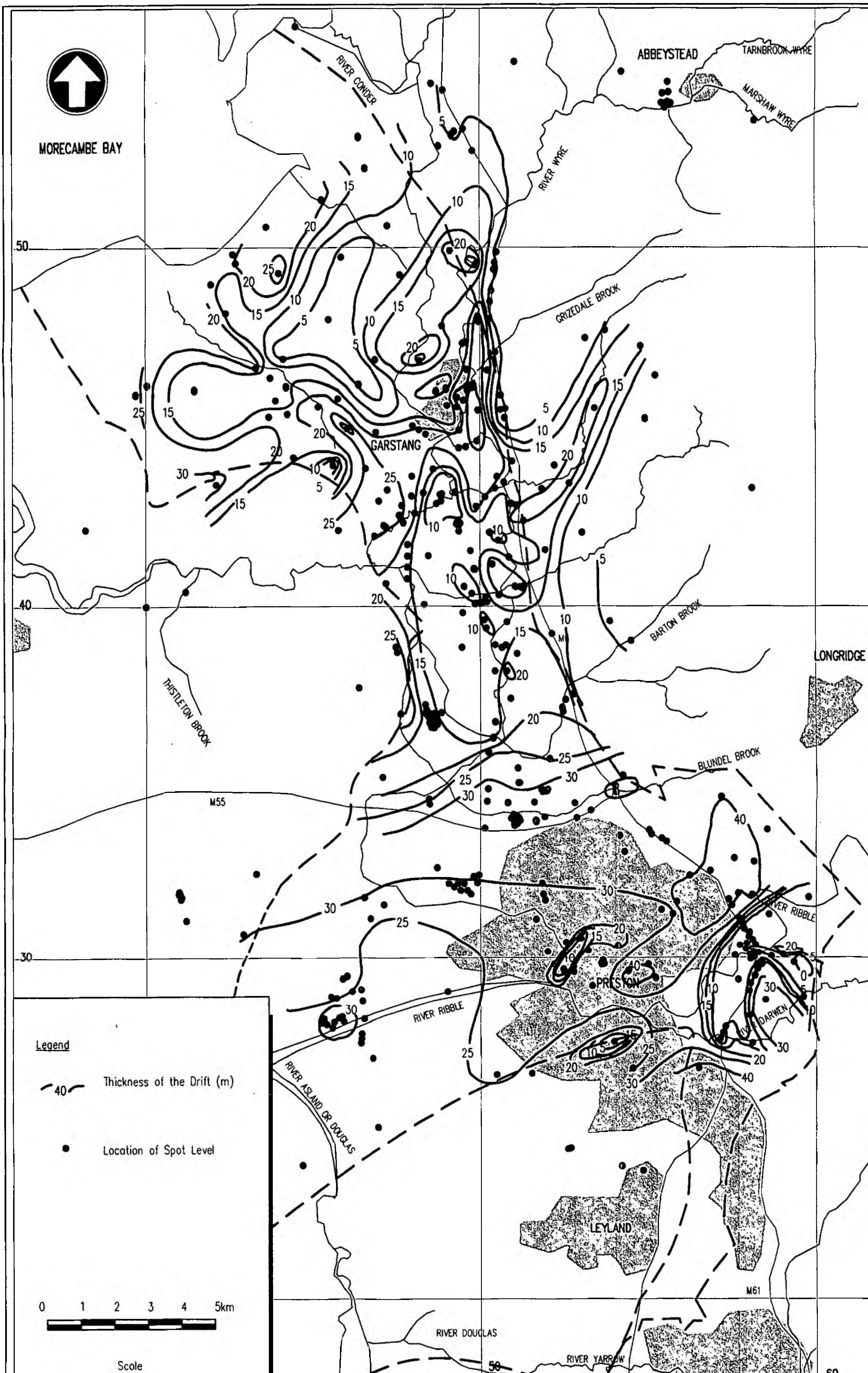


31/07/97 O:\EWR\PROJECTS\38436BA.01\ACAD\FINAL\FIG2-06A



31/07/97 Q:\EWR\PROJECTS\38436BA.01\ACAD\FINAL\FIG2-07a

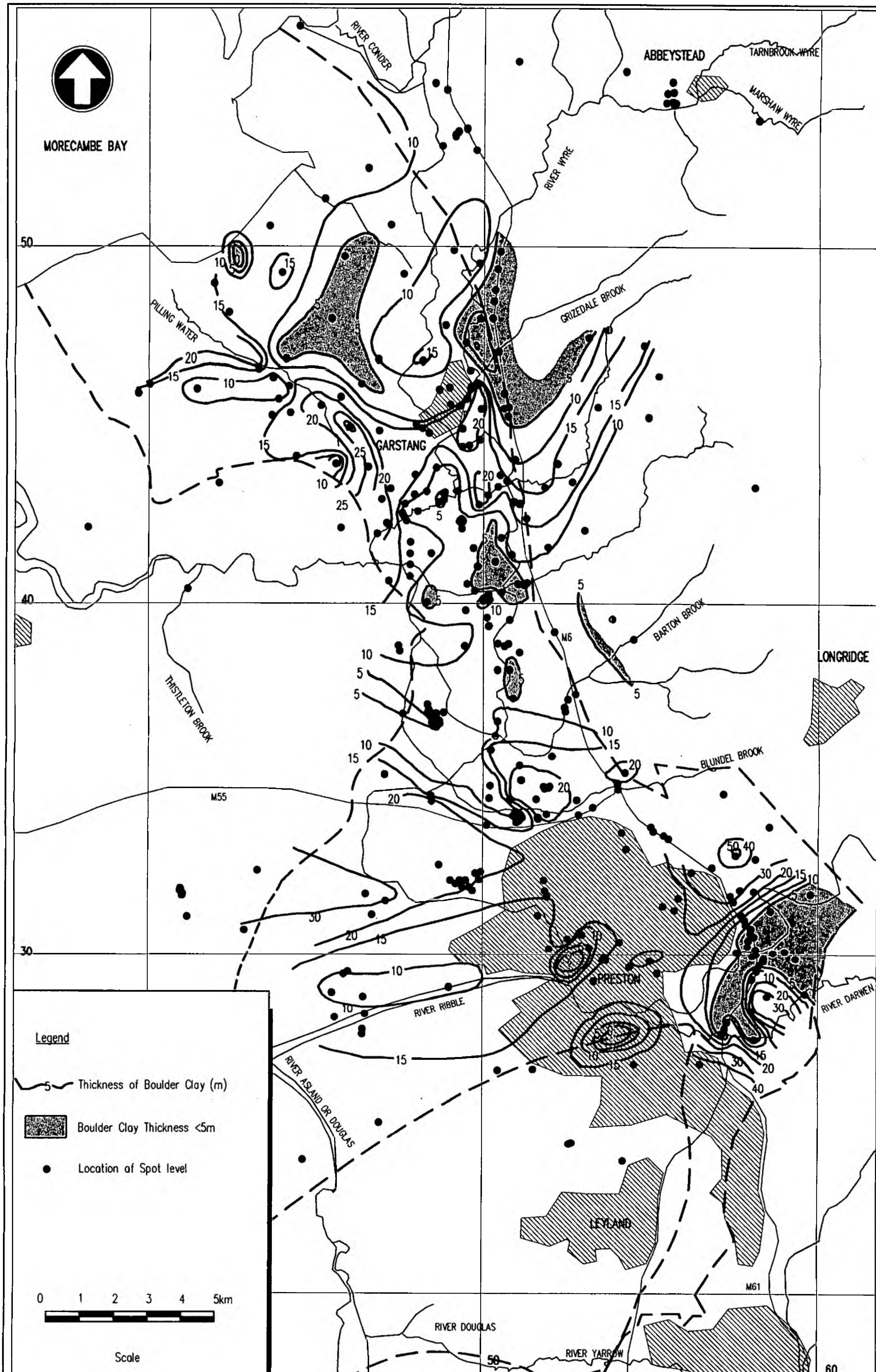
Figure 2.8
Thickness of Drift



18/02/97 D:\EMR\PROJECTS\38436BA.01\ACAD\FINAL\FIG2-08

Figure 2.9

Thickness of Boulder Clay



31/07/97 Q:\EWR\PROJECTS\38436BA.01\ACAD\FINAL\FIG2-09a

Figure 2.10 Mean Section Permeability of Sandstone Aquifer

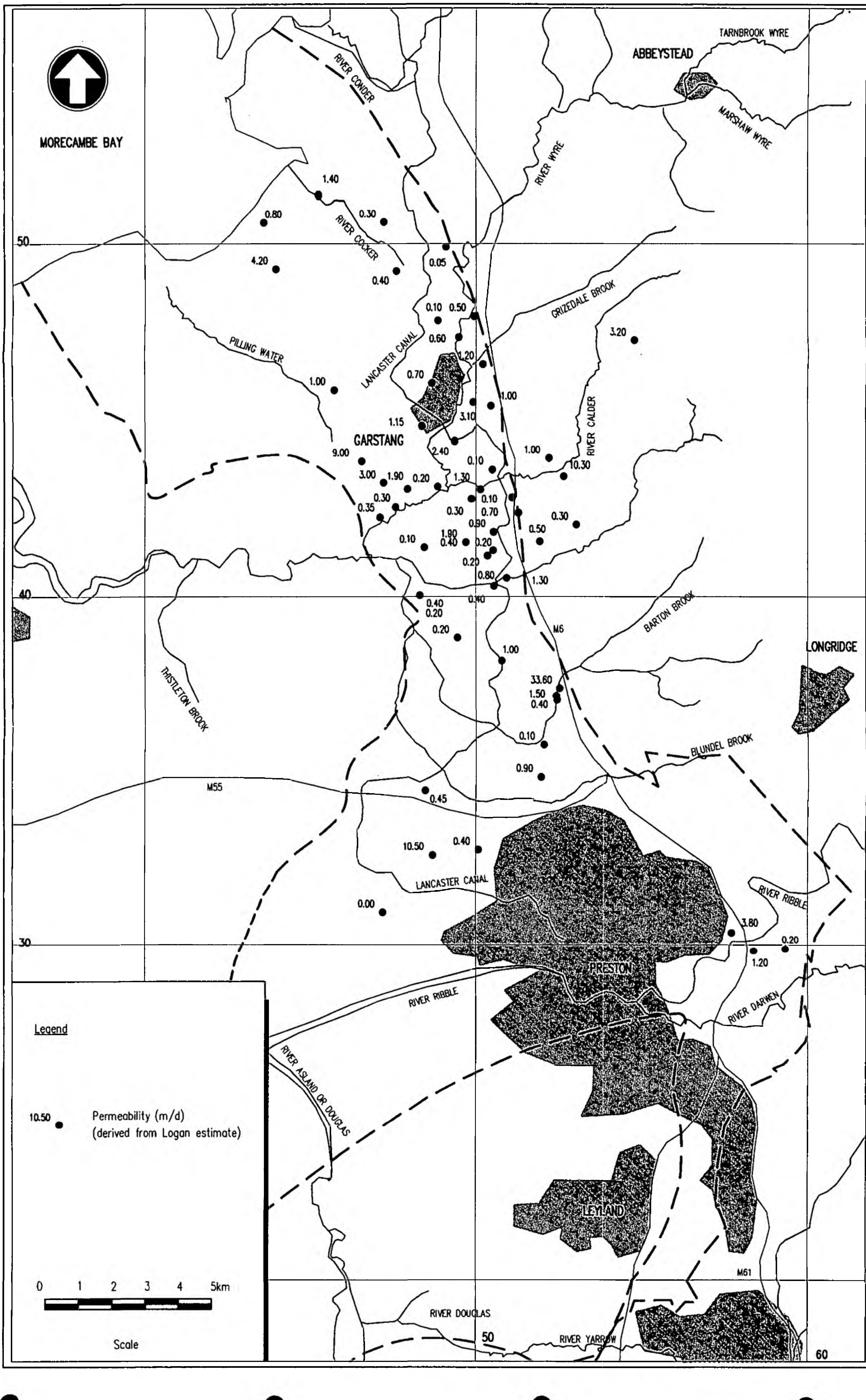
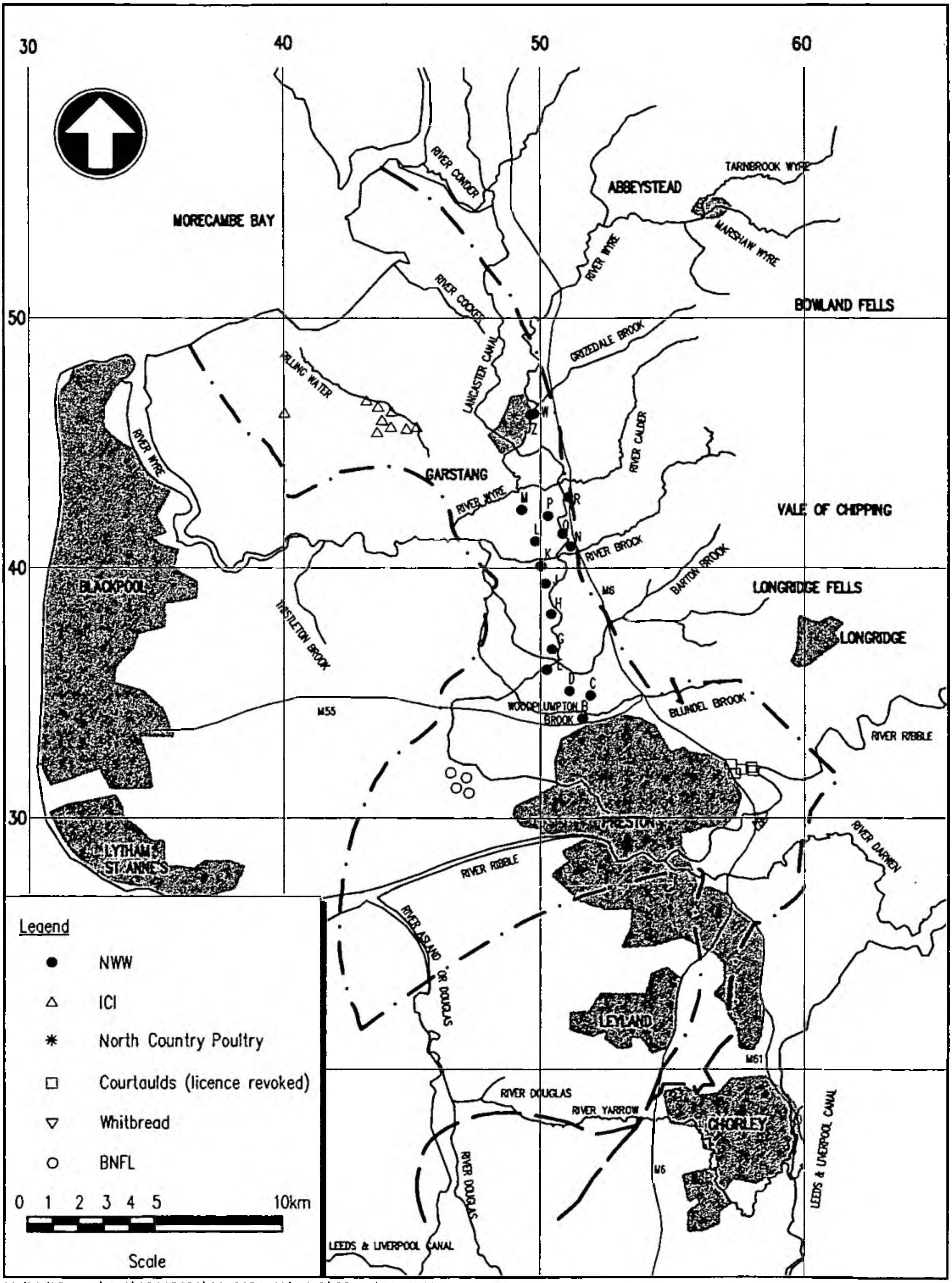


Figure 2.11

Location of Abstraction Boreholes



20/02/97 Q: \EWR\PROJECTS\38436BA.01\ACAD\FINAL\FIG2-11

Figure 2.12
Historical Annual Groundwater Abstractions

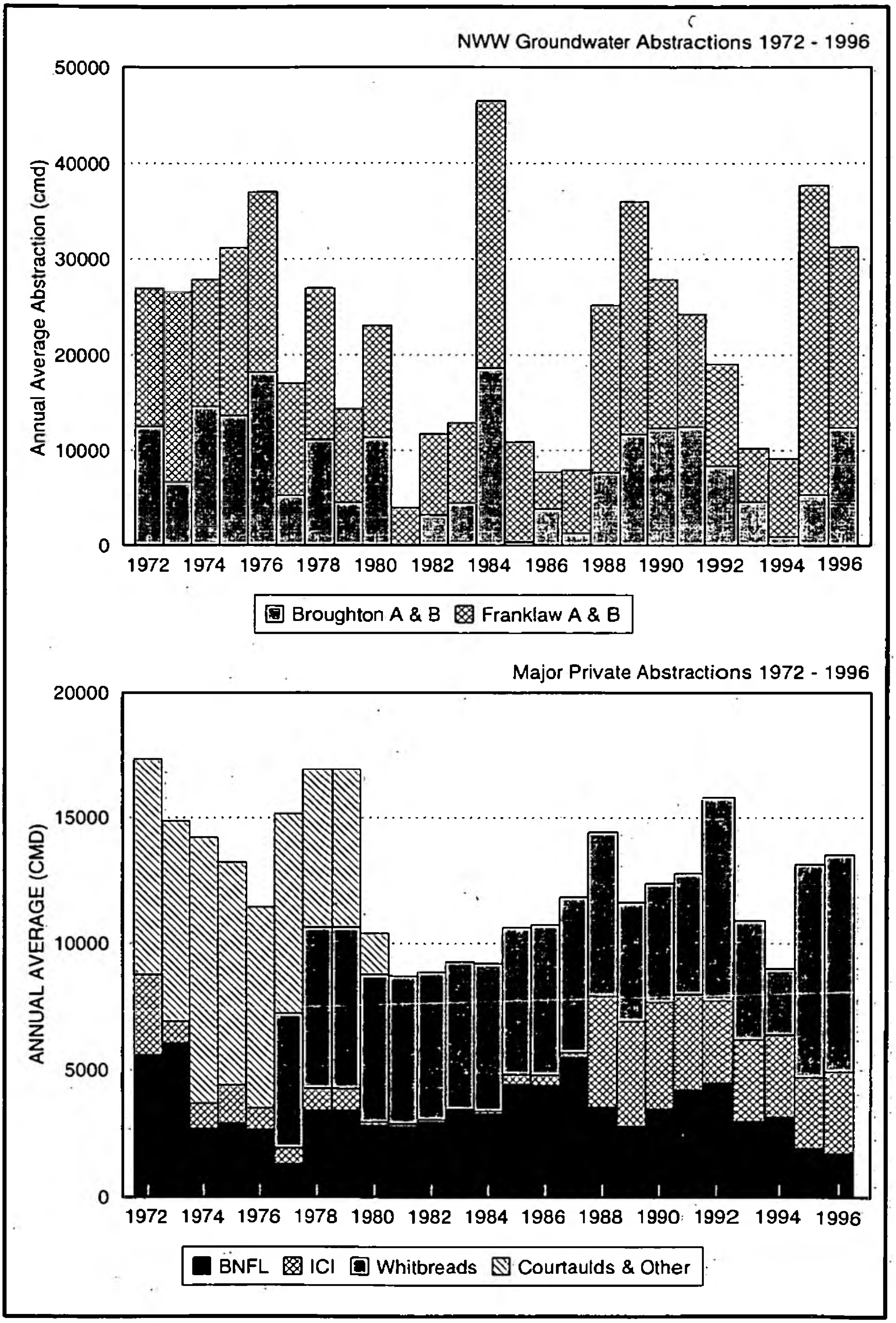
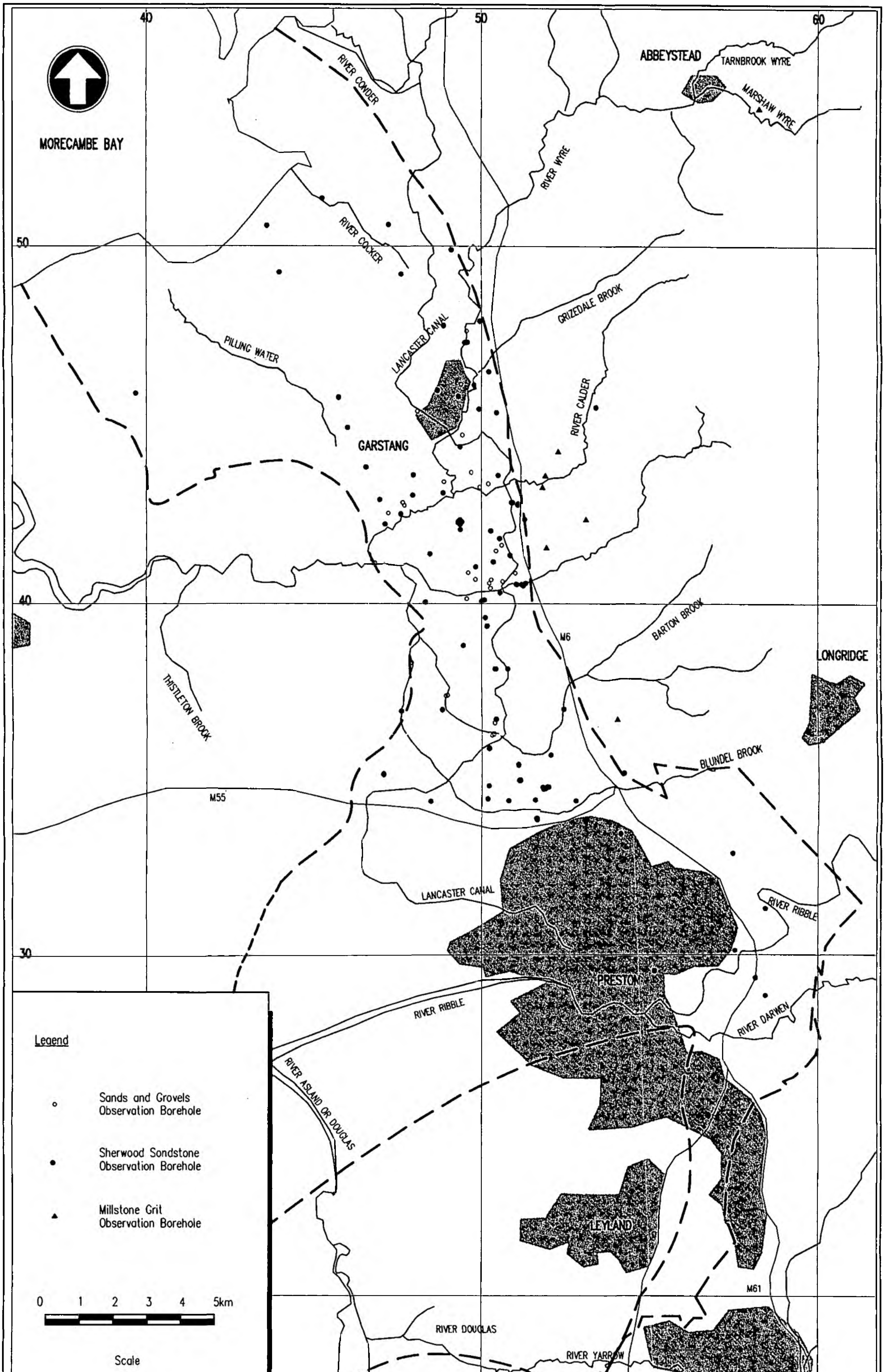


Figure 2.13

Location of Observation Boreholes



31/07/97 Q:\EWR\PROJECTS\38436BA.01\ACAD\FINAL\FIG2-13A

Figure 2.14

Piezometry: April 1987 and September 1976

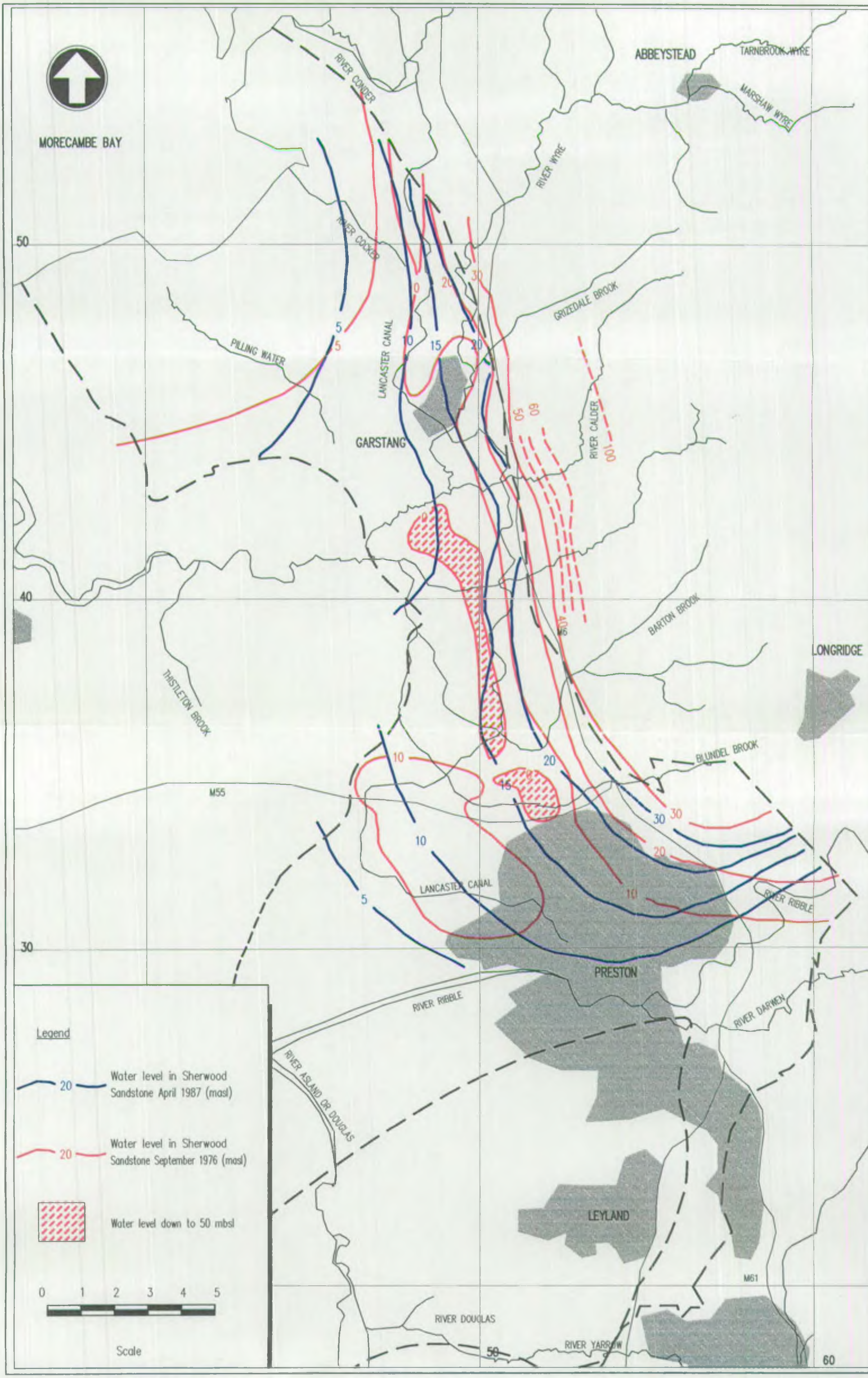
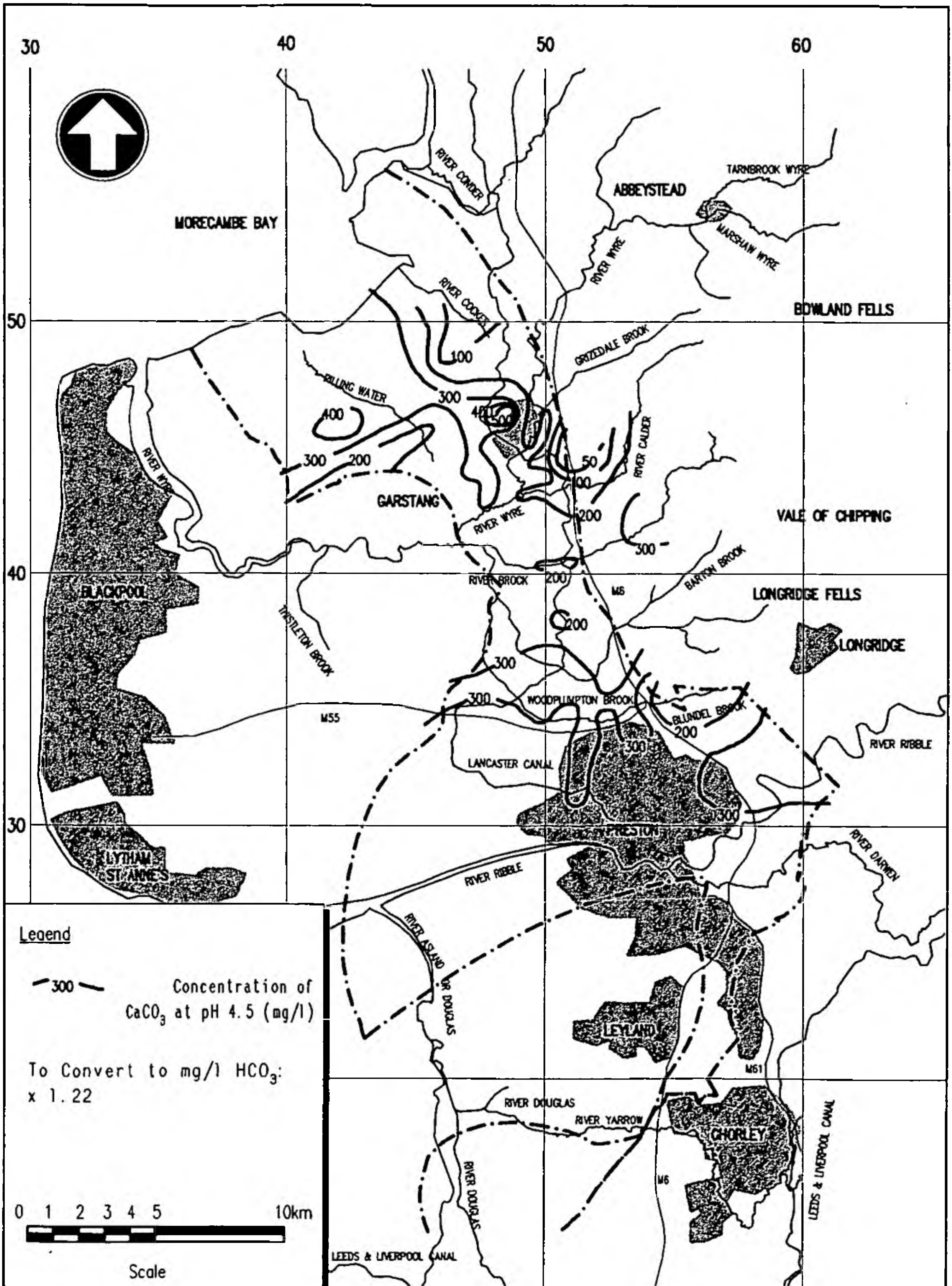


Figure 2.15

Distribution of Bicarbonate Concentrations



31/07/97 Q: \EWR\PROJECTS\38436BA.01\ACAD\FINAL\FIG2-15A

CHAPTER 3

MODEL CONCEPTS, DEVELOPMENT & CALIBRATION PROCESSES

CHAPTER 3

MODEL CONCEPTS, DEVELOPMENT & CALIBRATION PROCESSES

3.1 General

The integrated surface water and groundwater model used in this study has been developed by Mott MacDonald over the last twenty years and has been used on a number of similar studies in the UK since 1990. The model is called the Integrated Catchment Management Model (ICMM) and is based on the integrated finite difference method. The model represents flow in multi-layered aquifer systems simulating horizontal within aquifers and vertical flow between aquifer layers. The mathematical solution to the model takes into account the inter-relationship of heads and flows in both the aquifer and river systems with exchange between the two. The model is capable of simulating the temporal and spatial distribution of groundwater heads and river flows in a network of variable sized grid cells covering the model area. The river systems are fully integrated within the model.

The model converges when all simulated water balance components are within pre-defined limits, ie

$$\Sigma(\text{inflows}) + \Sigma(\text{outflows}) - \text{Storage change} < \text{allowable imbalance} \quad (3.1)$$

Convergence is achieved by correcting the simulated groundwater and surface water heads until the simulated imbalance is within the allowable limits.

The following water balance components are simulated in the Fylde aquifer groundwater model:

Groundwater

- horizontal flow in aquifers and horizontal flow into and out of the model and the surrounding hydrogeological environment;
- vertical flow between modelled layers;
- inflow of water to the uppermost aquifer (the Drift) from rainfall recharge;
- leakage between surface water features (ie rivers) and the aquifers;
- abstraction from aquifers;
- drainage outflow when the simulated level of the uppermost aquifer rises above ground level.

Surface Water

- surface flows in the rivers;
- leakage between the rivers and the aquifer system;
- inflow of the drainage outflow from the aquifer system;
- river abstractions and augmentation.

These water balance components are schematically represented in the cross-sections shown in Figure 3.1

The following sections relate to all these components in the development of the conceptual model of the Fylde aquifer and Wyre catchment. Full details of the conceptual model can be found in Chapter 4 of the Phase I Report (MM, April 1995).

3.2 Model Domain and Grid

The extent of the groundwater model is shown in Figure 3.2.

The eastern boundary extends locally beyond the contact between the Fylde aquifer and the Carboniferous strata. The model covers all of the Fylde aquifer between its southern limit at Chorley and its northern limit along the Morecambe Bay coast.

To the west, the model area was extended into the area of the Kirkham Basin where the sandstone is overlain by the Mercia Mudstone, to allow for an assessment of any transfer of groundwater from the Fylde aquifer to the sandstone to the west, if such a flow occurs.

The model was only extended 1 - 3 km into the Carboniferous for the following reasons:

- very limited piezometric data are available for the Carboniferous for model calibration;
- river flows at the contact between the Fylde aquifer and the Carboniferous have been simulated with reasonable accuracy (using model HYSIM - refer to Section 2.1.5);
- the geology of the Carboniferous is complex and its hydrogeological parameters are uncertain.

For these reasons, the simulation of sub-surface flows from the Carboniferous to the Fylde aquifer would not be more accurate if the model were fully extended into the Carboniferous.

The model grid was created by systematic and repeated subdivision of a regular mesh of squares. The smallest grid cells were used where rapid changes in aquifer piezometry were expected, such as around major abstraction sources. In addition, the grid was designed to accurately represent the river systems and model boundaries.

The resulting grid (see Figure 3.2) comprised 980 polygons, ranging in size from 400 x 400 m to 1 600 x 1 600 m. The area covered by the network is approximately 430 km^2. The external model boundary consists of 135 external nodes for which boundary conditions are specified.

Also shown in Figure 3.2 is the simulated river system, consisting of 204 adjoining "river elements". A river element is an additional element within the groundwater model network positioned along the polygon faces of adjacent model polygons. The conceptualisation of the river system and the interaction of the rivers with the aquifer system is explained in Section 3.6.

3.3 Model Boundary Conditions

Three different boundary conditions can be specified:

- a fixed head where the piezometric level at the external node is set;
- a fixed gradient where the water level difference between the external and the internal node is specified;
- a fixed flow where the inflow (or outflow) across any boundary face is specified.

Different boundary conditions can, if necessary, be specified for each time step of the model simulation.

Boundary conditions were defined for each simulated model layer. However, although some lateral transfers occur in the Drift, these are thought to be insignificant and therefore, no-flow conditions were specified for the Drift layer during initial model construction and throughout model calibration.

The following sections describe the boundary conditions for the sandstone aquifer.

3.3.1 The Carboniferous Boundary

The selection of boundary conditions was based partly on Carboniferous geology and partly on the response of a number of hydrographs within the Carboniferous.

Initially the following assumptions were made:

- In the north, from Morecambe Bay to the River Brock the Carboniferous contact with the Permo-Triassic is generally a faulted contact (the Bilsborrow Fault, refer to Figure 2.7 and Section 2.2.2), with Millstone Grit units in direct contact with the Sherwood Sandstone aquifer. Significant quantities of water may flow from the Carboniferous (from the Ellel Crag, Wellington Crag and Park Wood Sandstones and Pendle Grit units) to the Triassic along this contact. The transmissivity of the Millstone Grit range from 6 to 105 m^2/d although most are in the range 6 to 16 m^2/d.

  Fixed head conditions were used in the initial model set up, based on the available piezometric data within the Carboniferous. However, by defining fixed heads the model is assuming that the Carboniferous Deposits have an infinite supply of groundwater to satisfy abstraction demands in the Fylde aquifer, with the only limitation being the ability of the Carboniferous Deposits to transmit the water. This was considered unrealistic conceptually, and were subsequently changed during calibration to fixed gradients (from 7.5 to 10 m/km) . The use of fixed gradients, rather than fixed heads, was considered more realistic as gradients imply that inflows across the model boundary are relatively constant and the volume of inflow is not greatly influenced by abstractions from the sandstone aquifer; this is supported by the observed piezometry.

- Between the River Brock and the Woodplumpton Brook, Manchester Marls are present along the Carboniferous boundary with Bowland Shale further east. The Marls along this unconformity are considered to act as an impermeable barrier. No flow conditions were adopted along this boundary.

- To the south of Woodplumpton Brook, an unconformity also exists. However, no low permeability Manchester Marls are present between the Carboniferous and Permo-Triassic. Millstone Grit is again in contact with the Sherwood Sandstone. However, there is little piezometric information available in this area in order to assess the potential inflow across the boundary. This was originally set as a no flow boundary. However during calibration, the most accurate simulations were achieved with an inflow defined. Hydrochemical information, i.e. the high iron content of water abstracted at the Whitbread boreholes is consistent with inflow from the Carboniferous. A fixed gradient (of 2m/km) was defined along this boundary.

3.3.2 Morecambe Bay and the Ribble Estuary

Only limited outflow is believed to occur into Morecambe Bay as most of the aquifer discharge takes place as vertical leakage through low permeability Drift to the sea bed. A fixed sea level head is defined at the external model polygons. Its effect on the behaviour of the aquifer has been limited by extending the model beyond the coastline. Similarly fixed heads at sea level were allocated to the south western boundary, in the Ribble Estuary.

3.3.3 Western and Southern Boundaries

Flow to the west, across the Woodsfold Fault to the Kirkham Basin is considered to be very low. There is no detailed piezometric evidence to suggest otherwise. In addition, the overlying Mercia Mudstone has a very low vertical permeability and thus there is unlikely to be any significant vertical exchange of water between the Sherwood Sandstone and Mercia Mudstone. Consequently, there is unlikely to be any significant lateral flow from the Fylde aquifer to the west since there is no obvious point for this inflow to discharge to. This boundary was, therefore, defined as a no flow boundary.

Similarly at the southern boundary, with very low permeability deposits in contact with the Fylde aquifer, a no flow boundary was adopted.

3.4 Model Layers and Geometry

The aquifer system was initially divided into three layers, namely (from the base upwards):

- the Sherwood Sandstone (layer 1);
- sand & gravel, where this lies directly above the sandstone (layer 2);
- undifferentiated drift, comprising varying proportions of sand & gravel and boulder clay (layer 3).

During calibration of the model, it became necessary to subdivide the Sherwood Sandstone into two layers separated by a leakance interface. During the early stages of calibration, simulation of Sherwood Sandstone piezometry was poor, particularly in the north and south of the Fylde aquifer. The conceptual flow system within the sandstone aquifer was then re-evaluated. Analysis of the lithology and observation borehole data indicated that:

- Most observation boreholes only penetrated the top 50 m of the aquifer, while abstraction boreholes were normally drilled to a depth of 100 to 200 m.

- Groundwater levels within the sandstone aquifer are stratified; water levels measured in boreholes terminating in the top 50 m of sandstone can show different responses to pumping/seasonal recharge to those monitored by deeper boreholes.

- Many borehole logs indicate marl bands within the top 50 to 100 m of the sandstone aquifer; these marls are likely to impede the vertical flow of water from the Drift to the deeper levels of the sandstone aquifer which are exploited by NWW's abstraction boreholes.

It was therefore considered more physically realistic to split the sandstone into two separate units, an "upper" and a "lower" sandstone layer, separated by a "leakance" interface defined to represent the impedance of the marl bands in the upper sandstone. (The validity of this approach was subsequently endorsed by the BGS geophysical remapping of the Fylde aquifer which identified the presence of the 'intra-Sherwood Sandstone marl' - Chapter 2).

Thus a four layered model was finally used to represent the Fylde aquifer system: lower sandstone, upper sandstone, sand & gravels and Drift.

Five elevations (to Ordnance Datum) were derived to define the top and base elevations of each layer (topography and the base elevation of each layer). Table 3.1 summarises the derivation of these surfaces.

TABLE 3.1 Geometry of Fylde Aquifer System

Surface	Derivation
Topography (top of Drift)	The Digital Terrain Model (DTM) was used to define topography for the area north of northing 4250. The DTM consists of point data on a 50 m x 50 m grid. 1:25000 Ordnance mapping was used for the area to the south of northing 4250 and to adjust levels in areas where there was insufficient detail in the DTM data.
Base of Undifferentiated Drift (top of Sands & Gravels)	The Drift is composed of layers of clay (mainly boulder clay) and sand & gravels. It is extremely variable and a clear identification of the extent of individual sub-layers within the Drift is generally not possible. However, analysis of all lithological logs collected for the study allowed the Drift to be split into two layers: undifferentiated drift and sand & gravel (which directly overlies the sandstone - see below). There are a few locations where there is locally exposed sands & gravels at ground surface, mainly in parts of the Barton and Woodplumpton Brooks and in Preston. To the east of Preston, terrace deposits occur along the valley of the River Ribble comprising mainly silty clays. Thickness of undifferentiated Drift for each model polygon was derived from borehole logs and geological maps (shown in Figures 2.9 and 2.10). The thickness was subtracted from surface topography to obtain the base elevation of the top layer. The resultant geometry was checked against geological sections derived from borehole logs (refer to Chapter 4).
Base of Sands and Gravels (top of sandstone)	The modelled thickness of sand & gravel layer over sandstone was also derived from borehole logs. This layer is not present over the whole model domain. It is present over most of the central area and in the upper reaches of the River Ribble and the River Wyre, coinciding approximately with the main NWW abstraction zones. The base of the sand & gravel layer was derived by subtracting the thickness from the base of the Drift. In addition the top of the sandstone aquifer was derived from lithological logs and compared with the base of the sands & gravels and geological sections. Adjustments were made so that the base of the sands & gravels and top of sandstone were consistent.
Base of upper sandstone (simulated position of leakance interface between upper and lower sandstone layers)	Initially, an effective sandstone aquifer thickness of 200 m was used everywhere except along the Carboniferous boundary where the actual thickness of the Sherwood Sandstone Group (SSG) reduces to about 50 m at the Bilsborrow Fault. During calibration the sandstone was split into two layers (refer above). The base of the "upper" sandstone was derived from lithological logs, where the significant marl bands were mapped and transferred to the polygon network to derive this surface. The sandstone at all polygons (except within the Carboniferous Deposits and to the west of the Woodsfold Fault) were split into two layers, even if lithology suggests that no marl bands exist. In areas where the lithological logs suggest that vertical stratification within the sandstone does not occur, the hydraulic parameters are defined so that there is no resistance to flow between sandstone layers.
Base of lower sandstone (effective base of aquifer system)	Base of the lower sandstone was NOT taken as the actual base of the Sherwood Sandstone. There is insufficient data to accurately define the effective thickness of the sandstone aquifer but the marl distribution within the aquifer suggests that active flow may be restricted to the upper 200m of the Sherwood Sandstone group. Consequently 200 m was subtracted from the base of the sands & gravels to define the effective base of the sandstone aquifer. Adjustments were made at three places: • at the Catterall Basin, where there is a deep depression (refer to Figure 2.5), the thickness was increased to 300 m; • at the Bilsborrow Fault where the actual thickness of the sandstone reduces to 50 m (here, the effective thickness was reduced to the actual thickness); • to the east of the Bilsborrow Fault, where the effective thickness of the Carboniferous deposits were defined as 100m.

3.5 Hydrogeological Characteristics

ICMM incorporates two directions of flow: horizontal flow within aquifers and vertical leakage between aquifers. In addition, ICMM allows for both confined and unconfined storage changes. The following sections define the conceptual understanding of these flow mechanisms as they relate to the Fylde aquifer system.

3.5.1 Undifferentiated Drift

The boulder clay and the sand & gravels within the Drift were considered as laterally continuous, with the proportion of each allocated to the model polygons as a weighted mean of values related to nearby borehole lithologies. Lateral transfer in the Drift is controlled by the horizontal permeabilities of the sand & gravel and clay layers and the extent of lateral transfer can thus be controlled by the allocation of appropriate permeability values.

The allocation of hydraulic properties to the Drift layer, and those specified for individual grid cells were as follows:

Single-layered Drift:

- The mean horizontal permeability was based on a weighted mean of permeabilities allocated to sand & gravel and clay layers, or

$$k_h = k_{h,s\&g} * p_{s\&g} + k_{h,c} * p_c \qquad (3.2)$$

where

$k_{h,s\&g}$ - horizontal permeability of sand & gravel [m/d]
$k_{h,c}$ - horizontal permeability of clay [m/d]
$p_{s\&g}$ - proportion of sand & gravel within the Drift
p_c - proportion of clay within the Drift

The above formulation implies that sand & gravel layers are laterally fully interconnected, an initial assumption of the model. Reduction factors were introduced to take account of a degree of lateral discontinuity between sand and gravel layers. These factors were varied during model calibration: between 0 (no lateral continuity) to 1 (full lateral continuity); a value in excess of 0.5 is generally considered appropriate for conditions in the Drift, since borehole lithological logs suggest that there is a high degree of continuity.

- The mean vertical permeability was based on the proportions of sand & gravel and clay within the Drift and their respective vertical permeabilities. It was assumed that the sub-layers of sand & gravel and clay act in series, or

$$k_v = (k_{v,s\&g} * k_{v,c})/(k_{v,s\&g} * p_c + k_{v,c} * p_{s\&g}) \tag{3.3}$$

where

$k_{v,s\&g}$	-	vertical permeability of sand & gravel [m/d]
$k_{v,c}$	-	vertical permeability of clay [m/d]
$p_{s\&g}$	-	proportion of sand & gravel within the Drift
p_c	-	proportion of clay within the Drift

In practice this means that the hydraulic resistance of the Drift is dominated by the total thickness and vertical permeability of the boulder clay.

- The specific yield was based on the occurrence of sand & gravel and clay in the upper part of the Drift as follows:

$$SY = SY_{s\&g} * p_{s\&g} + SY_c * p_c \tag{3.4}$$

where

$SY_{s\&g}$	-	specific yield of sand & gravel
SY_c	-	specific yield of clay
$p_{s\&g}$	-	proportion of sand & gravel within the Drift
p_c	-	proportion of clay within the Drift

The initial settings for the individual permeability and storage parameters for this Drift layer are shown in Table 3.2.

TABLE 3.2

Initial Drift Hydrogeological Parameters

Parameter	Boulder Clay	Sand & Gravel	Estuarine Deposits	River Alluvium	Terrace Deposits	Simulated Maximum	Simulated Minimum
Horizontal permeability	0.001 - 0.010 m/d	1 - 20 m/d	0.001 - 0.010 m/d	0.0001 - 0.001 m/d	0.0001 - 0.001 m/d	5 m/d	0.001 m/d
Vertical permeability	0.0001 - 0.005 m/d	0.1 - 1 m/d	0.001 - 0.010 m/d	0.001 - 0.010 m/d	0.001 - 0.010 m/d	1 m/d	0.0001 m/d
Specific yield	0.01 - 0.03	0.05 - 0.10	0.01 - 0.05	0.02 - 0.05	0.02 - 0.05	0.10	0.01

Note: Simulated maximum coincides with areas of Drift where boulder clay is not present (such as at the upstream ends of the River Ribble, locally around Garstang and between the Rivers Wyre and Calder). The simulated minimum coincides with area of relatively thick boulder clay, where there is only very limited thickness of sands & gravels (such as at the western end of Woodplumpton Brook).

During model calibration it was found that both the vertical and horizontal permeabilities were defined too high: horizontally the model simulated too much lateral flow towards the river system while vertically, the model allowed too much leakage into the sandstone aquifer thus raising simulated sandstone groundwater levels above the observed levels. Consequently significant variations in the Drift parameters were made during calibration of the model. Very little variation in the specific yield of the Drift was required during model calibration. The resultant range in parameters define in the calibrated model is shown in Table 3.3. The final settings of these parameters are defined in more detail in Chapter 4.

The vertical permeability of the Drift is very low in places (as low as 0.000001 m/d). This is considered unrealistically low even for stiff, firm boulder clay. Therefore, it was decided that the mechanism of leakage through the Drift to the sandstone should be investigated further. This is described in Appendix E. The detailed modelling of the Drift described in this appendix confirms that the "effective" vertical permeability defined in the regional model accurately represents the leakage mechanism.

TABLE 3.3

Drift Hydrogeological Parameters at Final Calibration of the Model

Parameter	Boulder Clay	Sand & Gravel	Estuarine Deposits	River Alluvium	Terrace Deposits	Simulated Maximum	Simulated Minimum
Horizontal permeability	0.0001 - 0.001 m/d	1 - 12 m/d	0.001 - 0.010 m/d	0.001 - 0.002 m/d	0.0001 - 0.001 m/d	4 m/d	0.00001 m/d
Vertical permeability	0.000001 - 0.0001 m/d	0.1 - 1 m/d	0.001 - 0.010 m/d	0.001 - 0.010 m/d	0.001 - 0.010 m/d	1 m/d	0.000001 m/d
Specific yield	0.01 - 0.03	0.05 - 0.10	0.01 - 0.05	0.02 - 0.05	0.02 - 0.05	0.08	0.01

3.5.2 Sand & Gravels Directly Overlying Sandstone

In the central area of the Fylde Plain, glacial sand & gravels directly overlie the Sherwood Sandstone. These deposits are thought to act as an additional storage reservoir for the NWW abstraction boreholes. The parameter settings initially adopted for this aquifer were as follows:

- horizontal permeability - 5 m/d;
- vertical permeability - 0.5 m/d;
- specific yield - 7.5 %;
- confined storage coefficient - 0.00005.

Dewatering of sand & gravel layers overlying the sandstone occurs in the central area of the Fylde plain during periods of intensive summer pumping. If water table conditions develop in these layers, the storage condition switches from confined to unconfined; both conditions were accounted for in the model.

During calibration, it was found that both the vertical permeability and storage coefficient of the overlying sand & gravels were an important influence on the impact of abstractions from NWW sources on sandstone groundwater levels and the impact on the river (refer to Section 4.4). These parameters were adjusted; the final adopted settings were:

- horizontal permeability - 5 m/d;
- vertical permeability - 0.5 m/d in the central area to 0.05 in the south west at Woodplumpton Brook;
- specific yield - 12% in the central area to 7.5 % in the south west at Woodplumpton Brook;
- confined storage coefficient - 0.00005.

3.5.3 Sandstone

The range in aquifer transmissivities around the NWW boreholes is from 100 to 1400 m^2/d (from pumping tests and Logan estimates), which gives a range of permeability of between 0.7 to 4.5 m/d. This reflects the heterogeneous nature of the sandstone, caused by a combination of intergranular flow, fissure flow and zones of intensive faulting.

Initially the permeability of the aquifer was set at 1 m/d throughout. With an effective thickness of 200m, the initial transmissivity was defined as 200 m^2/d.

Significant variations in permeability were made during model calibration, which are explained in Section 4. However, generally the final permeability distribution reflected that defined from pumping tests, although a slightly greater range was adopted (0.2 to 5.0 m/d).

With the split of the aquifer into two sub-layers in order to simulate the vertical stratification within the aquifer (refer to Section 3.4), the permeability of the "upper" and "lower" sandstone layers was maintained at the same level.

Initial values for unconfined and confined storage coefficients for the sandstone were set at 0.06 and 0.00005 respectively. No data exists on which to base any spatial variations in these parameters. The sensitivity of these parameters was tested during model calibration and it was found that the initial settings were acceptable.

The conductivity of the leakance interface between the two sandstone layers was simulated by varying the vertical permeability of the lower sandstone layer. With a low vertical permeability (representing significant marl beds within sandstone) the model simulated a difference between the upper and lower sandstone groundwater levels and resulted in lower fluctuations as a result of groundwater abstraction in the upper sandstone than the lower sandstone. With a high vertical permeability the model does not simulate any vertical stratification and the sandstone aquifer acts as a single layer. The vertical permeability at final calibration ranged from 0.000 01 m/d in the south of the model between Woodplumpton Brook and the River Ribble to 1 m/d in the central area (refer to Section 4.5).

3.5.4 Carboniferous Deposits and Contact Between Carboniferous and Sandstone

Based on only limited knowledge of the properties of the Carbiniferous deposits and the contact between the Carboniferous and sandstone, and considering the observed Carboniferous groundwater levels, four different permeabilities were initially adopted to represent horizontal flow between the two units:

- Millstone Grit was defined as 0.1 m/d;
- Bowland Shales 0.01 m/d;
- Bilsborrow Fault 0.05 m/d;
- Manchester Marls - 0.0 m/d (impermeable).

As calibration progressed and further analysis of the Carboniferous deposits was made significant variations to these parameters were made. The variations and finally adopted parameters are described in Chapter 4.

Vertical permeabilities and storage coefficients for the Carboniferous were maintained throughout modelling at the levels set for the Sherwood Sandstone.

3.6 Simulation of River/Aquifer Interaction

3.6.1 Leakage Between Rivers and Aquifers

Evidence of the influence of groundwater abstraction on river baseflow was derived from hydrochemical data and river flow records.

Low bicarbonate concentrations in sandstone groundwater along river valleys is likely to be an indication of displacement of more bicarbonate-rich groundwater by low carbonate river water. The bicarbonate distribution in Figure 2.15 shows that leakage probably occurs from the rivers Wyre, Calder and Brock through the Drift to the aquifer, as a result of groundwater abstraction. The considerable thickness of boulder clay which underlies the Barton and Woodplumpton Brooks indicates that the connection with the aquifer is likely to be poor in the southern part of the Fylde plain and that observed river flow losses are a consequence of Drift water table declines. Section 2.1.3 summarises the locations of the river reaches where a reductions in river flows have been observed.

Rivers have been represented in the model as river elements along the sides of model grid cells - all major rivers have been represented in the model as shown in Figure 3.2.

Different types of river element were used to represent varying degrees of connection between the river and the aquifer system. Three main types of river/aquifer flow mechanisms are simulated by the model (as represented schematically in Figure 3.3):

1 Where there is significant thickness of boulder clay (> 15 m) beneath the river, the volume of water either leaking from the river to the sandstone aquifer or leaking from sandstone to river is expected to be small (Figure 3.3a). In this case the difference between surface flow into the river element and surface flow out of the element is balanced by leakage between the river and the Drift. Leakage into and out of the Drift is dependent upon the resistance of the river bed and the head difference between the river and the Drift, or

$$RLEAK = W * L_r * (H_r - H_d) / R \quad (3.5)$$

where

RLEAK = leakage from river to Drift
W = width of river
L_r = length of river
H_r = river water level
H_d = water table level in Drift at the river
R= resistance of river bed

In terms of water balances, the flow balance at the river element must satisfy two criteria:

$$Qin - Qout - RLEAK = Imbalance \quad (3.5a)$$

$$Q_{1d} + Q_{2d} - RLEAK = Imbalance \quad (3.5b)$$

where

Qin = surface inflow to river element

Qout = surface outflow from element

Q_{1d}, Q_{2d} = horizontal flow in Drift from aquifer on each side of river element to the river element (based on Darcy's equation)

Imbalance = predefined maximum imbalance

Both equations must be satisfied before convergence has been established.

With a low river resistance (ie "permeable" river bed), then leakage is greater but only if the Drift is sufficiently transmissive to balance horizontal flow with the leakage. On the other hand, with a high river resistance, leakage between river and Drift is low.

This mechanism exists in the south of the model, around Barton and Woodplumpton Brooks where the boulder clay thickness exceeds 15 m.

2 Where the boulder clay thickness is less than 15 m, there is potential for leakage between the sandstone aquifer (or the sands & gravels aquifer which directly overlies the sandstone) and the river through the Drift (Figure 3.3b). In this case, the model simulates the mechanisms for the Drift/river leakage described in 1 as well as leakage between the Drift and the underlying aquifer. In this case three flow balance equations need to be satisfied before convergence is achieved:

$$Qin - Qout - RLEAK = Imbalance \quad (3.6a)$$
$$Q_{1d} + Q_{2d} - RLEAK - DLEAK = Imbalance \quad (3.6b)$$
$$Q_{1a} + Q_{2a} + DLEAK = Imbalance \quad (3.6c)$$

where

Q_{1a}, Q_{2a} = horizontal flow in underlying aquifer on each side of river element to the river element (based on Darcy's equation)

DLEAK = leakage between Drift and underlying aquifer, defined by the equation:

$$DLEAK = W * L_r * C_{da} * (H_d - H_a) \quad (3.7)$$

where

H_a = groundwater level in underlying aquifer below the river

C_{da} = conductance between Drift and aquifer

This mechanism was applied over most of the modelled area, where the leakage between the rivers and aquifer system was dependent upon the river bed resistance and the conductance of the Drift/underlying aquifer defined during model calibration. Low resistances and high conductances result in large volumes of leakage from the river when abstractions lower sandstone groundwater levels relative to the river. Under these conditions further declines in groundwater levels at the river as a result of groundwater abstractions are limited due to increased river recharge. Such conditions were simulated at Garstang, near NWW's sources W and Z.

3) The third mechanism is where the river valley cuts through the Drift deposits such that the river is in "direct" contact with the sandstone aquifer (Figure 3.3c). In this case, the mechanism of leakage is exactly as the first mechanism (where the river interacts with the Drift only) except that leakage is between river and sandstone directly. The flow balance equations are thus:

$$\text{Qin} - \text{Qout} - \text{RLEAK} = \text{Imbalance} \quad (3.5a)$$

$$Q_{1a} + Q_{2a} - \text{RLEAK} = \text{Imbalance} \quad (3.5b)$$

(where parameters are as previously defined).

This mechanism occurs at the downstream end of the river Wyre (just upstream of St Michaels gauging station). Analysis of lithological records and river section surveys suggest that only thin clay occurs beneath the river in this area. In addition, observation boreholes to the north of the river suggest that the river acts as a "recharge" barrier since the decline in groundwater levels as a result of groundwater abstractions is very low in comparison with the levels observed to the south of the river.

In all cases if the groundwater head is below the river bed resistance layer, there is a fixed rate of leakage due to unit hydraulic gradient (ie the rate of leakage is independent of the properties of the aquifer or drift underlying the riverbed).

When the model was first set up mechanism 1 was adopted throughout the model, with river bed resistances approximated from the observed losses in 1994, by assuming the loss occurs linearly over the length of river where losses were observed under unit hydraulic gradient. The river bed resistance was calculated to vary between 0.1 to 10 days on this basis, resulting in a losss of between 100 and 1000 m^3/d.

During calibration, all three mechanisms were introduced and variations were made to the river bed resistance and the conductance between the Drift and the underlying aquifers. River bed resistances were varied between 0.1 and 10 days, while conductances were varied by changing the vertical permeability of each model layer below the river.

The mechanisms adopted throughout the model at final calibration are shown in Figure 3.4. The values of river bed resistances and aquifer conductances are described for each river in Chapter 4.

3.6.2 River Flows

River flows are simulated in the model as the resultant flow balance of the river-aquifer interaction, river abstractions and augmentations and lateral inflows from rejected recharge, given by the equation:

$$Qin - Qout + RAUG - RABS + QLAT = Imbalance \qquad (3.8)$$

where

Qin = inflow from upstream element(s)
Qout = outflow to downstream element
RAUG = augmentation
RABS = river abstraction
QLAT = lateral inflow of rejected recharge
Imbalance = pre-defined imbalance convergence criteria

The lateral inflow is simulated by routing recharge rejected by the groundwater system (when the water table is at ground surface) along surface topography (see Section 3.7).

3.7 Simulation of Recharge

As has been explained in Section 2.2.2, 2.3.3 and 3.5.1, it is extremely difficult to establish accurately the flow system within the Drift and between Drift and underlying sandstone due to the heterogeneity of the deposits. Therefore, the mechanism of recharge to the Drift and leakage through the Drift simulated by ICMM is a simplification. However, the flow volumes simulated by the model are considered to accurately represent conditions on a regional scale.

The simplified mechanism of recharge through the Drift described below has been expanded and studied in further detail, through the development of "vertical strip" models. A "vertical strip" model is a model which only simulates vertical flows at one discrete point. This modelling allowed the Drift to be split into a number of sub-layers in order to investigate and confirm the simplified recharge/leakage mechanisms described in the follwoing sections. The mechanisms and model resutls if this investigation are described in detail in Appendix E.

3.7.1 Definition of Terms

Different models use different terminology to define the recharge mechanisms. The following terms describe the recharge mechanism in ICMM:

- ***Potential Recharge*** - This represents the rate of vertical flow through the base of the active root zone. The word potential implies that there are no restrictions to this vertical flow caused by either water table elevation or hydraulic characteristics of the sub-soil. In urban areas, potential recharge may also include the potential leakage from water supply distribution, storm drainage and sewer systems.

In reality the rate of percolation through the base of the root zone or from leakage in urban areas is restricted by a variety of factors, including:

- The deep percolation capacity (or vertical hydraulic conductivity) of the sub-soil (the layer present between the base of the root zone or urban distribution systems and the water table) may be smaller than the potential recharge rate. If this is the case, moisture levels in the root zone will build up in excess of field capacity. Fully saturated conditions may even be attained resulting in the rejection of surplus water as surface run off and interflow (a form of natural drainage in the upper soil profile) or to an artificial drainage system.

- If the water table is located above the base of the root zone, rejection of flow in the form of natural or artificial drainage, or as upward capillary flux, may occur.

The existence of artificial drainage systems in the study area, both as sub-surface and open drains, indicates that rejection of part of the potential recharge may occur, particularly during winter periods.

- *Actual Recharge to the Drift Water Table* - This is defined as the volume of water added to the water table. This volume may be restricted by the water table elevation or the hydraulic characteristics of the sub-soil. The rate of recharge to the water table is always less than or equal to this deep percolation capacity. If potential recharge is in excess of the deep percolation capacity, water will be temporarily stored within the sub-soil. This storage may take a variety of forms:

  - The moisture holding capacity of a uniform homogeneous soil is a function of the rate of deep percolation. The higher this rate, the greater the amount of moisture in storage. During periods without potential recharge, recharge to the water table will continue until the moisture reservoir in the sub-soil has declined to field capacity (Figure 3.5a).

  - In reality the sub-soil will be heterogeneous and non-uniform. Localised increases in soil moisture and even perched conditions may develop as a result. During periods without potential recharge, recharge to the water table may be sustained by the release of water from this excess soil moisture storage (Figure 3.5b).

  - Localised saturated conditions may develop in sand lenses located within the sub-soil. Lateral groundwater movement within these layers would then be possible and could be directed towards open drains or rivers (Figure 3-5c).

- *Recharge Through the Drift to the Underlying Aquifer* - This is the volume of leakage through the Drift layer and is dependent upon the conductance of the Drift and the water level difference between the water table elevation and the groundwater level of the underlying aquifer.

3.7.2 Potential Recharge

Two sources of potential recharge exist, namely:

i) precipitation recharge;

ii) leakage from water supply distribution, storm drainage and sewage systems, known collectively as urban recharge.

Other forms of potential recharge include inflow from the Carboniferous boundary and leakage from the rivers. These components are defined in separate sections (Section 3.3.1 and 3.6 respectively). The following sections define the recharge mechansims associated with precipitation and water supply leakages through the overlying Drift deposits.

Precipitation recharge was based on the analysis of a daily moisture balance of the combined surface and root zone systems, using the Penman-Grindley method.

Urban recharge may be important in the main urban centres of Preston and Garstang.

Precipitation Recharge

A lumped parameter model, based on the Penman-Grindley method, was used to simulate potential recharge. This model simulates the water balance in two inter-connected reservoirs:

- the *surface reservoir*, simulating rainfall (based on the St Michaels gauge), interception storage, surface run off (simulated by HYSIM) and evaporation from interception storage and surface infiltration;
- the *root zone reservoir* which simulates surface infiltration, actual evapotranspiration soil moisture storage and potential recharge.

Evapotranspiration rates were derived from MORECS potential rates.

Potential recharge (from precipitation) evaluated from this model for the period 1992 to 1995 is shown in Figure 3.6.

Urban Recharge

In the major urban areas of Preston/Leyland and Garstang, urban recharge relates mainly to leakage from water supply distribution networks, storm drainage and sewer systems, which may be significant. Initial estimates of leakage were based on population density alone. NWW subsequently provided leakage values for the two urban areas, of 16 Ml/d and 1 Ml/d respectively, equivalent to a potential additional recharge component of 0.2 mm/day in the urban areas.

However, this element of recharge was not included in the model since the volume is only equivalent to

3 % of the rainfall recharge (based on the ratio of urban to total modelled area). This was considered acceptable for a two reasons:

- in urban areas, rainfall recharge will be less than in rural areas due to the larger proportion of impermeable surfaces (such as roads and buildings) and because some proportion of the rainfall recharge will infiltrate into storm water and sewer systems.

- the volume of recharge from urban sources is considered to be within the uncertainty range of the rainfall recharge estimation.

3.7.3 Actual Recharge to the Drift Water Table

The model allows for specification of a limiting factor (relating to the constraints described in Section 3.7.1) the deep percolation capacity of the unsaturated sub-soil.

Limitation to the deep percolation capacity is a function of the vertical permeability of the Drift deposits. For example, the vertical permeability of the Drift may be defined at, say, 0.01 mm/day, whereas the potential recharge rate in winter may rise to 3 mm/day. Under such circumstances it is not possible for the full 3 mm/day to reach the water table. By defining, the percolation capacity at, say, 0.02 mm/d then the model will simulate an actual recharge to the Drift water table at 0.02 mm/day with the remainder being simulated as interflow which is routed along surface topography to the simulated river system. This mechanism is shown schematically in Figure 3.7a.

The major influence of the deep percolation rate is during drought conditions. Under these conditions, the deep percolation capacity limits the rise in the water table such that the model shows a decline in the simulated water table elevation during the next summer. This mechanism is shown schematically in Figure 3.7b.

This mechanism was invoked to the south of Woodplumpton Brook where groundwater levels have been observed to decline between 1972 and 1984. This is explained fully in section 4.5, where this area is discussed in detail.

3.7.4 Recharge Through the Drift to the Underlying Aquifer

Recharge (or leakage) through the Drift to the underlying aquifer (which may be sands & gravels or sandstone) is calculated according to Darcy's equation:

$$LEAK = A * C * (H_d - H_a) \quad (3.9)$$

where

A = area of polygon

H_d = water table elevation

H_a = aquifer water level
C = conductance between drift and aquifer

$$C = 2/((H_d - B_d)/k_{vd} + (T_a - B_a)/k_{va})$$

where

B_d = base of drift
k_{vd}= vertical permeability of drift
T_a = top of aquifer (= B_d)
B_a = base of aquifer
k_{va} = vertical permeability of the aquifer

If the underlying aquifer is unconfined, then leakage is defined as

$$LEAK = A * K_{vd} * (H_d - B_d) \qquad (3.10)$$

where

A = area of polygon
H_d = water table elevation
B_a = base elevation of Drift
K_{vd} = vertical permeability of Drift deposits.

The resultant volume of leakage through the Drift deposits was evaluated through model calibration.

3.8 Abstractions, Augmentation and Transfers

Groundwater abstractions were defined from historical data and applied to the nearest groundwater model polygons.

River abstractions, augmentations and transfers were also defined from the historical data and applied to the river element corresponding to the position of the actual augmentation location.

For steady state simulations the average abstraction rates for the period 1970 - 1994 were calculated, while for transient simulations, which use monthly timesteps, the historical average monthly rate was used. In many instances, only annual rates were available (eg ICI and Whitbreads groundwater abstraction rates). In these cases, the annual rate for the specified year divided by twelve was adopted for each month of the simulation.

3.9 Model Calibration: Criteria and Processes

3.9.1 Calibration Criteria

Once the model was constructed and tested, calibration commenced. Although it was originally intended that calibration would cover the period 1975 to 1993, the calibration period was extended over the period 1969 to 1995 because:

- it was agreed that the drought of 1976 would be better simulated if the calibration period was extended back to 1969.

- the Agency requested that the calibration be extended to include 1995 following preliminary calibration (as detailed in the Phase II report, MM January 1996); it was important that the model was capable of reproducing the observed 1995 groundwater levels, since these were the lowest on record.

Agreed calibration criteria included obtaining an acceptable match between:

- Observed and simulated piezometry for selected time periods, representative of different conditions. The following four periods were chosen: summer 1976 (drought, heavy pumping), winter 1987 (very wet, low abstraction), 1991 (approximately average summer abstractions) and September 1995 (drought and low groundwater levels).

- Observed and simulated groundwater level hydrographs over the whole area for the total study period. All hydrographs were examined during calibration but a number of key hydrographs were also selected on the basis of their location, record length and quality.

- Observed and simulated river flows at the 6 major gauging stations (Garstang, St Michael's, both on the River Wyre; Grizedale Brook, River Calder, River Brock upstream of the A6 and Barton Brook at Hollowforth).

- Observed and simulated river gains and losses. Observed spot gauging data exist for 1971/72 and 1994 - 1995 for the Wyre, Calder, Brook, Barton Brook and Woodplumpton Brook.

In addition, for each model run a maximum imbalance was set for the overall model. During model calibration it was found that model convergence was considered to have been achieved when the simulated imbalance fell below 0.1% for steady state runs and 0.5% for transient runs. These criteria were found to be acceptable in terms of accuracy of simulation of piezometric levels (ie limited head corrections to below 0.00001 m/d) and duration of model runs. The maximum errors associated with individual model polygons (in terms of absolute and relative imbalances and piezometric head corrections) were output for each modelled time step.

3.9.2 Calibration Processes

The calibration involved the adjustment to hydraulic parameters until the calibration criteria were satisfied. Generally this involved the variation in the following parameters:

- horizontal and vertical permeabilities for each model layer;
- storage coefficients (confined and unconfined) for each model layer;
- river bed resistances and conductance between Drift and sandstone below river elements.

At some stages changes to the conceptual model were required. These were as follows:

- splitting of the sandstone layer to two different layers (refer to Section 3.4);
- introduction of the percolation capacity to the Drift to alter the recharge mechanism (refer to Section 3.7);
- variations to the geological structure as a result of the reinterpretation of the structure based on the geophysical remapping (BGS, 1995) and new borehole data.(see Section 2.2.2.2)

A total of 108 steady state and 58 full transient simulations were made during model calibration. This reflects the complexity of the Fylde aquifer system, the importance of assessing the influence of individual and multiple parameter variations on the simulated flow mechanisms in order to fully understand the flow systems and the accuracy of level of calibration required.

There were five main stages in model calibration. These are as follows:

- ***Stage 1 - Initial Steady State Calibration***, where the sensitivity of the major hydraulic parameters were evaluated and an initial calibration of sandstone piezometry was obtained.

- ***Stage 2 - Initial Calibration of the Central Area***, where the response of sandstone groundwater levels to groundwater abstractions around the NWW sources was accurately simulated.

- ***Stage 3 - Regional Adjustments***, where the sandstone layer was split into two individual layers resulting in a four layer model and calibration runs concentrated on the area to the north of the River Wyre and to the south of Woodplumpton Brook.

- ***Stage 4 - Preliminary Calibration and Sensitivity Runs***, when a preliminary calibration was achieved. This is presented in the Phase II Report.

- ***Stage 5 - Final Calibration Runs***, where the model was extended to include data for 1995 and 1996, the results of the geological re-interpretations were incorporated into the model, further sensitivity analyses were carried out and detailed modelling of the Drift was used to confirm the leakage mechanisms adopted in the model.

The result of the final calibration, and the major parameter changes to achieve the calibration are described in detail in the next Chapter.

Figure 3.1

Schematic Cross Sections

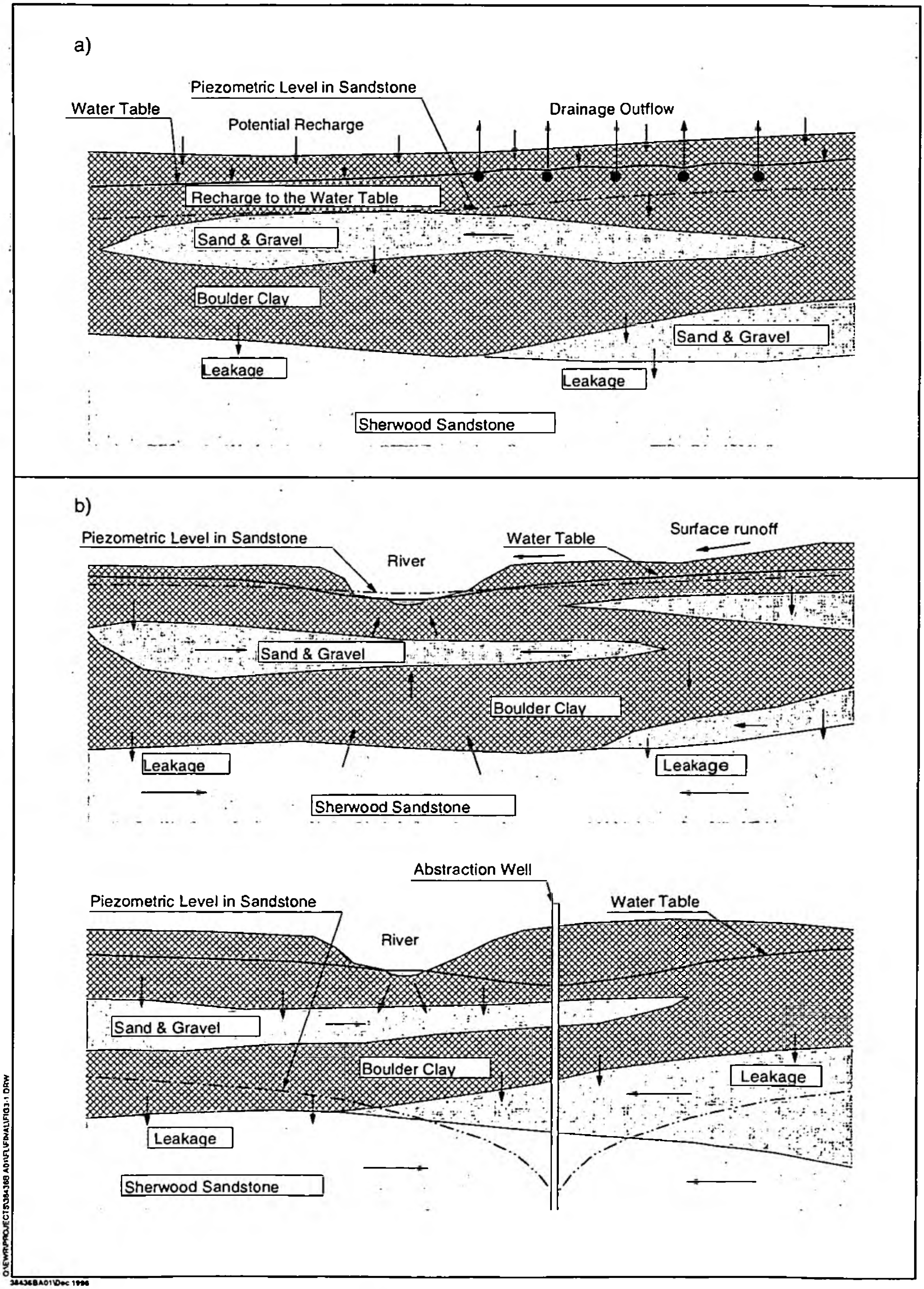
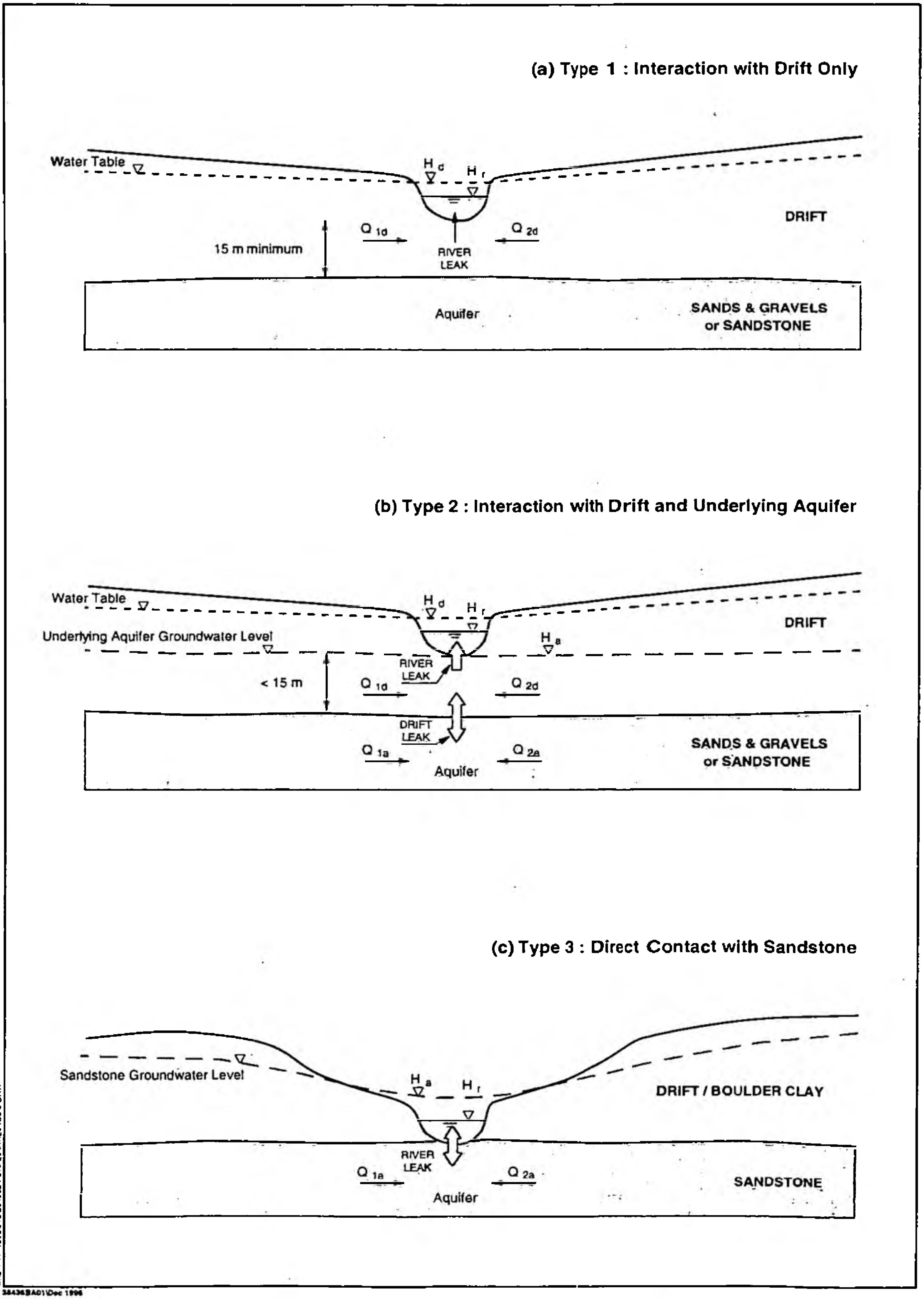


Figure 3.2
Model Grid

Figure 3.3

River - Aquifer Leakage Mechanisms



River Aquifer Mechanisms at Final Calibration

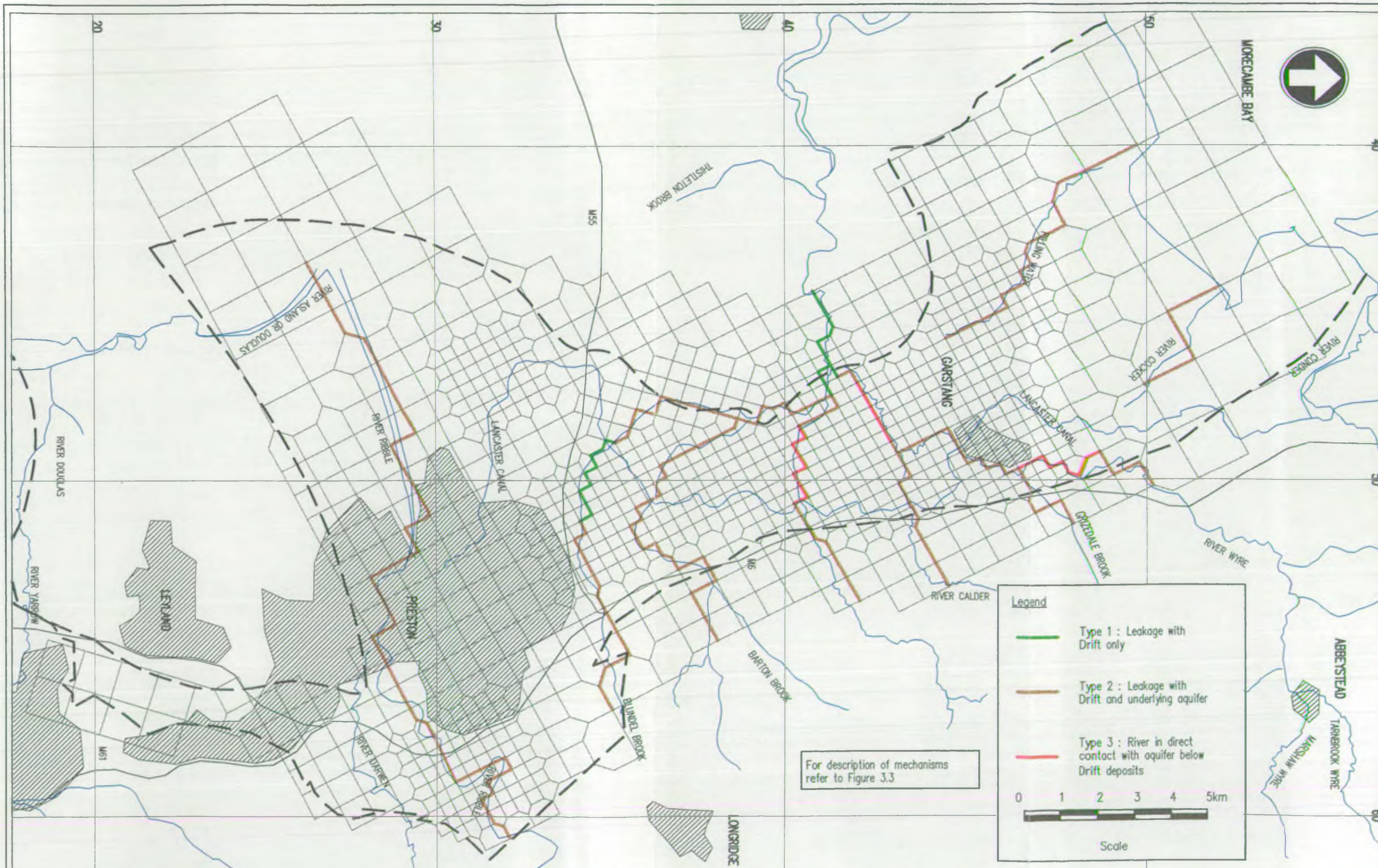
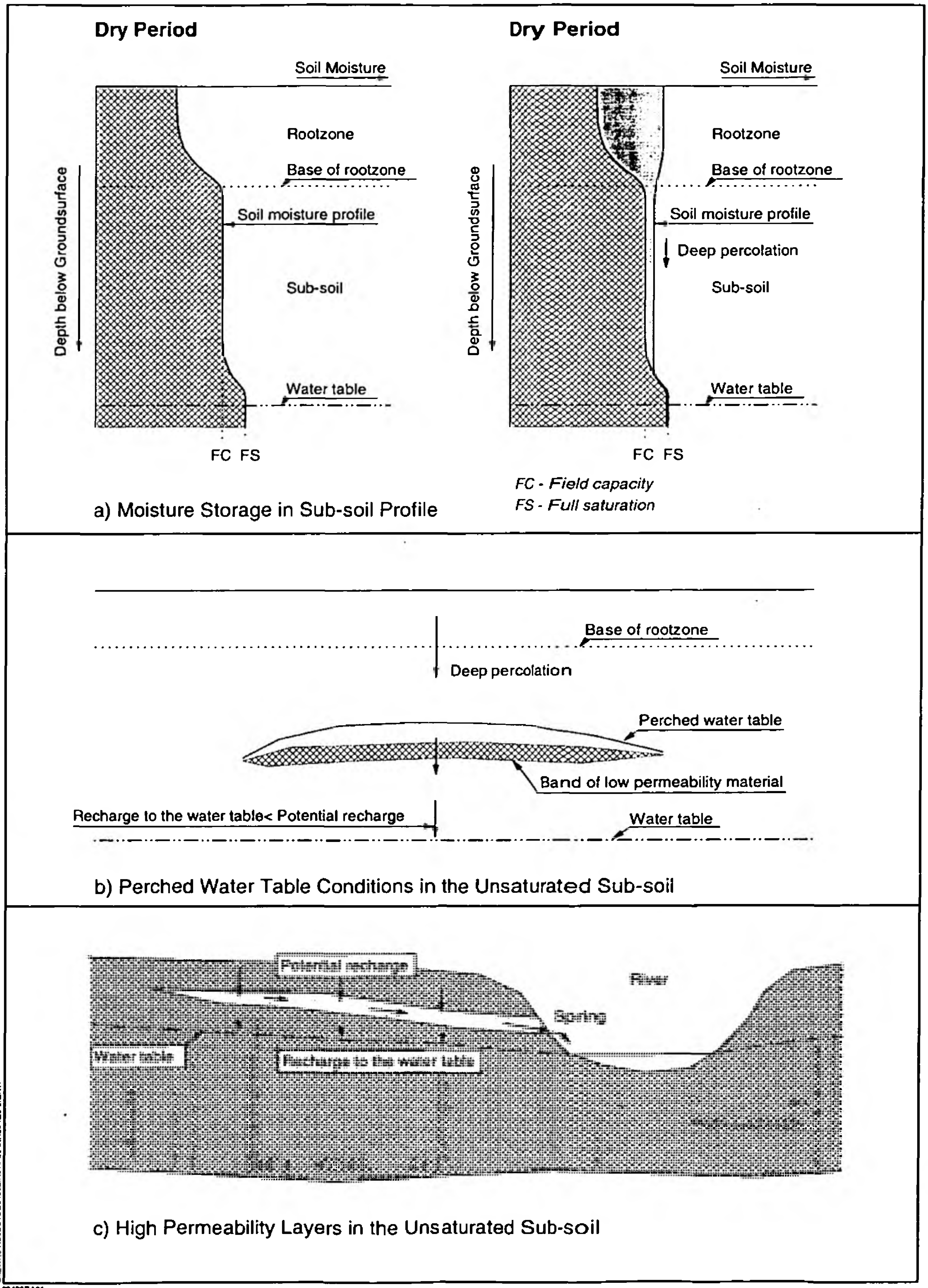


Figure 3.5

Storage within the Unsaturated Sub-soil



a) Moisture Storage in Sub-soil Profile

b) Perched Water Table Conditions in the Unsaturated Sub-soil

c) High Permeability Layers in the Unsaturated Sub-soil

Figure 3.6
Rainfall and Simulated Potential Recharge 1993-95

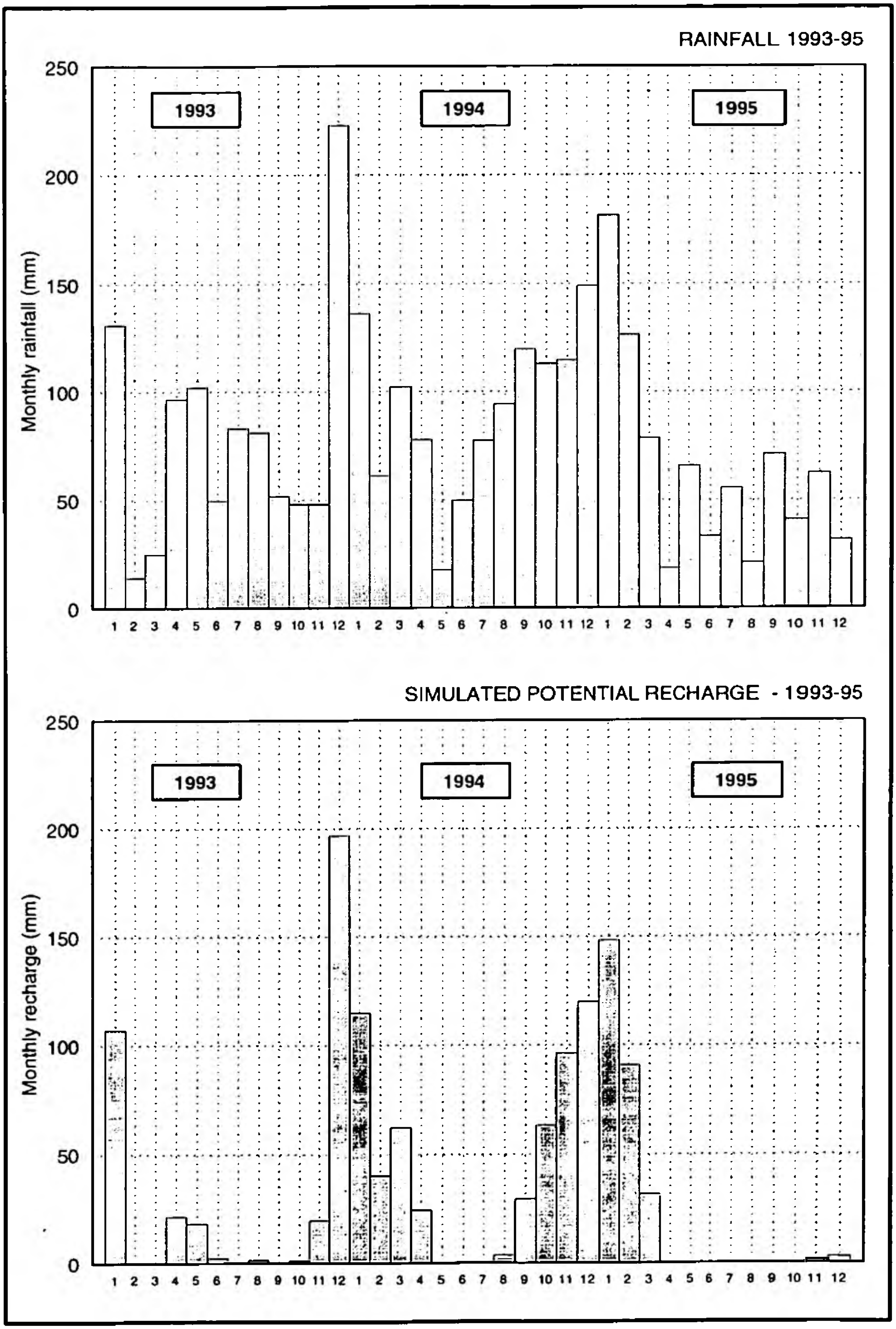
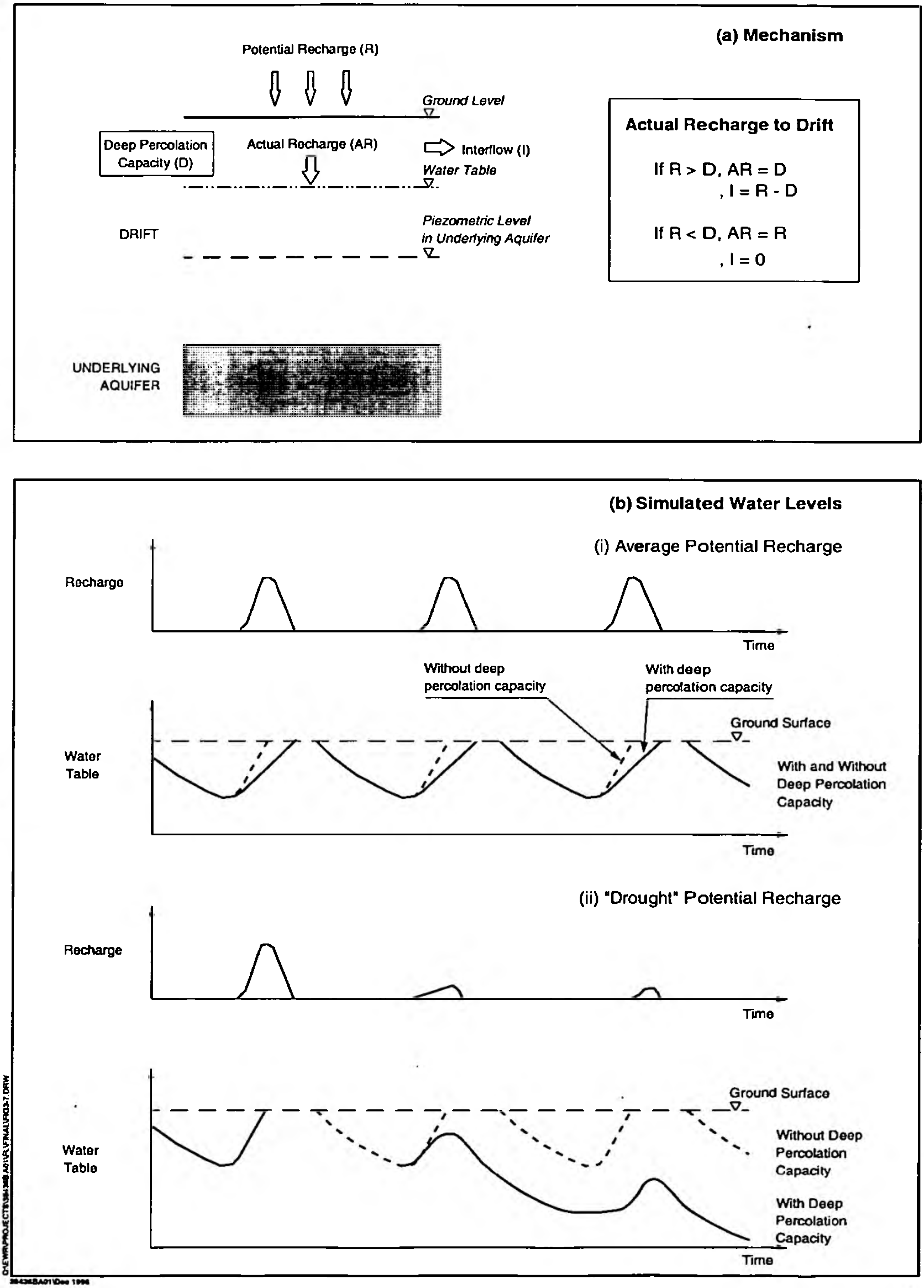


Figure 3.7

Influence of Deep Percolation Capacity



CHAPTER 4

MODEL RESULTS

CHAPTER 4

MODEL RESULTS

4.1 Introduction

This chapter presents the results of the model calibration. The model has been split into sub-five areas (Figure 4.1), as follows:

Area 1 ***North West Fylde*** - The north of the model covering Morecambe Bay, Pilling Water and the River Cocker and extending south towards the River Wyre at St Michaels and to the south east towards Garstang. The area includes the ICI abstraction boreholes.

