NRA Southern 88.

NRA

National Rivers Authority

# RIVER DARENT
# LOW FLOW ALLEVIATION

## ANNEX II

**Darent Catchment Investigation,**
**Model Calibration Results**
**(GDC, November 1993)**

National Rivers Authority
Southern Region

July 1994

National Rivers Authority
(Southern Region)

NRA

# Darent Catchment Investigation
# CWP/8709

Catchment Model Calibration Report

November 1993



Groundwater Development Consultants
Cambridge, UK



70223B01/GDC/2/B/DCI

70223B01/GDC/2/B/DCI/WP

Darent Catchment Investigation
CWP/8709
Catchment Model Calibration Report

Issue and Revision Record:

| Version | Date | Originator | Checked | Approved | Scope of Revision |
|---|---|---|---|---|---|
| A | 4/11/93 | P Rippon | P Mason | B Misstear | - |
| B | 17/11/93 | P.W. Rippon | [signature] | [signature] | Minor text changes |

Groundwater Development Consultants Limited
(Mott MacDonald)
Demeter House
Station Road,
Cambridge
CB1 2RS

CONTENTS

CONTENTS (cont)

CONTENTS (cont)

## LIST OF TABLES

# LIST OF FIGURES

## LIST OF FIGURES (cont)

## SUMMARY


The River Darent has been identified by the National Rivers Authority as one of forty over-abstracted catchments in England and Wales. The catchment, located in north Kent, is regarded as being of particular importance, owing to the severity of river flow depletion.

The river is fed by springs from the Lower Greensand lying along the northern rim of the Weald of Kent, and also from the Chalk of the North Downs. These aquifers are sources of major groundwater abstraction for public water supply. In periods of low rainfall the river has dried up completely in some sections for durations of several months.

Groundwater Development Consultants was appointed by the National Rivers Authority in 1991 to undertake a water resources investigation of the Darent catchment. The scope of work for this investigation included development of a computer-based catchment model with simulation of the inter-relationship between the aquifers and the river. The model was to be used for a detailed assessment of various engineering options for low flow alleviation.

This report describes the development of the Darent catchment model and model calibration work carried out in 1992.


### Basis of the Model

The model is based on the integrated finite difference method. It takes into account the inter-relationship of water levels and flows in both aquifer and river system with exchange between the two. It comprises a network of irregular polygons varying in size, shape and orientation to fit local details and physical characteristics of the surface water and groundwater system. Rivers are incorporated as additional elements located between adjacent groundwater polygons.

The model covers an area of about 530 $km^2$ including the catchment of the River Cray, a major tributary of the Darent located within the south-east corner of Greater London.

The groundwater system is defined in the model by six separate layers. Four aquifers are specified, the Hythe Beds and Folkestone Beds within the Lower Greensand, the Chalk and an aquifer within Tertiary deposits in the River Cray catchment and northern-most parts of the model area. Alluvium is also included with the uppermost Tertiary aquifer. Other layers within the system are aquitards. External boundary conditions are specified as either fixed head, for example along the northern boundary formed by the River Thames, or with a fixed groundwater gradient. Chalk fissure systems can be simulated using a depth dependent permeability function.

**Recharge Estimation**

Aquifer recharge which forms the main contribution to river baseflow is estimated using a separate lumped-parameter hydrological model (a modified version of the Stanford Watershed Model). This also provides surface runoff and interflow components. Hydrological models of three gauged subcatchments were calibrated against river flow data principally through adjustment of soil moisture parameters. Monthly recharge estimates were then extrapolated to cover the entire model area and transferred to the catchment model taking into account the effects of variation in outcrop geology, rainfall and urbanisation. A good calibration against flows was achieved, with simulation to an accuracy of 3%. This is within normal measurement accuracy.

**Catchment Model Calibration**

Catchment model calibration comprises two stages. The first is steady state calibration in which mean groundwater conditions, often inferred from scattered historical evidence, are simulated for either pre-development periods in which natural hydrological conditions prevailed, or periods in which abstraction was well established and remained reasonably constant. No changes in storage are simulated for steady state conditions, hence the number of model calibration parameters is reduced, simplifying the initial stage of calibration.

Steady state calibration is used mainly to establish aquifer transmissivity. For the Darent, reasonably uniform transmissivities averaging about 400 $m^2/d$ were found appropriate for both the Lower Greensand aquifers. For the Chalk, transmissivities specified during steady state calibration ranged between 20 to 300 $m^2/d$ in relatively impermeable Chalk beneath upland interfluves and 500 to 2 000 $m^2/d$ in highly fissured zones in valley areas.

The second stage of catchment model calibration is for the transient state. Variations in the groundwater and surface water systems with time were simulated for the period 1970 to 1990 using a monthly timestep. Variations in river flows are controlled by the recharge pattern, river bed leakage and aquifer storage properties. Good simulations of flow at the three permanent gauging stations on the River Darent were obtained to an accuracy of 4% of observed or better by applying an unconfined storage coefficient of 3.5% and 10% for the Hythe and Folkestone Beds respectively, and 2% for the Chalk. Difficulties in simulating flows for the River Cray were resolved to some extent by modelling a hydraulic connection between the river and both the Chalk and the Tertiary deposits.

Groundwater levels at two observation well sites with long-term records for the Lower Greensand were simulated reasonably accurately. For the Chalk, simulated variations in groundwater levels were initially much greater than observed. Considerable improvement was achieved in simulation by specifying depth dependent permeability to model fissure flow in a zone corresponding to the normal range of Chalk groundwater level fluctuations and resulted in an acceptable comparison with observed data.

Options for further improving model calibration are discussed at the end of the report. These include the possibility of segmenting the separate hydrological models to improve recharge estimation taking into account variations in geology and possibly urban development. At present there is poor definition of actual groundwater conditions in a number of areas of the model. Groundwater monitoring data from new observation wells constructed by the National Rivers Authority in 1992 will be important for further model verification and, if necessary, improving the calibration.

## Conclusion

Good simulations of hydrological conditions have been obtained throughout the catchment model area for the 20 year period of simulation. This applies particularly to river flows at the three historical gauging stations on the River Darent where low flow periods are simulated well. As a result, there was high confidence in using the model to predict the effects of water resources management strategies.

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

The River Darent has been identified by the National Rivers Authority as one of forty over-abstracted catchments in England and Wales. The catchment, located in north Kent (Figure 1.1), is regarded as being of particular importance, owing to the severity of river flow depletion.

The river is fed by springs from the Lower Greensand lying along the northern rim of the Weald of Kent, and also from the Chalk aquifer of the North Downs (Figure 1.2). These aquifers are sources of major groundwater abstraction for public water supply. In recent periods of low rainfall, particularly the early to mid 1970s and from 1989 to 1991, the river has dried up completely in certain sections for durations of several months. The reach from Lullingstone to Hawley has been particularly severely affected in these periods, with flow losses occurring along a length of several kilometres of river bed.

## 1.2 Objectives and Scope of Work

Groundwater Development Consultants Limited (GDC) was appointed by the National Rivers Authority (Southern Region) in February 1991 to undertake a water resources investigation of the River Darent catchment. The original objective of the investigation was to identify the most appropriate measures from a large number of engineering options to alleviate low flow conditions in the river. This objective was to be achieved by:

- an initial water infrastructure and water balance study to assess the feasibility of various potential engineering options to alleviate low flow conditions;
- a broad costing of options;
- computer-based, integrated catchment modelling with simulation of the inter-relationship between the aquifers and the river, allowing detailed assessment of the effects of engineering options;
- recommendations based on benefits to the river, technical feasibility and comparison of costs.

Many of the engineering options such as reduction in abstraction, river support and river bed lining were well established prior to the start of the investigation. Detailed modelling of the catchment had not been carried out previously, however. The present investigation therefore provided the first opportunity to assess in detail the effects on river and aquifer conditions of abstraction and options to improve flows.

A Pre-feasibility Report produced in November 1991 contained the following:

- a review of all previous work of relevance to the investigation;
- an assessment of hydrogeological and hydrological data;
- a description of surface water modelling work carried out during the first part of the investigation and resulting water balances for the main aquifers and subcatchments;
- initial assessments and costings of all foreseeable engineering options.

The detailed catchment model was developed in late 1991 and calibrated in the period July to October 1992. The model includes the catchment of the River Cray, a tributary to the west of the Darent, and the Ebbsfleet catchment to the east (Figure 1.1). The present report describes the development of the Darent catchment model and results of calibration work carried out in 1992.

In October 1992 a joint project team was set up between the National Rivers Authority and Thames Water Utilities Limited (TWUL) who are responsible for a major part of all abstraction for public water supply from the catchment. The objective of the team was to agree a means of restoring river flows to the Darent whilst safeguarding drinking water supplies. During October and November 1992 the calibrated model was used by GDC to test a large number of public water supply abstraction strategies, combined in some cases with river support, to predict the effects on river flows and catchment hydrological conditions. The results were used by the joint project team in formulating a 'Plan for the Darent'.

The NRA has undertaken a programme of well construction and testing to collect additional information on groundwater levels and aquifer properties in the Darent catchment. Model calibration, however, was carried out prior to the availability of data from the well contract and hence calibration results should be considered as interim. They may be revised as a result of the findings of the well contract.

## 1.3 Catchment Description

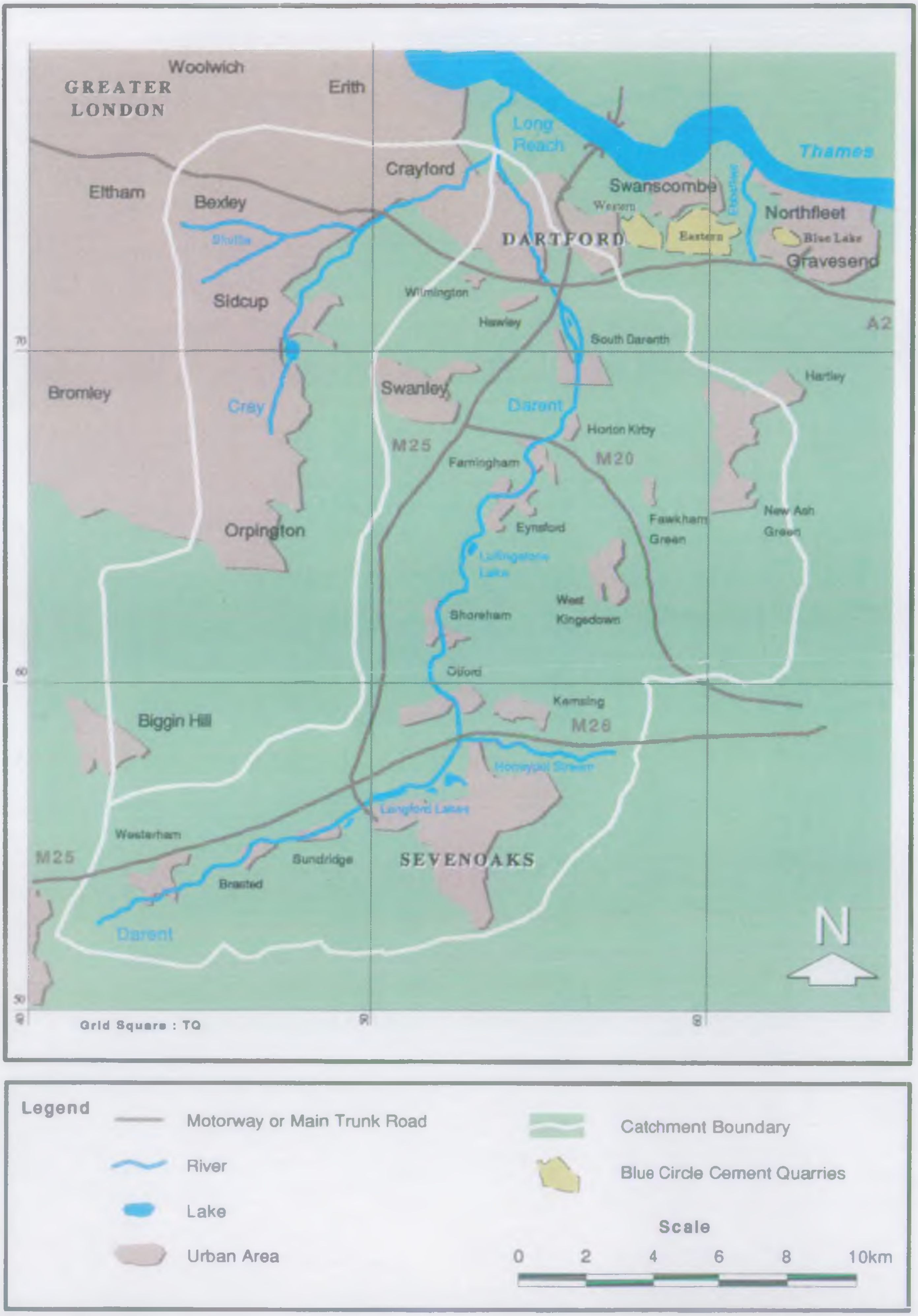
### 1.3.1 Topography, Land Use and General Hydrology

The River Darent rises near Westerham about 10 km west of Sevenoaks (Figure 1.1). The upper reaches of the river are fed by springs both from the dip slope of the (Lower) Greensand to the south and the scarp slope of the Chalk of the North Downs to the north. Both the Greensand and Chalk outcrops attain heights of more than 200 m AOD in the vicinity.

The river first flows in an easterly direction towards Sevenoaks. Disused sand quarries just to the west of Sevenoaks have given rise to lakes (Longford Lakes and others) which are connected with the river system. The river then follows a major valley cutting through the North Downs towards the Thames basin. Within the valley the river receives further contributions to flow from Chalk springs or seepages. A series of flooded gravel pits is located close to the northern end of the river valley.

Figure 1.1

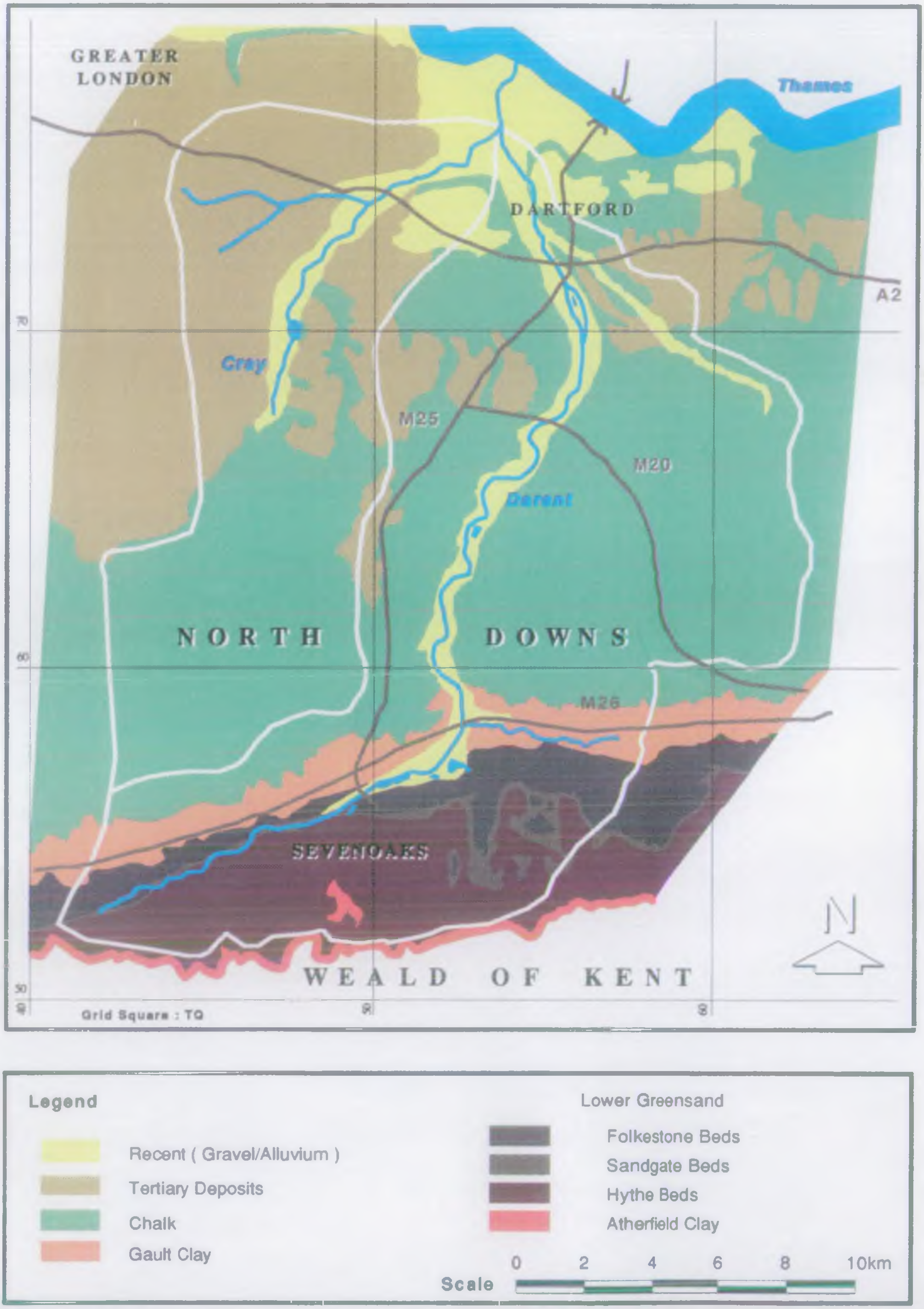
Location




70223B01\GDC\2\A\DCI

Figure 1.2

Geology



The river emerges on to the Thames floodplain about 20 km north of Sevenoaks where it is joined by a major tributary, the River Cray which rises within the Chalk of the North Downs to the west of the Darent.

The Darent surface water catchment to the confluence with the Cray has an area of 250 $km^2$; the surface water catchment area for the Cray is 130 $km^2$. Long term mean flows in the Darent between gauging stations at Otford and Hawley are in the range 0.5 to 0.7 $m^3/s$. The mean flow in the Cray at Crayford is 0.5 $m^3/s$. The Darent is tidal to approximately 3 km above the point of discharge into the Thames. Mean annual rainfall varies from less than 500 mm along the Thames floodplain to more than 700 mm in some upland areas of the North Downs.

Land use in the Darent catchment is a mixture of pasture and arable with extensive areas of woodland on both the Chalk and Greensand outcrop areas. There are some water meadows in the valley bottom. The main urban area in the upper Darent catchment is at Sevenoaks. The lower 6 km of the catchment down to the confluence with the Thames is dominated by urban and industrial development in and around Dartford.

Land use on the uplands and dry valleys of the upper Cray catchment is pasture with some arable and woodland. The mid and lower Cray catchment from Orpington just above the source of the river to the confluence with the Darent is highly urbanised with much of it lying within the bounds of Greater London.

The Ebbsfleet catchment to the north-east of the Darent has been extensively altered from its natural state as a result of massive chalk quarrying operations by Blue Circle Cement, major industrial development and urbanisation at Northfleet and Gravesend. The original source of the river is about 3 km from the Thames, to the south-west of Gravesend. No flow records exist for the river which was found to be dry when visited in 1991.

### 1.3.2 Geology

The Darent catchment is located on the southern side of the London Basin. Formations dip gently to the north with successively younger formations overlying older formations from south to north. A geological map showing outcrop areas is shown in Figure 1.2 and geological cross sections and succession are given in Figure 1.3.

The oldest formation present at outcrop, the Lower Greensand, is found along the southern boundary of the Darent catchment. Lower Greensand comprises a basal clay (the Atherfield Clay) with two sandstone aquifers above, the Hythe Beds and Folkestone Beds. These are separated by an aquitard of silts and clays, the Sandgate Beds. The Lower Greensand is overlain by the impermeable Gault Clay which forms an important aquitard between the aquifers of the Lower Greensand and the Chalk.

The outcrop of the Chalk in the central part of the Darent catchment forms the main geological feature in the study area. It gives rise to a well defined escarpment in the southern part of the Cray catchment and to the east of the M20, with the Chalk dipping gently to the north. The chalk is characterised by three distinct units, the Upper, Middle and Lower Chalk. The Chalk lithology comprises a soft microporous, white limestone becoming increasingly grey and marly in the lower units. The bases of the Upper and Middle Chalk are marked by hard, nodular chalk beds, the Chalk Rock and the Melbourn Rock, indicated on Figure 1.3.

The Northern part of the catchment is characterised by the outcrop of Tertiary formations, mainly silty sands of the Thanet Beds but overlain successively in the north-west of the Cray catchment by clays of the Woolwich Beds and fine sands of the Blackheath Beds. There are also some areas of London Clay.

Superficial deposits include gravels and alluvium. Gravels flank the river valleys and also cap some high ground. Alluvium of varying extent and thickness is deposited in the main river valleys.

## 1.4 Modelling Approach

The catchment model used in this study is an integrated surface water/groundwater model based on the integrated finite difference method. The mathematical solution to the model takes into account the inter-relationship of heads and flows in both aquifer and river system with exchange between the two. Aquifer recharge which is the main contributor to river baseflow is estimated initially using a separate lumped-parameter hydrological model (a modified version of the Stanford Watershed Model). This also provides surface runoff and interflow components. The hydrological model is calibrated against river flow data principally through adjustment of soil moisture parameters. Recharge is then used as an input to the catchment model.

The catchment model is capable of simulating the temporal and spatial distribution of groundwater heads and river flows in a network of variably sized polygons covering the catchment. The river system is fully integrated within the groundwater model. It is incorporated as a line of internal boundary elements aligned along the interfaces of adjacent model polygons. The catchment model is calibrated mainly by variation of input parameters describing aquifer properties until a reasonable match is obtained between model results and observed historical river flows and groundwater levels over the entire period of record. Once an acceptable match between simulated and observed data has been achieved, the model can be used with confidence to predict the effects of changes in abstraction patterns and river support.

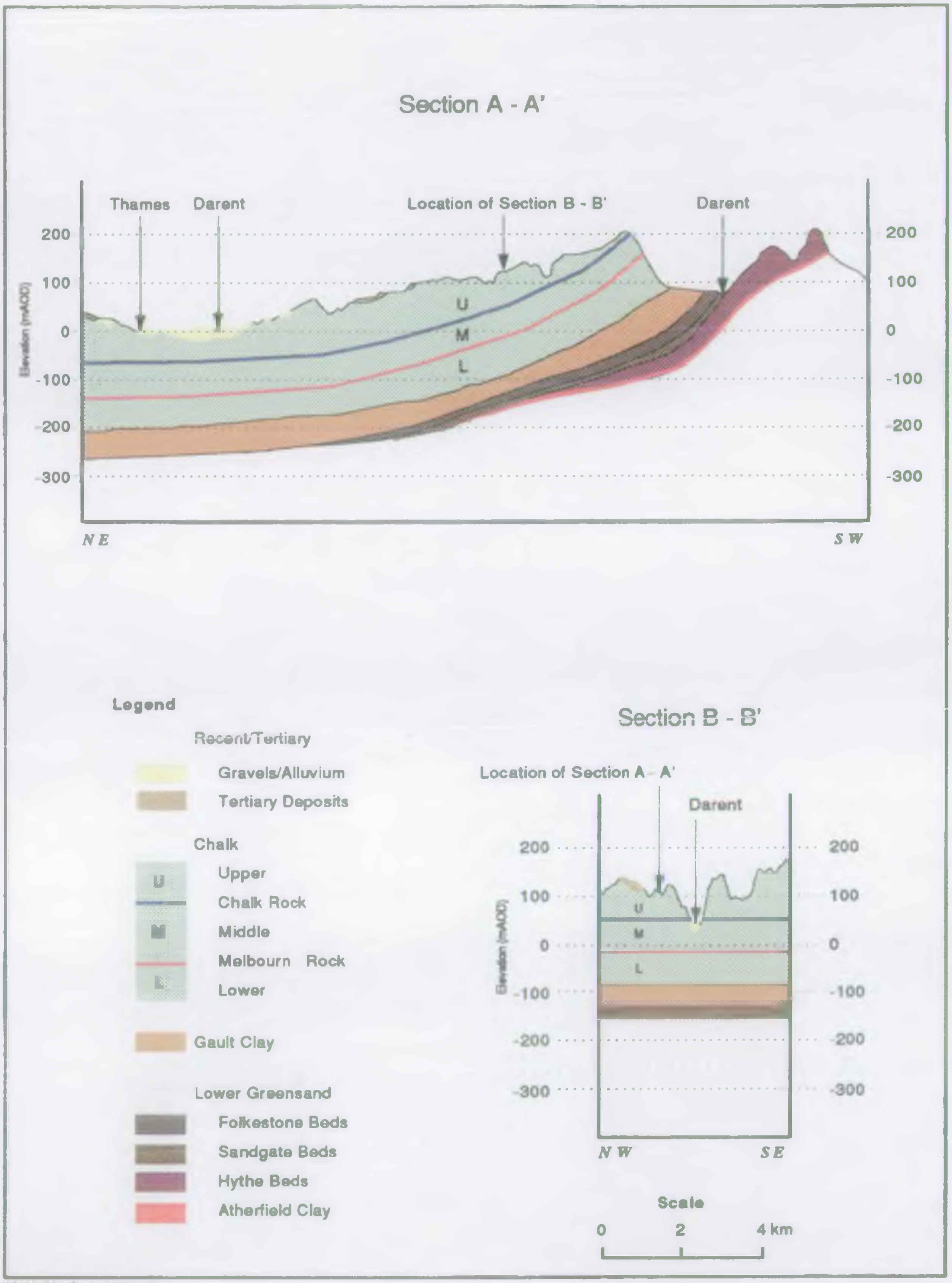
The main data requirements for catchment modelling are:

- For recharge estimation:

    - rainfall (precipitation);
    - potential evapotranspiration;

Figure 1.3

## Geological Cross Sections




70223B01/GDC/2/A/DCI

- groundwater and surface water abstraction;
- river support discharges;
- surface water catchment topographical characteristics;
- land use;
- river flows for comparison with hydrological model output.

- For the main catchment model:

    - geological information to define the geometry of the aquifer system;
    - observation well water level data within the catchment to provide aquifer piezometry for comparison with model simulation results;
    - water levels from wells in surrounding catchments for definition of model boundary conditions;
    - test pumping and well logging information to provide an indication of aquifer properties;
    - abstraction and river support discharges;
    - river flows for comparison with catchment model surface water output.

The catchment model was calibrated using data for the period January 1970 to September 1990. Continuous flow records are available for four gauging stations in the catchment from 1970 onwards. Data required for modelling were available up to 1990 at the time of calibration.

## 1.5 Data Sources

Many of the data required for modelling were provided for the work described in the Pre-feasibility Report and are documented in that report. However, the catchment model was expanded to include the Cray and Ebbsfleet catchments following the initial drafting of the Pre-feasibility Report. Additional abstraction and hydrometeorological data for these catchments have been provided subsequently. In addition, potential evapotranspiration data from 1961 onwards for two MORECS grid squares covering the model area were obtained by the NRA from the Meteorological Office. Some autographic rainfall records for four stations in the catchment were also provided by the NRA.

A programme of test pumping of existing public water supply wells was recommended in the Pre-feasibility Report to obtain additional data on aquifer properties. Testing was undertaken at selected TWUL wells in 1992 and additional existing information obtained from TWUL for some other sources. This work was carried out separately to the Well Construction and Testing Contract undertaken by the NRA. West Kent Water Company also provided data on the testing of a Lower Greensand well in 1992. IGS (1975) give discharge and some rest and pumping water level data for more than 100 Chalk wells in the Dartford area.