Area 2 ***Garstang*** - The Garstang area which covers the River Wyre and Grizedale Brook and extends towards the River Calder to the south. The area includes NWW abstraction boreholes W and Z.

Area 3 ***Central Fylde*** - This area is bounded to the north by areas 1 and 2 and to the south by area 4. It covers the Rivers Wyre, Calder and Brock and includes the majority of NWW's LCUS boreholes (Franklaw A+B & Broughton B).

Area 4 ***Preston and Southern Fylde*** - This area covers Barton and Woodplumpton Brooks, the BNFL abstractions and NWW's LCUS boreholes (Broughton A). It also includes Preston.

Area 5 ***South East Fylde*** - This area covers the extreme south east of the Fylde aquifer and the upstream end of the River Ribble. Whitbreads are the main abstractors in this area, although abstractions by Courtaulds in the 1970's also took place.

These areas do not represent isolated aquifer units, each is dependent upon groundwater level and abstraction conditions of the surrounding areas. They have been defined in order to facilitate reporting and to demonstrate particular geological and hydrogeological conditions prevalent in each area. .

For each area the following information relating to the hydrogeology and model simulations are presented:

- Definition of sub-area, including features of the model grid, groundwater abstractions, surface water features and location of observation boreholes.
- Geology of the area including the sandstone structure, the presence of faults, Drift coverage and Carboniferous deposits.
- Hydrogeological considerations: recharge through Drift, aquifer properties and available hydrochemical information.

- Representation of the aquifer system in the model, including discussion on steps in calibration process and the simulated flow mechanisms.

- Final Model Calibration: piezometry, flow balances, hydrographs and river/aquifer interaction.

(The locations of all geological cross sections shown in this chapter are shown in Figure 4.1)

4.2 Area 1: North West Fylde

4.2.1 Features of the Area

Figure 4.2 shows the area in detail. This is a relatively low-lying and flat area bounded to the north by Morecambe Bay and to the east by the edge of the Fylde aquifer. Two rivers drain the area: Pilling Water and the River Cocker, both flowing from the south and discharging into Morecambe Bay.

One Site of Special Scientific Interest (SSSI) exists within the area: the Winmarleigh Mosses. This site was designated a SSSI in 1984 (and extended in 1991) and is important as the largest area of lowland raised mire remaining in Lancashire. The main vegetation types are "*heather and purple moorgrass-dominated mire over deep peat, birch scrub and birch woodland*" (APEM, March 1996). The SSSI also supports rare insect breeds. The number of ponds and springs in the area have reduced over the last sixty years, possibly as a result of lowering of the groundwater table, which has had a negative impact upon its SSSI status.

There are few observation boreholes in the area compared with the rest of the Fylde aquifer. The main observation boreholes are located in the north and north east, constructed during the original LCUS investigations in the 1970's to monitor groundwater levels adjacent to the coast in order to assess the potential for saline intrusion from Morecambe Bay.

ICI abstract from the Fylde aquifer from a number of boreholes in the west of the area, as shown in Figure 4.2.

A relatively coarse grid has been defined in this area, reflecting both the limited data availability and the general lack of influence of NWW's LCUS abstractions compared with the Garstang and Central areas.

4.2.2 Hydrology of the Area

There are three rainfall stations present within the North West Fylde area: Nateby (station number 579215), Myrtle Bank (579149) and Abram House (579155). Mean annual rainfall for these three stations is 816 mm/annum.

There are no permanent flow gauging stations either on the River Cocker or Pilling Water. Furthermore, spot flow measurements by the Agency between 1994 and 1996 do not include these rivers. However, river cross section information were provided by the Agency during the course of the studies.

4.2.3 Geology

The geology consists generally of boulder clay over Sherwood Sandstone. There are fewer lithological logs available for this area than elsewhere on the Fylde, reflecting the fact that there has been only limited borehole construction and exploratory drilling in the area (being remote from the complex of NWW's LCUS abstraction sources).

Relatively thin Drift deposits exist in the central part of this area, at the low lying Winmarleigh Mosses, where the Drift (and boulder clay) thickness is as low as 2 m in places (refer to Figures 2.9 and 2.10). There are no significant sands & gravels lenses in this area, apart from along Pilling Water and at the coast where 3 - 6 m of sands & gravels are present overlying sandstone. This "pocket" of sands & gravels was not considered extensive enough to have any influence on the regional flow mechanisms in the area and was, therefore, not included in the model as a separate layer. However, its significance, in terms of higher permeabilities, was accounted for in the definition of the Drift properties. Section MM, Figure 4.3, presents these Drift features.

Structurally, the Bilsborrow Fault defines the north eastern boundary of this area, bringing the Carboniferous (Ellel Crag, Wellington Crag and Haversham House Sandstones) into faulted contact with the Permo-Triassic. There is therefore potential for flow between the Sherwood Sandstone and Carboniferous sandstone formations.

Originally the Woodsfold Fault was positioned to run from south west to north east (see Figure 2.2, based on the published 1:50,000 scale geological maps). However, recent reinterpretations of geophysical evidence (BGS, 1995) suggests that the Woodsfold Fault runs south to north through the North West Fylde area (see Section 2.2.2 and Figures 2.2B & 2.5).

The model was originally set up as two layers in this area: Drift overlying sandstone (using an effective aquifer thickness of 200m). During calibration a number of minor changes to the geological structure were made. The most significant changes were:

- The subdivision of the sandstone layer into two separate layers - upper and lower sandstones separated by a leakance interface. Lithological logs at the ICI boreholes suggest significant marl bands exist at a level of between 20 and 50m below the top of the sandstone section. There is, however, insufficient information to establish whether the marl bands cause vertical stratification of sandstone water levels in this area. However, the use of the leakance interface proved beneficial in simulating groundwater levels observed at deep observation boreholes (at Morecambe Bay) and at relatively shallow boreholes near Pilling Water and the ICI abstraction boreholes.

- The Woodsfold fault was moved from its originally published position to the revised location, although the effect of the fault on the groundwater flow system in this area was considered to be negligible..

4.2.4 Hydrogeological Data and Simulated Aquifer Properties

There are limited aquifer property data for this area. Based on step test data and the Logan approximation of transmissivity, the mean section permeability varies from 0.3 m/d (to the west of the River Cocker) to 4.2 m/d midway between Pilling Water and the River Cocker (at the coast), typical of the range observed for the whole modelled area (refer to Figure 2.11).

There were no data relating to the river bed in order to help define the river bed conductance. This was, therefore, evaluated during model calibration.

The available observation boreholes and length of records for the North West Fylde area are shown in Table 4.1.

TABLE 4.1
Observation Boreholes - North West Fylde

Reference WRB No. (LCUS Ref)	Name	Aquifer	Record Length	Average (m OD)	Minium		Maximum	
					m OD	Period	m OD	Period
SD45/1 (T21)	Sand Villa	Sandstone	65 - 96	3.0	-1.2	6/91	4.4	4/89
SD45/2 (T19)	Crookall Bridge	Sandstone	65 - 96	5.5	1.6	5/89	6.6	12/81
SD45/3 (T30)	Cocher Bridge	Sandstone	65 - 96	3.5	1.9	5/89	5.9	10/87
SD44/15 (T15)	Moss Edge Farm	Sandstone	65 - 96	2.5	0.3	9/72	4.9	1/81
SD44/36 (T52)	Fowlers Farm	Sandstone	68 - 96	6.0	4.7	5/91	6.8	6/81
SD44/35	Primrose Hill	Sandstone	68 - 95	6.4	5.3	12/95	7.2	2/81
SD44/20 (T46)	Middle Holly	Sandstone	65 - 96	23.1	20.8	6/91	24.0	12/92
SD44/21 (T31)	Throughway Top	Sandstone	65 - 91	7.8	7.1	9/89	8.2	3/68

Piezometry is relatively flat in the area (refer to Figure 2.15), with the maximum gradients found at the eastern boundary and the flattest gradients at Morecambe Bay. Generally groundwater flow directions are from south east to north west in the eastern area and from south to north in the eastern/central area.

Groundwater levels observed in the area are influenced by abstractions from both the ICI boreholes and the abstractions from NWW sources in Garstang (in the "Garstang" area - refer to Section 4.3).

During model calibration various changes to the aquifer properties were made to simulate the observed groundwater levels at the various observation boreholes. The main changes were as follows:

- During initial runs the gradient across the area was relatively constant: too steep at the north and too shallow at the south eastern boundary. At the south eastern boundary of the area (between the North West Fylde and Garstang areas) high bicarbonate concentrations have been found. This was considered to represent long residence times of groundwater, thus indicating a low permeability zone. Consequently, a low permeability zone was defined to the north west of Garstang to represent a partial flow barrier as indicated by piezometry and the high bicarbonate concentrations. This low permeability zone is located to the east of the revised position of the Woodsfold Fault.

- To increase the impact of ICI abstractions on surrounding groundwater levels particularly to the north east of the ICI boreholes, the permeability of the sandstone was raised to 5.0 m/d. This increases the areal influence of the abstractions but reduces the magnitude of drawdown with distance from the boreholes, as observed in practice. However this resulted in a large volume of outflow to Morecambe Bay which was not considered to be the case. Permeabilities of polygons at Morecambe Bay were thus reduced to 2 m/d.

- To reduce the seasonal fluctuations at the upstream end of Pilling Water and the River Cocker, the bed resistances were reduced and the vertical permeability between the river, through the Drift, to the sandstone increased. (This is consistent with anecdotal evidence of historical artesian discharge to these water courses).

- To reduce the seasonal fluctuations further to the east of the ICI boreholes, the vertical permeability of the interface between upper and lower sandstone was reduced from 0.05 m/d to 0.0025 m/d.

- The permeability of the faulted contact between Carboniferous and Sherwood Sandstone was increased to 0.5 m/d (from the original setting of 0.05 m/d) in order to improve piezometry across the Bilsborrow Fault.

4.2.5 Results of Model Simulations

Piezometry

Figures 4.4 and 4.5 present the simulated piezometry and observed groundwater levels at the observation boreholes for April 1987 (low abstraction, high groundwater levels) and September 1995 (high abstractions, low groundwater levels) respectively.

A relatively good match between the observed and simulated piezometry has been achieved throughout the area.

Flow Mechanisms

The simulated flow balance components for the North West Fylde area are included in Appendix C.1. The main components of the simulated flow balance are described below:

- The potential recharge to the Drift layer was simulated at 160.15 Ml/d (average 1972 - 1995 inclusive). However, the actual leakage from the Drift to the sandstone was simulated at only 1.2 Ml/d. The volume of leakage is dependent upon the level of abstraction: during September 1995 the volume of leakage peaked at 3.94 Ml/d, while during April 1987 leakage was simulated at only 0.06 Ml/d.

- At the Winmarleigh Mosses SSSI leakage would naturally occur from sandstone to the Drift. However the direction of leakage is reversed as a result of abstractions at ICI and in the Garstang area, with leakage from the Mosses to the sandstone thus potentially affecting the wetland areas.

- At Morecambe Bay, the outflow from the model varies from 2.11 Ml/d to 5.05 Ml/d depending upon the level of abstraction.

- Pilling Water and the River Cocker have little influence on the simulated water balance components. The model simulates a minor leakage from Pilling Water to the aquifer system during each summer (from 0.1 to 0.5 Ml/d) when the ICI abstraction boreholes are in operation. Otherwise the Drift and sandstone aquifers leak into the river system at all times (refer to Figure 4.4 and 4.5).

- At the south eastern boundary the average inflow from the Garstang area was simulated by the model as 4.37 Ml/d. This however varies according to the abstraction from NWW sources W and Z. During April 1987 (when W and Z were not operated) the inflow was 5.31 Ml/d, while during September 1995 (following a period of relatively high abstractions) the flow direction changed with an outflow from the North West Fylde area to the Garstang area of 0.77 Ml/d. Consequently, abstractions by NWW in Garstang do influence conditions to the north west.

Groundwater Level Fluctuations

Table 4.2 summarises the simulated groundwater levels at each of the observation boreholes in the North West Fylde.

TABLE 4.2

North West Fylde - Simulated and Observed Groundwater Levels

Reference WRB No. (LCUS Ref)	Aquifer	Average		Seasonal Fluctuations		Comments
		Observed (m OD)	Simulated (m OD)	Observed (m)	Simulated (m)	
SD45/1 (T21)*	Sandstone	3.0	4.2	1.2	0.9	Trends simulated accurately
SD45/2 (T19)*	Sandstone	5.5	5.6	0.7	0.8	Model does not accurately simulate water level decline in 1989 when ICI abstractions increased
SD45/3 (T30)	Sandstone	3.5	4.4	0.6	1.1	
SD44/15 (T15)	Sandstone	2.5	3.5	0.9	1.1	
SD44/36 (T52)	Sandstone	6.0	6.0	1.1	1.1	
SD44/35	Sandstone	6.4	6.4	0.9	1.2	Overstimulates impact of ICI abstractions
SD44/20 (T46)	Sandstone	23.1	24.2	0.4	0.6	
SD44/21 (T31)	Sandstone	7.8	7.7	0.7	0.7	Good simulation of impact of ICI abstractions

Simulated and observed groundwater level hydrographs for two of the observation boreholes within this area (SD45/2 & SD44/35) are shown in Figure 4.6.

The simulated hydrographs accurately represent the flow mechanisms within this area - in terms of level, trend and response to abstractions. Attempts were made to improve the accuracy of boreholes at the River Cocker where the influence of ICI abstractions is less than simulated. Increased sandstone permeability improves this (while causing a lowering in the simulated piezometry). However the permeability was already defined at 5 m/d, at the upper end of the measured values, and thus any further increase over a regional scale could not be justified.

River-Aquifer Interaction

Leakage from the Drift and sandstone aquifers to the River Cocker and Pilling Water was maintained throughout the simulation, apart from low leakages during relatively high abstractions from ICI boreholes and the NWW sources W and Z (eg during September 1995).

The river bed resistance was finally set at 1 day (representing a relatively leaky river) and the vertical permeability of the Drift deposits directly below the river were defined at 0.01 m/d at Pilling Water and 0.005 m/d at the River Cocker. These values were derived during model calibration in order to accurately simulate the extent of the influence of the ICI abstractions eastwards and groundwater levels at observation boreholes around the rivers.

4.3 Area 2: Garstang

4.3.1 Features of the Area

Figure 4.7 shows the area in detail. This includes urban Garstang in the north east of the modelled area. The River Wyre and Grizedale Brook flow off the Carboniferous uplands into the Fylde plain in this area. Transferred water from the River Lune is discharged to the Wyre at Abbeystead, transported along the Wyre, and subsequently abstracted at Garstang for treatment at Franklaw WTW, as part of the Lancashire Conjunctive Use Scheme.

There are no SSSI's or other environmentally sensitive sites in this area.

There are a large number of observation boreholes in the area. These were drilled as part of the 1970's LCUS investigations to monitor groundwater level responses in the Sherwood Sandstone and overlying Drift deposits to abstraction from NWW sources W and Z.

A more recently licensed abstraction borehole is located within the area: North Country Poultry Ltd., to the west of W and Z sites.

A relatively detailed grid was defined in this area in order to accurately simulate conditions around NWW sources W and Z.

4.3.2 Hydrology of the Area

There are three rainfall stations present at the model boundary of the Garstang area: Barnacre Reservoir (station number 578008) and two at Scorton (577975 and 577982). Mean annual rainfall for these stations is around 1072 mm/annum, around 150 - 200mm higher than in the Fylde plain.

There are three permanent gauging stations: Scorton at the model boundary, Garstang on the River Wyre and Grizedale Brook (refer to Figure 4.7). The Scorton gauge was used, along with the results of the HYSIM modelling, to define river inflows to the model. The other two stations were used to calibrate river flows in the model.

At Garstang, spot flow measurements in 1971/2 (during the original LCUS studies) and in 1994 - 96 indicate that the River Wyre loses significant quantities of water during summer when NWW sources W and Z are pumping: with losses of around 3 - 5 Ml/d recorded (although up to 6.5 Ml/d loss was measured in October 1995).

Due to these losses, there is provision within the NWW abstraction licences to augment the River Wyre at Garstang from abstraction borehole W2. When the flow in the River Wyre at St Michaels gauging station falls below 50 Ml/d then either 3.0 Ml/d is pumped to the river, or, if borehole W2 is in operation, 5.5 Ml/d is added to the river.

4.3.3 Geology

The geological structure of this area is particularly complex, with extensive faulting combined,with highly variable Drift stratigraphy.

Structurally, the Bilsborrow Fault defines the contact between the Carboniferous and Permo-Triassic. The Sherwood Sandstone is further displaced by the parallel Catterall Fault, with relatively thin sandstone (up to 100m thick) in the east and much thicker sandstone (up to 750m) to the west (forming the 'Catterall basin', a N-S trending fault bounded trough/graben defined by the Catterall and the repositioned Woodsfold faults); originally the Woodsfold Fault was assumed to run SW-NE through the area, but this was revised by the subsequent BGS geophysical remapping of the Fylde aquifer (refer to Section 2.2.2 and Figures 2.2B & 2.5)

The Drift varies considerably throughout the area. Boulder clay exists throughout in varying thicknesses. However, relatively thin boulder clay exist to the north east of Garstang (refer to Section MM - Figure 4.3). Here, leakage of rainfall recharge to the sandstone aquifer is expected to be higher than in areas of thick boulder clay cover. In addition, the rivers cut through the boulder clay in this area, resulting in significant hydraulic connection between the rivers and the sandstone aquifer. This interaction is confirmed from both the observed river flow losses and the data from observation boreholes, where the impact of abstractions from NWW sources W and Z are "dampened" by the effect of river interaction with the sandstone aquifer (at observation boreholes SD44/32 (T47) and SD54/15 (T44)).

Within the Drift, significant sands & gravels exist (refer to Section MM - Figure 4.3). The continuity of the sands & gravels is, however, uncertain. Boreholes to the north and south of Section MM indicate boulder clay over sandstone. To the south of this section at Garstang and at NWW sources W and Z, sands & gravels is located in few boreholes and where it does occur it is bounded top and bottom with boulder clay.

The fence diagram of the area around Garstang (Figure 4.8) indicates the variability in Drift composition and the difficulty in correlating between borehole logs. The diagram indicates, however, the likelihood of a good connection between the River Wyre and the sands & gravels in the area. The absence of the boulder clay to the east of the river indicates a potential high permeability connection with the sandstone.

The model structure was set up to represent the structure of the sandstone/Carboniferous contact and the Drift composition described above. Originally three model layers were used: Drift, sands & gravels and sandstone.

Initially, the effective sandstone thickness was defined at 200m throughout, except at the contact with the Carboniferous where the thickness was reduced to the actual thickness, which fall to around 30 m in places. The thickness of the Carboniferous Deposits, to the east of the Bilsborrow Fault were defined at 100m, while Drift thicknesses and the separate sands & gravels layer were evaluated from the available lithological logs.

During model calibration, and once the revised geological structure was developed by BGS, a number of changes to the sandstone layer were made. The major changes were as follows:

- The sandstone was split into two layers as described previously. However, analysis of the borehole logs indicated that the sandstone was relatively free of marl bands, Consequently during calibration, the leakance interface between the two sandstone sub-layers was defined to be highly "conductive" such that there was no vertical stratification in groundwater levels simulated in the Garstang area.

- The faults (Bilsborrow, Catterall and Woodsfold) were repositioned according to the revised BGS mapping.
- The sandstone thickness was increased (to 350 m) around the 'Catterall basin' to simulate the deep depression in this area.
- Minor modifications to the area of boulder clay free Drift were made to change the simulated volume of leakage through the Drift to the sandstone aquifer.

4.3.4 Hydrogeological Data and Simulated Aquifer Properties

Based on step test data and the Logan approximation of transmissivity, the mean section permeability varies from 0.05 m/d (in the north of the area at the Bilsborrow Fault) to 3.1 m/d in Garstang. No long term pumping test analysis results were available for the abstraction boreholes in the area.

Evidence for the permeability of Carboniferous deposits and the faulted contact between the Sherwood Sandstone and Carboniferous were derived from the observed piezometry. Steep gradients are observed across the Carboniferous deposits, indicating a relatively low permeability.

The available observation boreholes and length of records for the Garstang area are shown in Table 4.3.

The piezometry of the Garstang area has two main characteristics:

- relatively steep gradients across the Carboniferous to the Sherwood Sandstone; and,
- relatively flat gradient in Garstang towards the piezometric "ridge" defined at the boundary with Area 1 (North West Fylde), coinciding with a zone area of relatively high bicarbonate groundwater (previously referred to as 'the Garstang anomaly').

The observation boreholes in the area indicate that the influence of abstractions from NWW sources W and Z is more prevalent to the west and north of the sources than to the south and east, across the River Wyre . Consequently a relatively high river conductance was specified for the Wyre at Garstang, in order to simulate this effect.

During model calibration various changes to the aquifer properties were made to simulate the observed groundwater levels at the various observation boreholes.

During the initial stages of calibration, both the piezometry and the seasonal fluctuations in the Garstang area were inaccurately simulated. The introduction of a low permeability zone, coincident with high bicarbonates of the 'Garstang anomaly', partially improved the simulation. Further improvement in the simulation of the influence of NWW sources W and Z to the west and north was made by increasing the mean section permeability to 6 m/d. This resulted in transmissivities around 1000 m^2/d around the abstraction boreholes in Garstang. Application of the Logan approximation to field data gave transmissivities between 329 m^2/d and 1180 m^2/d. It should be noted, however, that the Logan approximation tends to underestimate transmissivity. Furthermore, the presence of fault zones , as defined from BGS geophysical mapping (refer to Figure 2.5) could result in preferential areas of high permeability in the Garstang area.

Although the piezometry was improved with these changes the seasonal fluctuations remained poorly simulated. The increased transmissivity resulted in seasonal variations four to five times too low in boreholes located around NWW sources W and Z.

TABLE 4.3
Observation Boreholes - Garstang Area

Reference WRB No. (LCUS Ref)	Name	Aquifer	Record Length	Average (m OD)	Minium		Maximum	
					m OD	Period	m OD	Period
SD44/23 (T37)	Fowlers Lane	Sandstone	65-96	15.5	14.1	10/90	17.1	5/83
SD44/12 (T12)	Gubborford Lane	Sandstone	72-96	20.0	16.5	12/91	21.3	1/82
SD44/22	Gubborford Bridge	Sandstone	73-91	16.5	14.0	10/89	18.9	1/82
SD44/68 (D117)	Clay Lane Head	Sands & Gravels	73-95	17.5	16.8	8/84	19.0	2/77
SD44/37	Gubborford Bridge	Sandstone	73-96	16.8	12.5	10/89	19.1	6/83
SD54/8 (T11)[(1)]	Hazel Head Lane	Sandstone	73-96	16.3	12.4	9/76	18.6	4/81
SD44/33 (T48)	Croston Road	Sandstone	68-94	18.0	9.3	9/90	15.7	3/83
SD44/10 [(2)]	Lancaster Old Road	Sandstone	66-96	12.5	-0.3	10/89	16.5	1/83
SD44/52 (D125)	Park Farm	Sands & Gravels	71-96	15.0	9.4	6/82	15.5	12/94
SD44/32 (T47)	Wyre Bridge	Sandstone	73-94	14.5	10.5	7/74	19.8	1/87
SD54/15 (T44)	Park Head Farm	Sandstone	74-95	22.5	19.9	6/84	28.0	12/80
SD44/13 (T14)	Byerworth Bridge	Sands & Gravels	72-89	13.5	4.8	9/84	15.2	1/81

Notes

(1) Fluctuations recorded during period 1973 - 1983. Thereafter relatively flat. Data in table related to period 1973-83.
(2) Borehole located 400 m from NWW sources W and Z.

Further analysis of the modelled and the observed data indicated that the simulated seasonal fluctuations represent the timing and amplitude of the hydrograph during periods of low abstraction (between 1980 and 1986). By comparing the simulated water balance components during periods of high and low abstraction, it was found that abstraction volumes were derived primarily from leakage through the Drift deposits. The Drift deposits are relatively thin around the River Wyre at Garstang. The high vertical conductance of the Drift allowed a significant inflow of rainfall recharge to the sandstone aquifer, particularly during periods of abstraction, thus limiting seasonal fluctuations.

The calibration was thus improved by reducing the vertical permeability of both the Drift deposits (reduced from on average 0.001m/d to 0.00015m/d) and the vertical permeability of the sands & gravels (from 0.5 m/d to 0.05 m/d). This resulted in an improved simulation of groundwater hydrographs on the west side of the River Wyre during abstraction, but with an increase in seasonal fluctuations during the period with little abstraction (1980-86). An increase in the specific yield of the sands & gravels (from 7.5% to 12.0%) improved the simulations further.

On the east side of the River Wyre, the impact of abstractions was too great. In addition there was very little leakage from the river, compared with the observations in 1994. To improve the simulations:

- The river bed resistances were reduced to allow more river leakage and reduce the impacts of abstractions on the east of the River Wyre. This also had the effect of dampening the seasonal fluctuations on the west side of the River Wyre.

- The inflow from the Carboniferous deposits was increased locally at the faulted contact, where Carboniferous sandstone aquifers were set to be more transmissive than originally defined, with permeabilities increased from 0.05 m/d to 0.5m/d.

These changes improved the simulations to the east of the river.

However, another possible explanation for the reduced impact from abstractions east of the river may be a result of anisotropic transmissivity as a result of north-south trending faults, where the influence of the faults is to reduce the effective transmissivity in east-west direction. This would also reduce the impact of abstractions towards the west. Such a feature was introduced around Woodplumpton Brook - section 4.5.4 - but was not introduced into the model here because there is less evidence of faulting in the Garstang area, to the west of the Billsborrow Fault.

4.3.5 Results of Model Simulations

Piezometry

Figures 4.9 and 4.10 present the simulated piezometry and observed groundwater levels at the observation boreholes for April 1987 (low abstraction, high groundwater levels) and September 1995 (high abstractions, low groundwater levels) respectively.

A relatively good match between the observed and simulated piezometry has been achieved throughout the area. Minor inaccuracies exist at the groundwater "ridge" in the north west of the area (bordering Area 1) where low permeabilities were defined to simulate the correct gradients (coincident with the 'Garstang anomaly').

Flow Mechanisms

The simulated flow balance components for the Garstang area are included in Appendix C.2. The main components of the simulated flow balance are described below:

- On average only 12 % of the potential recharge leaks through the Drift to the sandstone aquifer.
- Based on the average abstraction rate from the Garstang area of 2.18 Ml/d (1972-95), abstractions are derived from leakage from the Drift (26%), leakage from the sands & gravels (30%) and from the River Wyre (38%).
- During high groundwater level/minimum abstraction conditions, the inflow of water (from Carboniferous and from vertical leakage) generally flows to the north west. Flow within the sandstone aquifer is not intercepted by the rivers during these conditions.
- During low groundwater levels/high abstractions conditions there is a minor increase in Carboniferous inflow (range - 0.33 to 0.40 Ml/d) and a large increase in losses from the rivers. Therefore, induced flow from the Carboniferous deposits as a result of abstractions in this area is relatively small. This primarily because the rivers were specified relatively "leaky" in order to accurately simulate river flows and groundwater hydrographs on the west side of the Wyre (where NWW sources W and Z are located) and the east side (refer to sections below).
- The sands & gravels act as an additional storage reservoir, dampening out river flow losses.

Groundwater Level Fluctuations

Table 4.4 summarises the simulated groundwater levels at each of the observation boreholes in the Garstang area, while the simulated and observed groundwater level hydrographs for four observation boreholes in the Garstang Area (SD44/10, 13, 32 & 33) are shown in Figure 4.11 and 4.12.

From Table 4.4 and the presented hydrographs, it can be concluded that a relatively accurate simulation of groundwater piezometry, fluctuations and trends has been achieved.

The main area of uncertainty is at the Carboniferous boundary, where the simulated hydrographs are less accurate than in other areas of the model. Various attempts to improve the simulation were made, involving changes to Carboniferous and Sherwood Sandstone permeabilities, Drift conductance and river parameters. The results presented in Table 4.4 are based on the most accurate simulations with the most plausible parameter settings.

TABLE 4.4

Garstang- Simulated and Observed Groundwater Levels

Reference WRB No. (LCUS Ref)	Aquifer	Average		Seasonal Fluctuations		Comments
		Observed (m OD)	Simulated (m OD)	Observed (m)	Simulated (m)	
SD44/23 (T37)	Sandstone	15.5	15.8	1.6	1.8	Accurate simulation of the low levels recorded 1984 and 1989-95.
SD44/12 (T12)	Sandstone	20.0	28.0	1.5	1.7	Node located 600 m "upstream" of observation well accounts for the apparent discrepancy in simulated level
SD44/22	Sandstone	16.5	20.0	2.2	1.8	Level difference due to borehole being positioned closer to river than the model node. River is "leaky" at this point and therefore groundwater levels greatly influenced by river water levels
SD44/68 (D117)	Sands & Gravels	17.5	-	-	-	S&G not simulated as separate layer in this zone
SD44/37	Sandstone	16.8	19.2	3.2	3.0	Level difference due to proximity of borehole to leaky river (as above)
SD54/8 (T11)(1)	Sandstone	16.3	14.8	1.2	2.1	Poor simulation due to close proximity of borehole to faulted contact between Carboniferous and Sherwood Sandstone
SD44/33 (T48)	Sandstone	18.0	17.5	3.1	3.6	Accurate simulation of trends, fluctuations and response to NWW W/Z abstractions
SD44/10	Sandstone	12.5	12.5	8.2	8.1	Accurate simulation of trends, fluctuations and response to NWW W/Z abstractions
SD44/52 (D125)	Sands & Gravels	15.0	-	-	-	S&G not simulated as separate layer in this zone
SD44/32 (T47)	Sandstone	14.5	19.5	4.2	3.9	Poor simulation of level but trends and fluctuations sufficiently accurate.
SD54/15 (T44)	Sandstone	22.5	21.5	2.1	2.8	
SD44/13 (T14)	Sandstone	13.5	13.7	1.9	3.2	

Notes (1) Borehole SD54/18 is located within 200 m of the Billsborrow Fault, where flow conditions are highly heterogeneous. The model grid is relatively course in this area and therefore it is not possible to accurately simulate conditions here.

River Flows and River-Aquifer Interaction

The simulated hydrograph for the Garstang river flow gauging station is shown in Figure 4.13. A very good agreement between observed and simulated low river flows has been achieved.

The simulated losses along the River Wyre upstream of the Garstang gauging station are shown in Figure 4.14. This compares favourably with the losses observed during 1994 and 1995.

In order to simulate these river flows and losses, the river conductance parameters to the north and east of NWW sources W and Z were increased during model calibration. The river bed resistance was set to 1 day, representing a relatively conductive river bed. The conductance of the Drift directly below the river was set at a high value (compared with other areas), with the vertical permeability of the Drift deposits at 0.5 m/d.

4.4 Area 3: Central Fylde

4.4.1 Features of the Area

Figure 4.15 shows the area in detail. It encompasses the majority of NWW's LCUS groundwater sources (Sites H, J, K, L, M, P and Q), and corresponds with the area of maximum groundwater level decline.

The area includes a number of rivers - the downstream end of the River Wyre , the Calder, the Brock and the downstream ends of Barton Brook and Woodplumpton Brook/New Draught. Three permanent gauging stations (St Michaels, the Calder and the River Brock upstream of the A6) are located in the area, which has been extensively spot gauged over the last three years. (The Calder gauging station was closed down in 1981.)

Augmentation of the rivers occurs at two locations:

- on the River Brock, where 3 Ml/d is added to the river from the Franklaw collector main whenever flows at the Brock gauging station fall below 5 Ml/d if Franklaw A sources are pumping and/or if sources K1 or K2 pumping;
- the River Calder, where 3.0 Ml/d is added to the river from boreholes R3 and R4 whenever flows recorded at St Michaels gauging station fall below 50 Ml/d if Franklaw A is pumping.

The area around St Michaels on the Wyre was designated as being a major wetland site. There has been a large decline in the number of ponds in the area since 1938, with a reduction in number of around 50% between 1938 and 1983. This decrease has been attributed to a number of factors including "*urbanisation, natural succession, use for landfill and the lowering of the water table*" (APEM, 1995).

There are a large number of observation boreholes in the area. They were drilled as part of the original LCUS investigations to monitor groundwater levels in the sandstone and overlying Drift deposits. To the east of the Bilsborrow Fault there are a few observation boreholes measuring groundwater levels within the Carboniferous deposits.

A fine grid of model polygons was defined in this area in order to accurately simulate groundwater levels around the abstraction sources and the interaction of the groundwater abstractions with the surrounding river system.

4.4.2 Hydrology of the Area

There are two main rainfall stations present within the Fylde plain in this area: St Michaels on Wyre (station number 578682) with an annual average rainfall of 853 mm/annum; and at Myerscough College (578321), with an average annual rainfall of 843 mm/annum.

Spot flow measurements during 1994, 95 and 96 indicated that significant losses from the rivers occur in three areas:

- upstream of St Michaels gauge on the River Wyre;

- along the river Calder at Calder Bridge and Calder Weir;
- along the River Brock between the A6 and Roe Bridge.

4.4.3 Geology

The contact between the Carboniferous and the Permo-Triassic in this area is an unconformity, with Manchester Marls separating Carboniferous water bearing formations and the Sherwood Sandstone aquifer (Figure 2.7). Therefore, there is not expected to be any significant flow of water between aquifers or any significant response in groundwater levels measured in the Carboniferous as a result of the NWW abstractions from the Sherwood Sandstone. This is confirmed through analysis of the observation borehole records (refer to the Section 4.4.4).

Within the Fylde Plain, the geology is characterised by a variable thickness of boulder clay overlying the sand & gravel aquifer which overlies the sandstone.

The contrast in the continuity of boulder clay across this area can be seen in the cross sections presented in Figures 4.16, 4.17 and 4.18. Section K - K (Figure 4.16) runs along the River Wyre through areas where boulder clay is absent. At this location significant river flow losses have been observed. In addition, groundwater fluctuation to the north of the Wyre in this area are much lower than to the south of the river. This indicates that the Wyre acts as a "recharge" barrier where the river has cut into the sands & gravels and sandstone aquifer.

Section L - L (Figure 4.17) runs north-south between Preston and Garstang and shows apparent continuity of the boulder clay, with the exception of the immediate vicinity of the River Brock..Again, significant interaction between the River Brock and the aquifer system is expected where there is limited boulder clay cover.

Section B-B (Figure 4.18) runs along the river Calder and shows a continuous layer of boulder clay. A direct connection between the river and the sands & gravels is not apparent. However, losses from the Calder as a result of groundwater abstractions have been observed. There may thus be localised areas where the boulder clay is absent, minimal or discontinuous.

Drift coverage is, therefore, highly variable across this area (particularly in relation to the rivers). Consistent, though, is the presence of a sands & gravels layer between the Drift and the sandstone. This occurs over the central area roughly coinciding with the line of NWW abstraction boreholes.

The sandstone in the Central area has been affected by dominant N-S trending faulting. The two main faults are the Catterall Fault in the north east of the area and the Woodsfold Fault in the west. To the west of the Woodsfold fault, sandstone is downthrown by up to 750 m and is overlain by effectively impermeable Mercia Mudstone.

The geological structure of the model was derived from lithological logs and BGS mapping. The features described above were incorporated into the model. Three layers were defined originally (as previously described). No significant alterations to the model structure of the Central area were required during model calibration, other than the splitting of the sandstone layer into two separate layers. Although marl bands within the sandstone were encountered in many of the lithological logs of this area, they occur relatively infrequently and at different depths. The marls in this area were therefore considered discontinuous. Consequently, the leakance interface separating the two sandstone layers in the model was defined to be relatively conductive (with vertical permeabilities defined at 0.5 m/d) so that the simulation of vertical stratification of groundwater levels was minimised.

4.4.4 Hydrogeological Data and Simulated Aquifer Properties

Pumping tests have been carried out at most of the NWW sources. Transmissivities derived from these tests vary from 104 m^2/d (at borehole K2) to 1354 m^2/d (at borehole L1): a relatively high range, reflecting the heterogeneity of the sandstone aquifer.

During model calibration the permeability was varied between 1 and 6 m/d (a transmissivity range of between 200 and 1200 m^2/d).

Properties of the sands & gravels could not be assessed from the pumping tests.

The available long-term observation boreholes and length of records for the Central area are shown in Table 4.5.

The piezometry of the Central area is characterised by a deep depression in groundwater levels that occurs (seasonally) when the LCUS sources are operated (refer to Figure 2.15). Under non-pumping conditions, flow is from east to west, with steep gradients across the Carboniferous and flat gradients within the sandstone. During periods of heavy abstraction from NWW's Fylde boreholes the deep depression reverses the flow direction from the west to the east, in the western area of the model.

The groundwater depression is limited in extent to the north, apparently by the influence of the River Wyre. Groundwater fluctuations from observation boreholes located to the north of the river (eg SD44/20) vary by around 1-2 m per annum on average while fluctuations monitored from boreholes to the south of the river (eg SD44/16) vary by about 5-10 m. This suggests that there is significant interaction between the Wyre and the aquifer system, which limits the influence of the central groundwater abstractions to the north, with the river acting as a "recharge barrier". This reach of river coincides with an area of river flow losses as observed during spot flow measurements between 1994 and 1996.

Groundwater levels in the Carboniferous deposits (eg SD54/18A and 18C) suggest that the Carboniferous sandstones are relatively unaffected by abstractions from the Fylde aquifer.

Most Drift monitoring boreholes are located close to the rivers; they were drilled in locations where significant losses from the rivers were thought to occur, with the intention of investigating the interaction between the rivers and the aquifer via permeable Drift layers. Generally, groundwater levels in the sands & gravels directly overlying the Sherwood Sandstone follow the fluctuations monitored within the sandstone, with reduced magnitude of variations and a delay of 1-2 months between sandstone and sands & gravels. This is because of the higher storage potential of the sands & gravels than the sandstone.

TABLE 4.5
Observation Boreholes - Central Area

Reference WRB No. (LCUS Ref)	Name	Aquifer	Record Length	Average (m OD)	Minium		Maximum	
					m OD	Period	m OD	Period
SD44/20 (T29)	Tyer Bridge	Sandstone	65-95	6.5	5.0	7/89	7.8	1/82
SD44/17 (T24)	Aispail Bridge	Sandstone	65-95	7.8	2.3	7/91	9.5	1/82
SD44/24 (T38)	Butlers Arms Farm	Sandstone	73-91	9.0	-2.5	10/89	11.1	2/93
SD54/5 (T27)	Howarth Farm	Sandstone	72-93	12.0	6.6	8/89	16.4	1/81
SD54/14A (T41)	Stubbins Lee	Sandstone	73-92	15.0	13.6	9/76	17.6	1/82
SD44/16 (T20)	Roe House Farm	Sandstone	73-94	6.0	-5.4	9/84	9.2	Various (= ground level)
SD54/1 (T39)	Catterall	Sandstone	74-95	7.5	-4.4	1/96	15.2	2/82
SD44/18 (T23)	Myersclogh Pump	Sandstone	66-95	5.8	-1.1	12/95	10.2	Various (= ground level)
SD54/21 (T54)	Stanzacker Hall	Sandstone	66-95	5.0	-9.7	8/84	14.2	3/81
SD54/18C (T59)	Cardners Lane	Carbon.	72-94	57.5	57.1	11/74	58.0	8/80
SD54/18A (T56)	Duckworth Farm	Carbon.	72-96	69.0	68.5	11/76	72.0	1/77
SD43/2 (T17)	Halidays Farm	Sandstone	73-93	7.1	-6.4	7/88	12.1	2/87
SD53/9 (T4)	White Horse Bridge	Sandstone	74-96	13.8	9.4	12/91	18.4	1/84
SD53/47 (D142)	St Michaels Rd	Sands & Gravels	72-96	10.0	5.9	8/84	14.8	12/81

During model calibration, the most sensitive parameters in this area were found to be the permeability of the sandstone, the specific yield of the sands & gravels, and the vertical conductivity of the Drift.

The vertical permeability of the Drift controls the volume of leakage into the Sherwood Sandstone/overlying sands & gravels. With high Drift vertical permeabilities, the sandstone piezometric level was higher and the groundwater level fluctuations in the sandstone and overlying sands & gravels in response to seasonal changes and abstraction was reduced (ie more water is drawn from the Drift and sand & gravel reservoir and less water is drawn from sandstone storage).

With higher specific yields defined for the sands & gravels layer, groundwater fluctuations were reduced as more water is drawn from the sands & gravels storage reservoir. In addition, losses from the river system are reduced during summer periods of high abstraction.

The permeability of the sandstone defines the piezometric gradients and the extent of the deep depression around the NWW sources With low permeabilities drawdown at the sources is greater, but the lateral extent of the deep depression is reduced.

Preliminary calibration of the Central area (Phase II report, MM, 1996) was achieved by varying these parameters within reasonable limits until piezometry, groundwater level hydrographs and river flows simulated by the model were in agreement with the observed data. To achieve an accurate simulation of groundwater level hydrographs a relatively high permeability was defined around the NWW sources (5 m/d) and the specific yield of the sands & gravels was set at 12%.

After inclusion of the 1995 data the model failed to accurately simulate the very low groundwater levels observed around the NWW sources. A review of the calibration of the Central area was therefore necessary. Although the total abstraction was similar during 1984, 1995 groundwater levels declined to a lower level than in 1984. Groundwater abstractions, however, were more intense during August, September, and October 1995, coincident with the period of lowest groundwater levels.

One possible explanation for the inaccurate simulation of minimum groundwater levels is the value of storage coeeficients adopted. Based on the results of earlier sensitivity model runs, a reduced storage coefficient would marginally improve the level of decline simulated in 1995, but would result in an oversimulation of the declines during other years (such as 1984). Reducing the storage coefficients was therefore not considered viable.

The main difference between 1995 and 1984 is the different volumes of rainfall, with much lower rainfall in 1995 (the lowest recorded for the calibration period). This is considered to be the major factor influencing the repective groundwater level declines of 1984 and 1995. The low rainfall in 1995 resulted in virtually no recharge from April onwards. To improve the model simulation it seemed appropriate to reconsider the recharge mechanism and consider the introduction of the "infiltration capacity" of the Drift (refer to Section 3.7) Recharge to the sandstone groundwater table was limited to the vertical permeability of the Drift, typically 0.5 mm/d. The recharge limitation resulted in the Drift water table remaining below ground surface during the winter of 1994/95, which in turn resulted in reduced sandstone levels during the 1995 abstraction season. This marginally improved the simulations.

A more significant improvement was achieved by reducing the permeability of the sandstone to 3 m/d from 5 m/d (closer to that observed from pumping tests).

When the model was updated to include data for 1996, the model maintained the same degree of accuracy for 1996 as for all other years in all areas of the Central area apart from the area around NWW sources P, Q and R. At observation borehole SD54/1, groundwater levels remain relatively constant once the abstraction sources have stopped pumping (in September/October 1996) until the end of the year. The model, however, simulated a recovery from October to December. Therefore it was necessary to carry out further calibration work. Analysis of the simulation indicated that the absence of a recovery at the end of 1996 may be due to two factors:

- The southern Broughton sources were operated during this time. The model was not simulating the influence of the Broughton sources far enough north.
- The model simulated a rapid recovery in Drift and sands & gravels water levels in this central area which resulted in a recovery in the sandstone levels since there is very little vertical impedance between the sands & gravels layer and the sandstone aquifer.

It was found that the cone of depression simulated from abstractions from the Broughton sources was limited in a northerly direction due to low permeabilities defined between Barton Brook and the River Brock. These were then increased from 0.5 to 2.0 m/d.

To reduce the leakage rates from sands & gravels to the sandstone (and therefore the recovery) the vertical permeability of the sands & gravels was reduced to 0.1 m/d from 1 m/d.

This resulted in both an improvement in the simulation of 1996 in the central area, as well as an improvement in the simulation of groundwater levels at observation boreholes located between the Broughton and Franklaw sources.

4.4.5 Results of Model Simulations

Piezometry

Figures 4.19 and 4.20 present the simulated piezometry and observed groundwater levels at the observation boreholes for April 1987 (low abstraction, high groundwater levels) and September 1995 (high abstractions, low groundwater levels) respectively.

A relatively good match between the observed and simulated has been achieved throughout the area. Inaccuracies, however, were simulated to the north of the River Wyre in 1995. The model simulated the deep depression to extend further north than was observed during September 1995. This is because the model simulates groundwater level recovery in this area one month later than has been observed. Attempts were made to improve this using different river leakage factors. However, all attempts resulted in a reduction in the accuracy of the simulation during other periods.

This apparent discrepancy may be a result of the fault controlled transmissivity in the west of the modelled area, similar to that observed and incorporated in the model for the Woodplumpton Brook area (refer to Section 4.5.4).

Flow Mechanisms

The simulated flow balance components for the Central area are included in Appendix C.3. The main components of the simulated flow balance are described below:

- On average only 13% of potential recharge leaks through the Drift and sands & gravels to the sandstone aquifer.

- Most of the abstraction volume is derived from vertical leakage through the Drift and sands & gravels (78% for the period 1972 to 1994) and from lateral flow from Areas 1 & 2 (3% and 7% respectively). The remainder is derived from river leakage and storage. This is demonstrated in Figure 4.21a.

- There is a substantial increase in leakage from the rivers with increased abstraction.

- Storage within the sands & gravels layers exercises a strong control on leakage from the rivers (Figure 4.21b). If this storage reservoir were not available, increased abstraction would be balanced rapidly by increased river leakage. With sands & gravels storage part of the abstraction is drawn from the storage reservoir, resulting in an attenuation of leakage from the rivers. After abstractions stops, leakage from the rivers continues to replenish the depleted sands & gravels storage reservoir.

Groundwater Level Fluctuations

Table 4.6 summarises the simulated groundwater levels at each of the observation boreholes in the Central Fylde.

Simulated and observed groundwater level hydrographs for six of the above observation boreholes (SD44/15, SD44/16, SD54/1, SD44/18, SD54/21 and SD54/18C) within this area are shown in Figure 4.22, 4.23 and 4.24.

Generally an acceptable simulation throughout the Central area has been achieved.

In addition, the trends and fluctuations in groundwater level in the sand & gravel (which directly overlie the sandstone aquifer) have been reasonably simulated as demonstrated in Figure 4.25. This confirms that the parameters, and in particular the specific yield (12%), of the sands & gravels accurately represent conditions in this aquifer.

River Flows and River-Aquifer Interaction

The simulated hydrographs for the Brock and St Michaels river flow gauging stations are shown in Figure 4.26. A very good agreement between observed and simulated low river flows has been achieved at both gauging stations. Similarly, the simulated losses along each of the river is equivalent to the losses measured during selected months of 1994 and 1995, as shown in Figure 4.27.

TABLE 4.6

Central Fylde - Simulated and Observed Groundwater Levels

Reference WRB No. (LCUS Ref)	Aquifer	Average		Seasonal Fluctuations		Comments
		Observed (m OD)	Simulated (m OD)	Observed (m)	Simulated (m)	
SD44/20 (T29)	Sandstone	6.5	6.5	1.4	2.2	Improvements could be made by adjusting river conductance parameters - see river/aquifer interaction section below
SD44/17 (T24)	Sandstone	7.8	7.8	2.4	3.4	-do-
SD44/24 (T38)	Sandstone	9.0	8.8	3.9	5.1	
SD54/5 (T27)	Sandstone	12.0	11.6	6.1	7.7	
SD54/14A (T41)	Sandstone	0.0	0.0	28.8	20.0	Values for period after 1981 when NWW source R operational
SD44/16 (T20)	Sandstone	6.0	6.0	6.5	6.2	
SD54/1 (T39)	Sandstone	7.5	7.3	10.5	11.2	Reduced accuracy prior to 1987
SD44/18 (T23)	Sandstone	5.8	5.8	8.4	7.8	
SD54/21 (T54)	Sandstone	5.0	5.0	14.8	14.8	Very accurate simulation
SD54/18C (T59)	Carboniferous	57.5	55.5	0.8	1.2	Trends and fluctuations acceptable
SD54/18A (T56)	Carboniferous	69.0	74.8	1.8	1.1	
SD43/2 (T17)	Sandstone	7.1	7.3	10.5	11.1	
SD53/9 (T4)	Sandstone	13.8	13.9	6.8	3.8	
SD53/47 (D142)	Sands & Gravels	10.0	10.1	5.0	5.0	

The losses from the Wyre, upstream of St Michaels, were simulated by defining a direct hydraulic contact between the sandstone aquifer and the river (Mechanism type 3 as defined in Section 3.6). In this area there is an absence of boulder clay below the river and the sands & gravels are relatively thin. The correct level of leakage was therefore simulated and the effect of the river on groundwater level variations as a result of abstractions were well simulated. In the final calibration, the groundwater level variations were simulated 1.5 to 2 times greater than those observed at observation boreholes to the north of the river. With higher river conductance parameter settings, there was an improvement in the groundwater level simulations but losses from the river were simulated 2 to 3 times greater than observed. As defined above, the reason for this apparent discrepancy may be a result of fault controlled transmissivity in the west of the modelled area, similar to that observed and incorporated in the model for the Woodplumpton Brook area (refer to Section 4.5.4). This, however, was not introduced into the model.

It was decided that in this area priority should be given to the accuracy in the simulation of river flow losses since this river reach coincides with the maximum river flow losses and is thus a good indicator of the impact of abstractions in the Central Area.

For the River Brock, relatively high conductance terms were defined at the observed loss reaches, which coincided with either absent or minimum cover of boulder clay. In other areas, where boulder clay thickness exceeds 10m, the river/sandstone hydraulic connection is very poor. In these areas, the river receives baseflow from the Drift.

For the River Calder, no areas were identified from the lithological logs where the boulder clay cover was either absent or of minimal thickness. However, river losses have been recorded. Consequently along the entire reach of the river the boulder clay permeability, beneath the river, was set at 0.01 m/d (for surrounding boulder clay the permeability of the Drift was simulated to be between 0.1 and 0.001 mm/d). This resulted in the simulation of losses along the Calder during period of relatively high abstraction.

4.5 Area 4: Preston & Southern Fylde

4.5.1 Features of the Area

Figure 4.28 shows the area in detail. This area covers the southern area of the model between Barton Brook and the River Ribble, not including the extreme south east of the model which is covered in Section 4.6. The area includes the southerly NWW abstraction sources (B,C D and E) and the BNFL abstraction boreholes in the south west, as well as central Preston.

The area includes a number of rivers - the upstream ends of Barton Brook and Woodplumpton Brook and the middle reach of the River Ribble. Only data for one permanent gauging station exist: Barton Brook at Hollowforth.

There are a large number of observation boreholes in the area, the majority of which were constructed during the original LCUS investigations. Most monitor groundwater levels in the Sherwood Sandstone aquifer, apart from in the east where a few were drilled in the Carboniferous strata. One borehole, SD43/19 (T74) has a hands-off level control which limits NWW abstractions from their Broughton 'A' group of sources whenever groundwater levels fall below 8.5 m AOD. This was originally imposed to protect the BNFL boreholes.

Under the LCUS licence, augmentation of Barton Brook takes place whenever the gauged flow at St Michaels falls below 50 Ml/d. Up to 2 Ml/d is added to the river from the Broughton collector main.

Two "environmentally sensitive sites" exist within this area: Cottam Hall (Biological Heritage Site) and the Great Crested Newt Site, north east of Preston. Much of the degradation of these sites in the past has been attributed to the urbanisation of Preston (APEM, March 1996). However, groundwater level decline is considered to have contributed to the reduction in the number of springs and marshland in the area.

A relatively dense grid of model polygons was defined around the NWW sources and along the rivers, while larger polygons are used in the south and south west, where there is less hydrogeological data.

4.5.2 Hydrology of the Area

There is one main rainfall station present within the Fylde plain in this area: Catforth (station number 578566) with an annual average rainfall of 904 mm/annum.

River flows are permanently monitored at Hollowforth on Barton Brook. No gauging station exists on Woodplumpton Brook.

River inflows at the eastern model boundary were derived from the hydrological model HYSIM. For Barton Brook, the inflow was derived by interpolating the infilled Barton Brook gauging record, based on the ratio of the surface water catchment upstream of the gauging station and the catchment area upstream of the model inflow point. The inflow to Woodplumpton Brook at the model boundary was derived by changing the parameters of the Barton Brook HYSIM model (catchment area, rainfall and evapotranspiration rates and groundwater and surface water abstraction/augmentation rates) to suit the Woodplumpton catchment and then rerunning HYSIM.

Inflow to the River Ribble was not derived using a hydrological model. A nominal inflow of 2 m^3 /s was applied throughout model simulations.

Spot flow measurements during 1994, 95 and 96 indicated that river flow losses occur from both Barton and Woodplumpton Brooks. Up to 1.4 Ml/d and 2.4 Mld has been observed to be lost from Barton and Woodplumpton Brooks respectively during 1994 and 1995.

4.5.3 Geology

The contact between the Carboniferous and the Permo-Triassic in this area is an unconformity with Manchester Marls separating Carboniferous water bearing formations and the Sherwood Sandstone aquifer. Therefore, there is not expected to be any significant flow of water between aquifers. However, groundwater levels observed at borehole SD53/13 (located approximately 500m from the contact between the Fylde aquifer and Carboniferous deposits, midway between Barton and Woodplumpton Brooks) suggest that the rising and falling trends seem to follow the increase and decrease in abstraction from NWW boreholes (B, C, D and E). Consequently a hydraulic connection between the two formations in this area does exist, although the transmissivity across the contact is expected to be low.

Within this area, there are relatively thick deposits of boulder clay, particularly between Woodplumpton Brook and the River Ribble, in the eastern part of the Fylde plain. However, along the western fringe near the contact of the Fylde aquifer with the Mercia Mudstone thin boulder clay overlies sand & gravel in contact with the sandstone, as is evident from Section F-F (figure 4.29). This area (to the east of Inskip) may have been a natural discharge zone where the westerly movement of groundwater is inhibited by the Woodsfold Fault.

The Drift and sand & gravel layers in the model were derived from the lithological logs. No changes to the initial Drift/sand & gravel layer geometry were made during calibration.

The geological structure of the sandstone of this area proved the most difficult to accurately assess. During the original calibration (refer to Phase II report, January 1996), it was necessary to reassess the original geological structure (presented in the Phase I report). Evidence in the BGS "Garstang" memoir and from lithological logs collected for this study suggested that the thickness of the sandstone aquifer to the west and east of NWW sources B, C and D was relatively low (less than 50 m in places) and relatively thick at the NWW sources. From both the BGS Memoir and lithological logs thick marls located at the base of the drilled boreholes were taken to represent Manchester Marls or underlying Carboniferous strata, and thus the base of the Sherwood Sandstone.

The most significant features of the first reconceptualisation of the geological structure in this area were as follows:

- The thickness of sandstone in the western region around Woodplumpton Brook was assumed to be relatively limited (as low as 29.5 m at one borehole (SD43/3). However, one kilometre to the east of this borehole, the thickness of sandstone exceeds 100 m. Similarly to the north (at Barton Brook), the thickness of sandstone was proven to be over 120 m and to the south the thickness increases to at least 200 m. This suggested that an 'anticline' or fault-bounded horst/ridge may exist along the downstream end of Woodplumpton Brook, reducing the effective thickness of the sandstone. Four observation boreholes (SD43/18, SD43/3, SD43/19 and SD53/12) are located this region.

- A faulted block, located during gravity mapping of the area (Worthington, 1970), may exist between Woodplumpton Brook and the River Ribble in the east. This faulted block raises the Manchester Marls and reduces the thickness of the sandstone. The thickness of sandstone was estimated to be around 50 to 70 m. The faults effectively isolate the Whitbread/Courtaulds abstraction boreholes from the NWW boreholes in the north and the BNFL boreholes in the west. Observation borehole SD53/33 is located within this faulted block.

- Between these two features (at the NWW sources B, C and D) the sandstone aquifer is at least 200 m thick. Effectively there is a "channel" connecting the thick sandstone encountered at BNFL boreholes and at the Ribble with NWW sources B,C and D.

This revised geological structure for the sandstone was introduced into the model during the preliminary model calibration and relatively accurate simulations of groundwater piezometry and the areal influences of abstractions were achieved. However, there remained a large degree of uncertainty over the structure of the sandstone in this area.

Understanding of the Preston and South Fylde area is fundamental to the overall management of the Fylde aquifer and Wyre catchment for two main reasons:

- The 'T74' control borehole (SD43/19) is located in this area; although this primarily limits abstraction from the Broughton 'A' sources, the way the LCUS licences are structured it also impacts on NWW's ability to fully exploit the Broughton 'B' and Franklaw 'A' & 'B' sources i.e. it effectively controls abstraction over all of their Fylde boreholes. The level in T74 has gradually declined down to the critical 'hands-off level' (8.50m AOD) in recent years.

- There is considerable interest in additional groundwater abstraction for industrial and commercial purposes in and around Preston (see Chapter 1 - Study Objectives).

Before the model could be used to assess the sustainability of the existing licensed abstractions and the impact of any new sources in this area it was considered necessary to reduce this uncertainty. Therefore, the Agency commissioned the BGS to review deep lithological logs and seismic geophysics in order to reinterpret the geological structure of the Fylde aquifer; it also drilled a 150 m exploratory borehole next to the existing 'T74' control borehole to establish whether the base of the sandstone aquifer existed within the top 150 m (as defined within the model) - see Section 2.2.2.2.

The main conclusions from these additional study components were as follows:

In the West:

- the base of the sandstone was not encountered within a depth of 150 m adjacent to 'T74', indicating that the base of the aquifer within the model was incorrectly assigned ;

- significant marl bands were encountered at depths, approximately equivalent to the depth assumed for the base of the aquifer. Consequently, the interpretation of the base of the sandstone defined in the Garstang memoir incorrectly assumed these marl bands to be equivalent to Manchester Marls;

- from geophysical evidence, a series of north-south trending faults to the west of NWW sources were delineated (refer to Figure 2.5) which may result in anisotropic flow conditions within the sandstone aquifer (with a higher effective transmissivity for groundwater flowing north-south than east-west).

In the south east:

- Logs from a number of historical boreholes for the area to the south east of the NWW sources, to the east of Preston, recorded red mudstone at relatively shallow depth; this had previously been interpreted as being either basal Manchester Marl or underlying Carboniferous strata (BGS- Garstang Memoir, 1990 and in this study, Phase II report, Chapter 3). In contrast, based on the limited seismic data available for this area the BGS's recent geophysical reinterpretation inferred gradual thickening of the aquifer south westwards from its eastern margin.

To further reduce the uncertainty over the geological structure of the sandstone between NWW and Whitbread/former Courtaulds sources in the south east (area 5) a 190 m deep fully cored borehole was drilled for the Agency in December 1996 in Moor Park, on the northern side of Preston. This encountered Carboniferous Strata (sandstones, mudstones/shales, and thin limestones) directly beneath the Sherwood Sandstone (ie no Manchester Marl) at a depth of 107 m whereas the Sherwood Sandstone was unbottomed at 320 m depth in one of the former Courtauld boreholes 2.5 km to the east. This confirms the original interpretations of the old borehole logs were correct and that there are considerable variations in aquifer thickness in the south east of the Study area: a north-south raised block (horst) separating the main trough (in which NWW sources are located) from the Red Scar basin to the east. This reinterpretation is consistent with geophysical (gravity and electro-magnetic) and piezometric evidence. The standing water level in the Moor Park borehole is higher than those recorded to the east and west. The revised understanding is shown in Figure 4.29A.

The results of these investigations were adopted during the final period of calibration (when the model was updated to include data for 1995 and 1996). An improvement in the calibration was made, and the uncertainty over the geological structure was significantly reduced.

4.5.4 Hydrogeological Data and Simulated Aquifer Properties

Pumping tests have been carried out at a few of the NWW sources in this area. Transmissivities derived from the pumping test data at NWW B sites were around 500 - 700 m^2/d . There is very little specific capacity information in this area to evaluate the permeabilities.

The available observation boreholes and length of records for this area are shown in Table 4.7. Most of the observation boreholes are located around Barton and Woodplumpton Brooks. There are very few observation points to the west (at BNFL sources) or to the south (in Preston).

The following features of the piezometry and hydrographs of this area have been assessed from the available data:

- during low abstraction rates groundwater tends to flow east to west along Woodplumpton Brook and north south from the catchment divide between Woodplumpton Brook and the River Ribble;

- during periods of abstraction, a depression forms around NWW sources B, C and D which creates "water level mounds" to the east and west of the sources. In effect there is a "break" in the high water levels separating the Woodplumpton and Ribble catchments (refer to Figure 2.15);

- a recession in groundwater levels has been measured at a number of boreholes in the area, particularly to the west and east of the NWW sources. This is in response to groundwater abstractions from NWW and BNFL boreholes. Groundwater abstractions for public supply started in the 1960's. Since then groundwater has been drawn from Drift storage which has not been replenished;

- the response of groundwater levels to the east and west of the NWW abstraction sources is suppressed in comparison with other observation boreholes located a similar distance to the north and south of the pumping boreholes i.e. there is some degree of anisotropic flow/aquifer compartmentalisation.

TABLE 4.7

Observation Boreholes - Preston & Southern Fylde

Reference WRB No. (LCUS Ref)	Name	Aquifer	Record Length	Average (m OD)	Minium		Maximum	
					m OD	Period	m OD	Period
SD43/1	Woodsfold Farm	Sandstone	74-96	9.0	2.9	1/96	12.2	3/75
SD43/18 **	Willacy Lane End	Sandstone	74-96	12.2	10.5	8/84	16.3	11/93
SD43/3 (T43) **	Rosemary Lane	Sandstone	74-96	11.5	9.7	11/91	13.4	5/74
SD43/19 (1) (T74) **	Saddle Inn	Sandstone	73-96	9.5	8.1	7/94	11.5	5/74
SD53/12 (T26) **	Maxy House	Sandstone	74-93	11.3	9.8	9/90	13.2	3/75
SD53/31 (T71)	Hollowforth Bridge	Sandstone	74-96	9.6	0.6	10/76	14.4	3/82
SD53/27		Sandstone	73-96	11.1	3.6	6/82	14.6	1/88
SD53/10 (T16)	Barton Hall	Sandstone	73-93	14.3	6.1	8/84	18.9	4/73
SD52/38	Brockholes View	Sandstone	72-96	10.0	6.3	9/95	12.4	4/73
SD53/32 (T70)	Yew Tree Farm	Sandstone	74-94	11.2	8.6	8/75	12.6	8/88
SD53/46B (A2)	Toplands Farm	Sandstone	74596	5.5	2.3	7/83	13.3	7/83
SD53/29 ** (T66)	Broughton Vicarage	Sandstone	76-95	15.0	13.4	6/88	16.0	6/88
SD53/33 ** (T68) (2)	Broughton Tower Farm	Sandstone	74-96	19.2	17.4	6/74	21.2	6/74
SD53/45 (T76)	Halsam Park	Sandstone	73-96	10.0	7.0	5/82	11.5	5/82

Note (1) 'Hands-off level' control borehole related to NWW's Broughton 'A' sources (to protect BNFL).

(2) Former 'hands-off level' control borehole (to protect former Courtaulds abstractions) - now removed from licence.

** Falling trend in observations from earliest measurements.

During calibration it was very difficult to simulate both the suppressed response to abstractions at boreholes relatively close to the abstraction points and the declining trend. During preliminary calibration, the muted response was achieved by changing the geological structure (as described in the previous section) and by introducing low permeability zones between the NWW sources and the areas to the east and west, where the sandstone aquifer thickness was assumed to be reduced.

The new geological and geophysical evidence, however, indicated that this was not the case to the west of the NWW sources on the 'Woodplumpton Terrace' (between the NWW and BNFL boreholes). The presence of a set of north-south trending faults suggested that groundwater flow may be preferential parallel to the faults, with only limited flow taking place across faults i.e. east-west. By introducing anisotropy in this area it was possible to simulate the suppressed response observed in local boreholes (SD43/3, 18 & 19). A permeability of 3 m/d was defined for groundwater flowing north-south and 0.2 m/d for water flowing east-west.

Between the NWW Broughton sources and the Whitbreads/former Courtaulds boreholes in the south east the geological structure and hydrogeological flow system remained uncertain. It was considered that the negligible response to abstractions observed at borehole SD53/33 (T68) may be a result of the marl layers which were reported to exist at relatively shallow depths and the relatively thin sandstone within the Horst block. By specifying a very low conductance at the interface between upper and lower sandstone layers (with vertical permeability defined at 0.02 mm/d), very little water is drawn from the upper sandstone layer in this area by the abstractions at NWW sources B, C and D or from the Courtaulds and Whitbread sources to the south east.

These changes resulted in an accurate simulation of the piezometric patterns in this area. However, the declining trend was not simulated. This was improved through the reassessment of leakage through the thick Drift deposits to the south of Woodplumpton Brook. Lithological logs in this area describe the clays as "very stiff", suggesting heavily overconsolidated glacial till with very low conductive properties, both for infiltrating recharge waters and water leaking to the underlying layers. Below these stiff clays, sands & gravels exist followed by another band of clay . Consequently water leaking from the Drift deposits into the underlying sandstone will originate mainly from drainage of storage in this isolated layer of sands & gravels within the Drift. However there will be very limited replenishment of this storage as a result of the low conductance of the overlying stiff clays.

As previously noted, both in the eastern and western areas to the south of Woodplumpton Brook, there has been a general decline in groundwater levels following the start of heavy groundwater abstraction (for public supply) in late 1960's. This was followed by little or no recovery in groundwater levels when the actual abstraction quantities were reduced in the early to mid 1980's. This suggests that the volume of leakage from the Drift since abstraction started has exceeded the volume of infiltrating recharge.Effectively the volume of recharge to the Drift must be limited by the conductive properties of the Drift deposits.

In the model, potential recharge greatly exceeds the conductance properties of the Drift deposits. If the Drift deposits are saturated (ie the simulated Drift water table is at ground surface) the recharge is rejected and flows overland to the river system. With an average potential recharge of 1.27 mm/d and a very low Drift vertical permeability in the southern region of the order of only 0.01 mm/d in some model polygons, the model simulates a constant Drift groundwater level at ground surface. As sandstone levels decline the volume of leakage increases as a result of the increasing difference in groundwater levels between the sandstone and Drift. This then reduces the rate of decline in groundwater levels in the sandstone.

In order to increase the rate of decline and minimise the recovery in sandstone groundwater levels with reductions in groundwater abstraction volumes, a maximum infiltration capacity was set (refer to Section 3.7). This was defined as the rate of leakage during steady state simulations with the abstraction set to zero, evaluated as 0.0015 mm/d for the sub-region. An infiltration capacity of 0.0015 mm/d was therefore applied to transient simulations. The remaining recharge is passed as overland flow to the rivers system.

This infiltration capacity was applied in the north of this area around Woodplumpton Brook, where significant (>15 m thickness) of Boulder Clay exists (from analysis of lithological logs). This infiltration capacity was not defined in the south of the region or in Preston where there are less clay deposits and thicker deposits of sands within the Drift.

By incorporating this feature, it was possible to simulate the decline in sandstone water levels observed at many of the observation boreholes. Figure 4.30 demonstrates the effect of the infiltration capacity at T74 (SD43/19). The Drift water level declines by 12 m (10 m between 1969 and 1981 and 2 m between 1981 and 1995), while the sandstone piezometric level declines by around 3m.

A study of the vertical leakage in these areas was carried out to establish whether the mechanism described above was acceptable (described in Appendix E). This detailed vertical leakage modelling established that:

- the decline in sandstone piezometry is due to the dewatering of isolated sands & gravels within the Drift as the outflow from the base of the Drift is not replenished by leakage through the top of the Drift due to the limitation in vertical conductance of the clay layers at the top of the Drift (Figure 4.30A);

- the low vertical permeabilities used in the regional model reflect the low permeabilities of the individual stiff boulder clays within the Drift;

- the infiltration capacity defined in the regional model represents the vertical permeability of the surface clays.

In Preston there is very little data relating to the sandstone and Drift properties. In addition there are very few observation boreholes. The hydrograph for Brockholes View (Liquid Plastic) shows a decline of 5.9 m between 1971 and 1996. This decline could be due to a number of factors:

- a similar mechanism to that observed around observation borehole T74 and T68, although the Drift thickness is lower (15 - 20 m) and the permeability of the Drift is considered to be much higher (based on lithological descriptions);

- as a result of groundwater abstraction (Supreme Laundry borehole is situated 350 m from the observation borehole), where the aquifer responds to abstractions as if it were fully confined and therefore limiting leakage through the Drift;

- influence of the Horst block, since Brockholes View is located within this block (refer to Figure 4.29A);

- low sandstone permeability and storage coefficient such that any abstractions would in fact effectively mine the groundwater supplies;

- influence of River Ribble is very small in this area such that there is no replenishment of abstracted water by river leakage;

- urbanisation has reduced the rate of rainfall recharge in the area.

Various combinations of the above were considered in the model. The most likely conditions, which did not necessarily produce the most accurate simulations but which are considered to be conceptually the most accurate, were defined as follows:

- Over tha majority of the length of the River Ribble no significant interaction between the river and sandstone aquifer exists. The River Ribble is only hydraulically.linked to the Drift, where relatively high permeability sands within Drift exist, particularly to the west of the horst block. A similar river-aquifer mechanism was defined in area 5, around the Whitbreads/Courtaulds boreholes.

- The faults at the southern end of the Horst block (refer to Figure 4.29A) have a low permeability (set at 0.2 m/d in the model) such that abstractions to the west and north of the Horst block draw only small quantities of water laterally from within the horst block.

- The effective vertical permeability within the Drift (consisting of sands and clays) is dominated by the clays limiting vertical leakage.

4.5.5 Results of Model Simulations

Piezometry

Figures 4.31 and 4.32 present the simulated piezometry and observed groundwater levels at the observation boreholes for April 1987 (low abstraction, high groundwater levels) and September 1995 (high abstractions, low groundwater levels) respectively.

A relatively good match between the observed and simulated piezometry has been achieved throughout the area.

Flow Mechanisms

The simulated flow balance components for the Preston and Southern Fylde area are included in Appendix C.4. The main components of the simulated flow balance are described below:

- On average only 10% of potential recharge leaks through the Drift and sands & gravels to the sandstone aquifer.

- abstraction volumes are derived primarily from leakage from the Drift and sands & gravels and secondly from induced leakage from the rivers to the sands & gravels in the west of the area.

Groundwater Level Fluctuations

Table 4.8 summarises the simulated groundwater levels at each of the observation boreholes in the Southern Fylde and Preston area.

Simulated and observed groundwater level hydrographs at five observation boreholes in this area (SD 43/3, SD43/19, SD53/46B, SD53/33and SD52/38) are shown in Figure 4.33, 4.34 and 4.34A. Relatively accurate simulations of the levels, seasonal fluctuations, trends and the influence of abstractions have been simulated throughout, apart from in one small area: at Barton Brook close to NWW sources C and D (boreholes SD53/27 and SD53/10). The response of groundwater levels to abstractions differs considerably from surrounding observation boreholes, where the change in water level between static and pumping levels is three to four times lower than in surrounding boreholes. The most likely reason for this, is that the observation boreholes are set in a relatively "isolated" area of sandstones, bounded by low permeability marl bands. This is not typical of the area as a whole and therefore such a feature was not included in the model.

Another possible explanation is that these two observation boreholes are located close to an extension of the Grimsargh Fault and therefore affected by the same isolated block that affects groundwater levels around T68.

River Flows

The simulated hydrograph for the Barton Brook river flow gauging station is shown in Figure 4.35. A very good agreement between observed and simulated river flows has been achieved.

The simulated losses along Barton and Woodplumpton Brooks are shown in Figure 4.36. This compares favourably with the losses observed during 1994 and 1995.

In both rivers the river resistance was set to 10 days (defining non-leaky conditions) apart from the western, downstream end of the rivers where there is relatively thin boulder clay cover. In this area the resistance was defined as 1 day and the vertical permeability of the Drift below the river set at 0.005 m/d (some 20 to 50 times the values for the surrounding Drift). Consequently when water levels in the sands & gravels are drawn down below the river level there is a relatively transmissive route for river water to leak into the sands & gravels (where the river has locally cut through the thick overlying clay deposits). Abstraction boreholes then draw this water out of the sands & gravels storage.

TABLE 4.8

Preston & Southern Fylde - Simulated and Observed Groundwater Levels

Reference WRB No. (LCUS Ref)	Aquifer	Average		Seasonal Fluctuations		Comments
		Observed (m OD)	Simulated (m OD)	Observed (m)	Simulated (m)	
SD43/1	Sandstone	9.0	8.7	2.9	5.2	
SD43/18	Sandstone	12.2	11.3	1.9	1.7	Accurate simulation of falling trends
SD43/3 (T43)	Sandstone	11.5	11.5	0.6	0.6	Accurate simulation of falling trends
SD43/19[(1)] (T74)	Sandstone	9.5	9.5	0.6	0.6	
SD53/12 (T26)	Sandstone	11.3	11.2	0.6	0.9	
SD53/31 (T71)	Sandstone	9.6	9.6	8.0	6.2	
SD53/27	Sandstone	11.1	11.9	8.4	7.2	Poor simulation - see page 4-35
SD53/10 (T16)	Sandstone	14.3	13.4.	10.5	20.1	Poor simulation - see page 4-35
SD52/38	Sandstone	12.0	12.5	0.8	0.5 - 1.2	Figure 3.34A
SD53/32 (T70)	Sandstone	11.2	11.4	1.2	1.6	
SD53/46B (A2)	Sandstone	5.5	5.5	13.0	14.0	Accurate simulation of conditions close to NWW southerly sources
SD53/29 (T66)	Sandstone	15.0	14.5	0.7	0.6	
SD53/33 (T68)	Sandstone	19.2	19.1	low	low	Accurate simulation of falling trend to east of NWW sources (refer to Figure 4.34)
SD53/45 (T76)	Sandstone	10.0	11.5	low	2.1	

4.6 Area 5: South East Fylde

4.6.1 Features of the Area

Figure 4.37 shows the area in detail. This area covers the extreme south east of the model, including the upstream end of the River Ribble and the Whitbread and Courtaulds abstraction boreholes. The licence for Courtaulds was revoked in 1981.

There are few observation boreholes in the area. Generally, these boreholes were constructed to observe groundwater levels in the sandstone, in response to abstractions from the Courtaulds and Whitbread sources.

A relatively course grid was defined for this area with smaller polygons defined around the abstraction boreholes and river.

4.6.2 Hydrology in the Area

There is no rainfall station present within the Fylde plain in this area . The closest station is at Preston, Moor Park (station number 576634) where an annual average rainfall of 843 mm/annum is recorded.

Although there is a flow gauging station at Samlesbury, the long term record was considered to be inaccurate and unreliable at low flows. (Recent work has improved the reliability). Therefore, inflow rates to the River Ribble at the model boundary were not derived using a hydrological model. A nominal inflow of 2 m^3/s was applied throughout model simulations. Consequently the simulation of the Ribble was not calibrated against any actual river flows. Therefore conclusions which involve the river-aquifer interaction of the Ribble should be treated with caution.

4.6.3 Geology

In this area, the contact between the Carboniferous and Permo-Triassic is in part faulted and partly an unconformity, but with the low permeability Manchester Marls absent (see Figure 2.6). Whereas the Worston Shale Group present in the north of the area is effectively impermeable, the sandstone units of the Namurian (Millstone Grit Series) (e.g. the Pendle, Warley Wise and Wiltshire Grits) act as significant 'minor aquifers', with quite extensive outcrops south of the Ribble. They have the potential to recharge the Sherwood Sandstone as water levels are drawn down by abstractions. This is inferred from: the following evidence:

- The geology, as shown on the published 1:50,000 geological maps
- There is a high iron content in the water abstracted at the Whitbread boreholes, which is consistent with water being derived partially from the Carboniferous, and in particular the Wilpshire Grit
- Calibration of this area (and the Southern Fylde & Preston area) indicated that either very high sandstone

storage coefficients (eg 15%) and permeabilities (>10m/d) would have to be adopted in order to simulate the observed groundwater levels if no inflow from the Carboniferous was allowed. Such parameter settings cannot be justified and therefore it was concluded that some inflow from the Carboniferous was required[1].

This inflow was achieved by specifying fixed gradients (of between 2 and 10 m/km) along the boundary.

Limited lithological data was available for this area,. However, relatively detailed information was available in the Whitbreads pumping test reports (NRA, 1980) and along with the geological remapping and exploratory boreholes discussed in the previous section (Area 4 - Preston and Southern Fylde - Section 4.5.3) the geological structure could be defined. The sandstone aquifer varies in thickness from 200 to 500m in this area, with the dip from the Carboniferous towards the abstraction boreholes. An effective thickness of 200m was applied throughout, except at the Carboniferous boundary where the aquifer was reduced to its actual thickness and at the Horst block on the western boundary (where the aquifer thickness was reduced to 100m).

Drift cover can be split into two categories: to the north of the abstraction boreholes significant thickness of boulder clay are present (> 15 m), while within the Ribble valley, sands & gravels are exposed (refer to Figure 2.10). These sands & gravels are at present being exploited by various gravel extraction companies. Significant vertical leakage of rainfall recharge is, therefore, expected to occur through the sands & gravels along the river valley.

4.6.4 Hydrogeological Data and Simulated Aquifer Properties

There is very little aquifer property information available for this area. Based on tests at the Whitbread abstraction boreholes, the mean section permeability is of the order of 1 to 3 m/d.

There are also few observation boreholes in the area. No boreholes have monitoring records stretching back to 1969, the start of the calibration period..

[1] although to the west of Area 5, the recently drilled exploratory borehole Moor Park, Preston proved fractured Carboniferous sandstones directly beneath the Sherwood Sandstone (no Manchester Marl). Potentially this could allow upflow as well as lateral inflow from the Carboniferous; further work is required to explore this possibility.

TABLE 4.9
Observation Boreholes - South East Fylde

Reference WRB No. (LCUS Ref)	Name	Aquifer	Record Length	Average (m OD)	Minium		Maximum	
					m OD	Period	m OD	Period
SD53/25 (C60)	Redscar Wood	Sandstone	80 - 96	10.0	8.7	10/84	11.8	2/95
SD53/50	Whitbread OBH C	Sandstone	80 - 95	6.0	4.7	7/82	6.9	4/81
SD52/54	Whitbread Brewery A	Sandstone	81 - 95	9.8	9.0	9/94	10.4	6/81
SD53/49	Whitbread OBH B	Sandstone	81 - 95	8.0	7.3	9/84	8.9	3/89

Due to the lack of good quality observed groundwater levels in this area it is very difficult to draw piezometric contours or draw conclusions from the hydrographs. The observed levels do, however, suggest that groundwater flows perpendicular to the Ribble at the upstream end of the river, with the river and valley gravels acting as sinks.

Various reports have been written on the hydrogeology of this area, including the pumping test report in support of Whitbreads licence application (NRA, 1980) and a series of reports relating to gravel excavation works on the banks of the River Ribble. These reports suggest:

- the sandstone piezometry is above the water level in the River Ribble and therefore there is potential for leakage from sandstone to the river, except during periods of high abstractions (from the Whitbread boreholes) when groundwater levels are depressed below the river bed;
- abstractions from the sandstone has negligible effect on flows in the Ribble (ie the river does not act as a recharge boundary);
- gravel excavations will have negligible impact on water resources of the sandstone aquifer.

The observed piezometric responses to pumping suggest that water abstracted by Whitbreads and Courtaulds is mainly derived from lateral flow within the sandstone aquifer. Initial simulations showed that the decline in groundwater levels was too great. The simulations were improved by adding two additional sources of recharge to the aquifer (in response to abstraction):

- The introduction of Carboniferous inflows.
- The sands & gravels within the Ribble valley were allowed to leak at a higher rate. Additional vertical downward leakage was thus simulated resulting in a reduction in rejected recharge. Although this influences contributions to the River Ribble it does not imply a good direct connection between the river and the aquifer.

The above changes reduced the magnitude of decline around the abstraction wells and improved the simulated piezometry.

4.6.5 Results of Model Simulations

Piezometry

Figures 4.38 and 4.39 present the simulated piezometry and observed groundwater levels at the observation boreholes for April 1987 (low abstraction, high groundwater levels) and September 1995 (high abstractions, low groundwater levels) respectively. The gradient in the extreme south towards the Whitbread sources is possibly too steep but there is no data to check this. In addition, the 5m and 10m contours suggest that the valley of the River Ribble controls sandstone groundwater levels in the area.

Flow Mechanisms

The simulated flow balance components for the South East Fylde area are included in Appendix C.5. The main components of the simulated flow balance are described below:

- abstractions from Whitbreads (which is presently well below the licensed rate) and prior to 1980 from Courtaulds were derived from two sources - leakage through the valley gravels (40%) and inflow of Carboniferous (60%);

- in periods of low abstraction the sandstone aquifer discharges to the river, with sandstone piezometric levels greater than river levels. However a reduction in baseflow to the river occurs through induced leakage from the sands & gravels to the sandstone aquifer during periods of prlonged groundwater abstraction. This leakage arises from the reversal of the gradient between the sands & gravels and the sandstone.

Groundwater Level Fluctuations

Table 4.10 summarises the simulated groundwater levels at each of the observation boreholes in this area.

TABLE 4.10

South East Fylde - Simulated and Observed Groundwater Levels

Reference WRB No. (LCUS Ref)	Aquifer	Average		Seasonal Fluctuations		Comments
		Observed (m OD)	Simulated (m OD)	Observed (m)	Simulated (m)	
SD53/25 (C60)	Sandstone	10.0	11.8	1.9	1.9	Borehole located closer to Ribble than polygon, therefore actual simulated level will be closer to the observed than presented
SD53/50	Sandstone	6.0	7.0	0.9	0.9	
SD52/54	Sandstone	9.8	9.4	0.9	1.6	Seasonal fluctuations poor, but accepted since level accurate
SD53/49	Sandstone	8.0	8.6	1.1	1.4	

Simulated and observed groundwater level hydrographs for two of the above observation boreholes (SD53/35 and SD54/24) are shown in Figure 4.40. In all cases the model has achieved an acceptable level of accuracy.

River Flows

The upstream end of the River Ribble was considered to be only weakly connected to the sandstone aquifer. The main hydraulic connection is with the valley gravels. The parameters were set to reflect this. The vertical permeability of the sands & gravels below the river bed was given a lower value than the surrounding gravels. This is considered to represent the lower permeability of the river bed deposits compared to the sands & gravels.

4.7 Regional Model

This section presents an overview of the calibration of the Fylde aquifer system through discussion on the modelled water balance components and the parameter definitions.

4.7.1 Simulated Water Balance Components

Tables 4.11, 4.12 and 4.13 show the simulated flow components for average conditions between 1972 and 1995, for September 1995 (high abstractions/low groundwater levels) and April 1987 (low abstractions/high groundwater levels) respectively.[2]

Figures 4.41, 4.42 and 4.43 demonstrate how the major flow balance components vary with time during 1994 and 1995.

A number of important conclusions can be made regarding these data, namely:

- Potential recharge minus rejected flow is negative during the summer period, indicating that the Drift remains saturated during summer months in areas of very low Drift permeabilities.

- The inflow from the Carboniferous deposits is generally very low, varying between 5 and 6Ml/d. In addition the induced inflow from the Carboniferous as a result of sandstone aquifer abstraction is small and considerably less than estimated by WRc (1975) where a "natural" inflow rate of 29 Ml/d was computed. This is probably the most important difference between the WRc model and the new model. In the WRc work, the major conclusion, on which water resource strategies have since been based, was that increases in abstraction from the Fylde aquifer would be largely satisfied from an increase in flow from the Carboniferous deposits.

- The model simulates an outflow at Morecambe Bay and the Ribble Estuary throughout the simulation period. WRc model results suggest that the flow direction reversed at Morecambe Bay as a consequence of increased abstractions from the ICI wells, although the groundwater level hydrographs in the region did not support this. The new model does, however, simulate a large reduction in outflow to Morecambe Bay with the ICI boreholes operating: reduced from 5000 m^3/d in 1987 (low abstraction) to 2100 m^3/d in 1995 (high abstractions). This may have implications on water quality in the region.

- Abstraction volumes are mainly satisfied from leakage through Drift deposits and the sands & gravels. Leakage from both layers increases as the abstraction rate rises: refer to Figure 4.41. During summer, leakage increases with abstraction, while in winter, when abstractions are low, the leakage exceeds abstraction as the storage reservoir in the sandstone is replenished.

- Due to the high storage properties of the sands & gravels in the Wyre catchment, where these directly overlie the sandstone aquifer, the leakage from the river system to the sand & gravel aquifer is maintained for a longer duration than leakage from the rivers to the sandstone aquifer, and continues past the period of maximum abstraction until the sand & gravel storage is replenished (Figures 4.42 and 4.43). Since sandstone levels recover relatively quickly under confined conditions, leakage from the rivers is reduced when abstraction reduces. Effectively, the sand & gravel aquifer attenuates the leakage from the rivers. Without this aquifer, leakage from the rivers of the Wyre catchment would be more pronounced during the summer.

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2 Sign convention for leakage between rivers and aquifers is as follows:
- Positive flow is equal to leakage from river to aquifer
- Negative flow is equal to leakage to river from aquifer.

TABLE 4.11

Average Simulated Water Balance Components 1972 - 1996

Components	Sandstone (Two layers)	Sands & gravels[2]	Drift
Inflows			
Potential recharge	0.0	0.8	623.6
Leakage from Drift	33.1	15.4	n.a.
Leakage from sands & gravels	19.8	n.a.	n.a.
Boundary inflows (Carboniferous):			
- South East (Ribble)	3.9	0.0	0.0
- Millstone Grit	0.3	0.0	0.0
- Garstang	0.5	0.0	0.0
Flow from rivers to layer	0.0	3.5	0.0
Storage release	0.8	0.3	2.0
Total inflows	*58.5*	*20.0*	*625.6*
Outflows			
Abstraction	-37.6	0.0	0.0
Leakage to sands & gravels	n.a.	n.a.	-15.4
Leakage to sandstone	n.a.	-19.8	-33.1
Boundary Outflows:			
- Ribble Estuary	-4.3	0.0	0.0
- Morecambe Bay	-4.2	0.0	0.0
Groundwater flow to rivers	-12.3	0.0	-19.9
Rejected flows (rejected recharge)	0.0	-0.1	-546.0
Storage gain	0.0	0.0	0.0
Total outflows	*-56.4*	*-19.9*	*-614.4*
Model imbalance	*0.1*	*0.1*	*0.2*

Notes (1) All units Ml/d
(2) The sand & gravel aquifer only partially covers the model area

TABLE 4.12

Simulated Water Balance Components for September 1995

Components	Sandstone	Sands & gravels[2]	Drift
Inflows			
Potential recharge	0.0	0.0	0.0
Leakage from Drift	30.4	7.4	n.a.
Leakage from sands & gravels	45.3	n.a.	n.a.
Boundary inflows (Carboniferous):			
- South East (Ribble)	3.9	0.0	0.0
- Millstone Grit	0.3	0.0	0.0
- Garstang	0.7	0.0	0.0
Flow from rivers to layer	0.3	4.6	0.0
Storage release	46.3	33.3	50.3
Total inflows	*127.2*	*45.3*	*50.3*
Outflows			
Abstraction	-121.6	0.0	0.0
Leakage to sands & gravels	n.a	n.a	-7.4
Leakage to sandstone	n.a	-45.3	-30.4
Boundary outflows:			
- Ribble Estuary	-3.5	0.0	0.0
- Morecambe Bay	-2.1	0.0	0.0
Groundwater flow to rivers	0.0	0.0	-12.2
Rejected flows (rejected recharge)	0.0	0.0	-0.3
Storage gain	0.0	0.0	0.0
Total outflows	*-127.2*	*-45.3*	*-50.3*
Model imbalance	*0.0*	*0.0*	*0.0*

Notes (1) All units Ml/d
(2) The sand & gravel aquifer only partially covers the model area

TABLE 4.13

Simulated Water Balance Components for April 1987

Components	Sandstone	Sands & gravels[2]	Drift
Inflows			
Potential recharge	0.0	0.3	266.0
Leakage from Drift	29.6	11.9	n.a.
Leakage from sands & gravels	10.2	n.a	n.a
Boundary inflows (Carboniferous):			
- South East (Ribble)	3.6	0.0	0.0
- Millstone Grit	0.3	0.0	0.0
- Garstang	0.4	0.0	0.0
Leakage from rivers to layer	0.0	0.3	0.0
Storage release	1.3	0.0	20.1
Total inflows	*45.4*	*12.2*	*286.1*
Outflows			
Abstraction	-13.9	0.0	0.0
Leakage to sands & gravels	n.a	n.a	-11.9
Leakage to sandstone	n.a.	-10.2	-29.6
Boundary outflows:			
- Ribble Estuary	-4.5	0.0	0.0
- Morecambe Bay	-5.0	0.0	0.0
groundwater flow to rivers	-22.4	0.0	-21.0
Rejected flows (rejected recharge)	0.0	0.0	-223.9
Storage gain	0.0	-2.0	0.0
Total Outflows	*-45.8*	*-12.0*	*-286.4*
Model Imbalance	*-0.4*	*-0.2*	*-0.3*

Notes (1) All units Ml/d

(2) The sand & gravel aquifer only partially covers the model area

4.7.2 Modelled Parameters

In Chapter 3, the initial and final parameter settings were defined. The following section summarises the parameter settings at final calibration.

Horizontal Permeability of Sandstone

The sandstone aquifer permeabilities is highly heterogeneous. Variations occur throughout the modelled area. Generally the following parameters were defined for the final calibration:

- In the north west, a permeability of 5 m/d was defined. This is relatively high in order to simulated the influence of the ICI abstractions observed at surrounding boreholes.
- At Morecambe Bay the permeability was defined at 2 m/d to reduce outflows.
- Between the north west and Garstang areas a low permeability (0.5 m/d) was defined in order to simulate the steep gradient in this region. This steep gradient coincides with the area of high bicarbonate concentrations of the 'Garstang anomaly'.
- In the Garstang region, a permeability of 6 m/d was defined.
- In the Central area, a permeability of 3 m/d was set in order to accurately simulate the very low groundwater levels associated with high abstraction rates and to closely simulate the observed areal extent of the cone of depression around the NWW boreholes.
- To the south west of Woodplumpton Brook, between NWW sources B, C and D and the BNFL boreholes, anisotropic conditions were defined, coinciding with the north-south trending faults identified by BGS. A north-south permeability of 3 m/d and an east-west permeability of 0.02 m/d were defined.
- At the fault, 1.8 km east of the Grimsargh Fault, separating Whitbreads/Courtaulds abstractions from NWW abstractions a permeability of only 0.02 m/d was defined in order to simulate negligible impact of abstractions in the south east from the NWW sources.
- The permeability around the BNFL sources, NWW sources B, C, D and E and the Whitbreads/Courtaulds sources was set to 3 m/d.

Vertical Permeability of Leakance Interface Between Sandstone Layers

This parameter proved important in accurately defining the fluctuations in groundwater levels as measured in the relatively shallow observation boreholes in response to abstractions from the deeper supply boreholes. Over most of the model the vertical permeability was defined at 0.5 m/d, such that no significant vertical stratification in groundwater levels was simulated. In two areas, the vertical permeability was reduced in order to simulate a reduced response in the upper sandstone compared with the lower:

- at the ICI boreholes where a vertical permeability of 0.0025 m/d was defined;

- to the south east of Woodplumpton Brook where a very low vertical permeability was defined (0.00001 m/d) in order to simulate a negligible response to abstractions from NWW sources B, C and D in the upper sandstone layer and to represent the thick marl bands that are believed to exist in this area (refer to Section 4.5.2 and 4.5.3).

Storage Coefficients of Sandstone

The specific yield for the sandstone was initially defined at 6%, with a confined storage coefficient of 0.00005. The simulation of seasonal fluctuations and responses to abstractions in the model were found to be only marginally influenced by the storage coefficients of the sandstone. Therefore, these parameter settings were maintained throughout calibration.

Carboniferous Permeabilities

In order to simulate the correct gradients between Carboniferous and Sherwood Sandstone and the observed fluctuations in Carboniferous piezometry as a result of abstractions from the sandstone the following permeabilities were defined:

- Carboniferous sandstone formations at Garstang and the upstream end of the Ribble - 0.5 m/d.

- Bowland Shales 0.01 m/d (central area).

- Bilsborrow Fault, where there is a faulted contact with the sandstone - 0.1 m/d.

- Bilsborrow Fault, where Manchester Marls are in contact with the sandstone aquifer - 0.0 m/d

Vertical Permeability of Drift

It was necessary to reduce the initial settings for the permeability of the Drift in order to reduce piezometry in the Fylde aquifer to the observed. The initial settings were as follows:

- boulder clay - 0.1 - 5 mm/d
- sands & gravels - 0.1 - 1.0 m/d

Overall these were reduced to 0.1 mm/d for boulder clay and 0.2 m/d for sands & gravels. In some areas, particularly, to the south west of Woodplumpton Brook, very low permeabilities were defined (0.01 mm/d for boulder clay and 0.1 m/d for sands & gravels).

Properties of the Sand & Gravel Layer

The sand & gravel layer (directly above rockhead) influences both leakage from the rivers and piezometric fluctuations in the sandstone aquifer. The parameter settings initially adopted for this aquifer were as follows:

- horizontal permeability - 5 m/d;
- vertical permeability - 0.5 m/d;
- specific yield - 7.5 %;
- confined storage coefficient - 0.00005.

During calibration, it was found that both the vertical permeability and storage coefficient were important influences on the impact of abstractions from NWW sources on sandstone groundwater levels and on river flows. Adjustments to these parameters were then made until the following settings were accepted:

- horizontal permeability - 5 m/d;
- vertical permeability - 0.5 m/d; in the central area to 0.05 in the south west at Woodplumpton Brook;
- specific yield - 12% in the central area to 7.5 % in the south west at Woodplumpton Brook;
- confined storage coefficient - 0.00005.

4.8 Model Sensitivity

4.8.1 Introduction

The purposes of the sensitivity analysis is to establish the influence of the model parameters on the final calibration as well as to define the confidence level associated with each parameter setting used in final calibration. Sensitivity analysis is also important in helping to define the main uncertainties in the model calibration.

During model calibration the sensitivity of each model parameter was assessed. A summary of this assessment is given in Table 4.1. Seven "key" parameters control the accuracy of the model calibration:

- the Drift vertical conductance;
- the permeability of the Carboniferous deposits;
- the permeability of sandstone;
- the specific yield of the sand & gravel aquifer;
- the river/aquifer leakage parameters;
- the specific yield of the Drift layer

For each one of these "key" parameters two sensitivity model runs were carried out (except for the Drift specific yield where only one run was made). The results of these runs are summarised in the following sections.

TABLE 4.14
Sensitivity of Model Parameters

Parameter	Influence on simulations	Used for formal sensitivity analysis	Range to be used in formal sensitivity analysis	Model Run Nrs
Vertical permeability of the Drift	Piezometry, water balances and seasonal fluctuations in groundwater levels highly influenced by permeability.	YES	+/- 20%	TS07 & TS08
Horizontal permeability of sandstone	Influences piezometry and seasonal fluctuations. Also influences outflow volumes to rivers and estuaries.	YES	+/- 25%	TS01 & TS02
Horizontal permeability of the Sands & gravels	Very little impact on piezometry, seasonal fluctuations, river flows or water balance components	NO	-	-
Horizontal permeability of the Carboniferous deposits and faulted contact with sandstone	Influences volume of boundary inflow and therefore piezometry in east of aquifer. The same effect is established if the Carboniferous boundary condition is changed.	YES	+/- 50% (high range because of high degree of uncertainty)	TS03 & TS04
Vertical conductance between sandstone layers	Large influence on the seasonal fluctuations in piezometry for the simulated sandstone layers.	YES	+/- 50%	TS05 & TS06
Specific yield of Drift	Influences on seasonal variations of sandstone groundwater levels and volume of actual recharge to the Drift	YES	+50%	TS13 (no lower limit tested because values defined in calibration are considered at lower end of justifiable scale)
Specific yield of Sands & gravels	Influences seasonal fluctuations in inflow/outflow from rivers and the sandstone groundwater levels	YES	+/- 50%	TS09 & TS10
Storage properties of Sandstone	Limited impact	NO		-
River Resistance	Only impacts seasonal fluctuations in groundwater levels (and to a lesser extent the simulated river flows) in areas where a low river resistance has been defined (downstream end of River Wyre, parts of Calder, Brock, Barton Brook and Woodplumpton Brook)	YES	+/- 50 %	TS11 & TS12

4.8.2 Horizontal Permeability of the Sandstone Aquifer

The permeability of the sandstone influences the seasonal fluctuations of groundwater levels, the extent of the influence of abstractions on surrounding groundwater levels and the volume of river baseflow and leakage from the river system.

The results of model runs TS01 and TS02 indicate, that within the range +/- 25 % the simulated piezometry and hydrographs are within the inaccuracies of the model calibration at observation boreholes apart from in locations where there is significant interaction between the river and the aquifer system. In such areas (eg at Garstang and upstream of St Michaels on the River Wyre), a reduced permeability results in much greater seasonal fluctuations in piezometry close to the rivers than in areas remote from the rivers. This is demonstrated in Figure 4.44 at two observation boreholes either side of the River Wyre, in close proximity to NWW sources W and Z. On the west side of the river (at SD 44/33) the variation in simulated levels between high and low permeability is relatively small and within the accuracy of the model calibration. However, on the east side of the river (at SD54/15) there is a much greater range in the simulated levels. With low permeability, the model simulates higher seasonal fluctuations since there is less leakage from the river and thus the cone of depression around W/Z is extended further eastwards across the river.

It can therefore be concluded that in areas remote from rivers equally acceptable simulations would apply for sandstone permeabilities within the range +/- 25%. At rivers there would need to be a corresponding change in river conductance for the simulation of sandstone piezometry to remain valid.

4.8.3 Permeability of the Carboniferous Deposits

The Carboniferous permeability was varied within the range +/- 50%. The model results suggest that with the calibration permeability settings being defined so low (0.01 - 0.5 m/d), the simulated piezometry of the Carboniferous and sandstone aquifers is only marginally influenced by permeability variations. In terms of simulated water balance components, the Carboniferous inflow varies from 4.2 Ml/d (low permeability) to 6.9 Ml/d (high permeability). The calibrated inflow was 5.8 Ml/d. This is a very low range and thus it is concluded that the model calibration is not affected by the level of permeability of the Carboniferous deposits within the range +/- 50% of the calibrated level.

4.8.4 Vertical Permeability Between Upper and Lower Sandstone Layers

The vertical permeability between sandstone layers has a high level of uncertainty associated with it. As explained in Section 4.7.2 there are two areas where a low vertical permeability was defined in order to simulate a lower response to groundwater abstractions in the upper sandstone (monitored by the relatively shallow observation boreholes) than the lower sandstone (tapped by the deeper abstraction boreholes): in the north west and south of Woodplumpton Brook. For sensitivity runs the vertical permeability was varied between -50 and +50 %. This had only a marginal influence on the simulated piezometry. This is because the values adopted in these two areas were very low and thus small changes of between +/- 50 % will not have much influence on the simulation. Consequently the uncertainty of the adopted settings remains high, although these values tend to produce the most accurate simulations.

4.8.5 Drift Vertical Permeability

The simulated piezometry and seasonal level fluctuations in the sandstone are very dependent upon the value of Drift vertical permeability adopted. Therefore, a relatively low range was tested during sensitivity analysis (+/- 20%). A higher range would result in the piezometric simulation being well outside the observed ranges.

With +/- 20%, the model simulates groundwater levels within the inaccuracy of the model calibration indicating that the confidence level of the vertical permeability is around +/-20%. With lower permeabilities, there is a reduction in piezometry of between 1 and 3 m and the volume of leakage is reduced. The variation in leakage volumes is shown in Figure 4.45

4.8.6 Sands & Gravels

The sand & gravel layer which directly overlies the sandstone is an important storage reservoir in the Central area. The influence of this storage reservoir on the simulations was defined by varying the specific yield of the sands & gravels by between -50 and +50% (or from 6% to 18% in the Central area and from 4% and 12 % at the south western side of the model).

Figure 4.46 details the simulated groundwater level hydrographs at two locations: at SD 54/21 midway between the River Wyre and the River Brock and at SD43/2 close to Barton Brook. This shows that with higher specific yield the seasonal sandstone levels are dampened and vice versa. In both cases the simulated sandstone levels are within the observed range during selected periods, although overall the accuracy of the simulation compared with the observed is reduced.

In terms of river flows, the simulated losses from the rivers, during summer when there is a high volume of abstraction, are significantly reduced when increased storage potential is defined for the sands & gravels. This is demonstrated in Figure 4.47, where the simulated river flow profile for the River Brock for July 1984 is presented.

To the south west of Woodplumpton Brook, where groundwater levels show a declining trend, the sands & gravels also have an influence. Figure 4.48 shows the results of the sensitivity runs at the 'T74' "control" borehole (SD43/19). With increased specific yield the model does not accurately simulate the declining trend. With a lower specific yield defined, the simulation remains relatively accurate. Thus the specific yield setting of the sands & gravels in this area (7.5%) is considered the upper limit and confirms that the adoption of a lower value in this region than in the area to the north is valid.

4.8.7 River Resistance

The river resistances adopted are sensitive at locations where there is a relatively good hydraulic contact between the sands & gravels/sandstone aquifers and the river (ie where there is very little boulder clay beneath the river). The results of the sensitivity runs on this parameter are demonstrated in Figure 4.49 for borehole SD44/20, north of the Wyre where the river was defined to be in direct contact with the sandstone. This shows the large variation in seasonal fluctuations with river resistance indicating that the calibration settings are of the correct order of magnitude.

However, the river-aquifer interaction is also dependent upon the sandstone permeability defined at the river, as described in Section 4.8.2. With lower permeability and lower river resistance an equally plausible simulation at the rivers could be achieved, although the accuracy of the simulated losses would be reduced.

4.8.8 Drift Specific Yield

The specific yield defined for the Drift generally varies from 4 to 9% This is considered towards the low end of the scale, considering that the Drift layer includes significant thickness of sands & gravels. One sensitivity run was therefore carried out with the specific yields raised by 50% (resulting in a range of between 6 and 13.5%). The results for the Central area (At borehole SD54/21) are shown in Figure 4.50. This indicates that the sensitivity of the model calibration to the Drift specific yield is relatively low.

At T74 (SD43/19) there is a greater impact. In this area recharge is limited by the Drift infiltration capacity which results in Drift storage playing a more important role than in other areas.

4.8.9 Summary of Sensitivity Analysis

Table 4.15 indicates the potential range of parameter settings for the most sensitive parameters in the Fylde model calibration. These are not confidence limits, but indicate the likely range of parameter settings which would result in simulated piezometry, groundwater level hydrographs and river flow losses similar to the observed, but without the same level of accuracy as the calibrated model.

TABLE 4.15

Range in Aquifer and River Properties Resulting in Relatively Accurate Simulations

Parameter	Lower Level (as % of calibration level)	Upper Level (as % of calibration level)
Permeability of Sandstone	-25%	+25%
Permeability of Carboniferous	-50%	+50%
Vertical Permeability between upper and lower sandstone layers	-50%	+50%
Drift Vertical Permeability	-20%	+20%
Sands & Gravels Specific Yield	-50%	+50%
River Resistance	-50%	+50%
Drift Specific Yield	0	+50%

4.9 Conclusions From Model Calibration

Th integrated catchment model of the Fylde aquifer presented in this chapter has demonstrated that the modelled flow system accurately represents the conditions within the Fylde.

The model results highlight one very significant feature of the Fylde aquifer: groundwater abstractions are primarily derived from vertical leakage of rainfall recharge through the overlying Drift deposits and from leakage through river beds. This is very different from the mechanism of flow adopted in the defined in the WRc model (1972), where groundwater abstraction volumes were primarily derived from the inflow of water from the Carboniferous deposits to the east. This has an important bearing on the licensing of groundwater abstractions. In the WRc model, the impacts of groundwater abstractions on the environment are minimised since the Carboniferous system is considered as a reservoir with infinite storage. In the current, revised model, groundwater abstractions are limited by the vertical conductance of the Drift deposits. A deficit in vertical flow through the Drift is made up by the inducement of leakage from the surrounding rivers system. The impacts of groundwater abstractions on the environment are therefore more pronounced and more accurate in the current, revised model.

A number of other conclusions can be made for each area of the Fylde aquifer. These are as follows:

Area 1 North West Fylde

- Abstractions from ICI sources, and to a lesser extent from NWW sources W and Z (in Area 2), caused a reversal from the historical upward leakage at the Winmarleigh Mosses SSSI, which may have resulted in a reduction of surface water levels/discharges around the SSSI.

- ICI abstractions reduce outflow to Morecambe Bay. This could potentially lead to a deterioration in groundwater quality in the north west of the Fylde as a result of saline intrusion[3].

Area 2 Garstang

- NWW sources W and Z cause a loss of flow in the River Wyre .

- Under non-pumping conditions, there is only a limited inflow of water from the sandstone formations of the Carboniferous along the eastern boundary, with NWW's abstraction only inducing small additional inflows.

Area 3 Central Fylde

- Abstractions from the central NWW sources (Franklaw 'A' & 'B' and Broughton 'B' boreholes) induce losses from all the rivers at different locations.

- The sands & gravels which directly overlie the sandstone aquifer in this area act as an important storage reservoir for NWW abstractions. Without this additional storage, abstractions would result in higher river losses during summer.

- Groundwater abstractions do not induce additional flow from the Carboniferous boundary because very low permeability Manchester Marls separate the Carboniferous from the Sherwood Sandstone aquifer.

Area 4 Preston & Southern Fylde

- There is marked horizontal anisotropy in aquifer permeability (caused by faulting) to the west of NWW Broughton 'A' sources (sites B, C and D) limiting the east-west groundwater flow in this area.

- The main 'trough' of aquifer exploited by NWW's boreholes is effectively hydraulically isolated by structural controls from the upstream end of the Ribble valley - the 'Red Scar Basin', in which the Whitbreads and the former Courtaulds boreholes are situated. (forming part of the South East Fylde area)

- Sands & gravels in the west of the area, at the Woodsfold Fault, act as a conduit linking Woodplumpton and Barton Brooks with the sandstone aquifer, resulting in river flow losses during abstractions from the central area and NWW's B, C and D sites.

Area 5 South East Fylde

- Groundwater levels within the upstream end of the Ribble catchement (i.e. the 'Red Scar basin', around Whitbreads and the former Courtaulds sites) are controlled by the river valley and inflows from the

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3 There is an agreement between ICI and NWW to maintain the ICI abstractions below their licensed rate in exchange for NWW supplying the shortfall from their LCUS sources. However, this has not operated during the calibration period.

Carboniferous.

Although a very good agreement in sandstone piezometry, groundwater levels and river flow hydrographs has been achieved throughout the model over the calibration period, there remains some degree of uncertainty. This relates in particular to:

- The geological structure and hydrogeological flow mechanisms of the sandstone between the main trough of aquifer exploited by NWW's sources, which extends into Preston, and the 'Red Scar Basin'. Recent geological and hydrogeological evidence has allowed further reconceptualisation of the geological structure. This broadly supports the settings defined in the numerical model, although the actual structure differs slightly from that built into the model.

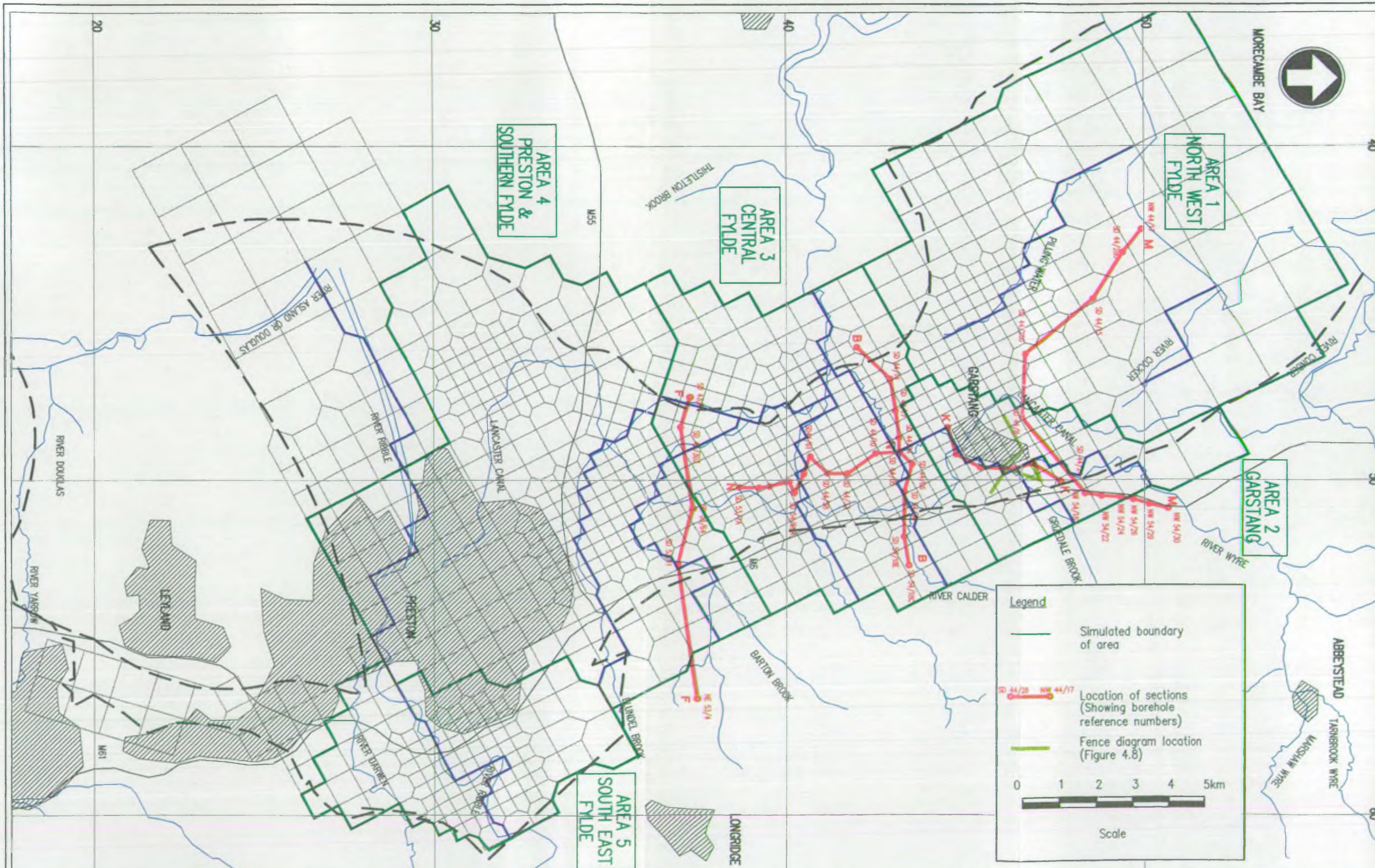
- The river/aquifer interaction defined at the River Ribble has not been calibrated against observed flows.

- In the model, outflow to the west beneath the Mercia Mudstone has been set to zero. Although this is a reasonable assumption, there is no evidence to confirm this.

- detailed mechanisms for recharge to the sandstone aquifer via the Drift, with special reference to the '95/96 drought response

Figure 4.1

Areas of the Fylde Model and Location of Geological Cross Sections



31/07/97 O:\EWR\PROJECTS\38436BA.01\ACAD\FINAL\FIG4-01A

Figure 4.2

North West Fylde - Location Map

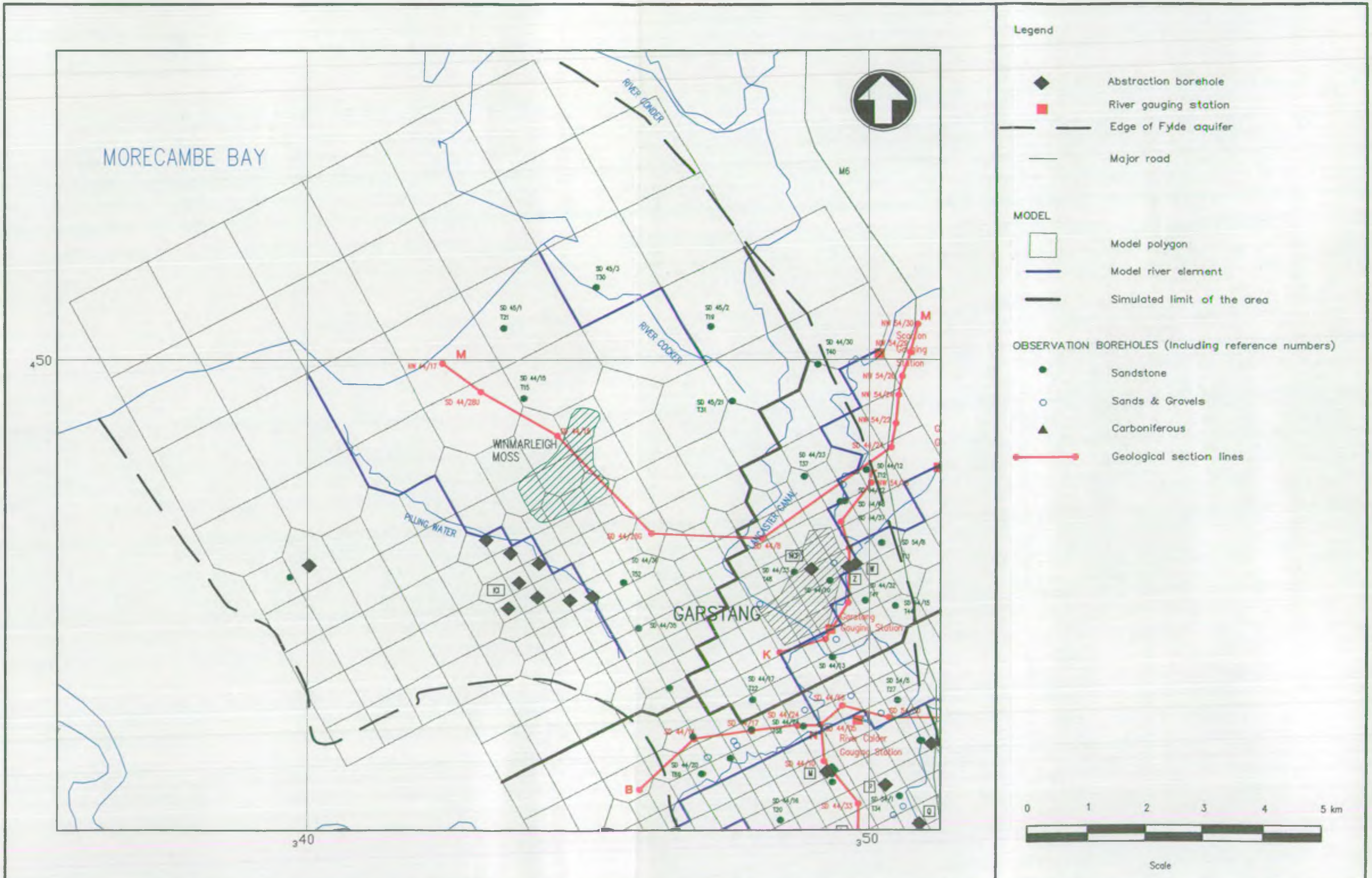


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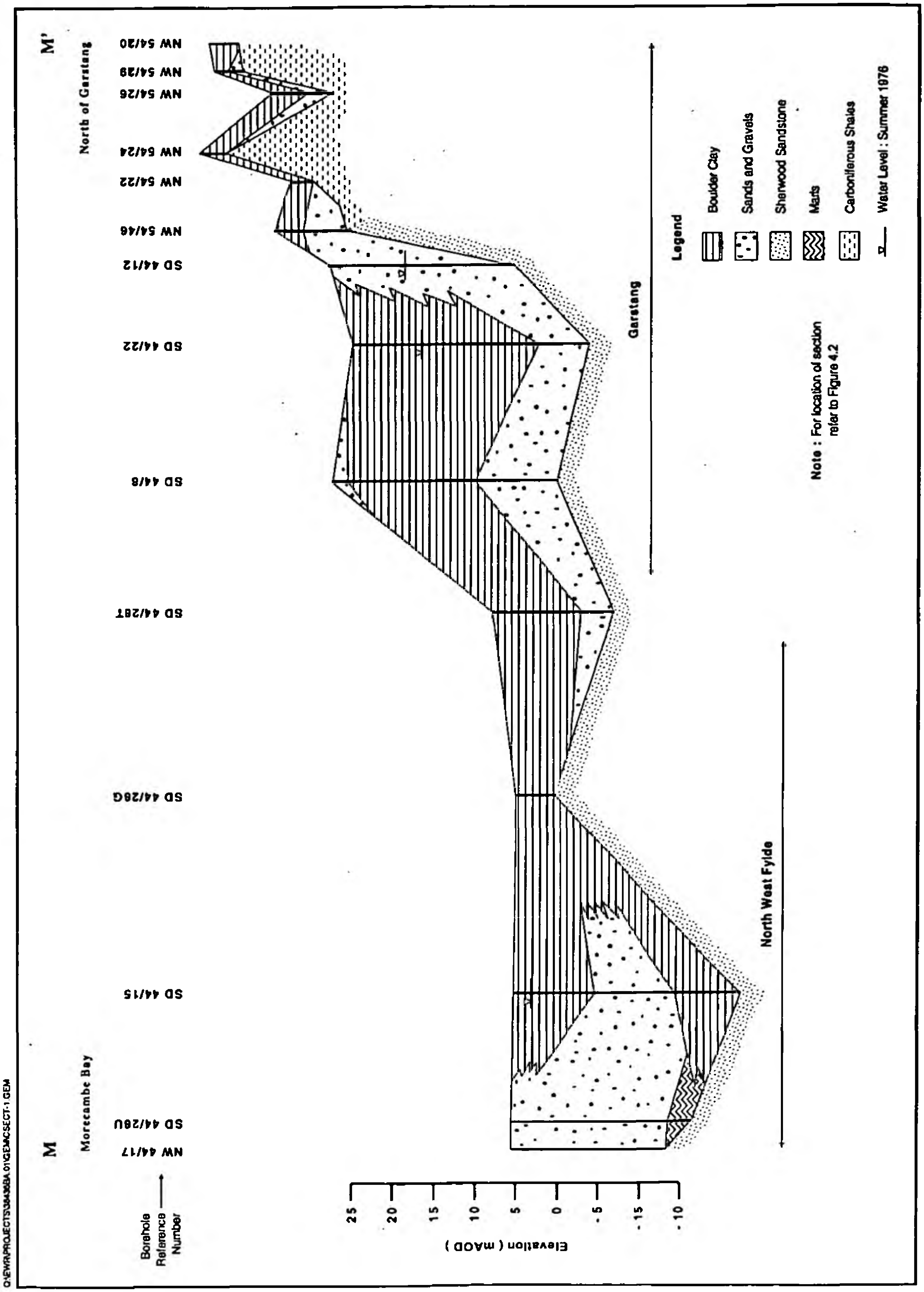
Figure 4.3

Cross Section : Morecambe Bay to Garstang (Section M M)



North West Fylde - Simulated Piezometry, April 1987

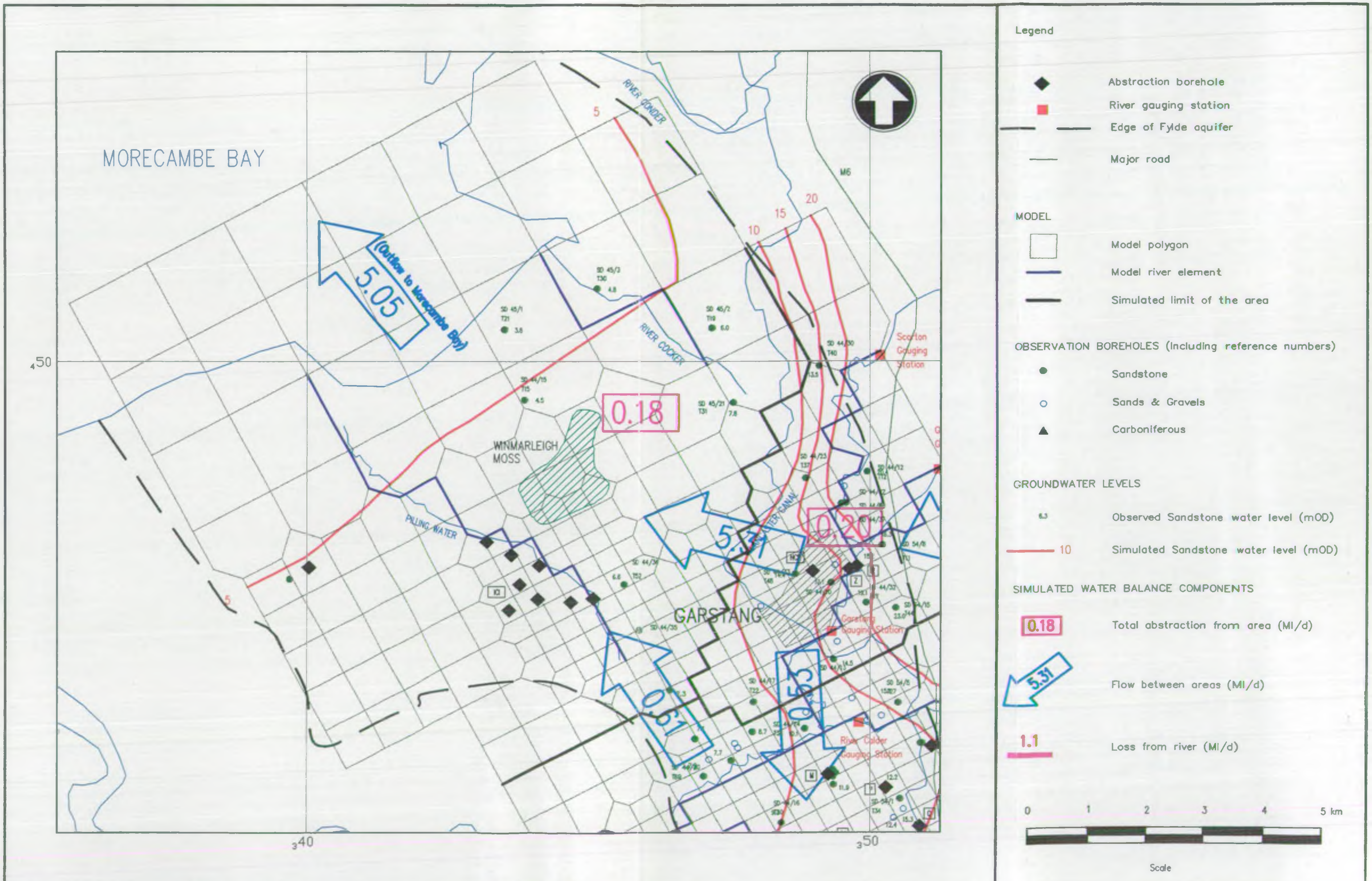


Figure 4.5

North West Fylde - Simulated Piezometry, September 1995

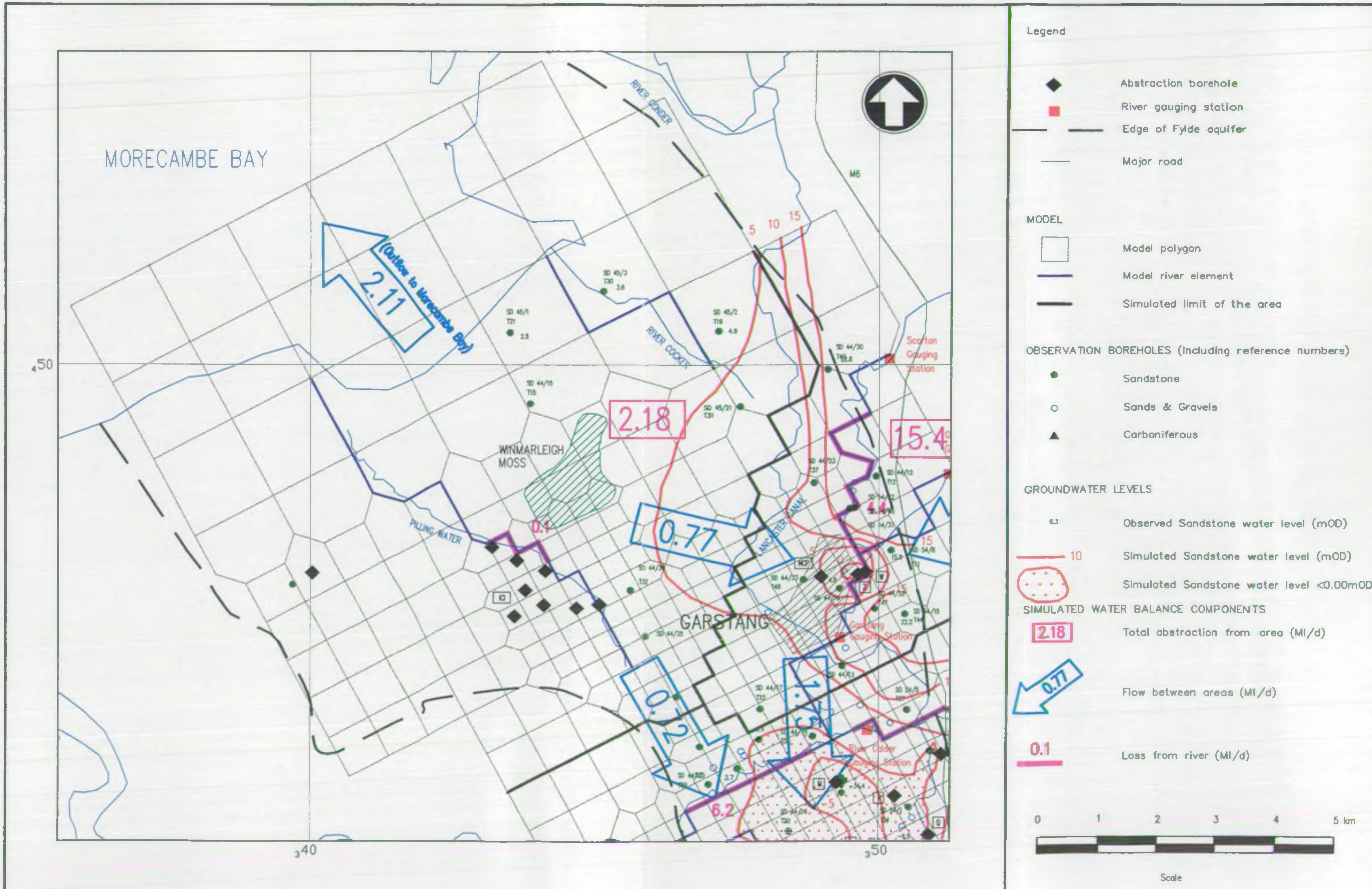


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Figure 4.6

North West Fylde: Simulated Groundwater Level Hydrographs

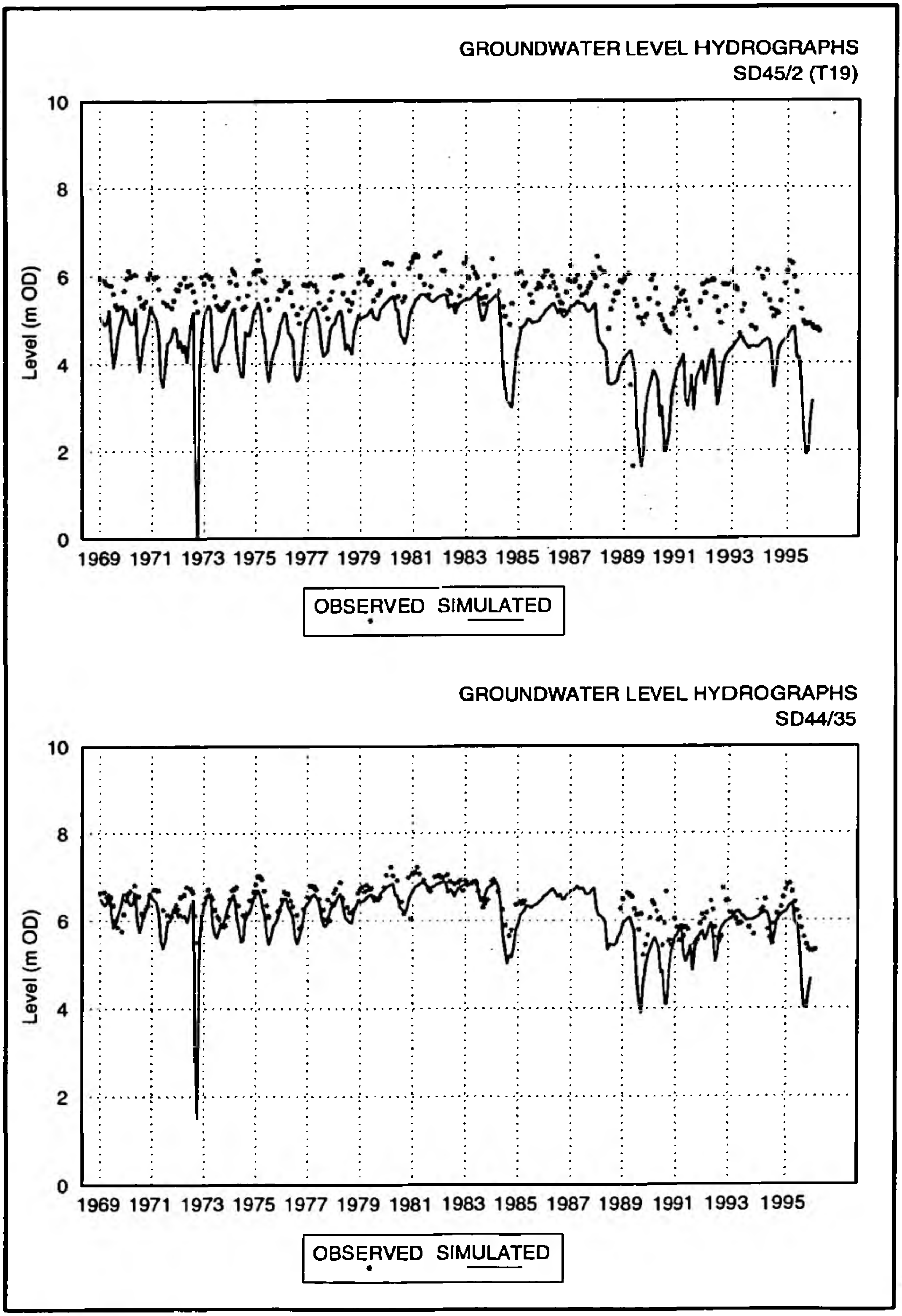
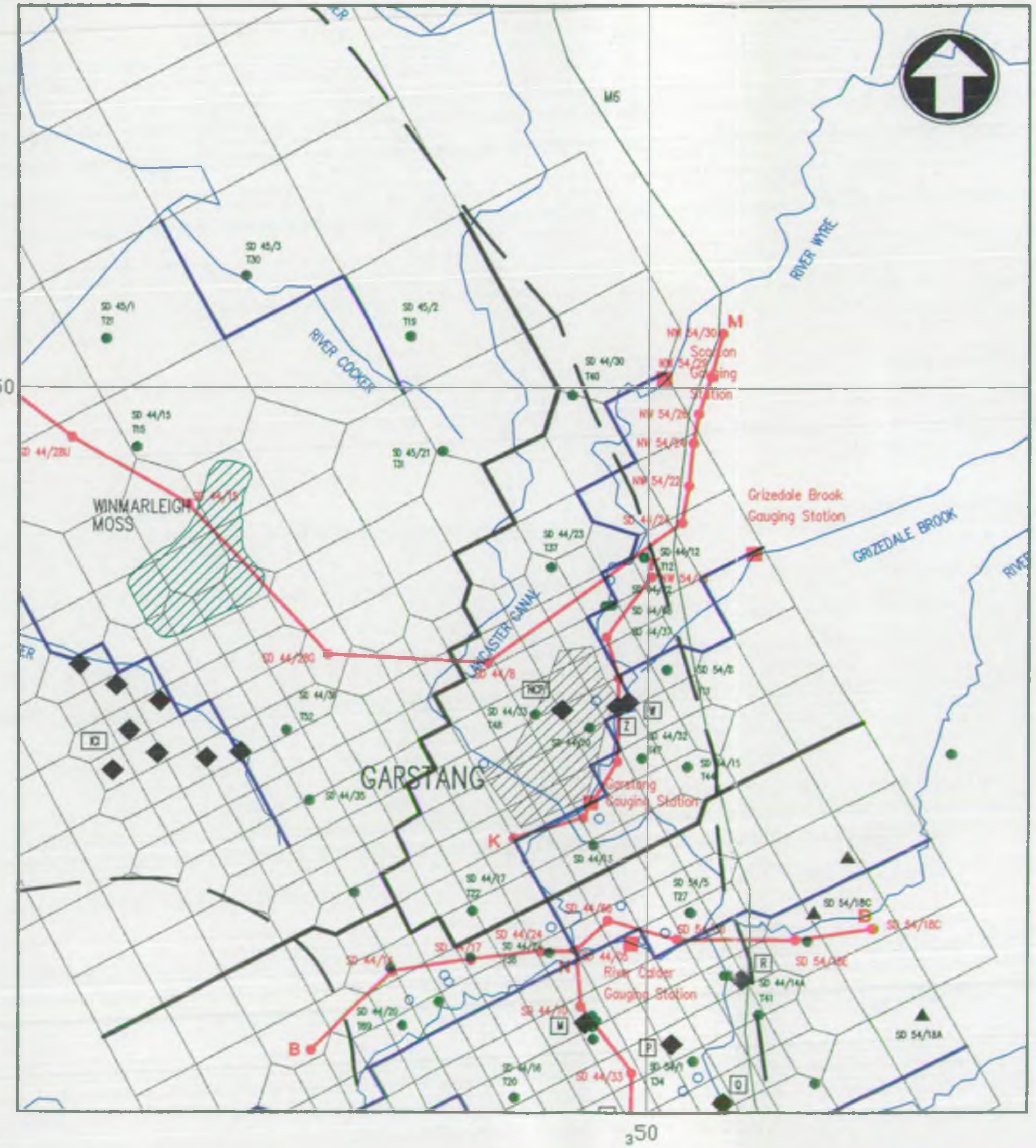


Figure 4.7

Garstang Area - Location Map



Legend

- Abstraction borehole
- River gauging station
- Edge of Fylde aquifer
- Major road

MODEL

- Model polygon
- Model river element
- Simulated limit of the area

OBSERVATION BOREHOLES (including reference numbers)

- Sandstone
- Sands & Gravels
- Carboniferous
- Geological section lines

0 1 2 3 4 5 km

Scale

01/08/97 Q:\EWR\PROJECTS\38436BA.01\ACAD\FINAL\FYL-02A

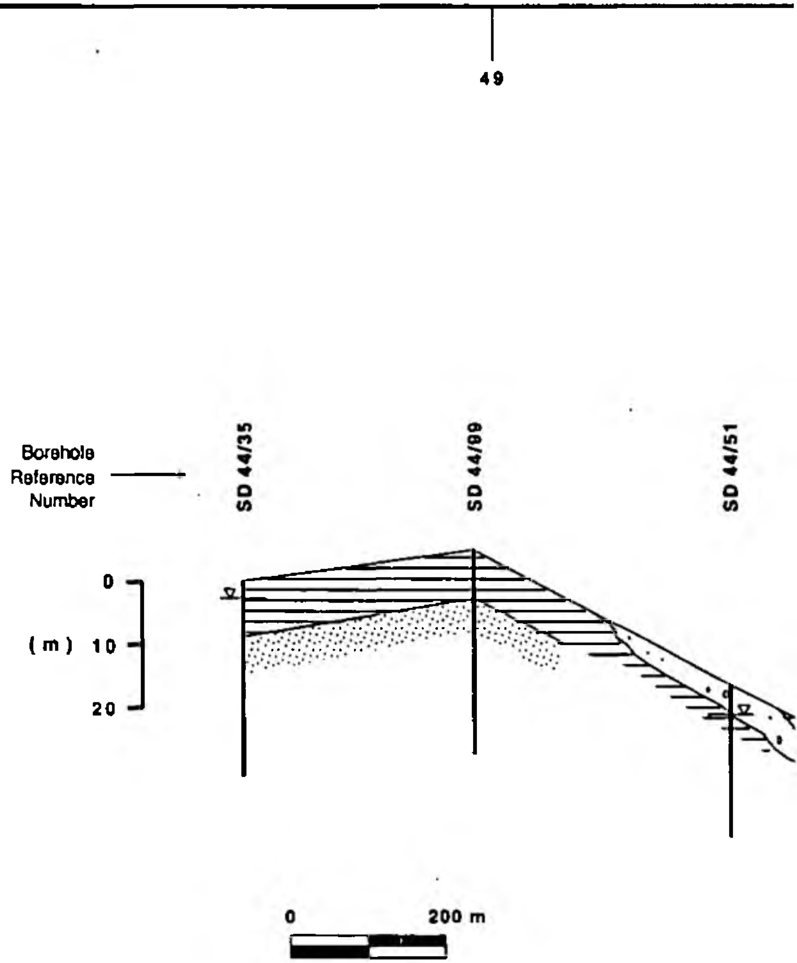

49
Borehole
Reference
Number
SD 44/35
SD 44/99
SD 44/51
0
(m) 10
20
0
200 m

Figure 4.8

Fence Diagram : Garstang Area

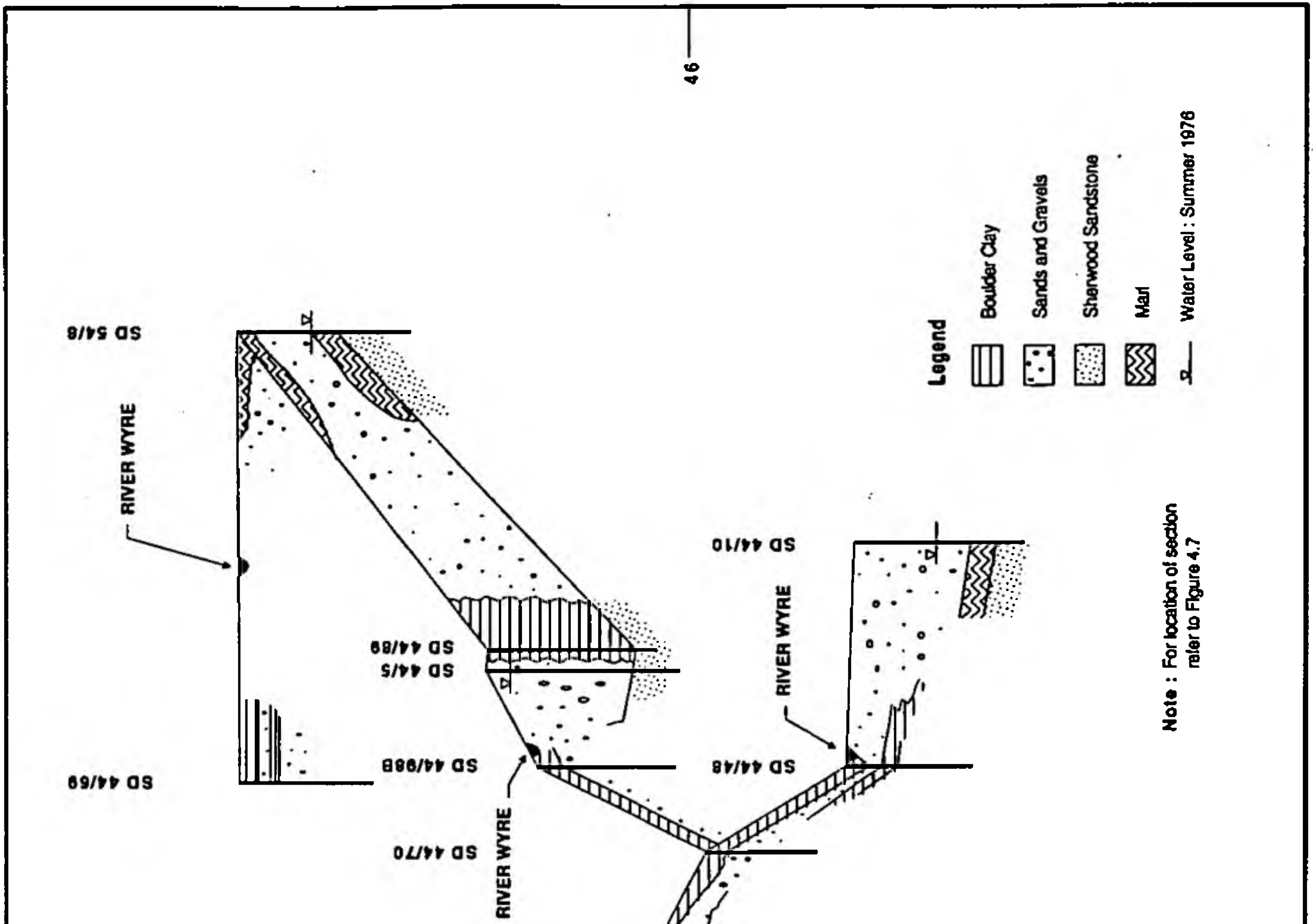
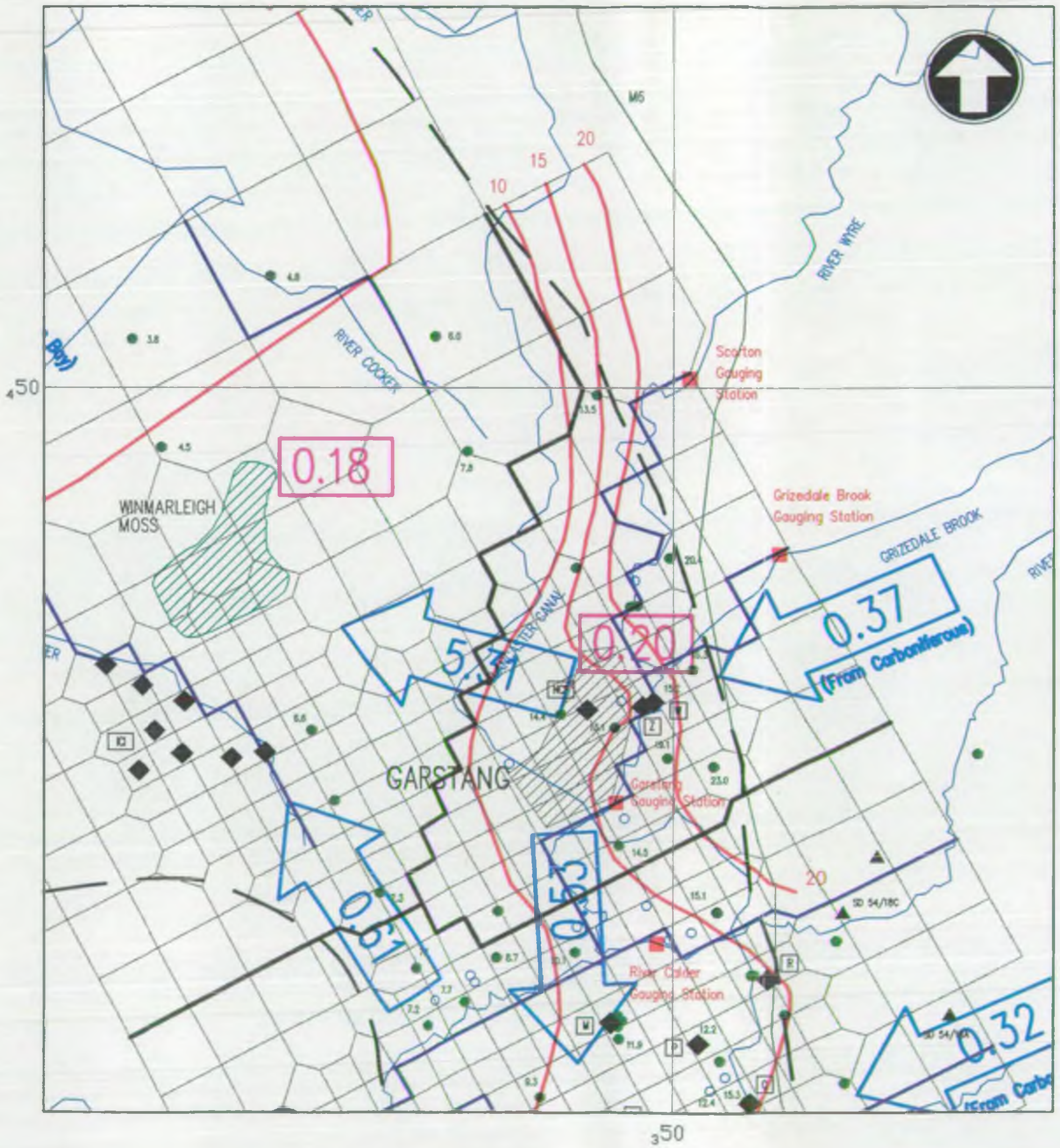


Figure 4.9

Garstang Area - Simulated Piezometry, April 1987



Legend

- Abstraction borehole
- River gauging station
- Edge of Fylde aquifer
- Major road

MODEL

- Model polygon
- Model river element
- Simulated limit of the area

OBSERVATION BOREHOLES (Including reference numbers)

- Sandstone
- Sands & Gravels
- Carboniferous

GROUNDWATER LEVELS

- 6.5 Observed Sandstone water level (mOD)
- 10 Simulated Sandstone water level (mOD)

SIMULATED WATER BALANCE COMPONENTS

- 0.20 Total abstraction from area (Ml/d)
- 0.37 Flow between areas (Ml/d)
- 1.1 Loss from river (Ml/d)

0 1 2 3 4 5 km

Scale

Figure 4.10

Garstang Area - Simulated Piezometry, September 1995

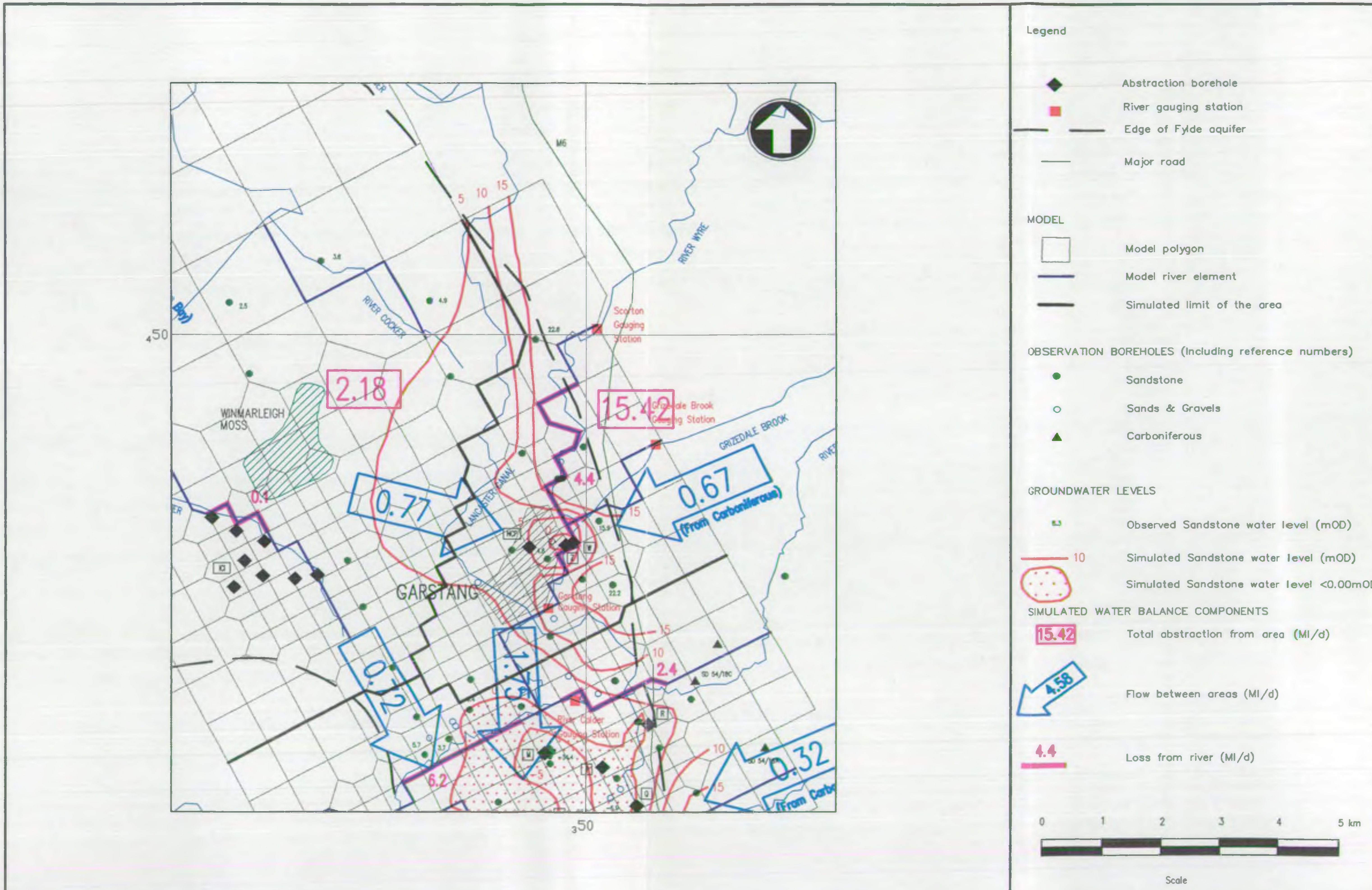


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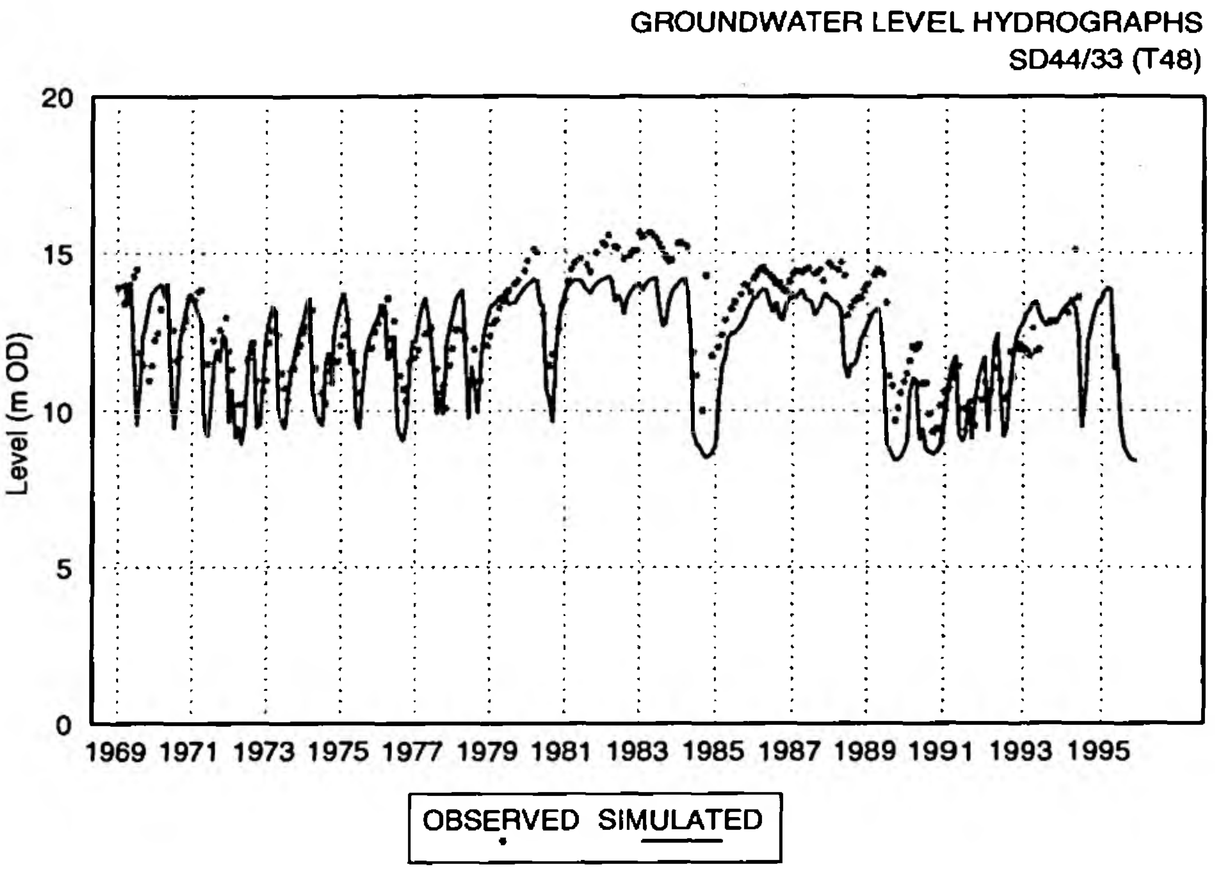
Figure 4.11
Garstang: Simulated Groundwater Level Hydrographs I



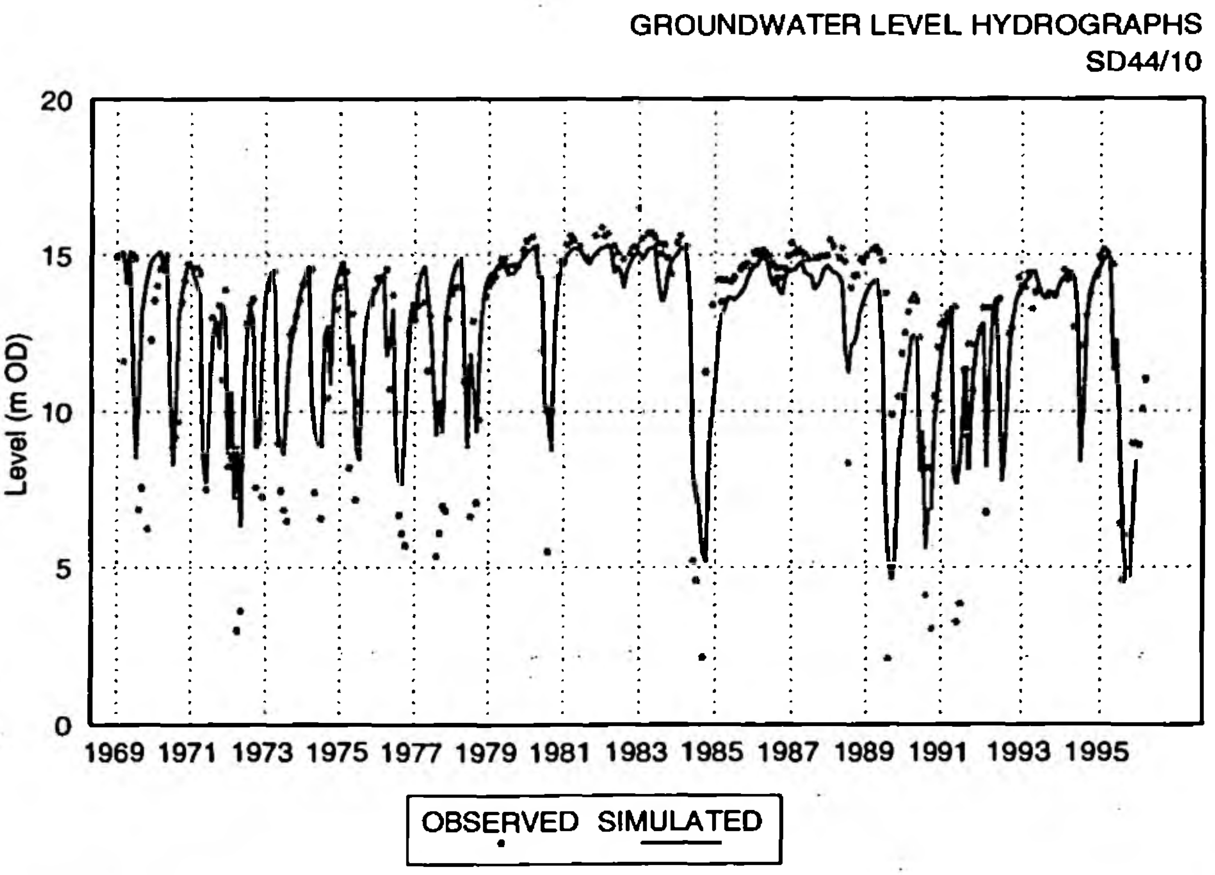
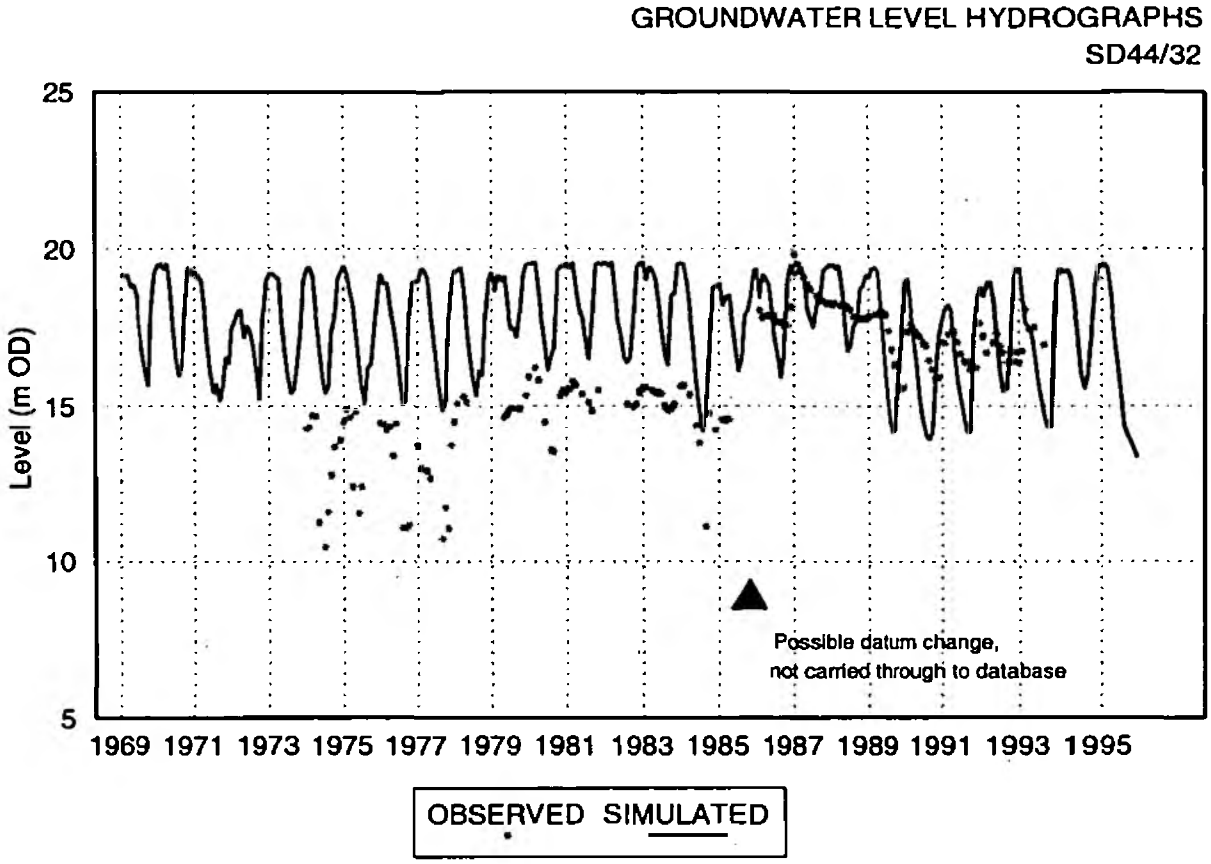
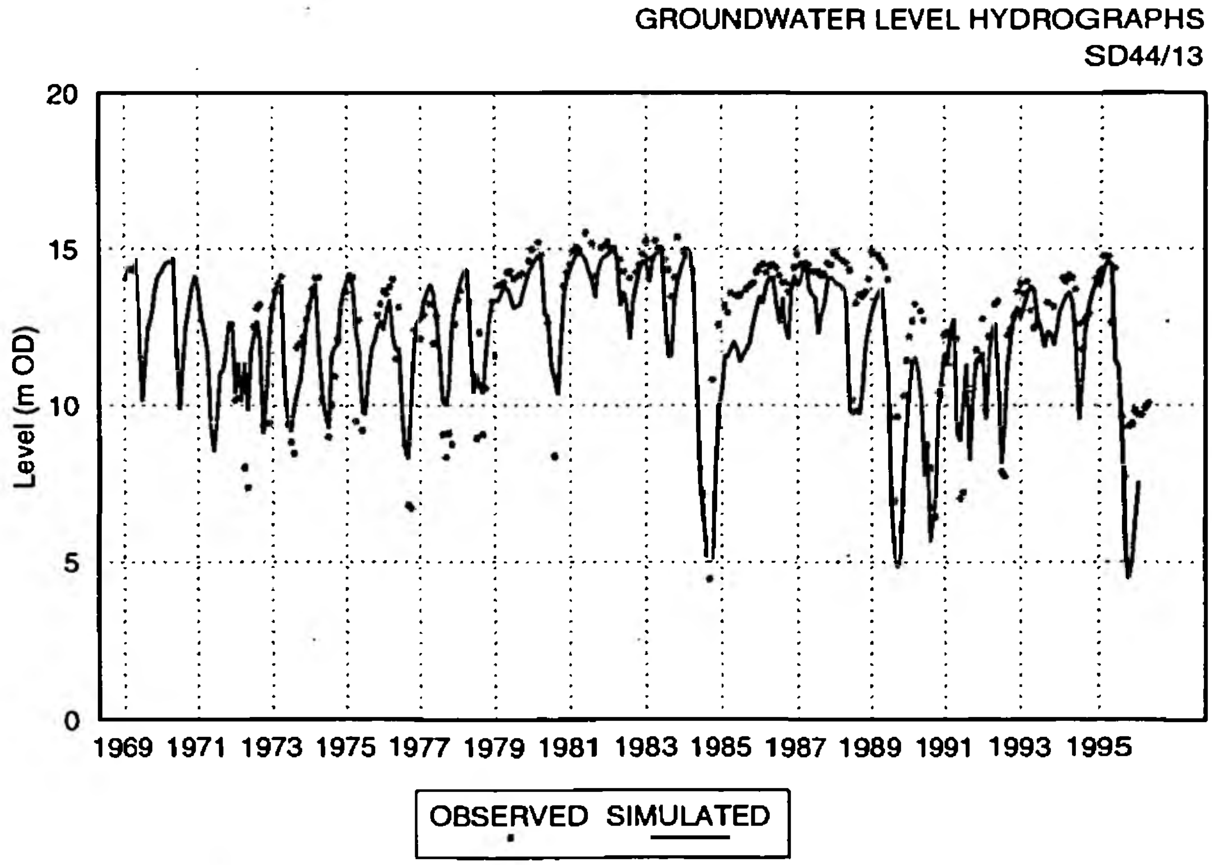


Figure 4.12

Garstang Area: Simulated Groundwater Level Hydrographs II





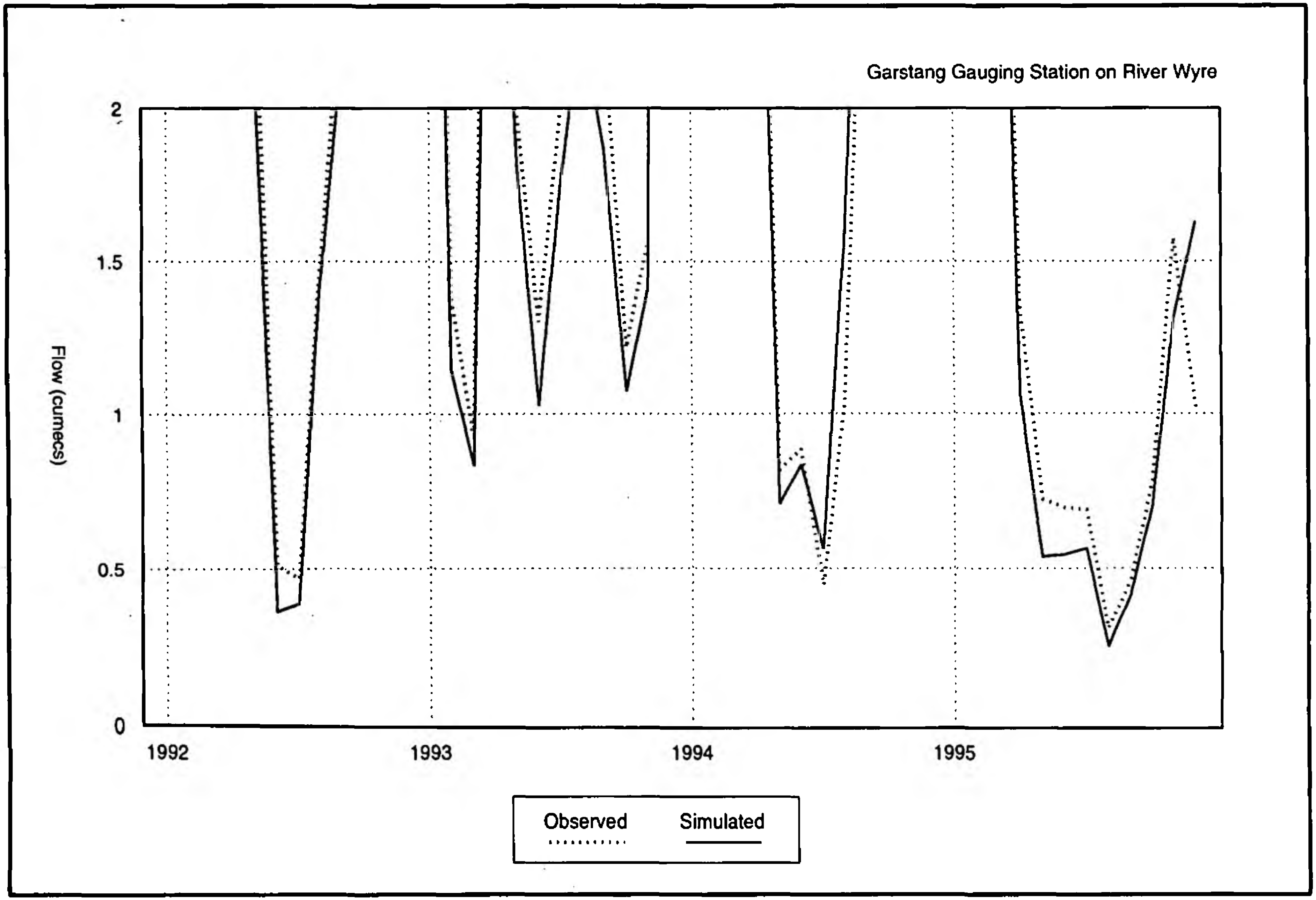


Figure 4.13
Simulated Low River Flows at Garstang Gauging Station (1993 - 1995)

Figure 4.14

Simulated and Observed River Flow Losses - Garstang Area

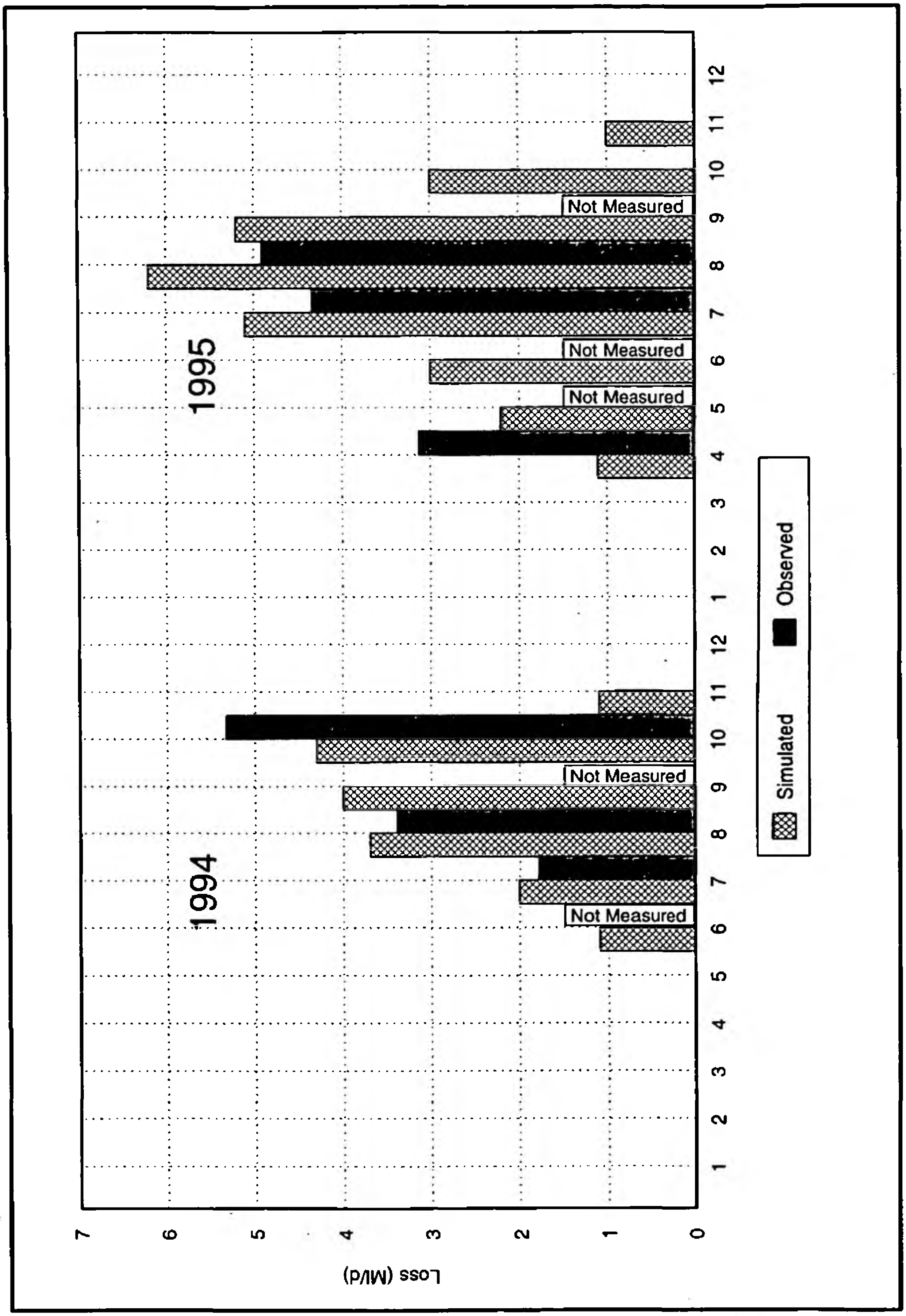
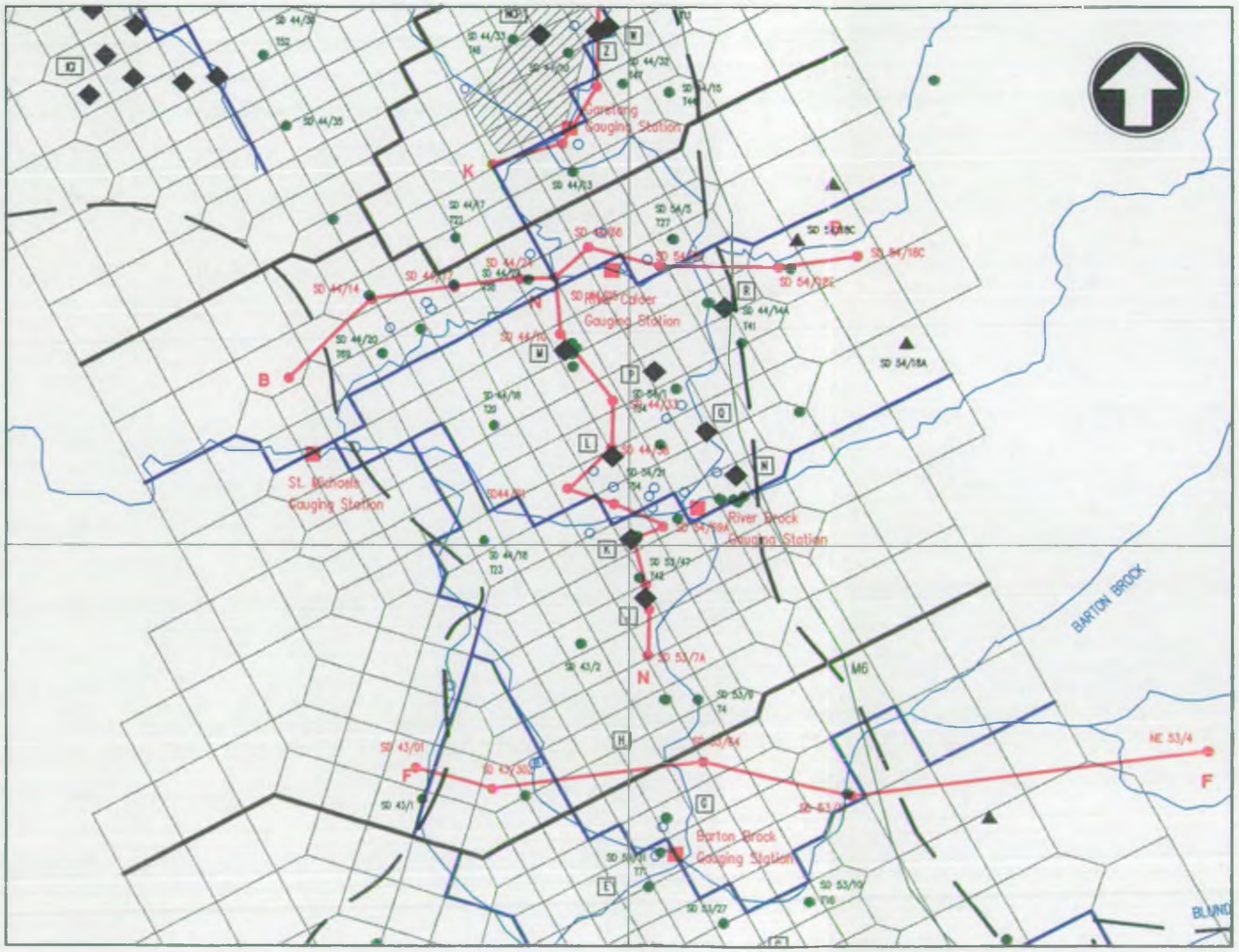