Some additional existing observation well records were made available following completion of the Pre-feasibility Report. The records are for wells which formed a part of the Thames Water Authority network for the region but were not being monitored at the time of transfer of responsibility for the catchment to the NRA (Southern Region) in 1990. Paper copies of the records were provided by Mr M Mansell-Moullin of the Darent River Improvement and Preservation Society who had been given the copies some years earlier by Thames Water Authority.

During 1992 GDC also undertook hydrogeological investigations and preliminary groundwater modelling of the Blue Circle Cement quarries in the Ebbsfleet area. The understanding of the hydrogeology of the Ebbsfleet and historical dewatering operations at the quarries resulting from these investigations proved useful in setting groundwater parameters for that area in the Darent catchment model.

# CHAPTER 2

# CONCEPTUAL BASIS OF THE MODEL

## 2.1 Type of Model

The model used for simulation is based on the Integrated Finite Difference Method (IFDM). The IFDM approach to model formulation is conceptually simple and involves the conversion of differential equations, which describe the groundwater flow, into water balance equations for the polygons of a model grid network. Polygons can be varied in size, shape and orientation to fit local details and physical characteristics of the modelled system. The time domain is also subdivided into timesteps of specified length.

The model is based on two fundamental principles: continuity of mass and Darcy's Law which assumes that flow is laminar and intergranular. The latter assumption is considered valid for a regional scale model of the Lower Greensand and Chalk aquifers. However allowance has also been made for rapid flow of water through fissures in the Chalk aquifer.

A further basic feature of the model is the resolution of three dimensional groundwater flow into its horizontal and vertical components. As the horizontal dimensions of the aquifer system are large in comparison with its thickness it is reasonable to assume that all flow within a permeable layer is horizontal. Transfer of water between aquifers is assumed to be vertical and is represented by a leakage mechanism either across an aquitard separating the aquifers or a leakage interface between two aquifers where these are in direct contact with each other.

Rivers and lakes are fully integrated within the model. Flow between rivers and the aquifer system is simulated either by a direct horizontal flow where the river is considered to fully penetrate the top aquifer or a leakage mechanism for partially penetrating rivers. River flows are evaluated using hydraulically modelled stage-discharge relationships. A leakage mechanism is incorporated to describe the flow between lakes and the aquifer system.

Both steady state flow conditions, when the inflow to the system balances the outflow, and transient conditions which include changes in aquifer storage can be simulated by the model.

## 2.2 Areal Extent

The Darent catchment model covers an area of about 530 $km^2$ and includes the rivers Darent, Cray and Ebbsfleet as shown in Figure 2.1. The model boundaries were chosen to cover the whole of the groundwater catchments of each of these three rivers at all times and are defined as follows:

- southern boundary, along the southern limit of the outcrop of the Hythe Beds defined from published geological mapping (BGS, 1970);

- eastern boundary along the groundwater divide in the Chalk between dry valleys of the Darent and Medway catchments;

- western boundary along the groundwater divide in the Chalk, coinciding in places with the western boundary of the Cray surface water catchment but located to the west of the surface water catchment in the vicinity of Bromley;

- northern boundary along the River Thames between Woolwich and Gravesend.

## 2.3 Model Features

### 2.3.1 Modelled Layers

Using published hydrogeological mapping (BGS 1970) and lithological logs of selected abstraction wells six individual layers were defined as shown in Figure 2.2. The six layers comprising the modelled system are described below:

(i) Hythe Beds (Lower Greensand)

The Hythe Beds outcrop along the southern boundary of the model area and dip from south to north. This aquifer unit has a maximum thickness of 60 m at outcrop and thins out completely in the direction of dip below the Chalk. The Hythe Beds comprise calcareous sand, sandstones and sandy limestones in which fissure flow predominates (BGS, 1970).

(ii) Sandgate Beds (Lower Greensand)

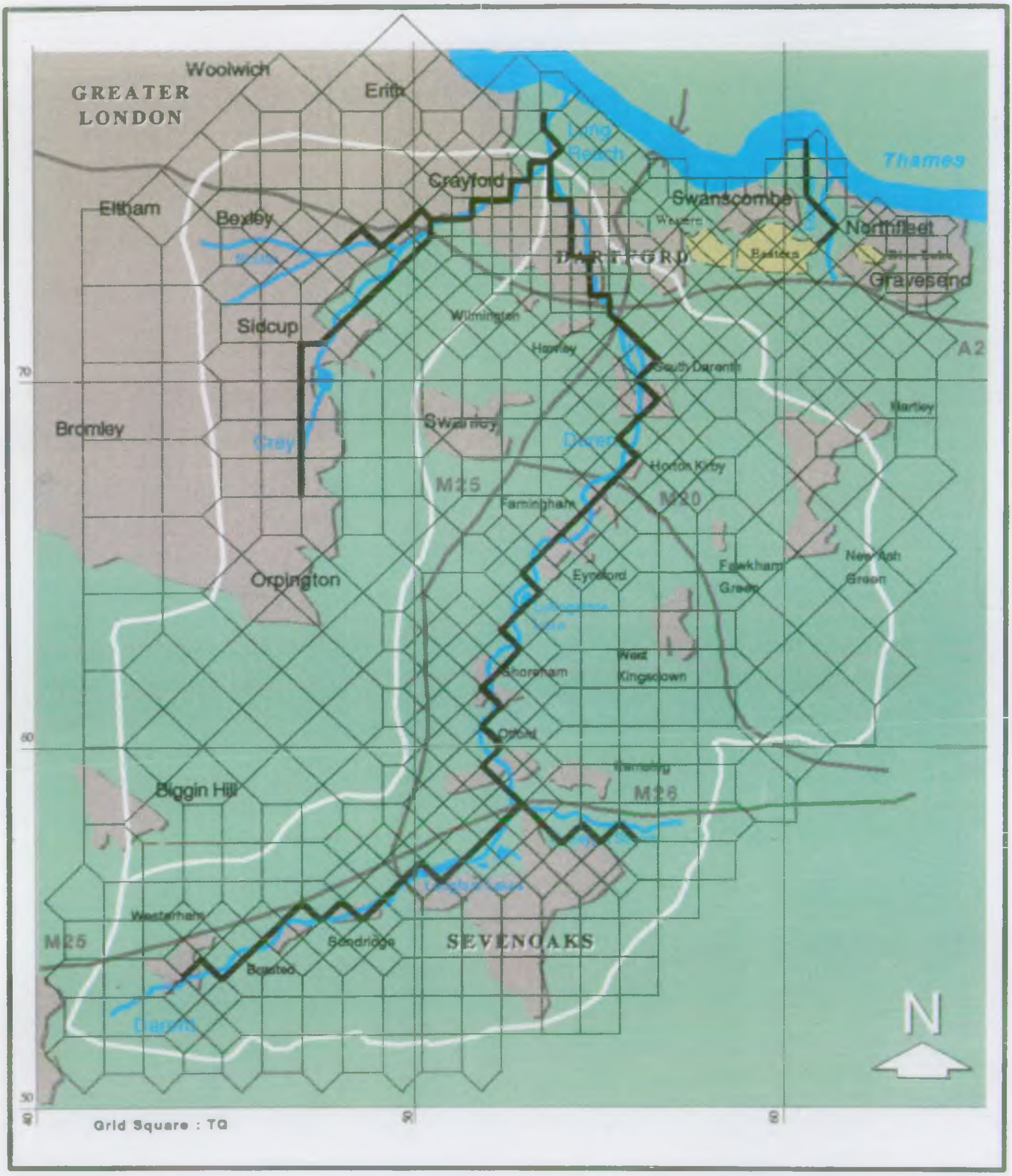
The Sandgate Beds act as an aquitard between the Hythe Beds and the overlying Folkestone Beds aquifer, and comprise silty clays and clays. The thickness varies between 0 m and 40 m but has been simplified in the model with a constant thickness of 10 m throughout.

(iii) Folkestone Beds (Lower Greensand)

The Folkestone Beds outcrop along the valleys of the upper Darent and the Honeypot Stream to the south of Otford. This aquifer has a maximum thickness of 70 m at the outcrop, thinning out completely beneath the Chalk at the northern boundary of the model. The Folkestone Beds consist of coarse to fine sands and sandstones with occasional clayey sands and sandy clays forming a porous, non-fissured aquifer.

Figure 2.1

## Catchment Model

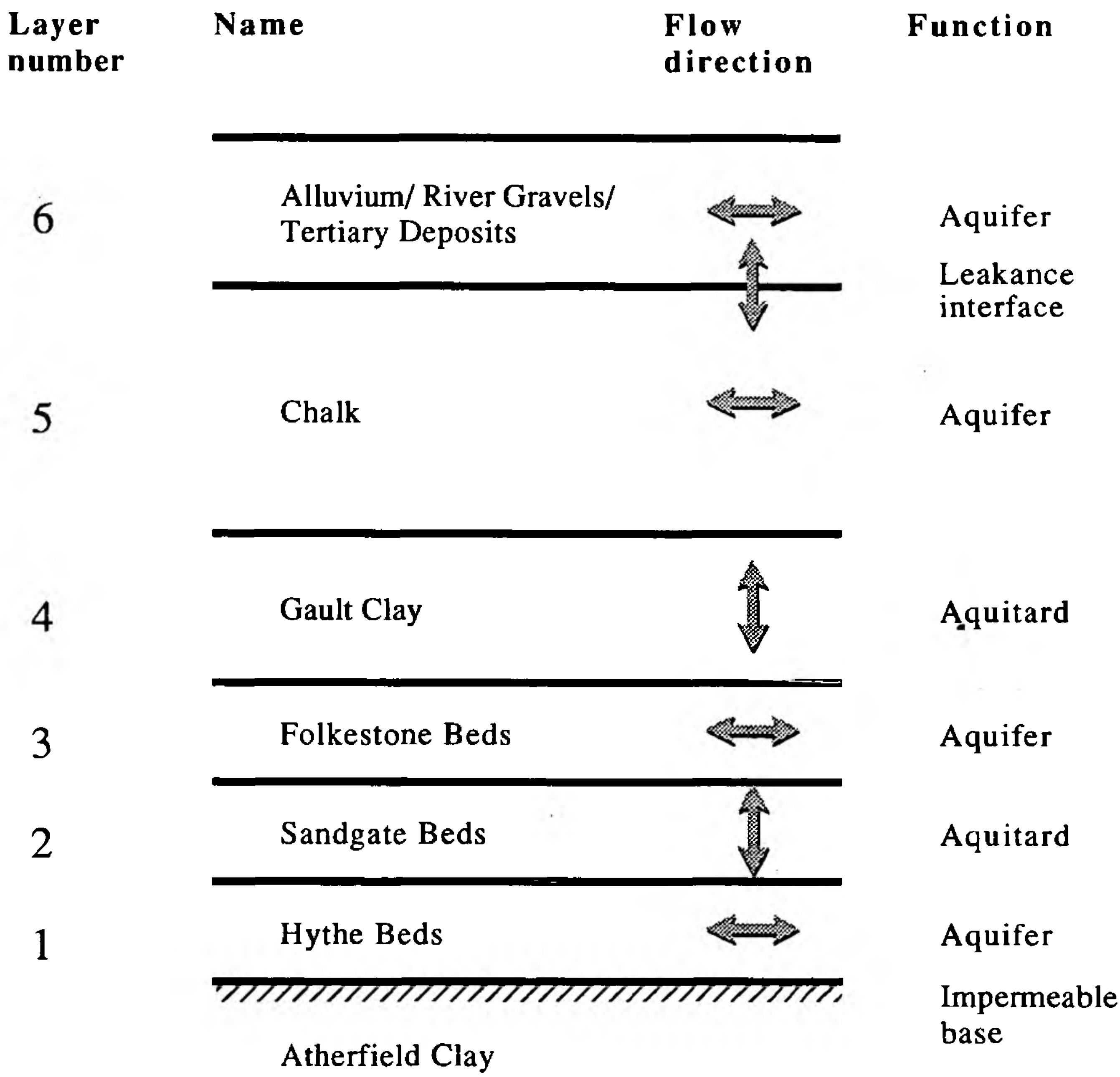




70223\B10\GDC\1\A

Figure 2.2

## Modelled Aquifer System




70223B01\GDC\2\A\DCI

(iv) Gault Clay

The Gault Clay is a thick (40 m to 110 m) and effectively impermeable clay formation separating the Chalk and Lower Greensand aquifers. This unit has been modelled as an aquitard with a constant thickness of 70 m. However, where it thins out at outcrop the actual thickness has been used.

(v) Chalk

Although the Chalk is characterised by three distinct geological units (Section 1.3.2), the units are not separated by aquitards and therefore the Chalk is modelled as a single geological layer. This varies in thickness from 50 m at the Lower Chalk outcrop along the North Downs to 210 m below the River Thames.

(vi) Tertiary and Recent Deposits

Three Tertiary formations are present in the modelled area:

- the Blackheath Beds occurring in the north-west of the Cray catchment, and in scattered outcrops in the northern Darent and Ebbsfleet catchments, consists mainly of fine sand with a maximum thickness of 25 m;

- the Woolwich Beds, consisting of loam and clay, forms an aquitard between the Blackheath and Thanet Beds. Woolwich Beds are relatively thin (0 m to 10 m) and have a similar distribution to the Blackheath Beds;

- the Thanet Beds occur extensively in the north-west of the model area and in the Ebbsfleet catchment. They consist of poorly cemented sands, becoming silty with depth. The full section thickness varies from 10 m to 30 m.

London Clay also occurs in some areas in the north-west of the Cray catchment.

The Tertiary deposits have been modelled as a single aquifer with varying horizontal and vertical permeabilities to account for the different characteristics of the three units. The total modelled thickness varies up to 60 m.

Recent alluvial deposits which line the Thames estuary and the Rivers Darent and Cray are included in the same layer as the Tertiary deposits. Alluvial deposits extend up to 500 m in width across the Darent valley, while lithological logs indicate a thickness of up to 12 m.

### 2.3.2 River/Aquifer Interface

Rivers are incorporated in the catchment model as additional elements defined between two adjacent groundwater polygons. At each of these elements a separate water balance calculation is carried out where the volume difference between water entering and leaving the element is balanced by a loss or gain to the aquifer system. This volume transfer between the river and the aquifer system is fully integrated within the catchment model.

River flows are determined from stage-discharge relationships, or from weir equations for locations where gauging structures are present on the river. Steady state hydraulic modelling of the river system is used to define the stage-discharge relationships.

Flow between the rivers and the aquifer system has been modelled as a combination of horizontal flow between the river and the uppermost aquifer where the river is in direct contact with the aquifer or with leakage mechanisms between the river and the uppermost aquifer unit at locations where the river flows across an aquitard or across river alluvium.

In the upper Darent catchment, the river bed crosses the Lower Greensand. The modelled flow between the Hythe and Folkestone Beds and the river is shown in Figure 2.3. There are two distinct components as follows:

- the river intercepts the horizontal flow of water through the Folkestone Beds, where the direction of groundwater flow follows the dip of this layer;

- leakage occurs between the river and the Hythe Beds through the Sandgate Beds.

In this region there are a large number of springs from both the Lower Greensand and the Lower Chalk. The model simulates these springs as rejected flow whenever a polygon becomes fully saturated to ground level. The volume of rejected flow from such a polygon is routed to the river following the gradient of the modelled topography down to the river system.

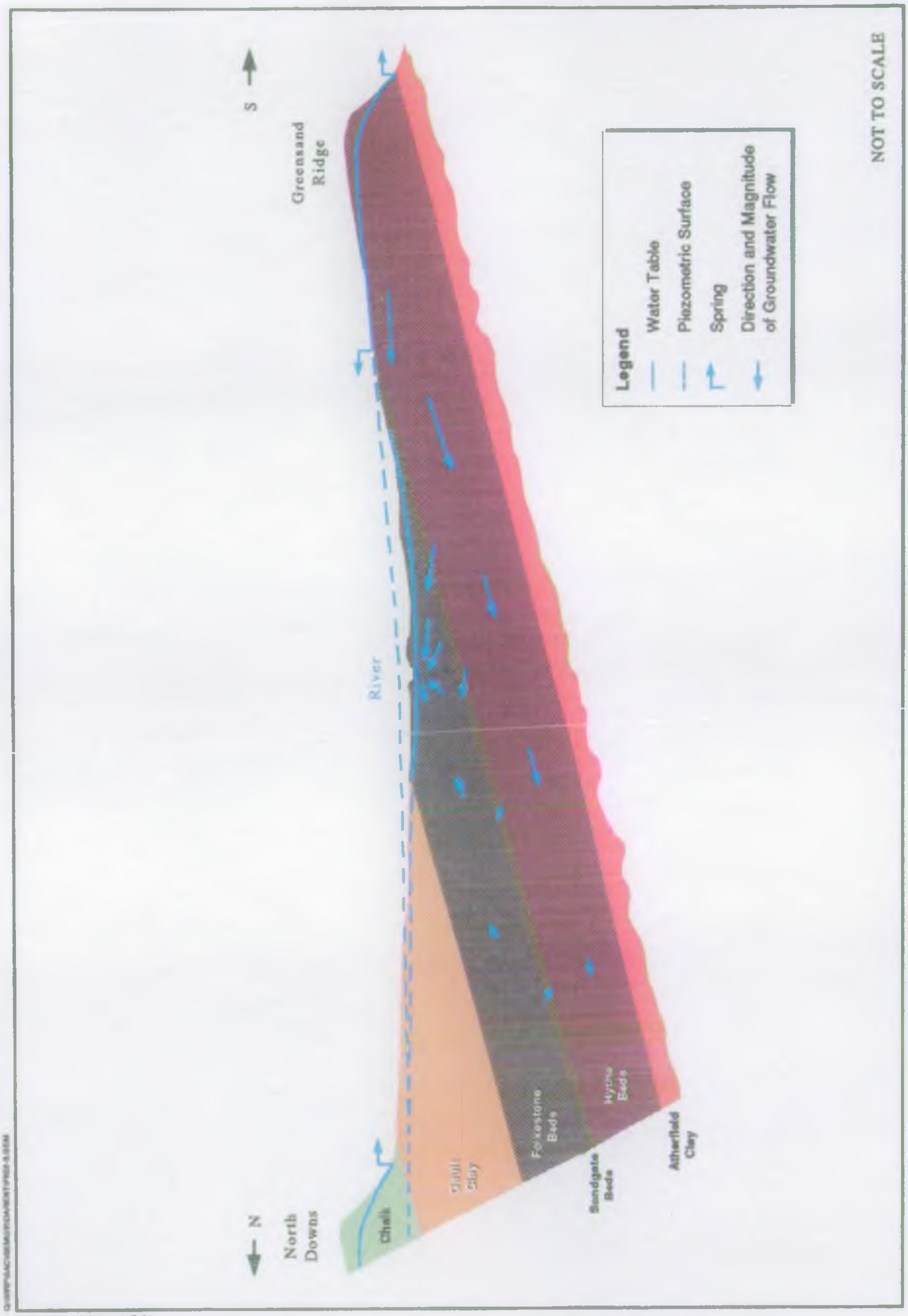
Where the river crosses Gault Clay just upstream of Otford no loss or gain from the aquifer is simulated as the Gault Clay is virtually impermeable.

In the lower Darent catchment a leakage mechanism has been adopted between the river and the Chalk aquifer. This is a much simpler mechanism in which the vertical leakage across the river alluvium to the Chalk aquifer is balanced with horizontal flows in the Chalk between the river element and the adjacent groundwater polygons. Over much of this reach, the river loses water to the Chalk aquifer as a result of abstraction from the Chalk aquifer.

Chalk spring flows are simulated and routed to the river in the same way as in the upper Darent catchment.

Figure 2.3

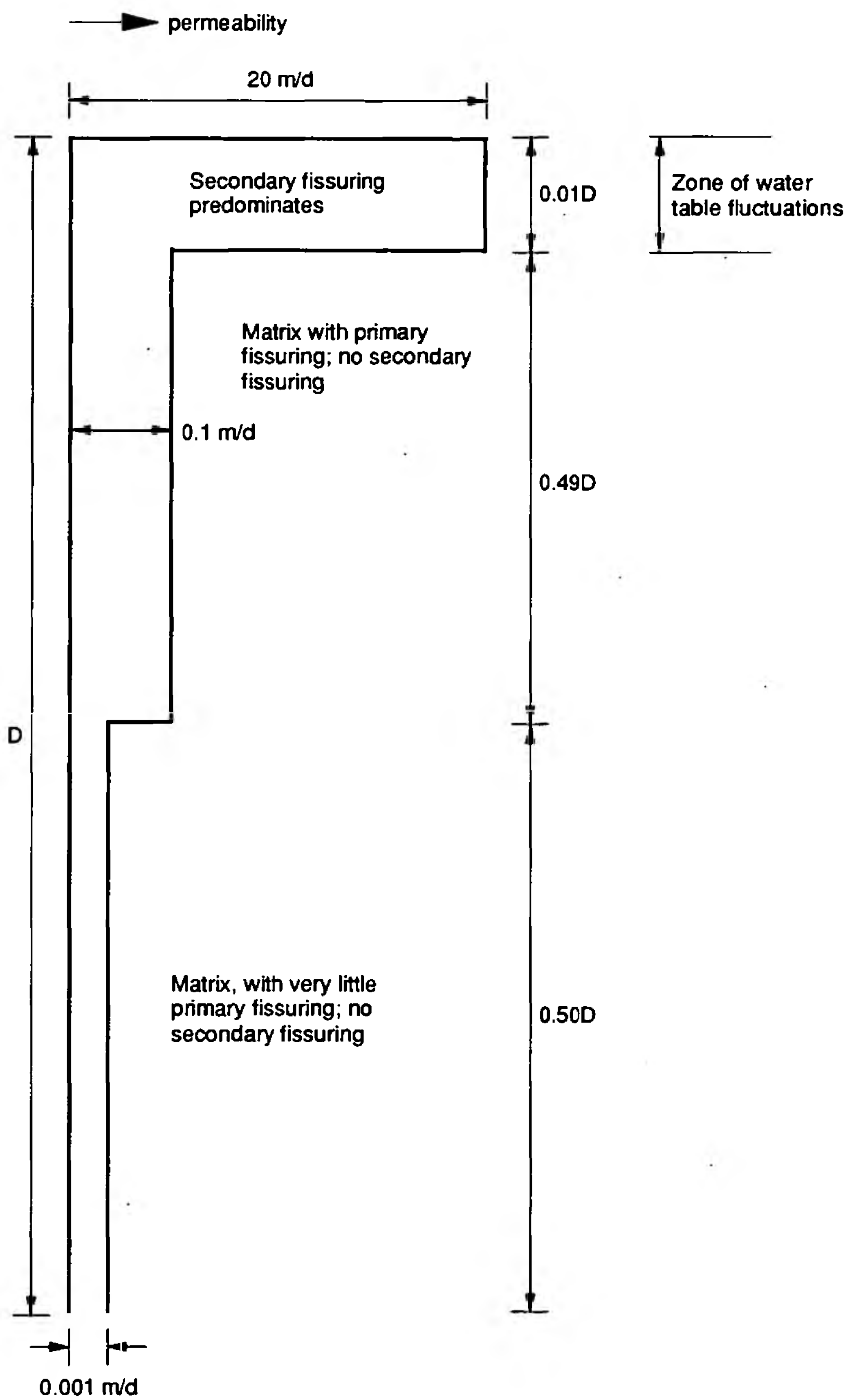
## River / Aquifer Interface - Upper Darent




70223B01/GDC/2/A/DCI

Figure 2.4

# Depth Dependent Permeability




NOT TO SCALE

**Typical permeabilities as indicated by Price (1987)**

A similar leakage mechanism to that for the lower Darent catchment was adopted initially for the Cray catchment. However during calibration it was concluded that the Tertiary deposits in the north-west of the catchment may also contribute significant quantities of baseflow to the River Cray. The model was therefore adjusted specifying a high specific yield and low vertical permeabilities for the Tertiary deposits. These are characterised by interbedded clay, silt and sand layers which would be expected to contribute a small but continuous baseflow discharge to the river throughout summer months. The River Cray was assumed therefore to fully penetrate the Tertiary deposits with a high resistance to flow imposed between the Chalk aquifer and the river.

### 2.3.3 Lakes

Lakes formed mainly from flooded gravel pits exist at a number of locations within the Darent and Cray catchments. The transfer of water between the largest of these lake systems, the Longford Lakes and the Lower Greensand aquifer system has been simulated as a leakage mechanism in which surface inflow and outflow from the lake are balanced by leakage between the lake and the uppermost aquifer and a storage change in the lake. This mechanism is also fully integrated within the model. A lake is defined over one or more polygons, and the leakage between lake and aquifer is controlled by the hydraulic resistance of the lake bed.

### 2.3.4 Fissuring

The Chalk aquifer has several components of porosity and permeability as discussed by Price (1987):

- the intergranular space within the rock matrix which exhibits high porosity but low permeability;

- the primary fracture or fissure component which has low porosity but higher permeability;

- the secondary fissure component comprising primary fissures which have been enlarged by solution occurring over the top few metres of the saturated zone.

The model was configured with the potential to include variations in permeability with depth in the Chalk where considered necessary. By specifying a high permeability within the region of normal water table fluctuations a rapid movement of groundwater recharge through the secondary fissure component to the river can be simulated. A typical depth/permeability distribution is shown in Figure 2.4.

The specific yield of the Chalk was not varied with depth as the high matrix porosity is considered to dominate groundwater storage even in a highly fissured zone.

### 2.3.5 Recharge

Recharge to the aquifer system is evaluated using a modified version of the Stanford Watershed model. The Stanford Watershed model is a lumped parameter model describing flow through the root zone and unsaturated zone to the aquifer system and direct overland flow and interflow to the river. Through calibration of the Stanford model at each gauging station recharge for each gauging station subcatchment can be evaluated. The results of calibration are then extrapolated to give recharge for any ungauged subcatchments within the catchment model area. Six subcatchments were defined, with gauging station records available at four sites, Otford, Lullingstone and Hawley on the River Darent and Crayford on the River Cray.

For the integrated catchment model the recharge evaluated by the Stanford model is distributed across each subcatchment according to surface geology, extent of urbanisation and rainfall distribution.

## 2.4 Simulated Water Balance and Model Solution Technique

The following groundwater and surface water balance components are included in the integrated catchment model:

- horizontal flow in aquifer layers computed from Darcy's flow equation;
- vertical leakage across the aquitards (Gault Clay and Sandgate Beds) and vertical transfer between aquifers;
- flow across external model boundaries;
- confined and unconfined storage changes in the aquifers;
- flow between rivers and aquifers, either horizontally where the river is assumed to fully penetrate the aquifer, or by vertical leakage where the river partially penetrates the aquifer;
- recharge to the aquifer system evaluated from the modified Stanford Watershed Model;
- abstraction from aquifers;
- direct abstraction from and augmentation of riverflow;
- spring flows from the aquifer system at times when aquifer storage is completely filled;
- surface runoff and interflow to the river system;

- implied discharge, which is a consequence of fixed water level conditions imposed on specified model polygons and layers, applied to the dewatering of quarries in the Ebbsfleet catchment;

- leakage into and out of lakes.