Figure 4.15

Central Area - Location Map



Legend

- Abstraction borehole
- River gauging station
- Edge of Fylde aquifer
- Major road

MODEL

- Model polygon
- Model river element
- Simulated limit of the area

OBSERVATION BOREHOLES (Including reference numbers)

- Sandstone
- Sands & Gravels
- Carboniferous
- Geological section lines

0 1 2 3 4 5 km

Scale

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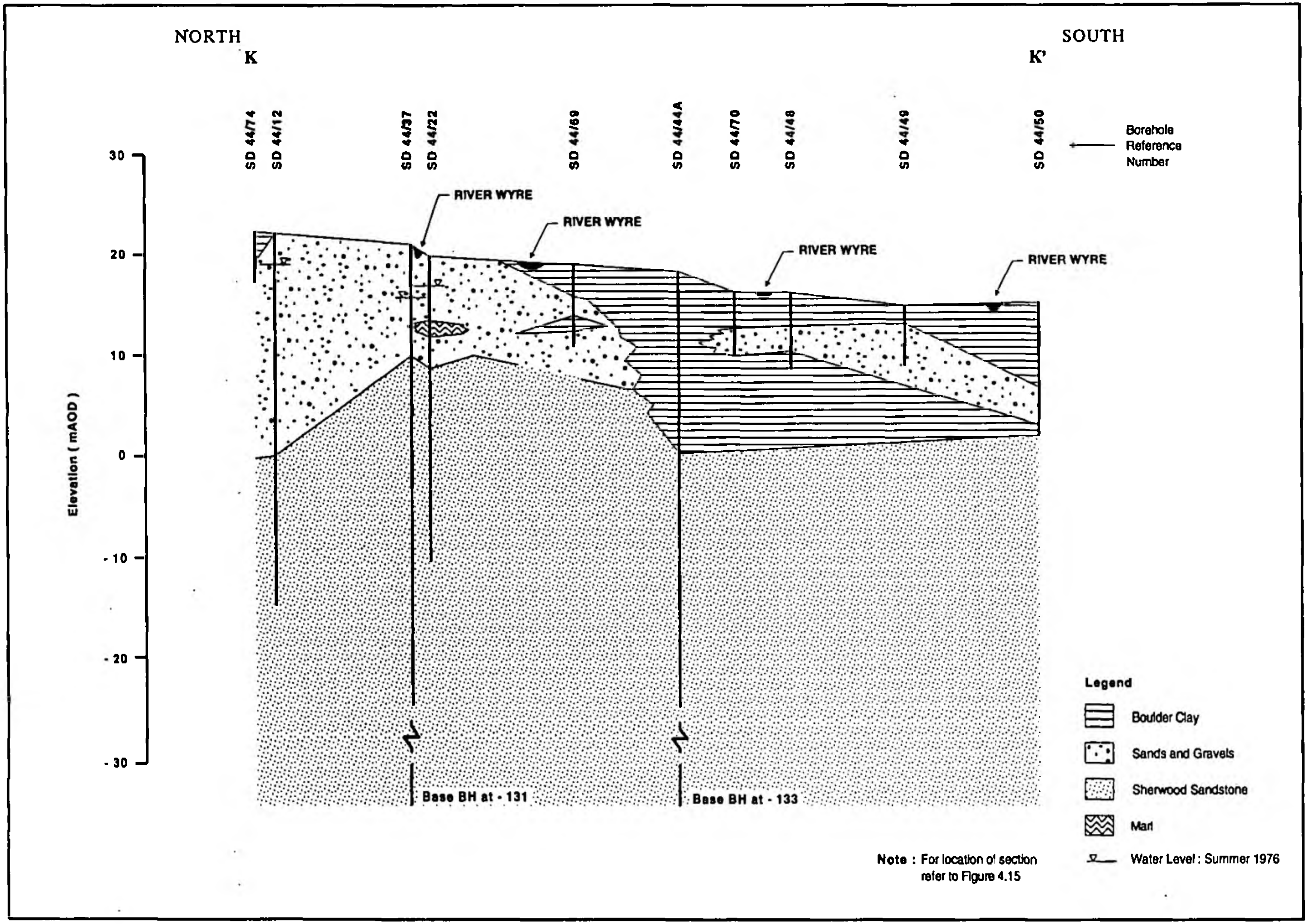
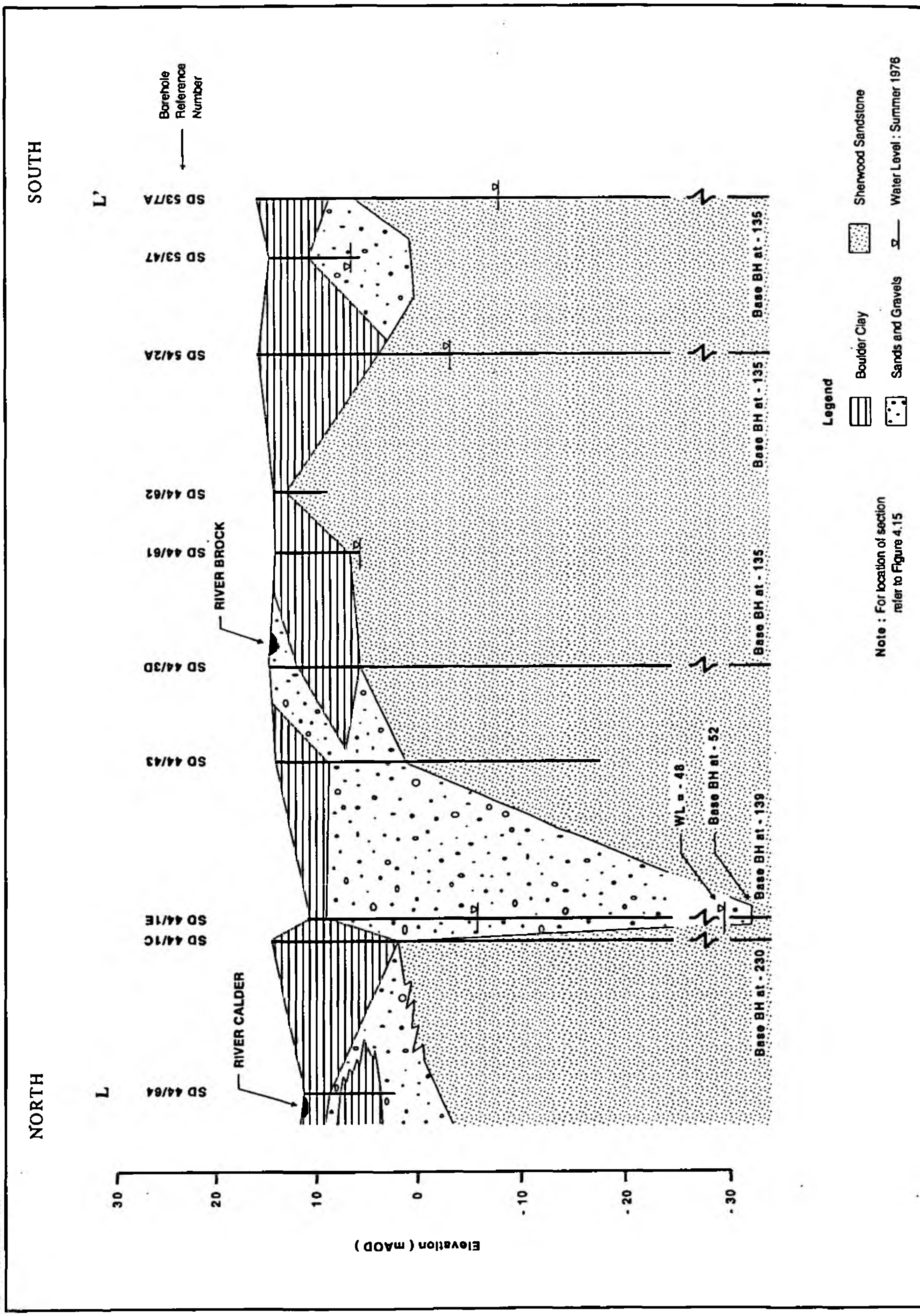


Cross Section along River Wyre (Section K K)

Figure 4.16

Figure 4.17

Cross Section :River Calder to River Brock (Section L L)



Q:\EWR\PROJECTS\384368.A01\FINAL\FIG4-18

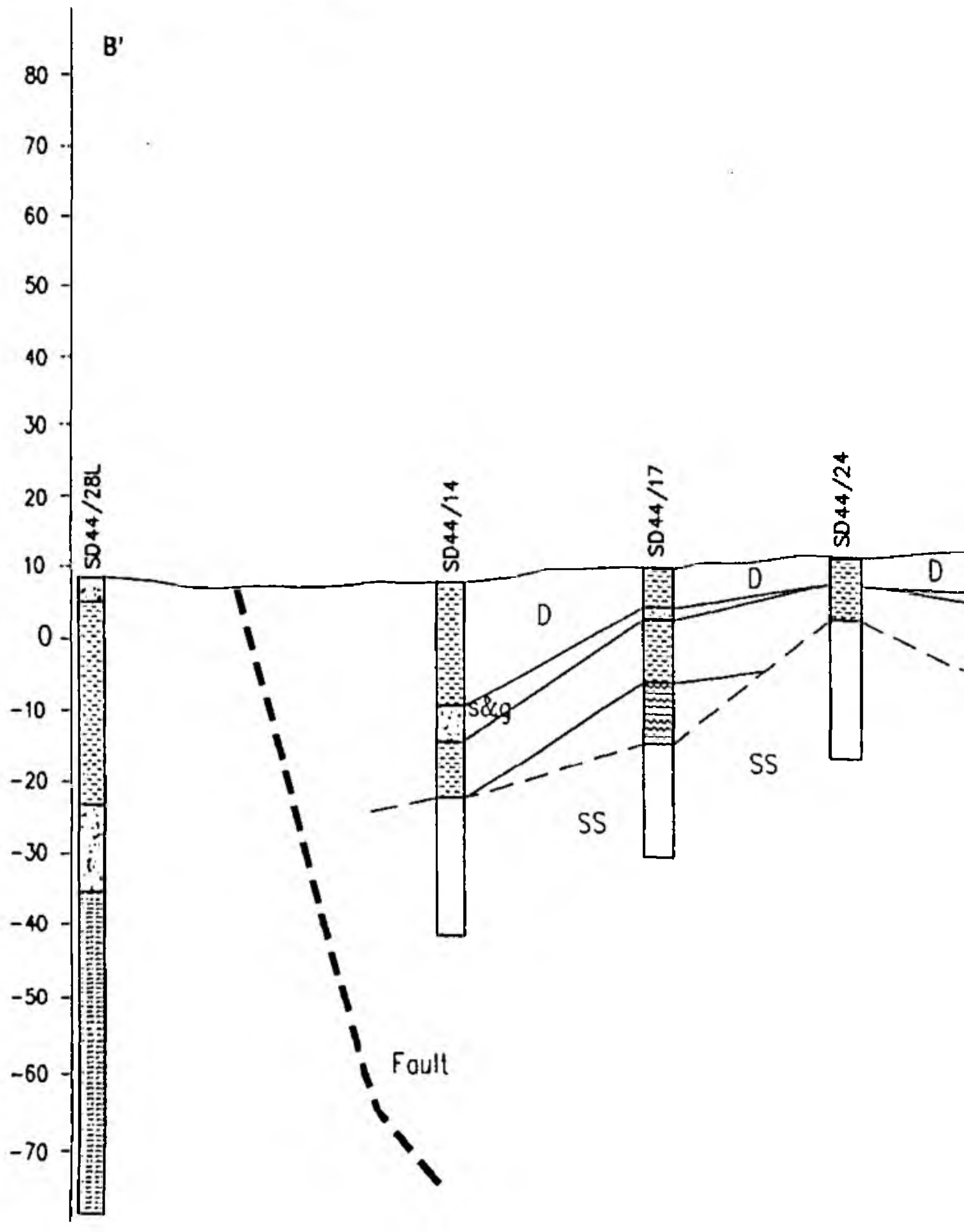


Figure 4.18

Cross Section along River Calder (Section BB')

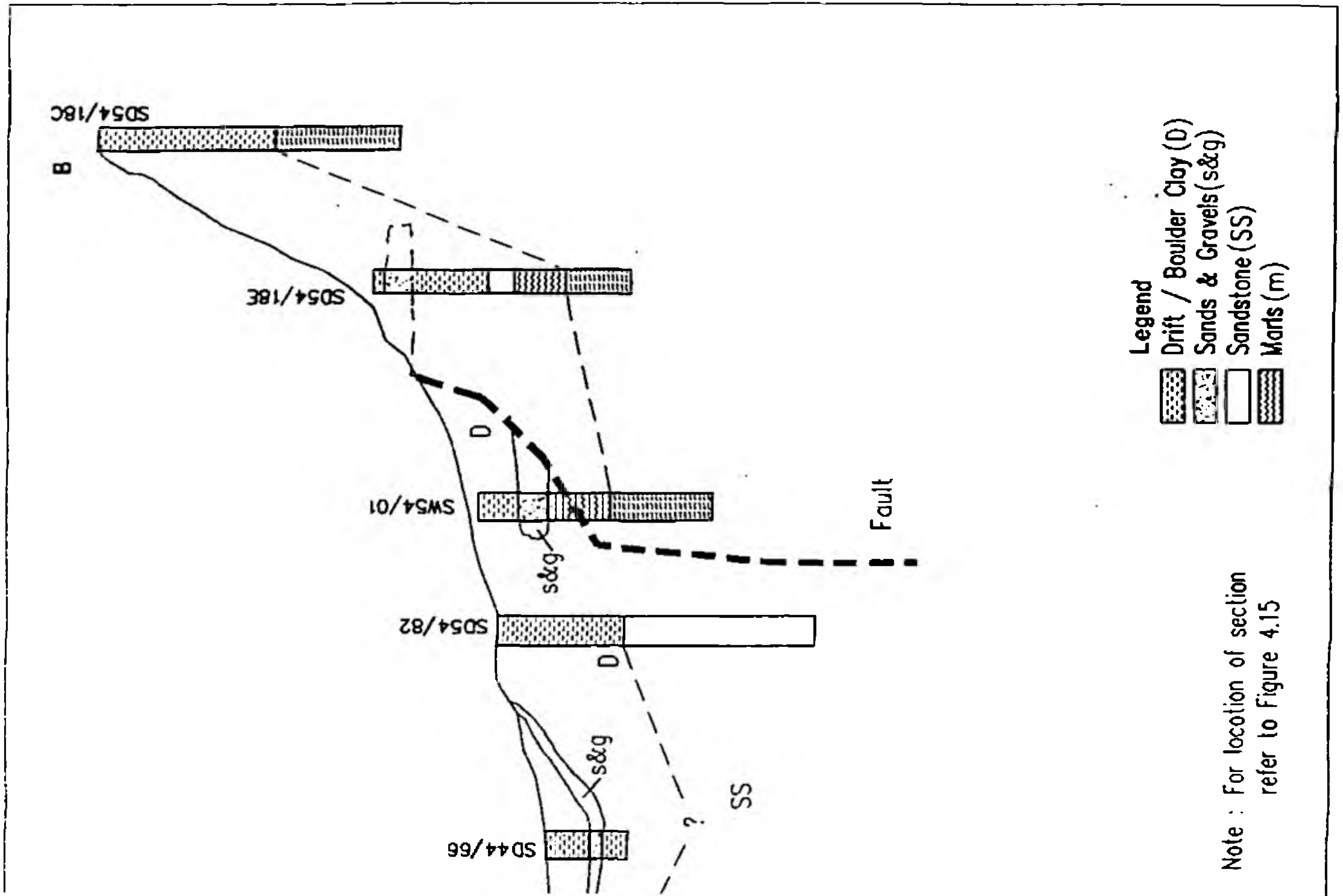
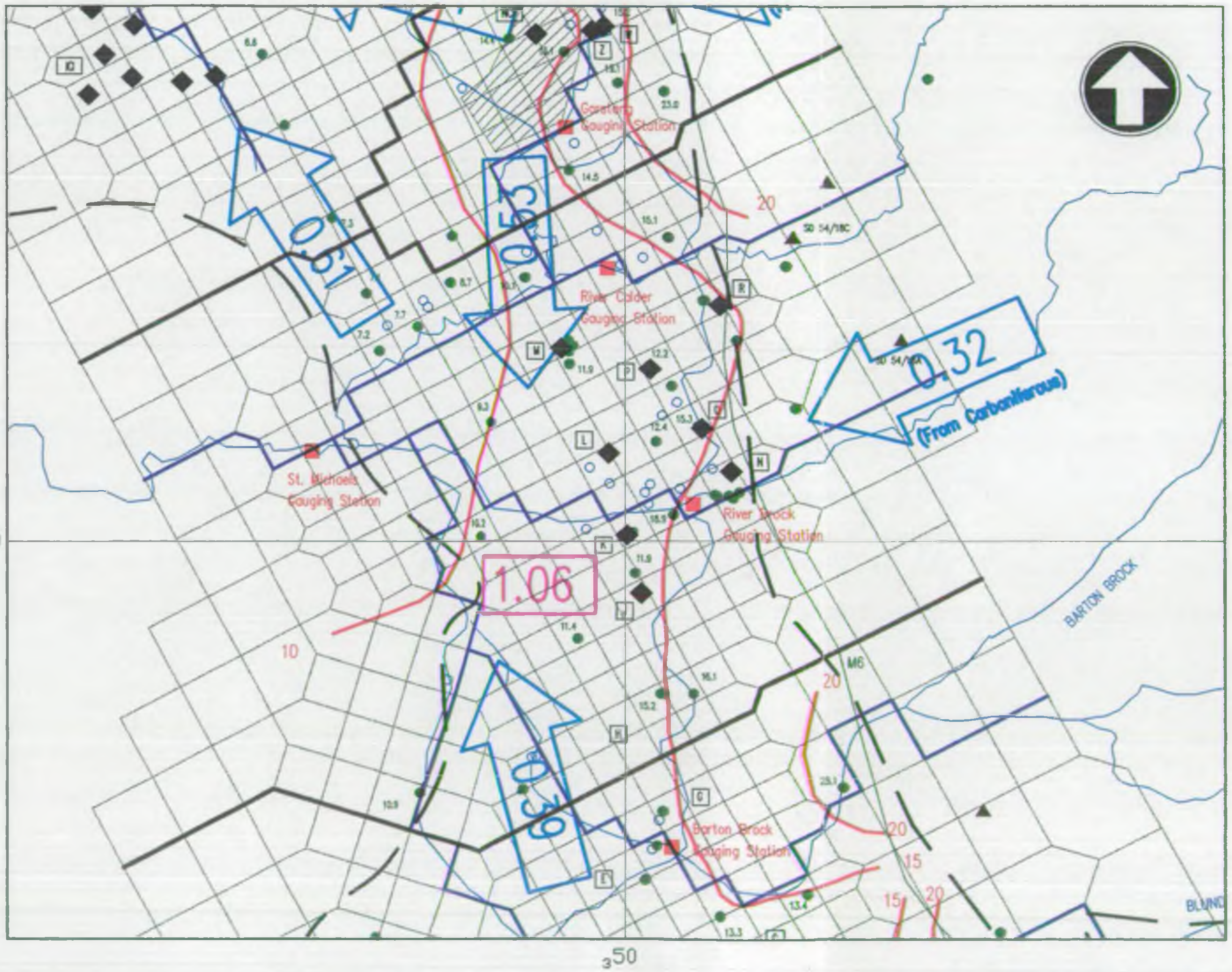


Figure 4.19

Central Area - Simulated Piezometry, April 1987



Legend

- Abstraction borehole
- River gauging station
- Edge of Fylde aquifer
- Major road

MODEL

- Model polygon
- Model river element
- Simulated limit of the area

OBSERVATION BOREHOLES (including reference numbers)

- Sandstone
- Sands & Gravels
- Carboniferous

GROUNDWATER LEVELS

- 1.3 Observed Sandstone water level (mOD)
- 10 Simulated Sandstone water level (mOD)

SIMULATED WATER BALANCE COMPONENTS

- 1.06 Total abstraction from area (Ml/d)
- 0.32 Flow between areas (Ml/d)
- 1.1 Loss from river (Ml/d)

0 1 2 3 4 5 km

Scale

17/02/97 Q:\EWR\PROJECTS\38436BA.01\ACAD\FINAL\FYL-03

Figure 4.20

Central Area · Simulated Piezometry, September 1995

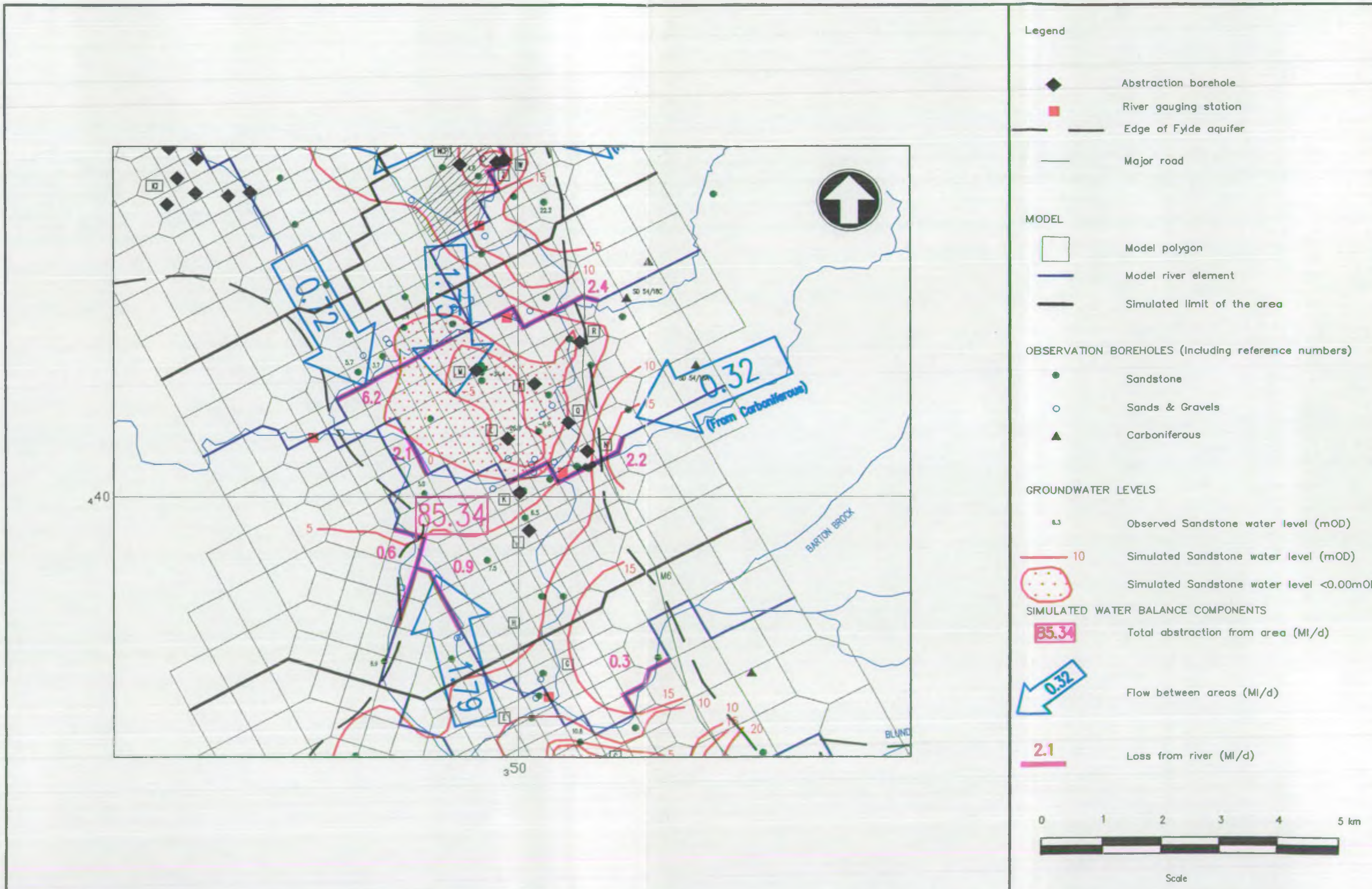


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Figure 4.21A

Cental Fylde: Simulated Leakage to Sandstone

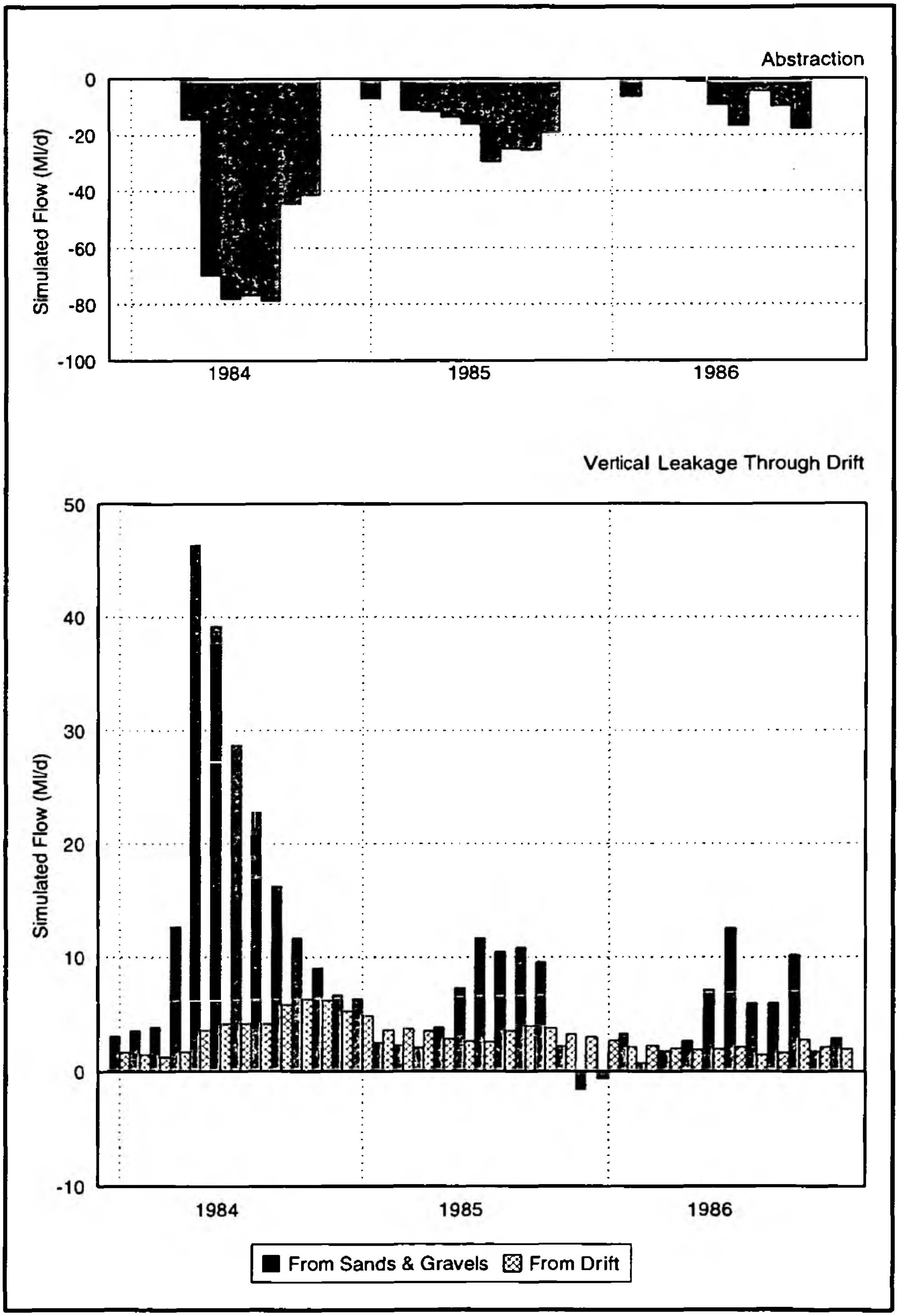


Figure 4.21B

Cental Fylde: Simulated Storage Changes

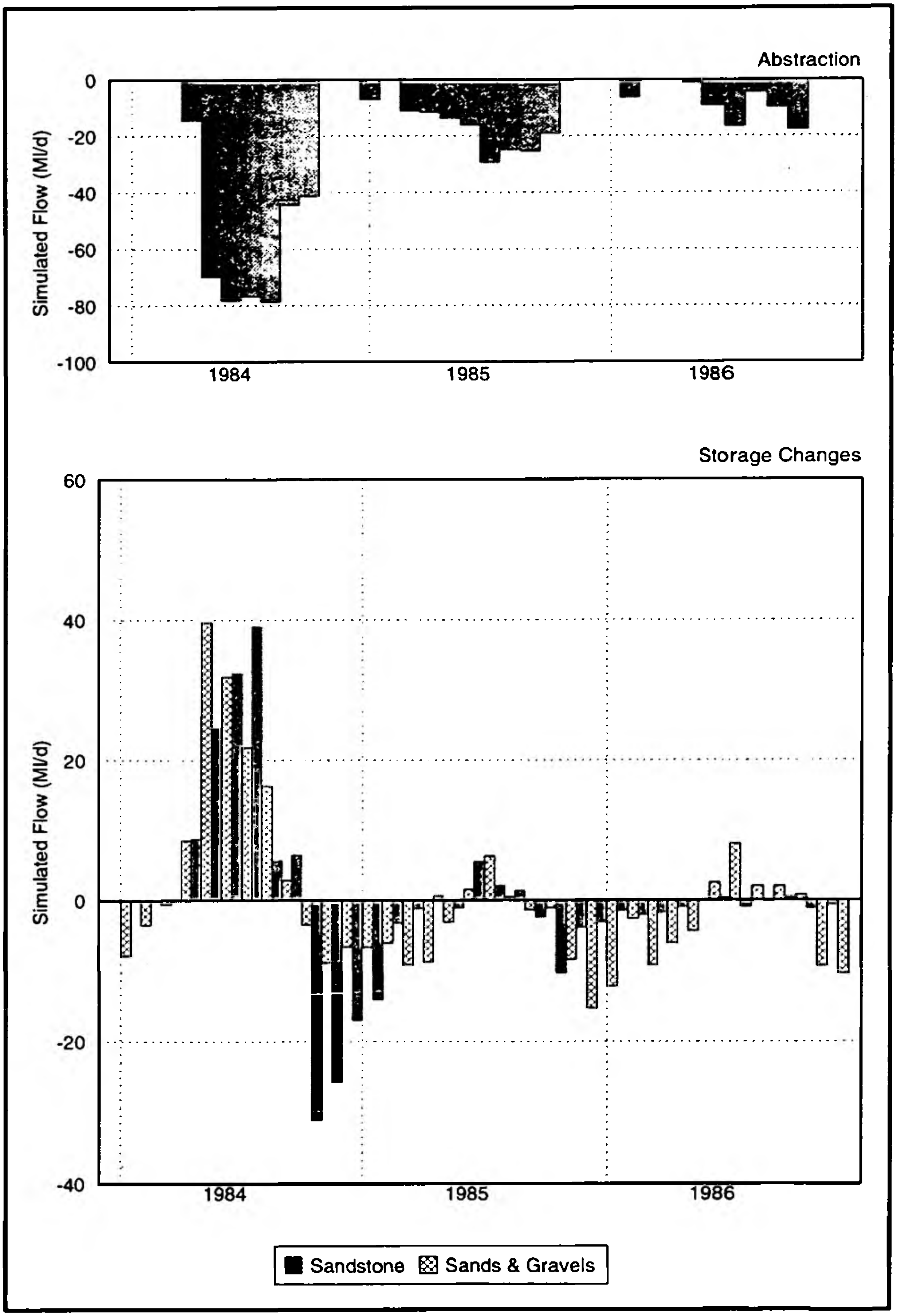
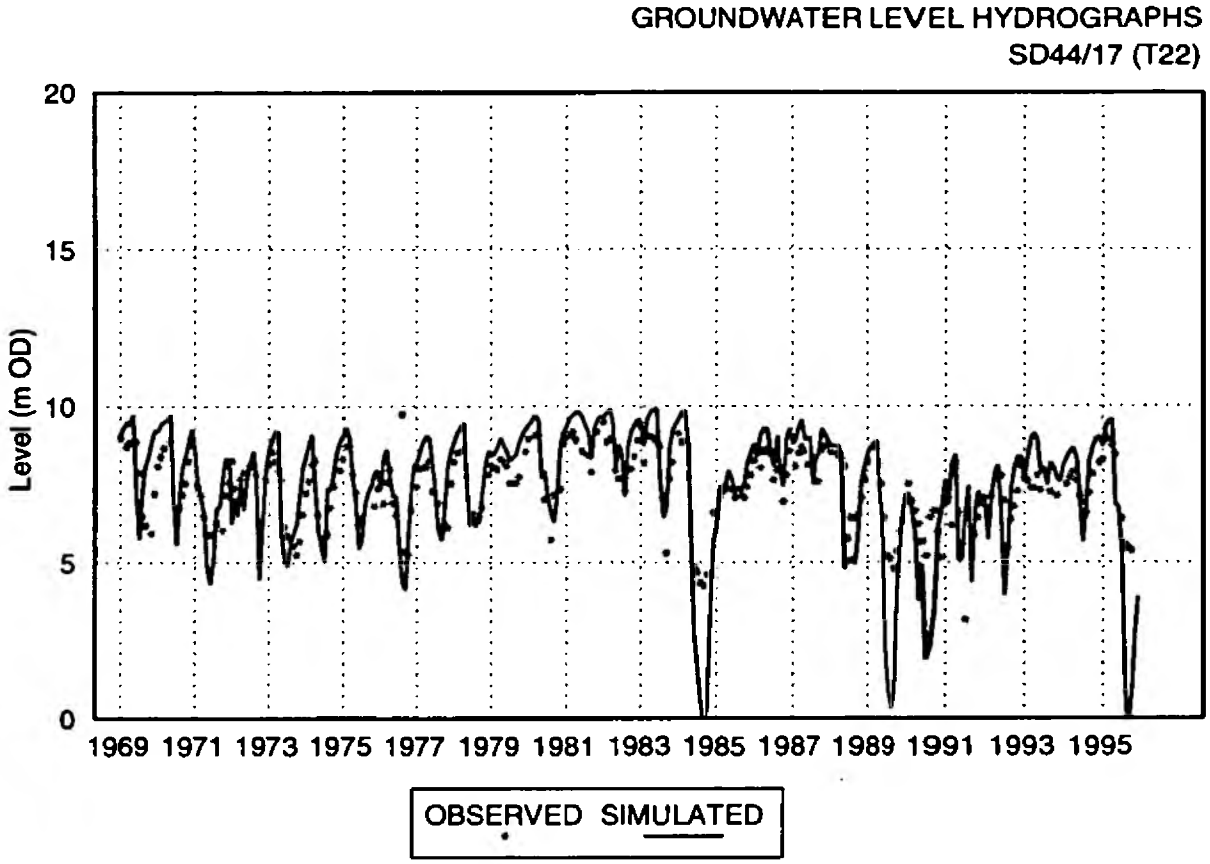


Figure 4.22
Central Area: Simulated Groundwater Level Hydrographs I



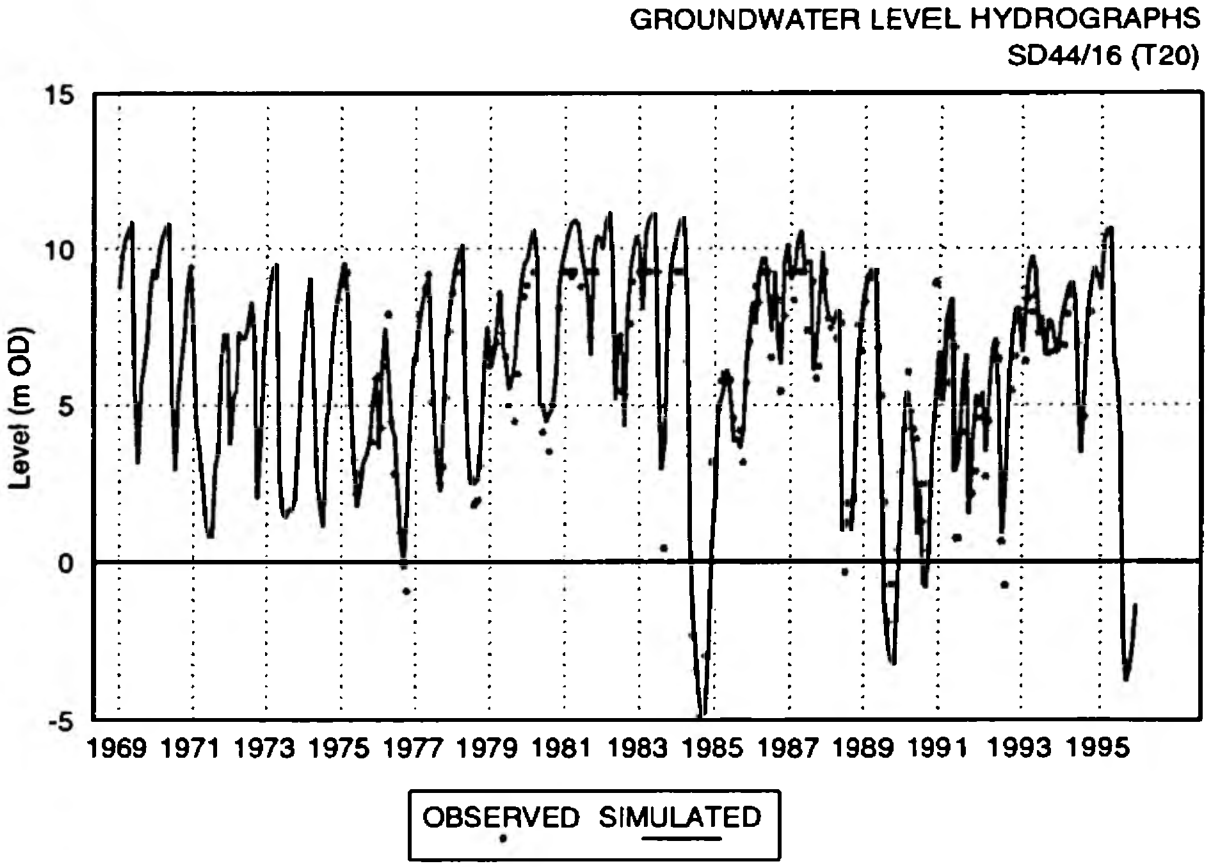


Figure 4.23

Central Area: Simulated Groundwater Level Hydrographs II

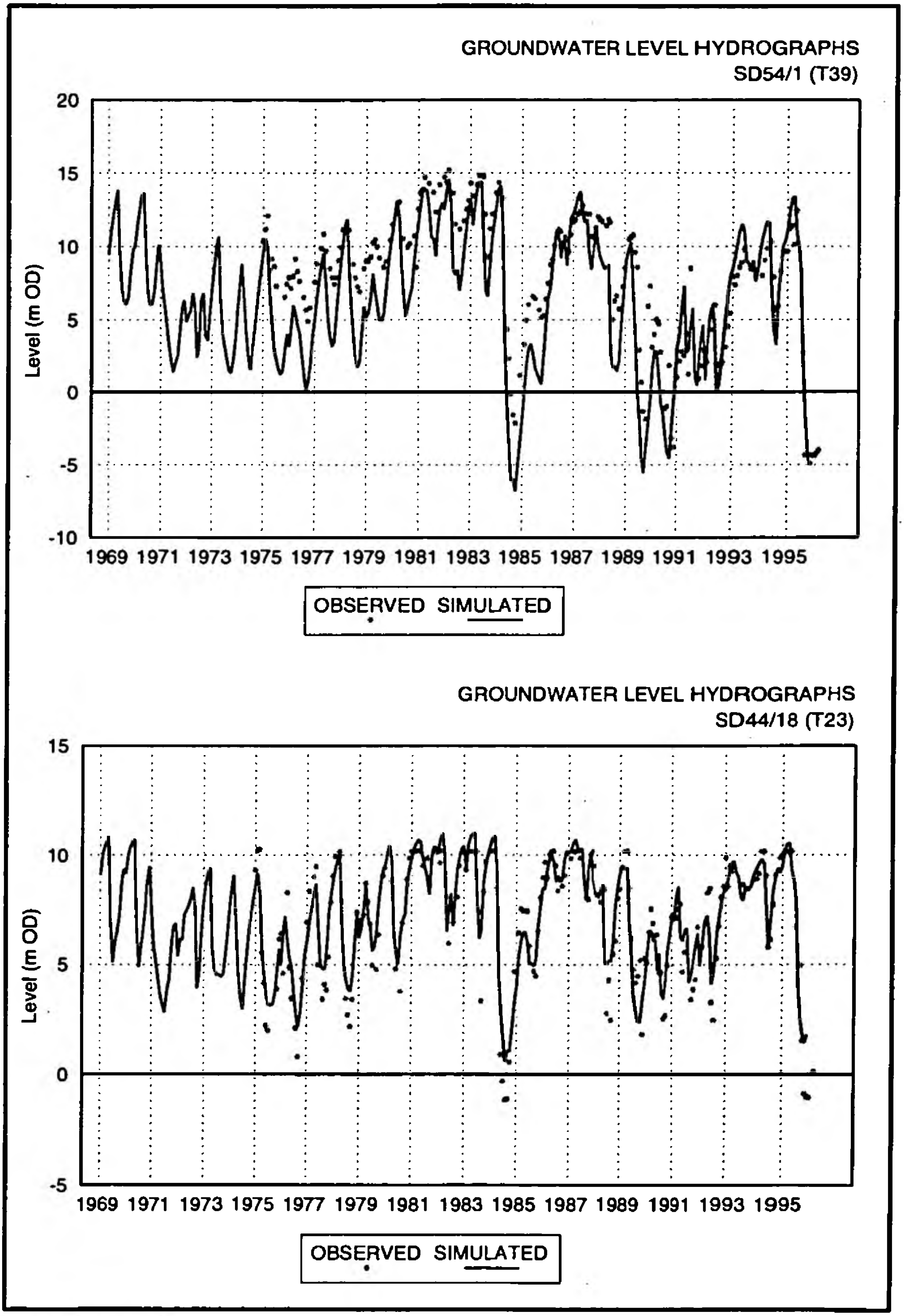
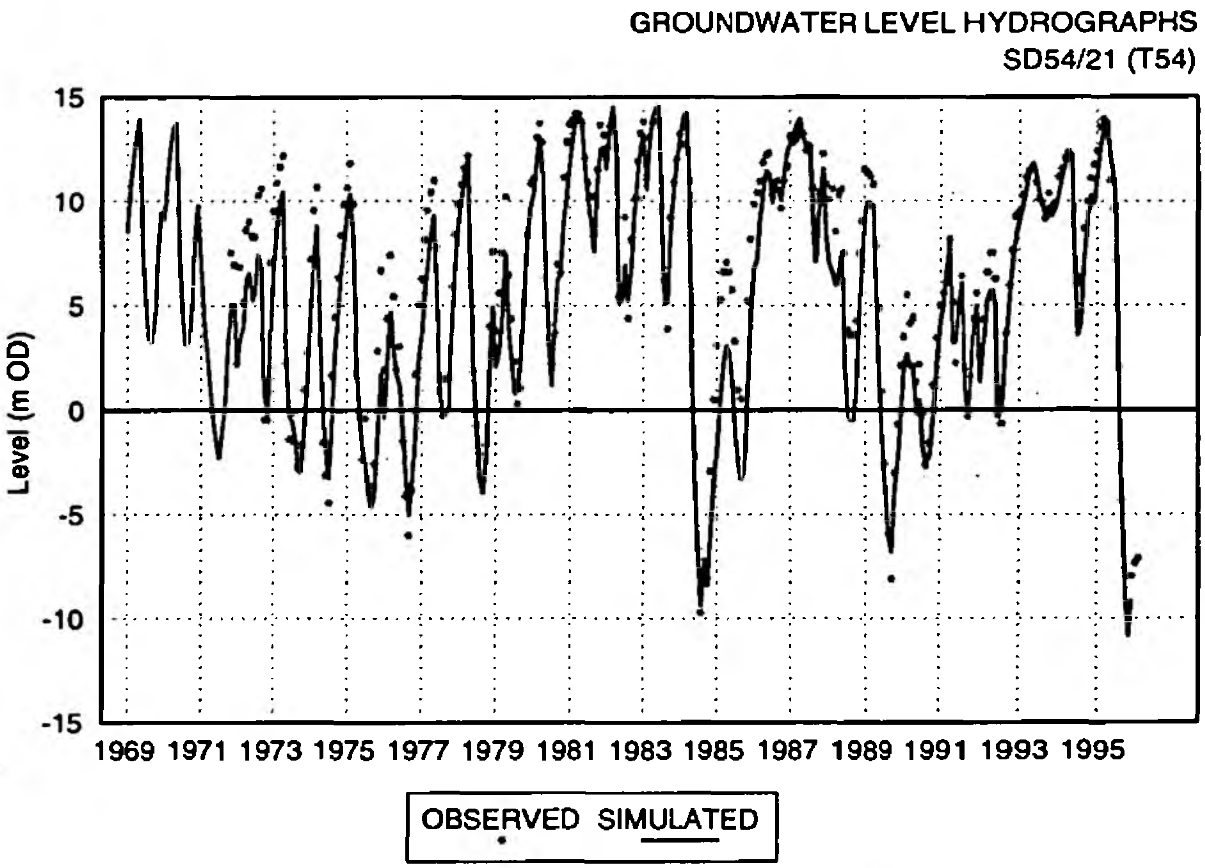


Figure 4.24

Central Area: Simulated Groundwater Level Hydrographs III



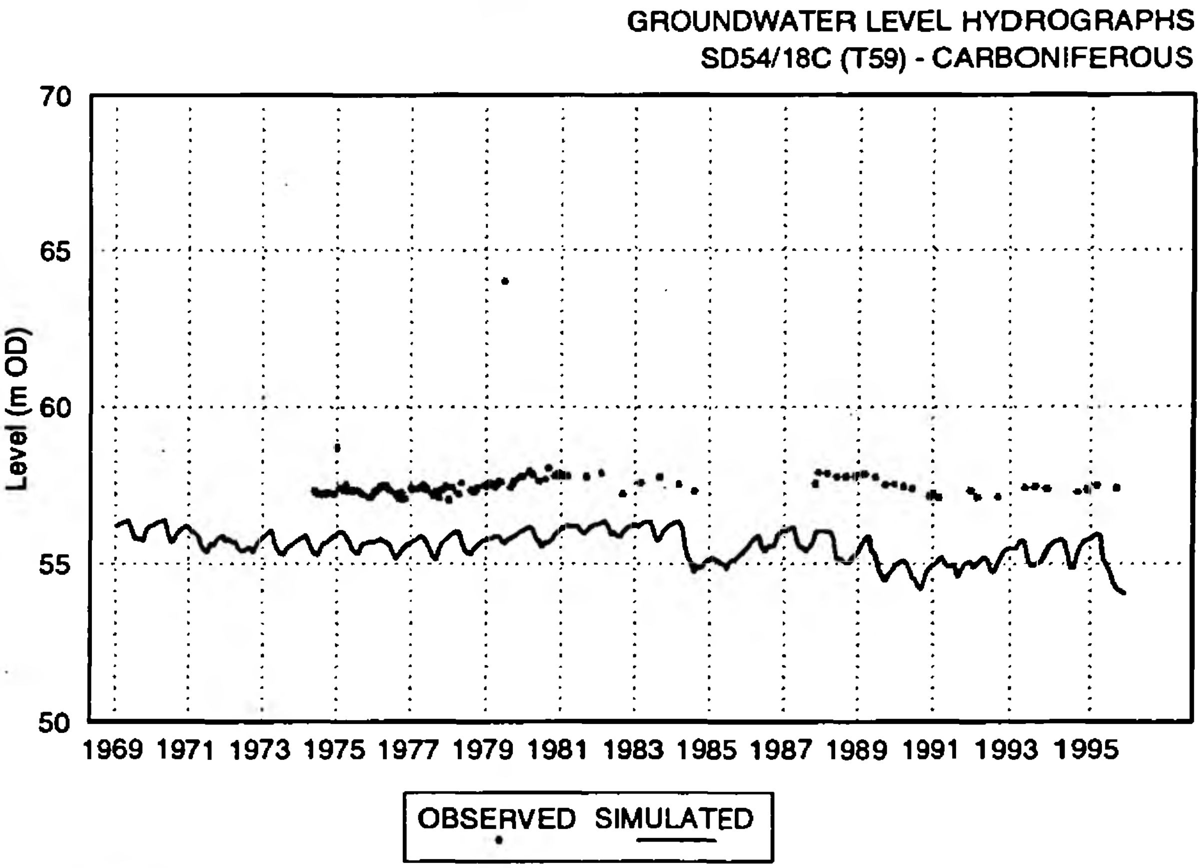


Figure 4.25

Simulated Sands & Gravels Groundwater Levels (Central Area)

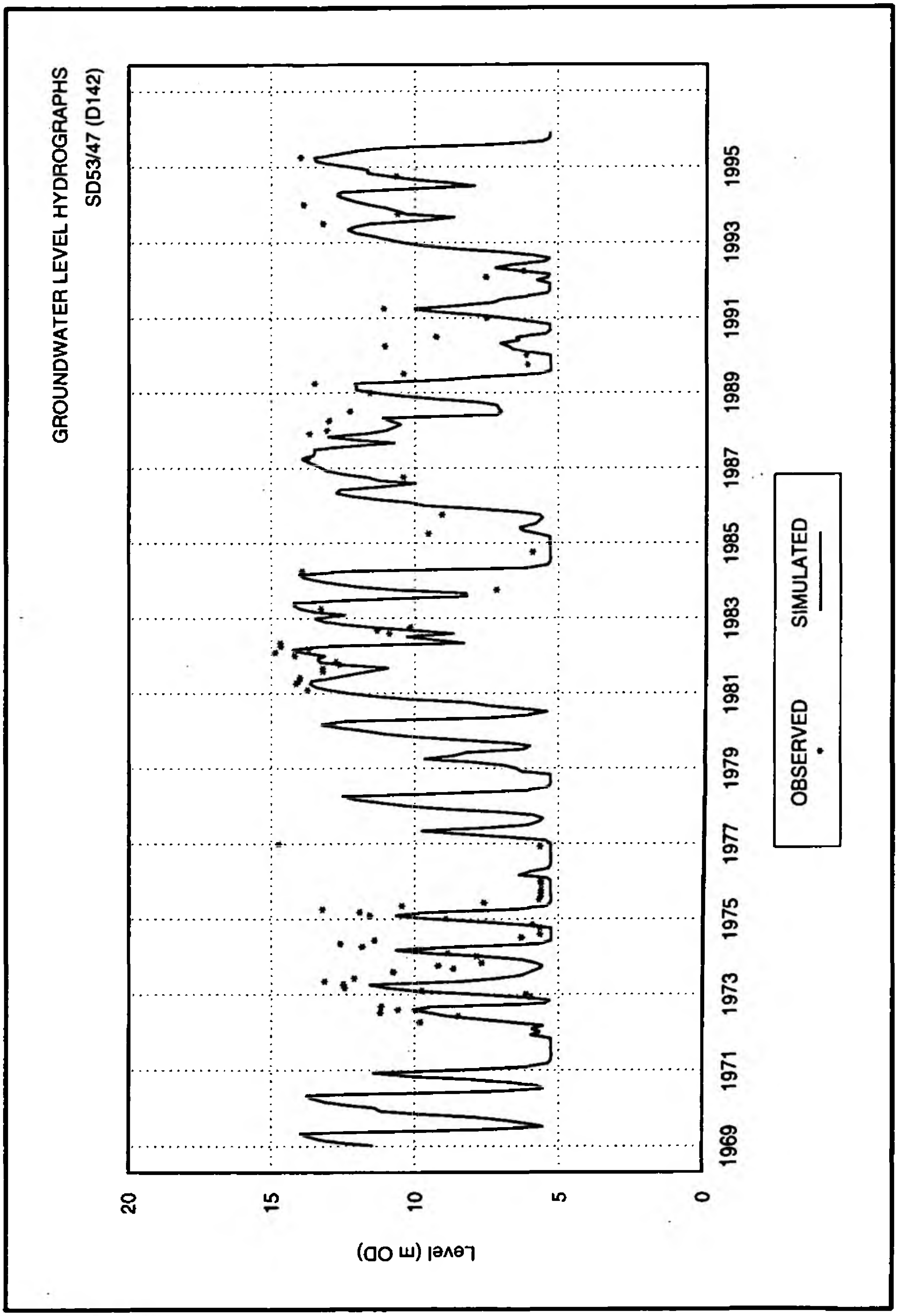


Figure 4.26

Simulated River Flow Hydrographs

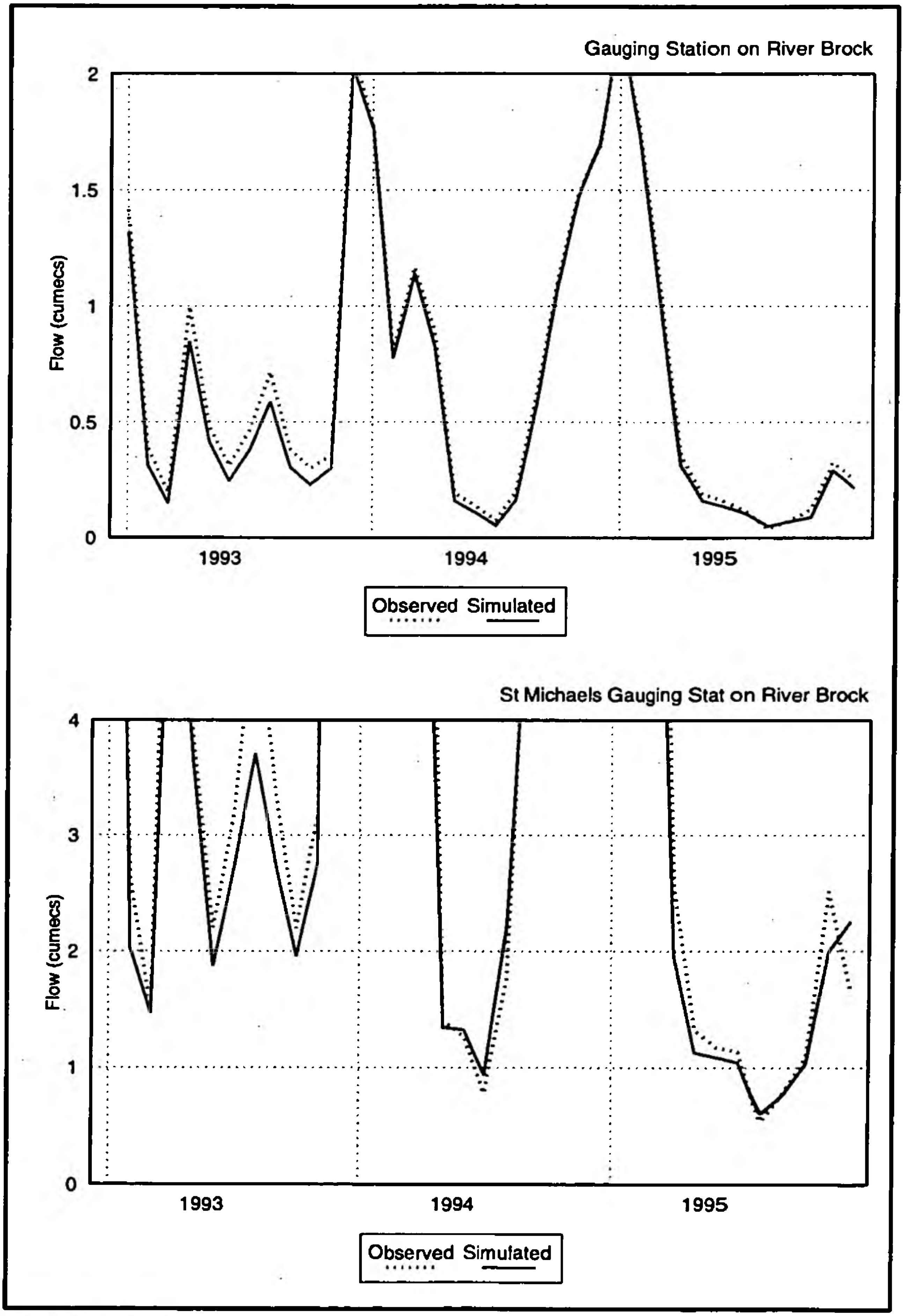


Figure 4.27

Simulated and Observed River Flow Losses (Central Area)

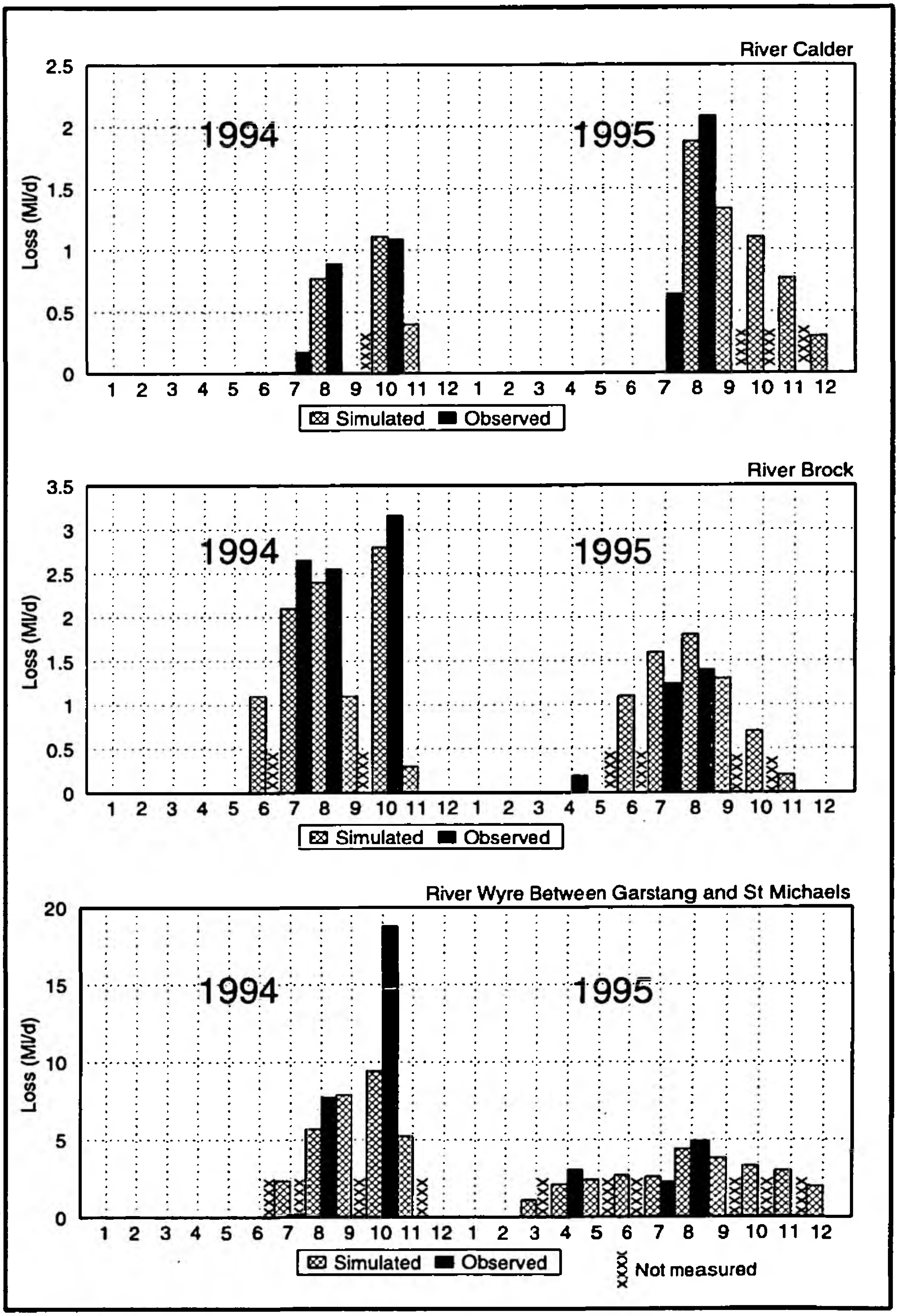
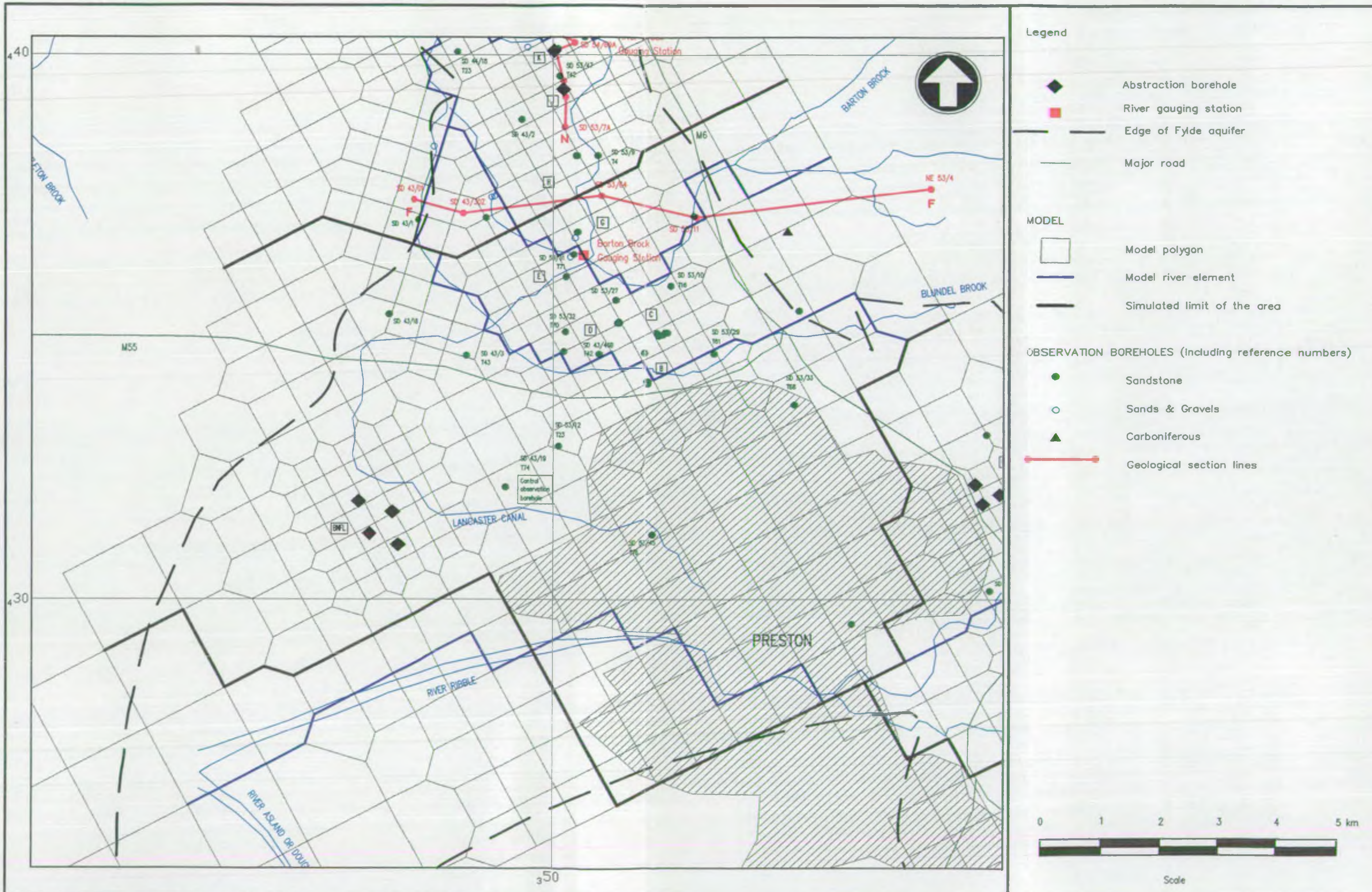


Figure 4.28

Preston and South Fylde - Location Map



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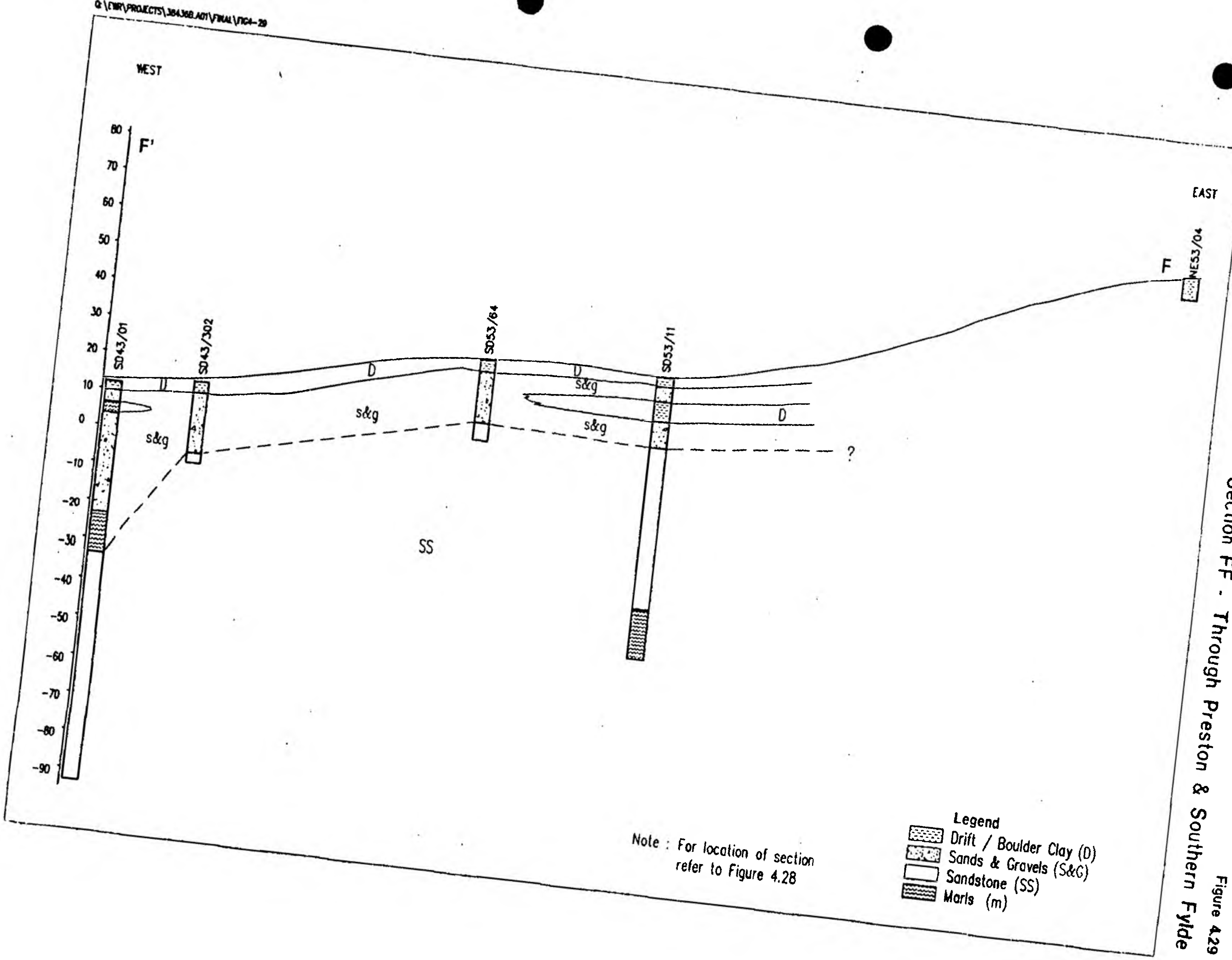


Section FF - Through Preston & Southern Fylde

Figure 4.29

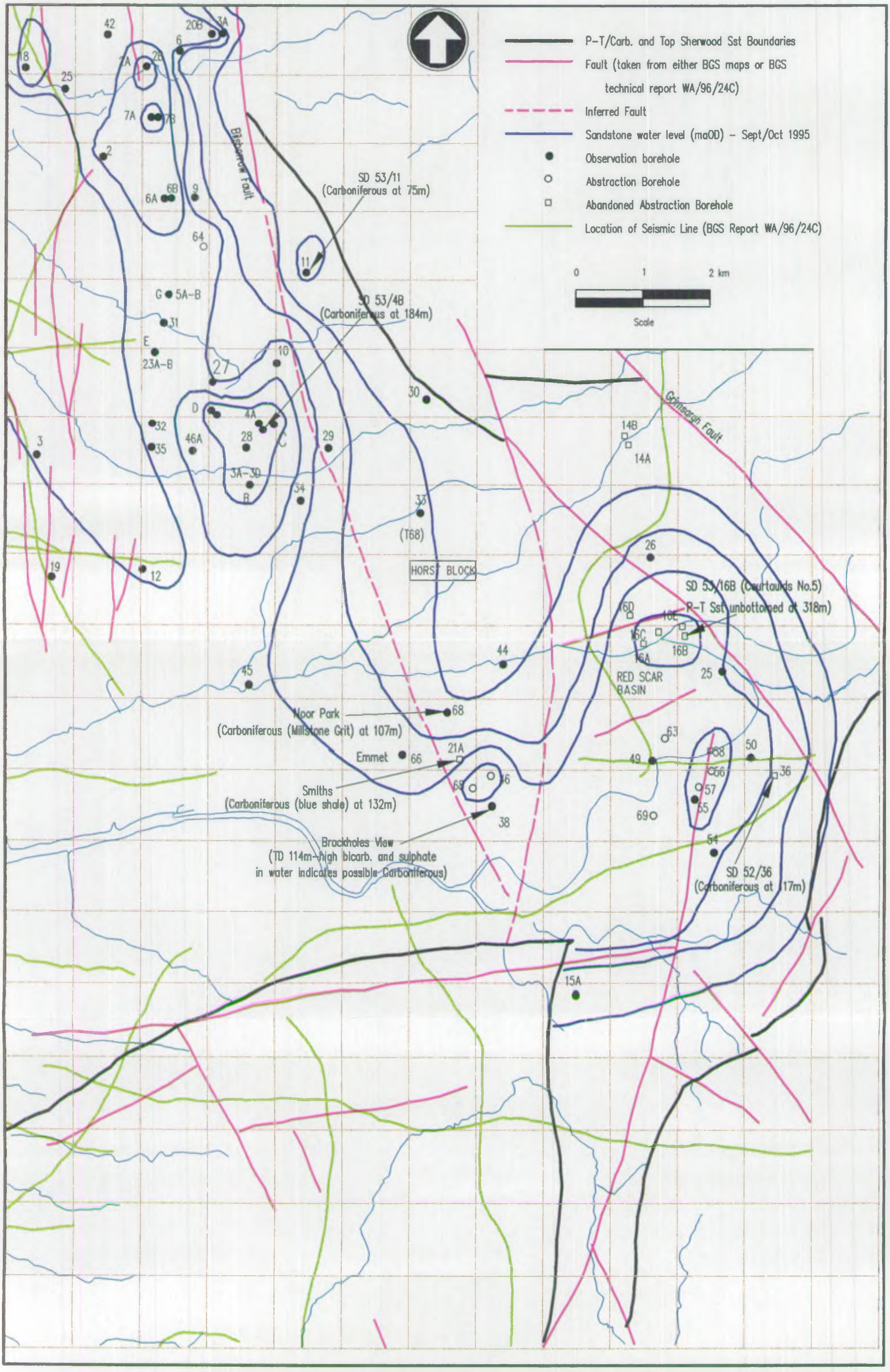


Figure 4.28A

Revised Geological Structure - Southern Flyde

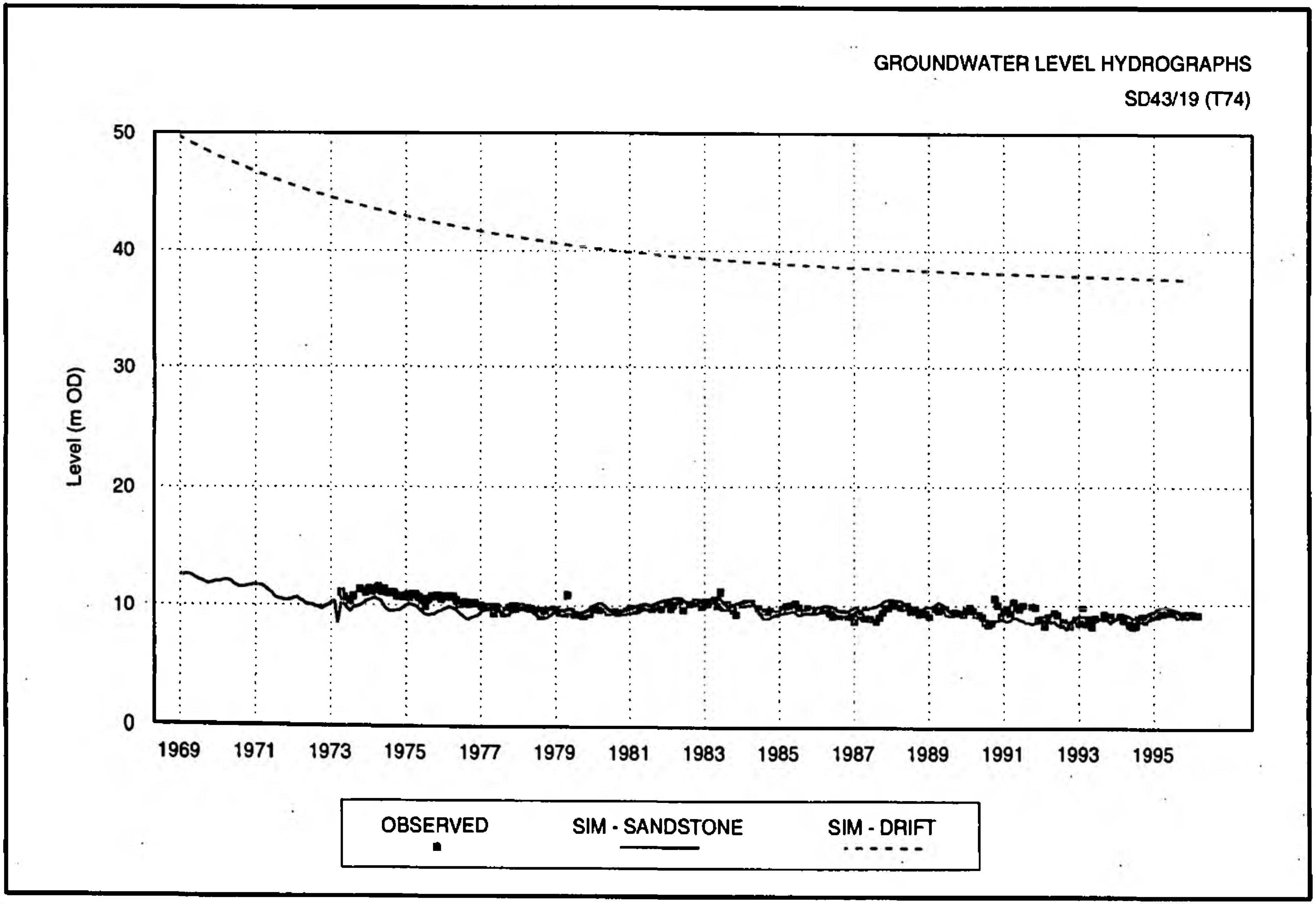
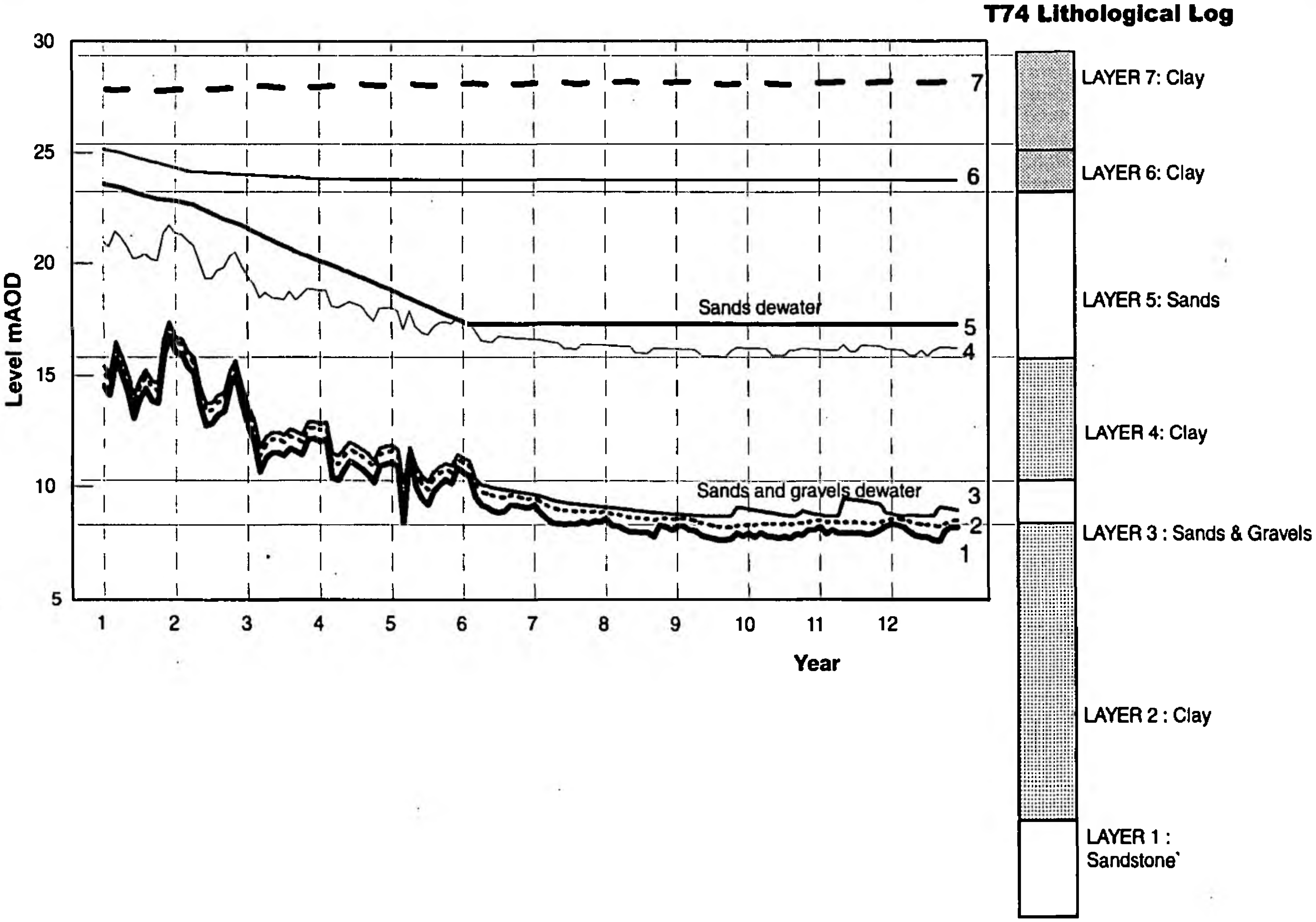


Figure 4.30

Simulation of Water Level Decline SW of Woodplumpton Brook



Increased vertical permeabilities compared with Regional Model

Figure 4.30A
Detailed Modelling at T74

Figure 4.31

Preston and South Fylde - Simulated Piezometry, April 1987

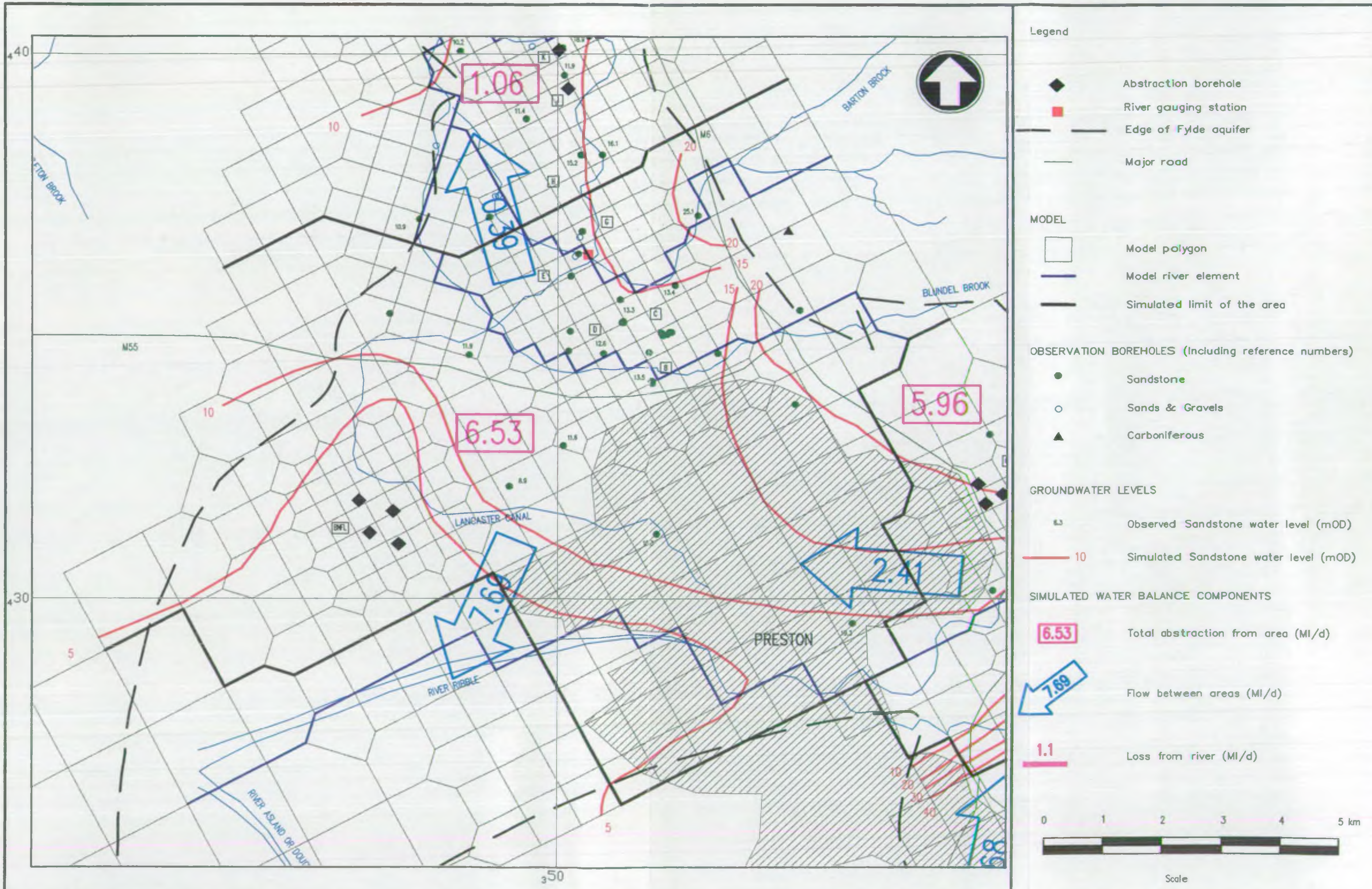


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Figure 4.32

Preston and South Fylde · Simulated Piezometry, September 1995

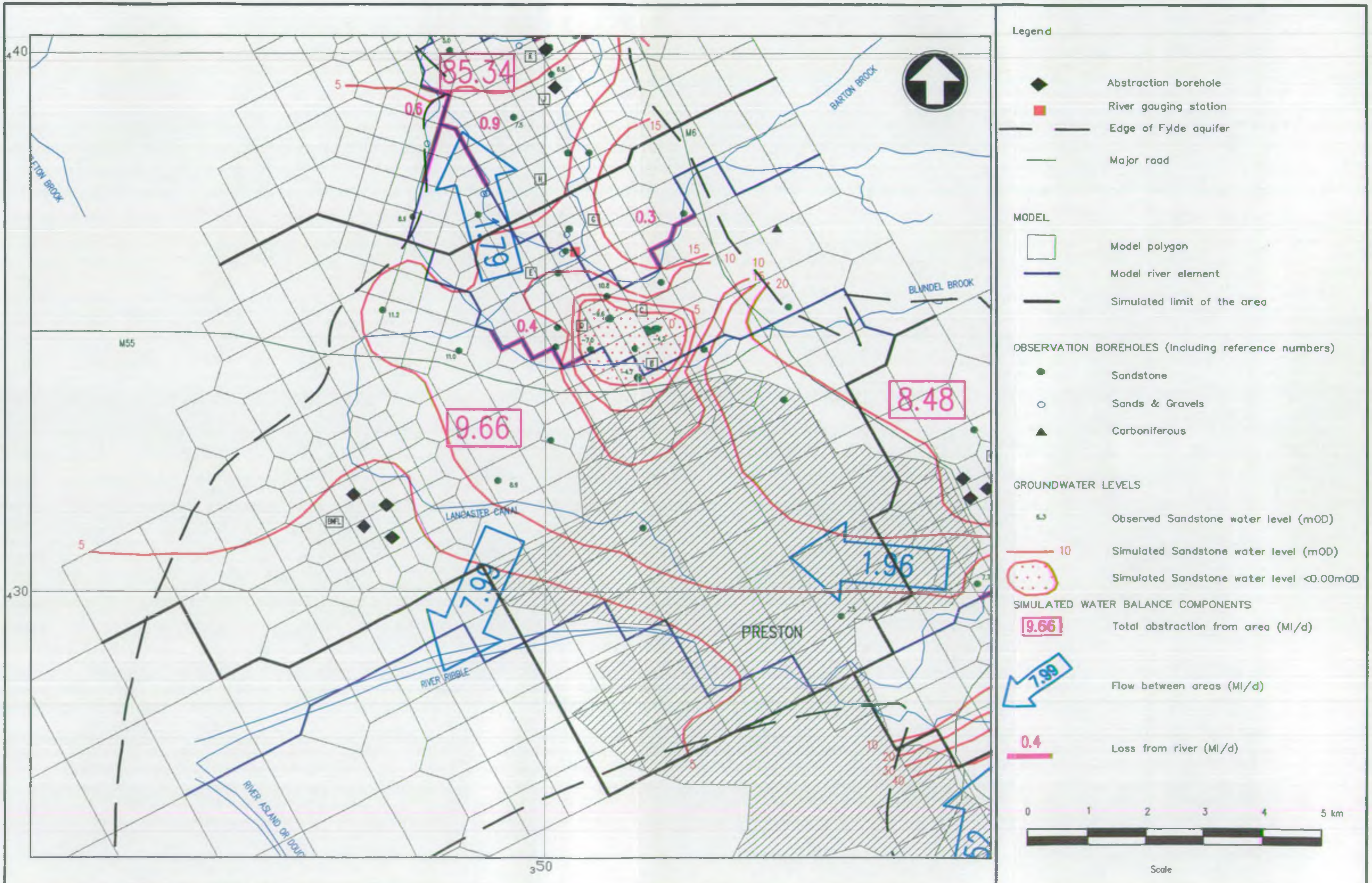

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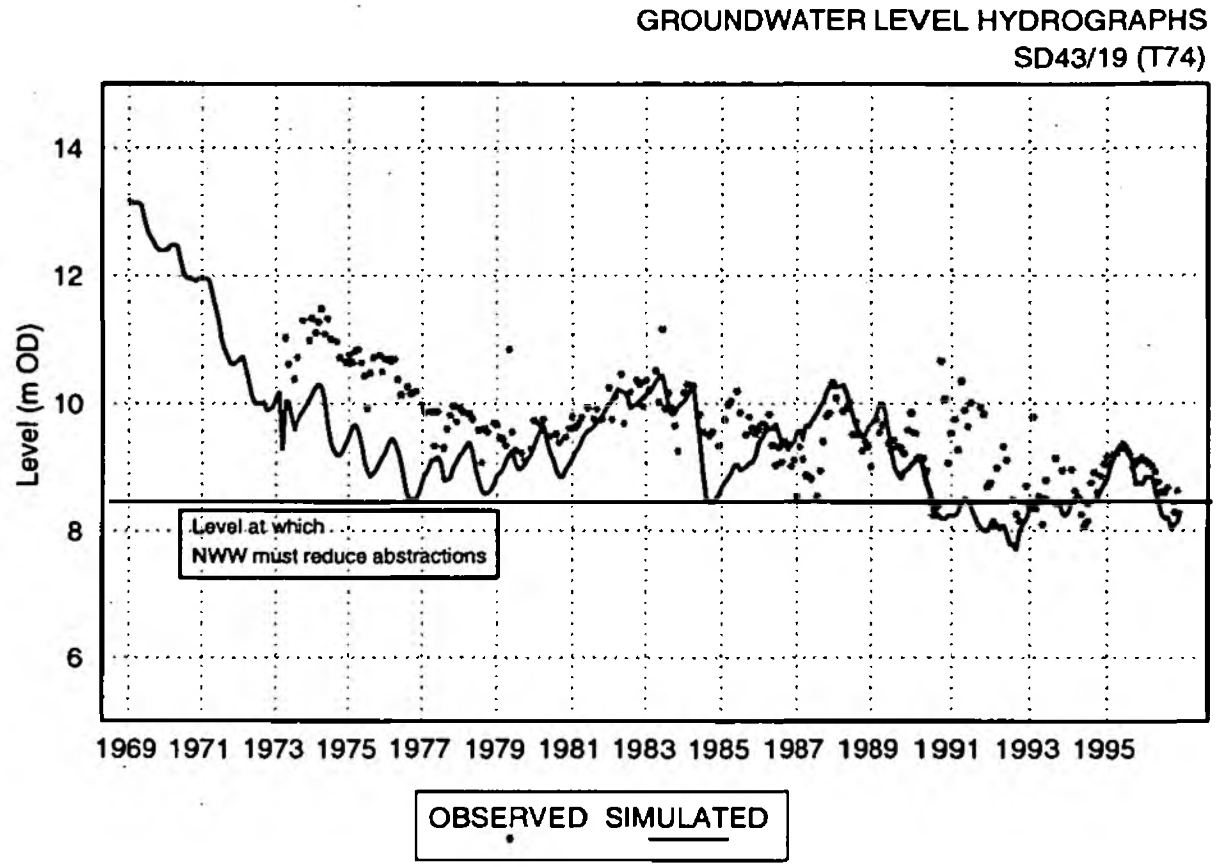
Figure 4.33

South and Preston Area: Simulated Groundwater Level Hydrographs I



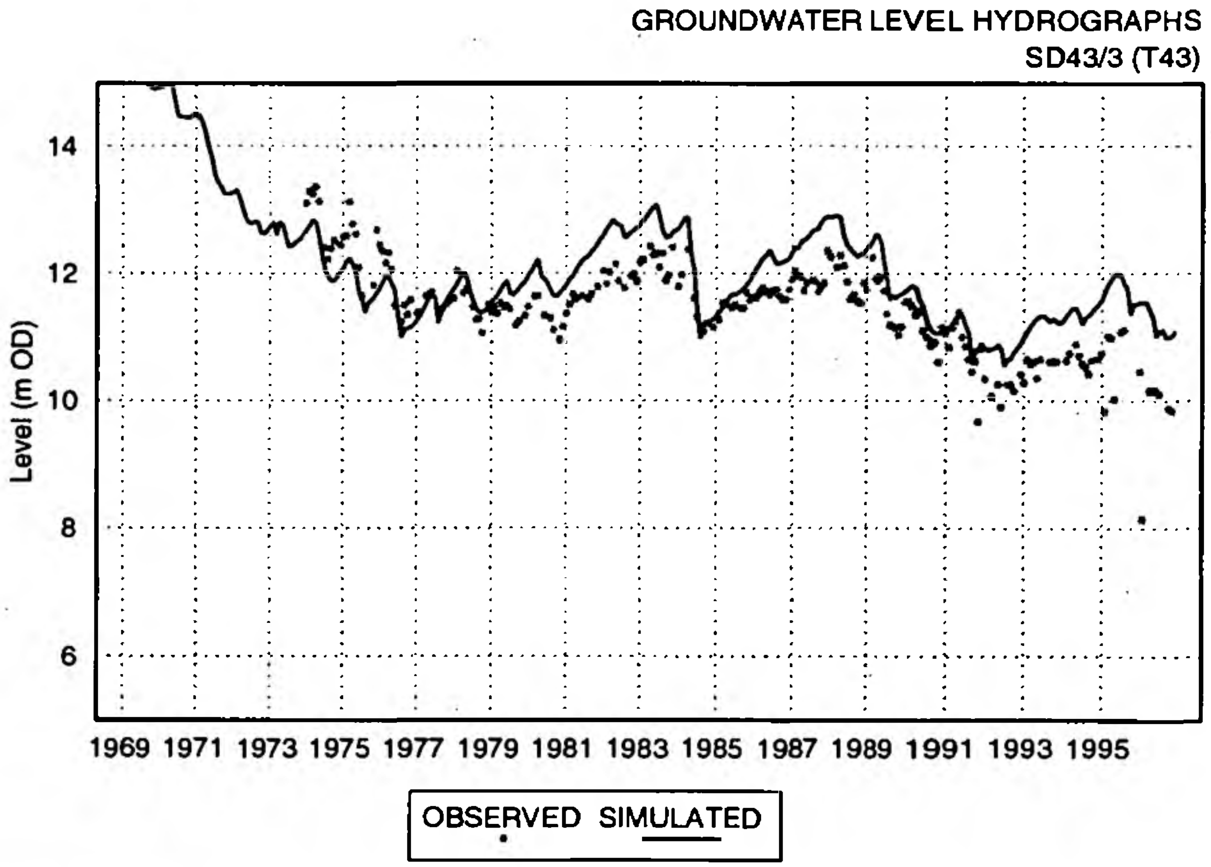


Figure 4.34

South and Preston Area: Simulated Groundwater Level Hydrographs II

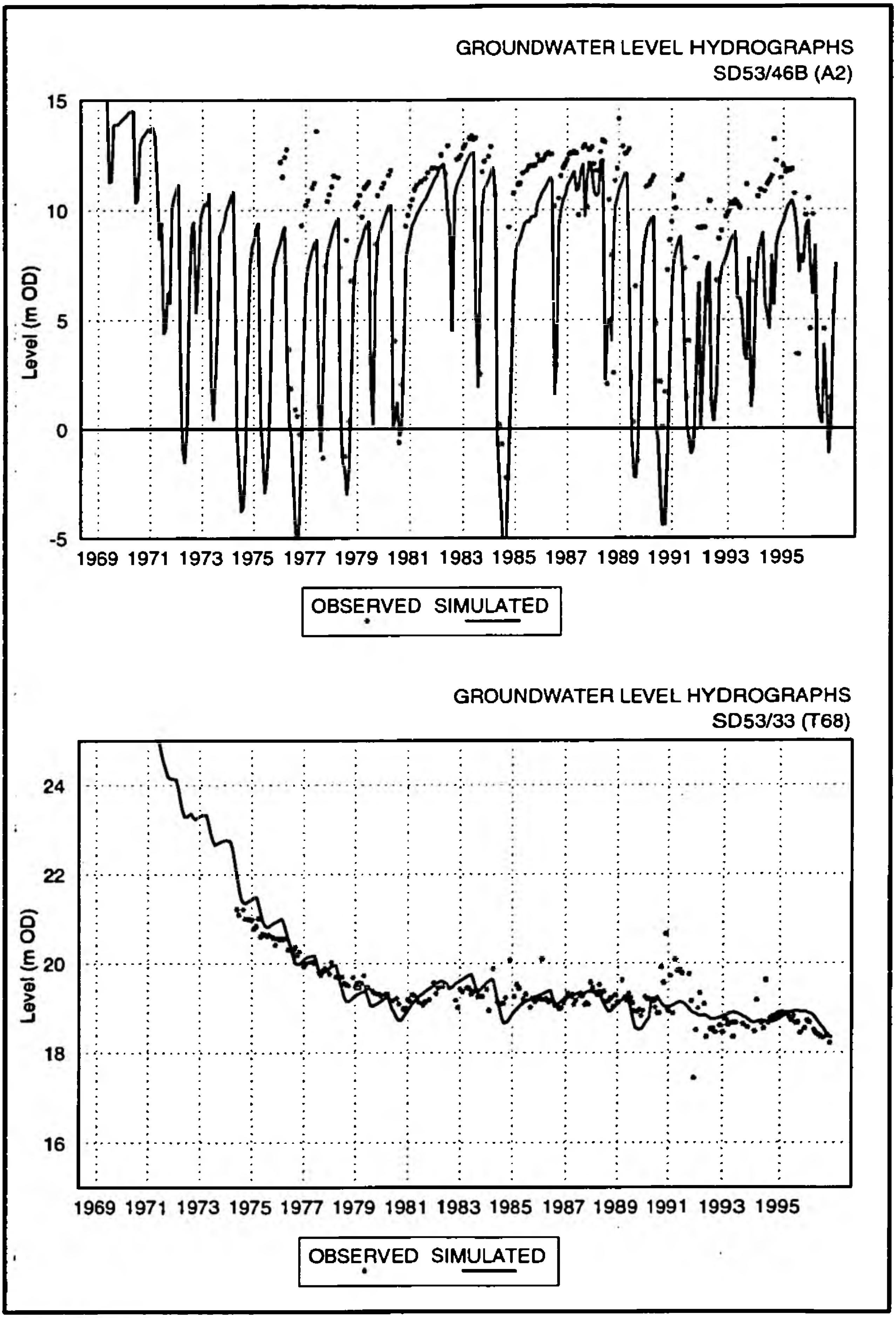


Figure 4.34A

South and Preston Area: Hydrograph at Brockholes View (SD52/38)

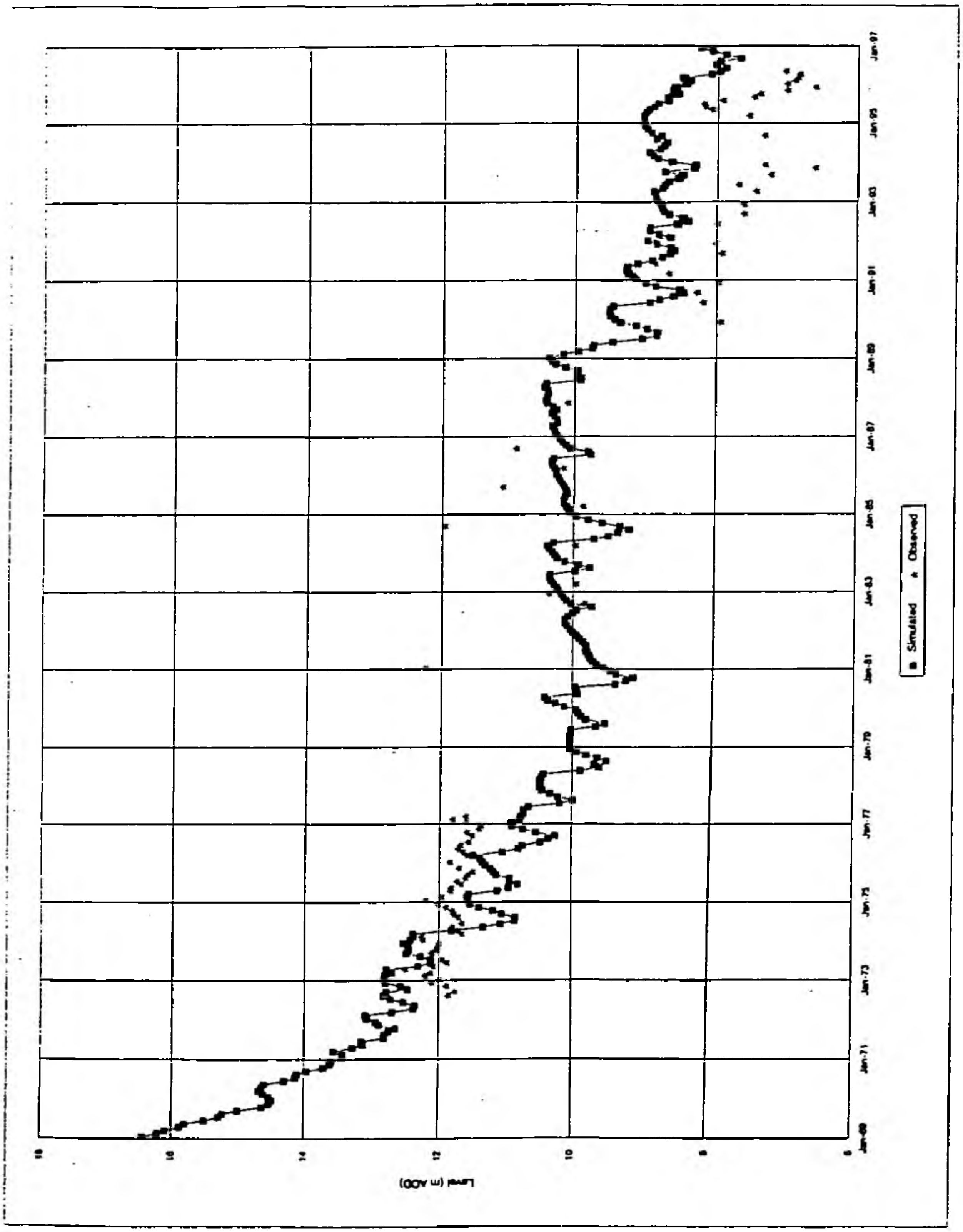


Figure 4.35

Simulated and Observed River Flows at Barton Brook Gauging Station

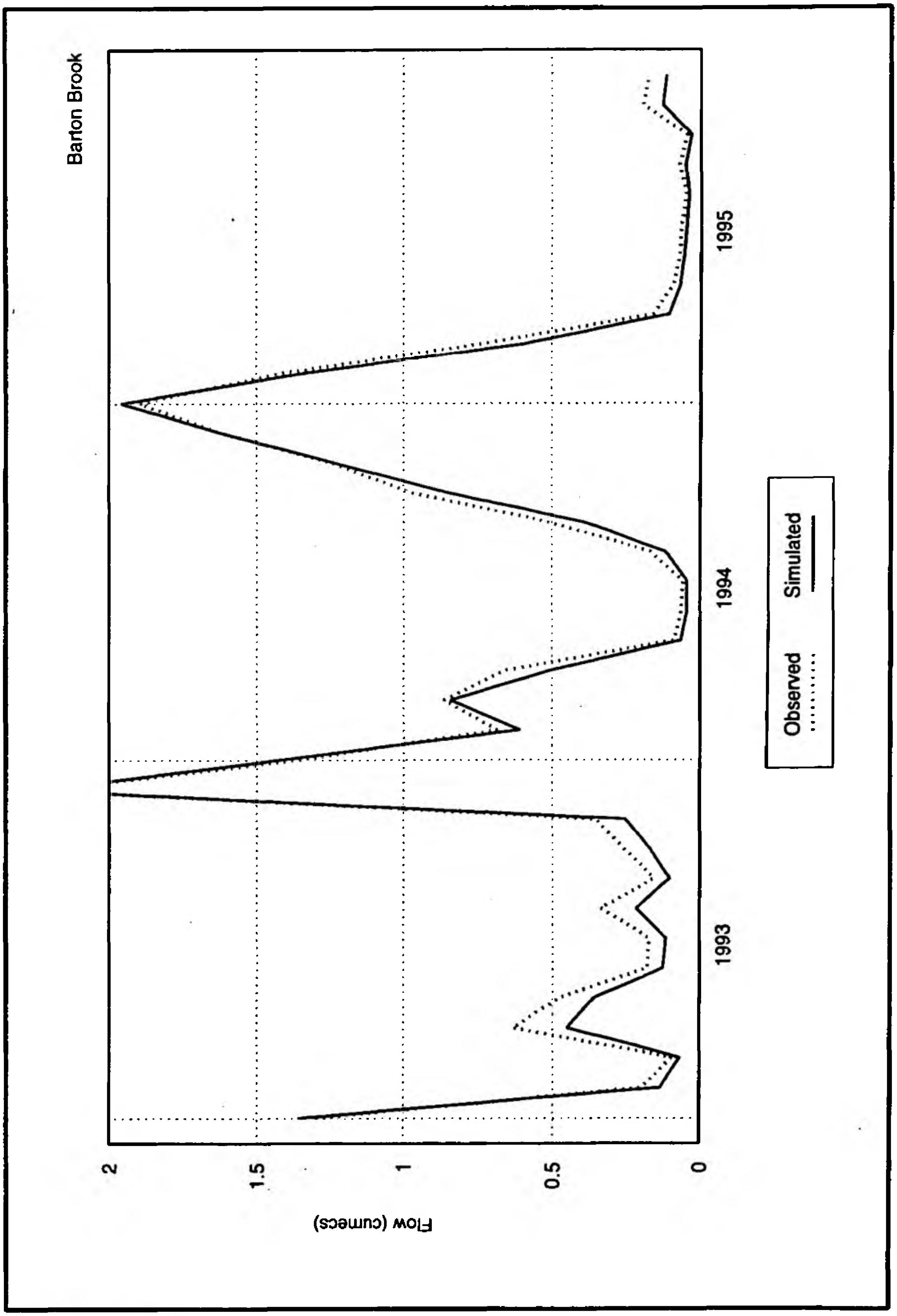


Figure 4.36
Losses Simulated from Barton and Woodplumpton Brooks

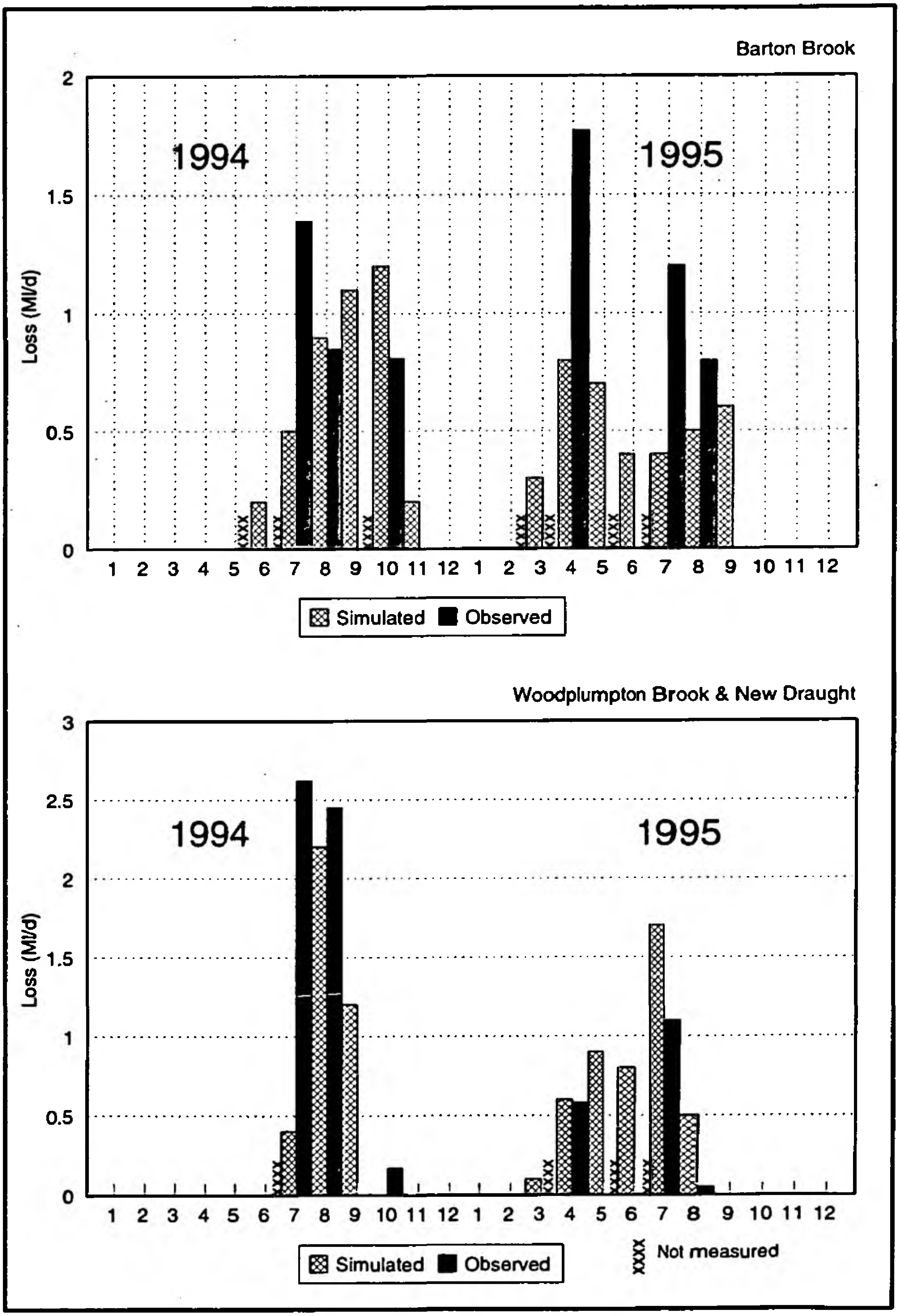
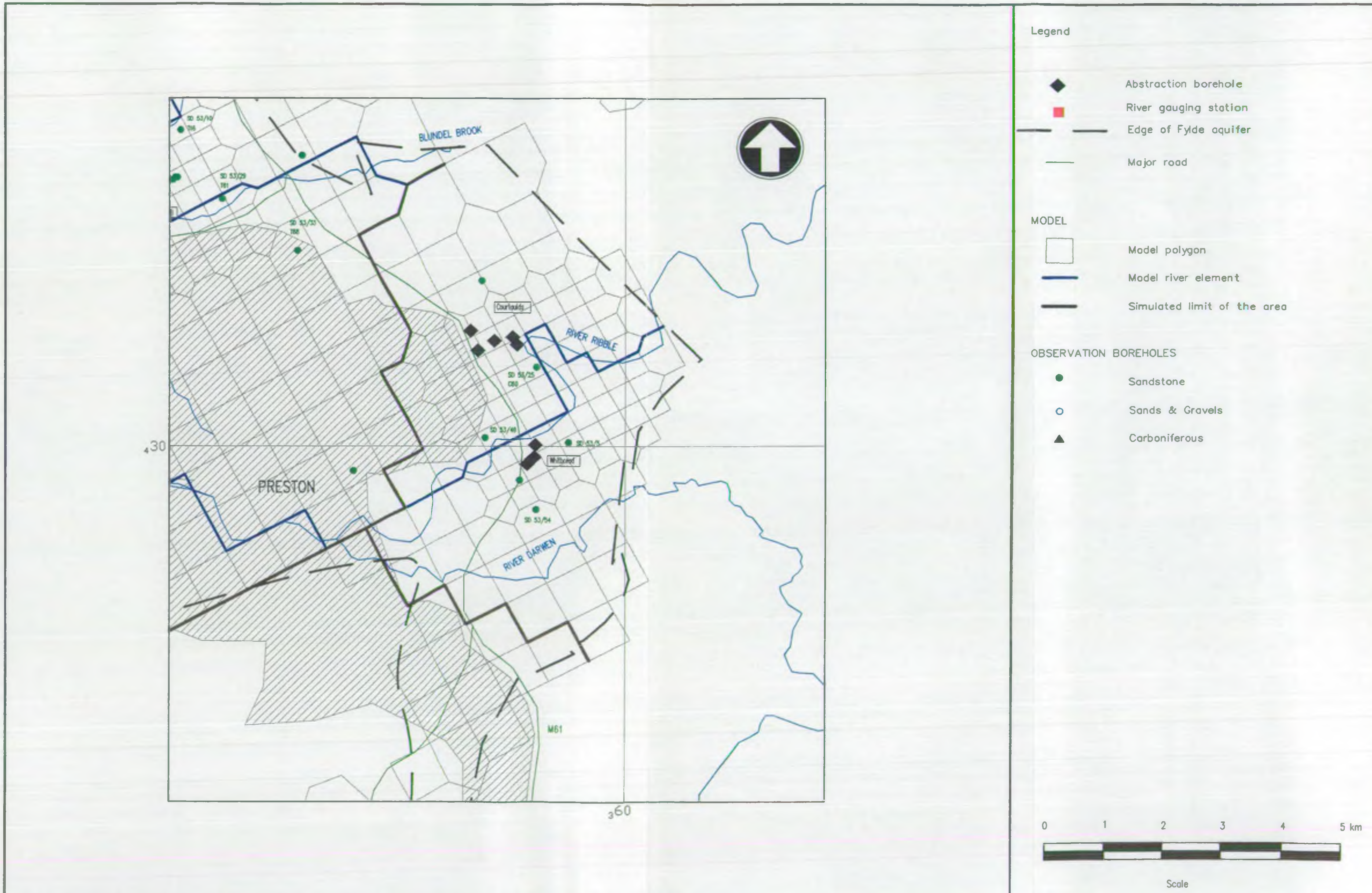


Figure 4.37

South East Fylde - Location Map



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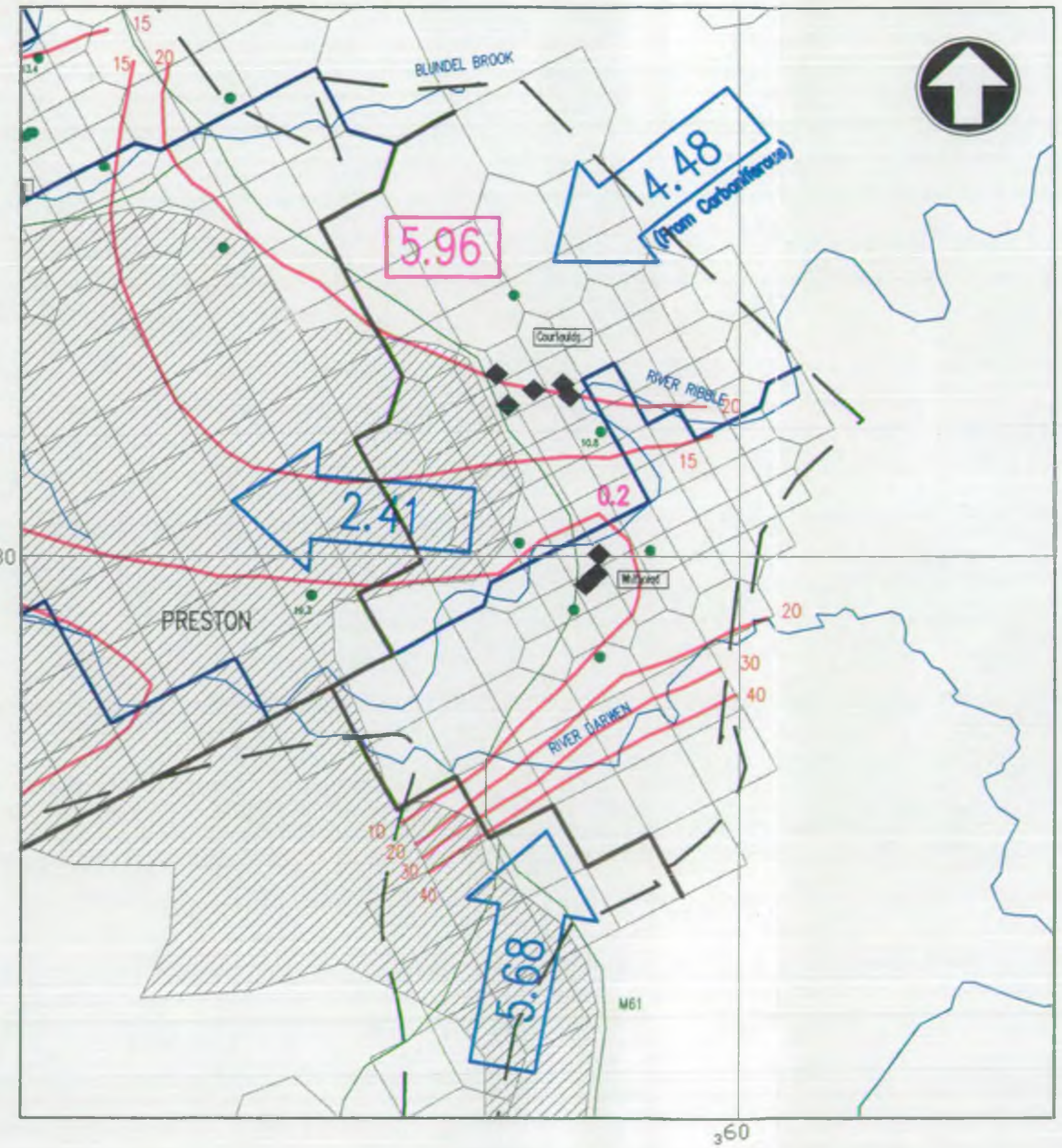
South East Fylde - Simulated Piezometry, April 1987



Legend

- Abstraction borehole
- River gauging station
- Edge of Fylde aquifer
- Major road

MODEL

- Model polygon
- Model river element
- Simulated limit of the area

OBSERVATION BOREHOLES

- Sandstone
- Sands & Gravels
- Carboniferous

GROUNDWATER LEVELS

- Observed Sandstone water level (mOD)
- 10 Simulated Sandstone water level (mOD)

SIMULATED WATER BALANCE COMPONENTS

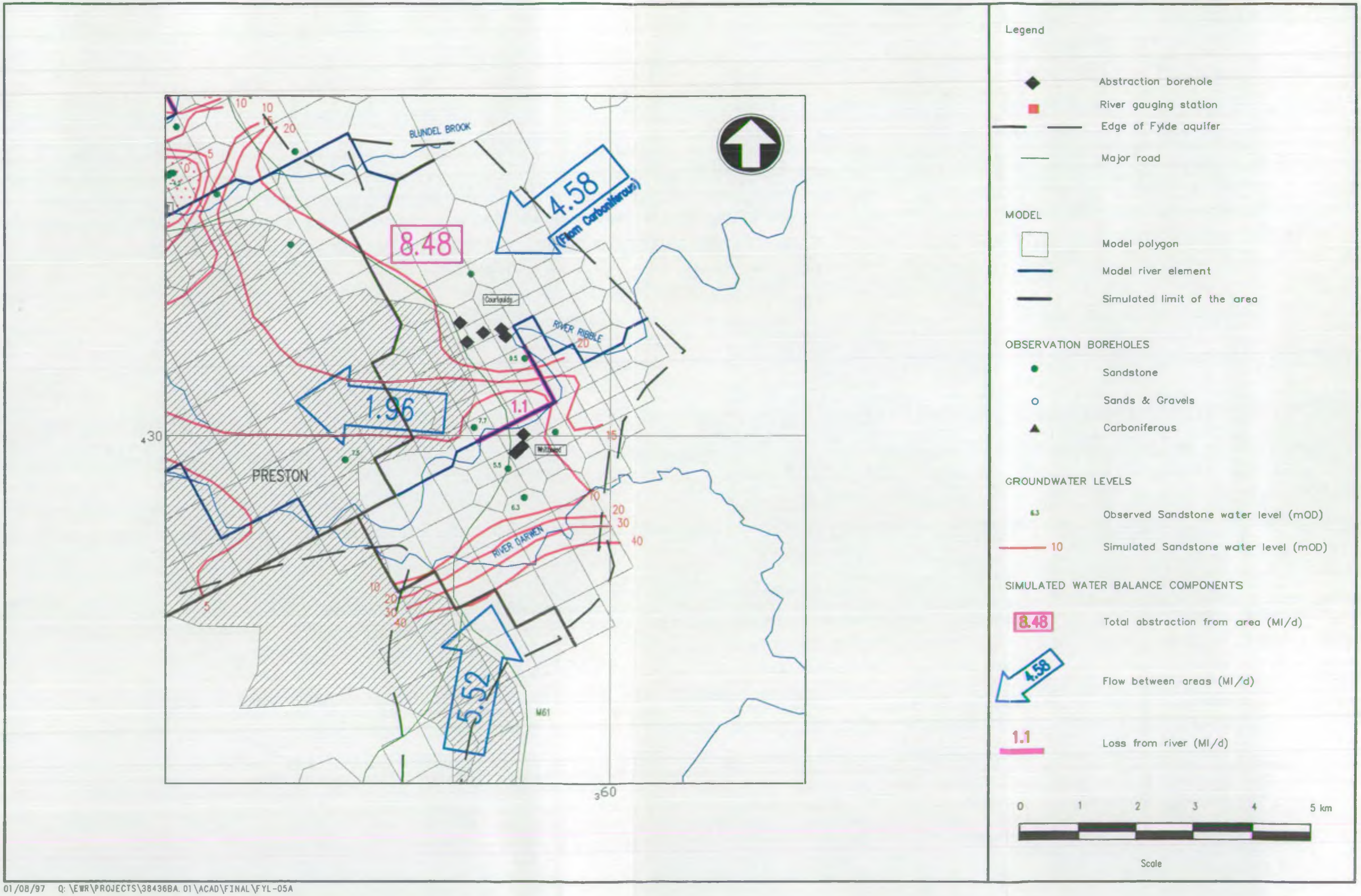
- 5.96 Total abstraction from area (Ml/d)
- 4.48 Flow between areas (Ml/d)
- 0.2 Loss from river (Ml/d)

0 1 2 3 4 5 km

Scale

Figure 4.39

South East Fylde - Simulated Piezometry, September 1995



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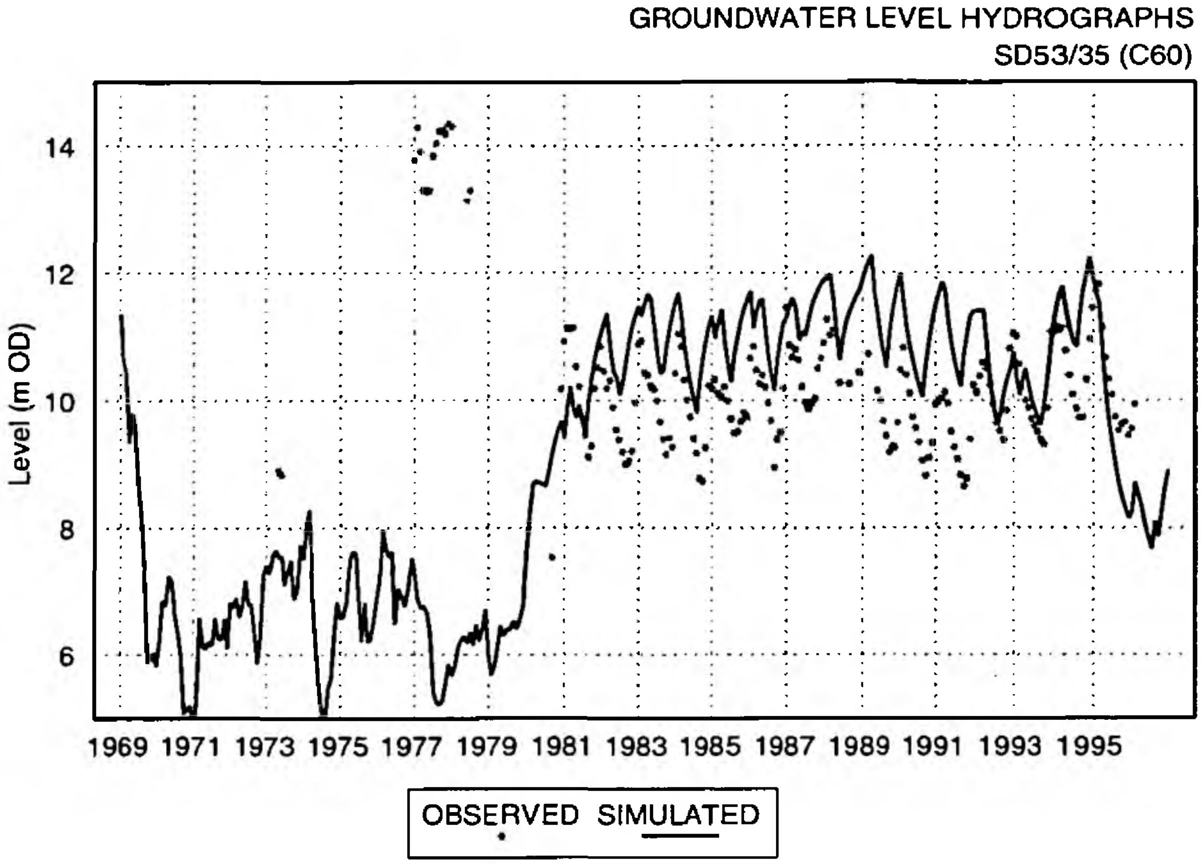
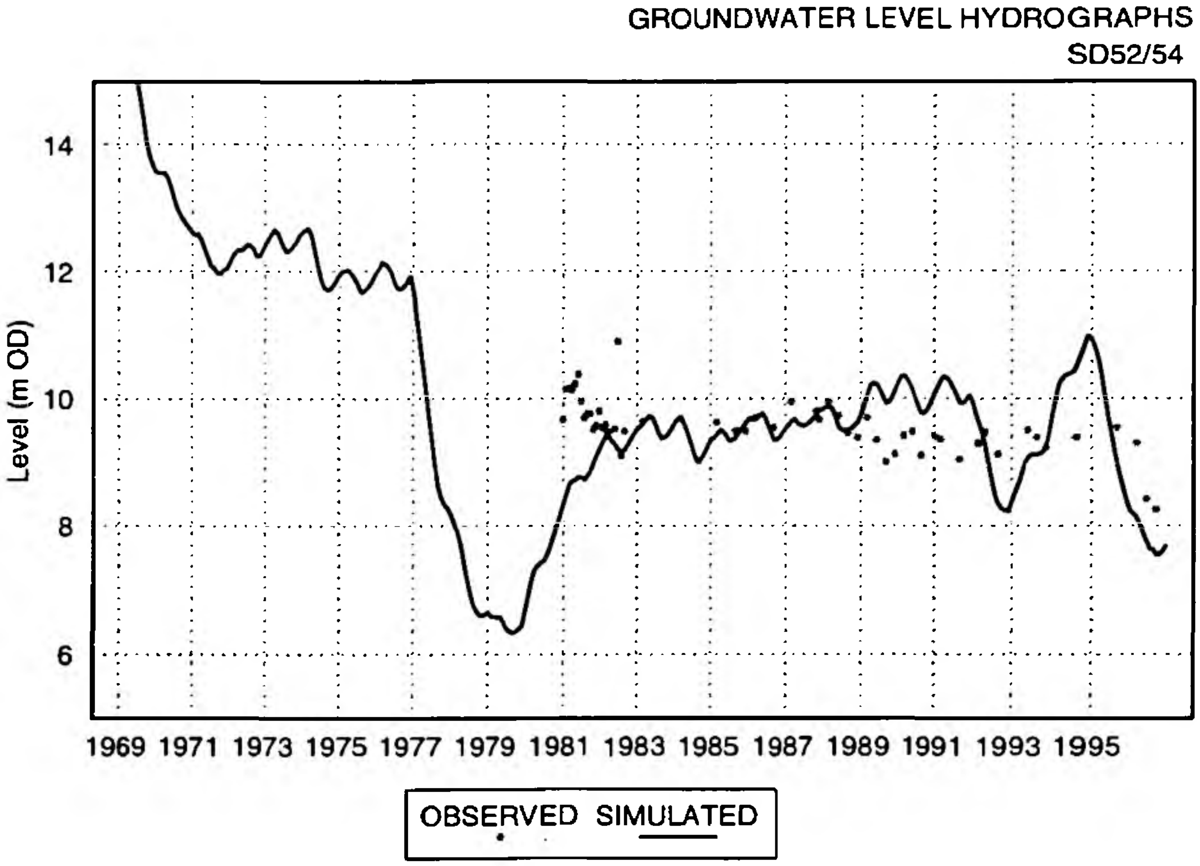
South East Fylde: Simulated Groundwater Level Hydrographs





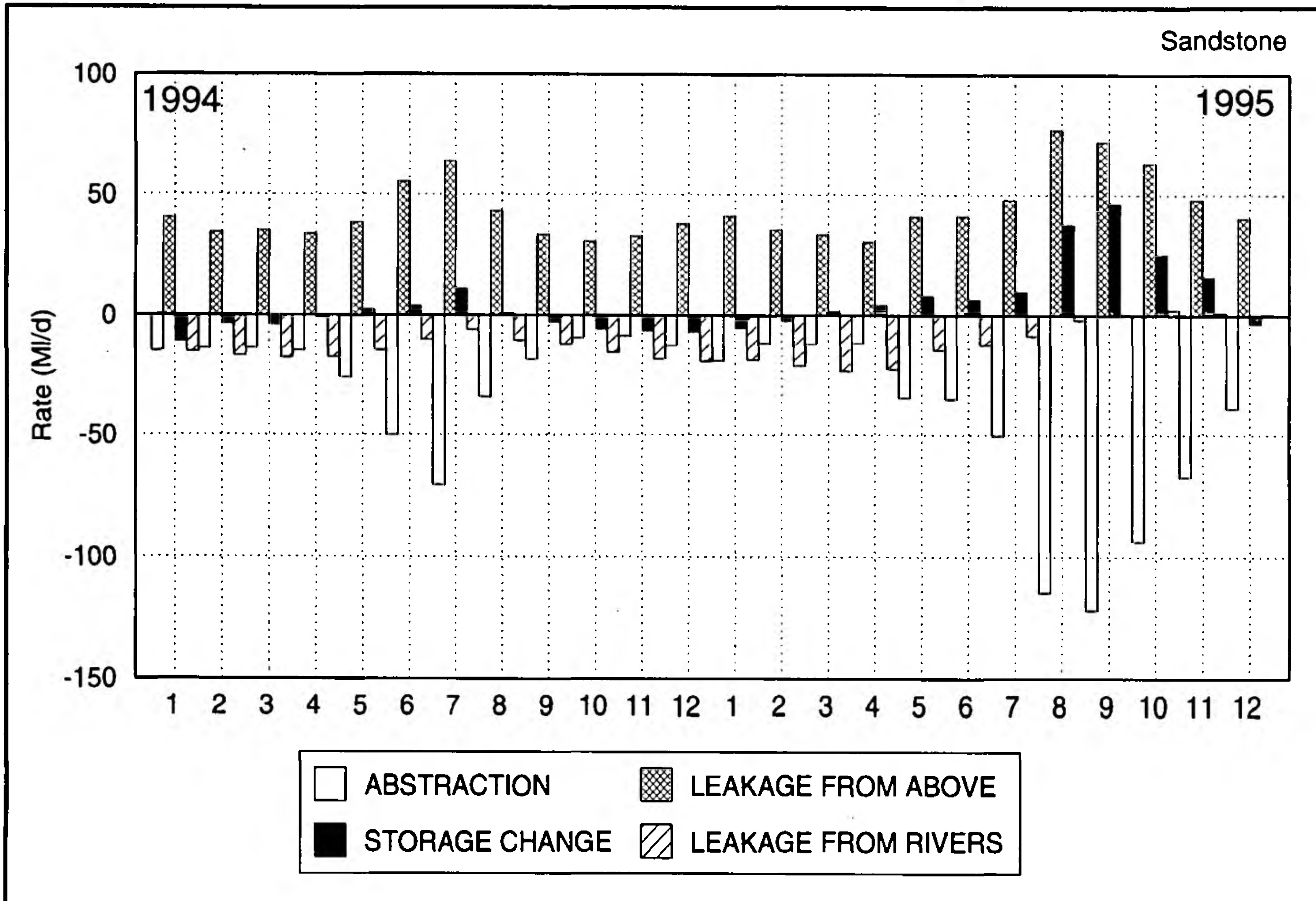


Figure 4.41
Simulated Flow Components - Sandstone

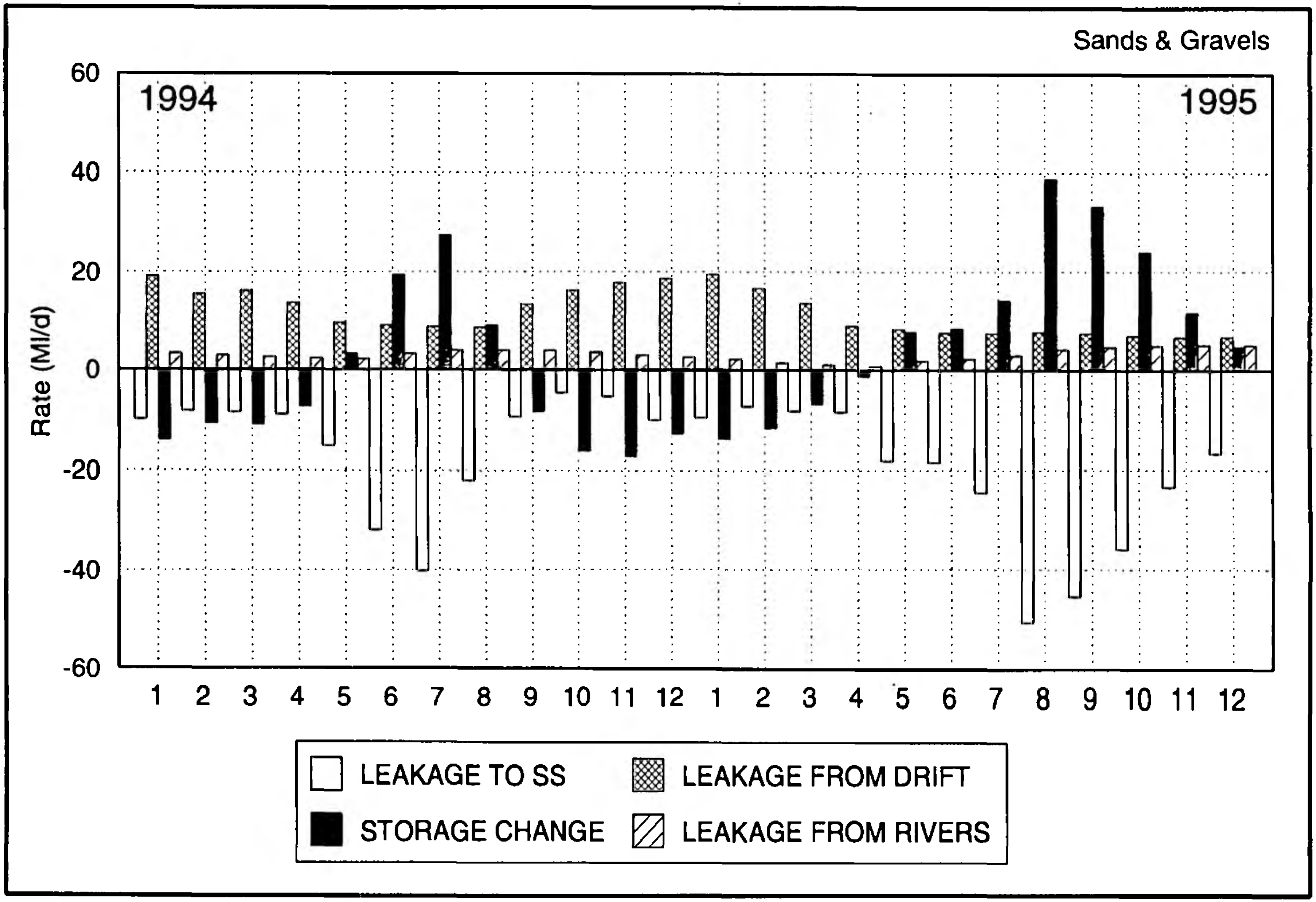


Figure 4.42
Simulated Flow Components - Sand & Gravels

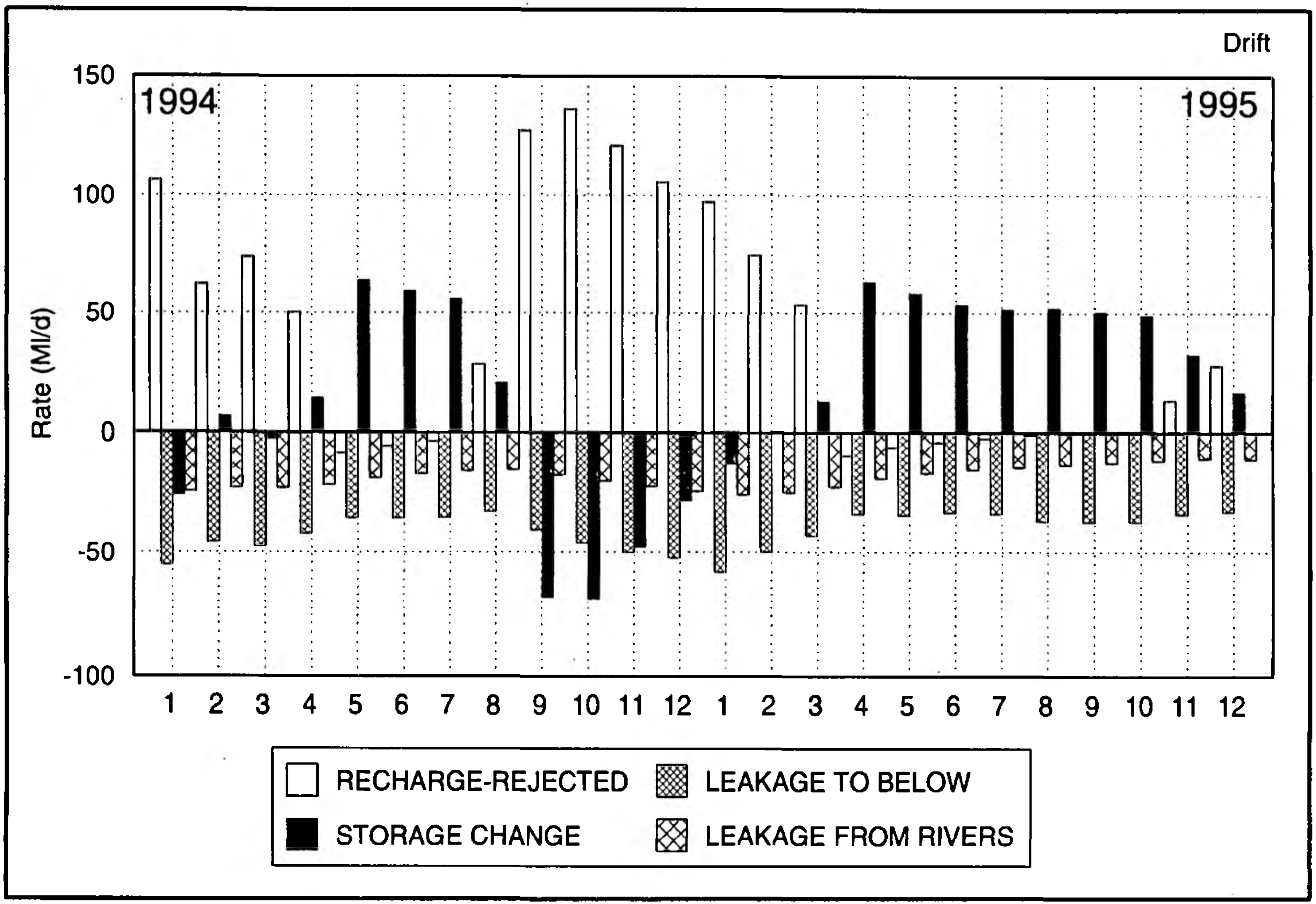


Figure 4.43
Simulated Flow Components - Drift

Figure 4.44

Influence of Sandstone Permeability at River Wyre, Garstang

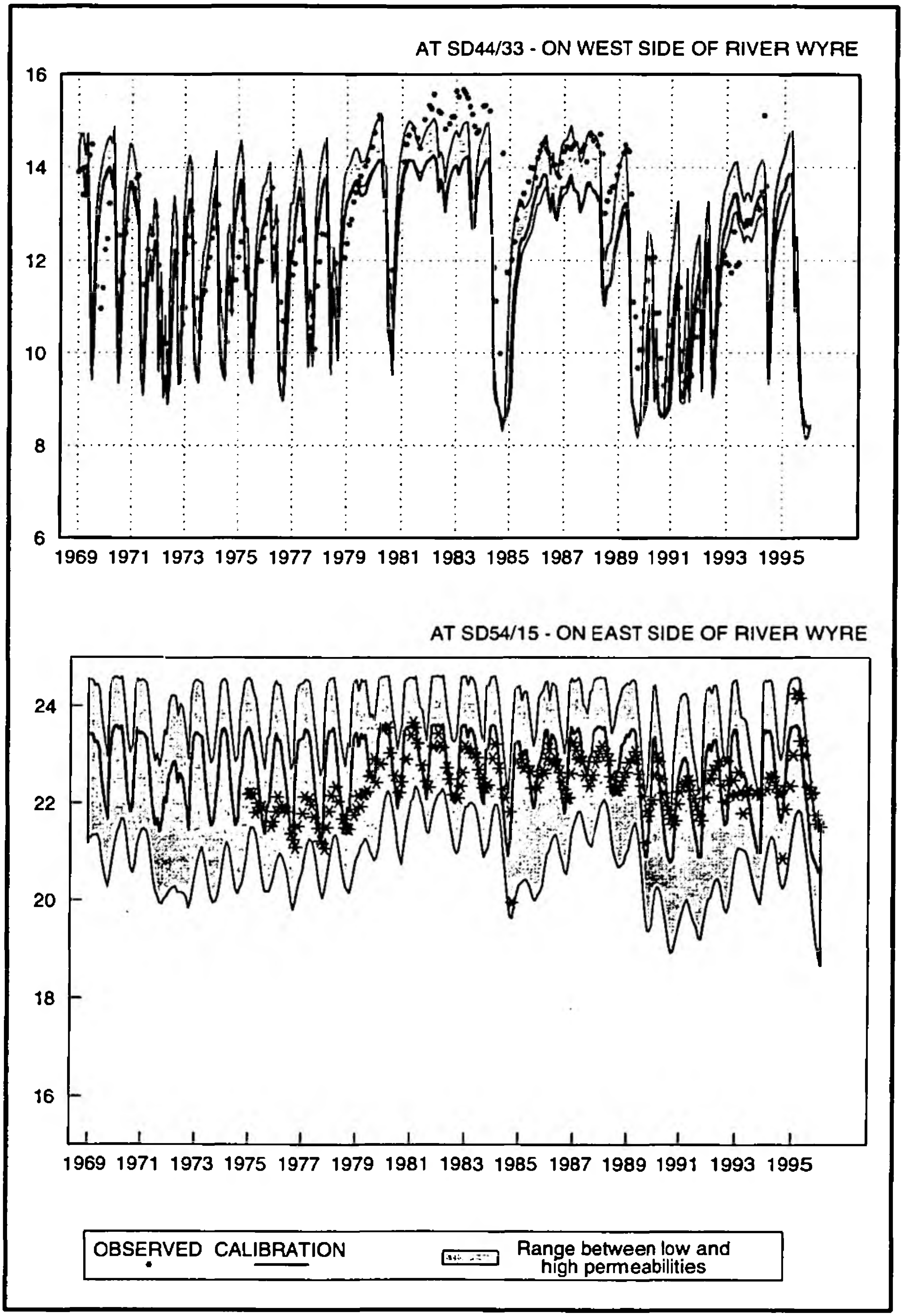


Figure 4.45

Influence of Drift Conductance on Leakage to Sandstone

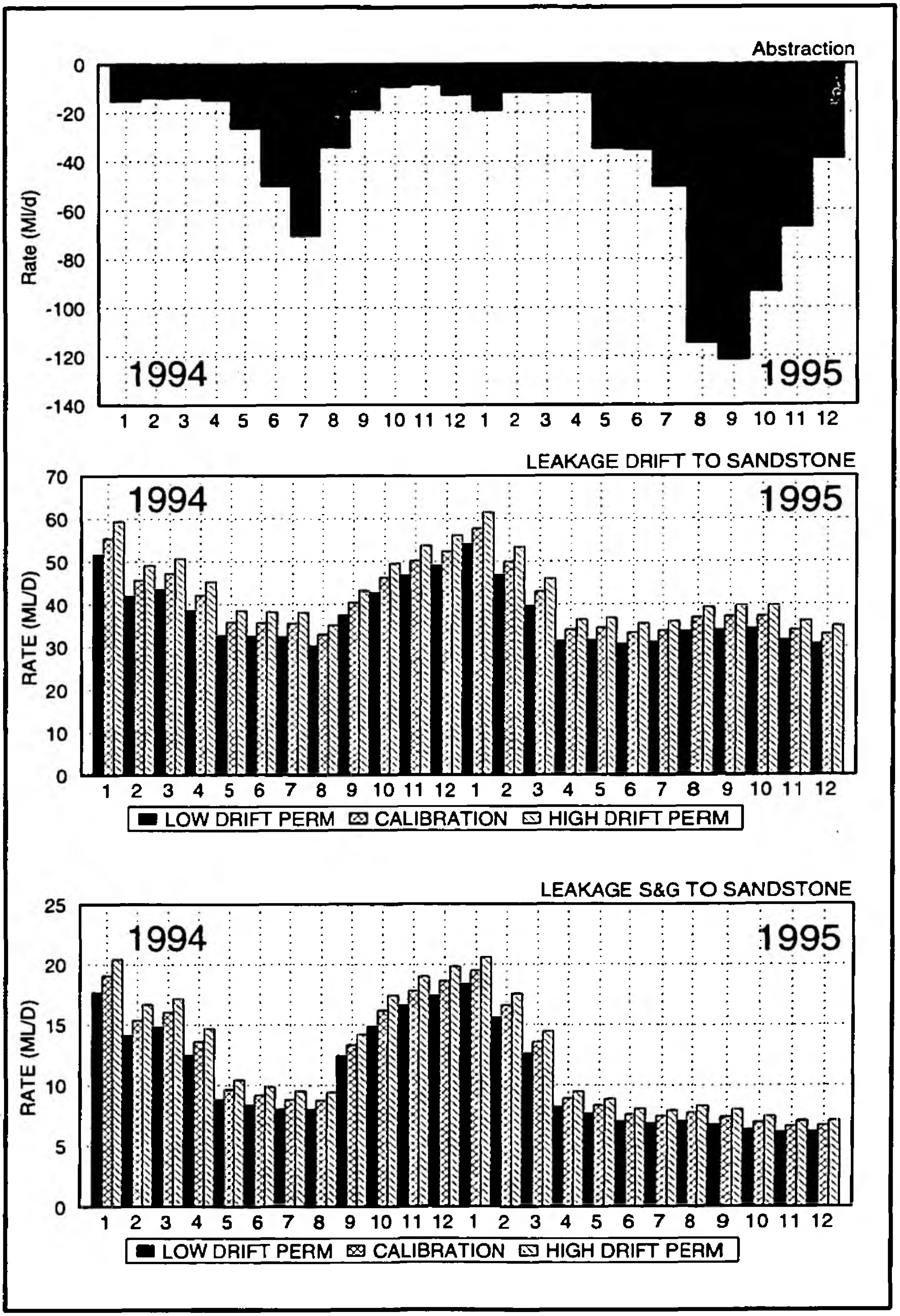
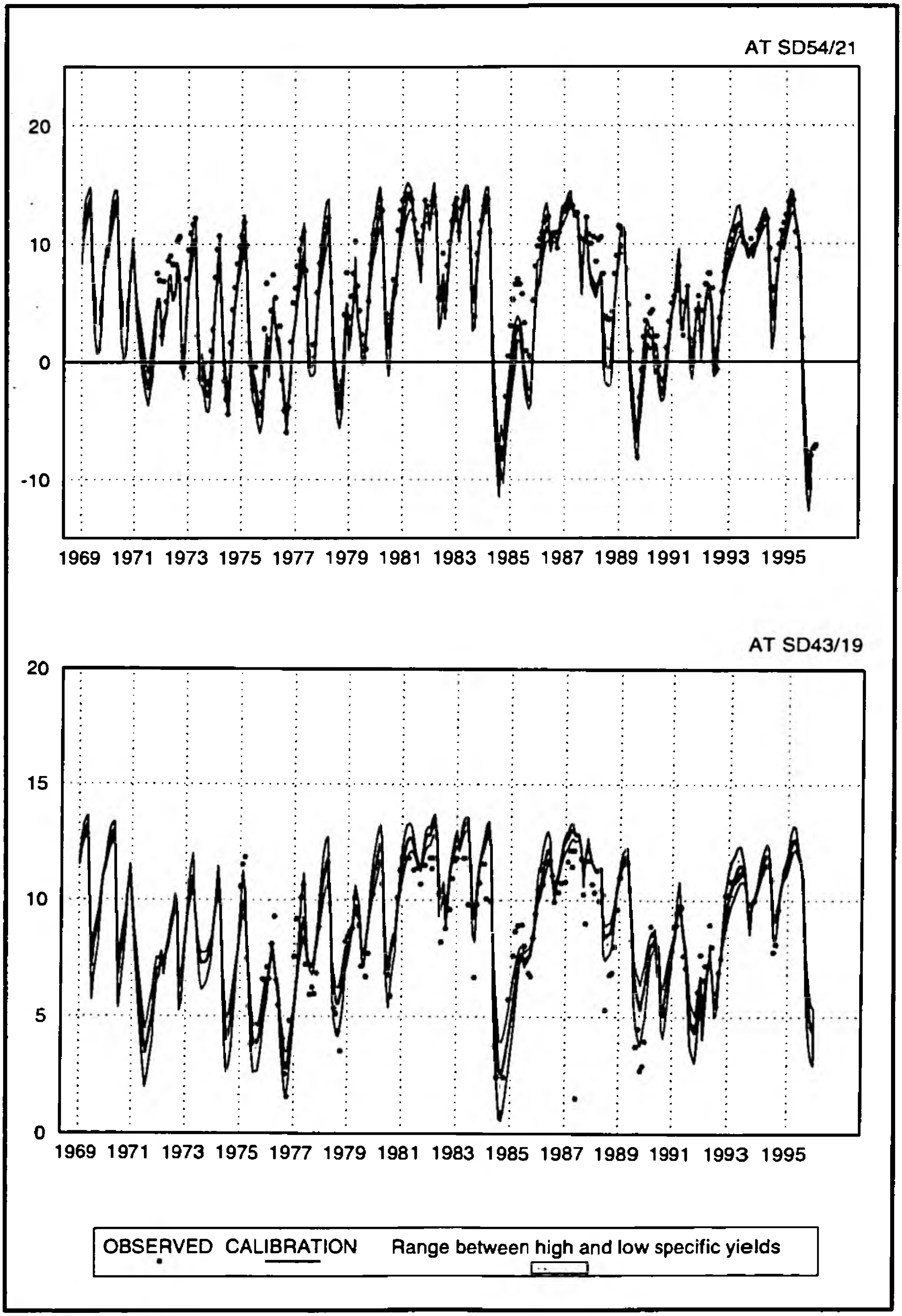
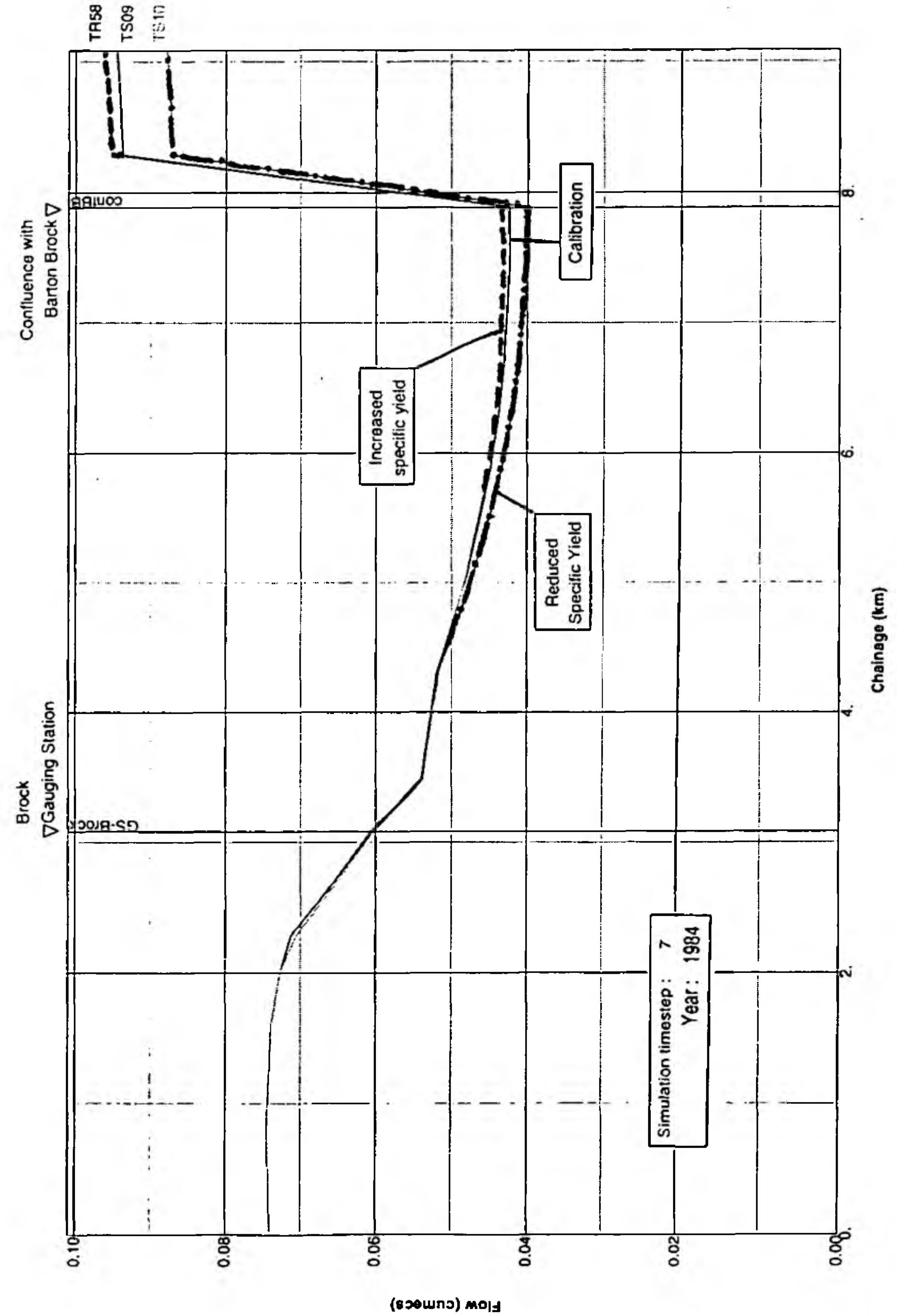


Figure 4.46

Sensitivity of Groundwater Levels to Specific Yield of S&G



River Brock Accretion Profile Showing Influence of Sands & Gravels Specific Yield



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38436BA01\Dec 1996

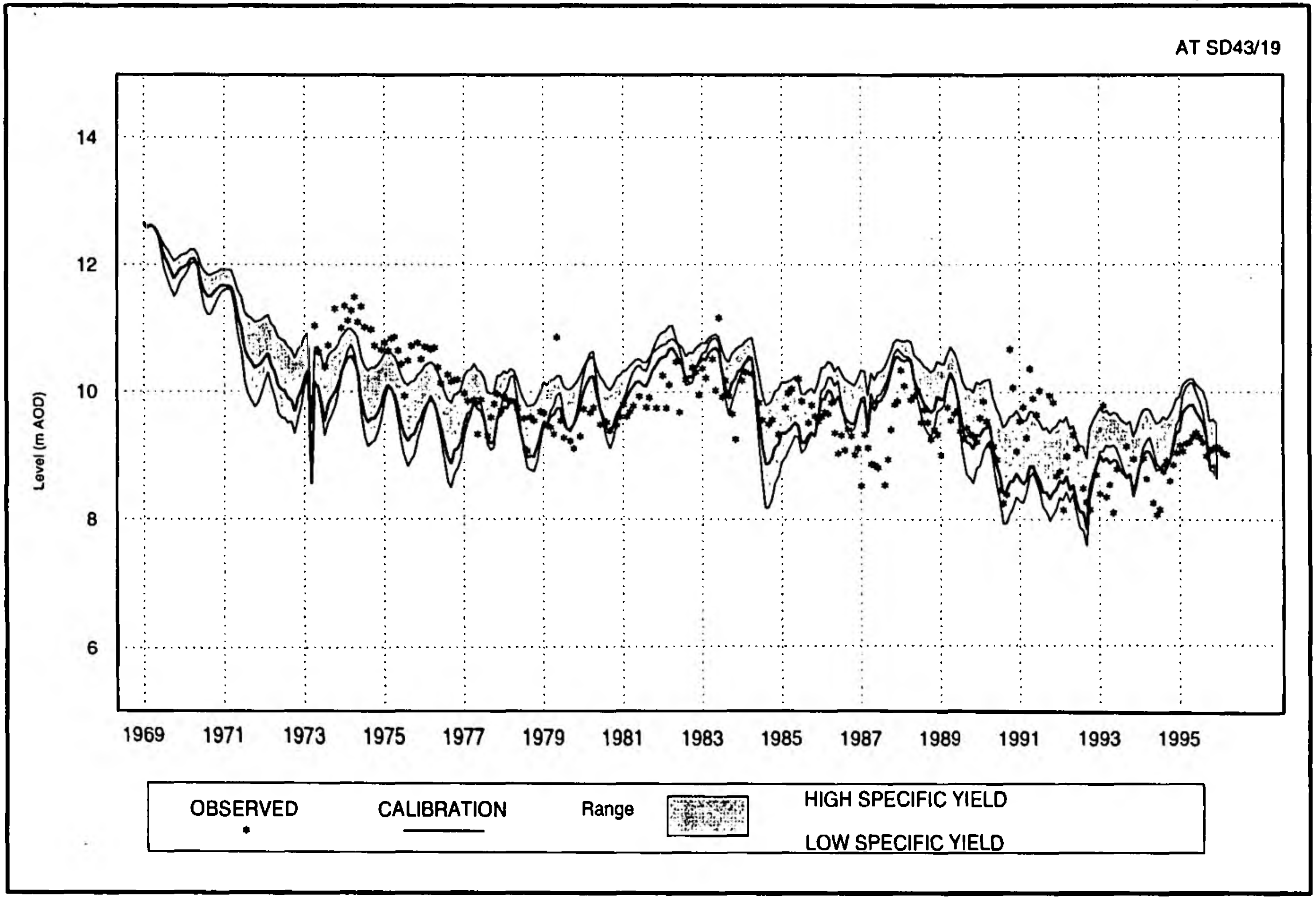


Figure 4.48
Sensitivity of S&G Specific Yield at Control Observation Borehole

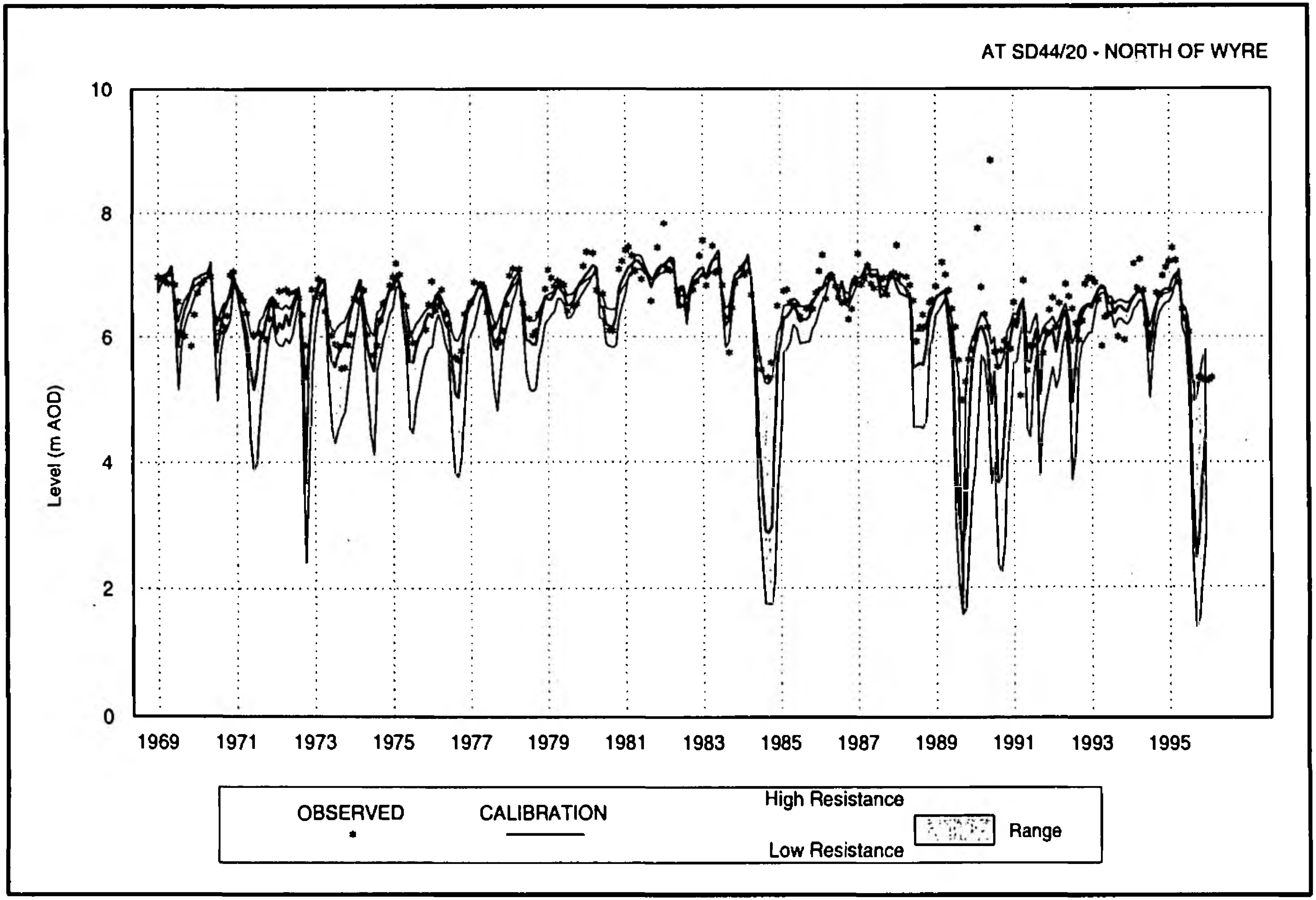
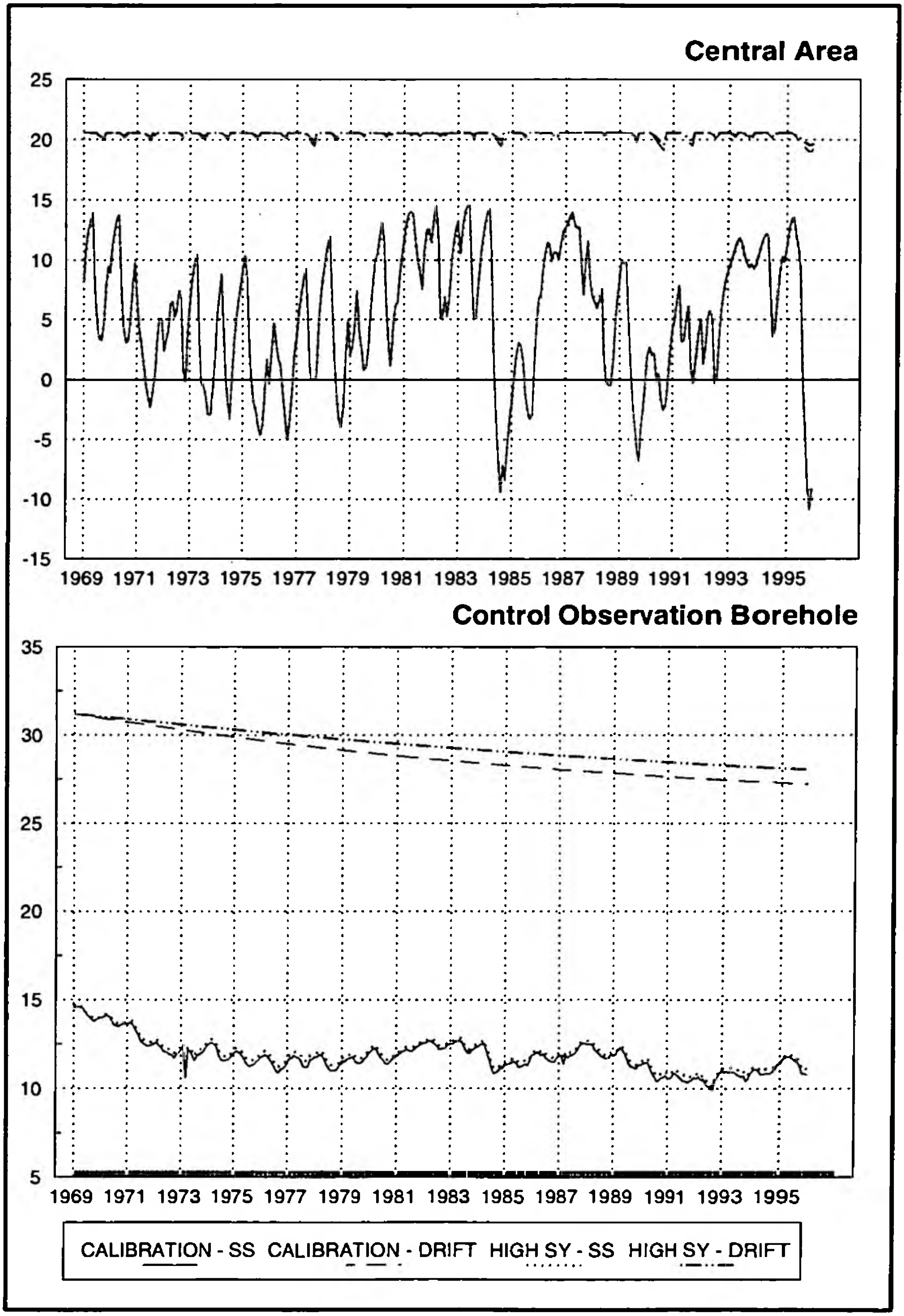


Figure 4.49

Influence of River Resistance on Groundwater Levels

Figure 4.50
Influence of Drift Specific Yield



CHAPTER 5

MODEL PREDICTIONS

CHAPTER 5

MODEL PREDICTIONS

5.1 Introduction

A total of 16 prediction runs have been carried out using the model: nine were carried out using the model as calibrated for the Phase II report (runs 1,3,4,5,6,10 and 14 in Table 5.1);e a further five predictions were based on the calibration defined using the calibrated model to the end of 1995 incorporating the revised geological structure and a further two runs were carried out using the calibrated model to the end 1996 (where minor changes to aquifer properties were made).

The Phase III report ("Modelling of the Resource Options", MM, February 1996) describes in detail the first seven prediction runs.

A separate report, prepared for North West Water, presents the results of two prediction runs (runs 12 and 13) which examined the impact of redeveloping the boreholes abandoned by Courtaulds in 1981 as an emergency water supply (MM, May, 1996). The output from a further run, assessing the impact of an additional industrial abstraction in Preston (Emmett Denim Care) is contained in Appendix D. This chapter summarises the results and conclusions from these runs, supplemented by the additional model runs carried out using the recalibrated model.

A full list of the model predictions is shown in Table 5.1.

The validity of the prediction runs which were based on the Phase II model calibration was evaluated by re-running one of these predictions using the recalibrated model. For this purpose the prediction run testing the influence of the NWW, three year licensed abstraction rates was used (model runs 5 and 7). The results of this comparison is described in Section 5.2.

The remaining sections describe the results from the different categories of prediction runs defined in Table 5.1.

TABLE 5.1

Model Predictions

Run number	Description/Objective	Groundwater Abstractions, River Augmentations and River Transfers					Run Period[D]	Other changes to model input files/comments
		NWW Abstractions	Industrial Abstractions	River Augmentations	Lune-Wyre Transfers	Calder - Lancaster Canal		
BASELINE RUNS								PR00 in Phase III report
1 [A]	Baseline case	Historical	Historical (1)	None	Historical	Historical	Yr 1 - 26	
2 [B]	Baseline case - revised calibration - to end 1995	Historical	Historical (1)	None	Historical	Historical	Yr 1 - 27	
15 [C]	Baseline case - revised calibration - to end 1996	Historical	Historical (1)	None	Historical	Historical	Yr 1 - 28	
INITIAL PREDICTIONS TO ASSESS RANGE OF CONDITIONS BETWEEN MAXIMUM AND MINIMUM ABSTRACTIONS								
3 [A]	Nominal maximum capacity of NWW sources to establish upper limit of impact of NWW abstractions	Historical 1984 abstractions repeated for each year	Historical	None	Historical	Historical	Yr 1 - 26	PR01 in Phase III report
4 [A]	Minimum abstraction from NWW sources to establish lower limit of NWW abstractions	Historical 1981 abstractions repeated for each year	Historical	None	Historical	Historical	Yr 1 - 26	PR02 in Phase III report

TABLE 5.1 (continued)

Model Predictions

Run number	Description/Objective	Groundwater Abstractions, River Augmentations and River Transfers					Run Period[D]	Other changes to model input files
		NWW Abstractions	Industrial Abstractions	River Augmentations	Lune-Wyre Transfers	Calder - Lancaster Canal		
ASSESS IMPACT OF NWW LICENCES ON GROUNDWATER LEVELS AND RIVER FLOWS								
5[A]	Maximum three year licensed abstractions for NWW sources to test impact of full license on groundwater levels and river flows	Three year licensed abstraction rates - (2a)	Historical (1)	None	Historical	Historical	Yr 1 - 26	PR03 in Phase III report
6[A]	Test effectiveness of river augmentations contained in NWW licenses.	Historical	Historical (1)	Applied according to licence (4)	Historical	Historical	Yr 1 - 26	PR05 in Phase III report
7[B]	Same run as run 5 but using revised model calibration	Three year licensed abstraction rates - (2a)	Historical (1)	None	Historical	Historical	Yr 1 - 27	

TABLE 5.1 (continued)
Model Predictions

Run number	Description/Objective	Groundwater Abstractions, River Augmentations and River Transfers					Run Period(F)	Other changes to model input files
		NWW Abstractions	Industrial Abstractions	River Augmentations	Lune-Wyre Transfers	Calder - Lancaster Canal		
8(B)	Maximum three year licence conditions. Peak abstraction years related to water supply demand and surface reservior levels.	Three year licensed abstraction rates (2b)	Historical (1)	None	Historical	Historical	Yr 1 - 27	
9(B)	As run 8 - but with all industrial abstractions at full licence	Three year licensed abstraction rates - (2a)	Annual licence rates	None	Historical	Historical	Yr 1- 27	
Evaluate Impact of Licence Applications in Preston Area								
10(A)	Test impact of new industrial licenses around the Preston Area	Historical	Historical - (3a)	None	Historical	Historical	Yr 1 - 26	Five new licenses totalling 22.2 Ml/d and increase in licence (Supreme Laundry) to 2.46 Ml/d. Applied at a constant rate throughout simulation period. (PR04 in Phase III report)
11(B)	Impact of Emmett Denim Licence - 1995 calibration	Historical	Historical - (3b)	None	Historical	Historical	Yr 1 - 27	New licence for Emmett Denim of 2.46 Ml/d
16(C)	Impact of Emmett Denim Licence - 1996 calibration	Historical	Historical - (3b)	None	Historical	Historical	Yr 1 - 28	New licence for Emmett Denim of 2.46 Ml/d

TABLE 5.1 (continued)

Model Predictions

Run number	Description/Objective	Groundwater Abstractions, River Augmentations and River Transfers					Run Period[(B)]	Other changes to model input files
		NWW Abstractions	Industrial Abstractions	River Augmentations	Lune-Wyre Transfers	Calder - Lancaster Canal		
12[(A)]	Test impact redevelopment of Courtaulds abstraction boreholes	Historical	Historical - (3c)	None	Historical	Historical	Yr 1 - 26	Abstraction of 12 Ml/d for three months per year (July, August and September)
13[(A)]	Test impact redevelopment of Courtaulds abstraction boreholes	Historical	Historical - (3c)	None	Historical	Historical	Yr 1 - 26	Abstraction of 12 Ml/d for six months per year (July to December inclusive)
Test influence of Sands & Gravels Layer								
14[(A)]	Sensitivity of model predictions to storage coefficients defined for the sands and gravels layer	Historical	Historical (1)	None	Historical	Historical	Yr 1 -- 25	Specific yield and confined storage coefficient of the sands and gravels layer doubled (PR06 in Phase III report)

Notes for Table 5.1

(A) An (A) defined next to the run number indicates that the prediction is based on the preliminary calibration presented in the Phase II report.

(B) A (B) defined next to the run number indicates that the prediction is based on the updated calibration to end of 1995 which includes the revised geological structure.

(C) A (C) defined next to the run number indicates that the prediction is based on the updated calibration to end of 1996 which includes minor changes to aquifer properties.

(D) The run period varies between which model calibration was used in the prediction run. For predictions based on the preliminary calibration, the model was run for 26 years using monthly time steps, equivalent to the calibration period of 1969 to 1994 inclusive. Recharge and all historical abstractions were taken from the calibration run. In addition, the initial conditions for predictions based on the preliminary calibration were taken from the last time step of the model calibration runs (ie December 1994).

For model predictions based on the revised 1995 calibration, the model was run for 27 years using monthly time steps equivalent to the calibration period of 1969 to 1995 inclusive. Initial conditions were again based on the last time step of the calibration run (ie December 1995). For predictions based on the revises 1996 calibration, a 28 year simulation was carried out with intital conditions derived from December 1996.

For run 7, which was used to compare the results of the same prediction for the two different model calibrations, year 27 was not simulated so that direct comparisons could be made and the initial conditions were derived from December 1994 simulated piezometry of the revised model calibration.

(1) Industrial abstractions for all runs (except runs 3 and 4) were taken exactly as historical except that abstractions from Courtaulds sources were set to zero since this licence has expired. For runs 3 and 4, the historical abstractions for Courtaulds were included in the sequence.

(2a) Three year licence for the NWW sources - for runs 5 and 7. The derivation of the abstraction rates for each of the NWW sources is explained in detail in Appendix A of the Phase III report (Section A.4.1.3). Peak abstractions are based on the historical rates of abstractions for 1984 for Franklaw A and B sources and for 1991 for Broughton A and B sources. Abstractions for the remaining two years of the cycle were calculated as half the remainder of the licence less the peak abstractions.

(2b) Model run 8 tests the three year licence rule more realistically. In runs 5 and 7, the full licence was taken every year, with a repeated three year cycle of peak abstraction followed by two years of abstraction to bring the total abstraction for three years to the rolling three year' licence limits. In 8, abstraction rates were redefined on the basis of water supply demand and the historical surface reservoir levels. Peak abstractions were set to occur during years 1971 (year 3 of the prediction), 1975 (7), 1984 (16), 1991 (22) and 1995 (27). The peak abstraction was set at 19912 Ml, equal to 71 % of the annual licensed quantity. The maximum abstractions for three years was set to 27305 Ml (80% of the three year licence maximum).

(3a) Run 6 - Impact of recent *(1993-96)* enquiries/applications for new groundwater abstractions in Preston area. The model run consists of five new abstractions and an increase in abstraction from an existing licensed source in Preston, as follows:

New Sources:

-	Emmett Denim Care	90 Ml/annum
-	West Coast Laundry	90 Ml/annum
-	Preston Royal Infirmary	360 Ml/annum
-	MD Foods	180 Ml/annum
-	Unnamed laundry firm	90 Ml/annum

Licence Increase:

-	Supreme Laundry	90 Ml/annum

(3b) This run tests the impact of the outstanding licence application by Emmett Denim Care (set to 90 Ml/annum).

(3c) Impact of redevelopment of Courtaulds boreholes 4 and 5. Redevelopment was requested by NWW as part of their emergency water supply network. Model set up to run both boreholes at 12 Ml/d for three months every year of the simulation (July, August and September).

(3d) As (3c) but with abstraction set for six months per annum (July to December inclusive)

(4) River augmentations defined from run 1 according to NWW licences. The derivation of the augmentation rates and frequencies are described fully in Section A.5 of Appendix A of the Phase III report. Augmentation licence requirements are shown in Appendix B.

5.2 Comparison of Predictions Based on Different Model Calibrations

Following preliminary calibration (Phase II report) the full three year licence volumes for NWW abstraction sources were defined to assess the impact of the present licence conditions on groundwater levels and river flows (model run 5). This run was repeated using the revised parameter settings in the updated 1995 model (run 7).

There are a number of differences in the simulated results between the two model runs. These are as follows:

Groundwater Levels

- In the North West area (around Morecambe Bay and the ICI boreholes), seasonal fluctuations are greater with the revised calibration settings as a result of the lower permeability defined at the Fylde/Morecambe Bay boundary defined to reduce outflows from the model from an average of 1300 m^3/d to 900 m3/d.

- At Garstang, seasonal fluctuations are greater on the west side of the river near NWW sources W and Z and lower in the west side of the river. This is because the River Wyre in this area was made more leakyr in order to improve the accuracy of the simulation of groundwater levels around NWW sources W and Z.

- In the Central area, drawdown around the NWW sources following peak abstraction is slightly greater (by up to 5 m) as a result of the lowering of the sandstone permeability in this area.

- Around NWW's Broughton 'A' sources B, C and D the drawdown from abstraction is also greater (by up to 15 m) as a result of reduced permeability.

- To the south and west of sources B, C and D there is a decrease in the decline of the groundwater levels under the new parameter settings (as demonstrated for the control observation borehole SD43/19 in Figure 5.1). This is because in the preliminary calibration the permeability between NWW sources B, C and D and the BNFL boreholes was higher than in the revised model, where anisotropic conditions have since been defined with a very low permeability in the east-west direction (0.02m/d).

- To the east of NWW sources B, C and D the model simulates an increased rate of decline under the new model calibration settings.