Some of the water balance components, such as horizontal flow in aquifer layers, vertical flow between layers and storage change, are dependent on the water level elevations in the layers. An iterative solution technique, using a backward difference method, is used to derive successively improved estimates of the aquifer heads, which cause the flow imbalances (the difference between inflow and outflow) for the polygons to converge towards zero. The iterative scheme used to solve the system of simultaneous equations which represent the water balance equations in the polygons, is essentially the successive over-relaxation method.

The simulation of flows in the river elements is also fully implicit. The flow balance for the river elements, which includes both surface and sub-surface components, is evaluated in a similar manner to the water balance in polygons of the standard groundwater model. An iterative procedure is used to derive successively improved estimates of river levels until the water balance convergence criterion for the river elements is reached.

The solution is accepted when the imbalance for the entire model, expressed as a proportion of the total inflows or outflows, drops below a preset value. For the River Darent model, the convergence criterion was set to 0.5% to ensure that close convergence was achieved in all polygons and at the river faces.

# CHAPTER 3

# MODEL PREPARATION

## 3.1 Model Grid Network

The geometry of the model is defined by subdividing the model area into a number of polygons whose internal nodes form an asymmetrical finite difference network. The model network was defined using the catchment model pre-processor.

The grid was designed in order to:

- accurately define the river system (where a river element is specified by the polygon face separating two adjacent polygons);
- accurately define the external model boundary;
- provide the greatest density of polygons at the locations of large abstraction ;
- minimise the computational times without adversely affecting the accuracy of simulation.

The resultant grid is shown in Figure 2.1. The grid network has a total of 619 polygons and 99 river elements defining the River Darent (including the Honeypot Stream), the Rivers Cray and Shuttle in the Cray catchment and the Ebbsfleet. Polygons vary in area from a maximum of 4.4 $km^2$ to 0.275 $km^2$ with the maximum density of polygons around the confluence of the Rivers Darent and Cray where the concentration of abstraction wells is very high, and in the Ebbsfleet catchment where dewatering at the quarries results in relatively steep water level gradients. The total model area is 527 $km^2$.

River elements vary in length from 1 050 m to 525 m. Along most of the course of the River Darent river elements are 700 m in length.

## 3.2 Aquifer System Geometry

The geometry of the six modelled layers was defined using a geological structure model. The following aquifer levels and thicknesses were digitised from topographical mapping (Ordnance Survey) and hydrogeological mapping (IGS 1970):

- topography (from 1 : 50 000 Landranger series);
- elevation of the top of the Upper Chalk;

- elevation of the top of the Melbourn Rock, separating Middle and Lower Chalk;
- thickness and elevation of the top of Folkestone Beds;
- thickness of Hythe Beds.

The elevations of the six modelled layers were then fully defined, assuming the following:

- base of Chalk was set 70 m below Melbourn Rock;
- thickness of Sandgate Beds was set at 10 m.

As the Gault Clay is effectively impermeable, upward leakage from the Lower Greensand, where confined by Gault Clay, is virtually zero. Minor groundwater flows may occur within and between aquifers of the Lower Greensand where confined by Gault Clay in the vicinity of the river as indicated in Figure 2.3. However, further down dip beneath the Chalk outcrop, groundwater flows and aquifer water balance components should be insignificant. Gault Clay and Lower Greensand layers were therefore only extended about 3 km down dip below the outcrop of the Chalk.

In order to simulate fissure flow in the Chalk by incorporating depth dependent permeability during transient calibration, an effective aquifer thickness had to be adopted for the Chalk. An assessment was first made of the effect of specifying a single effective thickness of the order of 50 m without variation in permeability. Model results were found to be very similar whether actual or effective thicknesses were used. An effective thickness of 60 m was adopted with depth dependent permeability in final calibration.

### 3.3 Hydrogeological Parameters

During the pre-feasibility study (GDC, November 1991) very few well testing data were found which could be used to define aquifer transmissivity. No data from observation wells were available to allow calculation of storage coefficients for any of the aquifers. However, during the period January to June 1992 well testing was carried out at five Thames Water Utilities Chalk groundwater sources in the Darent and Cray catchments. In addition, West Kent Water Company provided comprehensive reports for recent testing at one Chalk and one Lower Greensand groundwater source together with data for testing carried out in the 1950s and 1960s at a further Lower Greensand source. The water company also provided data from the testing of a new Lower Greensand well. Finally IGS (1975) give information on more than 100 Chalk wells in the Dartford area, some of which can be used to determine specific capacity values.

Using the data available for the Hythe Beds of the Lower Greensand, which indicate transmissivity in the range 300 to 500 $m^2/d$ for an aquifer thicknesses of about 40 m, a permeability of 10 m/d was adopted. No test data were available specifically for the Folkestone Beds. As a starting point for model calibration the same permeability was adopted for the Folkestone Beds as for the Hythe Beds.

IGS mapping suggests that the Folkestone Beds piezometry is on average 2 m to 5 m higher than water levels in the Hythe Beds. In addition, while testing at Brasted pumping station, it was noted that a 5 m difference in water levels exists between the two aquifers (Thames Water, 1991). In order to simulate the piezometric difference a relatively low vertical permeability (5 mm/d) was specified for the intervening Sandgate Beds aquitard.

Pumping test results for the Chalk aquifer indicate a high variability in transmissivity within individual abstaction sites and between sites. In general transmissivity appears to increase towards the river valleys and away from the interfluve areas.

As a first estimate of the Chalk transmissivity distribution, the piezometry, as defined on the IGS hydrogeological map of the region, was used to define the relative magnitude of transmissivity between different regions in the model. For example where the water level gradient is high, indicating considerable resistance to groundwater throughflow, a low value of transmissivity was adopted. Using pumping test results and specific capacities derived for boreholes from data in the IGS well inventory, the following initial transmissivities were adopted:

| | |
|---|---|
| Darent and Cray Valleys | 1 000 $m^2/d$ |
| Ebbsfleet Valley | 2 000 $m^2/d$ |
| River Elements | 2 000 $m^2/d$ |
| Upper Darent/Upper Cray Catchments | 250 $m^2/d$ |
| Lower Darent/Lower Cray Catchments | 700 $m^2/d$ |

The initial values for all other hydrogeological parameters were taken from published data, and from the results of other studies. These initial values are summarised in Table 3.1.

**TABLE 3.1**

**Initial Values of Aquifer Parameters**

| Layer | Transmissivity (m²/d) | Horizontal Permeability (m/d) | Vertical Permeability (m/d) | Specific Yield (%) | Confined Storage Coefficient (%) |
|---|---|---|---|---|---|
| Hythe Beds (aquifer) | 200 - 600 | 10 | 2.0 | 5 | 0.01 |
| Sandgate Beds (aquitard) | - | - | 0.05 | - | - |
| Folkestone Beds (aquifer) | 200 - 600 | 10 | 2.0 | 5 | 0.01 |
| Gault Clay (aquitard) | - | - | 0.0001 | - | - |
| Chalk (aquifer) | 250 - 2 000 | - | 1.0 | 1 | 0.001 |
| Tertiary Deposits | 20 - 600 | 20 | 0.1 | 10 | - |
| Alluvium (aquifer) | 100 - 200 | 20 | 1.0 | 15 | - |

## 3.4 Rivers Data and Hydraulic Modelling

River elements are defined in the model along the boundary of two adjacent polygons. The model polygon grid was developed so that the river elements follow the course of the river as closely as possible within the limits of network subdivision.

For each river element a number of parameters are required to define the transfer of water between river element and groundwater polygon. These are as follows:

(i) Transfer Mechanism

The connection between the aquifer system varies throughout the model as the surface geology varies. In general a combination of leakage and horizontal flow occurs between river and the aquifer system. The different transfer mechanisms are described in Section 2.3.2.

(ii) River Bed Level

The bed level of the river is of fundamental importance in calculating the volumes of transfer between river and aquifer system. Without accurately defining the base of the river it is not possible to quantitatively evaluate baseflow, and piezometry around the river will not be simulated correctly. With poorly specified river base levels transmissivities along the valley floor cannot always be defined correctly during calibration.

River base levels were obtained from detailed cross-sectional surveys carried out on the River Darent during July 1991 and the River Cray during April 1992. Cross-sections were surveyed at intervals of between 500 m and 1 000 m along the rivers.

(iii) River Bed Resistance

Hydraulic resistance of the river bed is a measure of the resistance to flow between the river and the aquifer over a unit area of riverbed. It takes into account the thickness and permeability of deposits lining the river and has units of time (days). The rate of transfer through the river bed decreases with an increase in the value of resistance expressed in days.

It is extremely difficult to define the resistance of the river bed from available data. Based on measured accretion profiles and the difference in river levels and aquifer levels, the hydraulic resistance may range between 0.5 and 25 days. The hydraulic resistance was assigned an initial value of 2.0 days throughout the length of each river.

(iv) Width of the River

The river widths and hence the effective widths of the river elements were defined from the cross-sectional surveys.

During each iteration of the model run, the river flow leaving an element is calculated from a stage-discharge relationship for that element. The water balance of the element is calculated, and then the river water level is corrected according to the stage-discharge relationship such that the element imbalance is reduced to zero. Consequently for each river element a function relating depth of flow in the river to river flow is required. Two types of relationships have been used in the catchment model: stage-discharge evaluated from steady state runs of an hydraulic model (HYDRO) developed by Mott MacDonald (1990), and the calibrated weir equations for permanent gauging stations.

Hydraulic models of both the River Darent and River Cray were set up to evaluate stage-discharge relationships for river reaches with hydraulic model nodes corresponding to the location of surveyed cross-sections. Stage-discharge relationships were derived for each cross section using the Manning's equation. For the River Darent hydraulic model, stage-discharge relationships were computed by also incorporating backwater analysis upstream of the three gauging station control points along the river (at Otford, Lullingstone and Hawley gauging stations). A constant Manning's roughness coefficient of 0.035 was used throughout. Stage-discharge relationships were derived over a flow range of 0 to 5 $m^3/s$.

For the River Cray model, a modified technique was adopted. The hydraulic model was used to compute a series of 'conveyances' (equivalent to the actual conveyance multiplied by the cross-sectional area). Using Manning's equation this conveyance was converted to a discharge by multiplying by the square root of the bed slope, evaluated from surveyed data. Manning's 'n' was again taken as 0.035, except along reaches which have been lined with masonry or concrete where a lower roughness coefficient of 0.02 was adopted. The stage-discharge relationships were derived over the range 0 to 2 $m^3/s$.

Weir equations were adopted at the Otford, Hawley and Crayford permanent gauging sites. No details were available of the weir equations for the Lullingstone gauging station.

The model results are relatively insensitive to the stage-discharge relationships adopted since the model converges only when inflow to the river element is balanced by outflow from the river element. The river/aquifer mechanism simulates volumes in the river correctly. It does not define river water levels accurately or changes in width of the river. However, provided the stage-discharge relationships adopted are reasonably accurate the model will converge rapidly to a balance. If the stage-discharge relationships or river widths are highly inaccurate, groundwater levels in the vicinity of the river and river flow accretion profiles will be poorly defined.

## 3.5 External Model Boundaries

Three possible external groundwater boundary conditions can be specified: fixed groundwater level (head) conditions, fixed groundwater gradient or fixed groundwater throughflow. The first two conditions have been adopted in the Darent model.

Much of the eastern and western boundaries of the model were set up to coincide with the groundwater divides between adjacent catchments. Consequently zero gradients were specified at these boundaries.

At the southern boundary, hydrogeological mapping indicates that there are a number of springs discharging from the scarp face of the Hythe Beds to the River Eden catchment, bordering the Darent catchment to the south. In order to simulate this outflow a fixed negative groundwater gradient was adopted.

The River Thames forms an appropriate boundary to the model in the north. However as detailed piezometry does not exist for the Thames estuary it is difficult to establish the connection between the Thames and the underlying Chalk aquifer. A fixed head has therefore been adopted along the northern boundary equal to mean tide level at Woolwich evaluated from tide tables (3.0 m AOD). Using a fixed head assumes that the Thames fully penetrates the Chalk aquifer and that there is no resistance to flow between river and aquifer. In reality, the Thames is banked and underlain by alluvial deposits comprising layers of silts, clays and peat which exhibit poor hydraulic characteristics. There is thus a very significant resistance to flow between the Chalk and the river. Actual flow from the Chalk aquifer to the river would occur by flow convergence and vertical leakage through the alluvium. In order to account for this resistance and to simulate flow convergence a low permeability screen or barrier was defined along the Thames boundary, as illustrated in Figure 3.1.

At the north-west boundary between Bexley and the River Thames a fixed gradient has been adopted. The model boundary does not coincide with a groundwater catchment divide but from the inferred pre-development piezometry (Water Resources Board, 1972) groundwater flows from the model area towards the Thames. Consequently a negative gradient was adopted.

### 3.6 Abstraction Data

Abstraction data have been processed mainly from paper copies of licensee returns and from microfiche archive records. The data were received in various forms from daily to annual abstractions with very variable units (metric and imperial). For this investigation the catchment model was run with monthly timesteps. Consequently for abstraction returns received for periods of greater than one month a constant monthly discharge over each period was assumed.

In order to simplify data processing, abstractions with an annual licence of less than 50 Ml/year were not included in modelling. These small licences have a total of less than 300 Ml/year (<1 Ml/d) which is less than 0.5% of total groundwater abstraction in the catchment. Full records of abstractions were not available for many abstraction wells as indicated in the Pre-feasibility Report (GDC, 1991). Missing data were therefore infilled, where possible by adopting the average monthly abstraction from preceding and subsequent months. For the period 1970 to 1975 very few data were available. Average monthly abstraction over the period 1976 to 1990 was adopted as required for 1970 to 1975.

The processed abstraction data indicate no major long-term changes in abstraction patterns for the Darent and Cray catchments in the period 1975 to 1990. Mean annual total abstractions for 1985 to 1990, the period with most complete and reliable abstraction data, are as follows:

| | | |
|---|---|---|
| Lower Greensand | (Darent catchment): | 36 Ml/d |
| Chalk | (Darent catchment): | 90 Ml/d |
| Chalk | (Cray catchment): | 68 Ml/d |

In the Ebbsfleet catchment, very few abstraction data were available at the time of calibration. In this region 70% of the licensed annual abstraction was applied for calibration throughout the period of simulation. Data for the area are now available and could be used in any future revised calibration of the model.

Extensive dewatering takes place in the Blue Circle Cement quarries near Northfleet but quantities are not recorded. Initial estimates of quarry abstraction were used in the first stages of catchment modelling and then appropriate fixed heads were specified in transient state model calibration. The fixed heads simulate dewatering to predetermined levels in the three main quarries as follows:

| | |
|---|---|
| Blue Lake | -0.5 m AOD |
| Western Quarry | -5.0 m AOD |
| Eastern Quarry | -0.5 m AOD |

Abstraction estimated for the Ebbsfleet catchment in the period 1970 to 1990 averages about 70 Ml/d, not including quarry dewatering.

## 3.7 Recharge

Recharge to the aquifer system was estimated using a modified version of the Stanford Watershed Model. The evaluation of recharge is considered in detail in Chapter 4.

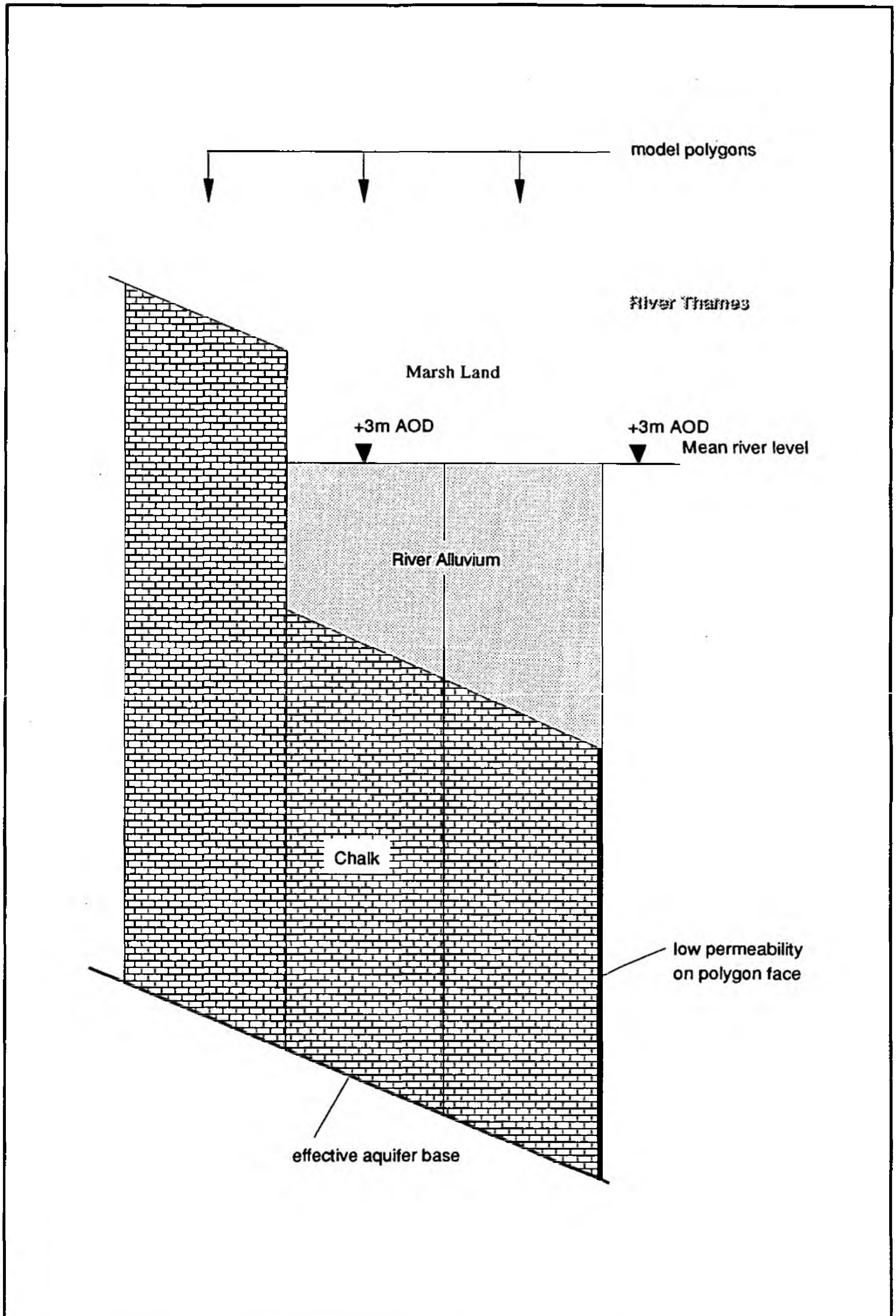
## 3.8 Piezometry

Observation well water level records available in the early stages of the investigation were indicated in the Pre-feasibility Report (GDC, 1991). Some additional records for wells which at various times formed part of the Thames Water Authority network for the region, but were not being monitored at the time of transfer of responsibility for the catchment to the NRA (Southern Region), have also been made available. Records for these additional wells generally extend over less than ten years, many are for periods before 1980 and some pre-date 1970. Nonetheless they form useful additional data for model calibration purposes. The locations of all observation wells are shown on Figure 3.2.

The overall number of observation wells is fairly reasonable for a catchment the size of the Darent. However there is very limited coverage in some areas. These include much of the north-west and south-east of the Cray catchment and the Lower Greensand in the southern part of the Darent catchment. There are also no observation wells located away from abstraction sources to monitor Chalk water levels close to the River Darent where it cuts through the North Downs. These deficiencies in the network should be rectified by the construction of new observation wells in late 1992 and early 1993. However no data for the new wells were available for this stage of model calibration.

Figure 3.1

# Simulated Northern Boundary




70223B01\GDC\2\A\DCI

Figure 3.2

## Observation Wells


**Legend**

- Monitored currently
- Monitoring previously by Thames Water Authority (TWA)

**Observation Well Reference Nrs**

TWA standard reference eg TQ56/25 abbreviated to 56/25 on the figure

NRA standard reference eg 441 346 001 abbreviated to 346/1

**Scale**

0 2 4 6 8 10km

# CHAPTER 4

# RECHARGE ESTIMATION

## 4.1 Introduction

A modified version of the Stanford Watershed Model was used during the pre-feasibility study to estimate recharge for a broad water balance assessment of the Darent catchment. Calibration for subcatchments of the Darent above gauging stations at Otford and Hawley and model verification were carried out using data for the period 1985 to 1989. Recharge was then estimated for the Darent catchment to the confluence with the River Cray for the period 1984 to 1990. Model calibration and results were described by GDC (1991).

For calibration of the integrated catchment model recharge values are also required for the Cray and Ebbsfleet catchments. The gauging station records for Crayford were used to calibrate a separate Stanford model for the Cray catchment. Results from the Stanford models for the Cray and subcatchments of the Darent were then used to extend modelling to include the ungauged Ebbsfleet catchment.

Long term mean annual rainfall varies across the area of the catchment model from about 473mm along the Thames Estuary to 730 mm in the Chalk uplands of the upper Cray catchment. There is therefore considerable variation in rainfall within each Stanford model catchment or subcatchment area. Recharge was distributed between polygons of the catchment model taking into account this variation in rainfall. In addition the effects of variations in outcrop geology and urbanisation on recharge need to be considered in some subcatchments. Monthly recharge sequences for the period 1970 to 1990 were computed for all catchment model polygons.

Calibration of the Stanford models also provides an assessment of surface runoff and interflow. These water balance components can be added to river baseflows calculated in catchment modelling to provide a valid comparison of simulated catchment model river flows with observed hydrographs at gauging stations.

The work carried out in calibrating the Stanford models and recharge estimation is described in the following sections.

## 4.2 Application of the Modified Stanford Watershed Model

### 4.2.1 Basis of the Model

The Stanford Watershed Model is recognised as being one of the most conceptually complete in its representation of the hydrological cycle. A flow chart of the model is shown in Figure 4.1. The model is effectively driven by hydrometeorological inputs, principally precipitation and evapotranspiration. Incoming precipitation first fills the interception storage of the surface vegetation before any moisture reaches the soil surface. Infiltration of the remaining moisture is the key process in determining catchment response to rainfall. It is principally dependent on the amount and distribution of soil moisture storage, soil permeability and precipitation rate and quantity. Two soil horizons defining infiltration are modelled: an upper zone representing the top few centimetres of soil, controlling overland flow and interflow, and which is depleted by evaporation; a lower zone, controlling infiltration to the groundwater reservoir which is depleted by evapotranspiration, interflow and recharge to groundwater storage.

Groundwater storage is depleted by groundwater abstraction and baseflow to the river. Baseflow is defined by a Horton type recession, although variable recession rates (applied to summer and winter) can also be modelled.

The Stanford model is a lumped parameter model, in which the catchment is considered as a single unit upstream of a defined catchment outflow point. The outflow point is frequently taken at a gauging station in order that the model can be calibrated by comparing simulated river flows with observed flow records.

There are three permanent gauging stations on the River Darent and one on the River Cray. The locations are shown in Figure 4.2 together with the surface water catchments above the gauging stations. Gauging station details are indicated in Table 4.1. Stanford models of the Otford, Lullingstone and Hawley subcatchments of the Darent were set up during the pre-feasibility study. However, it was found that the model for the Lullingstone subcatchment could not be calibrated accurately owing to its small area and the large size of groundwater abstractions relative to recharge. Calibration was thus carried out on models of subcatchments upstream of Otford and between Otford and Hawley gauging stations.