- Around the Whitbread sources, the results remain the same under both calibration settings, other than minor changes in the average simulated level.

River Flows

With the lower permeabilities defined in the Central and Woodplumpton Brook areas, the model more accurately simulates historical groundwater levels and river flow losses. Generally predicted losses from rivers are concentrated in shorter sections than previously simulated. The revised calibration results in river flow loss which more accurately reflect spot measurements taken during 1994 to 1996. Due to this there are significant variations between the predictive model simulations under full groundwater abstraction conditions using the two different calibration parameter settings. This is demonstrated in Figures 5.2a for the River Wyre and 5.2b for the River Brock. The River Wyre loses approximately the same volume of water, but this is concentrated over a shorter reach, upstream of the St Michaels gauging station. The simulation of the River Brock indicates a longer reach where losses are simulated, with a greater magnitude of loss. Similar differences occur at the other rivers.

Water Balance Components

Table 5.2 shows the average simulated water balance components comparing the prediction run results. The major differences are in the potential recharge, leakage through the Drift and sand & gravels layers and the river leakage.

The potential recharge difference is a result of corrections to the original assessment of recharge and has no effect on the simulations.

The revised calibration simulates a slightly greater volume of leakage from the sands & gravels and a minor reduction in leakage from the Drift. Effectively the revised calibration increases the volume of water stored within the sands & gravels layers.

The most significant variation is in the leakage from the river to the sands & gravels and sandstone aquifers as described in the previous section.

Conclusion

The most significant difference between the two simulations is the simulated river losses. However, since greater losses are now simulated than previously, the revised calibration does not invalidate the conclusions reached from the model predictions carried out using the preliminary calibration. These conclusions are thus repeated in the following sections.

Changes to the model between 1995 and 1996 calibrations were very minor and will, therefore, have only minor influences on the results of the predictions described in the follwoing sections.

TABLE 5.2

Average Simulated Water Balance Components (Years 3 - 26) Comparing Results of Simulation with NWW Sources at Full Licences

Components	Sandstone (Two layers)		Sands & Gravels[2]		Drift	
Parameter Settings	Preliminary	Final	Preliminary	Final	Preliminary	Final
Inflows						
Potential recharge	0.0	0.0	0.7	0.8	559.8	628.2
Leakage from Drift	32.5	29.1	17.3	15.8	n.a.	n.a.
Leakage from sands & gravels	22.6	23.4	n.a.	n.a.	n.a.	n.a.
Boundary inflows (Carboniferous):						
- South East (Ribble)	2.3	5.1	0.0	0.0	0.0	0.0
- Millstone Grit	0.3	0.3	0.0	0.0	0.0	0.0
- Garstang	1.5	1.2	0.0	0.0	0.0	0.0
Flow from rivers to layer	1.3	3.8	4.4	6.7	0.0	0.0
Storage release	0.5	1.0	0.3	0.1	0.0	0.0
Total inflows	*61.0*	*63.9*	*22.7*	*23.4*	*559.8*	*628.2*
Outflows						
Abstraction	-59.1	-59.1	0.0	0.0	0.0	0.0
Leakage to sands & gravels	n.a.	n.a.	n.a.	n.a.	-17.3	-15.8
Leakage to sandstone	n.a.	n.a.	-22.0	-23.4	-32.5	-29.1
Boundary Outflows:						
- Ribble Estuary	-0.9	-2.9	0.0	0.0	0.0	0.0
- Morecambe Bay	-1.3	-1.9	0.0	0.0	0.0	0.0
Groundwater flow to rivers	0.0	0.0	0.0	0.0	-19.3	-20.0
Rejected flows (rejected recharge)	0.0	0.0	0.0	0.0	-490.7	-563.3
Storage gain	0.0	0.0	0.0	0.0	0.0	-0.3
Total outflows	*-61.2*	*-63.9*	*-22.0*	*-23.4*	*559.8*	*-628.5*
Model imbalance	*-0.2*	*0.0*	*0.1*	*0.0*	*0.0*	*-0.3*

Notes (1) All units Ml/d
(2) The sands & gravels aquifer only partially covers the model area

5.3 Minimum and Nominal Maximum NWW Abstractions

The "upper"and "lower" NWW abstraction limits were defined from the maximum and minimum rates observed during the historical calibration sequence: 1984 for the maximum (equal to 19,777 Ml from NWW sources or 70% of the total annual licence) and 1981 for the minimum (equal to 1542 Ml/annum for the NWW sources; closest to "naturalised" conditions observed in the Fylde aquifer system). These abstraction rates were applied in each year of the simulation (run 3 to define the nominal maximum and run 4 to define the minimum). In reality, NWW could not abstract 1984 quantities each year since the volume over three years would exceed the three year licences.

However, the following conclusions can be drawn from these runs.

If the NWW abstraction boreholes were operated at maximum capacity each year:

- there would be a substantial reduction in river flows which in some cases would dry up the rivers;
- there would be a further decline in groundwater levels in (by around 1.25 m at control observation borehole T74) the southern part of the Fylde aquifer which would take an estimated 15 years to recover once abstraction ceased;
- due to the decline in groundwater levels at the coast and a corresponding reduction in outflow from the Fylde aquifer to the coast, saline intrusion from Morcambe Bay could adversely affect ICI sources.
- the licence constraint at observation borehole SD43/19 (T74), which prevents abstraction from the Broughton 'A' sources if the piezometric level falls below 8.5 m OD, would be violated every year;
- the increased abstraction does not induce additional inflow of water from the Carboniferous deposits.

If NWW abstracted only a minimal volume of water each year then:

- there would be a net leakage from aquifer system to the rivers at all times;
- most recharge to the Fylde aquifer would be via leakage through the overlying layers, with only a small percentage (around 2%) being derived from lateral inflow from the Carboniferous.

These conclusions were based on the preliminary calibration. Since the revised calibration lowered the transmissivity of the Sherwood Sandstone in the central area, the impact of the 1984 abstractions on groundwater levels and river flows would, in fact, be greater.

5.4 Influence of Present NWW Abstraction Licences on Groundwater Levels and River Flows

If the NWW Fylde abstraction boreholes were operated at their full licensed rates, irrespective of water supply demand or surface water stocks (model runs 5 and 7 - refer to Section 5.3) then the model simulates the following impacts:

- the decline in sandstone water levels when the NWW are operated at the maximum licence capacity is such that it is unlikely that the pumping equipment installed in the boreholes could deliver the licensed volumes;
- there is a decline in sandstone groundwater levels of up to 3 m (around sources NWW sources M, L, P and Q) over the 27 year simulation period in the central area, indicating that the licensed quantities exceed long-term recharge to the aquifer (i.e they are not sustainable);
- it is not possible to pump the southerly sources (Broughton A) at licensed capacity without groundwater levels at observation borehole SD43/19 (T74) falling below the licence constraint (refer to Figure 5.1);
- following a year of maximum abstractions, such as occurred in 1984, leakage from the river system is maintained into the following winter as groundwater levels recover (refer to Figure 5.3).

These model runs were considered unrealistic since the LCUS Fylde boreholes are only used at times of peak demand/when cheaper surface water supplies are not available; NWW would not operate all their groundwater sources at the maximum licence rate over successive years, regardless of overall supply and demand. Therefore, a revised 'licensed' abstraction scenario was devised, with the full annual licensed quantity redistributed to coincide with 'drought' years such as 1995, based on historical climate, water supply and demand conditions (run 8)

The abstractions for the NWW sources set for this model run compared with actual historical rates are shown in Figure 5.4. In some years, the rate specified in the prediction falls below the historical abstractions: over the full simulation there is a net reduction in abstraction of 2.2Ml/d over the historic.

The results of this run are summarised below:

Groundwater Levels

Figure 5.5 and 5.6 show the simulations at four observation boreholes. These four locations were chosen to demonstrate the differences between the historic baseline prediction and the revised groundwater abstraction rates shown in Figure 5.4

At borehole SD44/33 (Croston Road), located to the west of sources W and Z, the model simulates an increase in drawdown during peak abstraction years. This is only a marginal increase because historical abstractions from W and Z sources have always been relatively high.

At borehole SD54/1 (Catterall), located midway between the rivers Wyre and Calder, near sources P and Q, the model simulates an additional drawdown of up to 12 m.

At boreholes SD53/66B (Toplands Farm), near source B at Woodplumpton Brook, the decline in groundwater levels is reduced over most years of the simulation since abstractions from the southerly sources were less than the historical.

At the control borehole, SD43/19 (T74), the model simulates a smaller decline in level over the first 13 years of the simulation since historically abstractions during this period were greater than specified in the prediction run. During years 14 - 17, however, the model simulates a similar level of decline as occurred historically. This suggests that if the Broughton sources are operated at around 70% of their licensed rates, future groundwater levels at T74 will decline below the minimum allowable level of 8.5 m OD.

River Flows

Similar volumes of leakage from the rivers were simulated in both the baseline model run and run 8. Differences occur in selected months where groundwater abstractions differ.

Figure 5.7 shows simulated low flows at To Michaels gauging station. This indicates that augmentation of the river is required on numerous occasions. The maximum deficit (below the augmentation trigger level of 50 Ml/d) is around 41 Ml/d during 1995. With a maximum available augmentation volume of only 13.5 Ml/d, the present augmentation requirements within NWW licences will not maintain river flows above the licensed prescribed levels.

Water Balance Components

Tables 5.3 and 5.4 show the simulated water balance components for both the baseline (historic) and revised abstraction predictions: Table 5.3 presents the average for years 3 to 27 of the simulation, while Table 5.4 presents the average during year 27 (or 1995) as a peak abstraction year.

The average water balance components for the runs (Table 5.3) show only minor variations between the baseline and the revised abstraction scenario, since the average abstractions are similar. However, during a peak abstraction year significant variations take place. With an increase in abstraction of 16.8 Ml/d (or 33 %) in year 27 (equivalent to 1995), the extra abstraction is primarily derived from three sources:

- aquifer storage (3.5 Ml/d);
- vertical leakage through the Drift (1.3 Ml/d) and sand & gravels (6.7 Ml/d)
- reduced total groundwater to the rivers (4.5 Ml/d)

This implies that further increases in abstraction, above the high levels of 1995, will result in reduced river flows and reduced aquifer storage (particularly within the sands & gravels aquifer, where these directly overly the sandstone).

TABLE 5.3

Average Simulated Water Balance Components (Years 3 - 27)

Comparing Results of Simulation Runs 2 and 8

Components	Sandstone (Two layers)		Sands & Gravels[2]		Drift	
Run	2[3]	8[4]	2[3]	8[4]	2[3]	8[4]
Inflows						
Potential recharge	0.0	0.0	0.8	0.8	623.6	623.6
Leakage from Drift	31.1	30.6	13.8	13.6	n.a.	n.a.
Leakage from Sands & Gravels	18.4	17.7	n.a.	n.a.	n.a.	n.a.
Boundary inflows (Carboniferous):						
- South East (Ribble)	4.6	4.5	0.0	0.0	0.0	0.0
- Millstone Grit	0.3	0.3	0.0	0.0	0.0	0.0
- Garstang	0.5	0.6	0.0	0.0	0.0	0.0
Flow from rivers to layer	0.0	0.0	3.7	3.3	0.0	0.0
Storage release	0.5	0.2	0.2	0.1	1.2	1.2
Total inflows	*55.7*	*53.9*	*18.5*	*17.8*	*624.8*	*624.8*
Outflows						
Abstraction	-34.0	-31.8	0.0	0.0	0.0	0.0
Leakage to Sands & Gravels	n.a.	n.a.	n.a.	n.a.	-13.6	-13.8
Leakage to sandstone	n.a.	n.a.	-18.4	-17.7	-30.6	-31.1
Boundary Outflows:						
- Ribble Estuary	-4.2	-4.5	0.0	0.0	0.0	0.0
- Morecambe Bay	-4.2	-4.8	0.0	0.0	0.0	0.0
Groundwater flow to rivers	-13.3	-12.8	0.0	0.0	-20.1	-20.1
Rejected flows (rejected recharge)	0.0	0.0	0.0	0.0	-560.3	-559.8
Storage gain	0.0	0.0	0.0	0.0	0.0	0.0
Total outflows	*-55.7*	*-53.9*	*-17.7*	*-17.7*	*-624.6*	*-624.8*
Model imbalance	*0.0*	*0.0*	*0.1*	*0.0*	*0.0*	*0.0*

Notes (1) All units Ml/d

(2) The Sands & Gravels aquifer only partially covers the model area

(3) Run 2 = baseline run with historic abstraction (without Courtaulds) and no river augmentation

(4) Run 8 =distributed 'licensed' abstraction scenario (defined by Agency)

TABLE 5.4

Simulated Water Balance Components For Peak Abstraction Year (27)

Comparing Results of Simulation Run 2 and 8

Components	**Sandstone (Two layers)**		**Sands & Gravels[2]**		**Drift**	
Run	2[3]	8[4]	2[3]	8[4]	2[3]	8[4]
Inflows						
Potential recharge	0.0	0.0	0.4	0.4	324.1	324.1
Leakage from Drift	29.0	30.3	9.8	10.0	n.a.	n.a.
Leakage from Sands & Gravels	22.2	28.9	n.a.	n.a.	n.a.	n.a.
Boundary inflows (Carboniferous):						
- South East (Ribble)	4.6	4.7	0.0	0.0	0.0	0.0
- Millstone Grit	0.3	0.3	0.0	0.0	0.0	0.0
- Garstang	0.6	1.0	0.0	0.0	0.0	0.0
Flow from rivers to layer	0.0	0.0	3.2	3.7	0.0	0.0
Storage release	12.2	15.7	9.0	15.0	35.3	36.5
Total inflows	*68.9*	*80.9*	*22.4*	*29.1*	*359.4*	*360.6*
Outflows						
Abstraction	-51.0	-67.8	0.0	0.0	0.0	0.0
Leakage to Sands & Gravels	n.a.	n.a.	n.a.	n.a.	-13.8	-10.0
Leakage to sandstone	n.a.	n.a.	-22.2	-28.9	-31.1	-30.3
Boundary Outflows:						
- Ribble Estuary	-4.1	-4.2	0.0	0.0	0.0	0.0
- Morecambe Bay	-2.1	-2.1	0.0	0.0	0.0	0.0
Groundwater flow to rivers	-11.7	-6.8	0.0	0.0	-16.8	-16.7
Rejected flows (rejected recharge)	0.0	0.0	0.0	0.0	-297.8	-303.6
Storage gain	0.0	0.0	0.0	0.0	0.0	0.0
Total outflows	*-68.9*	*-80.9*	*-22.2*	*-28.9*	*-359.5*	*-360.6*
Model imbalance	*0.0*	*0.0*	*0.2*	*0.2*	*-0.1*	*0.0*

Notes (1) All units Ml/d

(2) The Sands & Gravels aquifer only partially covers the model area

(3) Run 2 = baseline run with historic abstraction (without Courtaulds) and no river augmentation

(4) Run 8 = redistributed 'licensed' abstraction scenario (defined by Agency)

5.5 Impact of Existing Fylde Licences

This scenario (run 9) was run to assess the impact of all existing licensed sources groundwater sources operating at their licensed capacity The NWW boreholes were set at the 'redistributed' three year rates (as in run 7) and all industrial abstractors (ICI, Whitbreads, BNFL and smaller licences) set at their full annual rates[1] (refer to Appendix B for the Fylde licence conditions)[1].

The impact on groundwater levels, river flows and water balance components are described in the sections below.

Groundwater Hydrographs

The model simulates a significant decrease in sandstone groundwater levels from the historical levels throughout the model. The most significant decline in simulated levels are in the north (at ICI and NWW sources W ad Z) as a result of licensed abstractions from ICI boreholes, and in the south of the Fylde aquifer as a result of the increased abstractions from BNFL, Whitbreads and from the smaller industrial sources in the Preston area. This decline is demonstrated in Figure 5.8. The level at the T74 control borehole level falls below the constraining level (8.5 m OD) once every three months on average.

This decline in levels will have significant impact upon the surrounding environment, in particular, on river flows, as is defined in the following sections.

River Flows

Full licensed rates result in much higher levels of leakage from each of the rivers crossing the Fylde aquifer than has been observed historically. Table 5.5 presents the peak levels of leakage from each river section in the model during year 27 of the model prediction. The most seriously effected rivers are in the northern and southern areas, where the maximum increase in abstraction was defined.

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1 The prediction takes account of the licence limit on NWW's Franklaw sources related to ICI's actual abstraction, but not an agreement between ICI and NWW to maintain the ICI abstractions below their licensed rate in exchange for NWW supplying the shortfall from their LCUS source; this agreement has never been implemented and, significantly, is not reflected in the ICI licences.

TABLE 5.5

Maximum Simulated Leakage From the River System (Year 27)

River Reach	Leakage under historical abstractions (Ml/d)	Leakage under full license conditions (Ml/d)	Difference (Ml/d)
River Wyre Upstream of Garstang	2.4	3.3	0.9
River Wyre Garstang to St. Michaels	5.8	6.3	0.5
River Calder	2.2	2.4	0.2
River Brock	3.2	3.6	0.4
Barton Brook	2.8	3.5	0.7
Woodplumpton Brook	2.6	3.9	1.3
River Ribble	0	0	No leakage but river flows reduce by up to 120 l/s (10Ml/d)
Pilling Water	0	0.2	0.2
River Cocker	0	0	0

Water Balance Components

Tables 5.6 and 5.7 show the simulated water balance components for both the baseline (historic) and full licensed abstraction predictions: Table 5.6 presents the average for years 3 to 27 of the simulation, while Table 5.7 presents the average during year 27 (or 1995) as a peak abstraction year.

The average water balance components for the runs (Table 5.3) show significant changes in vertical leakage through the Drift and sands & gravels, as well as the storage changes and river leakages. The increase in abstraction of 20.4 Ml/d between years 3 and 27 is derived from the following sources:

- vertical leakage through the Drift (10.2 Ml/d) and sand & gravels (1.2 Ml/d)
- reduced total groundwater to the rivers (8.3 Ml/d)
- reduced outflow to Morecambe Bay and the Ribble Estuary (1.0 Ml/d)
- increased inflow from the Carboniferous Deposits (1.3 Ml/d)

During year 27, the model also simulates increased leakage, reduced river flows and changes to the flows at the model boundary along with a decrease in groundwater resources.

As well as reducing groundwater resources and causing a decline in river flows, the outflow at Morecambe Bay is reduced (by up to 20%) as a result of abstractions primarily from the ICI boreholes. It is important that at least the present levels of outflow are maintained, or there may be a further reduction in the available groundwater resource as a result of saline water intrusion at the coast.

5.6 Licensed Augmentations

Augmentation of the rivers, according to NWW licences, does not result in an increase in leakage to the underlying aquifer system. Consequently, as long as augmentation does not result in additional abstractions, the volume of water added to the river results in an increase in river flows at all points downstream of the augmentation point equal to the augmentation inflow rate.

However, licensed augmentation rates are insufficient to maintain river flows at the gauging stations above the prescribed limits.

TABLE 5.6

Average Simulated Water Balance Components (Years 3 - 27)
Comparing Results of Simulation 2 and 9 (Full Licence Conditions)

Components	**Sandstone** (Two layers)		**Sands & Gravels**[2]		**Drift**	
Run	2[3]	9[4]	2[3]	95[4]	2[3]	9[4]
Inflows						
Potential recharge	0.0	0.0	0.8	0.8	623.6	623.6
Leakage from Drift	31.1	41.3	13.8	13.9	n.a.	n.a.
Leakage from Sands & Gravels	18.4	18.6	n.a.	n.a.	n.a.	n.a.
Boundary inflows (Carboniferous):						
- South East (Ribble)	4.6	5.6	0.0	0.0	0.0	0.0
- Millstone Grit	0.3	0.4	0.0	0.0	0.0	0.0
- Garstang	0.5	0.7	0.0	0.0	0.0	0.0
Flow from rivers to layer	0.0	0.0	3.7	3.9	0.0	0.0
Storage release	0.5	0.2	0.2	0.1	1.2	1.4
Total inflows	*55.4*	*66.8*	*18.5*	*18.7*	*624.8*	*625.0*
Outflows						
Abstraction	-34.0	-54.4	0.0	0.0	0.0	0.0
Leakage to Sands & Gravels	n.a.	n.a.	n.a.	n.a.	-13.6	-13.9
Leakage to sandstone	n.a.	n.a.	-18.4	-18.6	-30.6	-41.3
Boundary Outflows:						
- Ribble Estuary	-4.2	-3.9	0.0	0.0	0.0	0.0
- Morecambe Bay	-4.2	-3.5	0.0	0.0	0.0	0.0
Groundwater flow to rivers	-13.3	-5.0	0.0	0.0	-20.1	-19.0
Rejected flows (rejected recharge)	0.0	0.0	0.0	0.0	-560.3	-550.8
Storage gain	0.0	0.0	0.0	0.0	0.0	0.0
Total outflows	*-55.7*	*-66.8*	*-18.4*	*-18.6*	*-624.6*	*-625.0*
Model imbalance	*-0.3*	*0.0*	*0.1*	*0.1*	*0.2*	*0.0*

Notes
(1) All units Ml/d
(2) The Sands & Gravels aquifer only partially covers the model area
(3) PB01 = baseline run with historic abstraction (without Courtaulds) and no river augmentation
(4) PB05= 'Redistributed NWW abstraction scenario with all industrial abstractions at licensed rates

TABLE 5.7

Simulated Water Balance Components For Peak Abstraction Year (27)

Comparing Results of Simulation Runs 2 and 8 (Full Licence Conditions)

Components	Sandstone (Two layers)		Sands & Gravels[2]		Drift	
Run	2[3]	9[4]	2[3]	9[4]	2[3]	9[4]
Inflows						
Potential recharge	0.0	0.0	0.4	0.4	324.1	324.1
Leakage from Drift	29.0	38.5	9.8	10.2	n.a.	n.a.
Leakage from Sands & Gravels	22.2	29.5	n.a.	n.a.	n.a.	n.a.
Boundary inflows (Carboniferous):						
- South East (Ribble)	4.6	5.6	0.0	0.0	0.0	0.0
- Millstone Grit	0.3	0.4	0.0	0.0	0.0	0.0
- Garstang	0.6	1.1	0.0	0.0	0.0	0.0
Flow from rivers to layer	0.0	0.0	3.2	4.2	0.0	0.0
Storage release	12.2	17.0	9.0	14.8	35.3	40.6
Total inflows	*68.9*	*92.1*	*22.4*	*29.6*	*359.4*	*364.7*
Outflows						
Abstraction	-51.0	-85.3	0.0	0.0	0.0	0.0
Leakage to Sands & Gravels	n.a.	n.a.	n.a.	n.a.	-13.8	-10.2
Leakage to sandstone	n.a.	n.a.	-22.2	-29.5	-31.1	-38.5
Boundary Outflows:						
- Ribble Estuary	-4.1	-3.9	0.0	0.0	0.0	0.0
- Morecambe Bay	-2.1	-1.8	0.0	0.0	0.0	0.0
Groundwater flow to rivers	-11.7	-1.1	0.0	0.0	-16.8	-16.2
Rejected flows (rejected recharge)	0.0	0.0	0.0	0.0	-296.8	-299.8
Storage gain	0.0	0.0	0.0	0.0	0.0	0.0
Total outflows	*-68.9*	*-92.1*	*-22.2*	*-29.5*	*-359.5*	*-364.7*
Model imbalance	*0.0*	*0.0*	*0.2*	*0.1*	*-0.1*	*0.0*

Notes
(1) All units Ml/d
(2) The Sands & Gravels aquifer only partially covers the model area
(3) Run 2= baseline run with historic abstraction (without Courtaulds) and no river augmentation
(4) Run 8='redistributed' NWW abstraction scenario with all industrial abstractions at licensed rates

5.7 Licence Applications in the Preston Area

Most of the model runs in this category were carried out using the preliminary model calibration. With so many changes to the geological structure in this area, the conclusions presented in the Phase III reports and the report submitted to NWW on the development of Courtaulds boreholes, although still valid (as described in section 5.2), should be treated with some caution. Nevertheless, the following conclusions can be drawn from the model runs which investigate increased groundwater abstractions in the 'Southern Fylde and Preston' area:

- With an increase in abstraction of 900 Ml/annum (for all recent enquiries/licence applications) the model simulated a decline in groundwater levels of about 0.15 m at control borehole T74 (SD43/19). This results in levels falling below the 'hands-off' level of 8.5 m OD, which prevents NWW from operating their Broughton'A' sources. With only one additional licence for 90 Ml/annum added, the decline at this borehole is limited to about 0.02 m (assuming all other abstractions were at historical rates; in the case of BNFL and Whitbreads these have been significantly below the annual licensed quantities).

- Groundwater levels around Preston may decline by as much as 1.8 m if 900 Ml/annum additional abstraction was allowed. This would seriously affect existing user particularly Whitbreads and to a lesser extent the southerly NWW sources.

- With 900 Ml/annum additional abstraction, groundwater levels decline as far north as the River Calder, which causes a reduction in the river flows measured at St Michaels gauging station. With 90 Ml/annum additional abstraction, groundwater level decline as far north as Barton Brook, but without inducing any additional river flow losses from Woodplumpton and Barton Brooks.

- The major impact of abstraction from new abstraction boreholes in the Preston will be on River Ribble flows The simulated River Ribble flows have not been calibrated against the actual observed flows. Consequently there is less confidence in the simulated river/aquifer interaction at this river.

  With an additional abstraction of 90 Ml/annum (Emmett Denim Care) the model simulates losses of about 2 l/s. This is not concentrated at the river nearest the source, but is spread throughout the length of the River Ribble since the aquifer is confined and there is reduced baseflow to the river as a result of the decline in sandstone levels.

- Redevelopment of the abandoned Courtaulds boreholes will result in a further decline in pumping water levels at the Whitbread sources and a reduction in flow in the Ribble.

Note: The above predictions are not exhaustive; some have been used to test the sensitivity and validity of the model during the calibration process. Others were used to investigate the impact of different abstraction scenarios on existing groundwater sources and resources, and on surface water interests. They serve to illustrate how the model can be used in the predictive mode for management purposes, as an aid to decision making.

It is intended to run additional scenarios and repeat previous ones as the model is updated and recalibrated (see Chapter 6).

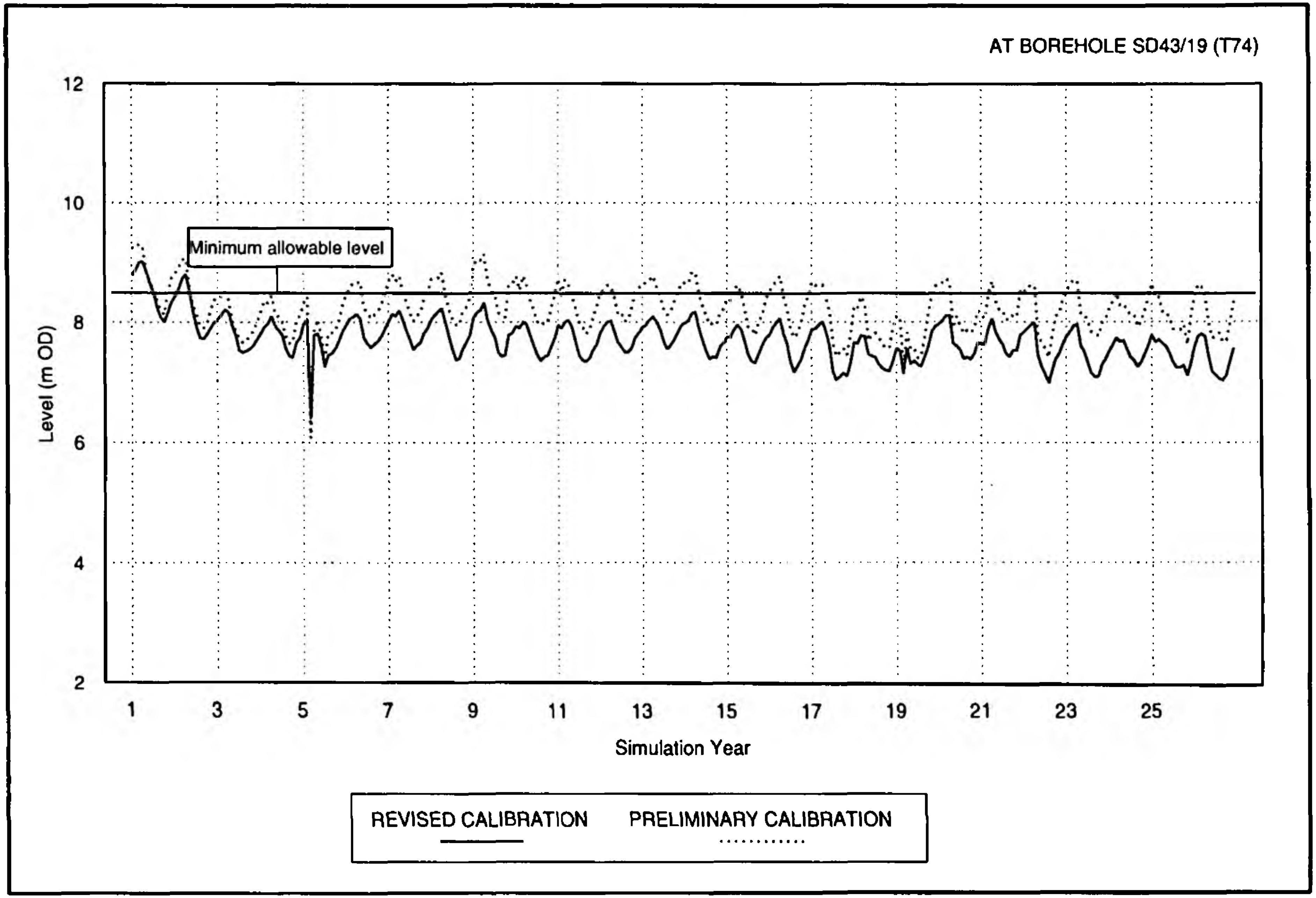


Figure 5.1

Comparison of Predictions at Control Observation Borehole

Figure 5.2A

Accretion Profile for River Wyre Comparing 3 Year Licensed Abstractions Using Different Model Calibration

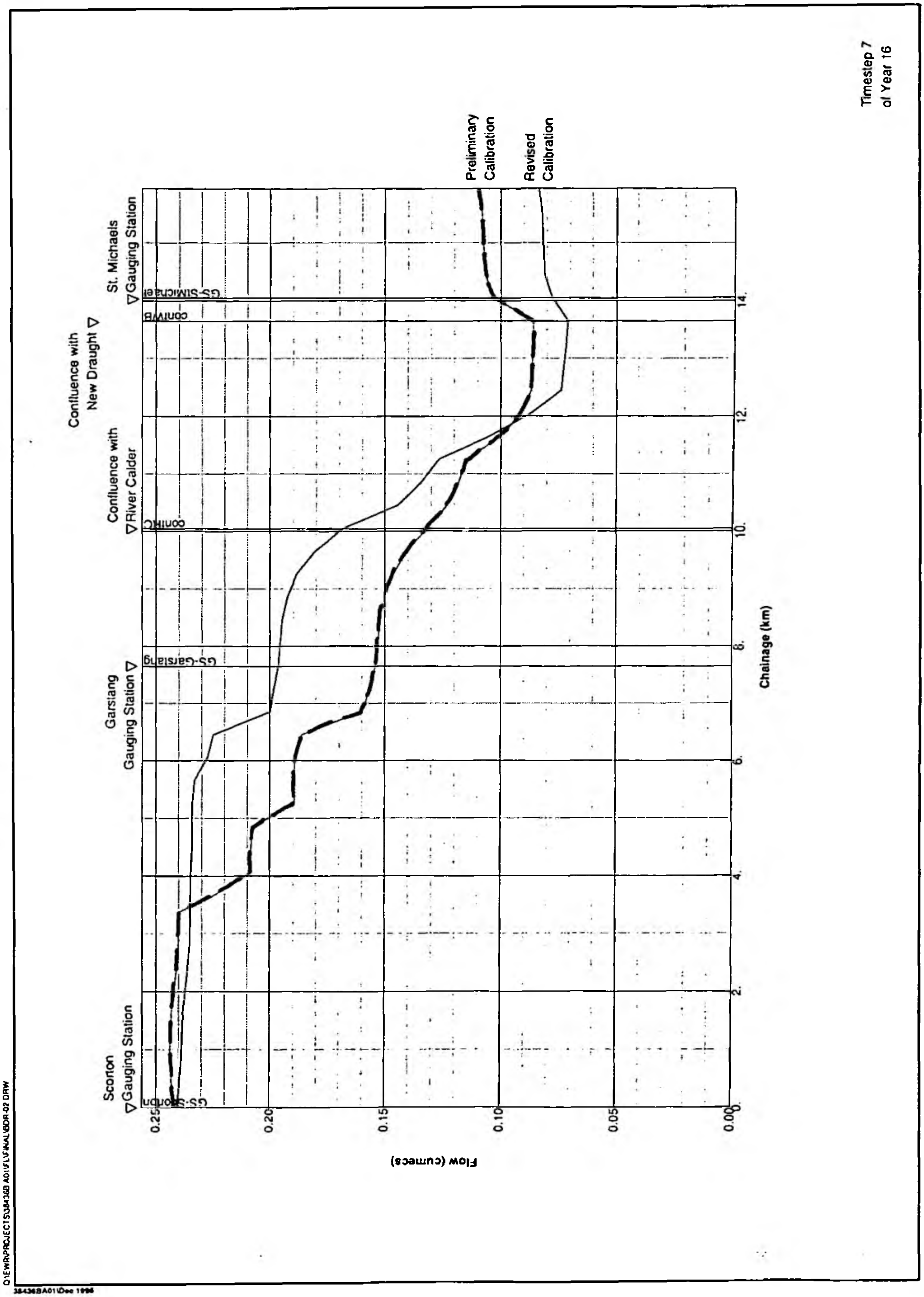
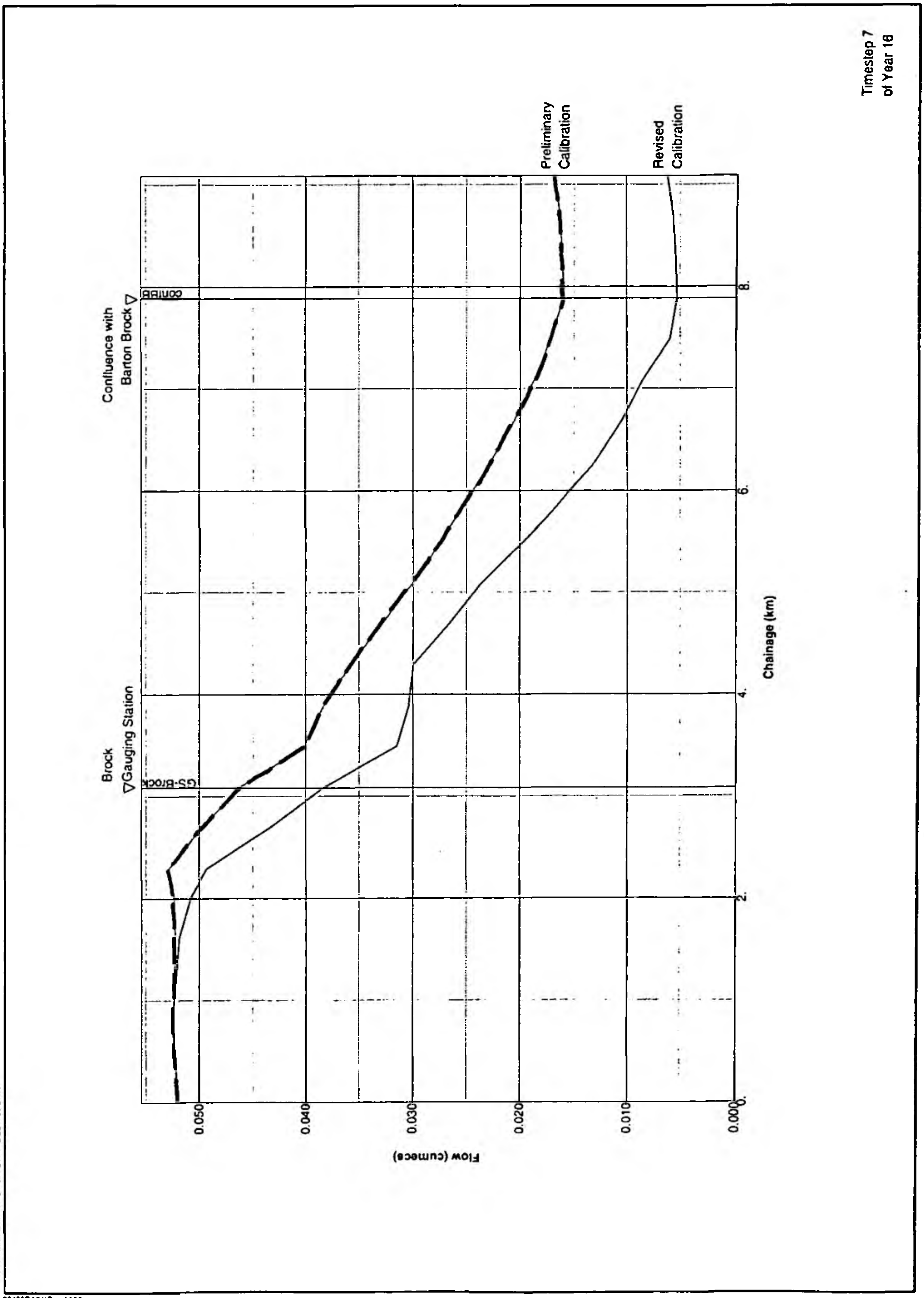


Figure 5.2B

Accretion Profile for River Brock Comparing 3 Year Licensed Abstractions Using Different Model Calibration



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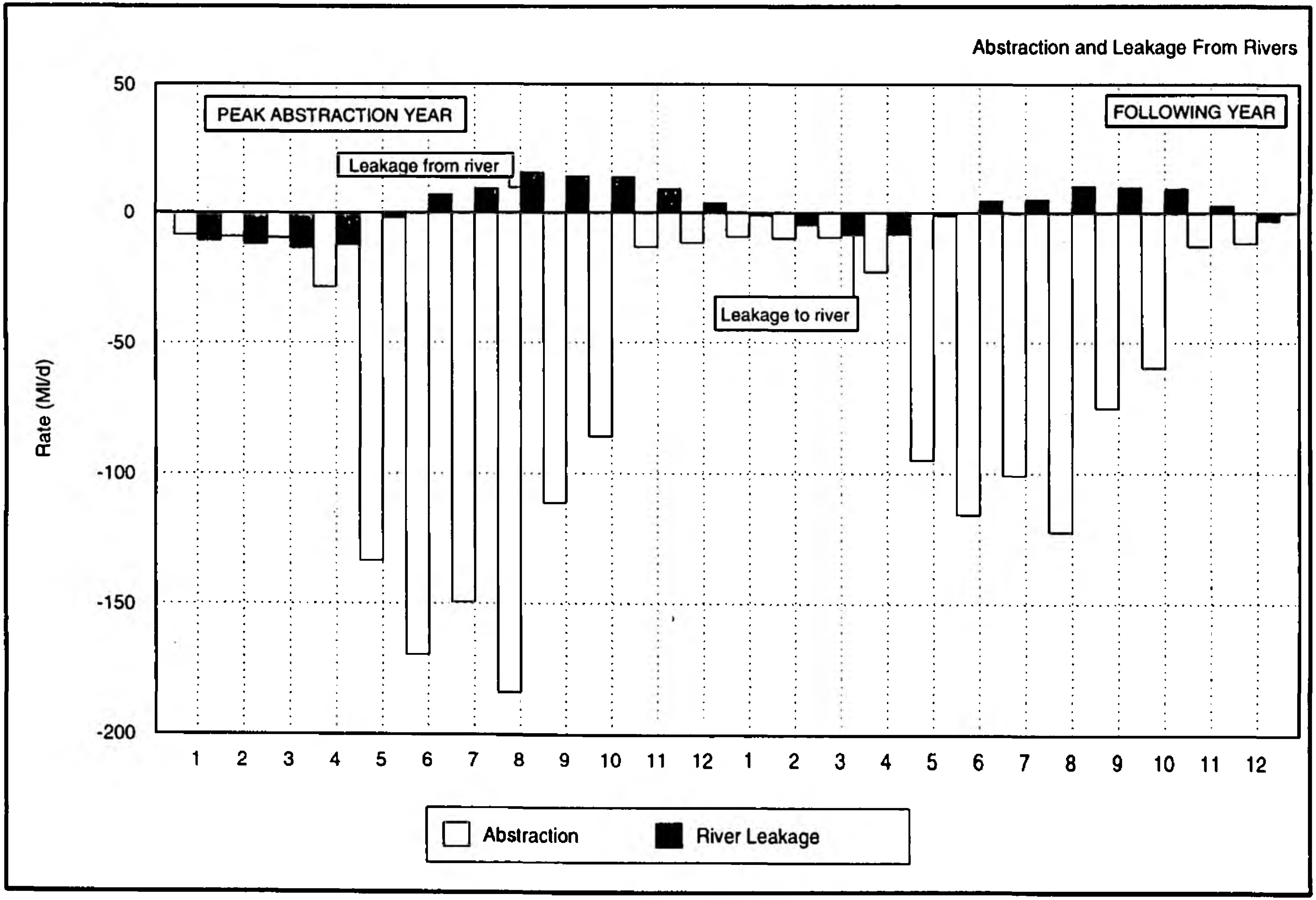


Figure 5.3
Leakage from Rivers Under Full Licensed Abstractions

Figure 5.4

Comparison of Historic NWW and Run 8 Abstractions (Operation at Licensed Rates, Redistributed for Climate Demand)

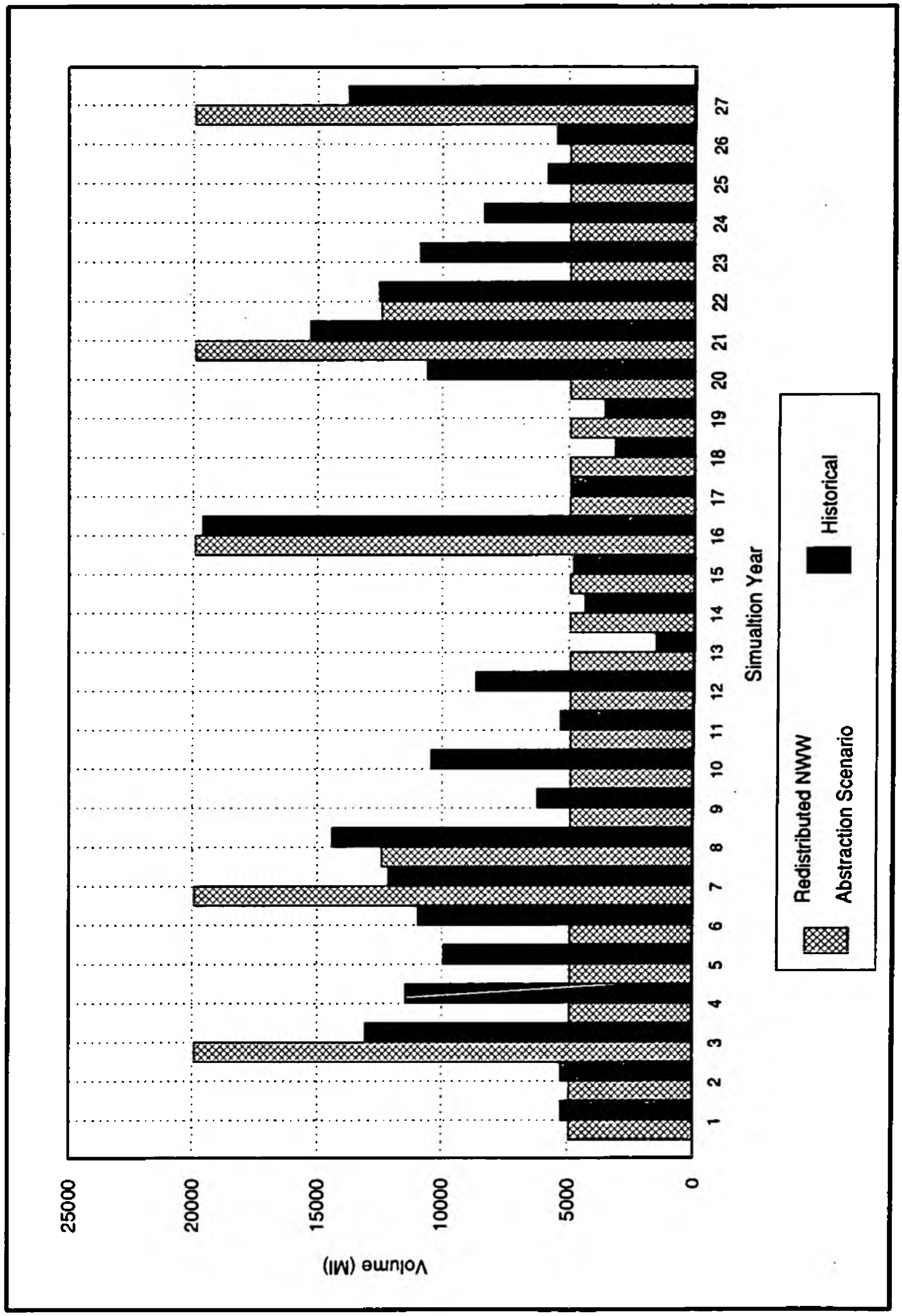
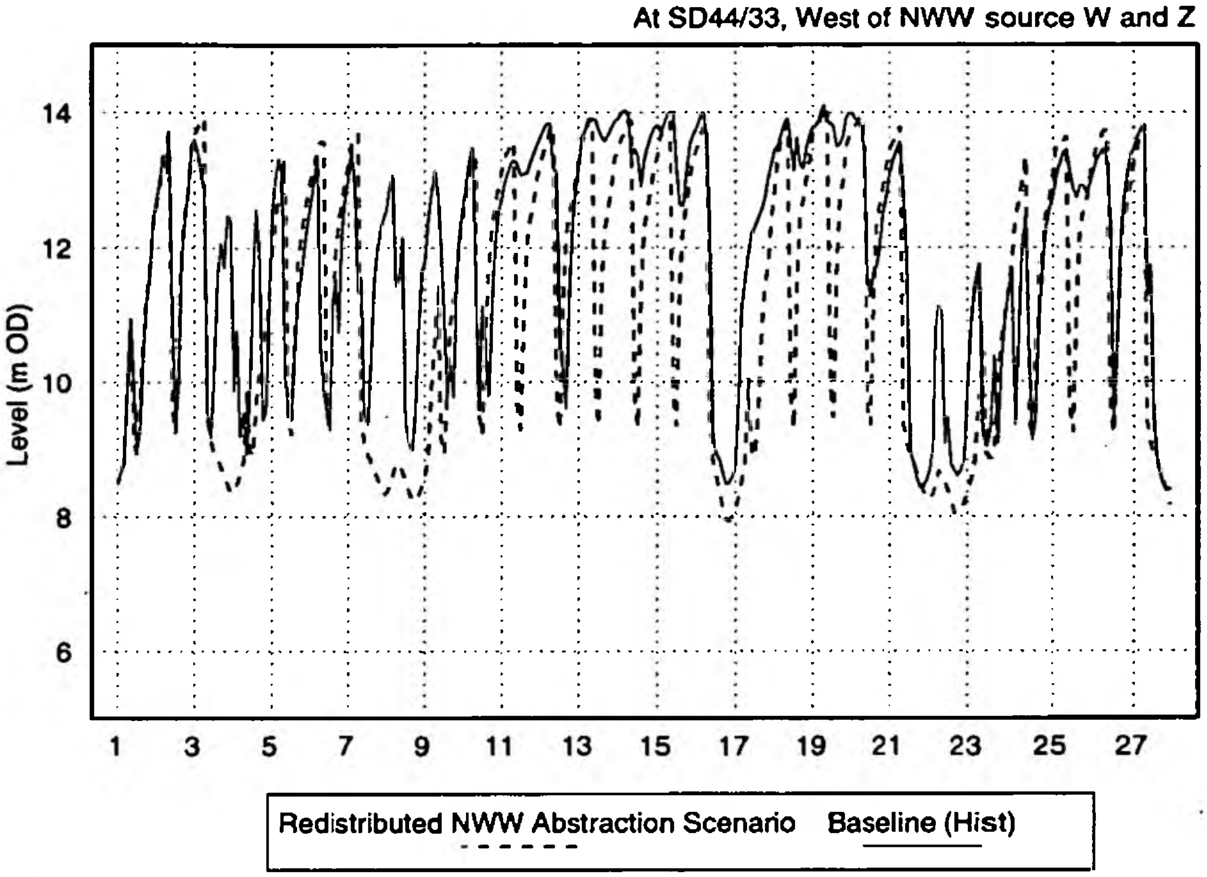


Figure 5.5

Redistributed NWW Abstraction Scenario: Groundwater Hydrographs I



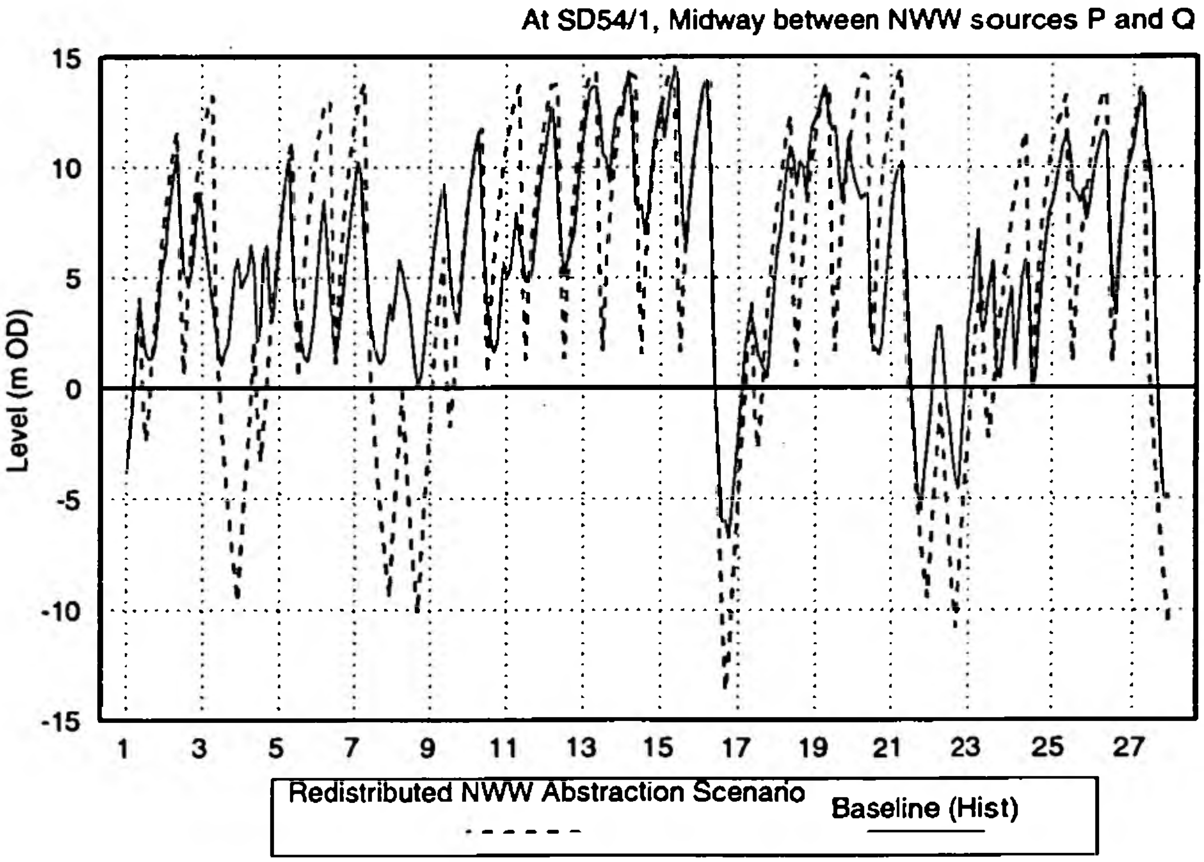
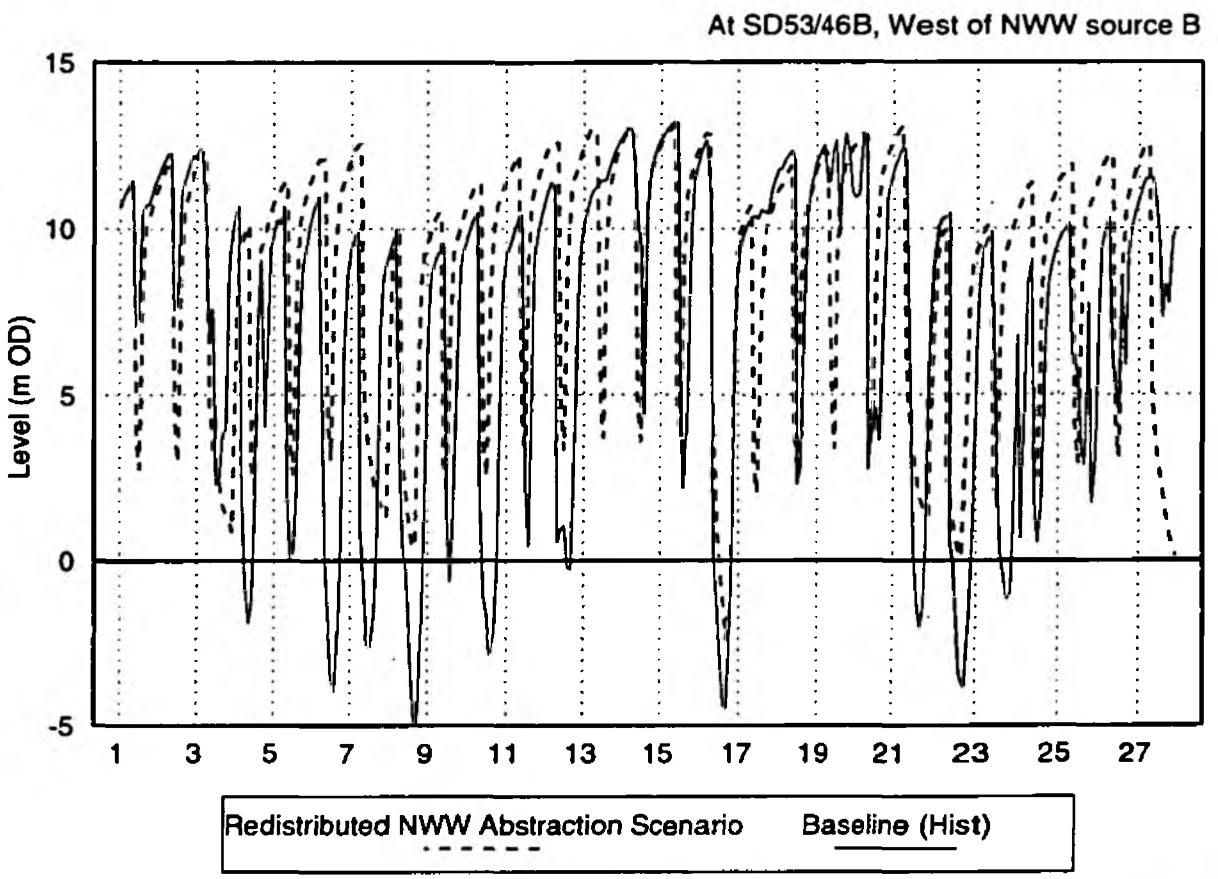
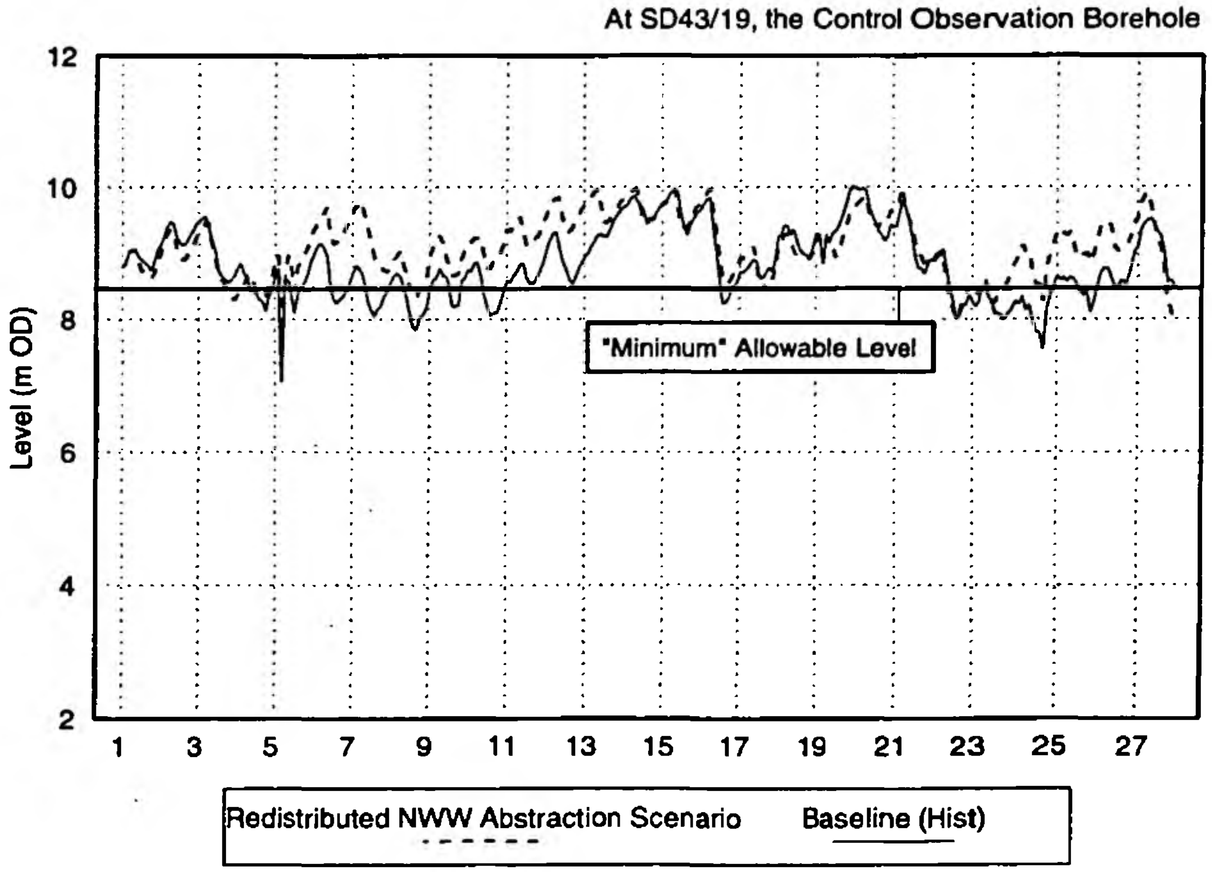


Figure 5.6

Redistributed NWW Abstraction Scenario: Groundwater Hydrographs II





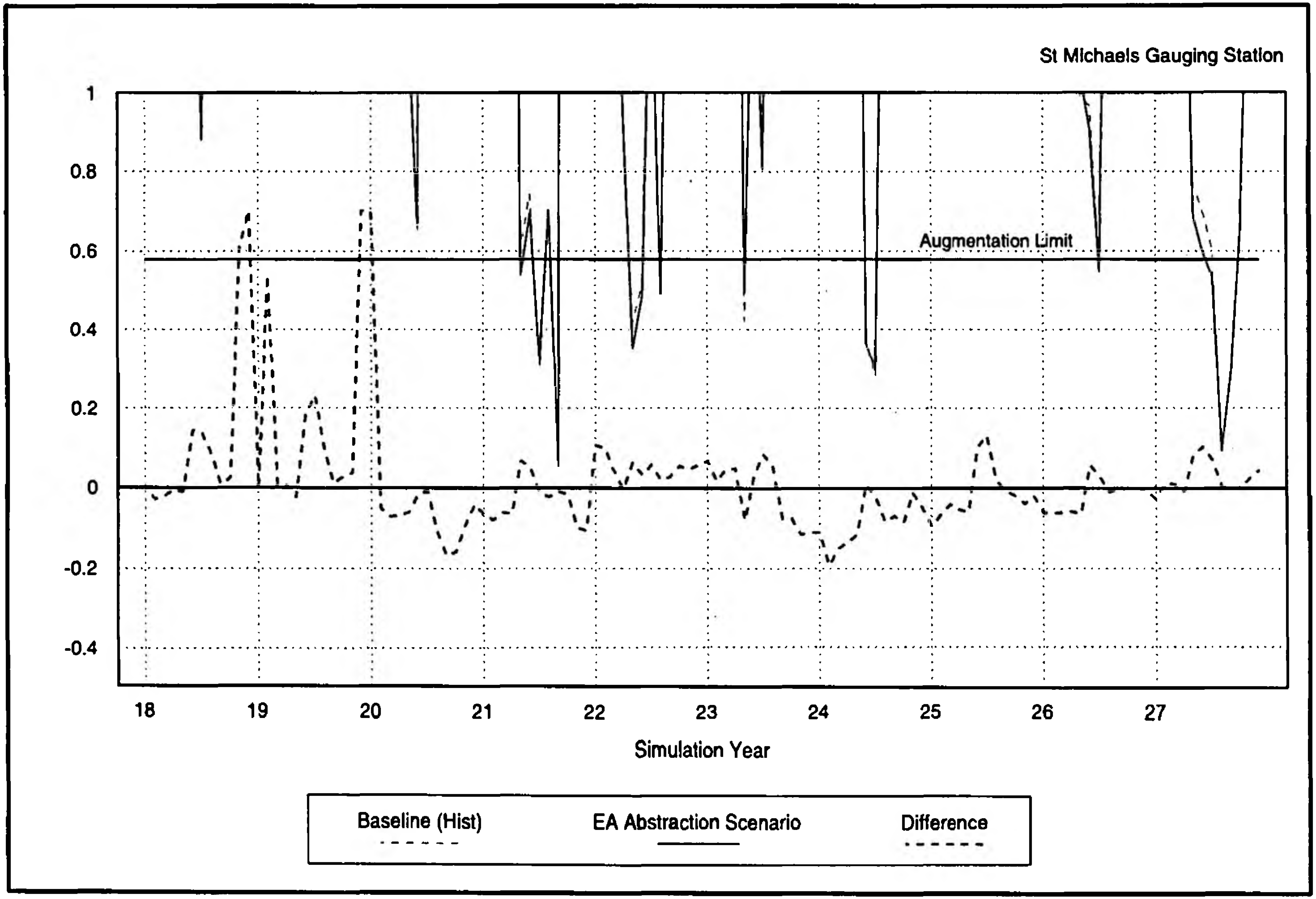
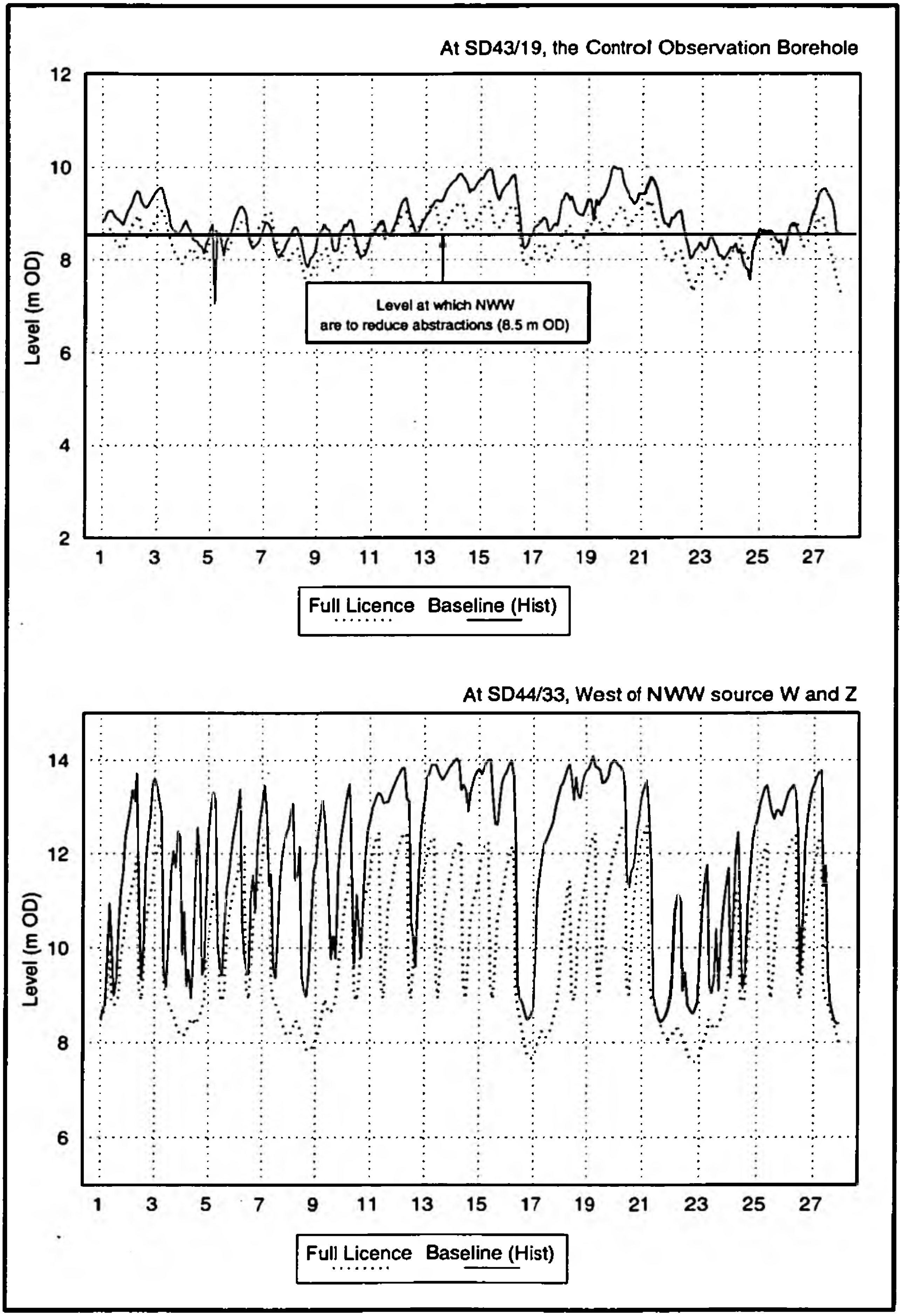


Figure 5.7
Simulated Flows at St Michaels (Run 8)

Figure 5.8

Simulated Groundwater Levels - Full Licence Conditions



CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

6.1.1 Specific Objectives

In terms of the specific objectives of the Fylde Aquifer/Wyre Catchment Water Resources Study (as set out in Section 1.3) the following conclusions can be drawn:

(i) Response of the Fylde aquifer to 20 years of operational use of the LCUS

Since the Fylde aquifer was first developed as part of the LCUS in the mid 1970's, the NWW boreholes have been operated on a seasonal basis to meet demand when surface water sources were not available. The peak abstractions have coincided with periods of drought, most notably in 1984 and 1995/96. Actual abstractions have been well below the annual licensed rates. Despite this, the following have been observed:

- there has been a general decline in groundwater levels to the south east and south west of NWW's Broughton abstraction boreholes. This has caused the hands-off levels in control boreholes T74 and T68[1] to be breached. These trends are attributable to NWW's abstractions causing drainage from a relatively isolated block of aquifer to the east and intercepting/preventing natural discharge 'down gradient', towards the BNFL sources and the Ribble estuary, west of Preston;

- although there has been no overall long-term decline in groundwater levels in the central part of the Fylde aquifer, around NWW's main abstraction sources (within the Wyre catchment), the aquifer recovers very slowly after periods of heavy abstraction e.g. it took three years to fully recover from the 1984 drought. Significantly, groundwater levels fell to their lowest on record and showed no recovery during the normal recharge season following the severe drought of '95/96;

- NWW experienced a fall in output from certain sources during the intensive pumping of their northern (Franklaw) boreholes during 1995;

- flow measurements carried out during '94-'95 have identified losses in river flows over extensive reaches of most watercourses in the Wyre catchment during and following NWW's seasonal abstractions;

- losses/deterioration in wetland features have been recorded across the Fylde aquifer since the LCUS

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1 originally imposed to protect the BNFL and former Courtaulds sources from derogation. The T68 limitation has been removed from the NWW licence with the closure of Courtaulds factory in the mid 1980's

abstraction commenced [2] (APEM, 1995).

(ii) Integrated groundwater/surface water numerical model

The Mott MacDonald Integrated Catchment Management Model (ICMM) has been successfully developed and adapted to the complex hydrogeological conditions of the Fylde aquifer[3]. It has taken account of the considerable amount of hydrometric, geological, hydrogeological, geochemical and abstraction data available for the study area; this has required the compilation of a comprehensive database.

The model was initially calibrated against, and proved capable of accurately simulating, observed groundwater levels and trends and river flows, including groundwater/surface water interaction (particularly under low flow conditions) over the 28 year period between 1969-96.

The geological structure of the Fylde aquifer has been re-evaluated and revised during the course of the Study, based on additional exploratory drilling and geophysical evidence, in conjunction with the model calibration process. The most significant changes are:

- enhanced understanding of Carboniferous boundary; there are relatively limited sections where the Sherwood Sandstone is in direct contact with the thicker sandstone units of the Millstone Grit Series in the northern half of the Fylde;
- the Sherwood Sandstone contains significant marl layers, effectively producing a multi-layered aquifer system;
- the aquifer is dissected and displaced by dominant N-S trending faults, resulting in localised horizontal anisotropy in aquifer permeability and marked variations in aquifer thickness (producing a series of ridges/horsts and troughs/graben);
- the line of the Woodsfold Fault has been revised. This has the effect of reducing the south western extent of the Fylde aquifer;
- although the majority of the aquifer is overlain by low permeability clay till (boulder clay), the drift geology is highly variable; there are extensive and thick sand & gravel deposits overlying bedrock which are locally in direct hydraulic connection with watercourses.

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2 although it has not been possible to establish whether there are other causes, e.g. land drainage works, urban redevelopment

3 although the scope of the Study was originally focussed on the low flow problems on the Wyre catchment it is apparent that the effects of abstraction extend across the whole of the Fylde aquifer, including part of the Ribble catchment in the south up to the Pilling in the north.

The key findings of the model (on a sub-area basis - Chapter 4) are:

Area 1 North West Fylde

- Abstractions from ICI sources, and to a lesser extent from NWW sources W and Z (in Area 2), caused a reversal from the historical upward leakage at the Winmarleigh Mosses SSSI, which may have resulted in a reduction of surface water levels/discharges around the SSSI.

- ICI abstractions reduce outflow to Morecambe Bay. This could potentially lead to a deterioration in groundwater quality in the north west of the Fylde as a result of saline intrusion[4].

Area 2 Garstang

- NWW sources W and Z cause a loss of flow in the River Wyre .

- Under non-pumping conditions, there is only a limited inflow of water from the sandstone formations of the Carboniferous along the eastern boundary, with NWW's abstraction only inducing small additional inflows.

Area 3 Central Fylde

- Abstractions from the central NWW sources (Franklaw 'A' & 'B' and Broughton 'B' boreholes) induce losses from various stretches of all watercourses within the Wyre catchment.

- The sands & gravels which directly overlie the sandstone aquifer in this area act as an important storage reservoir for NWW abstractions. Without this additional storage, abstractions would result in higher river losses during summer.

- Groundwater abstractions do not induce additional flow from the Carboniferous boundary because very low permeability Manchester Marls separate the Carboniferous from the Sherwood Sandstone aquifer.

Area 4 Preston & Southern Fylde

- There is marked horizontal anisotropy in aquifer permeability (caused by faulting) to the west of NWW Broughton 'A' sources (sites B, C and D) limiting the east-west groundwater flow in this area.

- The main 'trough' of aquifer exploited by NWW's boreholes is effectively hydraulically isolated by structural controls from the upstream end of the Ribble valley - the 'Red Scar Basin', in which the Whitbreads and the former Courtaulds boreholes are situated. (forming part of the South East Fylde area)

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[4] The agreement between ICI and NWW, to maintain the ICI abstractions below their licensed rate in exchange for NWW supplying the shortfall from their LCUS sources, has not operated during the calibration period.

- Sands & gravels in the west of the area, at the Woodsfold Fault, act as a conduit linking Woodplumpton and Barton Brooks with the sandstone aquifer, resulting in river flow losses during abstractions from the central area and NWW's B, C and D sites.

Area 5 South East Fylde

- Groundwater levels within the upstream end of the Ribble catchement (i.e. the 'Red Scar basin', around Whitbreads and the former Courtaulds sites) are controlled by the river valley and inflows from the Carboniferous.

Although a very good agreement in sandstone piezometry, groundwater levels and river flow hydrographs has been achieved throughout the model over the calibration period, there remains some degree of uncertainty. This relates in particular to:

- The geological structure and hydrogeological flow mechanisms of the sandstone between the main trough of aquifer exploited by NWW's sources, which extends into Preston, and the 'Red Scar Basin'. Recent geological and hydrogeological evidence has allowed further reconceptualisation of the geological structure. This broadly supports the settings defined in the numerical model, although the actual structure differs slightly from that built into the model.

- The river/aquifer interaction defined at the River Ribble has not been calibrated against observed flows.

- In the model, outflow to the west beneath the Mercia Mudstone has been set to zero. Although this is a reasonable assumption, there is no evidence to confirm this.

- detailed mechanisms for recharge to the sandstone aquifer via the Drift, with special reference to the '95/'96 drought response

(iii) Validity of WRc model & LCUS licence conditions

The boundary conditions of the Fylde aquifer, as defined in the model developed by WRc in 1973, are no longer considered to be valid. In the WRc model, the impacts of groundwater abstractions on the environment were minimised since the Carboniferous system to the east was considered as a reservoir with infinite storage. The current study has shown that groundwater abstractions from the Fylde aquifer are not balanced by inflow from the Carboniferous. Geological evidence indicates that there are only very limited sections of the Fylde aquifer in direct contact with the Carboniferous sandstone aquifers. Therefore, the volume of groundwater flow across the boundary between the Carboniferous and Permo-Triassic is much lower than assumed by WRc.

In the current, revised model, recharge to the sandstone aquifer is restricted by the low vertical conductance of the Drift deposits. A deficit in vertical flow through the Drift caused by historical public supply and industrial abstractions is made up in part by induced leakage from the surrounding rivers system, particularly in the Wyre catchment. The impacts of groundwater abstractions on the environment are therefore more pronounced than previously assumed when the LCUS licence was granted; the integrated groundwater/surface water model developed during the Study more accurately represents these mechanisms and effects.

This has an important bearing on the sustainability of currently licensed groundwater abstractions and the effectiveness of the existing licence conditions to adequately protect the aquatic environment.

(iv) Predictions: impact of specified abstraction/climate scenarios

Of the abstraction scenarios run to date, a number have been to test the sensitivity and validity of the model. Others have been used to investigate the impact of existing and possible additional licensed groundwater sources on the protected rights of existing abstractors, on groundwater resources, surface waters and groundwater dependant features. Although additional scenarios need to be considered and previous runs repeated for revised model calibrations, the model has demonstrated that if:

All existing licensed sources were operated at full licensed rates[5] (under historic climatic conditions)

- there would be a serious impact upon the environment: river flows would be substantially reduced in summer and some river reaches would dry up (along the River Calder, Brock, Barton Brook and Woodplumpton Brook) and wetlands such as Winmarleigh Mosses, would be adversely affected. The flow augmentation conditions attached to NWW's licences are inadequate to fully protect the watercourses.

- there is potential for saline intrusion from Morecambe Bay causing a deterioration in groundwater quality in the north east of the Fylde, which could adversly affect the ICI sources.

- there would be a severe and possibly irreversible decline in groundwater storage in parts of the Fylde aquifer (particularly to the south of Woodplumpton Brook); groundwater levels in the area around the control borehole T74 could continue to decline. This would seriously constrain abstraction from NWW's Broughton sources in the south. The licence conditions are such that it would also limit abstraction from the Franklaw groups further north.

- the decline in groundwater levels along the Ribble valley would result in a reduction of baseflow to the Ribble from the aquifer 10Ml/d (i.e. about 6% of the low flow assumed in the model).

- although not specifically simulated in the model, the observed response of the aquifer and NWW's Franklaw borehole performances during the '95/'96 drought indicates that they would experience difficulties in maintaining their licensed output from these sources; considerable periods of non-pumping would be necessary to allow the aquifer to recovery sufficiently to ensure reliability of output /security of supply in

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5 The prediction takes account of the licence limit on NWW's Franklaw sources related to ICI's actual abstraction, but not the agreement between ICI and NWW to reduce the ICI abstraction (see Footnote 4); this agreement has never been implemented and, significantly, is not reflected in the ICI licence.

subsequent years.

Additional abstraction in Preston (using actual historic abstractions and climate conditions)

- With an increase in abstraction of 900 Ml/annum representing the increase if all recent enquiries/licence applications for the Preston area were allowed) the initial model calibration ('69-'94) simulated a decline in groundwater levels around Preston by about 1.8 m; this could derogate existing local licensed sources. The control borehole T74 would be subject to additional drawdowns of about 0.15 m. This would prevent NWW from operating their Broughton 'A' sources at times when the water level falls below the licence threshold ('hands-off level'). It would also limit abstraction from their other borehole groups further north because of the integrated nature of the LCUS licences and operating rules. As such, this scale of additional abstraction would constitute derogation of their protected rights.

- With only one additional licence in Preston (for 90 Ml/annum) the revised calibration predicts an induced decline of about 0.02 m at T74. Although small, again, this would represent derogation of NWW's abstraction rights at times when it caused the groundwater level to fall below the licence threshold.

- The other impact of abstraction from any new abstraction boreholes in Preston will be on flows in the River Ribble.

6.1.2 Overall Aims

In addressing the overall aims of the Fylde Aquifer/Wyre Catchment Water Resources Study (Section 1.3) , the work to date has significantly increased the understanding of the behaviour and controls on the groundwater and surface water systems and their interaction and response to abstraction..

(i) Adequacy of Groundwater Resources

The study has highlighted the fact that the reliable output from the LCUS groundwater sources is less than that predicted when the Scheme was originally licensed.

The results indicate that the aquifer is over-licensed; even under the historic abstraction regime over the past quarter of a century there has been detriment to the aquatic environment, particularly in the Wyre catchment and northwards. The aquifer could not sustain the current licensed quantities without depletion of aquifer storage, deterioration in quality, falling groundwater levels and further impact on surface water flows and wetland features.

It is therefore concluded that the aquifer cannot support additional/increased groundwater abstraction without derogating existing protected rights and/or exacerbating the adverse effect on the surface aquatic environment.

(ii) Alleviation of Low Flows

There is a need to investigate possible solutions to mitigate or at least ensure no further deterioration in the low flow problems of the Wyre catchment whilst having regard to the rights of existing licence holders, in particular maintaining the strategic role of the Fylde aquifer as part of North West Water's integrated regional water resource network.

(iii) Management Plan for Sustainable Use of Groundwater & Surface Water Resources

The findings of the Study indicate that the Fylde aquifer is over-licensed; the short term management plan should be to prevent an increase in either actual or licensed abstraction, although options for 'redistributing' abstraction could be considered.

A longer term strategy for the alleviation of low flows whilst safeguarding the security of public water supply will require further investigation and analysis.

The groundwater/surface water model developed during this Study provides a tool to address these issues.

6.2 Recommendations

The objectives of future work in the Fylde aquifer are twofold:

- to reduce areas of uncertainty in the model calibration, including hydrogeological controls on the aquifer system, thereby increasing confidence in the model;

- to investigate different abstraction/augmentation scenarios to safeguard the aquatic environment whilst optimising groundwater abstractions i.e.sustainable development of resources.

The first objective is satisfied through further hydrogeological research, including the construction of additional exploratory/observation boreholes, continued and improved monitoring of groundwater levels and surface flows and the continuous use of the model. These items are described in the following four sections.

The final section describes the work required to develop a water resource management plan for the Fylde aquifer.

6.2.1 Hydrogeological Research

The major area of uncertainty in the calibrated model is the influence of fracturing (faulting) on flow mechanisms & borehole output. The Fylde model can be used to investigate the likely significance of fracturing (high tranmissivity/low storage) on the reported decline in output from certain NWW sources during heavy pumping in the '95/96 drought. This aspect is principally of concern to NWW from an operational perspective, albeit also relevant to redefining the reliable output from their Fylde groundwater sources.

The influence of fracturing would form an important part of any feasibility study into aquifer storage and recovery (ASR) - see Section 6.2.5 below), requiring both desk study and field investigations.

6.2.2 Observation Borehole Network Enhancement

Preston

There are relatively few observation boreholes in and around Preston, although there is considerable local interest in additional abstraction. The Agency has recently lost access to a previously disused but licensed borehole at Liquid Plastics, due to it being recommissioned. This was an important part of the network in central Preston. The hydrograph for this source showed a continuous declining trend over the last 20 years or so. Therefore, there is a need for the network to be enhanced in this area.

A data logger should will be installed on the new Moor Park exploratory borehole which will then be incorporated into the observation network.

It is proposed that a survey is carried out of sites with existing licensed sources or records of old boreholes. Suitable sites should ideally have loggers installed and brought into the network. Depending on the results of this survey, it may be necessary to construct up to three 100m deep purpose drilled boreholes at key locations, as well as possibly into the Drift (see below).

Drift

Abstractions from the Fylde aquifer are generally satisfied by vertical leakage through the overlying Drift deposits, and from river leakage. In the model, the Drift has been simulated as a single layer, thus simplifying the leakage mechanism. Although there is confidence in the simulation of leakage in the model, the construction of a number of Drift observation boreholes would aid the understanding of the Drift leakage mechanism at a local scale which could be related to the leakage calculations defined regionally within the groundwater model. There are four areas where Drift observation boreholes are recommended:

- In Preston, to assess the relationship between shallow sand aquifers in the Drift and the deeper sandstone aquifer. Borehole pumping test results and groundwater level trends/responses indicate that the sandstone is confined and that recharge is limited (as assumed in the model). However, certain borehole logs identify significant sand bodies. It is uncertain whether these could provide preferential recharge pathways. (Site investigation data may be available in this area to assist in better understanding the Drift/sandstone aquifer relationship).

- At the T74 control borehole (SD43/19), where lithology indicates the Drift consists of a sands & gravels layer bounded above and below by stiff boulder clay. In this area, sandstone groundwater levels have been declining since the early 1970's. The Drift observation boreholes would be used to assess the interaction between the Drift and sandstone, and in particular, the influence of the sands & gravels;

- In the Central area, around NWW abstraction source L, where the impact of abstraction on Drift water levels could be observed (there may be suitable boreholes available from the original LCUS investigations);

- In or adjacent to Winmarleigh Moss; depending on the lithology, completion into sandstone bedrock may be approriate.

6.2.3 Monitoring

Groundwater Levels

General

Monitoring of groundwater levels in the existing comprehensive network of observation boreholes and NWW's abstraction sources[7] should be continued as present; monthly manual dipping (by NWW) supplemented by data loggers installed on new boreholes and other strategic sites.

BNFL/T74

In view of the critical role[8] of the T74' control level in terms of NWW's LCUS abstractions, it is essential to understand the relative influence of BNFL's and NWW abstractions compared with barometric and normal seasonal effects on the groundwater level trend therein. Long term manually dipped records exist for T74 and data loggers are now installed on both T74 and the adjacent deep borehole (Saddle Inn), drilled as part of the Study. However, access to one of BNFL's four abstraction boreholes was only gained in October 1996. Prior to that, no water level measurements are available for their site.

It is recommended that a data logger is maintained on the accessible BNFL source and incorporated into the Agency's logger network; the condition of the remaining three should be investigated with a view to manual dipping by the company. These records should be compared periodically with abstraction records for all BNFL and NWW's Broughton sources. (In view of the relative proximity of T74 to BNFL the drilling of a new 'sandstone' observation borehole close to BNFL is not justified).

Other Abstractors

The Study has demonstrated the importance of maintaining high quality (accurate and frequent) records of abstraction quantities and groundwater levels for all licensed groundwater sources. This should be achieved by close liaison between Agency licensing staff and source operators.

Surface Water

The low flow gaugings within the Wyre catchment initiated in 1994 as part of this Study should be continued, subject to ongoing review.

In the model, the interaction between the River Ribble and the aquifer system was simulated but not calibrated against permanent gauging station records or spot flow measurements. It is understood that historical records for the Samlesbury flow measuring station, at the upstream end of the Study area were unreliable. Any past validated and future flows

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7 It is recommended that NWW investigates the use of loggers on some if not all of its Fylde sources in view of the quality of data and ease of handling/analysis, particularly in connection with the UKWIR source evaluation study.

8 T74 not only protects BNFL's sources but also safeguards existing 'small' abstractors in Preston and also watercourses in the Wyre catchment and other environmental features (because of the integrated nature of the LCUS licences it limits abstraction from all of the Broughton and Franklaw 'A' sources). This is important in view of the inadequacy of the flow augmentation conditions).

recorded at Samlesbury should be included in the analysis of model results, particularly to allow the options of reuse of the Courtaulds sources or new abstraction in Preston to be further evaluated.

In addition, Woodplumpton Brook has no permanent gauging station. If the water resource policies formulated in the future involve augmentation of this river, a permanent gauging station is recommended to facilitate the operation of the augmentation.

A review of the current status and reliability of continuous recording flow measuring stations across the aquifer, particularly regarding low flow monitoring, should be carried out

Environmental Monitoring

The recommendations of the APEM report (which complements this Study) should be pursued, along with other surveys/ongoing monitoring; this is essential to provide baseline data against which to measure any changes (detrimental/ beneficial) in response to amended abstraction/augmentation practices and/or climate change (eg effects of '95/96 drought).

This is in addition to the recommended new shallow observation borehole at Winmarleigh Moss (see above).

6.2.4 Model Updates

It is extremely important that the model is updated with hydrometric, climatic and abstraction data, preferably annually, but at least every two years by the Environment Agency so that calibration can be checked and updates to the calibration can be made. This will ensure that decisions made from model predictions are based on the most up to date data. In addition, confidence in the model is continuously improved.

6.2.5 Management Plan

The water resources management strategy for the Fylde aquifer should be to balance the needs of existing abstractors with protecting the water environment (see Section 6.1.2). There is a need to review current licences and operational practices following this Study and the aquifer response (record decline in groundwater levels) during the '95/96 drought; by the Agency, in terms of *resource management*, sustainability and the adequacy of environmental protection and by NWW, regarding reliable output and *operational management*.

Before such a strategy can be developed it will be necessary to obtain further information on environmental constraints; studies into the environmental impact of groundwater abstractions, reliable source output and the feasibility/effect of any change to current abstraction/augmentation arrangements.

This will require:

- definition of the acceptable minimum flows at different sections of the rivers and at different times;
- monitoring of Drift groundwater levels at environmentally sensitive areas, such as the Winmarleigh Mosses;
- investigating the criteria for the control of groundwater abstractions from observed groundwater levels (as is carried out with the T74 control borehole (SD43/19);
- enhanced understanding of the aquifer flow and recharge mechanisms.

The Fylde model can also be used to test the impacts of different augmentation and aquifer storage strategies, for example aquifer storage and recovery (ASR) where excess water supplies in winter are pumped into the aquifer for storage, and recovered during summer for both water supply and augmentation.

In developing a management plan for the Fylde aquifer, and particularly the LCUS groundwater abstractions, regional water supply needs must be taken into account. These are currently being modelled in a joint project with NWW. Outputs from the regional modelling will be used to develop more realistic aquifer demand scenarios for input into the Fylde aquifer model. These can be used to test the acceptability of proposals, and if necessary can be then lead to modifications of regional strategy. In this way the two management models are complementary.

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NRA	1994	Review of the Water Resources of the Fylde Aquifer and Wyre Catchment.
NWW K1,	1988	Geological Services Reports: B3, B4, C2, G1, G2, K2, L1, L2, M2, Z2
Rushton K, Kawecki M Brassington F	1988	Groundwater Model of Conditions in Liverpool Sandstone Aquifer, Jl IWEM, 2, p 67-84.
Rushton K	1993	Modelling Study of the Doncaster Aquifer, Final Report, University of Birmingham.
Rushton K and Bishop	1993	Water Resource Study of the Nottingham Sherwood Sandstone Aquifer System of Eastern England, for NRA Severn Trent Region.

Sage R	1976	A Hydrogeochemical Appraisal of the Triassic Sandstone Aquifer of the Fylde Area of Lancashire (MSc Thesis, Birmingham).
Sage R and Lloyd J	1978	Drift Influences on the Triassic Sandstone Aquifer of Northwest Lancashire, QJlEng Geol, 11, p 209-218.
Walsh P	1976	Investigation into the Yield of an Existing Surface Reservoir and Aquifer System, JL Hydrology, 28, p215-228.
Walsh P	1977	Lancashire Conjunctive Use Scheme (PhD, Birmingham).
Wilson A and Evans W Sheet	1990	Geology of the Country around Blackpool, BGS Memoir 66.
Worthington P	1970	Geophysical Investigation of a Permo-Triassic Sandstone Aquifer (MSc Thesis, Birmingham).
Worthington P and Griffiths D Aquifers,	1975	The Application of Geophysical Methods in the Exploration and Development of Sandstone QJl Eng Geol, 8.
Worthington P 303.	1977	Permeation Properties of the Bunter Sandstone of Northwest Lancashire, Jl of Hydrology, 32, p295-
WRC Bunter	1972	Interim Report on the Investigation of the Fylde Aquifer.
WRC	1973	Investigation of the Triassic Sandstone of the Fylde Area (unpublished draft).
WRC	1975	Technical Report no 12-The Lancashire Conjunctive Use Groundwater Model.