Development and calibration of a Stanford model for the Cray catchment above the gauging station at Crayford was carried out as part of catchment modelling. Further work was also carried out using the existing Stanford models for the Darent in extending the period of calibration to the full period of catchment modelling from 1970 to 1990. An uncalibrated Stanford model for the subcatchment between Hawley and the Darent/Cray confluence, set up during the pre-feasibility study, was also extended to include the Ebbsfleet catchment and catchment model areas along the Thames estuary.

q:\wrp\dnj\gem\uk\darent\wells\fig4-1.gem by dnj

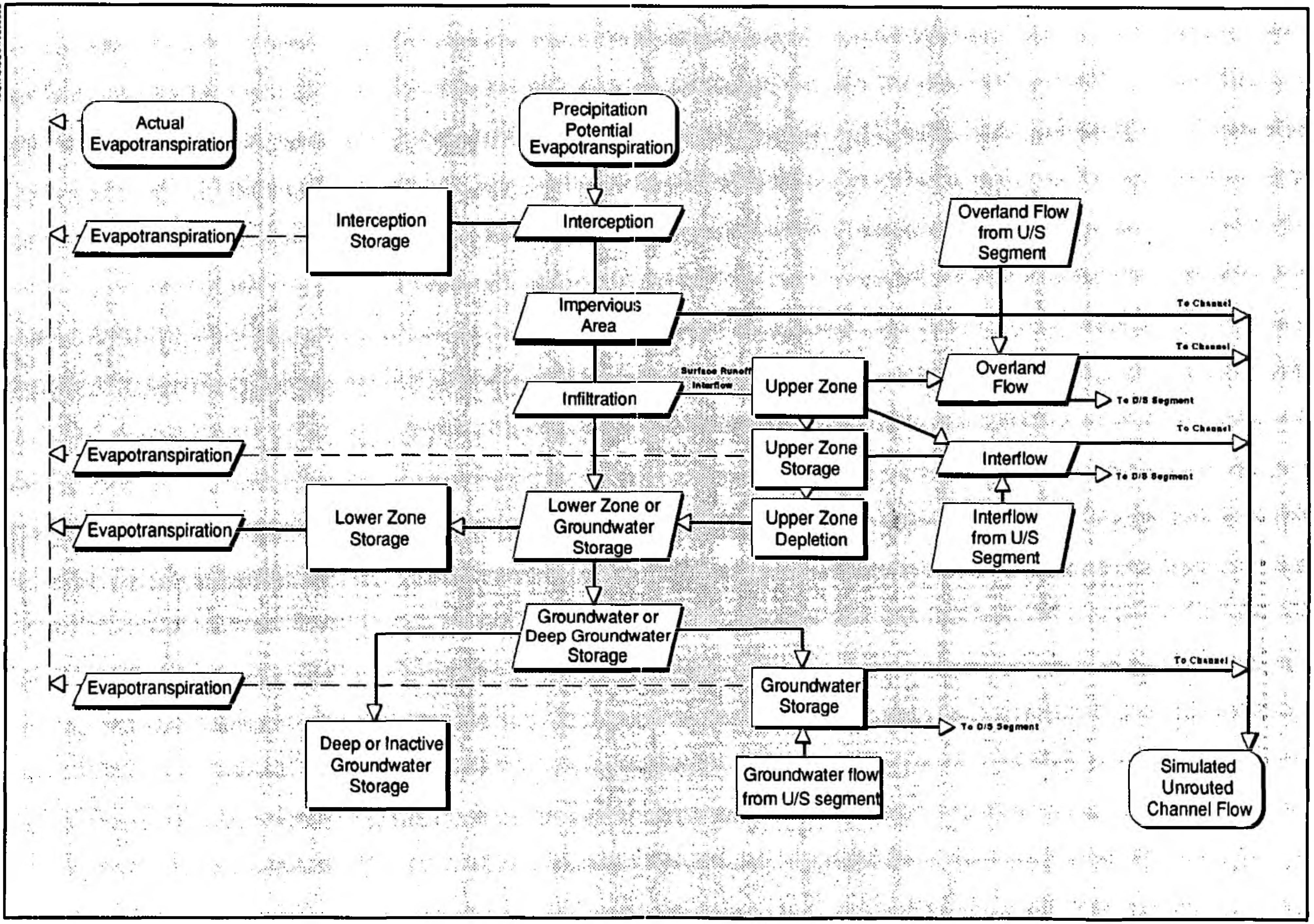



Figure 4.1 Flowchart for the Modified Stanford Watershed Model

Figure 4.2

## Hydrometric Stations and Subcatchments

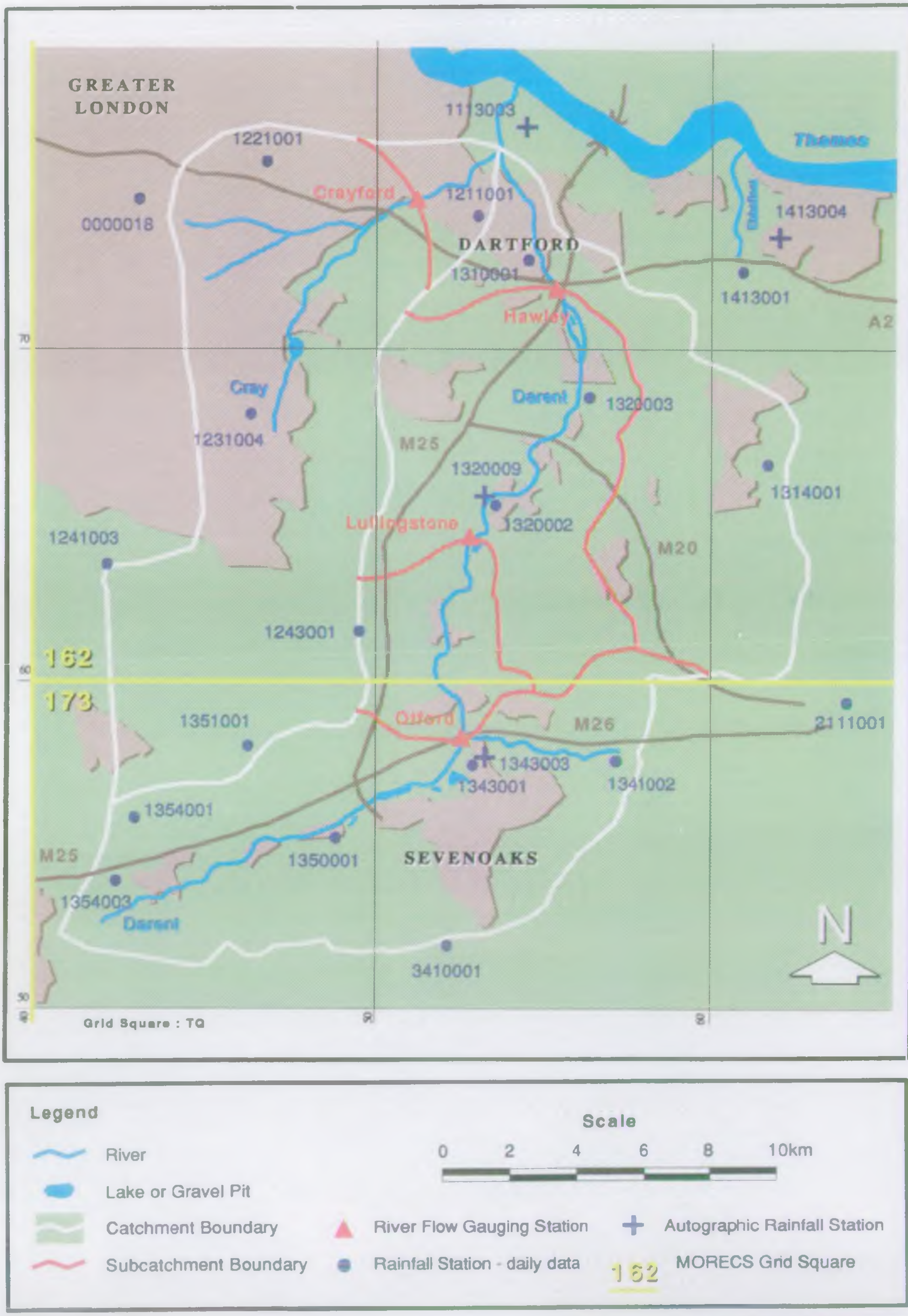


**TABLE 4.1**

**Gauging Station Details**

| Gauging Station | River | Grid Reference | Surface Subcatchment Area ($km^2$)* | Surface Geology | Start of Record |
|---|---|---|---|---|---|
| Otford | Darent | TQ 525 584 | 100.5 | Lower Greensand, Gault Clay and Chalk | 1969 |
| Lullingstone | Darent | TQ 530 643 | 17.9 | Chalk | 1968 |
| Hawley | Darent | TQ 551 718 | 75.0 | Chalk | 1963 |
| Crayford | Cray | TQ 511 746 | 141.6 | Tertiary Deposits and Chalk | 1969 |

Note: * refers to area between gauging station and the next gauging station upstream.

### 4.2.2 Data Preparation

Data preparation for the Stanford models comprises the definition of physically based catchment parameters and the pre-processing of time variant information which includes hydrometeorological data.

The model includes up to 30 physically based parameters describing conditions in the catchment which influence its hydrological response. These parameters are defined from 1:25 000 or 1:50 000 topographical mapping (area and average catchment gradient), land use surveys and observed streamflow hydrographs which are used to define river flow recession characteristics.

Time variant data includes precipitation (rainfall), potential evapotranspiration and groundwater abstraction data.

**Land Use Surveys**

Information on land use was collected from topographical mapping and by driving through the catchments via many of the minor roads covering the area. The survey of the Darent catchment was carried out during the pre-feasibility survey in May 1991. The survey for the Cray catchment was in March 1992.

**Rainfall**

The Stanford model simulates infiltration and surface runoff processes for a 15 minute timestep. Hourly rainfall data are required for accurate simulation of flood response. However, in order to provide estimates of recharge and surface runoff on a monthly basis for the catchment model it is possible to use daily rainfall data and to generate hourly rainfall data stochastically from this using relatively short autographic rainfall records.

Daily rainfall data from a total of 19 stations were used in calculating daily sub-catchment rainfall estimates by the method of Thiessen polygons. Details of the rainfall records are shown in Table 4.2 and locations of the gauges are indicated in Figure 4.2. Autographic rainfall records which were analysed to provide the statistics for converting daily to hourly rainfall are indicated in Table 4.3.

**TABLE 4.2**

**Daily Rainfall Stations**

| Station Name | NRA Gauge Nr | Grid Reference (Square TQ) | Mean Annual Rainfall (mm) | Data Available |
|---|---|---|---|---|
| Bayleys Hill | 3410001 | 519521 | 704 | 1952 - 1990 |
| Christchurch Road | 1211001 | 531740 | 531 | 1957 - 1990 |
| Colgates Farm | 1243001 | 495617 | 669 | 1969 - 1990 |
| Cramptons RDPS | 1343001 | 530570 | 680 | 1942 - 1990 |
| Danson Park | 1221001 | 468754 | 474 | 1935 - 1990 |
| Eltham High School | 0000018 | 433745 | 505 | 1970 - 1990 |
| Eynsford PS | 1320002 | 535655 | 594 | 1931 - 1990 |
| Hartley | 1314001 | 617664 | 617 | 1944 - 1990 |
| Holwood | 1241003 | 422636 | 645 | 1972 - 1990 |
| Horton Kirby | 1320003 | 561685 | 557 | 1934 - 1990 |
| Kemsing PS | 1341002 | 569576 | 692 | 1930 - 1990 |
| Knockholt WW | 1351001 | 466583 | 729 | 1930 - 1990 |
| Orpington | 1231004 | 462768 | - | 1987 - 1990 |
| Southfleet WW | 1413001 | 610724 | 512 | 1930 - 1990 |
| Sundridge PS | 1350001 | 489556 | 684 | 1930 - 1990 |
| Trottiscliffe | 2111001 | 640594 | 652 | 1930 - 1990 |
| Westwood PS | 1354003 | 425541 | 711 | 1960 - 1990 |
| Wilmington WW | 1310001 | 543728 | 509 | 1930 - 1990 |
| Westerham PS | 1354001 | 429558 | 734 | 1930 - 1990 |

## TABLE 4.3

### Autographic Rainfall Data

| Station Name | NRA Gauge Nr | Grid Reference (Square TQ) | Data Available |
|---|---|---|---|
| Northfleet | 1413004 | 619735 | 14.08.90 - 11.04.91 |
| Sevenoaks | 1343003 | 532571 | 12.09.90 - 11.04.91 |
| Eynsford | 1320009 | 535655 | 10.09.90 - 11.04.91 |
| Dartford | 1113003 | 543767 | 22.08.90 - 06.04.91 |

**Evaporation**

Potential evapotranspiration data for two MORECS grid squares (Nrs 162 and 173) were used. The locations of the grid squares are indicated on Figure 4.2. MORECS data are available for the whole period of model simulation from 1970 to 1990.

**Groundwater Abstraction**

Data were processed as indicated in Section 3.5. Average daily abstraction derived from monthly data were used in Stanford modelling.

### 4.2.3 Calibration

Calibration of the Stanford model is normally done by varying four different parameters:

- the nominal upper zone soil moisture storage which controls the volume of rainfall which is evaporated from the soil surface and the excess volume which percolates to the lower, unsaturated zone;

- the nominal lower zone soil moisture storage which controls evapotranspiration and the volume of water passing to the groundwater reservoir;

- the rate of infiltration of rainfall to the upper soil zone;

- a recession parameter governing the shape of the streamflow hydrograph.

The soil moisture storages control the annual water balance while the infiltration rate affects the timing of the streamflow hydrograph. In general terms the upper zone storage is high for a low permeability soil unit and the infiltration rate is low. This gives rise to simulation of a large relative volume of surface runoff and interflow. For a relatively permeable surface, for example where only thin soil cover exists over Chalk, the infiltration rate is higher with very little upper zone storage. This results in a large volume of baseflow.

Details of calibration of catchment and subcatchment Stanford models are given below. Calibration plots are included for the period October 1985 to March 1990 as Figures 4.3 to 4.5. This covers particularly wet years in the mid-1980s and dry years from late 1988 onwards. Water balance components are indicated in Table 4.4.

**Darent Subcatchment Upstream of Otford**

The geology of the subcatchment is very varied with Lower Greensand, Gault Clay and Chalk present. Steep slopes within the subcatchment tend to produce many short duration high flow events. The hydrology is also complicated by the presence of a series of moderately large lakes formed in old excavations in the Sevenoaks area.

During the initial stages of calibration simulated surface runoff in the summer was much higher than the observed flow hydrographs. It was considered that lake storage could attenuate flows at Otford and also prevent some runoff from impervious areas on the Gault Clay reaching the river directly. A very significant improvement in hydrograph peaks was achieved by reducing the initial estimate of impervious areas. Winter flows have been simulated reasonably well (see Figure 4.3) as have recession characteristics. Some discrepancies in winter peaks may be due to differences between synthetic hourly rainfall and actual hourly rainfall data. Long term mean river flows are within 3% of observed river flows (see Table 4.4).

**Darent Subcatchment between Otford and Hawley**

The underlying geology is primarily Chalk. This should make calibration of a Stanford model easier than for the Otford subcatchment as there should be less variability in soil characteristics. Some difficulties arose in calibration as groundwater abstraction in the subcatchment is of the same order of magnitude as recharge.

Simulated flow hydrographs for the Otford subcatchment and the subcatchment between Otford and Hawley have been combined and compared with observed flows at Hawley in Figure 4.4. There is reasonable simulation throughout. Some under-simulation occurs for winter and spring flows and over-simulation of the dry river condition in the summer of 1989.

Table 4.4 indicates that the long term mean simulated flow at Hawley is only 3% less than observed. The values of soil moisture storage and infiltration parameters are higher than for the Otford subcatchment model. This is reflected in the lower surface runoff for the subcatchment between Otford and Hawley.

Figure 4.3

## Stanford Model Simulation : River Darent at Otford

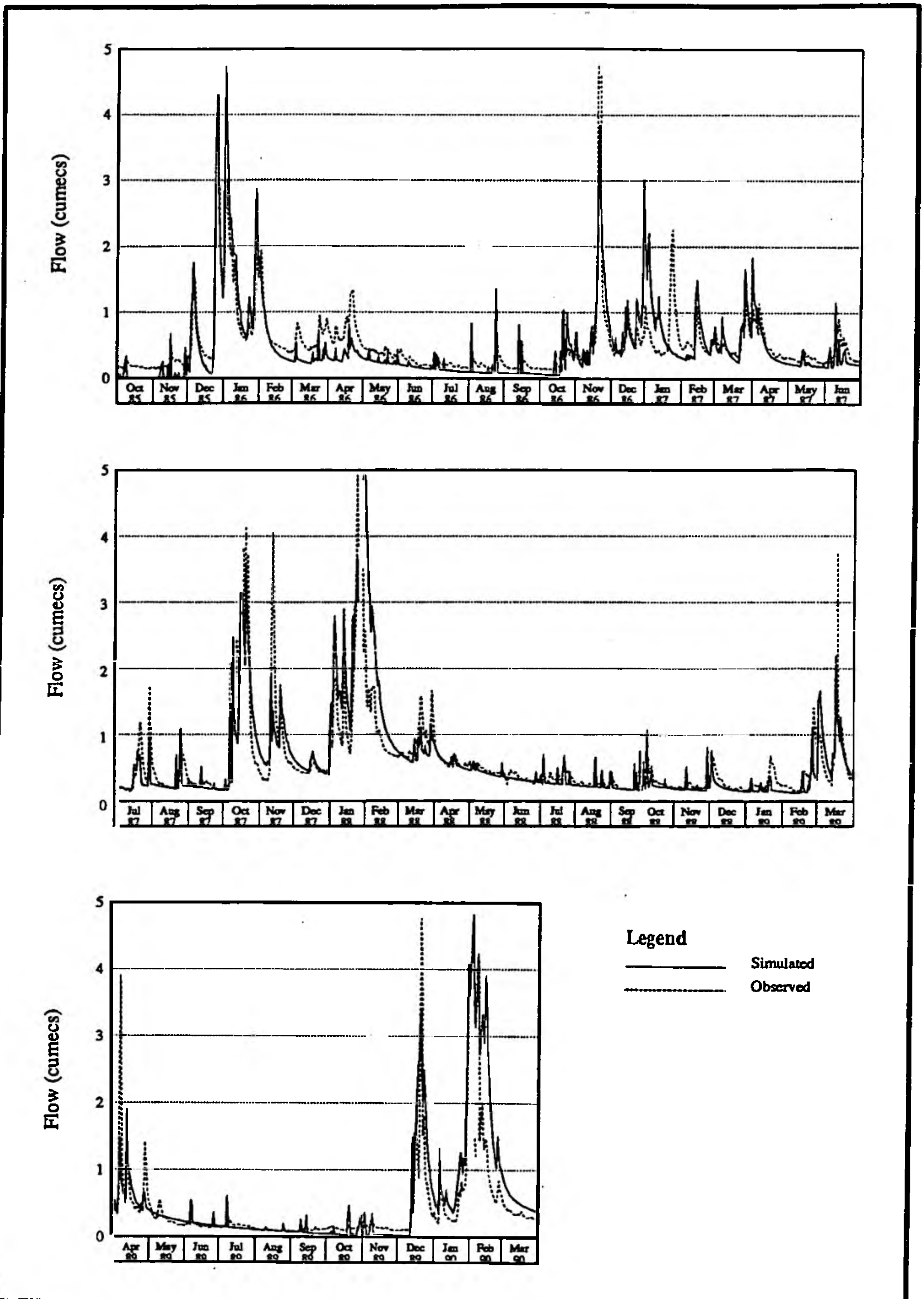
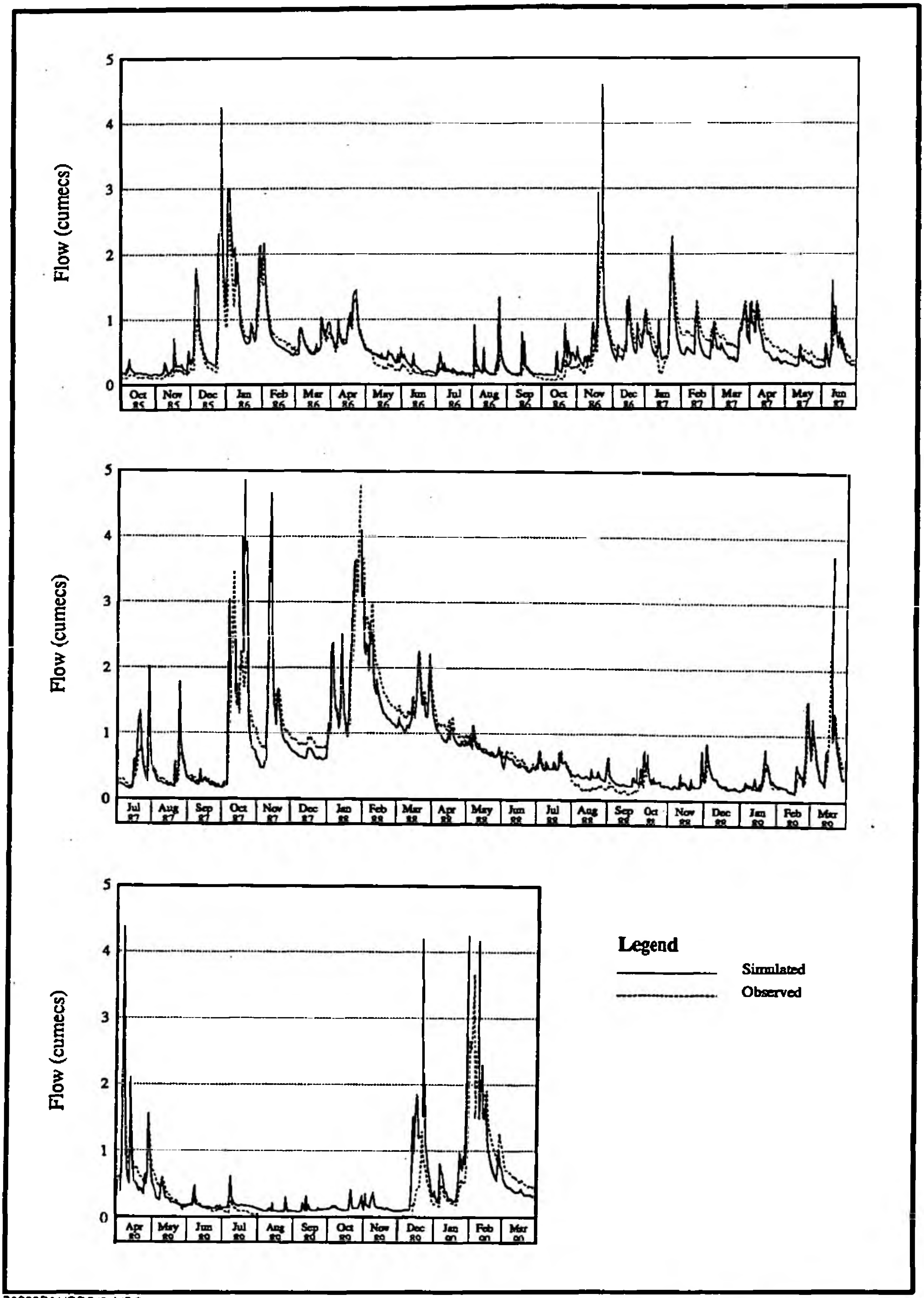


Figure 4.4

## Stanford Model Simulation : River Darent at Hawley




70223B01/GDC/2/A/DCI

## TABLE 4.4

### Stanford Model Water Balances

| Subcatchment | River flow ($m^3/s$) | | Subcatchment annual water balance components (mm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Observed | Simulated | River flow components | | | | Rainfall | Actual Evaporation | Groundwater Abstraction | Recharge |
| | | | Surface Runoff | Interflow | Baseflow | Total | | | | |
| Darent to Otford | 0.579 | 0.564 | 17.7 | 6.9 | 139.1 | 163.7 | 740.6 | 445.5 | 131.5 | 270.6 |
| Darent from Otford to Hawley | 0.625 | 0.605(1) | 11.6 | 2.8 | 17.4 | 31.8 | 659.0 | 440.5 | 186.7 | 204.1 |
| Darent from Hawley to Darent/Cray Confluence | -(2) | - | 26.3 | 1.3 | 0.3 | 27.9 | 630.4 | 405.6 | 196.9 | 197.2 |
| Cray to Crayford | 0.521 | 0.531 | 10.4 | 25.7 | 60.7 | 96.8 | 674.9 | 432.4 | 145.6 | 206.3 |

Notes: (1) Simulated Hawley flow = Simulated flow at Otford + the simulated flow for the subcatchment between Otford and Hawley.

(2) Ungauged subcatchment .

For the water balance :

Recharge = Rainfall - Actual Evaporation - Surface Runoff - Interflow.

Recharge = Baseflow + Groundwater Abstraction.

Balances give mean values for 1985 to 1989

**Cray Catchment to Crayford**

The geology of the catchment comprises Chalk with overlying Tertiary deposits in many areas within the northern part of the catchment. The Tertiary Deposits include clays, silts and fine sands of the Woolwich and Reading Beds and Thanet Beds, with some London Clay outcropping in the north-west.

The presence of Tertiary deposits tends to produce localised high runoff events of short duration giving rise to peaky riverflow hydrographs. High infiltration and low runoff over the Chalk produces much flatter flow recession characteristics. The combination of these two conditions in a lumped parameter watershed model makes accurate simulation of observed river flow hydrographs difficult. The model is further complicated by the large urban area within the catchment, much of which falls within the south-east corner of Greater London. Large volumes of urban storm water runoff are not readily simulated by the Stanford model.

The results of calibration are shown in Figure 4.5. Despite the problems with modelling the Cray there is reasonable simulation of some recession periods as in 1987 and 1989. Undersimulation occurs in other years. Riverflows in high rainfall periods such as January and February 1986 could not be simulated accurately. The high rainfall in these periods would be expected to result in a much higher volume of runoff than is indicated at the gauging station. It was suspected that high levels of runoff might be routed out of the catchment through storm overflows. However, discussions with NRA engineering staff with experience of drainage in the catchment indicated that this was unlikely.

Following periods of high winter rainfall such as in 1986 observed flows in the following summer are generally significantly higher than simulated. This points to some large winter storage mechanism (groundwater or surface water) within the catchment. However, it was found that these summers could not be more accurately simulated without a considerable decrease in accuracy of simulation for other periods.

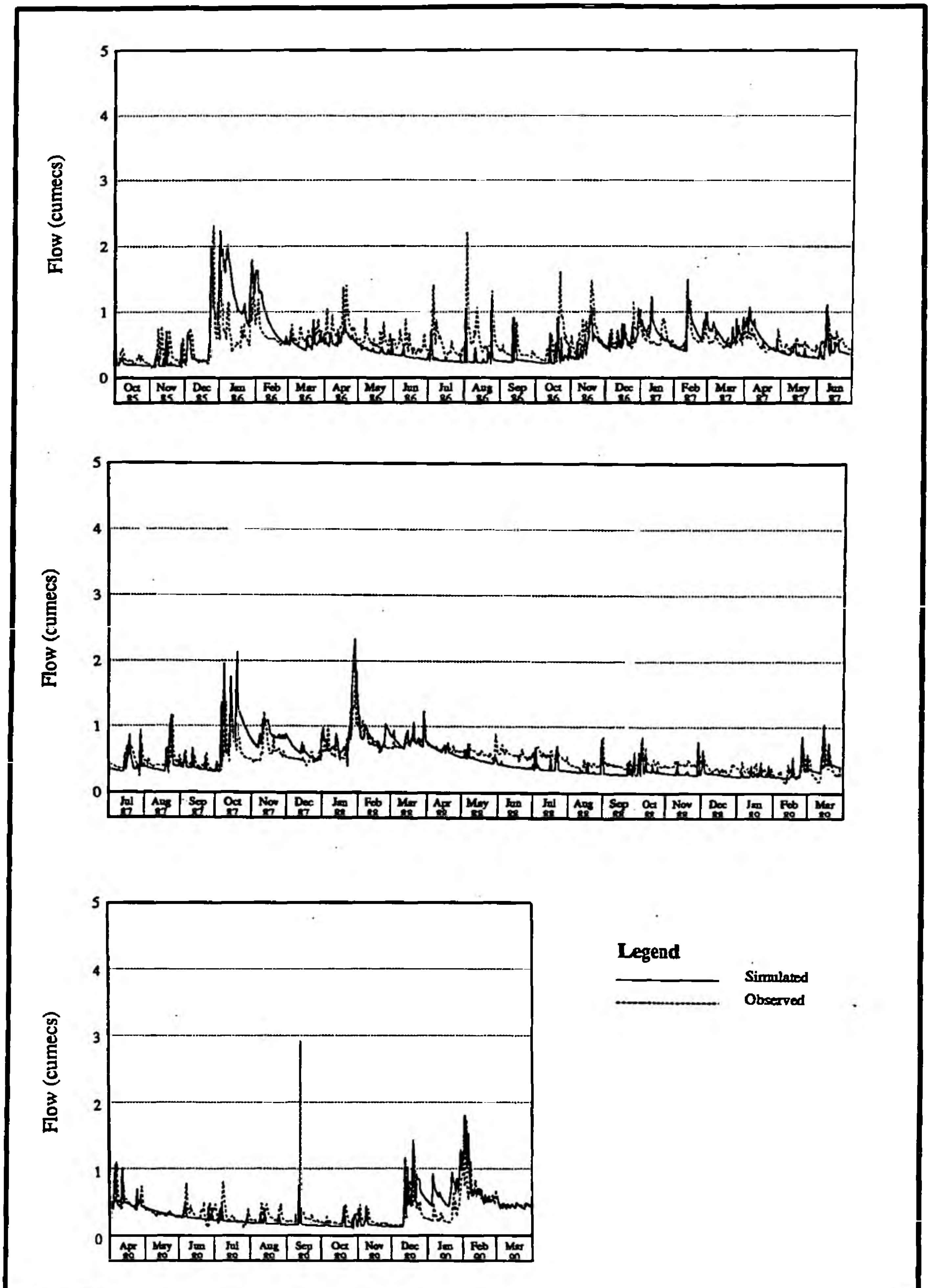
The overall accuracy of simulation of riverflows is reasonably good as shown in Table 4.4. There is a high proportion of interflow indicated for the catchment. This may be due to the presence of extensive urban areas and/or Tertiary deposits. These deposits provide a large volume of storage in silts and fine sands and also dampen down variations in recharge to the Chalk due to the presence of clay lenses which control vertical leakage. For the Cray catchment the combination of recharge and interflow is better considered as the potential recharge to the aquifer system in catchment modelling. This allows a more accurate representation of the flow processes between the Tertiary and Chalk aquifers as discussed in Chapter 5.

**Darent Subcatchment between Hawley and the Cray Confluence**

The Darent is not gauged downstream of Hawley and therefore it is not possible to calibrate a Stanford model for this subcatchment. The subcatchment geology comprises mainly Chalk. It was modelled therefore using the same values for soil parameters as determined by calibration of the model to the Hawley gauging station. The high proportion of surface runoff indicated in Table 4.4 is a result of urbanisation in the Dartford area.