APPENDICES

APPENDIX A

ORIGINAL TERMS OF REFERENCE FOR THE STUDY

Project Structure

Introduction

The NRA envisage that the Study will comprise the following four Phases of work:

Phase I: Data Collation and Formulation of Conceptual Model;

Phase II: Model Development and Calibration;

Phase III: Modelling of Resource Options; and

Phase IV: Training and User Support.

Each of these Phases is described in more detail below.

Phase I: Data Collation and Formulation of Conceptual Model

It is proposed that Phase I will comprise the following nine tasks:

Task 1: Study Inaugural Meeting and Area Visit
The Study will be launched at a one-day Inaugural Meeting, to be held at the NRA offices in Warrington and attended by two senior representatives of the Consultants project team (the Project Manager and Senior Modeller) and the Project Review Panel (including the independent modelling expert). On the following day a member of NRA will travel with the senior consulting staff on a one-day visit of the Study Area. As part of its proposal the Consultant will be expected to indicate what it considers to be the key items to discuss and to examine during the meeting and site visit.

Task 2: Data Collation
It is proposed that the mathematical model(s) should be capable of adequately representing historical aquifer and riverflow conditions for the period 1975 to 1993 inclusive. The collation of geological, hydrological and hydrogeological information available and relevant to the Fylde Plain and calibration period will primarily be the responsibility of the Consultant, though NRA and NWW staff will assist with the collation of in-house data where the task is not too onerous or does not impinge on their other work commitments.

Project Structure *continued*

As an absolute minimum the Consultant will be expected to have acquired and inspected the following data covering the above stated calibration period:

1) The most recent topographic (1:25000 and 1:50000), geology (1:10000 and 1:50000) and soils maps and memoirs for the Fylde Plain;

2) Lithological logs for the Superficial deposits within the Fylde Plain (hard-copy records are available from the NRA (incomplete) and/or British Geological Survey in Keyworth);

3) Daily rainfall for a number of Meteorological Office rainfall stations, the number and choice to be agreed with the NRA (data available as ASCII files from the NRA);

4) Potential evapotranspiration (monthly figures distributed on a daily basis) for a number of Meteorological Office climate stations (monthly figures are available as hard copy from NWW);

5) Parish Crop Returns for a number of sample parishes, the number and choice to be agreed with the NRA (data available as hard copy from the Public Record Office);

6) Daily riverflow records for thirteen permanent gauging sites in the River Wyre catchment (approximately 210 station years of data are available as chart records and ASCII files from the NRA);

7) Occasional current-meter gauging surveys along low-flow sections of the river network during summer conditions (hard copy summary records are available from the NRA);

8) Licensed (annual and peak daily) and actual (monthly) surface and groundwater abstractions for all public water abstraction sites and large (>180 Ml/a) industrial and private abstractions (available from NWW in the form of Lotus spreadsheets);

9) Daily augmentation rates for all public groundwater abstraction sites (approximately 400 station years of data, to be extracted by the Consultant from NWW pumping station record books);

10) Groundwater levels for approximately 50 observation boreholes and about 21 multiple-borehole public water abstraction sites in the

Project Structure *continued*

Sherwood Sandstone and Superficial deposits (approximately 1400 station years of data available as NRA HYDRODAT files);

11) Any interpolated piezometric maps for the Sherwood Sandstone and Superficial deposits; and

12) Interpretations of earlier pumping tests and borehole geophysical/fluid logging in the area (hard-copy records from the NRA and NWW). The Consultant is not expected to undertake its own analysis or interpretation of pumping test data.

In its proposal the Consultant is expected to demonstrate an awareness of the various issues that are likely to arise during this extensive data search. Any possible additional sources of data should also be mentioned (but not costed) in the proposal. It should be noted that for this Study the NRA does not favour the use of MORECS based climate data.

Where appropriate the Consultant will enter or import the raw data into Excel or Excel-compatible spreadsheets to enable later presentation of the data (for example, Task 9) or further analysis (for example, Task 6). These spreadsheets should be passed over to the NRA at the end of the project.

Task 3: Literature Review

The hydrology and hydrogeology of the Study Area has been extensively studied in the past, and the NRA expects the Consultant to review and demonstrate an awareness of this previous work. A list of References is given in Chapter 4. This list is not meant to be all-inclusive, and the Consultant will be expected to examine other reports and papers as appropriate. A brief summary of each key paper will be presented by the Consultant as an Appendix to the Phase I report (see Task 9).

Task 4: Interpretation of Lithological Logs

The borehole records acquired by the Consultant during Task 1 should be entered into a database to enable visualisation of the Superficial deposits in aerial plan and cross-section. This work is considered of the highest priority and will form the main basis for assigning the various layers in the later mathematical model.

Project Structure *continued*

In its proposal the Consultant should state which software package it intends to use for this database work. The resulting data set must be made available to the NRA at the end of the project.

Task 5: Calculation of Effective Rainfall
The calculation of effective rainfall is an important 'first-step' in the estimation of both rainfall recharge (through the Fylde Superficial deposits into the underlying Sherwood Sandstone) and runoff (from the Superficial deposits on the Fylde Plain into the River Wyre and its tributaries).

The Consultant should describe in its proposal how it intends to use the rainfall, potential evapotranspiration, soils and landuse data collected earlier to calculate effective rainfall on a daily (not monthly) basis for various rainfall stations over the previously defined calibration period, and then distribute the deduced monthly effective rainfall for these stations over the Flyde Plain. The Consultant in its proposal should briefly describe how it proposes to calculate effective rainfall; the MORECs method of effective rainfall estimation is not acceptable for this Study. Any executable computer programs used by the Consultant to undertake this calculation should be available to the NRA at the completion of the project.

Task 6: Riverflow Analysis
The daily riverflow records from certain permanent gauging stations (number and choice to be agreed later with the NRA) will be analysed using conventional baseflow separation techniques to establish the monthly baseflow and runoff contributions to each of the main water courses during the calibration period.

In its proposal the Consultant should demonstrate that it has an awareness (and an acceptance) of the problems that this Task is likely to involve.

Task 7: Calculation of a Preliminary Water Balance
The Consultant is expected to calculate a preliminary water balance for the likely model area prior to commencement of the Phase II modelling. This water balance should be computed on a monthly basis for the calibration period, and will indicate the general availability of water resources in the area. The Consultant should state in its proposal the likely assumptions it will probably be necessary to make in the calculation of this preliminary water balance.

Project Structure *continued*

Task 8: Development of a Surface Water/Groundwater Conceptual Model
Prior to the commencement of the modelling the NRA will require the Consultant to formulate its ideas concerning the dominant aquifer flow mechanisms and the degree of river-groundwater interaction into a conceptual model. This model is likely to take the form of a generalised cross-section through the area, annotated to highlight key features and to indicate average flow quantities and aquifer parameter values.

Task 9: Formulation of Phase I Report
Four copies of a draft Phase I report should be presented within four months from the date of commission of the Consultant. The report will include the following items:

1) Presentation in graphical and tabular form (where appropriate) the raw data as collated in Task 2 e.g. digitised (AutoCad) topograghic, geological and piezometric maps, 20-year riverflow and groundwater hydrographs, tabulation of groundwater and surface water licence information,

2) Summary (in the form of an Appendix) of the key reference papers identified in Task 3;

3) Interpretation and presentation (again preferably in graphical form) of data and information collated in Tasks 2,4 and 6 e.g. maps and cross-sections showing the thickness and nature of Superficial deposits deduced from borehole log information, results of baseflow separation analysis and interpretation of NRA low-flow survey results;

4) Presentation of the effective rainfall and water balance estimates from Tasks 5 and 7, preferably on a monthly basis, and the proposed conceptual model from Task 8; and

5) Formulation of the initial model design, including model dimensions, recharge and boundary conditions, general aquifer and riverbed characteristics, calibration and sensitivity analysis criteria.

This draft report will be discussed at a progress meeting between the Project Manager and Senior Modeller of the Consultant and the Project Review

Project Structure *continued*

Panel. Four copies of the final version of the report will be issued within one month of this meeting.

Phase II: Model Development and Calibration

It is proposed that Phase II should comprise the following four tasks:

Task 10: Construction of Model
This Task will involve entering the model specifications agreed at the Phase I report stage as data files into the model. This process will of necessity require definition of grid spacing , boundary and recharge conditions, but the Consultant will also be expected to agree with the NRA at this stage a means of evaluating the performance of the model (i.e. agree calibration criteria). As a demonstration of the Consultants modelling ability it should include in its proposal a brief discussion of the likely model boundary conditions for this Study and its suggestions as to the sort of calibration criteria that may be appropriate.

Task 11: Model Calibration
The model will be calibrated against the historical surface water and groundwater response until the above mentioned calibration criteria have been met or the NRA has agreed that further calibration runs are unnecessary.

The calibration criteria will be set to ensure that due regard has been paid to simulated absolute groundwater levels and water level trends, groundwater flow patterns and hydraulic gradients, and volumes of total riverflow and surface-groundwater interactions. The models annual water balance will be examined to ensure that model convergence has not been achieved by assuming inappropriate error criteria.

Task 12: Model Sensitivity Analysis
The Consultant will undertake a rigorous sensitivity analysis of key model parameters. This may indicate the need for additional field investigation. As a further demonstration of the Consultants modelling capabilities it is asked in its proposal to provide an indication of the parameters likely to require investigation in this way.

Task 13: Formulation of Phase II Report
Four copies of a draft Phase II report should be presented within nine months from the date of commission of the Consultant. The report will include the following items:

1) Presentation of details of the model calibration, including comparison of modelled and observed river and groundwater hydrographs, river-aquifer interactions and groundwater hydraulic gradients and flow directions;

2) Model piezometric maps and groundwater cross-sections;

3) Deductions as to the impact of historical groundwater abstractions on surface water flows and regional groundwater levels.

This draft report will be discussed at a progress meeting between the Project Manager and Senior Modeller of the Consultant and the Project Review Panel. Four copies of the final version of the report will be issued within one month of this meeting.

Phase III: Modelling of Resource Options

It is proposed that Phase III should comprise the following three tasks:

Task 14: Identification of Resource Management Options
The Consultant will seek the advice of the NRA and NWW to identify five plausible resource options for the future management of the Fylde aquifer. Written confirmation of these options will be provided by the NRA before proceeding with the investigation.

Task 15: Model Predictive Runs
The model will be rerun using the historical rainfall recharge inputs and boundary conditions with each of the five different abstraction scenarios to identify the impacts of each of these resource options.

Project Structure *continued*

Task 16: Formulation of Phase III Report
Four copies of a draft Phase III report should be presented within eleven months from the date of commission of the Consultant. The report will include the following items:

1) Presentation of details of the resource option modelling, including comparison of original calibration and new river and groundwater hydrographs, river-aquifer interactions and groundwater hydraulic gradients and flow directions;

2) Presentation of predicted piezometric maps and groundwater cross-sections;

3) Deductions as to the impact of each of the proposed resource options on surface water flows and regional groundwater levels.

This draft report will be discussed at a progress meeting between the Project Manager and Senior Modeller of the Consultant and the Project Review Panel. Four copies of the final version of the report will be issued within one month of this meeting.

Phase IV: Training and User Support

It is proposed that Phase IV should comprise the following three tasks:

Task 17: Compilation of a User Manual
The Consultant is expected to develop a User Manual (other than the standard guide that accompanies the software) which NRA and NWW staff can use to become acquainted with the key commands and error codes of the software and the model layout. The form of any ASCII data files should also be described, so that as the NRA and NWW become proficient in the use of the model they can make data entries and modifications direct through a text editor. The User Manual should be accompanied by copies of the model data files and any executable programs, spreadsheets and databases developed by the Consultant during the Study on $3^1/_2$ inch floppy disc media.

Task 18: Provision of a Model Training Course
The Consultant will run a two-day 'hands-on' course to four NRA and NWW staff at the NRA Warrington offices on the setup and use of the

model(s), on computers to be provided by the Consultant. It is particularly important to demonstrate how the model calibration can be refined and updated and how other resource options can be investigated.

Task 19: Provision of Model Support
The Consultant will provide twelve months telephone support for the model, guaranteeing a two-day response time to NRA queries regarding the setup and running of the model.

Phase IV does not require to be formally reported on. However, the Consultant will be expected to have completed Tasks 17 and 18 within twelve months of the date of commission of the Consultant.

Fylde Aquifer/Wyre Catchment Water Resources Study

ADDENDUM TO PROJECT BRIEF

Background

This addendum should be read in conjunction with the above Project Brief (Ref. KJS July 1994). It clarifies issues and itemises additional works which will form part of the Contract for the above Study. As such, the contents of this addendum shall supersede the Project Brief, where differences occur.

Phase I: Data Collation and Formulation of Conceptual Model.

Task 2: Data Collation
Additional data :

14) Groundwater quality data for abstraction/observation boreholes within the study area. (available from NRA Groundwater Quality Archive in comma separated format - approximately 100 sites with variable range of analyses and frequencies of sampling).

Task 4: Interpretation of Lithological Logs
Additional requirement:

The Consultant shall use the groundwater quality data obtained from Task 2 to assess the type and origin of the groundwaters within the study area, and whether there has been any change with time.

Task 9: Formulation of Phase I Report
Additional Requirement:

The Consultant shall not proceed with Phase II of the Study unless or until the Authority has agreed:

1) the standard of data interpretation and details of the conceptual model (Phase I)
2) the methodology for development of the numerical model (Phase II)

Should agreement not be reached at this stage, the Authority reserves the right to terminate the contract.

Phase IV: Training & User Support

Tasks 18 & 19: Provision of Model Training Course & Support
Clarification

These tasks are not required to cover recalibration of the model.

General

Tasks 9, 13 & 16: End of Phase Reports

The reports prepared at the end of Phases I, II & III should be produced to a high quality. They should be comb bound, laser printed and photocopied, unless otherwise agreed with the NRA. Colour photocopies shall be provided of relevant graphical outputs etc.

Use of Sub-Contractors

The use of sub-contractors will be only be permitted subject to due notice, and approval by the NRA.

Development of Model Code

Whilst any model code developed by the Consultants for use in the Study may remain the copyright of the Consultants, the NRA and NWW Ltd. shall be provided with an unlimited free licence.

Other Proposal Items:

Project Organisation & Schedule
Item 3.4

Appointment of the successful Consultant is expected in early October. Unless otherwise agreed by the Authority, Tasks 1-18 shall be completed within 12 months of the start of the Study.

Consultant Fees and Costs
Item 3.9

The Consultant is required to submit a fixed sum for carrying out the Study. No additional payments will be made for any works covered by the Project Brief and this Addendum.

General Conditions of Contract:

Insurance

For the purpose of Paragraph 5.1, the insurance limit shall be £500,000.

Contract Period

For the purpose of paragraph 10, the period of the agreement shall be 24 months from the 15 October 1995.

APPENDIX B

GROUNDWATER LICENCES OF THE FYLDE AQUIFER

APPENDIX B

GROUNDWATER LICENCES OF THE FYLDE AQUIFER

B1 North West Water Licences

Licence Group	Licence Number	Boreholes	Daily Licence (Ml/d)	Annual Licence (Ml)
Broughton A[1]	410001	B1-4	20	7 051
	410001	C1-4	13	
	410001	D1-3	6	
Broughton A/B	409004	E1,E2	4.5	included in
	409004	G1,G2	8	Broughton B
	409004	H1,H2	5	included in
	409004	J1,J2	5.5	Broughton A
Broughton B	411002	K1,K2	7	2 778
Franklaw A	408015	L1,L2	34	13 390
	408020	L3,L4,M1-6	39	
Franklaw A/B	405010	W2	6	included in Franklaw A
	405010	Z2	10	included in Franklaw B
Franklaw B	408021	P1,P2,Q1,Q2	14	4 840
	405006	W1,Z1	10	
TOTAL			**190**	**28 059**

Note (1) Broughton A licence is subject to a groundwater level constraint. If the level monitored at obnservation borehole SD43/19 (T74) falls below 8.5 m AOD, then abstractions from the Broughton A sources are to be reduced.

The NWW licences include the following augmentation conditions:

B2 NWW Augmentation Conditions

Augmentation Point	Rate	Borehole condition	River Flow Condition	Augmentation From
River Brock at SD 506404	3.0 Ml/d	If Franklaw A sources pumping and/or Sources K1 or K2 pumping	River Brock at Roe Bridge < 5 Ml/d	Franklaw collecting main
River Wyre at SD 498463	3.0 Ml/d	If Franklaw A pumping	River Wyre at St Michaels < 50 Ml/d	Borehole W2
River Wyre at SD 498463	2.5 Ml/d	If source W2 pumping	River Wyre at St Michaels < 50 Ml/d	Borehole W2
River Calder at SD 498463	3.0 Ml/d	If Franklaw A pumping	River Wyre at St Michaels < 50 Ml/d	Boreholes R3 and R4
New Mill Brook at SD 504363	2.0 Ml/d	If Broughton B pumping	River Wyre at St Michaels < 50 Ml/d	Broughton Collecting Main
Possible Total	13.5 Ml/d			

B3 Major Industrial Abstraction Licences

Abstractor	Site ID	Grid Reference	Licence Number	Licence Quantity Ml/d	Licence Quantity Ml/yr
ICI	SD44/27A	40034618	2672/532/001		
	SD44/27B	43264665	2672/532/001		
	SD44/27C	43704640	2672/532/001		
	SD44/27D	43854586	2672/532/001		
	SD44/27E	44184627	2672/532/001		
	SD44/27F	44774553	2672/532/001		
	SD44/27G	44184559	2672/532/001		
	SD44/27H	45184559	2672/532/001		
	SD44/27J	43664537	2672/532/001		
TOTAL				20.0	5 455
BNFL	SD43/4A	47103160	2671/348/005		
	SD43/4B	46503180	2671/348/005		
	SD43/4C	46703120	2671/348/005		
	SD43/4D	47203100	2671/348/005		
TOTAL				13.0	2 982
Whitbread	SD52/56	58392981	2671/339/006		
	SD52/57	58262961	2671/339/006		
TOTAL				12.3	3 273
Courtaulds (abandoned 1980)	SD54/16A	50934290	2671/339/002	4.9	1 791
	SD54/16B	51094284	2671/339/002	6.3	2 318
	SD54/16C	57683192	2671/339/002	4.4	1 591
	SD54/16D	57273212	2671/339/002	4.9	1 791
	SD54/16E	51094283	2671/339/002	7.9	2 873
TOTAL				28.4	4 281
Supreme Denim Services	SD52/68	54902970	27/71/347/012	0.2	54
Liquid Plastics Ltd		55202950	26/71/347/001	0.1	114
Somic'		55202990	27/71/347/006	0.141	
North Country Poultry	SD44/99	48984610	2672/405/001	0.15	455
TOTAL (not including Courtaulds)				**45.9**	**12 197**

APPENDIX C

SIMULATED WATER BALANCE COMPONENTS FOR THE MODEL CALIBRATION

AVERAGE WATER BALANCE COMPONENTS: 1972-1996

TR64
Area 1-NORTH WEST FYLDE

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	157.24
LEAKAGE FROM DRIFT	1.22	0.00	n.a
LEAKAGE FROM S&G	0.00	n.a	n.a
BOUNDARY INFLOWS			
- FROM AREA 2 (GARSTANG)	4.60	0.00	0.00
- FROM AREA 3 (CENTRAL)	0.52	0.00	0.00
- FROM MORECAMBE BAY	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	0.00	0.00	0.00
STORAGE RELEASE	0.01	0.00	0.01
TOTAL INFLOWS	6.35	0.00	157.25
OUTFLOWS			
ABSTRACTION	-1.67	0.00	0.00
BOUNDARY OUTFLOWS			
- TO AREA 2 (GARSTANG)	0.00	0.00	0.00
- TO AREA 3 (CENTRAL)	0.00	0.00	0.00
- TO MORECAMBE BAY	-3.82	0.00	0.00
LEAKAGE TO SANDSTONE	n.a	0.00	-1.22
LEAKAGE TO S&G	n.a	n.a	0.00
NET GROUNDWATER FLOW TO RIVERS	-0.86	0.00	0.00
REJECTED FLOW	0.00	0.00	-156.29
STORAGE GAIN	0.00	0.00	0.00
TOTAL OUTFLOWS	-6.35	0.00	-157.52
MODEL IMBALANCE/ROUNDING ERROR	0.00	0.00	-0.27

WATER BALANCE COMPONENTS: APRIL 1987 - MAXIMUM WATER LEVEL CONDITIONS

TR64
Area 1-NORTH WEST FYLDE

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	68.30
LEAKAGE FROM DRIFT	0.09	0.00	n.a.
LEAKAGE FROM S&G	0.00	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM AREA 2 (GARSTANG)	5.38	0.00	0.00
- FROM AREA 3 (CENTRAL)	0.49	0.00	0.00
- FROM MORECAMBE BAY	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	0.00	0.00	0.00
STORAGE RELEASE	0.00	0.00	0.00
TOTAL INFLOWS	5.96	0.00	68.30
OUTFLOWS			
ABSTRACTION	-0.18	0.00	0.00
BOUNDARY OUTFLOWS			
- TO AREA 2 (GARSTANG)	0.00	0.00	0.00
- TO AREA 3 (CENTRAL)	0.00	0.00	0.00
- TO MORECAMBE BAY	-4.52	0.00	0.00
LEAKAGE TO SANDSTONE	n.a	0.00	-0.09
LEAKAGE TO S&G	n.a	n.a	0.00
NET GROUNDWATER FLOW TO RIVERS	-1.10	0.00	0.00
REJECTED FLOW	0.00	0.00	-68.52
STORAGE GAIN	-0.04	0.00	-0.04
TOTAL OUTFLOWS	-5.85	0.00	-68.66
MODEL IMBALANCE/ROUNDING ERROR	0.11	0.00	-0.36

WATER BALANCE COMPONENTS: SEPT 1995 - MINIMUM WATER LEVEL CONDITIONS

TR64
Area 1-NORTH WEST FYLDE

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	0.00
LEAKAGE FROM DRIFT	3.72	0.00	n.a.
LEAKAGE FROM S&G	0.00	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM AREA 2 (GARSTANG)	0.75	0.00	0.00
- FROM AREA 3 (CENTRAL)	0.59	0.00	0.00
- FROM MORECAMBE BAY	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	0.19	0.00	0.00
STORAGE RELEASE	0.59	0.00	4.14
TOTAL INFLOWS	5.85	0.00	4.14
OUTFLOWS			
ABSTRACTION	-2.79	0.00	0.00
BOUNDARY OUTFLOWS			
- TO AREA 2 (GARSTANG)	0.00	0.00	0.00
- TO AREA 3 (CENTRAL)	0.00	0.00	0.00
- TO MORECAMBE BAY	-2.93	0.00	0.00
LEAKAGE TO SANDSTONE	n.a	0.00	-3.72
LEAKAGE TO S&G	n.a	n.a.	0.00
NET GROUNDWATER FLOW TO RIVERS	0.00	0.00	0.00
REJECTED FLOW	0.00	0.00	-0.51
STORAGE GAIN	0.00	0.00	0.00
TOTAL OUTFLOWS	-5.72	0.00	-4.24
MODEL IMBALANCE/ROUNDING ERROR	0.13	0.00	-0.10

AVERAGE WATER BALANCE COMPONENTS: 1972-1996

TR64
Area 2-GARSTANG

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.51	35.45
LEAKAGE FROM DRIFT	2.02	1.31	n.a.
LEAKAGE FROM S&G	2.26	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM AREA 3 (CENTRAL)	0.00	0.00	0.00
- FROM CARBONIFEROUS	0.37	0.00	0.00
- FROM AREA 1 (NORTH WEST)	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	3.63	0.69	0.00
STORAGE RELEASE	0.09	0.04	0.09
TOTAL INFLOWS	8.37	2.56	35.55
OUTFLOWS			
ABSTRACTION	-2.18	0.00	0.00
BOUNDARY OUTFLOWS			
- TO AREA 3 (CENTRAL)	-1.46	0.00	0.00
- TO CARBONIFEROUS	0.00	0.00	0.00
- TO AREA 1 (NORTH WEST)	-4.59	0.00	0.00
LEAKAGE TO SANDSTONE	n.a.	-2.26	-2.02
LEAKAGE TO S&G	n.a.	n.a.	-1.31
NET GROUNDWATER FLOW TO RIVERS	0.00	0.00	-0.17
REJECTED FLOW	0.00	-0.30	-31.79
STORAGE GAIN	0.00	0.00	0.00
TOTAL OUTFLOWS	-8.23	-2.55	-35.29
MODEL IMBALANCE/ROUNDING ERROR	0.13	0.00	0.25

WATER BALANCE COMPONENTS: APRIL 1987 - MAXIMUM WATER LEVEL CONDITIONS

TR64
Area 2-GARSTANG

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.22	15.40
LEAKAGE FROM DRIFT	1.84	1.40	n.a.
LEAKAGE FROM S&G	2.17	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM AREA 3 (CENTRAL)	0.00	0.00	0.00
- FROM CARBONIFEROUS	0.37	0.00	0.00
- FROM AREA 1 (NORTH WEST)	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	1.68	0.54	0.00
STORAGE RELEASE	0.45	0.01	0.45
TOTAL INFLOWS	6.50	2.17	15.85
OUTFLOWS			
ABSTRACTION	-0.20	0.00	0.00
BOUNDARY OUTFLOWS			
- TO AREA 3 (CENTRAL)	-1.21	0.00	0.00
- TO CARBONIFEROUS	0.00	0.00	0.00
- TO AREA 1 (NORTH WEST)	-5.38	0.00	0.00
LEAKAGE TO SANDSTONE	n.a.	-2.17	-1.84
LEAKAGE TO S&G	n.a.	n.a.	-1.40
NET GROUNDWATER FLOW TO RIVERS	0.00	0.00	-0.16
REJECTED FLOW	0.00	0.00	-12.38
STORAGE GAIN	0.00	0.00	0.00
TOTAL OUTFLOWS	-6.78	-2.17	-15.77
MODEL IMBALANCE/ROUNDING ERROR	-0.28	0.00	0.08

WATER BALANCE COMPONENTS: SEPT 1995 - MINIMUM WATER LEVEL CONDITIONS

TR64
Area 2-GARSTANG

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	0.00
LEAKAGE FROM DRIFT	1.90	0.97	n.a.
LEAKAGE FROM S&G	5.23	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM AREA 3 (CENTRAL)	0.00	0.00	0.00
- FROM CARBONIFEROUS	0.37	0.00	0.00
- FROM AREA 1 (NORTH WEST)	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	4.35	0.65	0.00
STORAGE RELEASE	5.57	3.61	3.34
TOTAL INFLOWS	17.42	5.23	3.34
OUTFLOWS			
ABSTRACTION	-15.43	0.00	0.00
BOUNDARY OUTFLOWS			
- TO AREA 3 (CENTRAL)	-1.28	0.00	0.00
- TO CARBONIFEROUS	0.00	0.00	0.00
- TO AREA 1 (NORTH WEST)	-0.76	0.00	0.00
LEAKAGE TO SANDSTONE	n.a	-5.23	-1.90
LEAKAGE TO S&G	n.a.	n.a	-0.97
NET GROUNDWATER FLOW TO RIVERS	0.00	0.00	-0.16
REJECTED FLOW	0.00	0.00	-0.26
STORAGE GAIN	0.00	0.00	0.00
TOTAL OUTFLOWS	-17.46	-5.23	-3.31
MODEL IMBALANCE/ROUNDING ERROR	-0.04	0.00	0.03

APPENDIC C3: WATER BALANCE COMPONENTS CENTRAL FYLDE

AVERAGE WATER BALANCE COMPONENTS: 1972-1996

TR64
Area 3-CENTRAL

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	90.83
LEAKAGE FROM DRIFT	2.12	4.09	n.a.
LEAKAGE FROM S&G	6.92	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM AREA 4 (SOUTH)	0.45	1.23	0.00
- FROM CARBONIFEROUS	0.32	0.00	0.00
- FROM AREA 2 (GARSTANG)	1.47	0.00	0.00
-FROM AREA 1 (NORTH WEST)	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	4.19	1.48	0.00
STORAGE RELEASE	0.28	0.13	0.28
TOTAL INFLOWS	15.75	6.93	91.11
OUTFLOWS			
ABSTRACTION	-15.29	0.00	0.00
BOUNDARY OUTFLOWS			
- TO AREA 4 (SOUTH)	0.00	0.00	0.00
- TO CARBONIFEROUS	0.00	0.00	0.00
- TO AREA 2 (GARSTANG)	0.00	0.00	0.00
-TO AREA 1 (NORTH WEST)	-0.52	0.00	0.00
LEAKAGE TO SANDSTONE	n.a.	-6.92	-2.12
LEAKAGE TO S&G	n.a.	n.a.	-4.09
NET GROUNDWATER FLOW TO RIVERS	0.00	0.00	-0.83
REJECTED FLOW	0.00	0.00	-84.11
STORAGE GAIN	0.00	0.00	0.00
TOTAL OUTFLOWS	-15.80	-6.92	-91.15
MODEL IMBALANCE/ROUNDING ERROR	-0.05	0.01	-0.04

WATER BALANCE COMPONENTS: APRIL 1987 - MAXIMUM WATER LEVEL CONDITIONS

TR64
Area 3-CENTRAL

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	39.45
LEAKAGE FROM DRIFT	1.40	4.08	n.a.
LEAKAGE FROM S&G	2.37	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM AREA 4 (SOUTH)	0.27	0.95	0.00
- FROM CARBONIFEROUS	0.32	0.00	0.00
- FROM AREA 2 (GARSTANG)	1.22	0.00	0.00
-FROM AREA 1 (NORTH WEST)	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	0.00	0.81	0.00
STORAGE RELEASE	0.00	0.00	0.00
TOTAL INFLOWS	5.57	5.85	39.45
OUTFLOWS			
ABSTRACTION	-1.06	0.00	0.00
BOUNDARY OUTFLOWS			
- TO AREA 4 (SOUTH)	0.00	0.00	0.00
- TO CARBONIFEROUS	0.00	0.00	0.00
- TO AREA 2 (GARSTANG)	0.00	0.00	0.00
-TO AREA 1 (NORTH WEST)	-0.49	0.00	0.00
LEAKAGE TO SANDSTONE	n.a.	-2.37	0.00
LEAKAGE TO S&G	n.a	n.a.	-4.08
NET GROUNDWATER FLOW TO RIVERS	-3.21	0.00	-0.99
REJECTED FLOW	0.00	0.00	-33.50
STORAGE GAIN	-0.86	-3.49	-0.86
TOTAL OUTFLOWS	-5.61	-5.85	-39.43
MODEL IMBALANCE/ROUNDING ERROR	-0.04	0.00	0.03

WATER BALANCE COMPONENTS: SEPT 1995 - MINIMUM WATER LEVEL CONDITIONS

TR64
Area 3–CENTRAL

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	0.00
LEAKAGE FROM DRIFT	3.34	2.03	n.a.
LEAKAGE FROM S&G	26.35	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM AREA 4 (SOUTH)	1.49	1.38	0.00
- FROM CARBONIFEROUS	0.32	0.00	0.00
- FROM AREA 2 (GARSTANG)	1.28	0.00	0.00
-FROM AREA 1 (NORTH WEST)	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	21.02	1.76	0.00
STORAGE RELEASE	31.63	21.17	6.33
TOTAL INFLOWS	85.43	26.35	6.33
OUTFLOWS			
ABSTRACTION	-85.34	0.00	0.00
BOUNDARY OUTFLOWS			
- TO AREA 4 (SOUTH)	0.00	0.00	0.00
-.TO CARBONIFEROUS	0.00	0.00	0.00
- TO AREA 2 (GARSTANG)	0.00	0.00	0.00
-TO AREA 1 (NORTH WEST)	-0.59	0.00	0.00
LEAKAGE TO SANDSTONE	n.a	-26.35	-3.34
LEAKAGE TO S&G	n.a	n.a.	-2.03
NET GROUNDWATER FLOW TO RIVERS	0.00	0.00	-0.56
REJECTED FLOW	0.00	0.00	-0.60
STORAGE GAIN	0.00	0.00	0.00
TOTAL OUTFLOWS	-85.94	-26.35	-6.54
MODEL IMBALANCE/ROUNDING ERROR	-0.51	-0.00	-0.21

AVERAGE WATER BALANCE COMPONENTS: 1972-1996

TR64
Area 4-SOUTHERN/PRESTON

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	166.64
LEAKAGE FROM DRIFT	8.71	7.66	n.a.
LEAKAGE FROM S&G	8.47	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM AREA 5 (SALMESBURY)	0.00	0.00	0.00
- FROM CARBONIFEROUS	0.00	0.00	0.00
- FROM AREA 3 (CENTRAL)	0.00	0.00	0.00
- FROM SOUTH WEST	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	0.00	1.79	0.00
STORAGE RELEASE	0.16	0.26	0.16
TOTAL INFLOWS	17.33	9.72	166.79
OUTFLOWS			
ABSTRACTION	-10.79	0.00	0.00
BOUNDARY OUTFLOWS			
- TO AREA 5 (SALMESBURY)	-0.09	-0.02	0.00
- TO CARBONIFEROUS	0.00	0.00	0.00
- TO AREA 3 (CENTRAL)	-0.45	-1.22	0.00
- TO SOUTH WEST	0.00	0.00	0.00
LEAKAGE TO SANDSTONE	n.a.	-8.47	-8.71
LEAKAGE TO S&G	n.a.	n.a.	-7.66
NET GROUNDWATER FLOW TO RIVERS	-5.77	0.00	-3.17
REJECTED FLOW	0.00	0.00	-147.11
STORAGE GAIN	0.00	0.00	0.00
TOTAL OUTFLOWS	-17.09	-9.71	-166.66
MODEL IMBALANCE/ROUNDING ERROR	0.24	0.01	0.14

WATER BALANCE COMPONENTS: APRIL 1987 - MAXIMUM WATER LEVEL CONDITIONS

TR64
Area 4-SOUTHERN/PRESTON

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	71.07
LEAKAGE FROM DRIFT	8.45	7.48	n.a.
LEAKAGE FROM S&G	4.02	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM AREA 5 (SALMESBURY)	0.32	0.00	0.00
- FROM CARBONIFEROUS	0.00	0.00	0.00
- FROM AREA 3 (CENTRAL)	0.00	0.00	0.00
- FROM SOUTH WEST	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	0.00	0.50	0.00
STORAGE RELEASE	0.00	0.00	0.00
TOTAL INFLOWS	12.80	7.97	71.07
OUTFLOWS			
ABSTRACTION	-6.65	0.00	0.00
BOUNDARY OUTFLOWS			
- TO AREA 5 (SALMESBURY)	0.00	-0.02	0.00
- TO CARBONIFEROUS	0.00	0.00	0.00
- TO AREA 3 (CENTRAL)	-0.27	-0.95	0.00
- TO SOUTH WEST	-5.87	0.00	0.00
LEAKAGE TO SANDSTONE	n.a.	-4.02	0.00
LEAKAGE TO S&G	n.a.	n.a.	-7.48
NET GROUNDWATER FLOW TO RIVERS	-0.18	0.00	-3.37
REJECTED FLOW	0.00	0.00	-59.69
STORAGE GAIN	-0.44	-2.97	-0.44
TOTAL OUTFLOWS	-13.40	-7.97	-70.98
MODEL IMBALANCE/ROUNDING ERROR	-0.60	0.00	0.09

WATER BALANCE COMPONENTS: SEPT 1995 - MINIMUM WATER LEVEL CONDITIONS

TR64
Area 4-SOUTHERN/PRESTON

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	0.00
LEAKAGE FROM DRIFT	6.75	5.36	n.a.
LEAKAGE FROM S&G	10.74	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM AREA 5 (SALMESBURY)	0.30	0.00	0.00
- FROM CARBONIFEROUS	0.00	0.00	0.00
- FROM AREA 3 (CENTRAL)	0.00	0.00	0.00
- FROM SOUTH WEST	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	0.00	1.40	13.91
STORAGE RELEASE	0.14	4.38	0.14
TOTAL INFLOWS	17.92	11.13	14.05
OUTFLOWS			
ABSTRACTION	-9.82	0.00	0.00
BOUNDARY OUTFLOWS			
- TO AREA 5 (SALMESBURY)	0.00	-0.01	0.00
- TO CARBONIFEROUS	0.00	0.00	0.00
- TO AREA 3 (CENTRAL)	-1.49	0.00	0.00
- TO SOUTH WEST	-7.00	0.00	0.00
LEAKAGE TO SANDSTONE	n.a.	-10.74	-6.75
LEAKAGE TO S&G	n.a.	n.a.	-5.36
NET GROUNDWATER FLOW TO RIVERS	-0.16	0.00	-1.74
REJECTED FLOW	0.00	0.00	0.00
STORAGE GAIN	0.00	0.00	0.00
TOTAL OUTFLOWS	-18.48	-10.75	-13.84
MODEL IMBALANCE/ROUNDING ERROR	-0.56	0.38	0.21

AVERAGE WATER BALANCE COMPONENTS: 1972-1996

TR64
Area 5-SALMESBURY

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	50.66
LEAKAGE FROM DRIFT	2.42	0.01	n.a.
LEAKAGE FROM S&G	0.06	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM CARBONIFEROUS	3.89	0.00	0.00
- FROM AREA 4	0.36	0.00	0.00
- FROM SOUTH	0.05	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	0.01	0.00	0.00
STORAGE RELEASE	0.41	0.03	0.41
TOTAL INFLOWS	7.21	0.04	51.07
OUTFLOWS			
ABSTRACTION	-7.24	0.00	0.00
BOUNDARY OUTFLOWS			
- TO CARBONIFEROUS	0.00	0.00	0.00
- TO AREA 4	0.00	0.00	0.00
- TO SOUTH	0.00	0.00	0.00
			0.00
LEAKAGE TO SANDSTONE	n.a.	-0.06	-2.42
LEAKAGE TO S&G	n.a.	n.a.	-0.01
NET GROUNDWATER FLOW TO RIVERS	0.00	0.00	-4.33
REJECTED FLOW	0.00	0.00	-44.71
STORAGE GAIN	0.00	0.00	0.00
TOTAL OUTFLOWS	-7.24	-0.06	-51.47
MODEL IMBALANCE/ROUNDING ERROR	-0.03	-0.02	-0.41

WATER BALANCE COMPONENTS: APRIL 1987 - MAXIMUM WATER LEVEL CONDITIONS

TR64
Area 5-SALMESBURY

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	21.61
LEAKAGE FROM DRIFT	2.04	0.01	n.a.
LEAKAGE FROM S&G	0.02	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM CARBONIFEROUS	3.89	0.00	0.00
- FROM AREA 4	0.36	0.00	0.00
- FROM SOUTH	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	0.00	0.00	0.00
STORAGE RELEASE	0.14	0.00	0.14
TOTAL INFLOWS	6.44	0.01	21.74
OUTFLOWS			
ABSTRACTION	-5.97	0.00	0.00
BOUNDARY OUTFLOWS			
- TO CARBONIFEROUS	0.00	0.00	0.00
- TO AREA 4	0.00	0.00	0.00
- TO SOUTH	-0.32	0.00	0.00
LEAKAGE TO SANDSTONE	n.a.	-0.02	-2.04
LEAKAGE TO S&G	n.a.	n.a.	-0.01
NET GROUNDWATER FLOW TO RIVERS	-0.30	0.00	-5.02
REJECTED FLOW	0.00	0.00	-14.97
STORAGE GAIN	0.00	-0.01	0.00
TOTAL OUTFLOWS	-6.59	-0.03	-22.03
MODEL IMBALANCE/ROUNDING ERROR	-0.14	-0.02	-0.29

WATER BALANCE COMPONENTS: SEPT 1995 - MINIMUM WATER LEVEL CONDITIONS

TR64
Area 5-SALMESBURY

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	0.00
LEAKAGE FROM DRIFT	1.21	0.00	n.a.
LEAKAGE FROM S&G	0.05	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM CARBONIFEROUS	3.88	0.00	0.00
- FROM AREA 4	0.37	0.00	0.00
- FROM SOUTH	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	0.49	0.00	0.00
STORAGE RELEASE	1.63	0.03	17.11
TOTAL INFLOWS	7.63	0.03	17.11
OUTFLOWS			
ABSTRACTION	-8.33	0.00	0.00
BOUNDARY OUTFLOWS			
- TO CARBONIFEROUS	0.00	0.00	0.00
- TO AREA 4	0.00	0.00	0.00
- TO SOUTH	-0.30	0.00	0.00
LEAKAGE TO SANDSTONE	n.a.	-0.05	-1.21
LEAKAGE TO S&G	n.a.	n.a.	-0.00
NET GROUNDWATER FLOW TO RIVERS	0.00	0.00	-2.20
REJECTED FLOW	0.00	0.00	-13.37
STORAGE GAIN	0.00	0.00	0.00
TOTAL OUTFLOWS	-8.63	-0.05	-16.78
MODEL IMBALANCE/ROUNDING ERROR	-1.00	-0.01	0.33

APPENDIX D

INFLUENCE OF NEW LICENCE IN PRESTON (EMMETT DENIM CARE LTD)

APPENDIX D

INFLUENCE OF NEW LICENCE IN PRESTON (EMMETT DENIMCARE LTD)

D1 Details of Prediction

Additional abstraction point added at NGR SD 539 302. Abstraction set at 246.5 m^3/d for every timestep of the simulation (equivalent to 90 Ml/annum). Location of borehole is shown in Figure D1.

All other abstractions as historical (except Courtaulds set to zero throughout).

Recharge sequence as historical.

Initial conditions taken from last timestep of calibration run (December 1995).

All results are compared with a "baseline" run, where model set up as above with no new abstraction from Emmett Denim borehole.

In following sections, run 2 refers to the baseline run while run 11 refers to the run with the additional Emmett abstraction.

D2 Results

D2.1 Sandstone Hydrographs

Figures D2 and D3 show the simulated sandstone hydrographs at two locations: at "control" observation borehole T74, and at the Whitbread, Samlesbury boreholes respectively. The model has simulated a limited decline in groundwater levels at these locations: a maximum of 0.023 m at T74 and 0.047 m at the Whitbread sources.

D2.2 Influence of Additional Abstraction

Figure D4 shows the difference in simulated sandstone groundwater levels around the Emmett source.

There are a number of licensed industrial/commercial boreholes in Preston, the nearest being 1 km away Supreme Laundry). The decline in groundwater levels at this distance was simulated to be around 0.15 – 0.2 m. The proposed licence may, therefore, result in an increase in pumping heads at these sites (Chris Miller Ltd, UniqueDenim Sevices[formerly Supreme Laundry], Somic Ltd and Liquid Plastics), which may affect abstraction rates.

Two "environmentally sensitive areas" exist within the simulated "cone of depression" around the Emmett source:

Cottam Hall (Biological Heritage Site) and the Great Crested Newt Site, north east of Preston. Much of the degradation of these sites in the past has been attributed to the urbanisation of Preston (APEM. March 1996). However, groundwater level decline is considered to have contributed to the reduction in the number of springs and area of marshland at these sites. The Emmett abstraction results in a limited decline in sandstone levels, while the decline in the Drift water table is negligible at these sites. Consequently, additional abstraction is not expected to result in any further environmental damage to these areas.

D2.3 River Flows

The major impact of abstraction from the Emmett source will be on flows in the River Ribble. The simulated River Ribble flows have not been calibrated against the actual observed flows. There is a simulated reduction in river flows of about 2 l/s. This is not concentrated at the river nearest the source, but is spread throughout the length of the river since the aquifer is confined and there is reduced baseflow to the river as a result of the decline in sandstone levels. The model simulates no reduction in river flow in the Woodplumpton Brook.

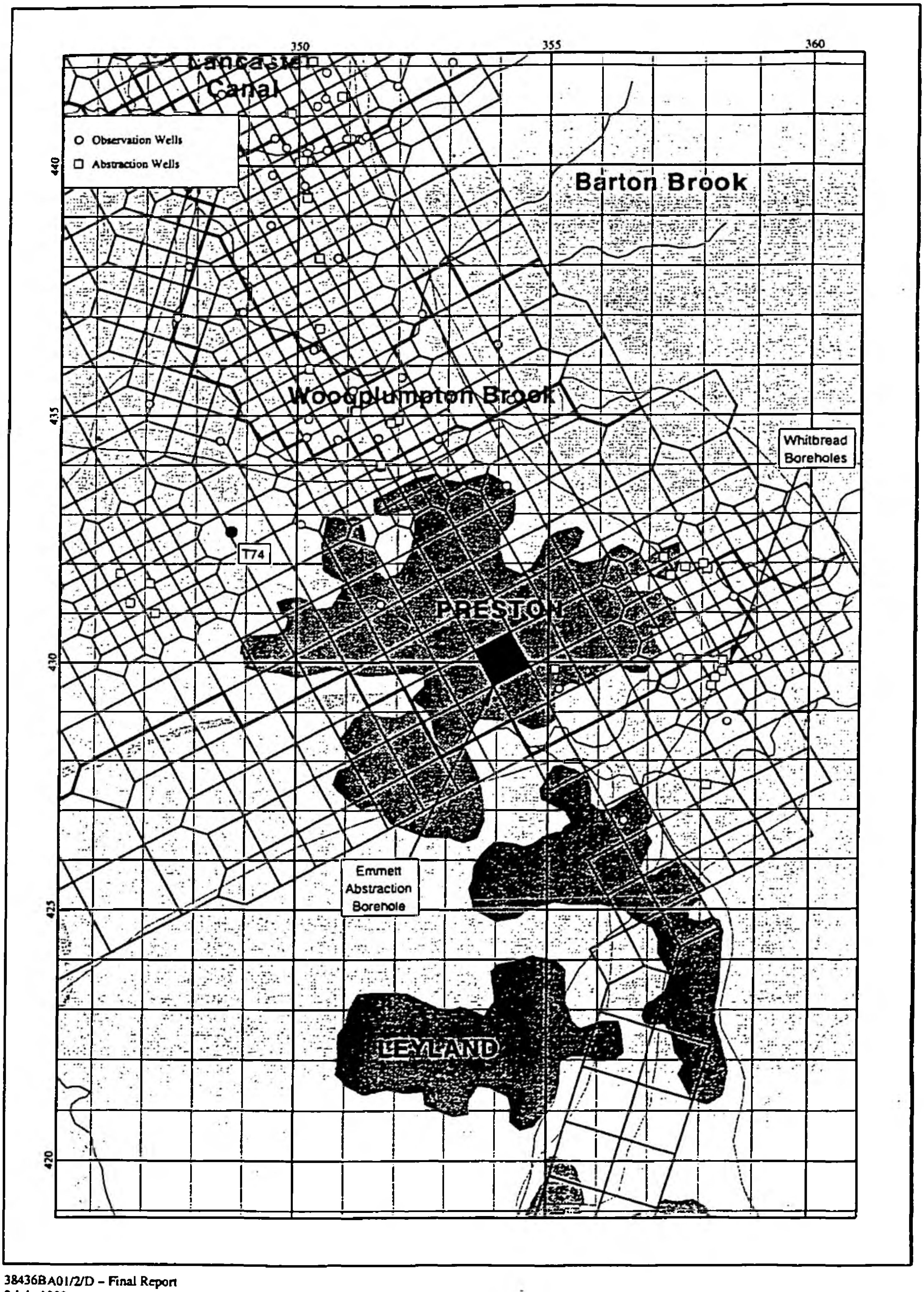
D3 Conclusion

The Emmett Denim abstraction borehole is located in central Preston, where there are a number of exisitng licensed industrial sources, the nearest being some 1 km away. The affect on these sources is unlikely to prevent the companies abstracting their licensed rates, albeit with additional pumping heads/costs.

It is more remote from the major NWW abstractions to the north, BNFL abstractions to the west and the Samlesbury boreholes to the east. However, in view of the declining trend in groundwater levels observed in T74, the additional induced drawdown by the proposed Emmett abstraction at T74 (about 0.02 m) would prevent NWW from abstracting from their Broughton 'A' sources at times when the superimposed drawdowns reduce groundwater levels to below 8.50 m AOD (ie the 'hands off' level). This would constitute derogation of NWW's protected rights.

Note: This predictive run was made with the 'major' licence holders (NWW, BNFL and Whitbreads) at actual historic rates. These have been below the full licensed rates during the model period. Therefore, the prediction does not take account of the sustainability of the currently licensed abstractions from the Fylde aquifer in terms of the available groundwater resources and the impact on surface water or groundwater dependent features.

Southern Area of Fylde Aquifer



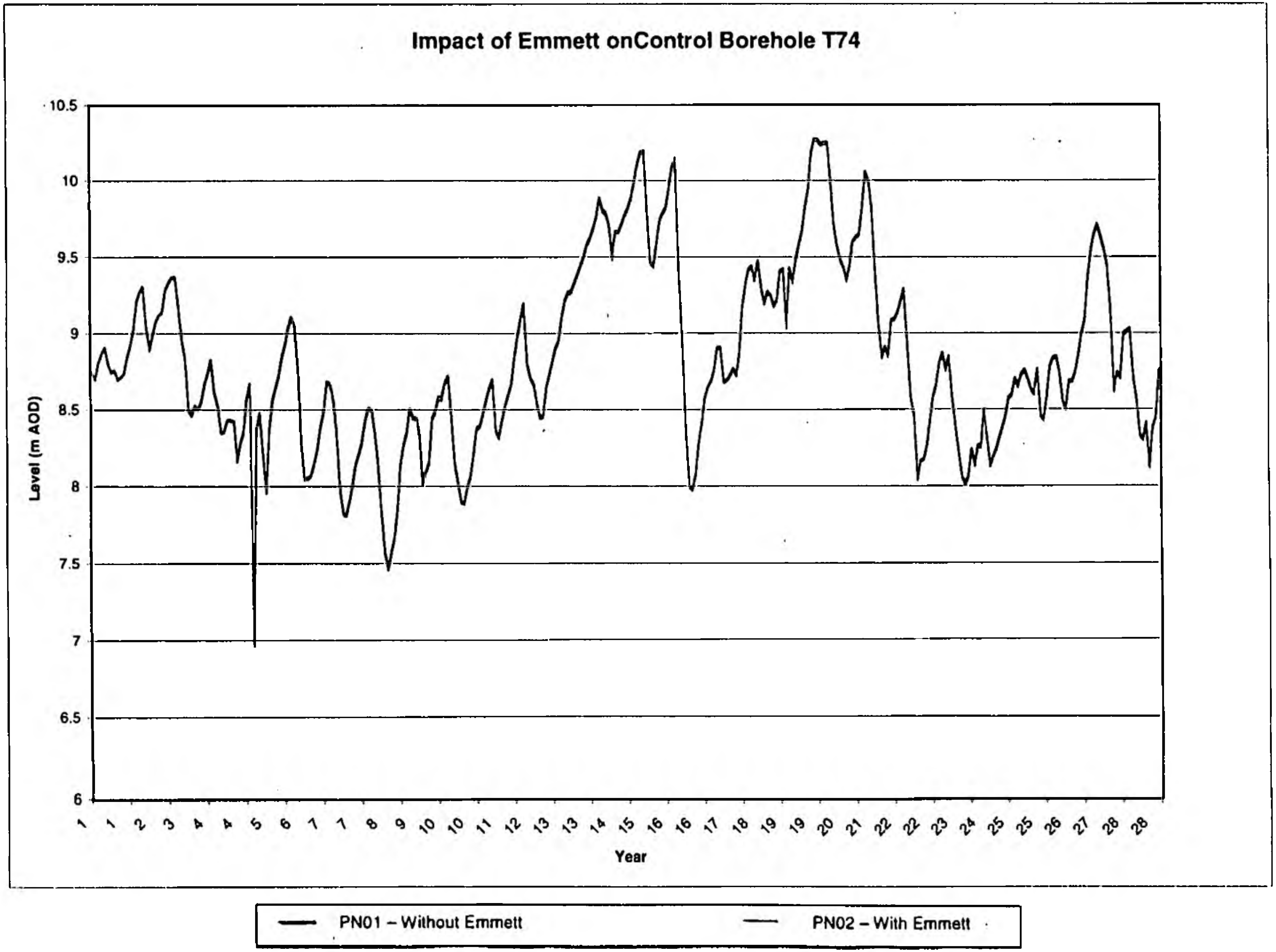


Figure D2
Sandstone Piezometry at Control Observation Borehole (T74)

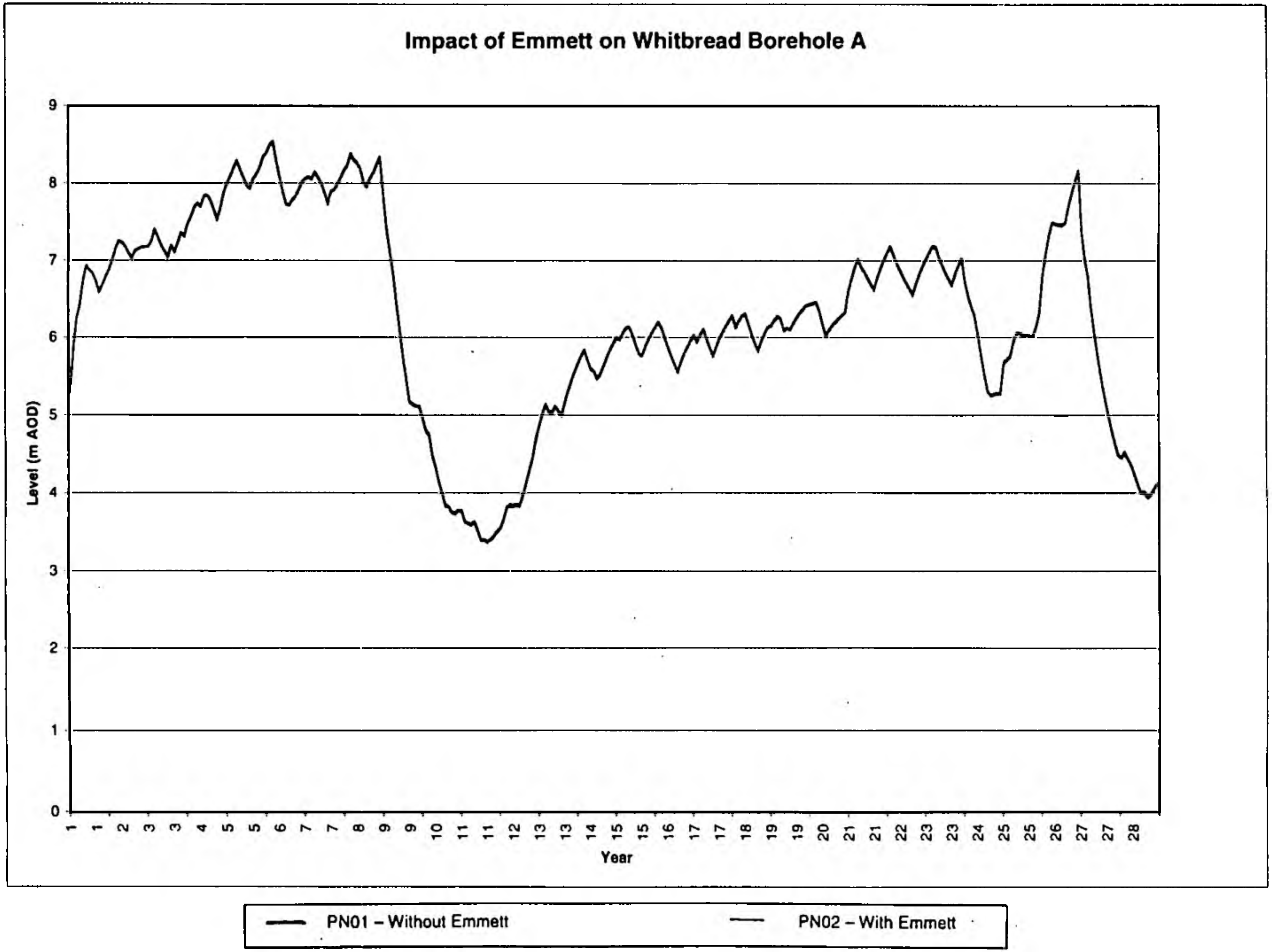


Figure D3
Sandstone Piezometry at Whitbread Observation Borehole A

Figure D4
Influence of Emmett Abstractions on Sandstone Piezometry

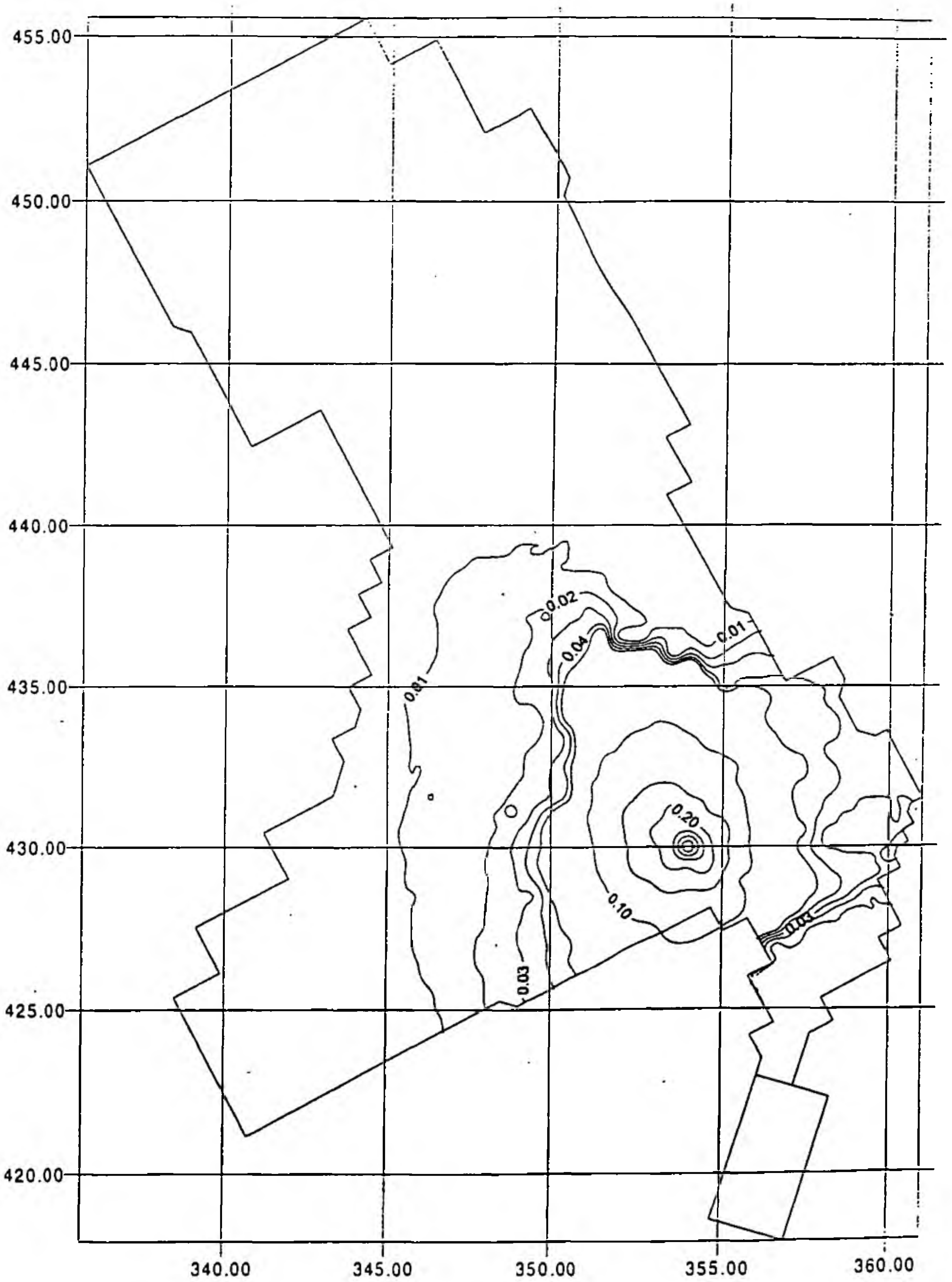
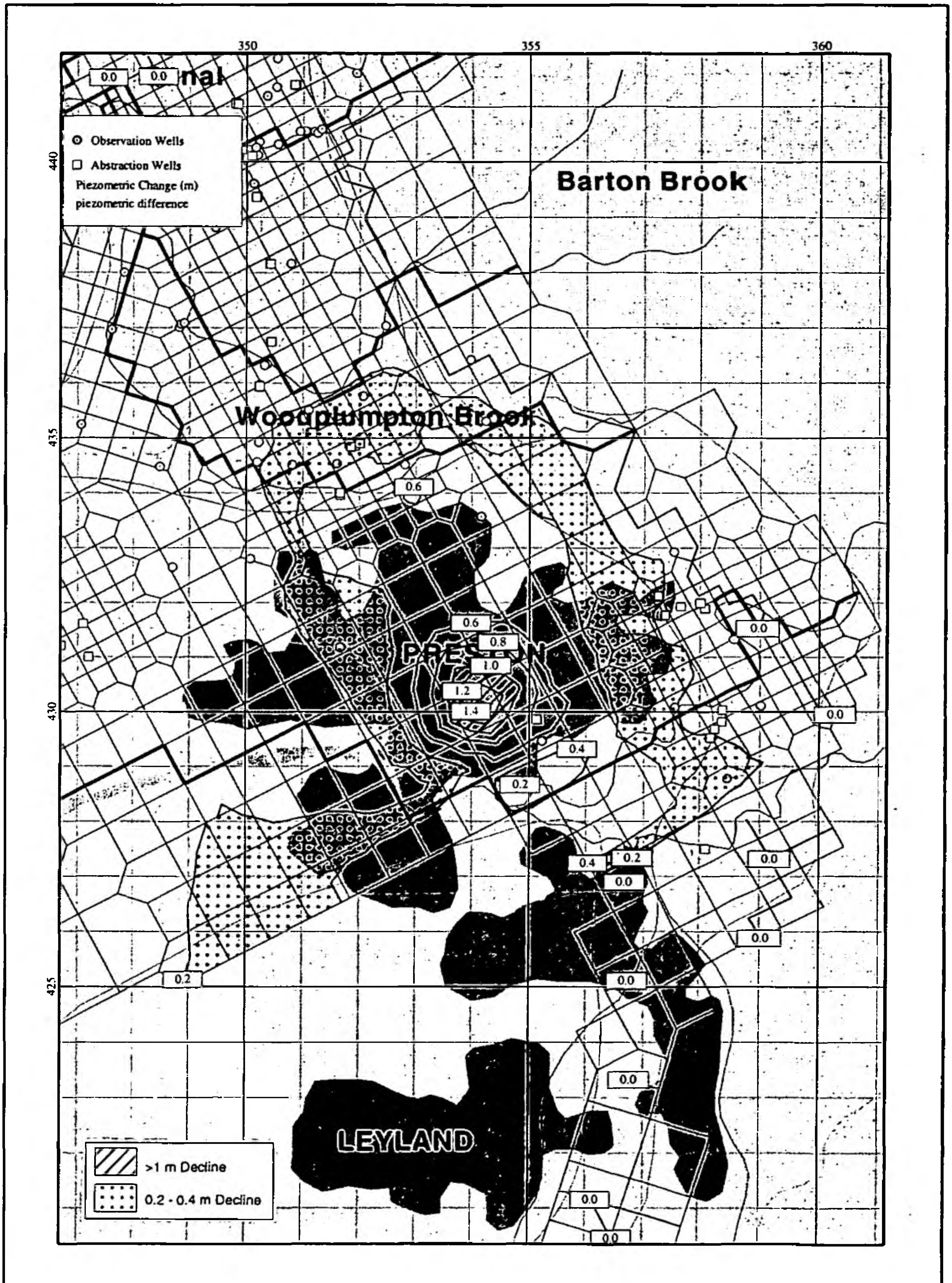


Figure D4

Influence of Emmett Abstractions - High Levels ("4/87")



Influence of Emmett Abstractions - Low Levels ("9/95")

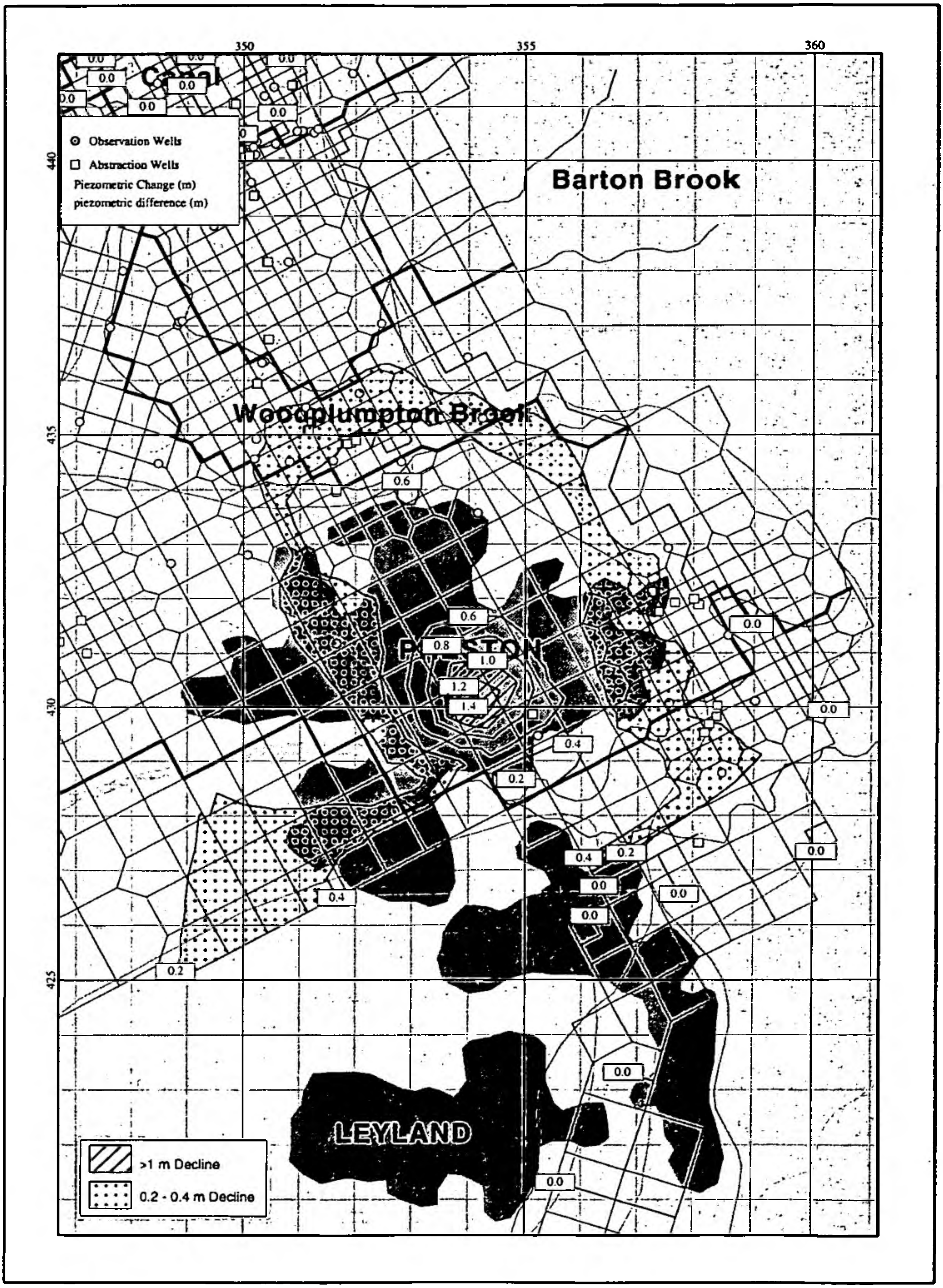
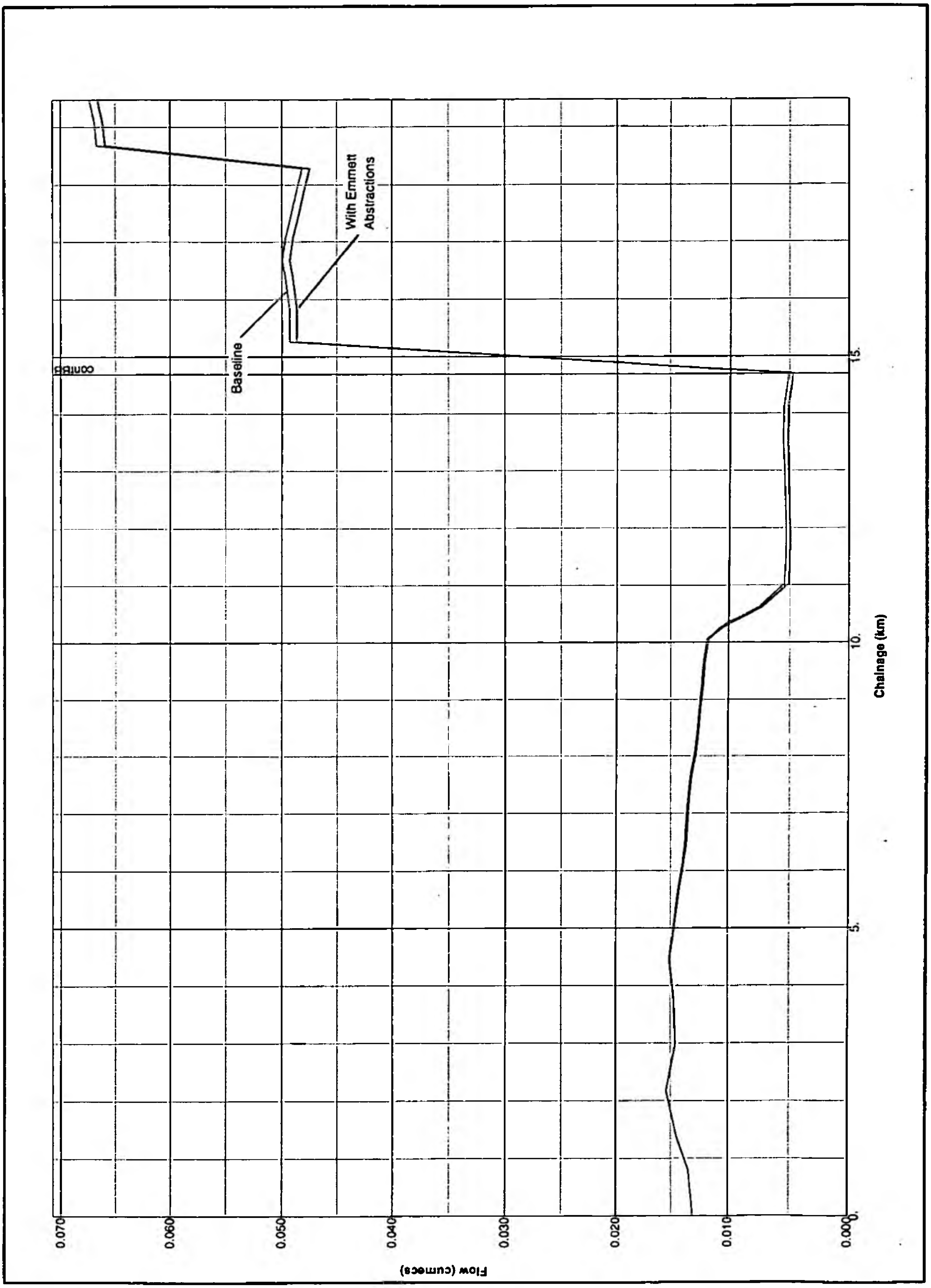


Figure D6

Woodplumpton Brook Accretion Profile "9/1995"



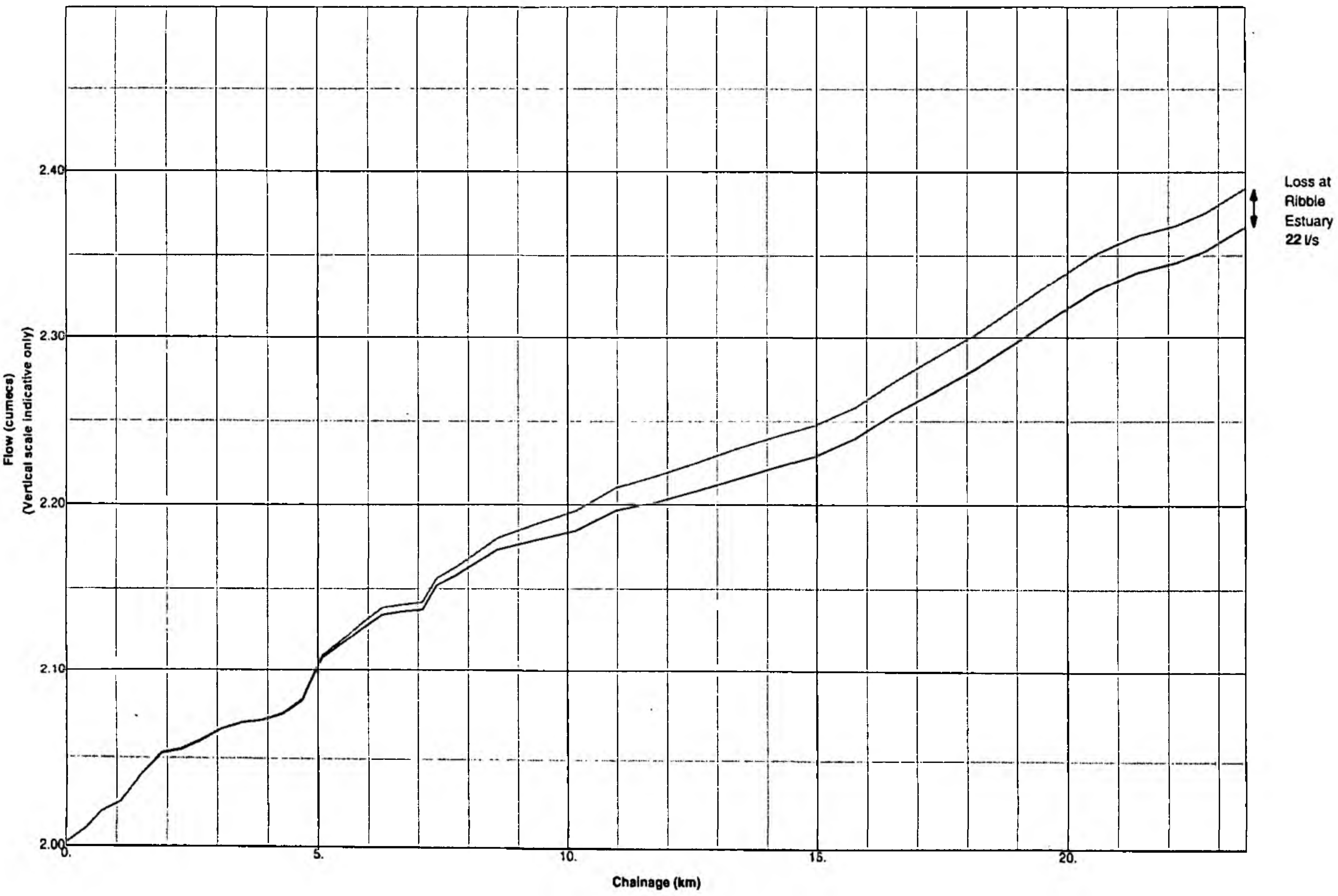
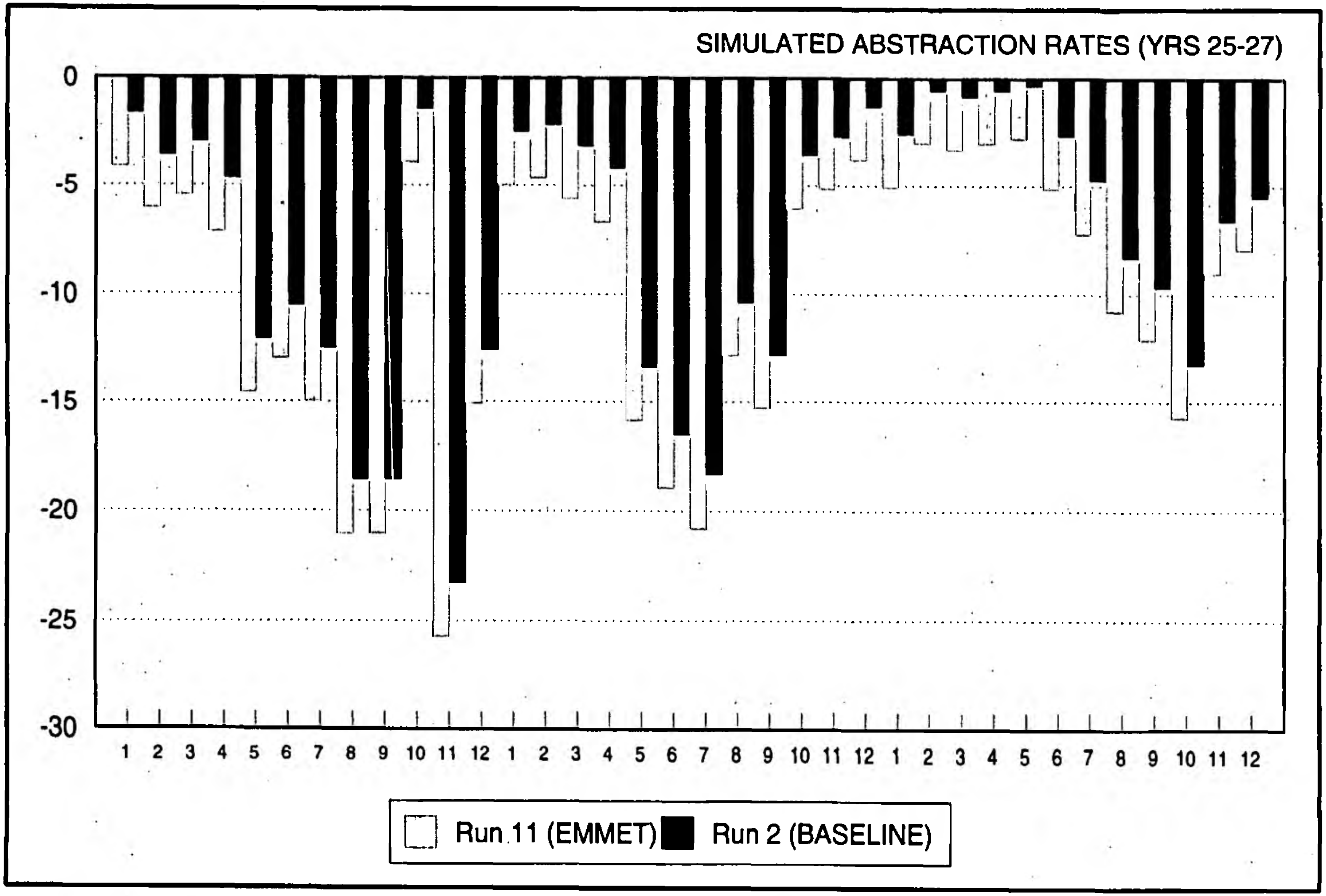


Figure D7
Ribble Accretion Profile "9/1995"