Figure 4.5

Stanford Model Simulation : River Cray at Crayford



## 4.3 Transfer of Recharge Results to the Catchment Model

The Stanford Watershed model is used to calculate monthly recharge estimates by summation of daily recharge on a subcatchment basis. As a lumped parameter model it does not allow for variation in recharge within subcatchments which arise from differences in geology, urbanisation and rainfall. These factors need to be taken into account in transferring recharge to the catchment model.

### Geology

Lower Greensand, Gault Clay and Chalk formations are present within the Otford subcatchment. Recharge through soils associated with the Lower Greensand and Chalk may be significantly different as a result of differing soil properties. Recharge is assumed to be zero over the highly impermeable Gault Clay.

Recharge to the Lower Greensand and Chalk were estimated by comparing recharge for the Otford and Hawley subcatchments using the Stanford models with an identical rainfall set. The rainfall set was derived using Thiessen polygons covering the entire Darent catchment area. Assuming that recharge to the Chalk (in mm depth) is then identical for both subcatchments, recharge to the Lower Greensand can be estimated from a simple balance, knowing the relative areas of Chalk, Gault Clay and Lower Greensand in the Otford subcatchment and the total recharge.

The ratios of depth of recharge over the Lower Greensand and the Chalk relative to mean catchment recharge (also expressed as a depth) can also be established. These ratios were then used in distributing recharge between catchment model polygons in the Otford subcatchment in order to take account of variations in outcrop geology.

### Urban Areas

A high proportion of the northern part of the catchment model area is covered by roads, housing and industrial development. These areas would be expected to have different recharge characteristics to those of the rural Chalk landscape. Recharge in urban areas within the Cray catchment was assessed in a similar way to the recharge for the Lower Greensand in the Otford subcatchment, by assuming that Chalk recharge in the Cray and the Hawley subcatchment were identical when generated from an identical rainfall set.

No separate assessment is possible for areas with outcropping Tertiary deposits in the Cray catchment. However, as the main outcrop coincides with areas of urbanisation in the south east corner of Greater London then dividing the catchment into only two areas of differing recharge characteristics should provide a reasonable simulation of actual recharge conditions. Catchment interflow was added to urban recharge to produce a potential recharge for urban areas as discussed in Section 4.2.3. Ratios of depth of recharge over rural Chalk and urban areas relative to mean catchment recharge were then used in distributing recharge between catchment model polygons.

Urban recharge was also used in calculating recharge in areas within and around the Ebbsfleet catchment, for which it is not possible to calibrate a separate Stanford model.

### Rainfall

The variation in rainfall has a significant effect on recharge across the model area. The variation was taken into account by evaluating the recharge at each rainfall station using the actual station daily rainfall record in place of the catchment or subcatchment rainfall derived for use in Stanford model calibration. A period of concurrent record for all stations (1984 to 1990) was used in the analysis. All other parameters were retained as for the calibrated model.

By plotting each resultant monthly recharge estimate for a particular rainfall station against the concurrent monthly subcatchment recharge estimate, and then fitting a straight line by linear regression to the scatter of monthly data points, a station rainfall variation factor was derived. An example of this procedure is illustrated in Figure 4.6 for the rainfall station at Colgates Farm.

Rainfall variation factors were then calculated for each polygon of the catchment model network taking the mean of factors for rainfall stations in the vicinity of the polygon, with each factor weighted according to distance of the station from the polygon.

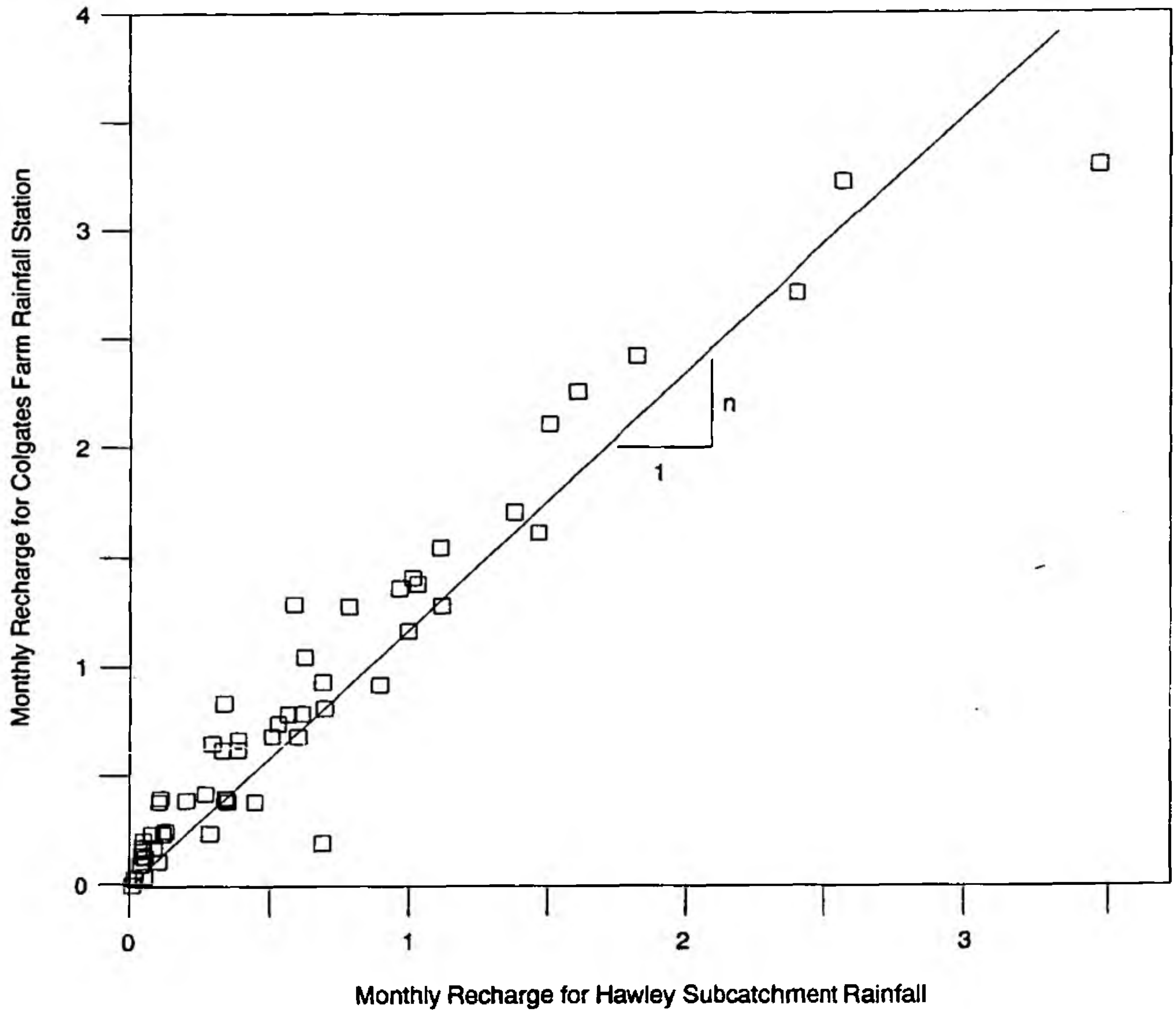
### Recharge on Model Polygons

Having derived factors to take into account geology, urbanisation and rainfall, a monthly recharge sequence was then calculated for each polygon. This was produced by multiplying the relevant Stanford model monthly recharge by the factors calculated for the polygon. For example, in the Otford subcatchment the recharge is multiplied by the adjustment factor for the geology (either Chalk or Lower Greensand) and the adjustment factor for rainfall. Over the Gault Clay, recharge is automatically taken as zero.

Monthly recharge sequences were produced for the period January 1970 to September 1990. Mean annual recharge for the period is shown in Figure 4.7. High recharge is indicated over the Lower Greensand (>300 mm) owing to a combination of high rainfall and sandy soils which, presumably, give rise to high infiltration. The more moderate recharge over the Chalk (generally 180 to 250 mm) increases in areas of urbanisation or Tertiary deposits cover where interflow is included as component of recharge.

Figure 4.6

# Derivation of Rainfall Adjustment Factor




Recharge units : mm/d

Recharge Adjustment Factor = Slope (n)

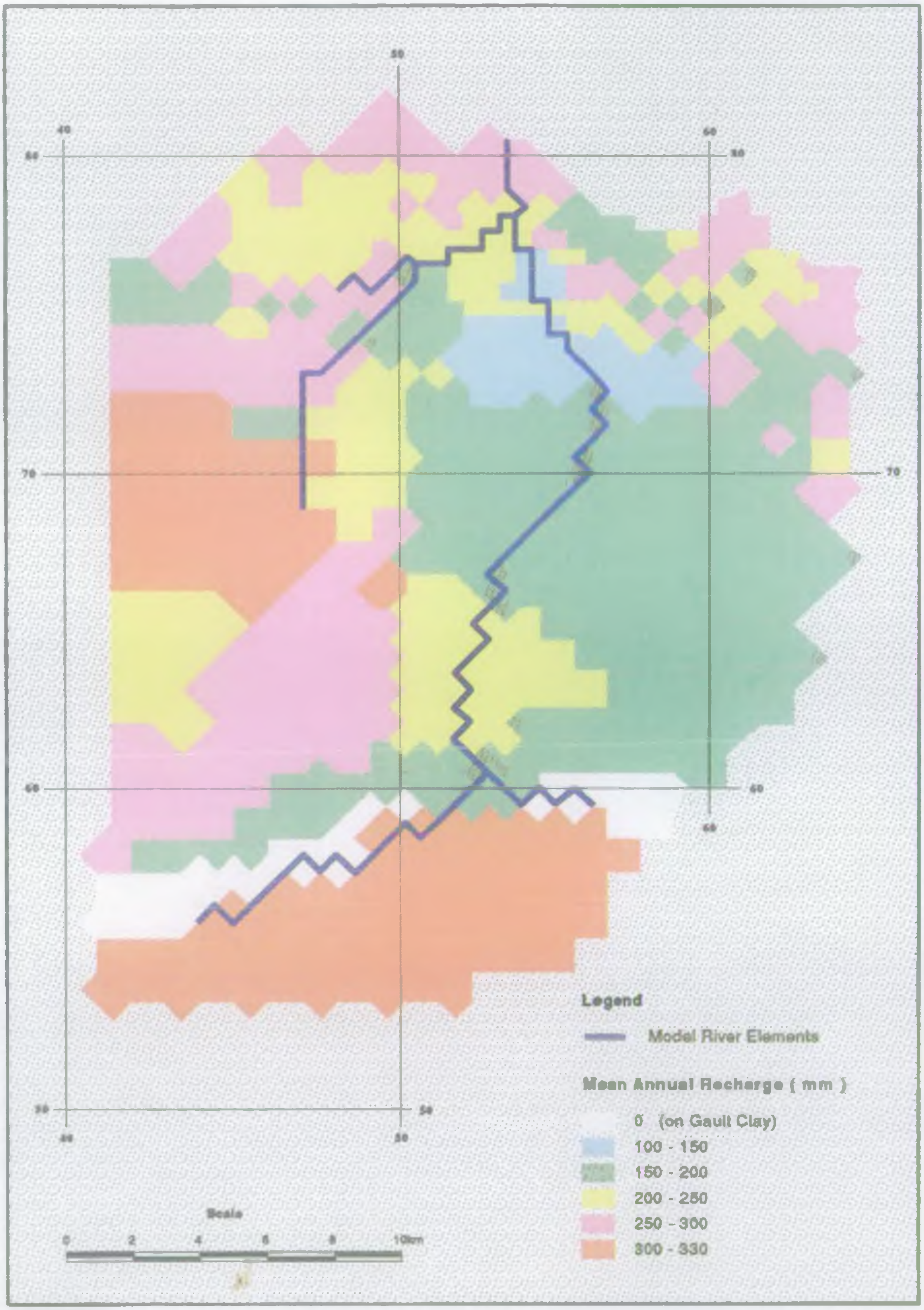
= 1.18

q:\wrp\dn\gem\uk\darent\fig4-6.gem

70223B01/GDC/2/A/DCI

Figure 4.7

## Mean Annual Recharge



# CHAPTER 5

# CALIBRATION OF THE CATCHMENT MODEL

## 5.1 Concepts and Procedures

Not all the parameters associated with the groundwater and surface water balance components are well defined for the whole model region. Uncertainties exist through a lack of data (particularly aquifer properties and piezometry), imprecision of data and through the extrapolation of data defined locally to the regional scale of the model.

For this reason it is necessary for the catchment model to undergo a process of calibration. This involves the comparison of the model's response with the equivalent known response of the real aquifer system. During calibration adjustments are made to the model parameters in order to create as close an agreement as possible between the model and the real system.

Catchment model calibration generally consists of two stages. The first is steady state calibration in which mean groundwater conditions are simulated for a period in which there is no change in long term inflows or outflows from the model area. Steady state calibration is applicable either for periods in which natural conditions prevailed or in which abstraction was established and remained constant over a number of years, hence producing no long term change in groundwater storage. Mean annual recharge is used as the main inflow to the groundwater system. Resulting simulated piezometry is compared with average groundwater levels measured for the period in assessing the accuracy of steady state calibration.

The second stage is a transient calibration where the response of the model to a historical record of abstraction and recharge is tested against the observed response of the aquifer and surface water system. Simulation therefore involves changes in groundwater storage in each model time step. The process of steady state calibration and subsequent transient calibration can follow an iterative path, with recalibration in the steady state if transient calibration results are not satisfactory.

The main objectives of calibration at this stage were as follows:

- to assess the transmissivity distribution of the Chalk aquifer and therefore to simulate Chalk piezometry with and without abstraction;

- to simulate accurately observed river flow hydrographs at each of the gauging stations, with particular emphasis on the River Darent during periods of low flows;

- to simulate river flow accretion profiles between Westerham and Hawley on the River Darent;

- to simulate the observed variation in groundwater levels between summer and winter;

- to highlight any areas where additional data are required to improve calibration of the model.

## 5.2 Steady State Calibration

### 5.2.1 Introduction

Two steady state conditions were considered: pre-development conditions where there is no abstraction from the aquifers or rivers and steady state conditions with abstraction established at a high level during the 1960s.

### 5.2.2 For Pre-development Conditions

Steady state conditions with no abstraction were simulated in order to define the full Chalk transmissivity for the model. The actual piezometry for such conditions is difficult to define as it would only have occurred prior to major groundwater development in the catchment during this century. Piezometry was inferred from data published by the Water Resources Board (1972) during a study into artificial recharge of the London Basin and from IGS well inventories (1968 and 1975). It is shown in Figure 5.1.

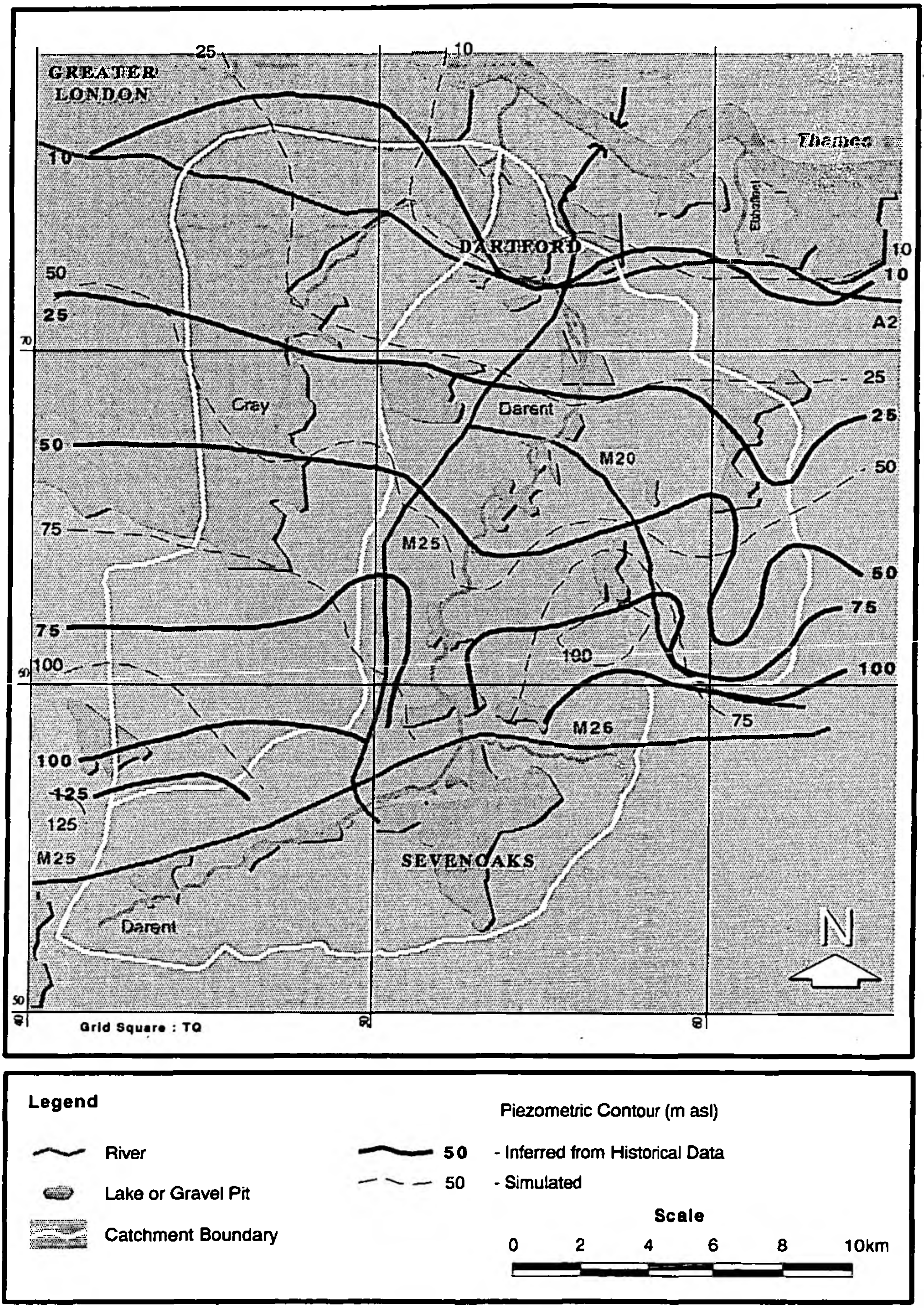
From this piezometry, and from work on the Blue Circle Cement model of the Ebbsfleet area, initial estimates of transmissivity were derived by the following methods:

- There is a steeper piezometric gradient in the southern area of the Chalk within the Middle and Lower Chalk outcrop than in the north of the catchment. To simulate this difference in piezometry a transmissivity of 250 $m^2/d$ was initially adopted in the southern area and 700 $m^2/d$ for the northern area.

- In the river valleys, piezometric gradients are much lower than in the interfluves. Pumping tests at Eynsford and Lullingstone indicate transmissivities of the order of 10 000 $m^2/d$. Published data indicate that primary and secondary fissuring is generally greater close to a river (Price, 1987), with possible increases in permeabilities from 1 to 200 m/d. Consequently a much higher transmissivity was adopted for the model polygons to either side of the river (2 000 $m^2/d$) with a transmissivity of 5 000 $m^2/d$ adopted for the river elements.

- For the eastern area of the model piezometry indicates that a zone of high transmissivity follows the line of a dry valley which originates close to the top of the Chalk escarpment south of New Ash Green. This zone of high transmissivity extends into the Ebbsfleet catchment. The BGS hydrogeological map of this area suggests that an old river course

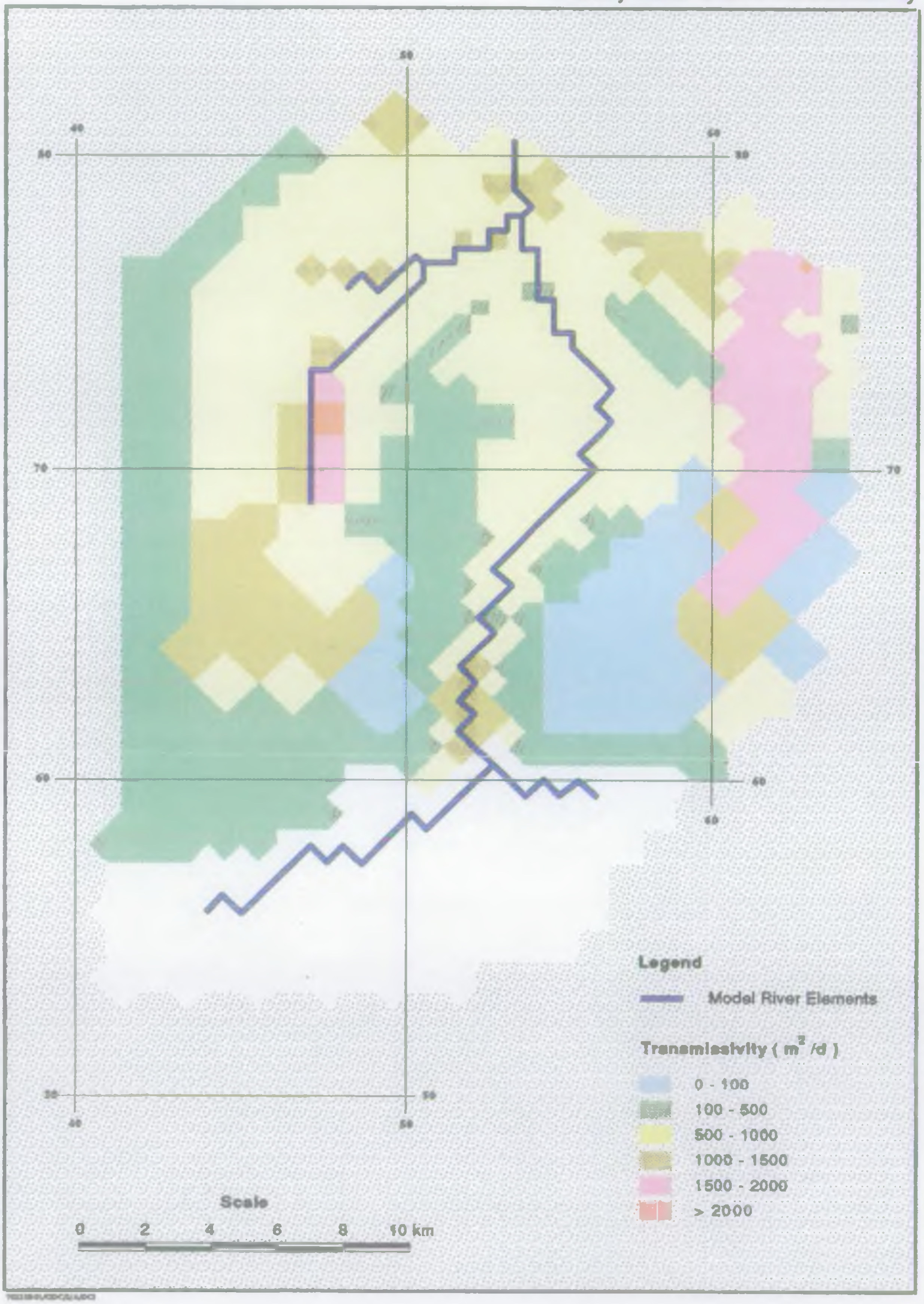
## Pre-Development Steady State Chalk Piezometry




70223B01/GDC/2/A/DCI

Figure 5.2

## Steady State Chalk Transmissivity



existed in the dry valley as indicated by the presence of river alluvium. A transmissivity of 2 000 $m^2$/d was adopted for this zone, extending into the Ebbsfleet catchment. As a result, the Ebbsfleet groundwater catchment extends into the Darent surface water catchment, intercepting recharge over an area of approximately 20 $km^2$. This has no significant effect on the calculation of recharge, as the Stanford model for this area is uncalibrated and recharge is distributed across the area for catchment modelling.

- Initial transmissivity in the Northfleet area was derived from steady state calibration of the Blue Circle Cement model.

The recharge used was based on the mean average values indicated in Figure 4.7. Recharge may have changed since the period prior to major development of water resources as a result of land use changes (decreased woodland cover, different cropping patterns and increased urbanisation) and possible climatic changes. It is not possible to evaluate the effects of these changes, although the overall change to recharge is unlikely to be very significant for model calibration.

Over ten steady state simulations were performed with variation in the transmissivity of the Chalk until reasonable agreement between simulated and the 'inferred' pre-development piezometry was obtained. The resultant simulated piezometry is compared with the 'inferred' pre-development piezometry in Figure 5.1. Reasonable simulation was achieved across the Darent valley and in the Chalk uplands to either side. The simulation was less accurate in other areas particularly the lower Cray catchment. However, as the overall pattern of piezometry was reasonably simulated and the inferred data are unlikely to be accurate anyway, further changes to calibration parameters were not made at this stage. The final parameters adopted for this steady state calibration are detailed in Table 5.1, while the resultant steady state Chalk transmissivity is shown in Figure 5.2.

In order to simulate the piezometry in the east of the model a very low transmissive zone (20 to 50 $m^2$/d) was added in the upland areas between the Darent and the dry valley in the vicinity of New Ash Green. Further low transmissive zones were added to interfluve areas between the Ebbsfleet and Darent catchments (100 to 200 $m^2$/d) and the Cray and Darent catchments (100 to 300 $m^2$/d).

Comparison of values shown in Table 5.1 with the initial values of parameters in Table 3.1 indicates some changes to vertical permeabilities during steady state calibration. River bed hydraulic resistance was set at 10 days throughout the model as a result of calibration.

**TABLE 5.1**

**Steady State Calibration Parameters**

| Layer | Horizontal permeability (m/d) | Vertical permeability (m/d) |
|---|---|---|
| Hythe Beds | 10.0 | 2.0 |
| Sandgate Beds | not applicable | 0.005 |
| Folkestone Beds | 10.0 | 2.0 |
| Gault Clay | not applicable | 0.0001 |
| Chalk | 2.0 - 50.0 | 0.5 |
| Tertiary deposits | 20.0 | 0.001 |
| River Alluvium | 20.0 | 0.5 |

### 5.2.3 Steady State with Abstraction

A second steady state calibration was done to simulate the reduction in groundwater levels and river flows as a result of abstraction, and to define the initial piezometry for subsequent transient state runs. Simulated groundwater levels were compared with contouring presented by the Water Resources Board (1972) for the mid 1960s and some observation well data available for this period.

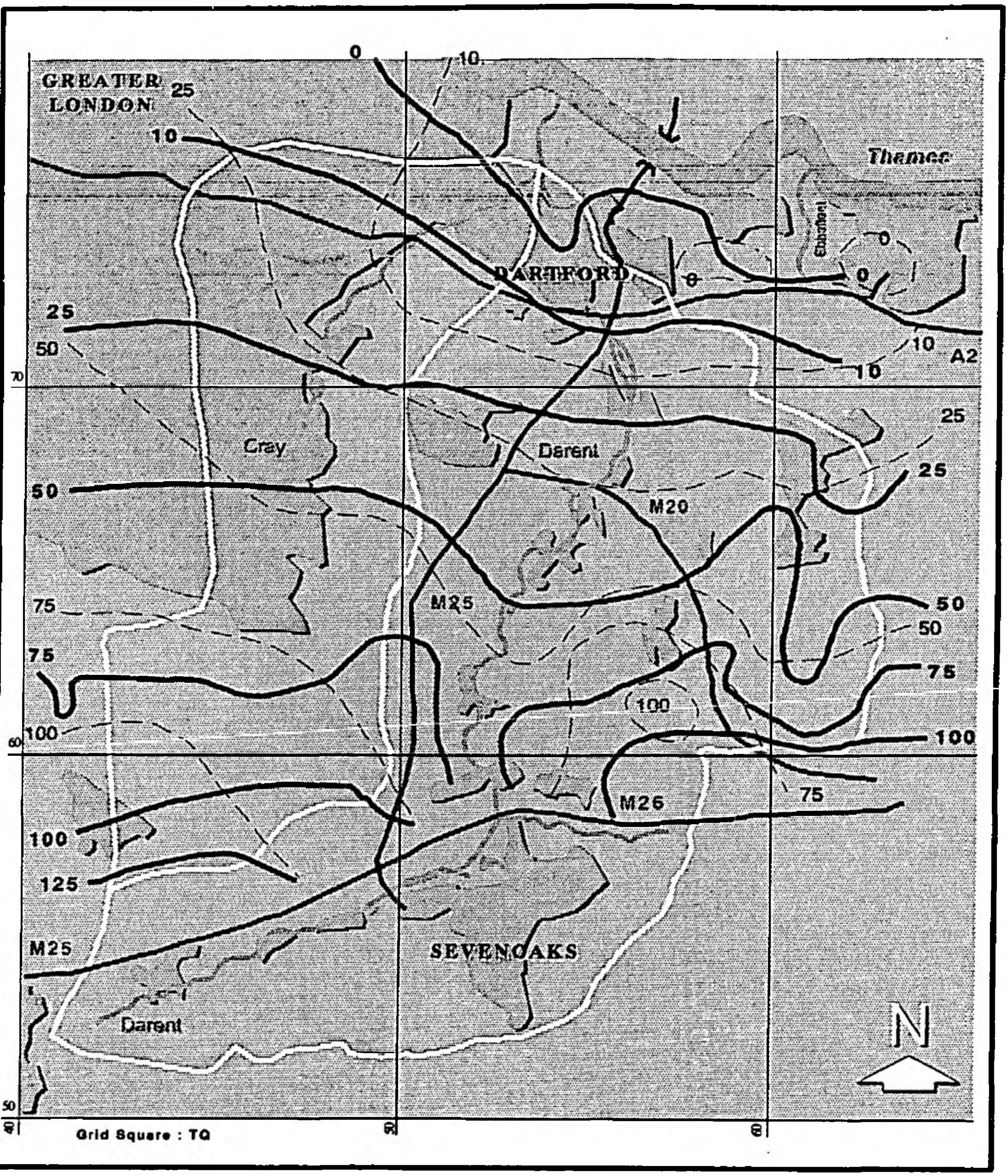
The same average recharge was adopted as in the historical steady state calibration. The mean abstraction was estimated from abstraction for the 1970s as detailed abstraction returns were generally not available for the 1960s. At the Blue Circle Cement quarries abstraction volumes are not recorded as a licence is not required for dewatering. Based on initial estimates derived for the Blue Circle Cement model, the following abstractions volumes were assumed for the three main excavations:

| | |
|---|---|
| Blue Lake | 25 Ml/d |
| Western Quarry | 15 Ml/d |
| Eastern Quarry | 6.5 Ml/d |

Simulated groundwater levels are compared with observed in Figure 5.3. As with the pre-development simulation there is reasonable overall agreement between observed and simulated watertable

Figure 5.3

## Steady State Piezometry with Abstraction




**Legend**

River

Lake or Gravel Pit

Catchment Boundary

Piezometric Contour (m asl)

**50** - Inferred from Historical Data

50 - Simulated

**Scale**

0 2 4 6 8 10km

70223B01/GDC/2/A/DCI

conditions. The model does not simulate the extensive area along the Thames with groundwater levels below mean sea level, although areas with groundwater levels below mean sea level are simulated around the Blue Circle Cement quarries. In the Darent Valley to the south of the 10 m AOD contour there is very little difference in piezometry between the inferred pre-development conditions (Figure 5.1) and the observed conditions with abstraction. Simulations, however, indicate a decline of several metres in the vicinity of the 25 m AOD contour as a result of abstraction at South Darenth, Horton Kirby and Eynsford. Some differences between simulated and observed conditions are therefore very likely to result from inadequacies in the water level data on which pre-development piezometry is based.

Over most of the Darent catchment simulated piezometry matches actual piezometry to within 5 m which is within the range generally achievable with models of this type. However, in parts of the urbanised area of the Cray catchment, the model simulates an excessive decline in groundwater levels due to abstraction. The data quality and availability are very poor in this region. Since the objective of this preliminary calibration was mainly concerned with accurate simulation of the Darent catchment, no further work was carried out to improve the steady state simulations in the Cray catchment. The particular problems with simulating the Cray catchment are discussed further in section 5.3.3.

Table 5.2 presents the water balance components for each steady state run on an aquifer basis. In the Lower Greensand aquifers, abstraction has simply reduced the net baseflow discharge to the river. There is no significant change in outflow from the aquifers indicating that abstraction has not caused an increase in the groundwater catchment area of this unit.

The baseflow from the Chalk is reduced to a point where total leakage from the river system in areas of high abstraction exceeds the baseflow contributions in the few remaining gaining reaches. Abstraction has also caused the total drying up of the Chalk springs and reversed the net leakage between the Tertiary deposits and the Chalk. A large leakage inflow occurs to the Chalk in response to the decline in Chalk groundwater levels. There is also a reduction in groundwater leaving the Chalk aquifer. Most of this outflow is simulated as discharging across the northern boundary at the Thames.

## TABLE 5.2

**Steady State Simulated Water Balance Components for Aquifers**

| Aquifer | Water balance component (Ml/d) | With abstraction | Without abstraction |
|---|---|---|---|
| Hythe Beds | Recharge | 40.9 | 40.9 |
| | Abstraction | -14.1 | 0.0 |
| | Inflow/Outflow | -6.2 | -6.4 |
| | Discharge to River | -0.5 | -0.8 |
| | Vertical Leakage | -20.7 | -33.6 |
| | Spring Flow | 0.0 | 0.0 |
| | Lake Leakage | 0.0 | 0.0 |
| Folkestone Beds | Recharge | 15.1 | 15.1 |
| | Abstraction | -16.8 | 0.0 |
| | Inflow/Outflow | -0.1 | -0.2 |
| | Discharge to River | -8.7 | -32.4 |
| | Vertical Leakage | 20.7 | 33.6 |
| | Spring Flow | -8.2 | -15.1 |
| | Lake Leakage | -2.0 | -1.6 |
| Chalk | Recharge | 128.0 | 128.0 |
| | Abstraction | -201.9 | 0.0 |
| | Inflow/Outflow | -7.0 | -16.5 |
| | Discharge to River | 3.7 | -80.8 |
| | Vertical Leakage | 77.4 | 24.1 |
| | Spring Flow | 0.0 | -54.5 |
| | Lake leakage | -0.3 | -0.2 |
| Tertiary Deposits | Recharge | 138.8 | 138.8 |
| | Abstraction | -0.6 | 0.0 |
| | Inflow/Outflow | -3.6 | -11.8 |
| | Discharge to River | -20.4 | -13.9 |
| | Vertical Leakage | -77.4 | -24.0 |
| | Spring Flow | -36.5 | -89.0 |
| | Lake Leakage | 0.0 | 0.0 |
| Otford | River Flows | 0.312 | 0.749 |
| Lullingstone | ($m^3/s$) | 0.499 | 1.177 |
| Hawley | | 0.416 | 1.474 |
| Cray | | 0.528 | 1.049 |

Notes: A positive value indicates a gain to the aquifer and a negative value indicates a loss from the aquifer.

Minor imbalances not shown.

### 5.3 Transient State Calibration

#### 5.3.1 Introduction

Transient state calibration was carried out for the period January 1970 to September 1990. This is the period of maximum data availability and includes major droughts in the years 1973 to 1976 and 1989 to 1990. There were three major considerations in transient state calibration:

(i) Simulation of river flows at Otford. The River Darent upstream of the Otford gauging station receives contributions by several different hydrological mechanisms. It is fed throughout the year by springs rising from the Lower Chalk in the north of the catchment, by springs and baseflow from the Lower Greensand aquifer system and periodically by surface runoff and interflow throughout the subcatchment. Downstream of Otford the Darent loses water to Chalk abstraction wells over much of its length in drought conditions. Consequently, if the complex conditions contributing to the Otford flow could be simulated accurately it seemed likely that flows in the Chalk reaches of the river between Otford and Hawley could be simulated accurately by the relatively straightforward procedure of varying Chalk valley transmissivities and river bed leakage.

(ii) Simulation of Chalk groundwater hydrographs through the introduction of depth-dependent permeability. This was used to simulate high permeability as a result of primary and secondary fissuring in the zone of groundwater level fluctuations.

(iii) Simulation of river flows and groundwater piezometry in the Cray catchment.

Steady state conditions simulated with abstraction were used to provide initial piezometry for transient state calibration.

#### 5.3.2 River Darent Flows

**Upstream of Otford**

The flow at Otford gauging station can be evaluated from the simple water balance:

Flow at Otford = Subcatchment recharge - Subcatchment boundary outflow

Most of the boundary outflow takes place along the southern boundary of the model at the Hythe Bed outcrop. Hydrogeological maps indicate many springs along this boundary. However, due to the coarseness of the model grid in this region it is not possible to simulate springs precisely. The springs were therefore modelled by a fixed gradient outflow along this boundary, with gradient specified to simulate accurately the residual mean flow at Otford in the above balance.

In order to simulate the correct variations in river flows at Otford three parameters are important: the storage properties of the Lower Greensand aquifer system, the hydraulic resistance of the Darent river bed and the storage properties of the Longford Lakes.

The specific yield of the Lower Greensand was varied in calibration from 1% to 10%. It was found that the best simulation of river flows was achieved by using a specific yield of 3.5% for the Hythe Beds and 10% for the Folkestone Beds and a confined storage coefficient of 0.01%. The resultant river flow hydrograph for Otford is shown in Figure 5.4. It indicates a reasonable simulation of low flows, with a tendency for winter peaks to be oversimulated. This inaccuracy is a result of minor oversimulation of winter flows from the subcatchment Stanford model calibration.

River flows from Westerham to Otford were simulated by varying the hydraulic resistance of the river bed and the lake beds. Over most of this reach the Darent gains, with minor reductions in flows around the major pumping stations (Brasted, Sundridge and Cramptons Road). A constant resistance of one day was adopted throughout the reach, with resistances of 2 000 to 5 000 days for the lakes. The lake resistance takes into account the model grid resolution and flow convergence in transfer between the lakes and the aquifer. The actual resistance is likely to be significantly lower.

Current metering data indicate a general increase in flow of between 10 and 50 l/s during late summer and early autumn between the inlet and outlet of the main lake, Marley Lake. The model simulates a flow contribution from the Lower Greensand aquifer system of between 8 and 30 l/s. Summer accretion profiles are highly sensitive to the lake resistance adopted. With a low resistance (500 days) the gains are substantially higher (50 to 150 l/s). Much of the water at Otford gauging station passes through the Longford Lakes. Further data are required to simulate the lakes more accurately.

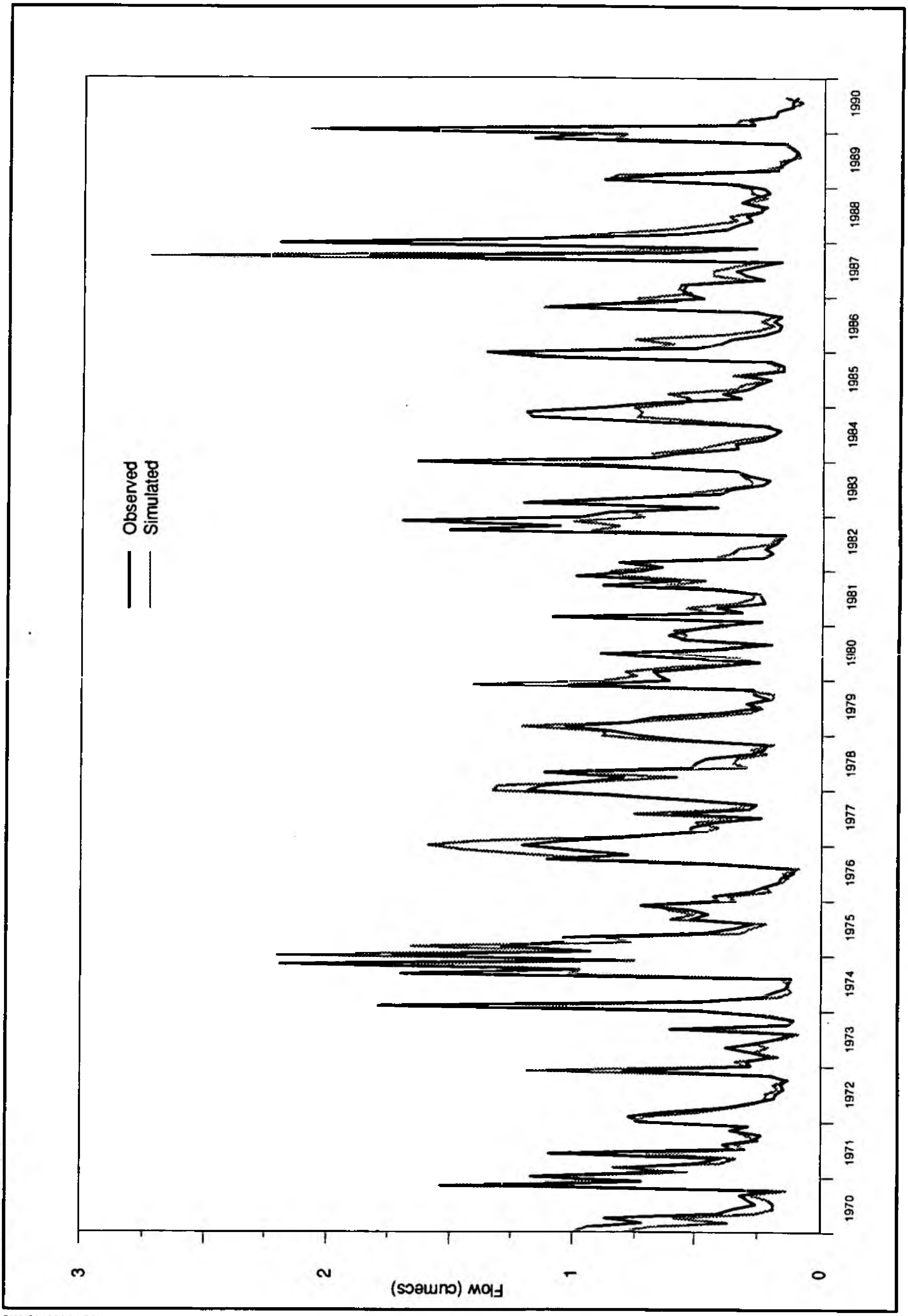
**Lullingstone and Hawley Gauging Stations**

Variations in river flows at Lullingstone and Hawley gauging stations were simulated by varying the storage properties of the Chalk. Published data suggest that the Chalk specific yield normally varies from 1% to 3%. These values were specified in two model runs of reduced length from 1974 to 1977. In order to achieve the correct response in the river it was found that the specific yield of the Chalk must be about 2%. With a specific yield of 1% the minimum simulated river flow is too low at Lullingstone each year (less than 50 l/s) while winter peaks are oversimulated. With a 3% specific yield low flows are oversimulated by more than 100%.

The simulated river flows at Lullingstone and Hawley gauging stations with a Chalk specific yield of 2% are shown in Figures 5.5 and 5.6. At both gauging stations the model has correctly simulated the timing and length of periods of low flow although peak winter flows are often overestimated. This inaccuracy has been carried forward from the Otford subcatchment.

Figure 5.4

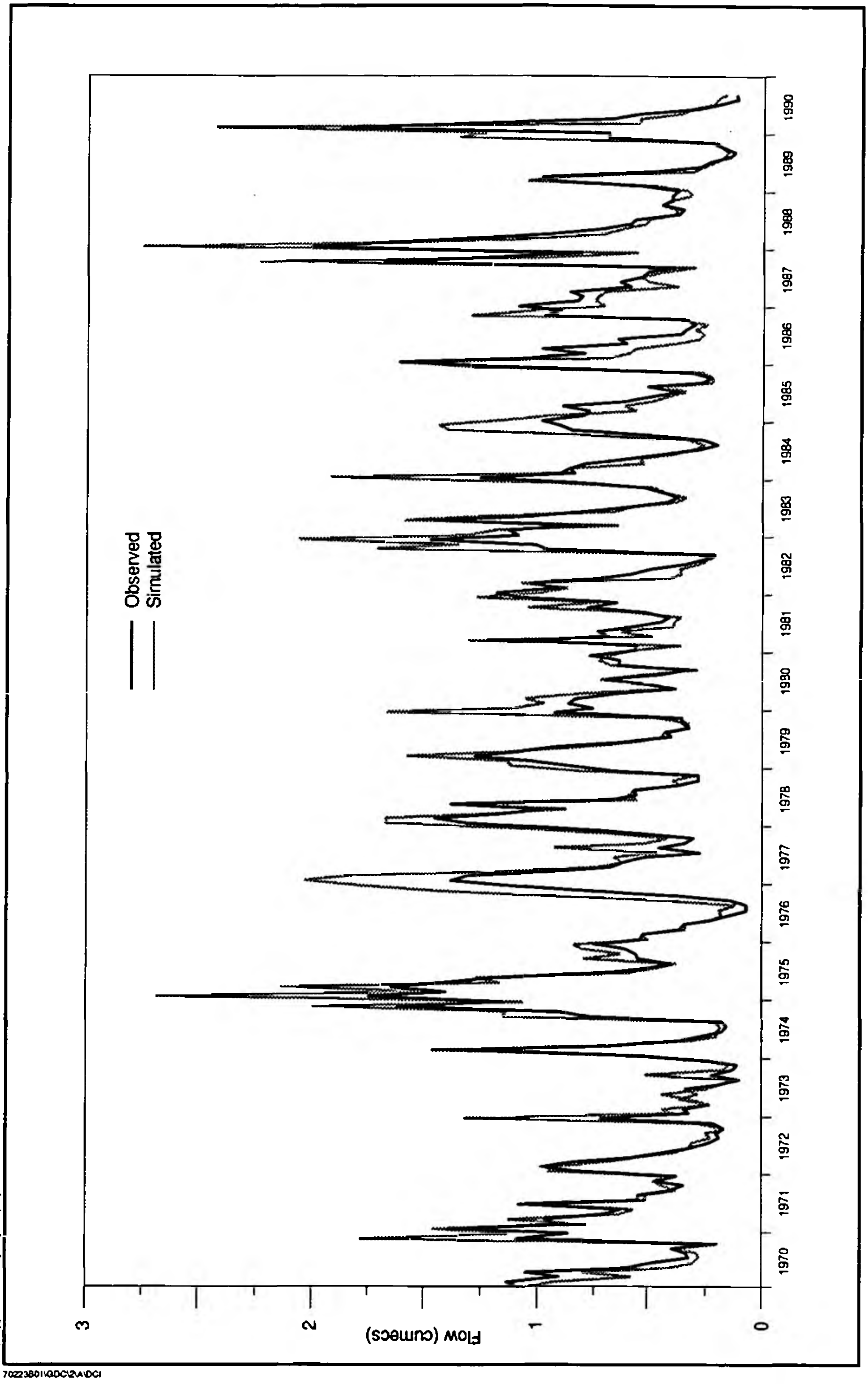
## River Darent : Simulated Flows at Otford




70223B01\GDC\2A\DCI

Figure 5.5

## River Darent : Simulated Flows at Lullingstone




70223801\GDC\2\A\DCI

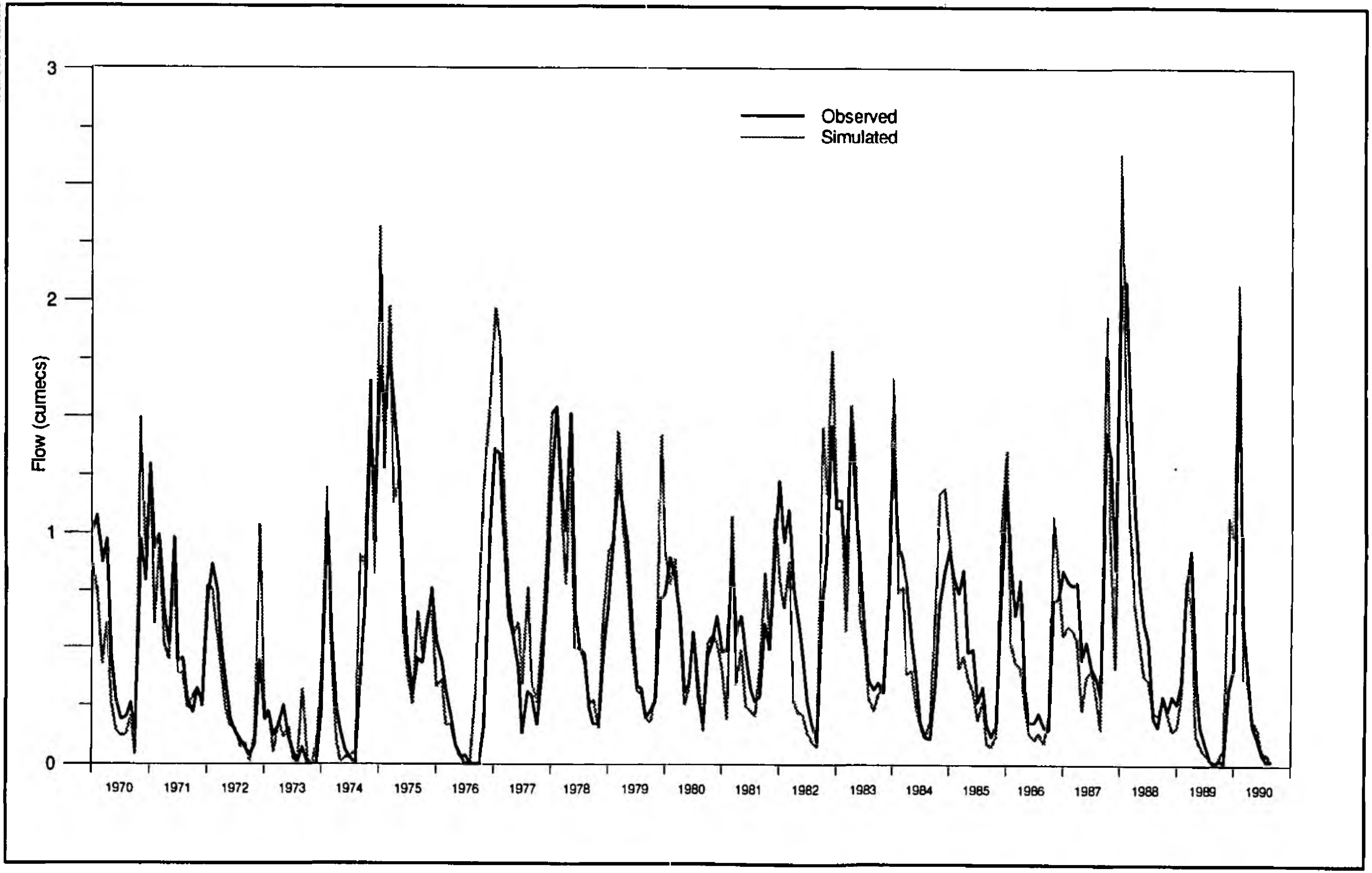



Figure 5.6

River Darent : Simulated Flows at Hawley

**River Flow Accretion Profiles**

The River Darent frequently loses water between Shoreham (about 3 km downstream of the Otford gauging station) and Hawley. The river resistance and Chalk transmissivities beneath the valley were varied to try and simulate flow accretion profiles determined from current metering along this section of the river. The river resistance was set at one day with Chalk transmissivities in the valley varying from 500 to 1 500 $m^2/d$. Two profiles, for periods of moderately high summer flows (July 1987) and low late autumn flow (November 1989), are shown in Figure 5.7.

Current metering data have been collected at irregular intervals averaging perhaps three times per year since the late 1970s. To be of use in model calibration, flow measurements have to be taken over the entire reaches between the permanent gauging stations in periods of low runoff and interflow in order to allow reasonable comparison with the monthly flows produced by the catchment model. However, at these times shallow depths of water at some sites may give rise to marked inaccuracies in gauging measurements. In assessing the validity of data for use in model calibration it is essential to check for consistency between adjacent gauging sites and for consistency with mean daily flows at permanent gauging stations.

There were five sets of current metering measurements taken on the Darent during July 1987. The mean flow profile from these measurements, and observed flows for 9 and 16 July are shown on Figure 5.7. The first half of the month was a period of low rainfall with the lowest flows measured on 9 July. Rainfall in the second half of the month gave rise to very large components of runoff and interflow along the whole river. The monthly mean flows for the three permanent gauging stations fall between the mean daily flows for 16 July and the average flows for the days on which the five sets of current meter measurements were taken. November 1989 was a generally dry month. The mean daily flow at Lullingstone on the day of current metering (17 November) was only 7% above the mean monthly flow at the gauging station.

Neither simulated accretion profile matches the observed data in all respects. For July 1987 the simulated profile falls generally within the envelope defined by the profile of lowest flow and mean flow for the five sets of measurements. However, inflow between Otford and Shoreham, either from Chalk springs or baseflow contributions, is undersimulated and the simulated gain in baseflow continues too far downstream to Lullingstone.

For November 1989 the flow profile is very markedly oversimulated although the general shape of the flow profile is modelled correctly. As the simulated flows at the Otford, Lullingstone and Hawley gauging stations are all oversimulated for this particular month it is not possible to get the magnitude of flow close to the observed data. A closer simulation of the flow profile should be achieved in other months when gauging station flows are more accurately simulated.

It might be possible to improve the flow profile simulations with further variations to Chalk transmissivities in the valley. However this was not considered worthwhile given the irregular availability of observed flow data and poor definition of groundwater levels for calibration in the vicinity of the river.

**Overall Accuracy of Simulation**

Mean simulated and observed river flows for the gauging stations on the Darent for the full years of transient state calibration are shown in Table 5.3. For the Darent the table indicates a slight overall undersimulation of flows despite some oversimulation of winter flows as referred to above. The general level of simulation is considered to be very reasonable.

**TABLE 5.3**

**Mean River Flows (1970 to 1989)**

| Gauging station | Observed (l/s) | Simulated (l/s) | Difference (%) |
|---|---|---|---|
| Otford | 556 | 532 | -4.3 |
| Lullingstone | 664 | 676 | 1.8 |
| Hawley | 584 | 578 | -1.0 |
| Cray | 507 | 525 | 1.6 |

### 5.3.3 Groundwater Level Variations

The accuracy of simulation of long term records of observed groundwater levels was also considered in assessing the suitability of storage coefficient values. For the Lower Greensand, simulation of changes in groundwater levels was achieved with reasonable success. The two observation well records which continue to the present are shown in Figures 5.8 and 5.9.