SOUTHERN/PRESTON AREA WATER BALANCE COMPONENTS

Figure D8a

Figure D8b

SOUTHERN/PRESTON AREA WATER BALANCE COMPONENTS

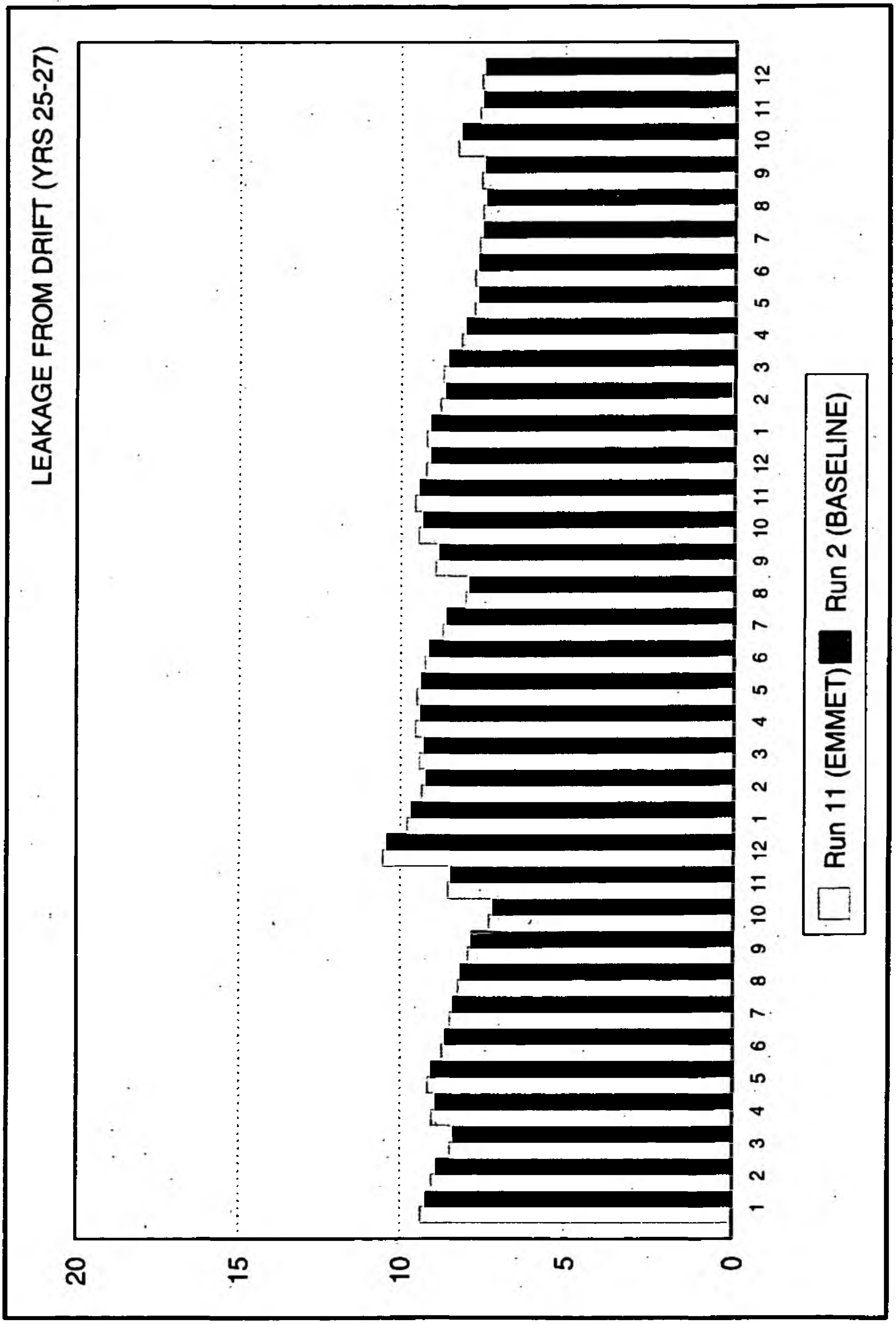


Figure D8c

SOUTHERN/PRESTON AREA WATER BALANCE COMPONENTS

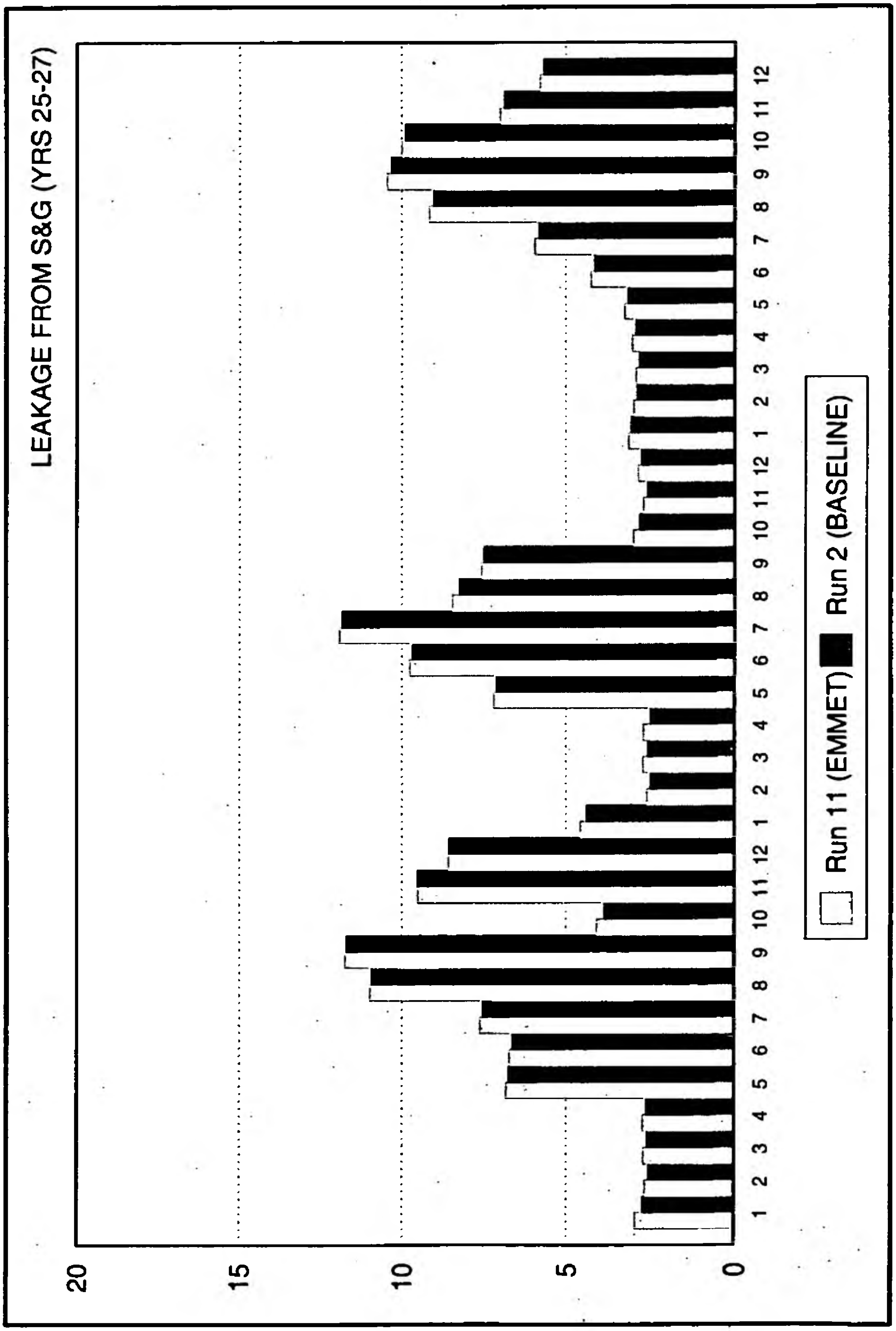


Figure D8d

SOUTHERN/PRESTON AREA WATER BALANCE COMPONENTS

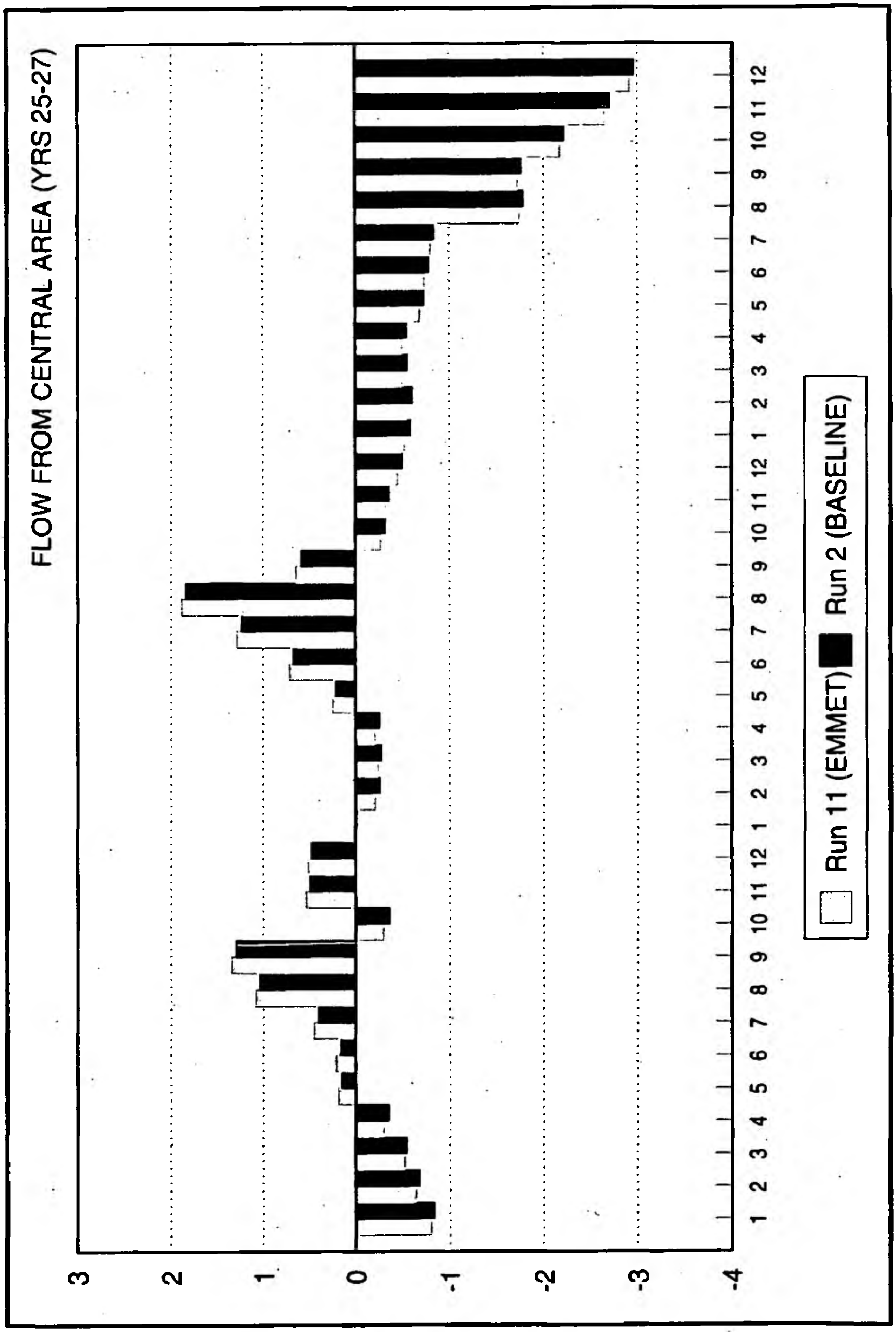


Figure D8e

SOUTHERN/PRESTON AREA WATER BALANCE COMPONENTS

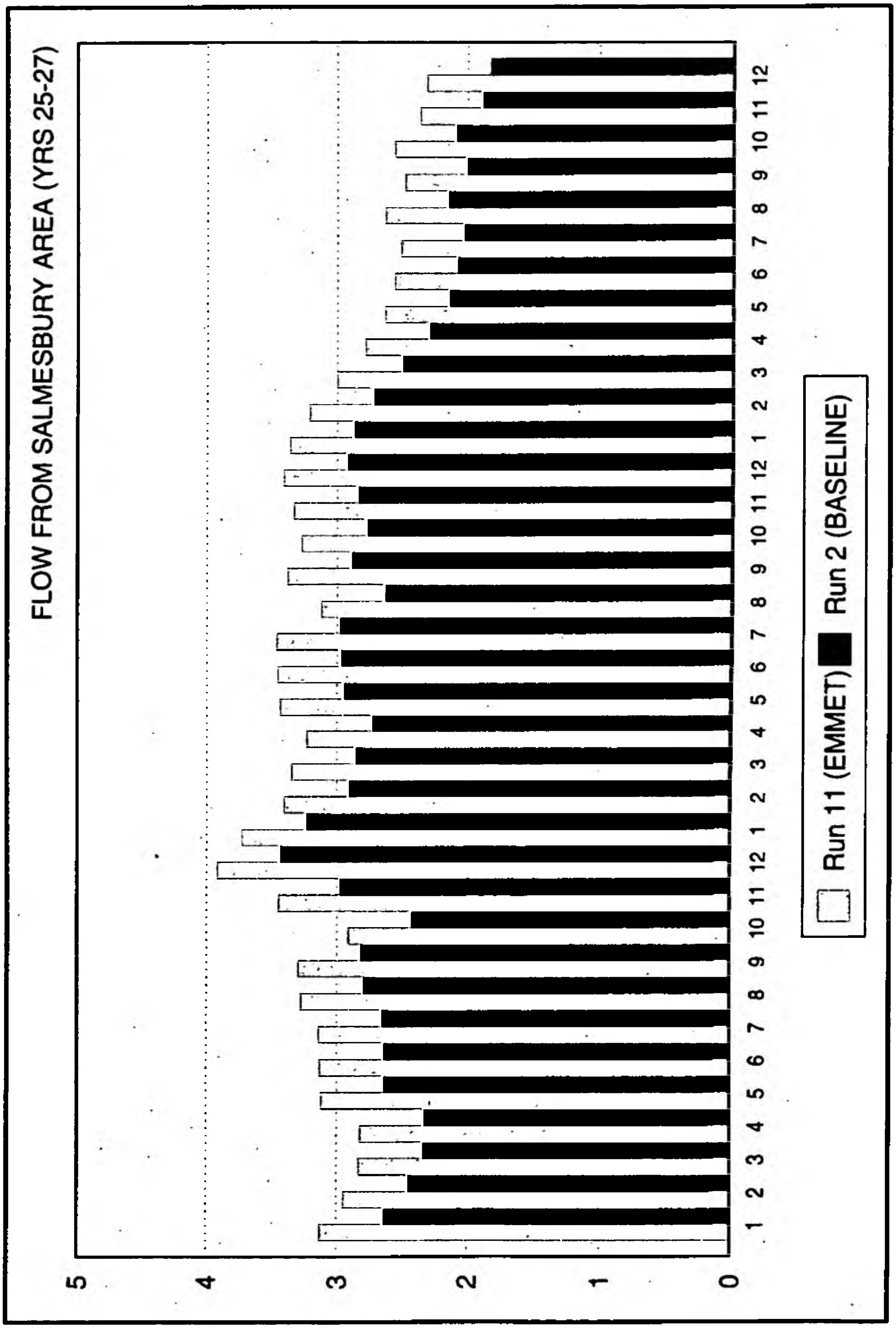
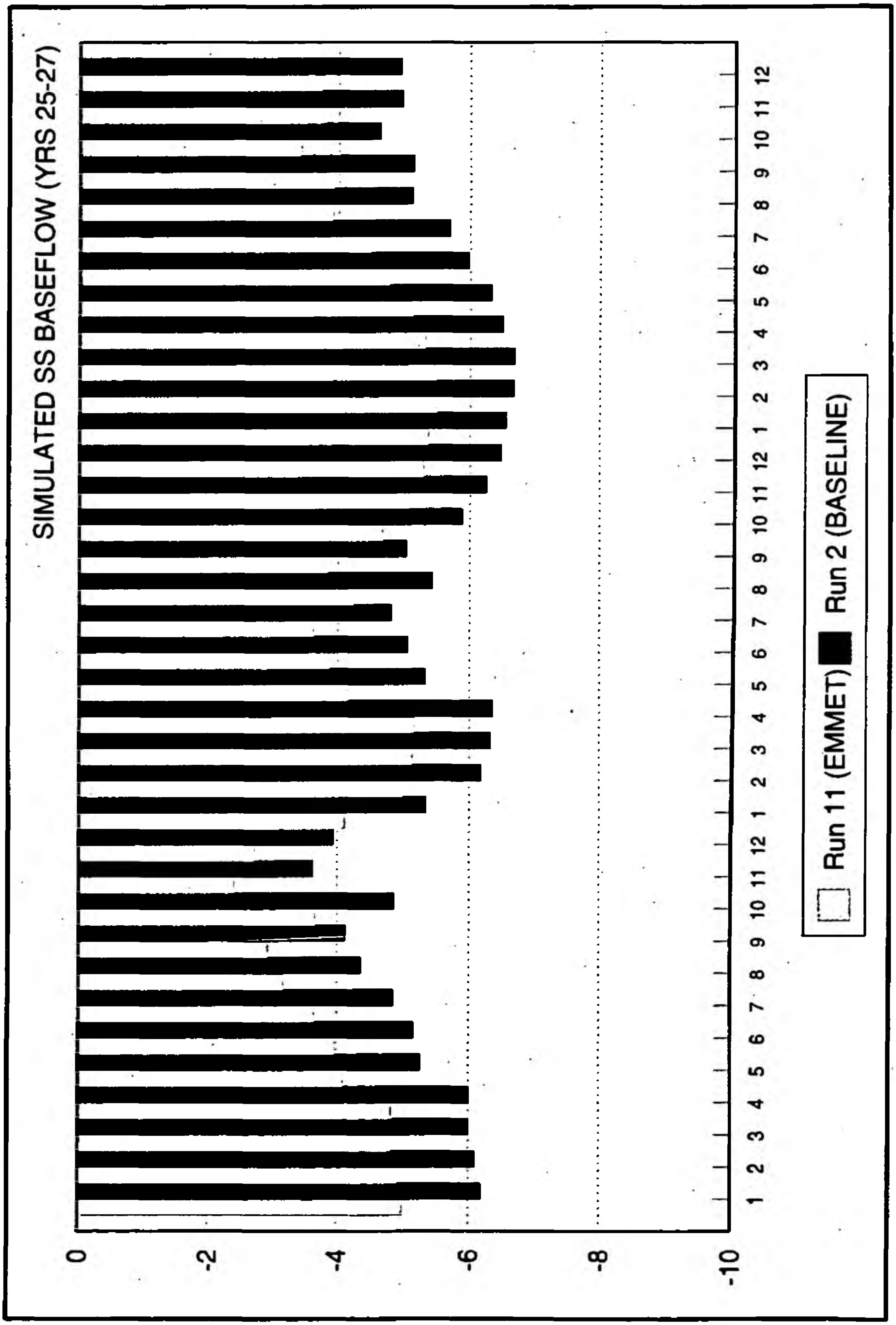
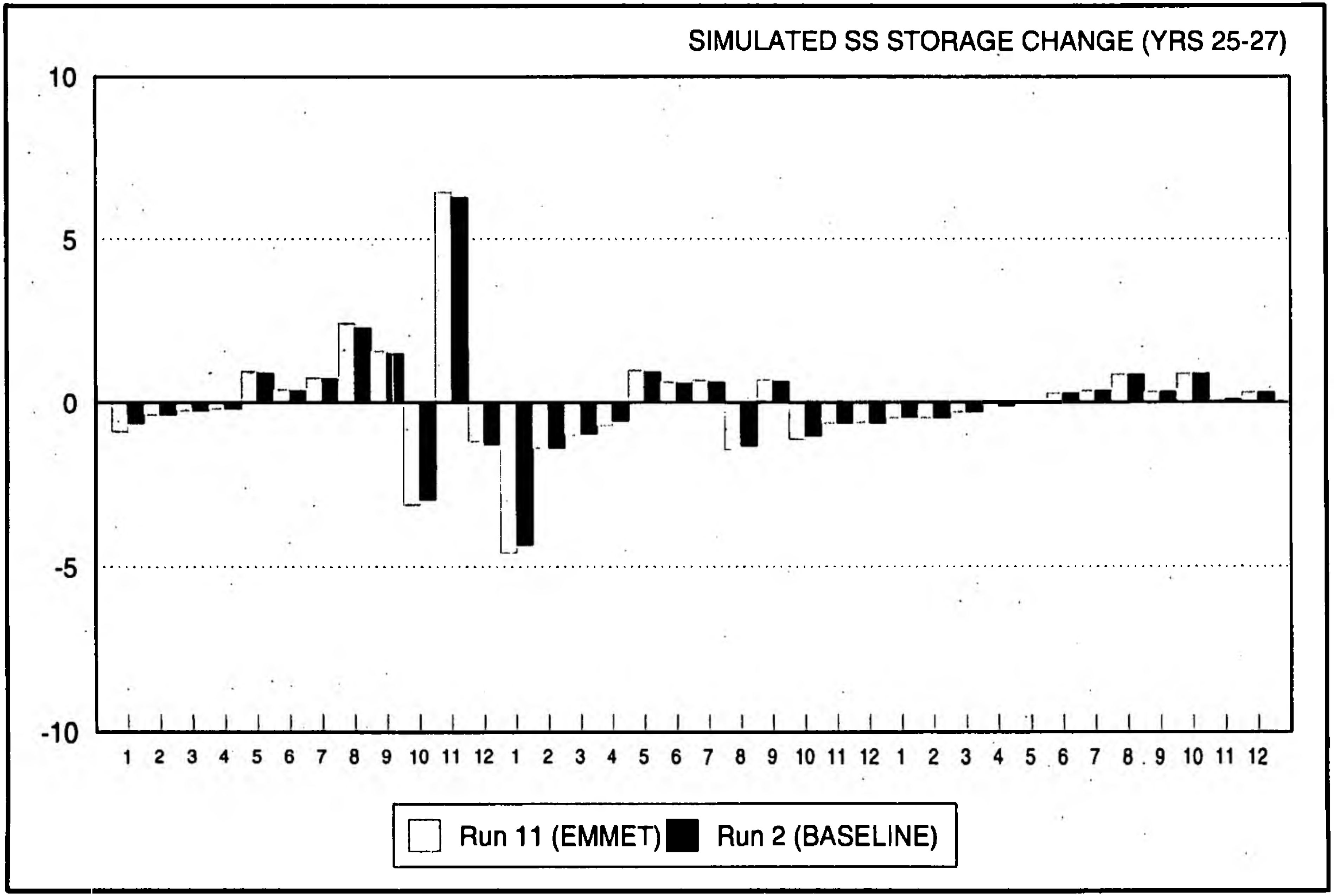


Figure D8f

SOUTHERN/PRESTON AREA WATER BALANCE COMPONENTS





SOUTHERN/PRESTON AREA WATER BALANCE COMPONENTS

Figure D8g

Figure D8h

SOUTHERN/PRESTON AREA WATER BALANCE COMPONENTS

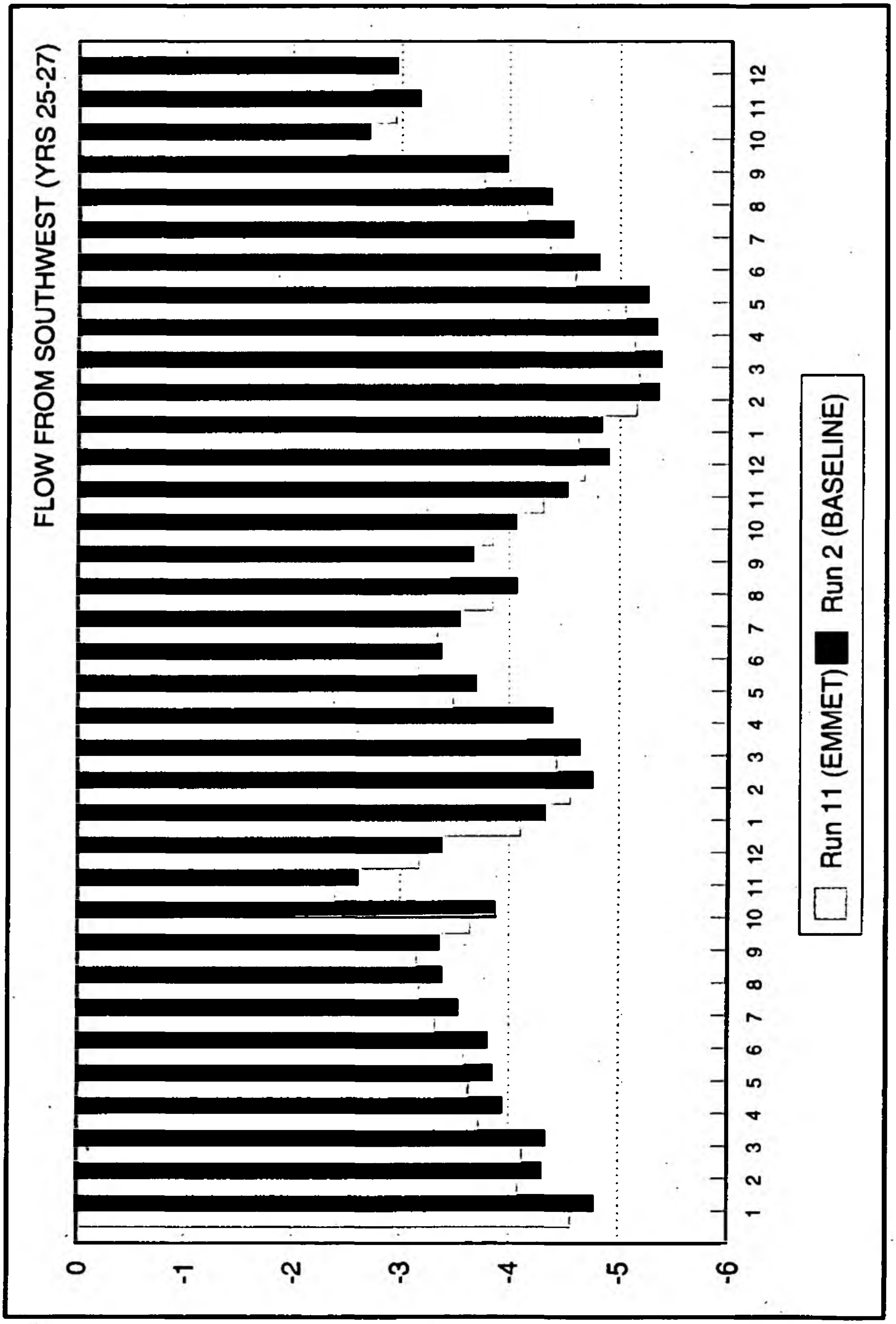
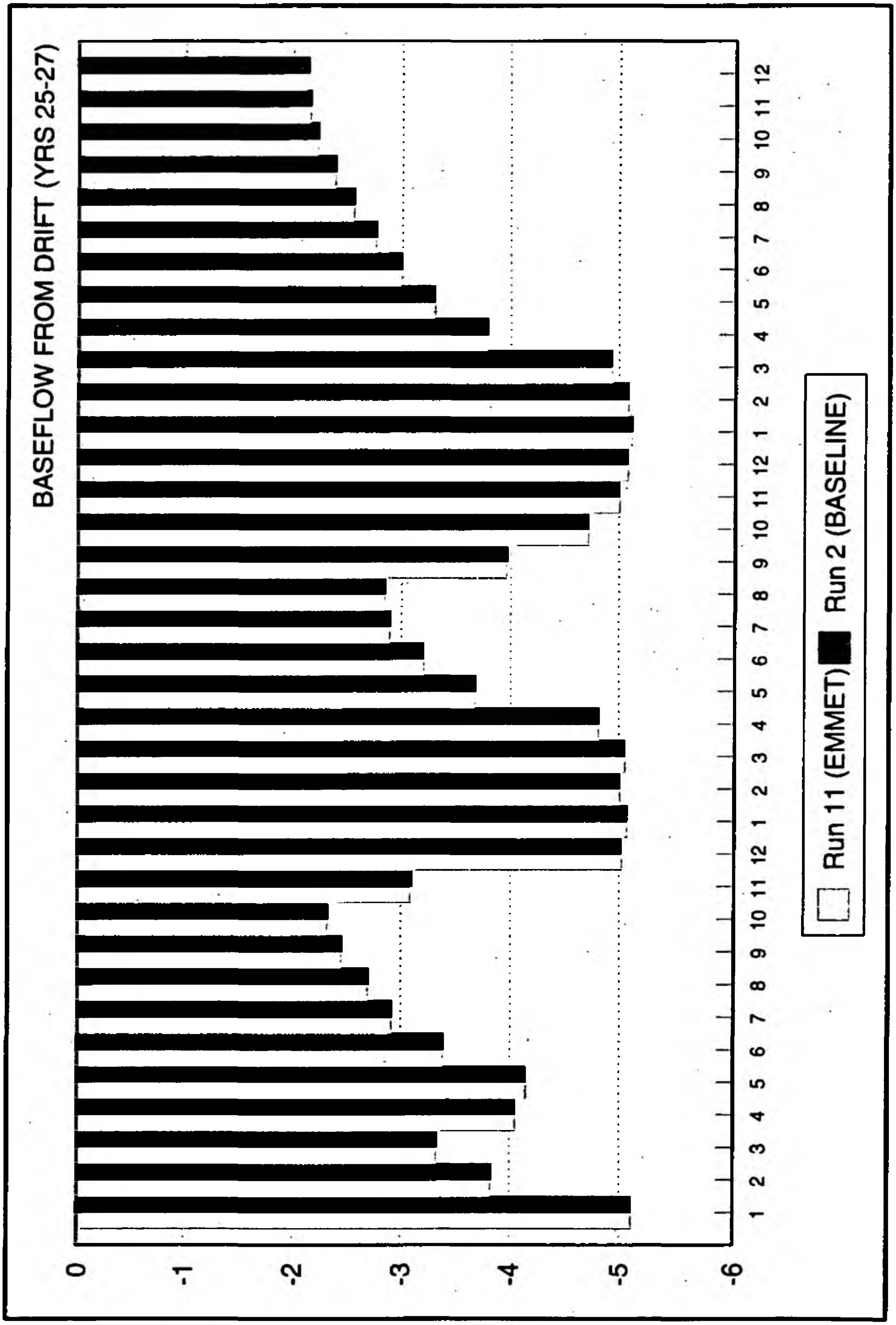


Figure D8i

SOUTHERN/PRESTON AREA WATER BALANCE COMPONENTS



WATER BALANCE COMPONENTS: MONTH 9, YEAR 27 - MINIMUM WATER LEVEL CONDITIONS

EMMETT LICENCE
Area 4-SOUTHERN/PRESTON

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	0.00
LEAKAGE FROM DRIFT	7.34	5.27	n.a.
LEAKAGE FROM S&G	11.02	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM AREA 5 (SALMESBURY)	0.66	0.00	0.00
- FROM CARBONIFEROUS	0.00	0.00	0.00
- FROM AREA 3 (CENTRAL)	0.00	0.00	0.00
- FROM SOUTH WEST	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	0.00	1.40	13.37
STORAGE RELEASE	0.94	4.71	0.44
TOTAL INFLOWS	19.96	11.38	13.81
OUTFLOWS			
ABSTRACTION	-12.29	0.00	0.00
BOUNDARY OUTFLOWS			
- TO AREA 5 (SALMESBURY)	0.00	-0.01	0.00
- TO CARBONIFEROUS	0.00	0.00	0.00
- TO AREA 3 (CENTRAL)	-1.41	0.00	0.00
- TO SOUTH WEST	-6.38	0.00	0.00
LEAKAGE TO SANDSTONE	n.a.	-11.02	-7.34
LEAKAGE TO S&G	n.a.	n.a.	-5.27
NET GROUNDWATER FLOW TO RIVERS	-0.14	0.00	-1.67
REJECTED FLOW	0.00	0.00	0.00
STORAGE GAIN	0.00	0.00	0.00
TOTAL OUTFLOWS	-20.22	-11.02	-14.28
MODEL IMBALANCE/ROUNDING ERROR	-0.26	0.36	-0.47

WATER BALANCE COMPONENTS: MONTH 4, YEAR 19 - MAXIMUM WATER LEVEL CONDITIONS

EMMETT LICENCE
Area 4-SOUTHERN/PRESTON

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	71.07
LEAKAGE FROM DRIFT	8.48	7.25	n.a.
LEAKAGE FROM S&G	3.88	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM AREA 5 (SALMESBURY)	0.48	0.00	0.00
- FROM CARBONIFEROUS	0.00	0.00	0.00
- FROM AREA 3 (CENTRAL)	0.00	0.00	0.00
- FROM SOUTH WEST	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	0.00	0.94	0.00
STORAGE RELEASE	0.00	0.00	0.00
TOTAL INFLOWS	12.83	8.19	71.07
OUTFLOWS			
ABSTRACTION	-6.65	0.00	0.00
BOUNDARY OUTFLOWS			
- TO AREA 5 (SALMESBURY)	0.00	-0.01	0.00
- TO CARBONIFEROUS	0.00	0.00	0.00
- TO AREA 3 (CENTRAL)	-0.19	-0.92	0.00
- TO SOUTH WEST	-5.68	0.00	0.00
LEAKAGE TO SANDSTONE	n.a.	-3.88	0.00
LEAKAGE TO S&G	n.a.	n.a.	-7.25
NET GROUNDWATER FLOW TO RIVERS	-0.17	0.00	-3.30
REJECTED FLOW	0.00	0.00	-58.91
STORAGE GAIN	-0.43	-3.38	-0.93
TOTAL OUTFLOWS	-13.11	-8.19	-70.39
MODEL IMBALANCE/ROUNDING ERROR	-0.28	0.00	0.68

AVERAGE WATER BALANCE COMPONENTS: YEAR 3-28

EMMETT LICENCE
Area 4-SOUTHERN/PRESTON

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	166.64
LEAKAGE FROM DRIFT	8.57	7.22	n.a.
LEAKAGE FROM S&G	8.24	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM AREA 5 (SALMESBURY)	0.91	0.00	0.00
- FROM CARBONIFEROUS	0.00	0.00	0.00
- FROM AREA 3 (CENTRAL)	0.00	0.00	0.00
- FROM SOUTH WEST	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	0.00	2.21	0.00
STORAGE RELEASE	0.00	0.00	0.00
TOTAL INFLOWS	17.72	9.43	166.64
OUTFLOWS			
ABSTRACTION	-12.07	0.00	0.00
BOUNDARY OUTFLOWS			
- TO AREA 5 (SALMESBURY)	0.00	-0.01	0.00
- TO CARBONIFEROUS	0.00	0.00	0.00
- TO AREA 3 (CENTRAL)	-0.30	-1.15	0.00
- TO SOUTH WEST	0.00	0.00	0.00
LEAKAGE TO SANDSTONE	n.a.	-8.24	-8.57
LEAKAGE TO S&G	n.a.	n.a.	-7.22
NET GROUNDWATER FLOW TO RIVERS	-5.44	0.00	-2.90
REJECTED FLOW	0.00	0.00	-147.72
STORAGE GAIN	-0.02	-0.03	-0.02
TOTAL OUTFLOWS	-17.84	-9.42	-166.44
MODEL IMBALANCE/ROUNDING ERROR	-0.12	0.01	0.20

WATER BALANCE COMPONENTS: SEPT 1995 - MINIMUM WATER LEVEL CONDITIONS

EMMETT LICENCE
Area 5-SALMESBURY

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	0.00
LEAKAGE FROM DRIFT	1.55	0.00	n.a.
LEAKAGE FROM S&G	0.03	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM CARBONIFEROUS	3.88	0.00	0.00
- FROM AREA 4	0.37	0.00	0.00
- FROM SOUTH	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	0.51	0.00	0.00
STORAGE RELEASE	1.65	0.03	17.24
TOTAL INFLOWS	7.99	0.03	17.24
OUTFLOWS			
ABSTRACTION	-8.33	0.00	0.00
BOUNDARY OUTFLOWS			
- TO CARBONIFEROUS	0.00	0.00	0.00
- TO AREA 4	0.00	0.00	0.00
- TO SOUTH	-0.66	0.00	0.00
LEAKAGE TO SANDSTONE	n.a.	-0.03	-1.55
LEAKAGE TO S&G	n.a.	n.a.	-0.00
NET GROUNDWATER FLOW TO RIVERS	0.00	0.00	-1.82
REJECTED FLOW	0.00	0.00	-13.89
STORAGE GAIN	0.00	0.00	0.00
TOTAL OUTFLOWS	-8.99	-0.03	-17.26
MODEL IMBALANCE/ROUNDING ERROR	-1.00	-0.00	-0.02

WATER BALANCE COMPONENTS: MONTH 4 YEAR 19 - MAXIMUM WATER LEVEL CONDITIONS

EMMETT LICENCE
Area 5-SALMESBURY

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	21.61
LEAKAGE FROM DRIFT	2.41	0.00	n.a.
LEAKAGE FROM S&G	0.01	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM CARBONIFEROUS	3.88	0.00	0.00
- FROM AREA 4	0.36	0.00	0.00
- FROM SOUTH	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	0.00	0.00	0.00
STORAGE RELEASE	0.00	0.00	0.00
TOTAL INFLOWS	6.66	0.01	21.61
OUTFLOWS			
ABSTRACTION	-5.97	0.00	0.00
BOUNDARY OUTFLOWS			
- TO CARBONIFEROUS	0.00	0.00	0.00
- TO AREA 4	0.00	0.00	0.00
- TO SOUTH	-0.48	0.00	0.00
LEAKAGE TO SANDSTONE	n.a.	-0.01	-2.41
LEAKAGE TO S&G	n.a.	n.a.	-0.00
NET GROUNDWATER FLOW TO RIVERS	-0.13	0.00	-4.43
REJECTED FLOW	0.00	0.00	-14.75
STORAGE GAIN	-0.14	0.00	-0.14
TOTAL OUTFLOWS	-6.72	-0.01	-21.73
MODEL IMBALANCE/ROUNDING ERROR	-0.06	-0.01	-0.13

AVERAGE WATER BALANCE COMPONENTS: YEAR 3-28

EMMETT LICENCE
Area 5-SALMESBURY

COMPONENTS	SANDSTONE	SANDS AND GRAVELS	DRIFT
INFLOWS			
POTENTIAL RECHARGE	0.00	0.00	50.66
LEAKAGE FROM DRIFT	1.20	0.00	n.a.
LEAKAGE FROM S&G	0.02	n.a.	n.a.
BOUNDARY INFLOWS			
- FROM CARBONIFEROUS	3.88	0.00	0.00
- FROM AREA 4	0.36	0.00	0.00
- FROM SOUTH	0.00	0.00	0.00
NET LEAKAGE FROM RIVERS TO LAYER	0.00	0.00	0.00
STORAGE RELEASE	0.26	0.01	0.26
TOTAL INFLOWS	5.72	0.01	50.91
OUTFLOWS			
ABSTRACTION	-4.49	0.00	0.00
BOUNDARY OUTFLOWS			
- TO CARBONIFEROUS	0.00	0.00	0.00
- TO AREA 4	0.00	0.00	0.00
- TO SOUTH	-0.91	0.00	0.00
			0.00
LEAKAGE TO SANDSTONE	n.a.	-0.02	-1.20
LEAKAGE TO S&G	n.a.	n.a.	-0.00
NET GROUNDWATER FLOW TO RIVERS	-0.58	0.00	-4.75
REJECTED FLOW	0.00	0.00	-44.63
STORAGE GAIN	0.00	0.00	0.00
TOTAL OUTFLOWS	-5.97	-0.02	-50.59
MODEL IMBALANCE/ROUNDING ERROR	-0.25	-0.01	0.32

APPENDIX E

DRIFT LEAKAGE INVESTIGATION

Fylde Aquifer/Wyre Catchment Water Resources Study

FINAL REPORT

APPENDIX E

Drift Leakage Investigation

E1 Introduction

The Fylde aquifer model and associated studies have shown that groundwater abstractions are largely met from two sources:

- by inducing leakage through the overlying Drift deposits;
- by inducing leakage from the rivers.

The simulation of leakage through the Drift, however, is based on a relatively simple approach, with the Drift represented as a single layer. In order to either confirm the acceptability of this approach or suggest methods of improvement a short study into the leakage mechanism has been carried out.

Since the Drift consists of different thicknesses of clays, silts, sands and gravels, it could be argued that leakage through the Drift would be more accurately modelled by sub-dividing the Drift into more layers, with different storage and permeability properties defined for each layer. However this was not considered a feasible option during the original model conceptualisation and development for a number of reasons but primarily because there are insufficient lithological data to delineate horizontal and lateral extent of individual sub-layers within the Drift.

It was decided that the simulation of the Drift and the interaction of the Drift with the sandstone aquifer would be best studied through detailed modelling flow within discrete sections of Drift. There were two components to this modelling:

- The redefinition of the mathematical basis of the vertical leakage mechanism so that the model more accurately reflects the process of the vertical movement of water through the Fylde Drift deposits. This was required so that the model allows intermediate Drift layers to dewater and dry out without resulting in numerical instabilities.

- Model the Drift around the "control observation borehole" (T74) where a decline in sandstone groundwater levels has been observed since 1972. In this area, the decline was simulated in the regional model by defining a low Drift "infiltration capacity" (the ability of the Drift to transfer rainfall recharge through the unsaturated zone to the Drift water table) along with relatively low values of vertical permeability (around 0.1 to 0.01 mm/d). Detailed modelling of a vertical section of the Drift in this area was therefore required to confirm the mechanism adopted in the main model and the parameter values defined.

This appendix details the methodology and results of these studies.

E2 Mathematical Basis of the Drift Leakage

The Fylde model incorporates a relatively simplistic approach to leakage. The model calculates an instantaneous vertical flow through the Drift aquitard in response to changes in the underlying Sandstone piezometry. The flow is defined in the following equation (neglecting horizontal flow components):

$$W^D\left[h_t^s - h_t^D\right] + R_e = S^D\left[h_t^D - h_{(t+\Delta t)}^D\right] \qquad \text{(E.1)}$$

where:

h_t^s	-	piezometric level at midpoint of sandstone at time t
h_t^D	-	water table level at midpoint of Drift at time t
$h_{t+\Delta t}^D$	-	water table level at midpoint of Drift at time t+Δt
R_e	-	effective recharge to water table
		= R when R < INF
		=INF when R > INF
		(R-potential recharge, INF = infiltration capacity of surface Drift)
W^D	-	vertical conductance of Drift/sandstone interface

$$W^D = \frac{1}{\left[\frac{(B^D - B^S)}{k_v^S} + \frac{(h_t^D - B^D)}{k_v^D}\right]} \qquad \text{(E.2)}$$

where

B^D	-	Base of Drift
B^S	-	Base of Sandstone
k_v^S	-	vertical permeability of sandstone
k_v^D	-	vertical permeability of Drift
S^D	-	specific yield of Drift

This mechanism is shown in Figure E1a.

This simple conceptual model oversimplifies the leakage mechanism in a number of ways, including:

- Drift is highly heterogeneous, where high permeability/storage layers (sands & gravels) exist within low permeability layers (clays);

- no definable water table may exist within the Drift;

- leakage is from the base of the Drift and a resultant measurable decline in the Drift water table (if a water table actually exists) may be significantly delayed, particularly in low permeability strata such as the Drift of the Fylde plain;

- sands & gravels within the Drift may dewater during leakage;

- specific storage properties of the Drift are an important component of the leakage mechanism, which may not be accurately represented by the above model.

In addition, the mechanism adopted in the regional model presents a numerical instability problem if this mechanism was adopted for a model where the Drift was sub-divided into numerous sub-layers. This instability is caused by the fact that the leakage is based on "nodal" piezometric levels (equivalent to the piezometric level at the midpoint of the layer). Instabilities occur as intermediate layers dry out, since a discontinuity is created in the leakage mechanism and nodal piezometric levels do not apply. Such instabilities do not occur in the main model since the Drift is modelled as a single layer and not subjected to drying out.

In order to resolve this problem the leakage mechanism was re-evaluated. In the revised mechanism, two piezometric heads are simulated for each layer:

- the nodal head; and,
- the head at the top of the layer

and continuity between the leakage simulated at the base of a layer and at the top of the underlying layer must be maintained.

This is demonstrated in Figure E1b.

Two leakage terms are calculated:

Term1 - from the top of layer (equal to the base of overlying layer) to the nodal point of layer:

$$q_{a,n} = \frac{2k_n}{B_{n-1} - B_n} \left(h'_{a,n} - h'_n\right) \qquad \text{(E.3)}$$

Term2 - from the nodal point of the layer to base of the layer (equal to top of underlying layer):

$$q_n = \frac{2k_n}{B_{n+1} - B_n} \left(h_n' - h_{a,n-1}'\right) \qquad \text{(E.4)}$$

where

k_n	=	vertical permeability of layer n
B_{n+1}	=	base of overlying layer
B_n	=	base of layer
$h_{a,n}$	=	head at top of layer n
h_n	=	nodal head of layer n
$h_{a,n-1}$	=	head at top of underlying layer (n-1)

For each layer the conservation of volume must be satisfied:

$$\Sigma q_{hor} + q_{a,n} - q_n + R_n - A_n = \Delta S \qquad \text{(E.5)}$$

and the continuity of the leakages calculated at the layer interfaces must also be satisfied:

$$q_{n+1} = q_{a,n} \qquad \text{(E.6)}$$

where:

q_{hor}	=	horizontal flow terms
S	=	storage terms
R_n	=	recharge
A_n	=	abstraction

For the top layer, the top head ($h_{a,n}$) is equal to the water table elevation when this head is above the nodal point. When the head falls below the nodal point the head at the top of the layer and the nodal head are set equal to each other.

If an intermediate layer dewaters, then the model simulates leakage rates as if this layer was a surface layer with water table conditions . The leakage from the overlying layer defines the recharge to the dewatered layer (ie independent of heads).

By imposing the continuity rule at the interface between two model layers numerical instabilities are removed.

During the initial runs, it became apparent that there were two major areas on uncertainty:

- When an intermediate layer becomes unsaturated the leakage from the layer above defines the leakage at the top of the layer (between the top and nodal heads). This inflow has, therefore, been defined independent of the vertical conductance of the layer. If the dewatered layer has a lower vertical conductance than the overlying layer, then the model effectively oversimulates inflow from the overlying layer.

  Consequently the rate of inflow to a dewatered layer was limited to the vertical conductance of the dewatered layer. For example if the leakage from above was equal to 0.2 m/d and the vertical conductance of the layer was only 0.1 m/d, then the maximum leakage rate into the dewatered layer is set to 0.1 m/d. A discontinuity is therefore established and the model iterates by correcting groundwater heads until the outflow from the overlying layer is equal to the inflow to the dewatered layer (defined by the vertical conductance of this layer).

  In some model runs the effect of reducing inflow to a dewatered layer as a proportion of the vertical conductance of the layer was investigated. This was used to test the impact of the reduction in vertical permeability when unsaturated conditions prevail.

- At the top layer, recharge is applied as a leakage such that the following continuity criteria are met:

$$R_m = q_{a,m} \qquad \text{(E.7)}$$

  where:

  R_m = recharge to surface layer m

  $q_{a,m}$ = leakage at top of surface layer m

  If the head at the top of this layer is not at ground surface, then the leakage to the water table (as leakage term $q_{a,m}$) may be greater than the vertical conductance of the top layer. This leakage was therefore limited to the vertical conductance of the surface layer, with the net difference between recharge and leakage being equal to a rejected flow component, ie the equation (E.7) was redefined as follows:

$$R_m - REJFLOW = q_{a,m} \qquad \text{(E.8)}$$

E.3 Simulations Around T74

E.3.1 Vertical Strip Models

Two different models were set up to simulate the Drift around T74. The first model consisted of seven layers: six representing the Drift deposits as defined in the drillers lithological log overlying a single layer representing the sandstone. The configuration is shown in Figure E.2.

The second model sub-divided each individual Drift layer into three sub-layers, resulting in a 19 layer model. The area of the vertical strip was set to 160,000 m^2 (a square of dimension 400 m).

In both models, the Drift layers were defined as aquitards (ie no horizontal flow was simulated).

E.3.2 Seven Layer Model

Initial runs were carried out on the seven layer model with fixed heads defined on the sandstone layer boundary. The fixed heads were derived from the regional model. This was used to make sure the revised coding was working properly. The results are not discussed here because the fixed heads constrain the leakage mechanism, exerting too strong an influence on the volumes of leakage out of the Drift and therefore the Drift water levels. Fixed heads result in a horizontal flow to/from the sandstone which must be satisfied by leakage from the base Drift sub-layer. The water level in this layer, therefore, is simulated at an elevation to produce this leakage, with the level being defined by the vertical conductance of the base Drift sub-layer. Consequently it would be possible to produce a large number of different solutions with different vertical conductances defined. However this would not have increased confidence in the leakage mechanism or helped confirm the mechanisms adopted in the regional model.

The boundary conditions were therefore changed to fixed flows, where the flows were derived from the regional model. Fixed flows do not constrain the movement of the sandstone groundwater level allowing the model to be used to investigate different parameter settings with more confidence.

The initial run adopted similar vertical permeability and storage parameters to those defined in the regional model, that is:

- a vertical permeability of 0.1 mm/d for clays;
- a vertical permeability of 0.015 mm/d for the surface layer representing the infiltration capacity defined in the regional model;
- a vertical permeability of 1m/d for the sands & gravels;
- confined storage coefficients of 0.0001 for clays and sands & gravels;
- specific yields of 10% for the clays and 15% for the sands & gravels;
- a horizontal permeability of 2m/d for the sandstone.

The simulated nodal water levels for each layer are shown in Figure E.3. The Drift and Sandstone levels at T74 simulated by the regional model are shown in Figure E.4. The vertical strip model simulates a much greater decline in sandstone groundwater levels than observed or simulated by the regional model. This is due to a number of factors including:

- The sandstone is unconfined after a few timesteps which results in a relatively constant leakage rate from Drift to sandstone, where the rate is dominated by the low permeability of the Drift Deposits. Outflow from the sandstone (defined by the fixed flows) were therefore satisfied by unconfined storage releases within the sandstone, with only minor leakage volumes simulated.

- The distance over which water leaks between two layers is reduced which results in a smaller head difference between layers within the Drift reducing the leakage between layers.

- All Drift layers remain confined (apart form the surface layer), while in the regional model the Drift is simulated as one unconfined layer with a defined water table. Thus much of the outflow from the sandstone is satisfied by a storage release form the Drift in the regional model, since recharge is limited by the low infiltration capacity adopted. Storage releases within the Drift simulated by the strip model are very low, with the surface layer water table remaining at a relatively constant level, and the other layer storage changes dominated by the confined storage coefficient.

Further runs were made with varying levels of vertical permeability defined in order to establish the level of permeability in order to simulate the correct response in the sandstone. Without altering the storage coefficients the following vertical permeability settings were adopted:

Layer	Vertical Permeability (m/d)
7 (clays)	0.00025
6 (clays)	0.001
5 (sands)	0.2
4 (clays)	0.001
3 (s&g)	1.0
2 (clays)	0.0005
1 (sandstone)	1.0

These amount to a rise in vertical permeability of up to 500 %.

The results are shown in Figure E.5.

The simulated decline in sandstone piezometry is similar to the observed data, with an exponential decline over the simulation period and greater seasonal fluctuations during the first six years than in the remainder of the simulation. During the simulation both the sands (layer 5) and the sands & gravels (layer 3) dewater. The sands dewater due to the limitation on the vertical transfer of rainfall recharge through the relatively low permeability overlying clay deposits, while the sands and gravels dewater as a result of both limitation in vertical recharge and the depletion as a result of the outflow from the sandstone. Groundwater levels at the top of the Drift remain relatively constant (within 0.25 m of ground surface) throughout as a result of the low conductance of the surface layer.

Thus the new mechanism and the subdividing of the Drift into different layers helps explain the parameters adopted in the Fylde regional model. A low vertical permeability and infiltration capacity were required to "force" the Drift to dewater and thus create a decline in groundwater levels. With the Drift split into many sub-layers, individual storage releases from layers with relatively high vertical permeability and storage properties (eg sands & gravels) satisfy sandstone outflows, without imposing unrealistically low vertical permeabilities.

E.3.3 Nineteen Layer Model

In order to further the understanding of the leakage mechanism each Drift sub-layer was sub-divided into three separate layers, resulting in a 19-layer model. The results of these more detailed studies are explained in the next section.

The first run adopted the same parameter settings as in the seven layer model. The simulated sandstone piezometry for the 19-layer and 7-layer models is shown in Figure E.6. The greater number of layers results in similar rates of decline during the first seven years, but a further decline in sandstone levels is simulated by the 19-layer model during year 8 as the clays directly above the sandstone also dewater due to the drying out of the overlying sands & gravels layers. The reason for this is the same as observed between the regional (single Drift layer) and the 7-layer model: storage changes for individual layers of the 7-layer model are greater than the sum of the storage change simulated in the corresponding three layers of the 19-layer model.

This model was then used to establish the influence of different parameter settings on the simulated flow system. The results of these sensitivity runs are described in the following sections:

Increased Vertical Permeabilities Throughout

With a 25% increase in vertical permeabilities, the model simulated a reduced level of decline, with a delay in the dewatering of the individual sands & gravels and clay layers.

Increased Vertical Permeabilities Above Sands & Gravels

With an increase in vertical permeabilities for layers above the sands and gravels only, the model simulated a reduced level of decline, without simulating dewatering of the clays directly above the sandstone.

Increased Vertical Permeability of the Surface Layer Only

Varying the vertical permeability of the surface layer is similar to changing the "infiltration capacity" of the Drift as defined in the regional model. With a high vertical permeability more recharge infiltrates to the water table. However, leakage to layers below is limited by the vertical permeability of the lower layers resulting in a rise in groundwater levels in the surface layer to ground surface, thus limiting the storage within the surface layer to accept more recharge.

However, the decline in sandstone water levels is reduced as leakage through the Drift is maximised.

On the other hand with a lower vertical permeability defined in the top layer, the model simulates a reduced level of infiltrating recharge and thus the simulated rate of decline in Drift and sandstone water levels is increased.

Decreased Vertical Permeabilities Below Sands & Gravels

With a decrease in vertical permeabilities for the clays between the sands & gravels layers and the sandstone layer, the following differences were simulated (compared to the simulation presented in Figure E.8):

- rate of decline in the sandstone is increased due to the reduction in leakage from the sands & gravels to the sandstone;
- groundwater levels in the sandstone are reduced as the reduced vertical conductance results in greater head differences between clays and sandstone in order to induce the same levels of leakage;
- rate of decline in the sands and gravels is reduced.

Reduce Vertical Permeability When Unsaturated Conditions Occur

The model was altered so that whenever an intermediate layer dewaters, the vertical conductance of the dewatered layer is reduced by a factor. This limits the through flow of rainfall recharge to a lower level whenever dewatering takes place and was intended to approximate the reduction in permeability associated with unsaturated flow conditions. This results in an increased rate of decline as the layer dewaters, as expected. The outflow from the sandstone is satisfied more from storage releases in the sandstone.

This was not studied further since the same impact can be achieved through variations in storage and permeability properties. In addition the "unsaturated flow" reduction factor adopted was considered to oversimplify the complex relationship between moisture conditions and permeability.

E.3.4 Influence of Specific Yields

In all of the above model runs, the specific yields remained constant. However, the specific yield of the Drift deposits are an important parameter governing the rate of decline in levels whenever layers dewater. In the regional model, the specific yield of the single Drift layer is defined at 12 % around T74, while in the 19-layer model runs described above the following settings were defined:

Layer	Specific Yield (%)
17-19 (clays)	10
14-16 (clays)	10
11-13 (sands)	15
8-10 (clays)	10
5-7 (s&g)	20
2-4 (clays)	10
1 (sandstone)	6

Two model runs were therefore carried out to establish the influence of the specific yield : one where the specific yields were doubled and the other where they were halved for each layer, apart form the sandstone layer. In both runs the corresponding confined storage coefficients for each layer (apart from the sandstone layer) were also doubled/halved.

The models were run over the full 28 year historical recharge sequence. The results are shown in Figure E.7 and E.8.

As expected, the higher the specific yield the lower the rate of decline. However, this simplistic conclusion obscures the complexity of the vertical permeability/storage coefficient relationships within the Drift. Figures E.9a and E.9b presents the leakage and storage changes within one of the sands & gravels sub-layers. During the first 10 years of the simulation the leakage through the system under both storage coefficient settings is the same (refer to Figure E9a). However, there is a greater rate of groundwater level decline simulated with low storage coefficients since for the same release in storage there is a greater drop in water level. The sands & gravels, therefore, dewater earlier with the low storage coefficients. The outflow from the sandstone is then partially satisfied from storage releases within the dewatered sands and gravels. At this stage the model simulates reduced leakage rates into the sands & gravels because the leakage "driving" head from the overlying layer reduces, since the leakage is based in the head in the layer (which is declining) minus the base elevation of the layer (which is fixed).

The same mechanism applies when higher storage coefficients/specific yield are applied, although at a slower rate. Over the 28 years of the simulation no dewatering was simulated resulting in a relatively constant rate of decline of groundwater levels.

In the case of low storage coefficients, the rate of groundwater level decline could be reduced by increasing leakage through the Drift deposits by increasing vertical permeabilities. On the other hand with increased storage coefficients, a decrease in vertical permeabilities would be required in order to simulate dewatering of intermediate layers. Both mechanisms are equally plausible.

Consequently the flow mechanisms within the Drift around T74 cannot be described solely by vertical permeabilities adopted. Effectively, the product of the vertical permeability and storage coefficient more accurately describe the process. With a high product (eg high vertical permeability and high storage coefficients) the rate of groundwater level decline is minimised, while a low product results in a high rate of decline. Around T74 it is therefore not possible to establish the most likely vertical permeability/storage coefficient settings since it is possible to simulate the same rate of decline with different settings. For example, the decline in the regional model was simulated with a low vertical permeability (0.0001 to 0.00001m/d) and a specific yield of 12 %, the same rate of decline could be achieved using a higher vertical permeability and lower specific yield. However, the actual mean level simulated in the sandstone would be much higher as a result of the higher permeabilities defined.

E.3.5 Discussion

It would be possible to combine the results of all the above runs in order to simulate the sandstone groundwater level response observed at T74 and simulated by the regional model. However such approach is not considered worthwhile for a number of reasons:

- The purpose of this Drift modelling was to investigate leakage mechanisms and in particular to evaluate whether the regional model leakage mechanism is a reasonable representation of the Drift.

- It would be possible to come up with a number of equally applicable permeability and storage coefficient settings which simulate the observed decline around T74 and therefore to the process of calibration would be subject to much uncertainty.

  In section E.3.4 it was shown that different vertical permeability/storage coefficient settings can yield the same results.

  Other factors can also yield the same results. For example, the leakage through the Drift to the sandstone is dominated by sub-layers of low permeability. It would be possible to simulate similar responses in the sandstone if a low permeability was defined at the top of the Drift or defined at the base of the Drift. Similarly, reduced leakage can be simulated by defining low vertical permeabilities or by defining high permeabilities which reduce substantially if a layer dewaters.

- The process of "calibration" would not improve understanding of the Drift leakage mechanism beyond that achieved from these studies.

However, the mechanisms and model results described above have confirmed that the simulation of leakage around T74, and the resultant decline of sandstone piezometry, as modelled by the regional model is an acceptable simplification of the complex flow systems within the Drift. In the regional model three main parameters were defined:

- a low infiltration capacity (limiting replenishment of Drift from rainfall recharge);
- low vertical permeabilities (0.0001 - 0.00001 m/d which is considered very low, even for "stiff" Boulder Clays) to limit leakage from the Drift;
- a specific yield of around 12%.

The vertical strip modelling has confirmed this approach. The regional model simulates a release from Drift storage in order to satisfy outflow from the underlying sandstone, while a low infiltration capacity is required to limit the recovery in Drift storage.

By sub-dividing the Drift into a number of individual layers, the modelling has shown that:

- The vertical permeability of the clay deposits within the Drift sequence may be much higher than that defined in the regional model, because with low vertical permeabilities set in the strip model most of the storage release within the Drift is made up of a confined storage release rather than the unconfined release simulated in the regional model. The sandstone level is therefore lowered such that leakage through the Drift is maximised, Storage releases from the sandstone are also maximised.

- With increased vertical permeabilities, sands & gravels layers within the Drift dewater as the outflow from the sandstone is satisfied by drawing water out of storage from the sands & gravels which is not replenished by leakage due to the limitation in vertical conductance of the overlying clay layers

- The leakage through the Drift to the sandstone is dominated by low permeability strata. In addition, the vertical permeability of the Drift defined in the regional model is equivalent to an "effective" permeability which is lower than the lowest vertical permeability defined in the strip models. The effective permeability is lower because of the influence of storage within the Drift Deposits. The higher the storage coefficients the lower the vertical permeability required to simulate a similar response in the sandstone.

- With the revised leakage mechanism, the leakage out of a layer and into another is calculated separately and the model converges when both volume balance and continuity of leakage at the interface between model layers is satisfied. This applies to all layers, including the surface layer, where the net recharge into the surface layer must equal the leakage through that layer. Consequently, the volume of recharge infiltrating to the water table is dependent upon the vertical conductance of the Drift. The approach taken in this revised mechanism is similar to the infiltration capacity defined in the regional model, thus confirming the adoption of the infiltration capacity parameter to limit the influx of rainfall recharge in the regional model.

Vertical Leakage Mechanisms

Fig E1a Leakage Mechanism in Fylde ICMM

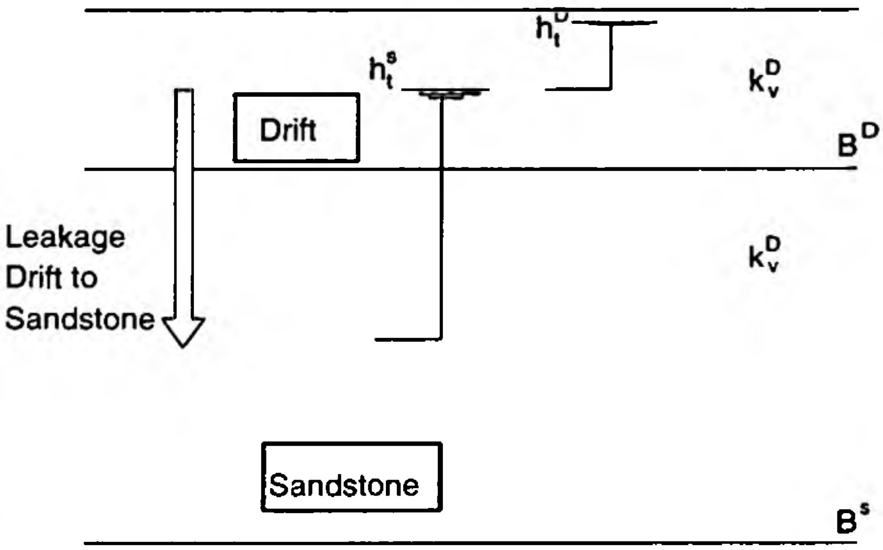
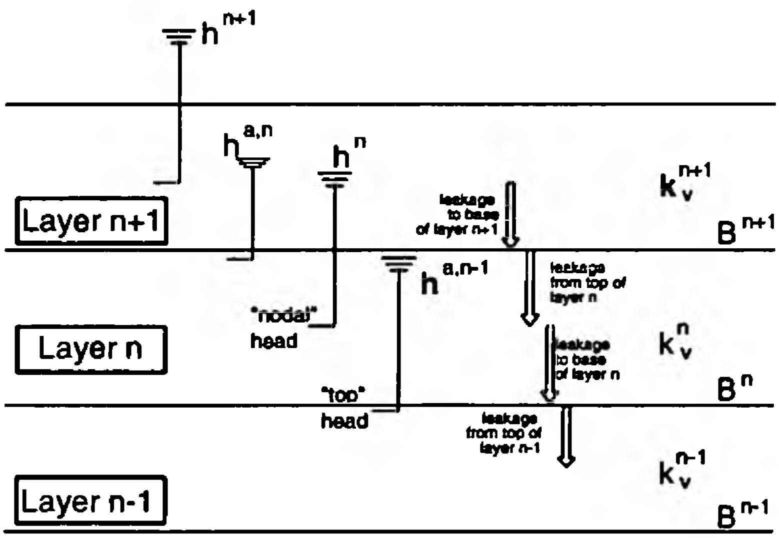
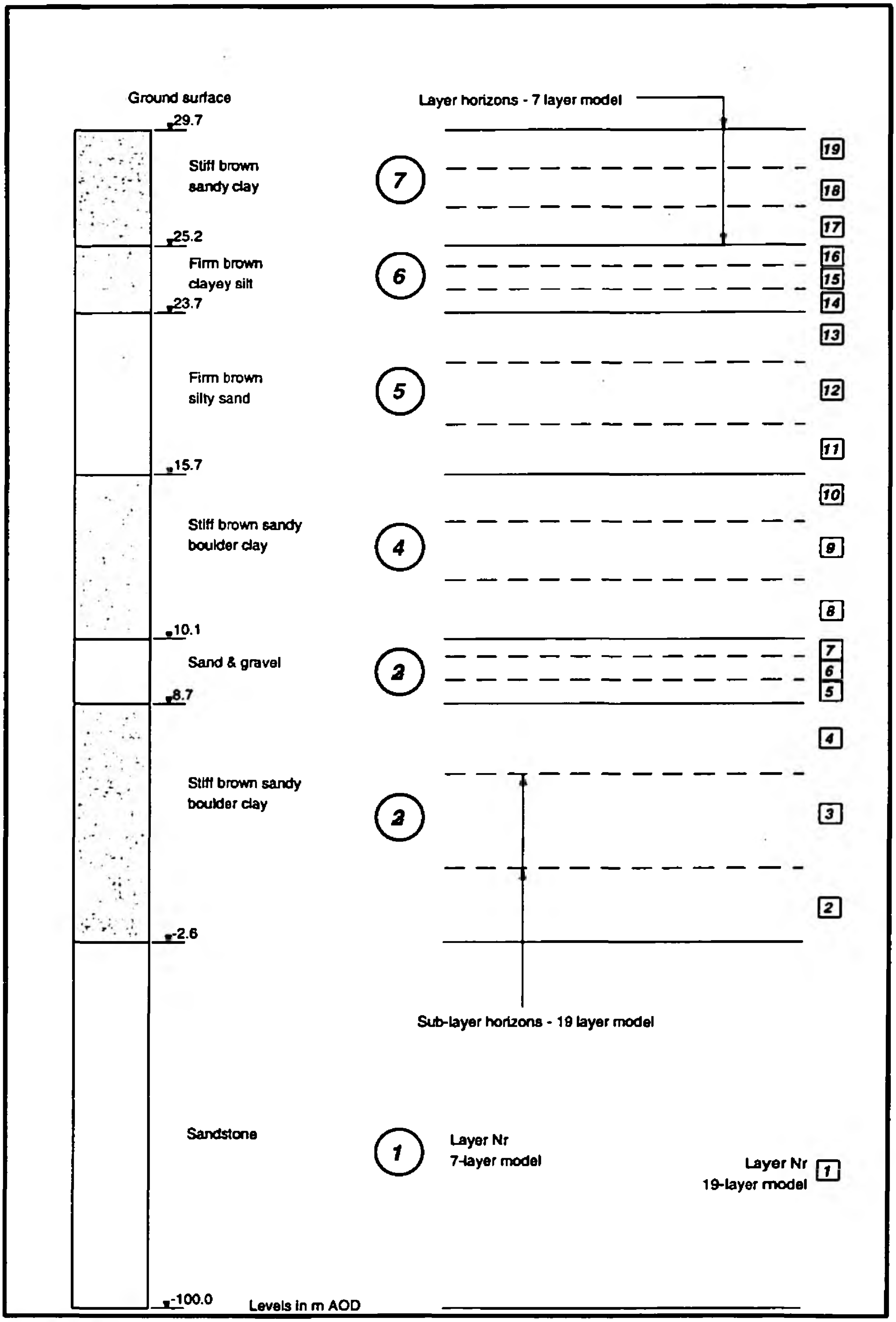
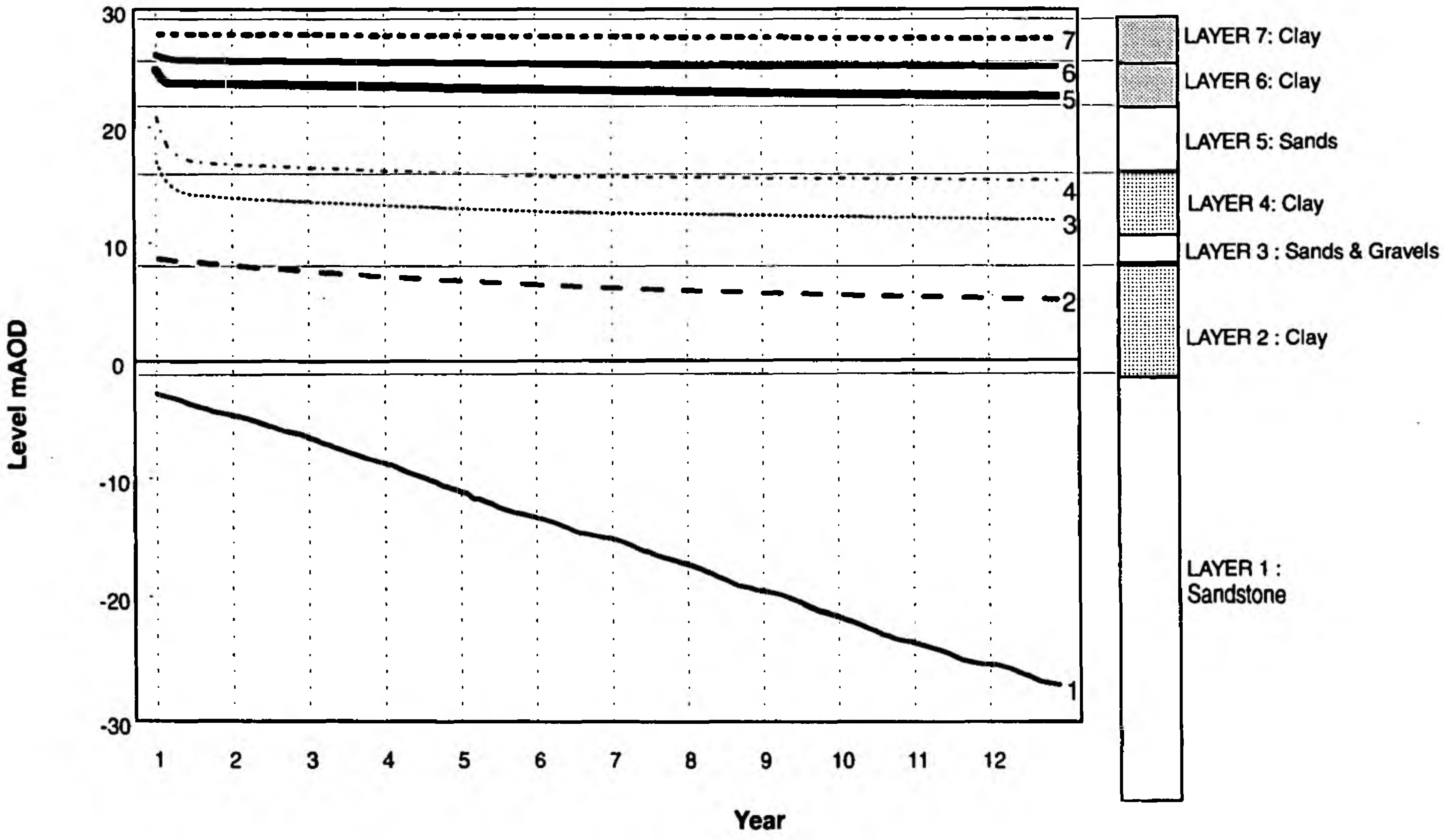


Fig E1b Revised Leakage Mechanism for Vertical Strip Modelling



Vertical Strip Models Around T74





Aquifer properties similar to Regional Model

Figure E.3 - Nodal Piezometry
7 Layer Model

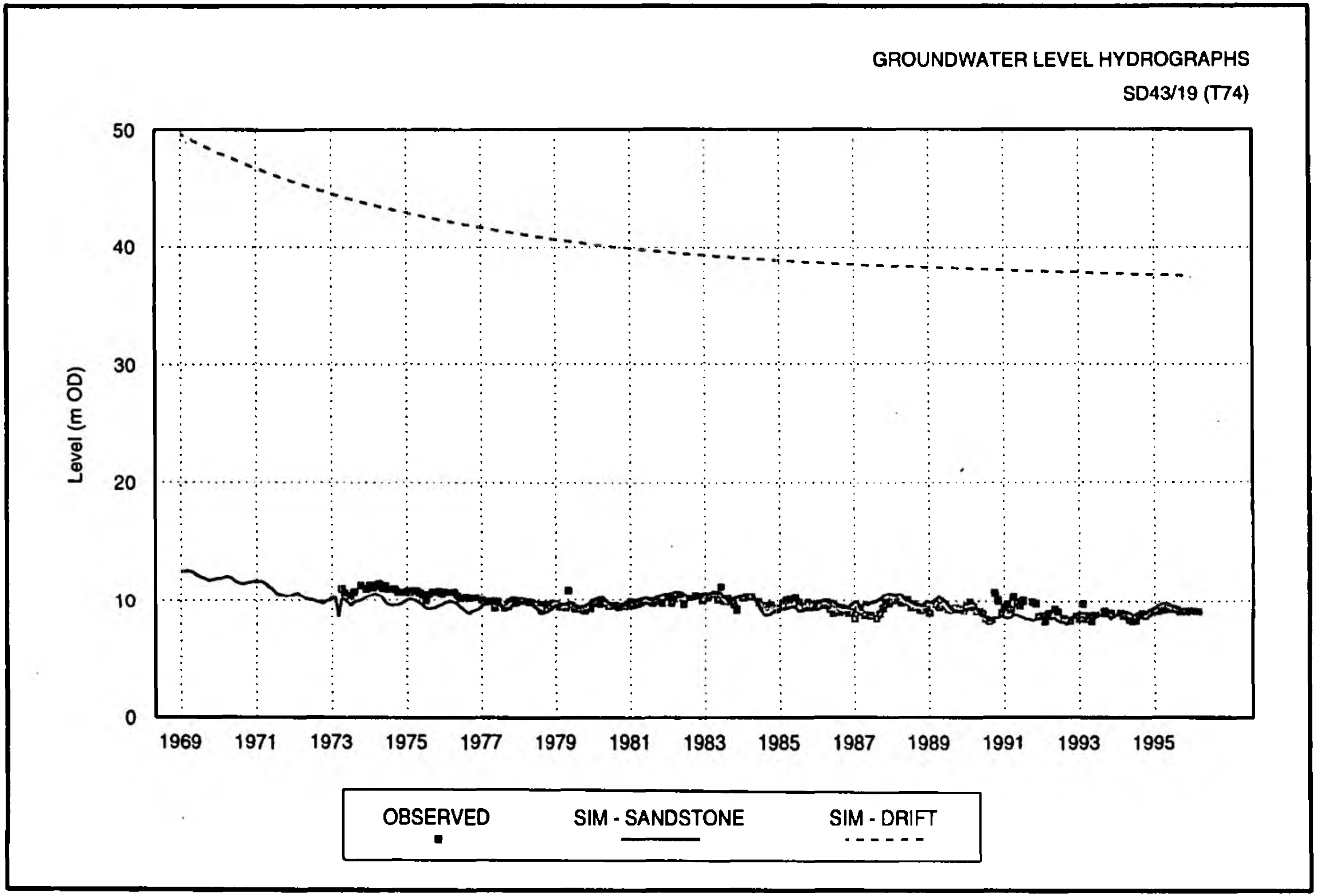
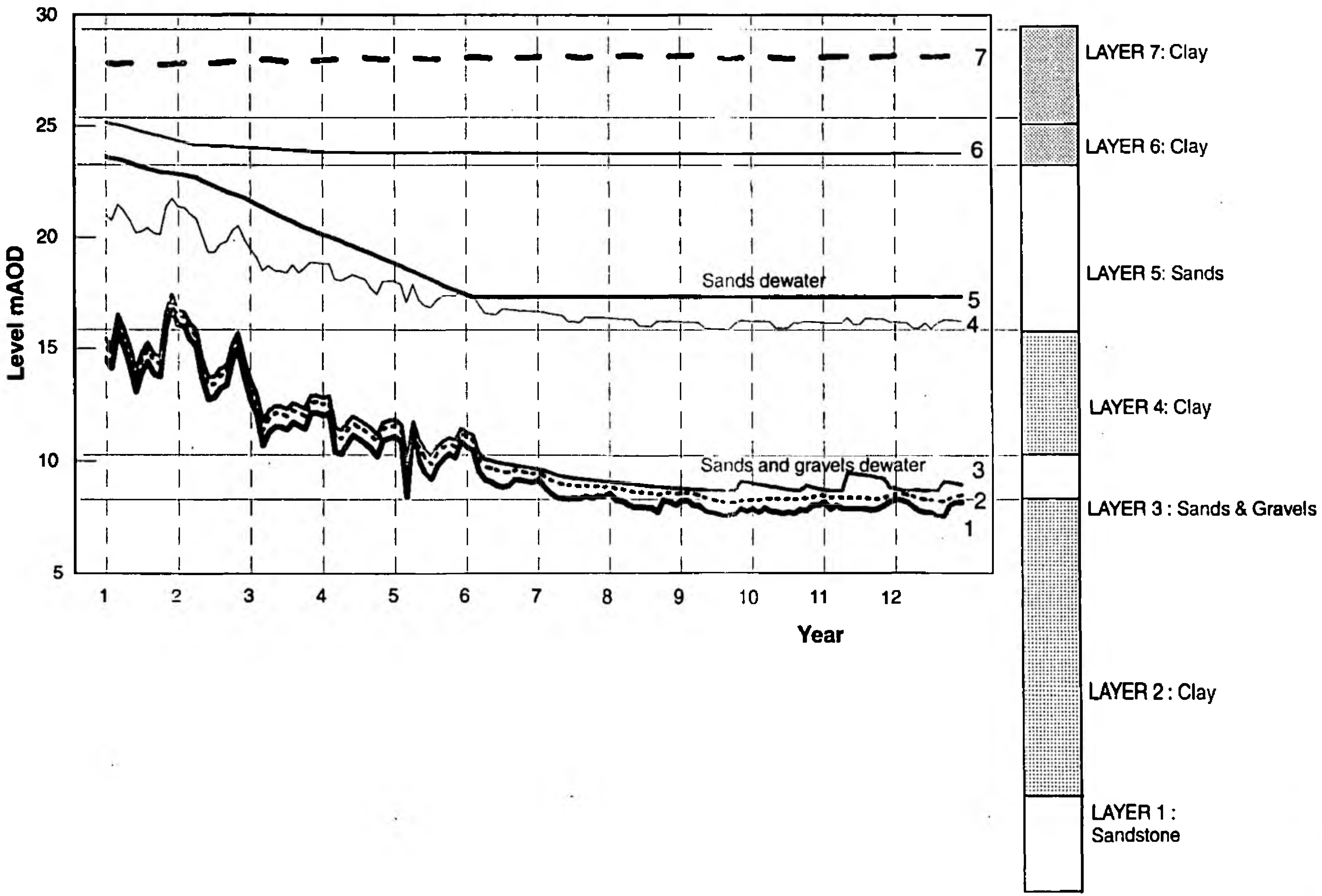


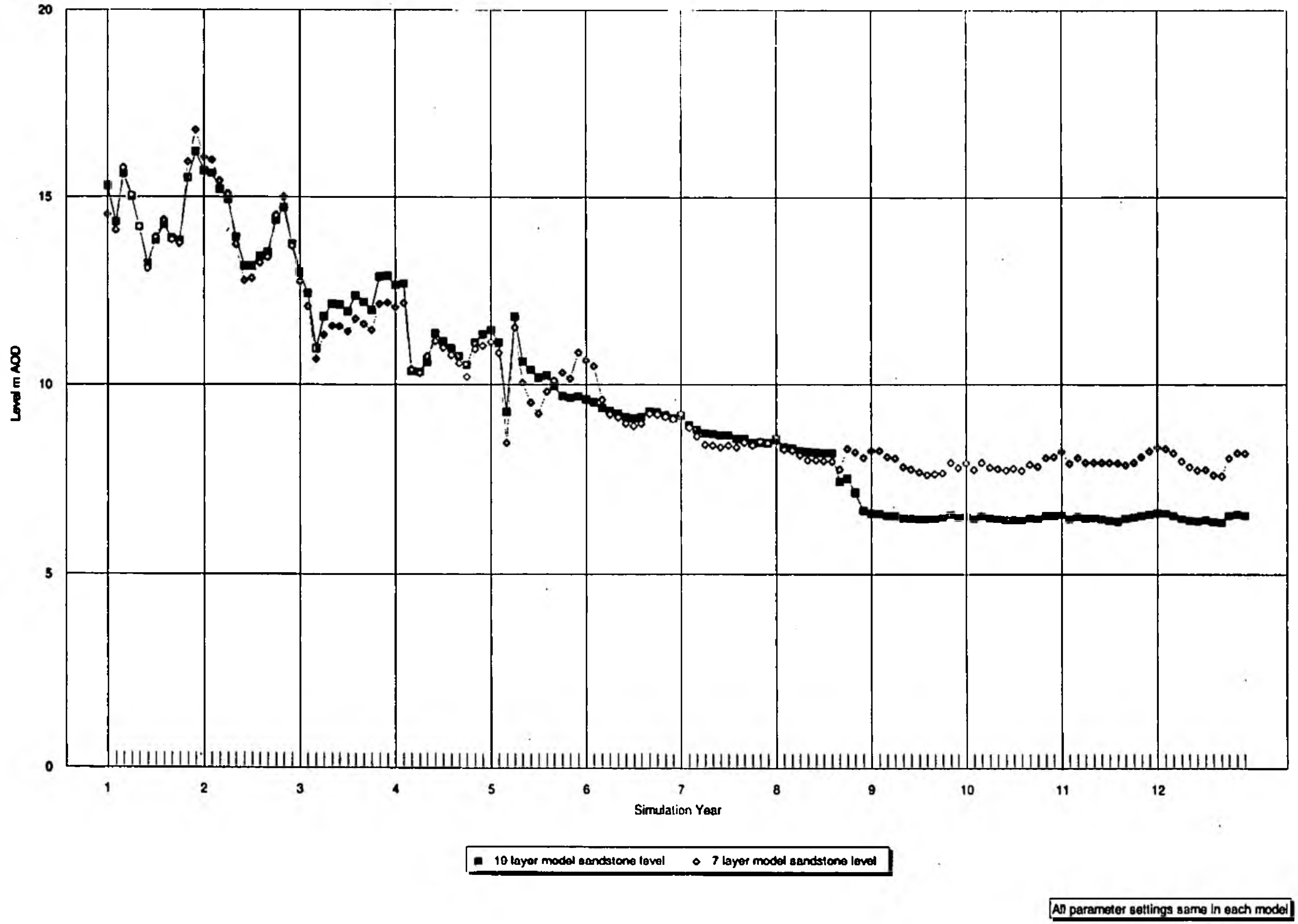
Figure E.4
Regional Model Simulation of Water Level Decline at T74



Increased vertical permeabilities compared with Regional Model

Figure E.5 - Nodal Piezometry
7 Layer Model

Figure E.6
Comparison of 19 layer and 7 Layer Model



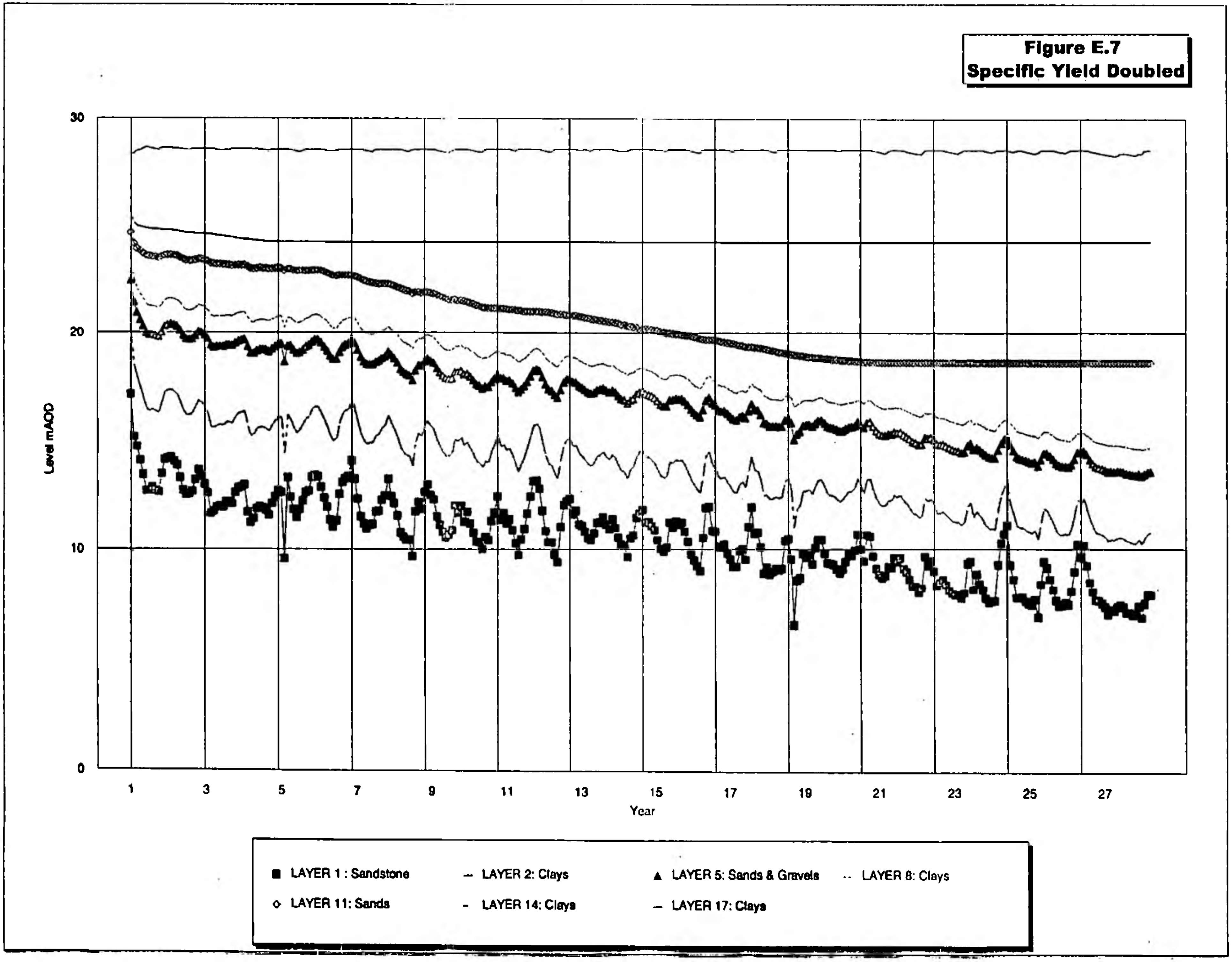


Figure E.7
Specific Yield Doubled
30
20
10
0
Level mAOD
1
3
5
7
9
11
13
15
17
19
21
23
25
27
Year
LAYER 1 : Sandstone
LAYER 2: Clays
LAYER 5: Sands & Gravels
LAYER 8: Clays
LAYER 11: Sands
LAYER 14: Clays
LAYER 17: Clays

Figure E.8
Specific Yield Halved

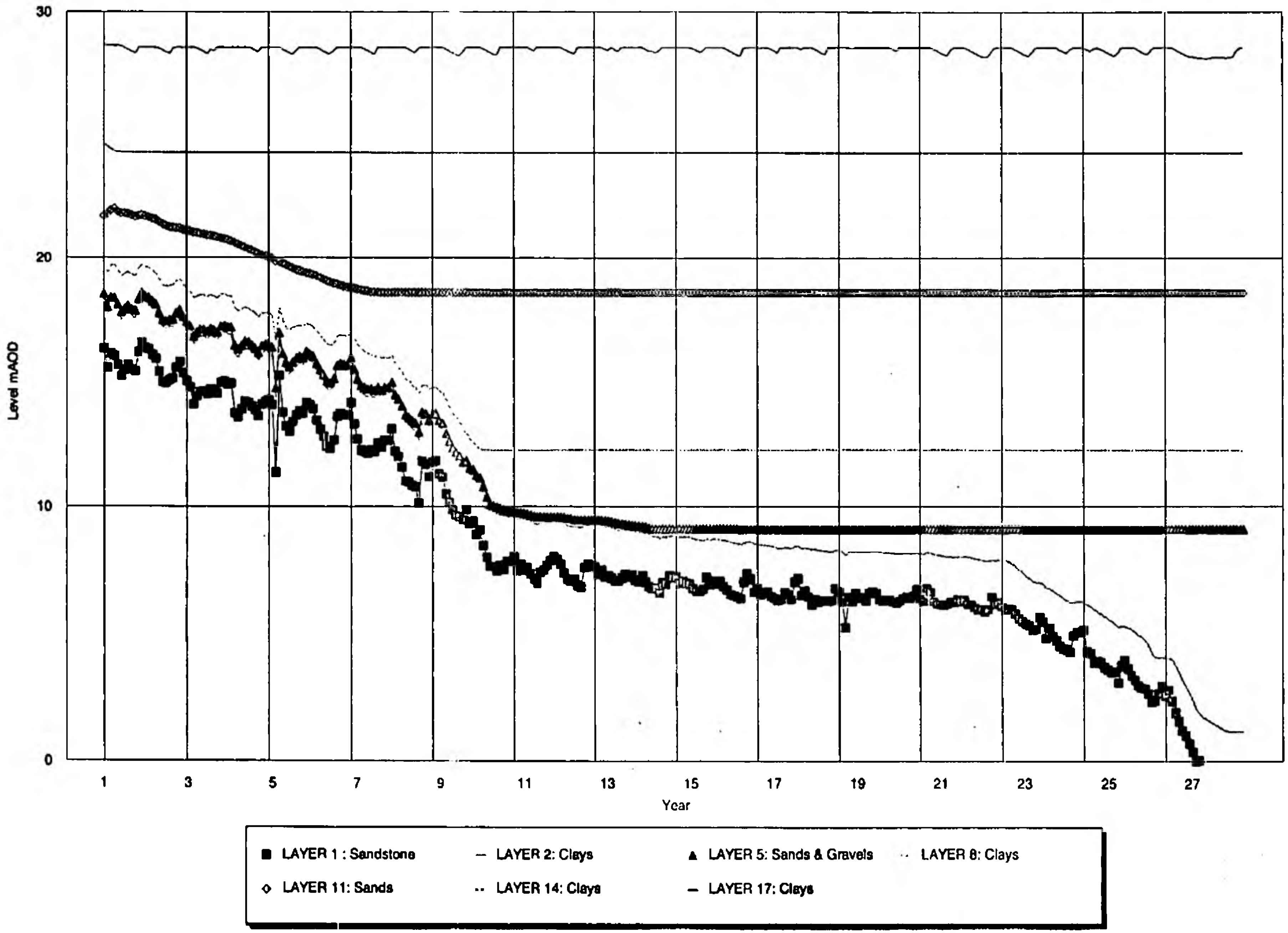


Figure E.9a - Influence of Specific Yield
S&G Leakage and Storage Changes - Years 2 - 6

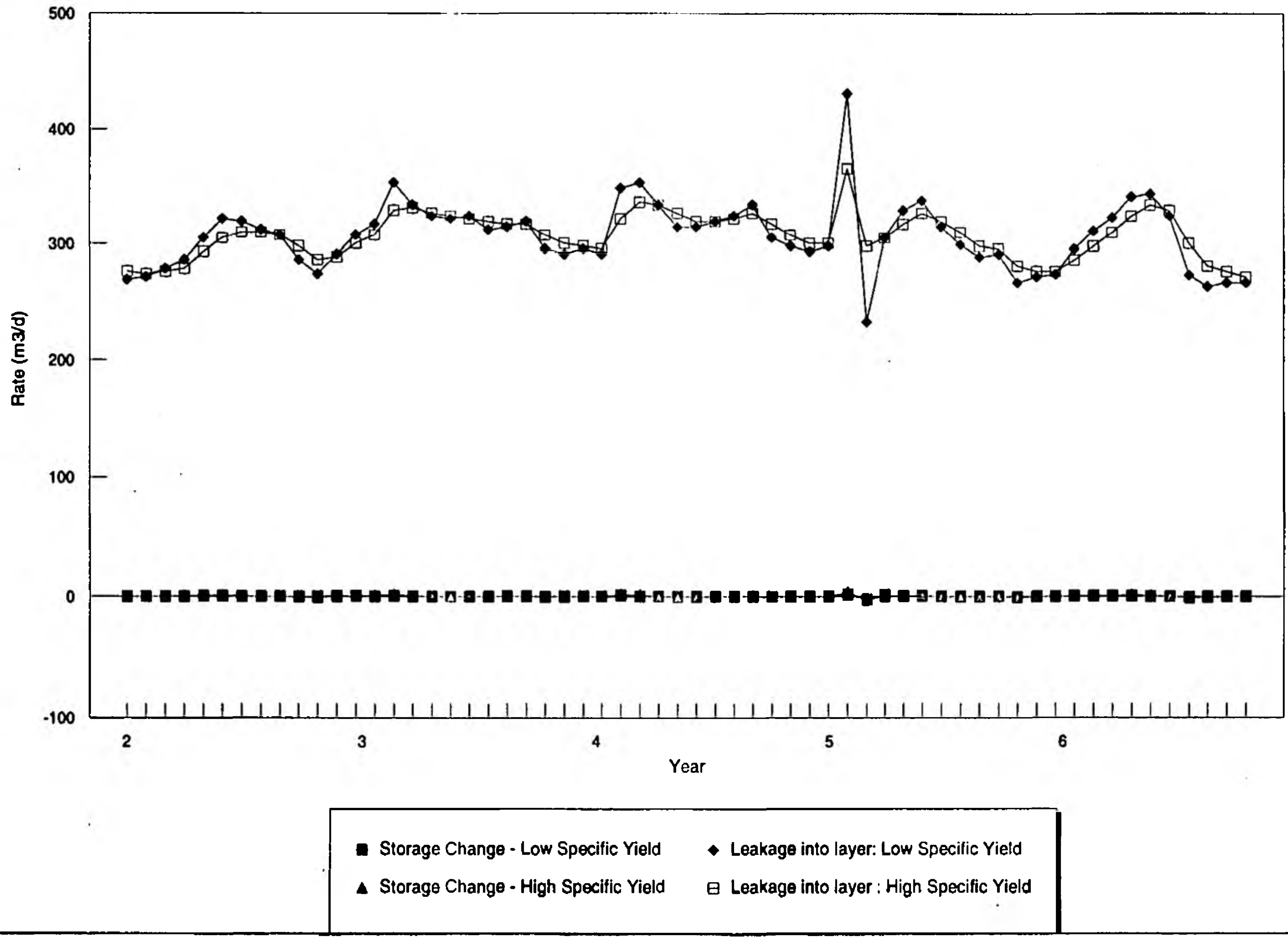
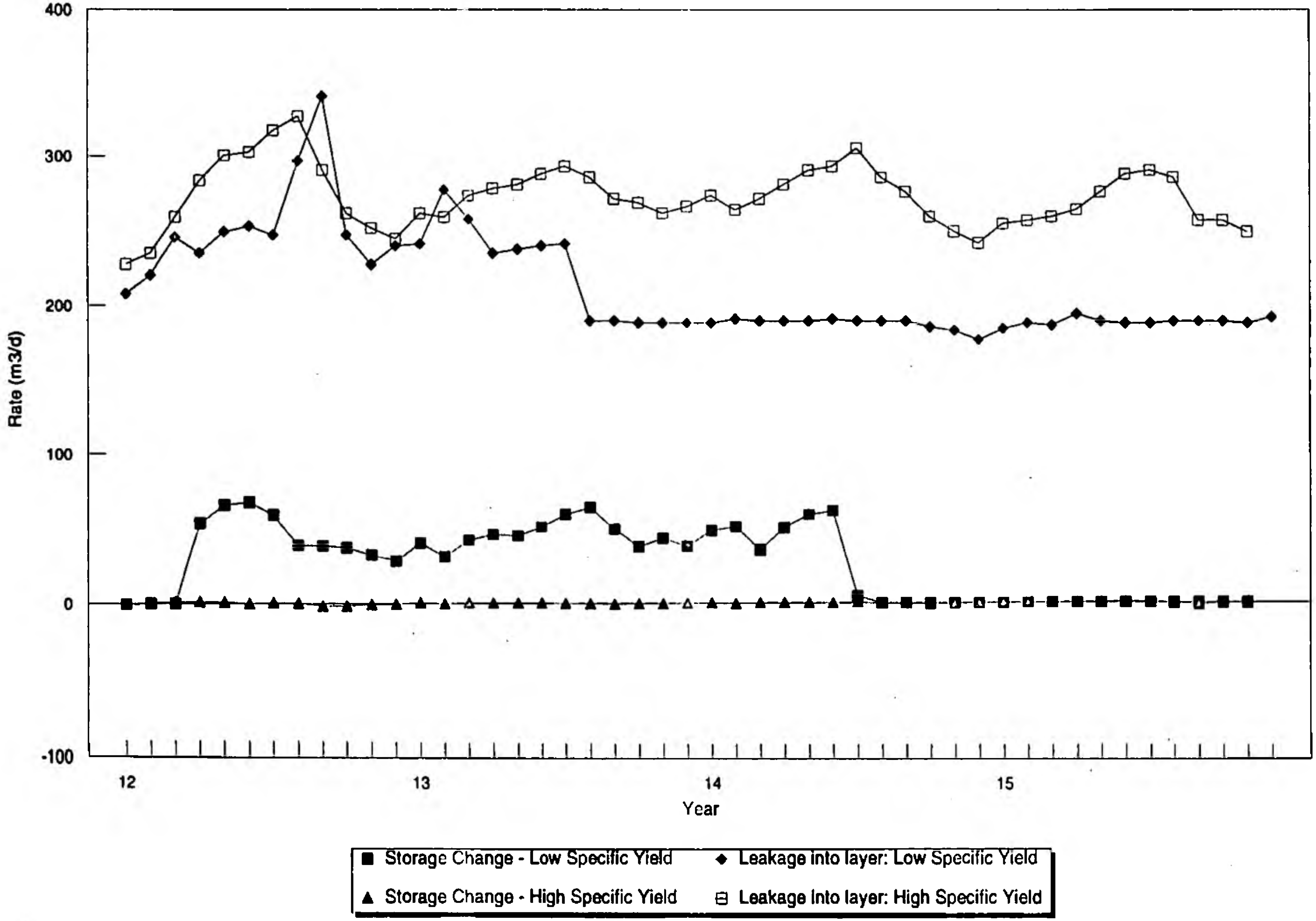


Figure E.9b - Influence of Specific Yield
S&G Leakage and Storage Changes - Years 12 - 15



APPENDIX F

MOTT MACDONALD QUALITY ASSURANCE REPORT DISTRIBUTION SHEET

Report Distribution and Revision Sheet

Project: Fylde Aquifer/Wyre Catchment Water Resources Study

Project Code: 38436BA01

Client: Environment Agency, North West Region

Report Title: Final Report

Rev Nr	Date of Issue	Originator	Reviewer	Approver	Scope of Revision
A	22/12/96	A J Wyness	J van Wonderen	J van Wonderen	
B	21/02/97	A J Wyness	J van Wonderen	J van Wonderen	Incorporating text and figure edits carried out by Environment Agency, Prof K Rushten and North West Water
C	15/08/97	A J Wyness	J van Wonderen	J van Wonderen	Calibration update to end 1997. Detailed Drift Leakage Investigation. Improved figure quality.

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