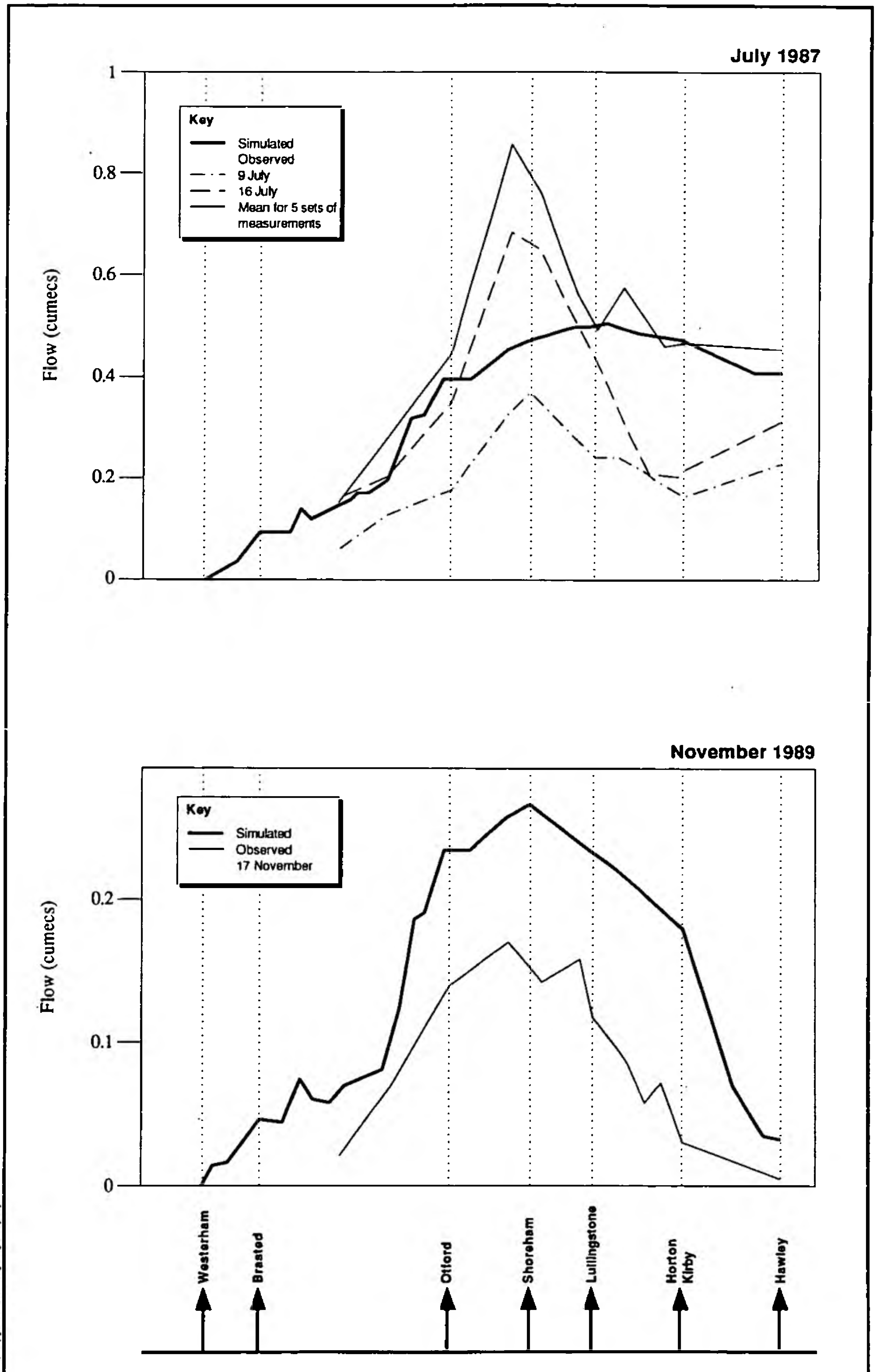
Observation well TQ55/1 at Riverhead near the Longford Lakes has been monitored weekly since 1962. It provides piezometric level data for the Hythe Beds which are confined in this area. The lakes may however influence groundwater levels at the site. Observation borehole reference 355/1 at Foxwold near Brasted has been monitored intermittently since 1972. It is situated in the upper part of the Otford subcatchment, again indicating water levels in the Hythe Beds. Observed and simulated water levels for the two sites and corresponding model polygons are shown in Figures 5.8 and 5.9.

The simulation of groundwater levels for TQ55/1 is much more accurate than can generally be achieved in catchment modelling. There are some periods of inaccuracy in monthly values by the 12 month running mean indicates very reasonable simulation of groundwater conditions for the aquifer.

Although the running mean is modelled reasonably, the simulated variation between summer and winter groundwater levels at the Foxwold observation well (355/1) is over twice as great as observed. However the observed data exhibits anomalous features. The lowest groundwater level was recorded for the summer of 1986 when Otford gauging station records indicate near-average summer flow

Figure 5.7

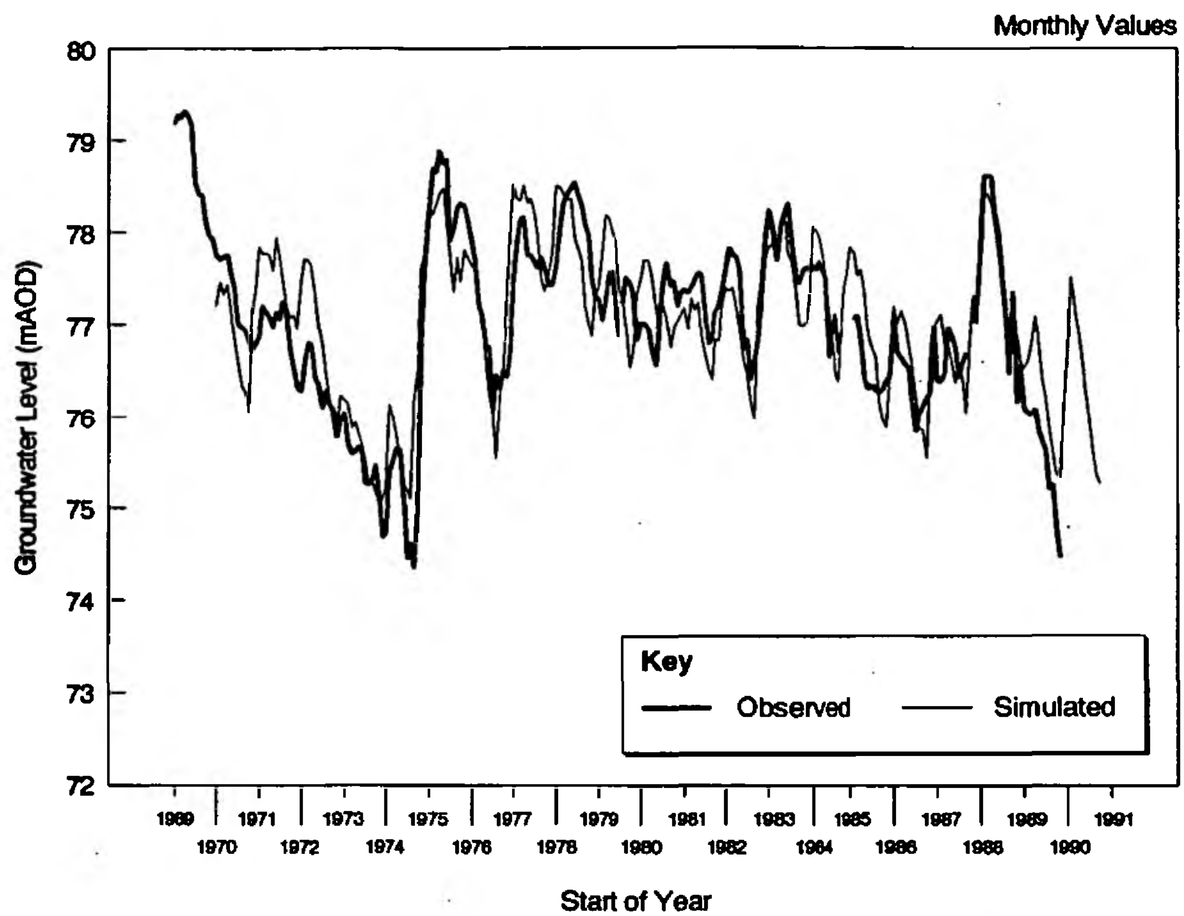
## River Darent : Simulated Flow Accretion Profiles




70223B01/GDC/2/A/DCI

Figure 5.8

# Simulation of Lower Greensand Groundwater Levels
# Riverhead Observation Well (TQ55/1)



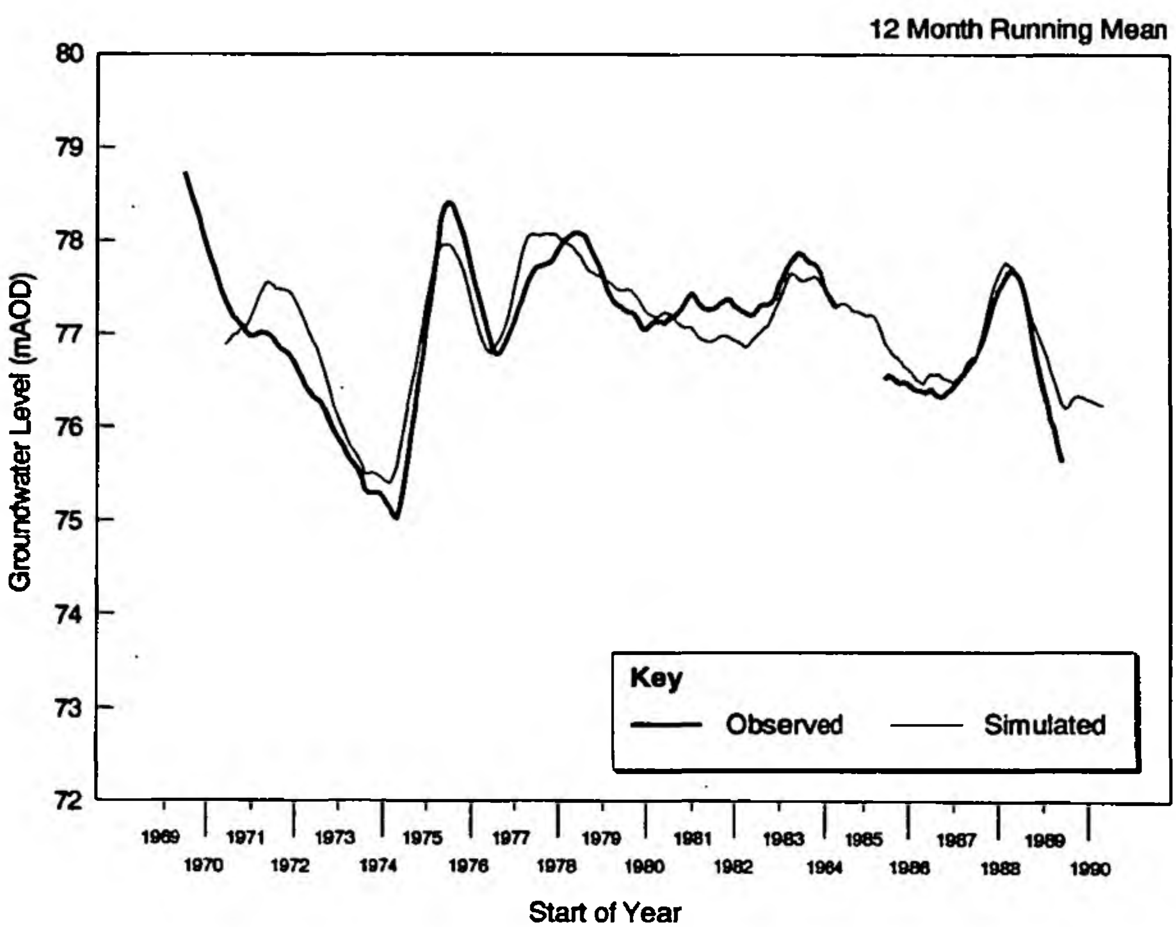
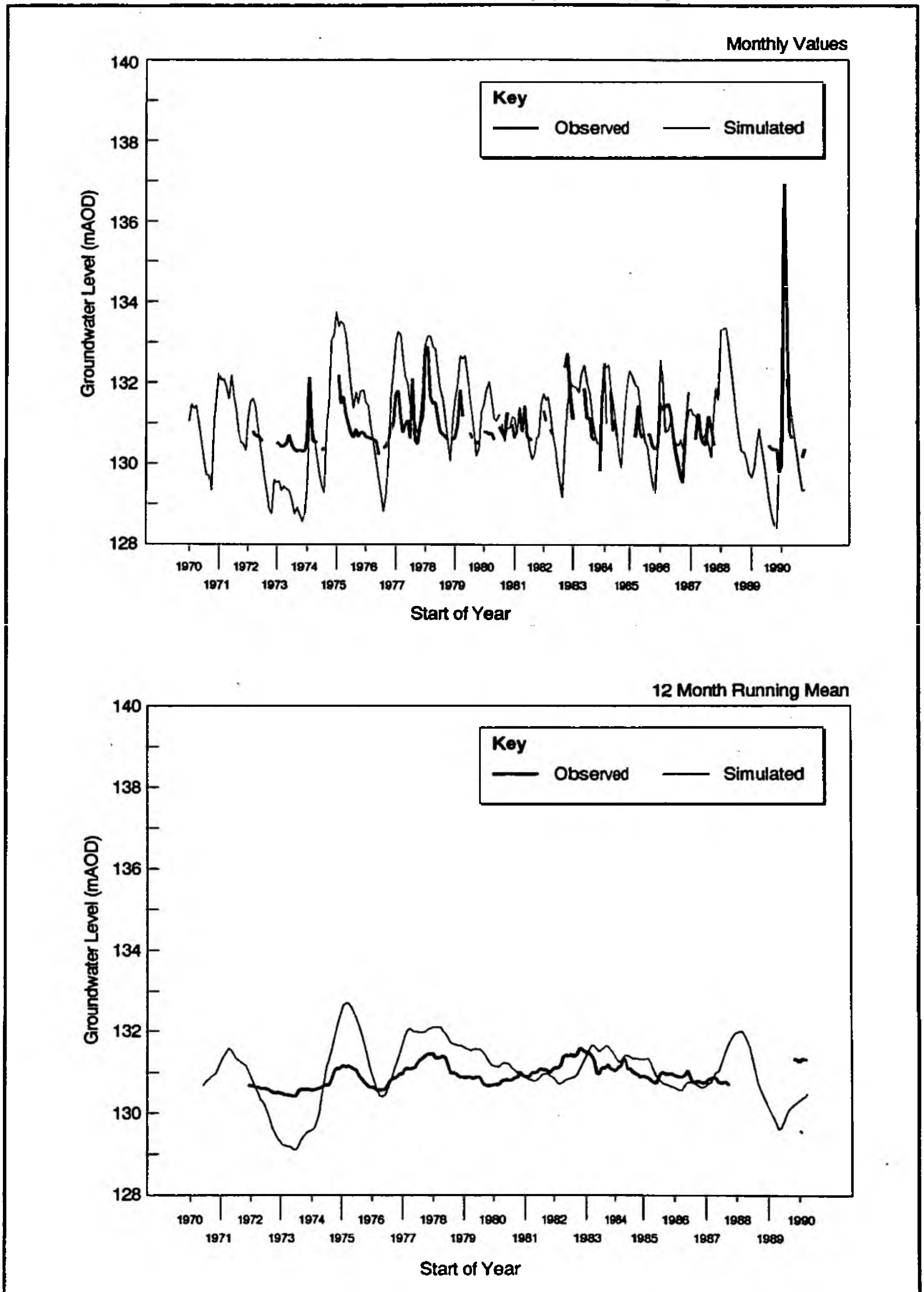



Figure 5.9

## Simulation of Lower Greensand Groundwater Levels
## Foxwold Observation Well (355/1)



conditions. In contrast, low groundwater levels were not recorded in drought years in the mid 1970s or in the summers of 1989 and 1990. Details of local groundwater conditions and well construction would be required to explain groundwater level variations at Foxwold.

For most Chalk observation wells the average annual variation in water levels between summer and winter is between 2 and 6 m. Specifying a Chalk specific yield of 2% to simulate river flows, results in a variation of over 10 m in groundwater levels throughout most of the Chalk including the areas around Lullingstone, Hawley and the Cray catchment. A higher specific yield to simulate less variation reduces the accuracy of river flow hydrograph simulations.

The low variation in groundwater levels may be caused by the rapid movement of recharge through fissures to the river. The presence of a highly transmissive zone reduces the variation in water levels. This occurs as a minor reduction in water level produces a substantial reduction in transmissivity, which in turn rapidly reduces discharge from the aquifer.

A highly transmissive band was introduced to the model by specifying very high permeability to simulate fissuring in a zone between the average maximum and minimum annual groundwater levels. The permeability distribution adopted is shown in Figure 5.10a. This takes the same form as the distribution indicated by Price (1987) and illustrated in Figure 2.4, but has been adjusted for the Darent catchment model through calibration.

The effect on simulated groundwater levels of modelling constant and variable permeability is illustrated in Figure 5.10b. This shows how water levels are maintained within the high transmissive zones at all times, except during drought periods as in 1976. Simulation of observed water levels is greatly improved with introduction of a highly transmissive band or depth dependent permeability.

Depth dependent permeability was not introduced throughout the model, but only in areas where the Chalk is unconfined. When included at river elements, depth dependent permeability gave rise to problems with model convergence and solution. Further research would be required to remove the instabilities were depth dependent permeabilities to be included as a permanent feature of the model in river elements.

Selected observed and simulated Chalk groundwater hydrographs are shown in Figures 5.11 and 5.12. These reflect the variable degrees of accuracy in simulation. Improvements to groundwater hydrograph simulation might be achieved through varying the specific yield and depth dependent permeability in different areas of the model.

Although the simulated hydrographs do not fully describe observed Chalk water level fluctuations accurately, the simulated variation in levels between summer and winter is of sufficient accuracy to conclude that the modelled flow mechanisms between the Chalk aquifer system and the river are acceptable. A cross-section from the source of the River Cray, across the Darent valley to West Kingsdown shown in Figure 5.13 demonstrates reasonable simulation across the Chalk outcrop.

### 5.3.4 Conditions in the Cray Catchment

After a number of initial calibration runs, it was apparent that the mechanisms of flow to the River Cray differ from those for the Darent. Seasonal variations in observed river flows in the Cray do not correspond with variations in flows at Hawley and Lullingstone on the Darent. During drought periods river flows in the Cray are maintained at a high level relative to the Darent. By using the same mechanism of baseflow from the Chalk the model underestimates the minimum flows particularly during drought conditions. There are two possible reasons for this. Either river levels are maintained artificially through urban drainage or the Tertiary deposits form a large storage reservoir which sustains baseflow during periods of low recharge. A combination of urban drainage and storage in the Tertiary deposits may also be possible.

The volumes of urban drainage to the Cray from distribution system leakage and stormwater drainage could not be evaluated accurately at this stage. In order to test whether the Tertiary deposits provide significant baseflow the river/aquifer mechanism in the Cray was redefined. The river was assumed to be connected hydraulically to the Tertiary layer only, with no contribution to baseflow from the underlying Chalk. Recharge is retained over a longer period in the Tertiary deposits by specifying a low vertical permeability (1 mm/d) between Tertiary deposits and Chalk, and a high specific yield for the Tertiary deposits of 15%.

The results for the simulation of river flows for the period 1973 to 1977 are shown in Figure 5.14. With baseflow derived from the Chalk, river flow recession is reasonably accurately simulated but in early summer flows rapidly decline below the observed minimum baseflow. Winter peaks are grossly overestimated. With baseflow from Tertiary deposits only, simulated winter peaks are closer to observed (although they remain overestimated) and baseflow is maintained through the summer and early autumn. However, the initial stage of river flow recession is much steeper than observed. It was concluded therefore that neither mechanism correctly defines baseflow to the River Cray, but low flows could possibly be simulated by combining the mechanisms.

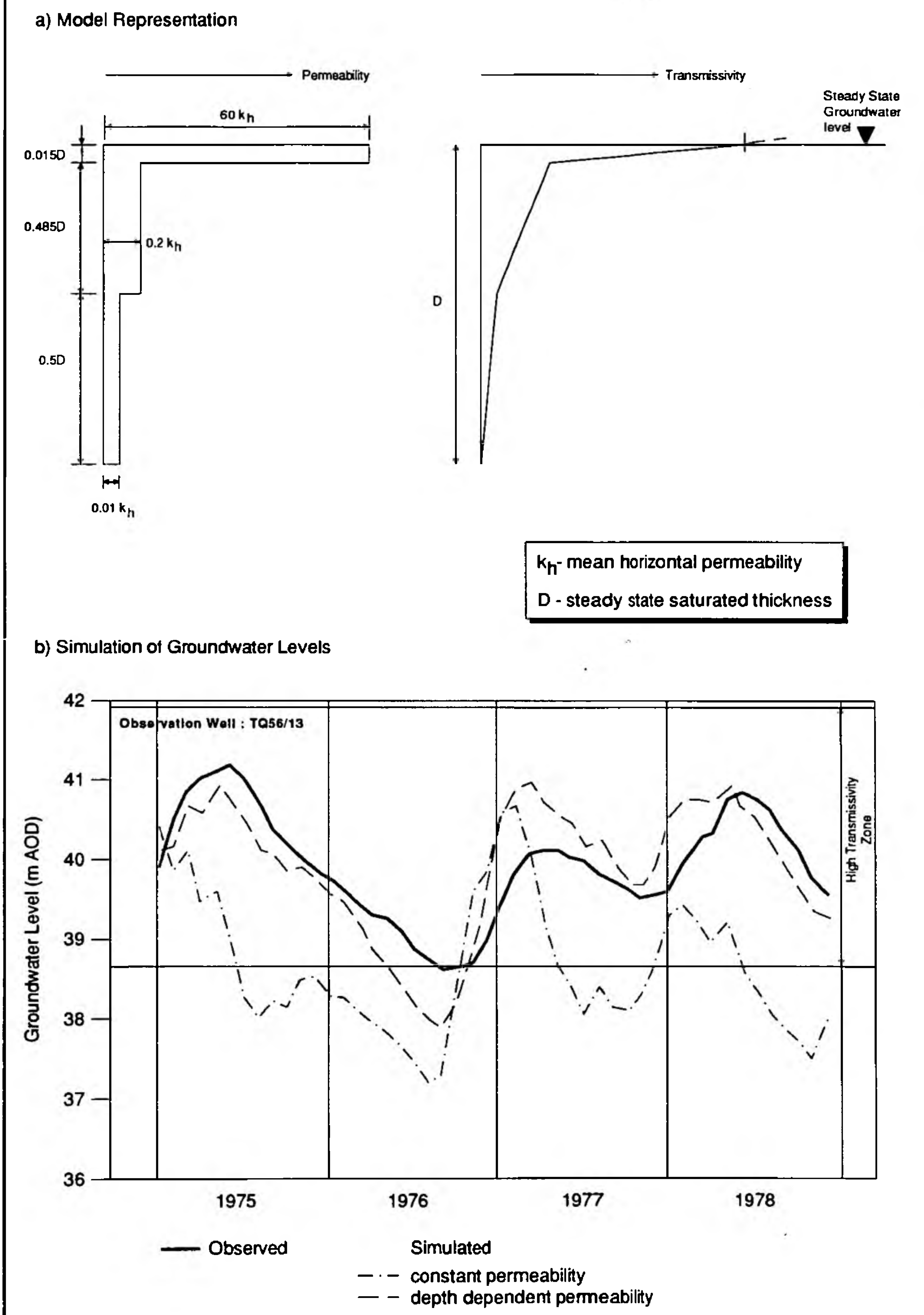
The major inaccuracy in the simulated Cray flows is however during winter. Peak winter flows include surface runoff and interflow components simulated by the Stanford model. These components are simulated as contributing directly to the river shortly after the corresponding rain event; there is no lag between the rainfall event and runoff reaching the river, and, on average, only two days between rainfall and resulting interflow contributing to the river flow hydrograph. These flow components are distributed uniformly along the river elements of the catchment model.

In reality interflow may be held in the Tertiary deposits and released slowly into the river. Consequently a final model run was carried out in which 70% of the simulated interflow produced by the Stanford model was considered as an additional potential recharge component. In addition the horizontal permeability of the Tertiary deposits was reduced to 1 m/d from 20 m/d to simulate approximately the unsaturated flow of the interflow component.

Simulated and observed flows at the Crayford gauging station for this final run are shown in Figure 5.15. The scale chosen for the flow axis matches that for other gauging stations shown in

# Modelling of Depth Dependent Permeability

a) Model Representation




q:\wp\dry\gem\uk\darent\wells\fig5-9 gem by drj

70223B01/GDC/2/A/DCI

Figure 5.11

## Simulation of Chalk Groundwater Levels
## Crocken Hill Nr 3 Observation Well (TQ56/12)

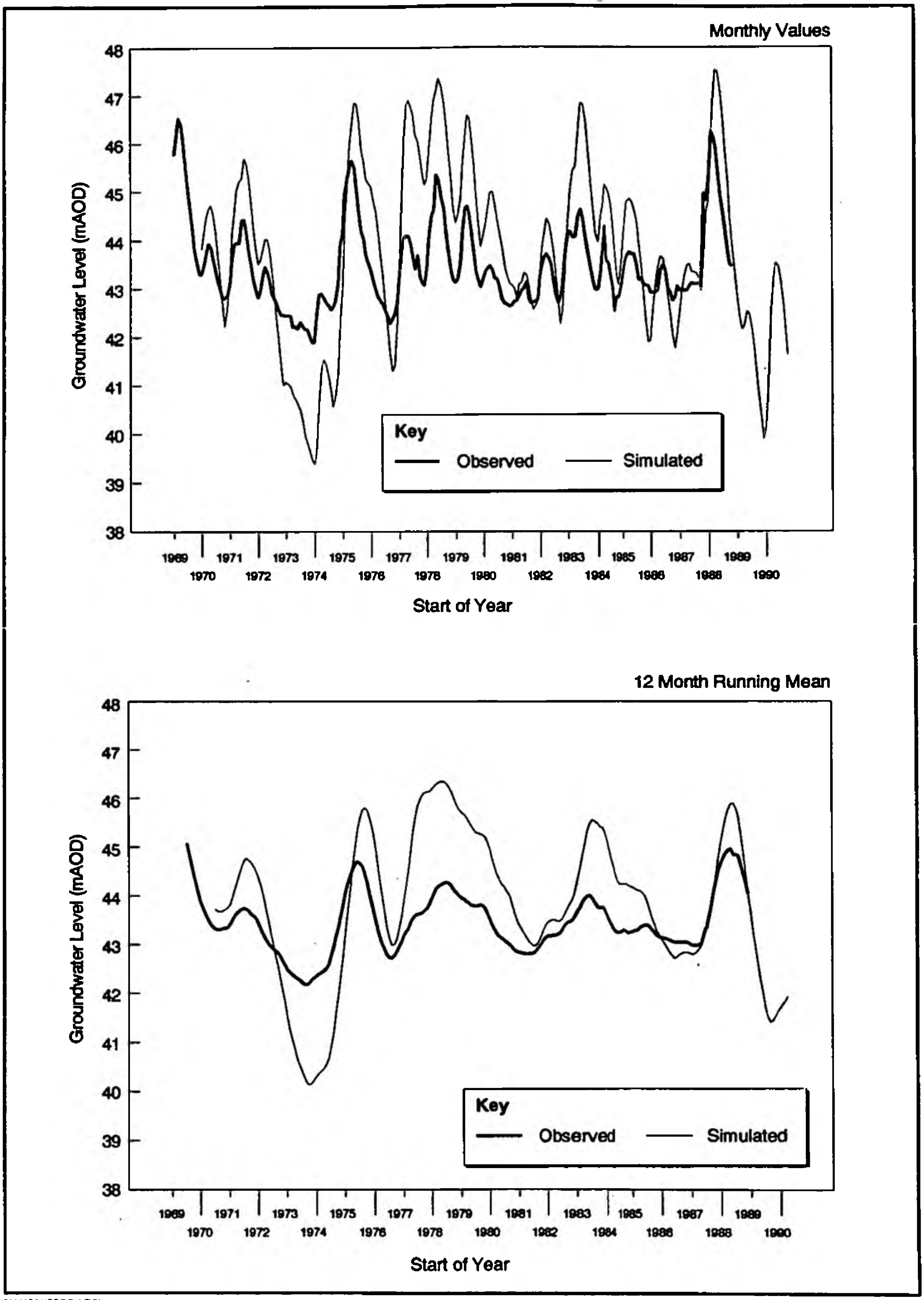
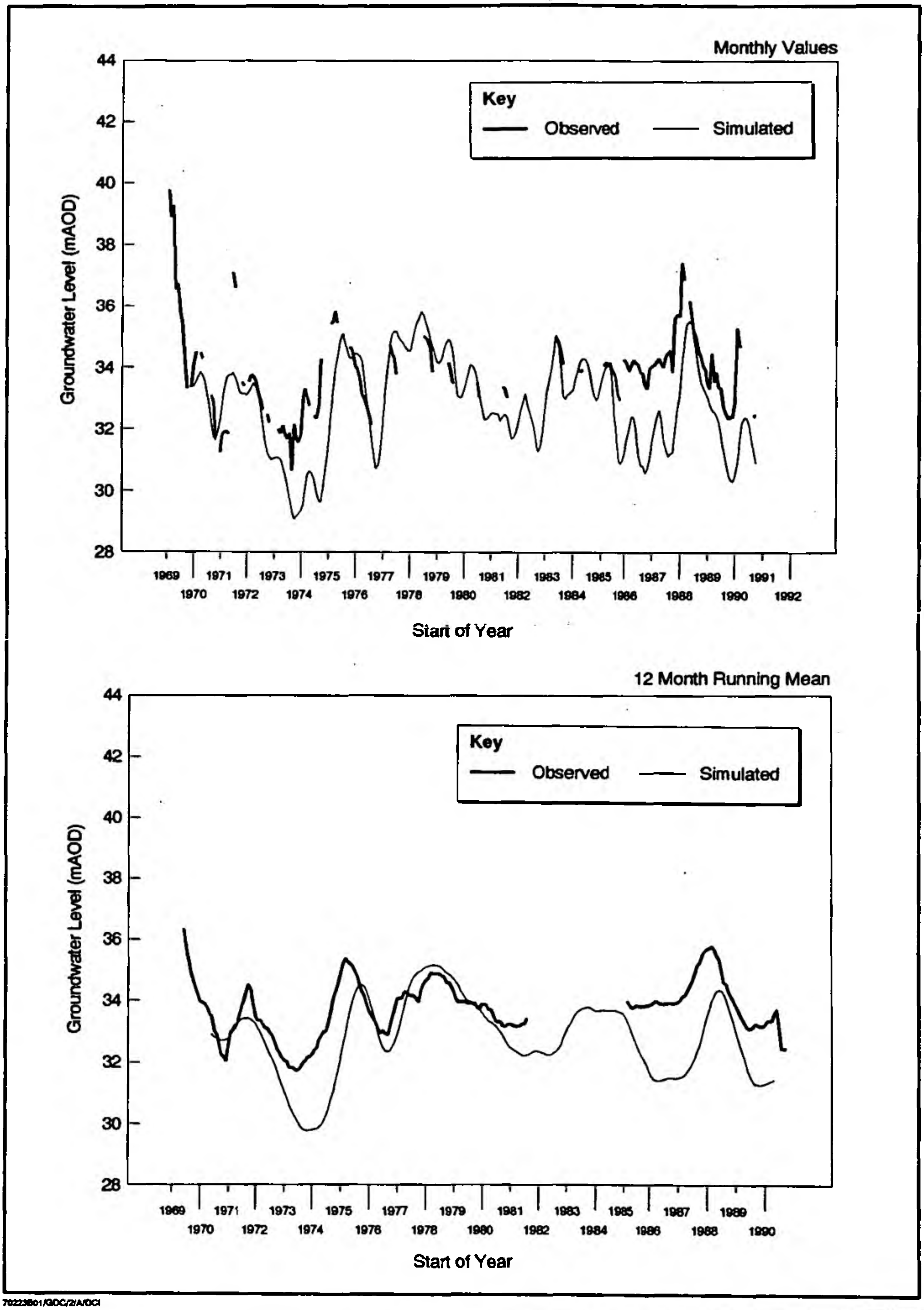


Figure 5.12

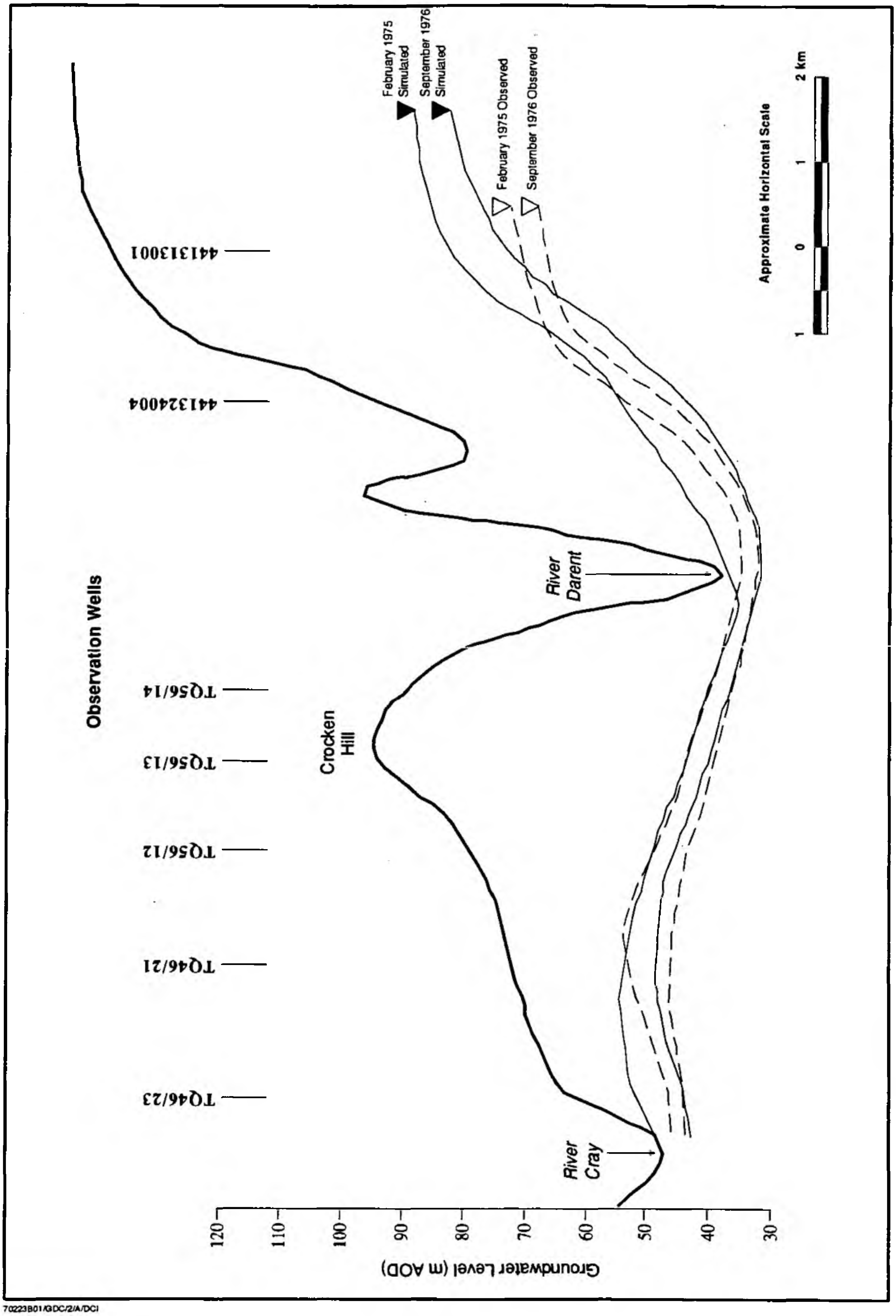
# Simulation of Chalk Groundwater Levels
# Clement Street Nurseries Observation Well (321/1)




70223B01/GDC/2/A/DCI

Figure 5.13

# Simulation of Chalk Groundwater Levels across the Darent Catchment




70223B01/GDC/2/A/DCI

Figure 5.14

# River Cray : Simulation of River Flows with Varying Baseflow Mechanisms

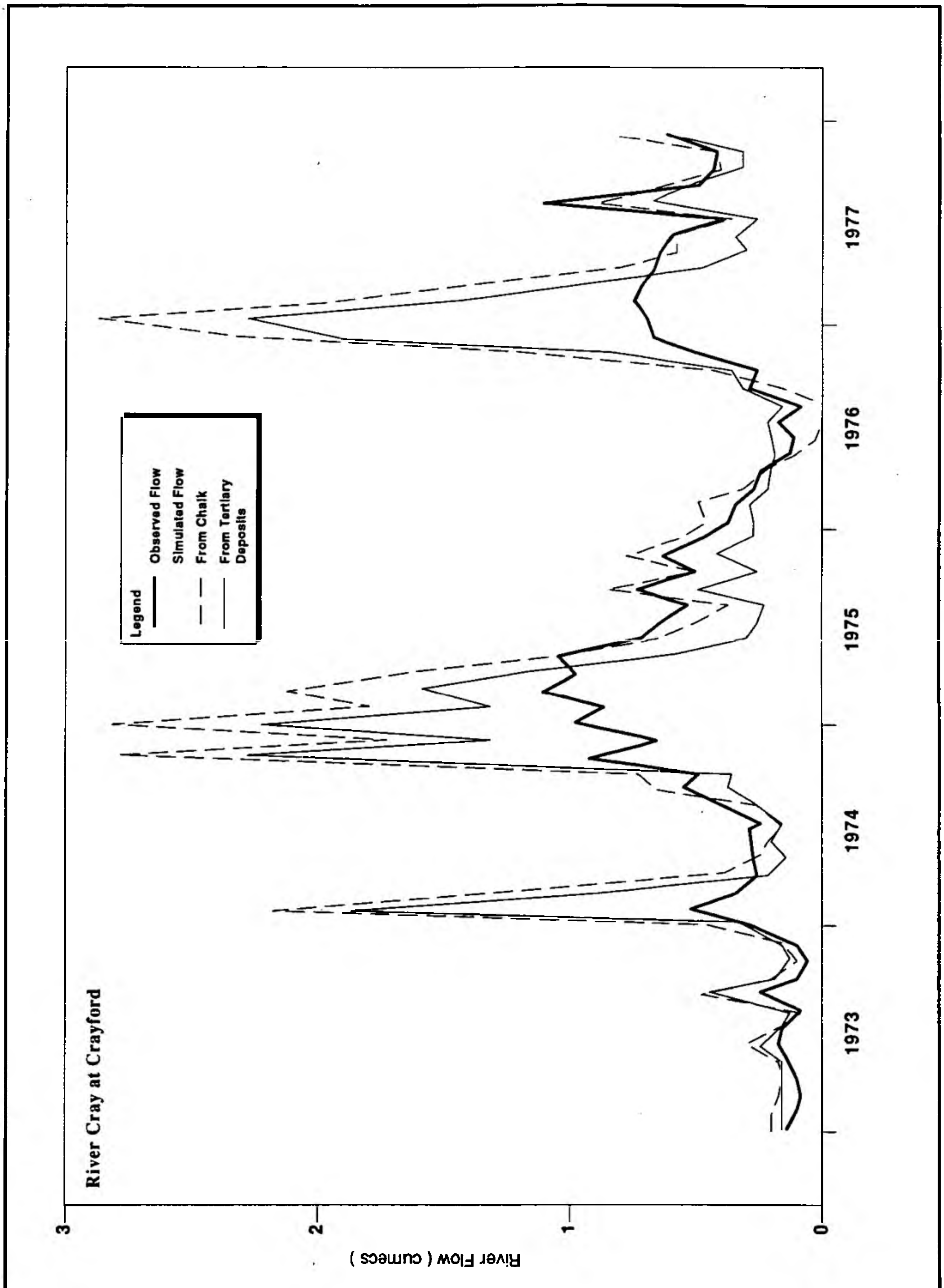
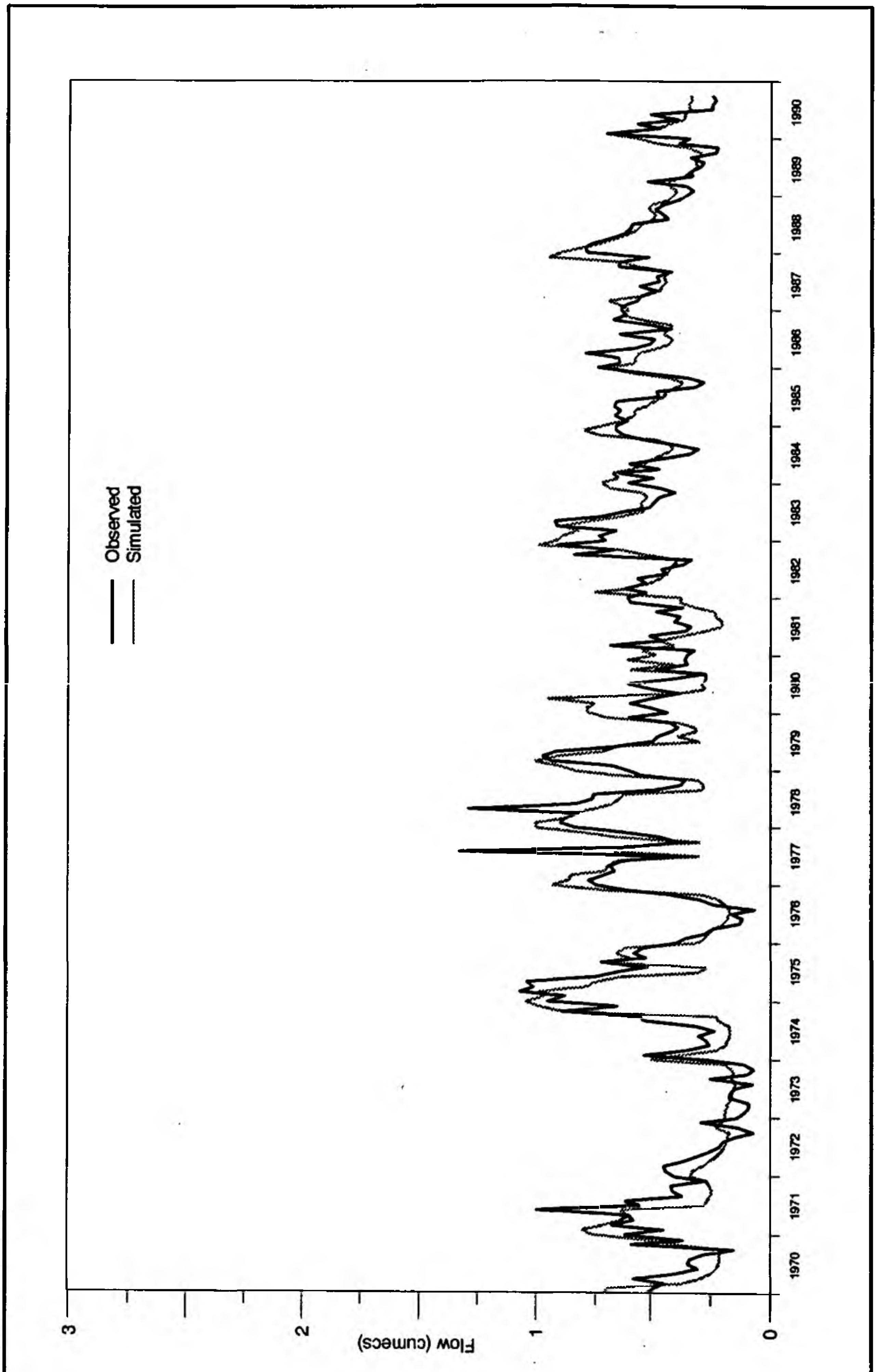


Figure 5.15

## River Cray : Final Simulation of Flows at Crayford




70223/801/GDC/2/A/DCI

Figures 5.4 to 5.6. The quality of the simulation is variable throughout the period of record. However it was considered adequate as the main focus of calibration at this stage is the Darent catchment itself.

The inaccuracy in simulation of river flows in the Cray catchment stems from conceptual simplifications in the Stanford model. The model simulates baseflow by depleting the 'active' groundwater storage. This storage component is termed 'active' since it is assumed that the groundwater storage reservoir contains only the groundwater that interacts with baseflow. The reservoir is depleted using a Horton type recession.

In the Cray catchment it is possible that two groundwater storage reservoirs exist: the Chalk reservoir which contributes rapidly to baseflow in response to recharge and a reservoir within Tertiary deposits in which recharge and interflow both contribute to storage and storage is depleted slowly in contributing to baseflow. It should be possible to develop the Stanford model to include two groundwater reservoirs and to test this concept on the Cray catchment simulation.

This 'two reservoirs' concept might also apply to simulation of baseflow derived from Chalk storage, the first reservoir simulating baseflow contributions through fissures and the second reservoir simulating the slow seepage from the rock matrix. This could improve simulation of the rising limb of river flow hydrographs. In its present form the Stanford model simulates an immediate response in baseflow to a recharge event.

Piezometry in the Cray catchment is very difficult to define, as there are very few reliable observed data. It is not known whether the Chalk is confined or unconfined below the Tertiary deposits. In order to improve the understanding of the flow mechanisms described above, it is important that more groundwater data are collected in this catchment.

# CHAPTER 6

# CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Recharge Estimation

A lumped parameter model, a modified version of the Stanford watershed model, was calibrated for each of the following subcatchment areas:

- the River Darent upstream of Otford;
- the River Darent between Otford and Hawley;
- the River Cray upstream of Crayford.

Water balance components were obtained for the period 1970 to 1990. The models were calibrated against observed flow data for permanent gauging stations. In all cases the long term mean flow was simulated to are accuracy of 3%. This is within the normal accuracy of flow measurement of the observed.

Daily flows for Otford were simulated well. The effects of lakes located close to the river were modelled by reducing the area of impermeable Gault Clay specified within the subcatchment. Some problems were encountered in calibrating the Otford to Hawley subcatchment model, as groundwater abstraction for this area is of the same order of magnitude as recharge. However a good simulation of daily flows at Hawley was achieved to an accuracy of 3% by combining flows at Otford with flows for the subcatchment between Otford and Hawley.

For the River Cray, Chalk outcrop and Tertiary deposits within the catchment would be expected to give rise to a combination of different recession characteristics for river baseflow. This makes simulation with a lumped parameter model difficult, but reasonable accuracy of simulation was still achieved for some summer flow recession periods. However flows in periods of high rainfall could not be simulated accurately. Observed flows at the Crayford gauging station show little response in periods of high rainfall implying very large storage (either groundwater or surface water) within the catchment. Because interflow would be expected to occur within the Tertiary deposits in the catchment, interflow was added to recharge to give a potential recharge for catchment modelling.

Recharge was distributed in the catchment model taking into account variations in geology, urban development and rainfall. Mean annual recharge varies from a maximum of 330 mm on the Lower Greensand and Chalk uplands to 120 mm in some non-urban areas in the lower Darent catchment. Recharge estimates for urban areas are generally in the range 200 to 300 mm.

## 6.2 Catchment Modelling

### 6.2.1 Steady State Conditions

Steady state groundwater conditions were simulated reasonably using a Chalk transmissivity distribution of 500 $m^2$/d to 1 500 $m^2$/d in valley areas and 20 $m^2$/d to 300 $m^2$/d on upland interfluves. Transmissivities of 1 500 to 2 000 $m^2$/d were needed to model watertable conditions in a dry valley system to the east of the main Darent valley. Groundwater from this dry valley area appears to drain into the Ebbsfleet catchment rather than to the lower Darent. A horizontal permeability of 10 m/d was adopted for both the Folkestone and Hythe Beds, giving transmissivities of 200 $m^2$/d to 600 $m^2$/d depending on formation thickness.

### 6.2.2 Simulation of River Flows

Good simulations of flow at all gauging stations in the Darent catchment were obtained in transient state calibration. The following specific yield values were adopted:

| | | |
|---|---|---|
| Lower Greensand | Hythe Beds | 3.5% |
| | Folkestone Beds | 10% |
| Chalk | | 2% |

Long term observed flows were simulated to an accuracy of 4% at Otford, 2% at Lullingstone and 1% at Hawley. For Otford, low flows were simulated accurately and the timing and duration of low flows were simulated well at Lullingstone and Hawley. There was some oversimulation of peak flows throughout the catchment originating from an overestimate of recharge for the Otford subcatchment. Features of flow accretion profiles for the Darent were simulated with variable success. Generally the overall shape or magnitude of observed accretion profiles were simulated reasonably.

For the River Cray, observed flows often persist at a moderate level during periods of low flow in the River Darent. It was concluded that this was due to high storage within the urban drainage system and Tertiary deposits for which a specific yield of 10% was adopted. The River Cray was modelled as being in hydraulic contact with both the Chalk and the Tertiary deposits in order to simulate both the observed rapid decline in river flow in early summer, a characteristic of Chalk catchments, and the reliable baseflow throughout the late summer/early autumn fed by seepages from the Tertiary deposits. The addition of 70% of interflow calculated by the Stanford model to recharge to the Tertiary deposits, with approximate simulation of unsaturated flow, led to an improvement in simulation of peak winter flows.

### 6.2.3 Simulation of Groundwater Levels

Accurate simulations of long term variations in groundwater levels were achieved for two observation wells with long term monitoring in the Lower Greensand. For one well at Riverhead, monthly variations are simulated to an accuracy not normally expected in catchment modelling. Data from recently constructed observation wells are considered necessary to test the accuracy of modelling in other areas of the Lower Greensand.

For the Chalk, specifying an unconfined storage coefficient of 2% gave rise to simulated variations in groundwater levels generally greater than observed. A zone of high transmissivity was introduced to simulate rapid flow in fissure zones within the range of normal groundwater table fluctuation. A considerable improvement in simulation of Chalk watertable conditions was obtained to achieve a reasonable comparison with observed data.

### 6.2.4 Conclusions

Good simulations of hydrological conditions have been obtained throughout the catchment model area for the 20 year period of simulation. This applies particularly to river flows at the three historical gauging stations on the River Darent where low flow periods are simulated well. As a result, there was high confidence in using the model to predict the effects of water resources management strategies.

## 6.3 Options for Improving Catchment Simulations

### 6.3.1 Introduction

Further worthwhile improvements to the model are considered possible. These could be included when undertaking an update of the period of simulation which currently ends in September 1990. Two main areas of simulation might be improved as follows:

- recharge estimation;
- watertable conditions.

Improvement in these aspects of the catchment model should lead to a greater understanding of hydrological mechanisms in the catchment and therefore in the simulation of river flows for various water resources management strategies.

### 6.3.2 Recharge Estimation

Improvements in recharge estimation relate to the Stanford models for the Otford subcatchment of the River Darent and to the River Cray catchment. Geology and land use are variable in these subcatchments. Although a reasonable distribution of recharge was achieved by comparison with recharge for the subcatchment of the Darent between Otford and Hawley, recent developments in segmenting subcatchment Stanford models could be applied effectively to the Darent.

The Stanford model in the modified form used for this investigation could be segmented into different regions on the basis of topography. The model has also been recently adapted to allow segmenting on the basis of geology or landuse. Distribution of recharge in the Otford subcatchment might be improved by segmenting into Lower Greensand and Chalk sub-areas. The Cray catchment could be considered as two or three segments representing unconfined Chalk and Tertiary deposits and/or urbanisation. Water balance components for the segments would then be combined in calibrating against observed river flows. Improvements to recharge estimation for the Cray catchment would also help to improve estimates for uncalibrated areas close to the Thames such as the Ebbsfleet catchment.

### 6.3.3 Catchment Modelling

Groundwater conditions are not defined equally well across the whole of the catchment model and may therefore be poorly simulated in some areas. Good simulation of groundwater conditions can be very important when predicting the effects of water resources management strategies. For example, the extent to which the groundwater divide between the Cray and Darent catchments moves with changing Chalk abstraction may influence very significantly the Chalk groundwater contributions to the River Darent.

In 1992 the NRA let a contract to construct and test pump observation and test wells in the Darent and Cray catchments. The wells were constructed in order to improve the understanding of watertable conditions in areas remote from abstraction wells where few or no existing data were available. Locations were chosen with a view to defining:

- Chalk piezometry close to the River Darent between Otford and the River Thames;
- groundwater conditions in the Cray catchment;
- groundwater conditions in confined and unconfined areas of the Lower Greensand aquifers in the Otford subcatchment.

In addition some test wells were located on upland Chalk interfluves in order to prove whether or not the Chalk has low transmissivity in these areas. Updating and, possibly, further calibration of the catchment model are recommended once at least a full year's water level monitoring data have been collected from the new observation wells. Data collection should preferably cover two periods of groundwater recession, with contrasting recessions representative of dry and wet years. In updating the model for the period from September 1990, use could also be made of the extensive river flow current metering data collected in dry periods since that time. With these data it should be possible to improve simulation of the flow accretion profiles for the River Darent.

At this stage no improvements are considered necessary to the representation of groundwater flow mechanisms in the catchment model. Reasonable results have been obtained by specifying the Chalk as a single aquifer with depth dependent permeability, although in recent work on other models simulations have been improved by separating the Chalk aquifer into two layers. These layers represent the fissured zone and the main Chalk rock which has low transmissivity but high groundwater storage. For the River Darent further calibration of the model in its existing form should be carried out before considering any major changes to the representation of the Chalk.

## REFERENCES


| | | |
|---|---|---|
| British Geological Survey | 1990 | Geological Survey of Great Britain<br>Sevenoaks Sheet 287<br>Solid and Drift Edition |
| British Geological Survey | 1977 | Geological Survey of Great Britain<br>Dartford Sheet 271<br>Drift Edition |
| Groundwater Development Consultants Limited | 1991 | Darent Pre-feasibility Report (Revision C) |
| Groundwater Development Consultants Limited | 1992 | Groundwater Study at Blue Circle Cement Northfleet Works Phase 1 Final Report |
| Institute of Geological Sciences | 1975 | Records of wells in the area around Dartford |
| Institute of Geological Sciences | 1970 | Hydrogeological Map of the Chalk and Lower Greensand of Kent |
| Institute of Geological Sciences | 1968 | Records of wells in the area of New Series One - Inch (Geological) Reigate (286) and Sevenoaks (287) sheets |
| Joint NRA/TWUL Project Team | 1992 | Plan for the Darent |
| Mott MacDonald | 1990 | River Severn Floodplain, Worcester, Final Report, Volume 1, produced for the City of Worcester and NRA (Severn-Trent Region) |
| Price M | 1987 | Fluid flow in the Chalk of England (from Geological Society Special Publication Nr 34) |
| Water Resources Board | 1972 | The Hydrogeology of the London Basin |