Low Flow Estimation in Artificially Influenced Catchments

INTERIM REPORT, DECEMBER 1992

by

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Executive Summary

The objective of the project is to develop procedures for estimating low flows on catchments where processes are artificially influenced. Specifically, the project is aimed at the production of methods of low flow estimation in ungauged or partially gauged catchments which are subject to (man's) influences. The project is extending the existing MICRO LOW FLOWS software (currently commercially available through the Institute of Hydrology) to produce estimation procedures which account for the following:

1) Surface water influences including abstractions, discharges and reservoirs

2) Bulk effects of groundwater abstraction

3) Land-use change in the form of afforestation/deforestation

The project aims to incorporate best practices currently applied in the NRA regions and to optimise the use of all relevant data archives.

The project commenced in December, 1990 and is due for completion in November 1993. The project leader was the late Dr John Pirt of NRA Severn-Trent region and is now Mr Nigel Fawthrop of NRA Anglian region. The project is a component of the Flow Regimes (B02) Topic of the Water Resources (B) Commission. The Institute of Hydrology are the sole research contractors. The project benefits from an Advisory Group comprising three representatives from the NRA, and one representative from the water utilities, universities and consultants.

This Interim Report is the second and covers the reporting period of December 1991 to November 1992. Staffing of the project by the Institute is as follows:

Project manager:	Dr Alan Gustard
Project leader:	Dr Andy Bullock
Project staff:	Andrew Young
	Karen Irving
	Ann Sekulin

The Project Investment Appraisal (Appendix C) lists 7 work items, excluding reporting requirements, which are to be achieved during the three year duration of the project. Good progress has been made with these objectives and the project remains on schedule for completion in November 1993. The status of achievement on the seven work items is as follows:

1. A review of NRA procedures for naturalising low flow statistics.

An assessment of the regional methods used for calculating and adjusting low flow statistics has been completed in order to identify the best procedures which can be modified and incorporated into the MICRO LOW FLOWS software.

A questionnaire was sent to each of the ten regional NRA headquarters requesting information about the procedures used to estimate low flow statistics in gauged and ungauged catchments.

The results were collated and presented in the first Interim Report. A forum of NRA staff was held at Wallingford in September 1992 to further discuss NRA procedures.

2. Simulation of the impact of artificial influences upon low flow statistics.

An assessment of the sensitivity of low flows (specifically MAM(7), Q95 and BFI) to the magnitude and seasonality of abstractions has been completed and reported in the first Interim Report. This identified difficulties in the estimation of artificially-influenced MAM(7) statistics, and subsequent work has been directed towards mean monthly minima (MMM(7)) and flow duration curves alone. Regression-based procedures have been finalised for the estimation of natural MMM(7) and the estimation of natural monthly flow duration curves is well advanced. Procedures have been developed for the construction of a monthly artificial influence profile based on upstream water use at an ungauged site. The estimated natural monthly low flow statistics are combined with the monthly artificial influence profile to estimate the artificially influenced low flow statistics.

3. Software developments for low flow adjustment and residual flow diagram production.

MICRO LOW FLOWS possesses the facility to bulk load archives of gauging station details and spot current meterings, abstraction, discharge and reservoir information. Once loaded, the existing editor offers facilities to edit values, to update the database, to delete features and to move features around the river network database. However, due to the complexity of abstraction licences, it shall be necessary to restructure the existing archive facility.

The software shall has been developed for accommodating the procedures for estimating artificially influenced statistics described above.

MICRO LOW FLOWS has developed the capability to produce and display residual flow diagrams based on estimated natural and artificial low flow estimates.

4. Procedure for estimating the impact of groundwater abstractions upon low flows.

Procedures have been developed for evaluating the impact of groundwater abstractions upon low flows in Chalk regions, expressed in terms of a Stream Depletion Factor, which distributes the abstracted volume as a monthly reduction in streamflow. The approach adopted has been a sensitivity analysis using a finite difference model of simple catchment configurations, combined with re-analysis of modelling results from catchment specific studies.

5. Develop procedure for incorporating spot current meterings into low flow estimation procedure.

The archiving facility for spot current meterings has been developed, and the procedure for their incorporation will be based upon that within the 1980 Low Flow Studies report for the flow duration curve.

6. Application of a simple conceptual model to estimate impact of forestry management on low flows.

Activities on this task are scheduled for 1993.

7. Combine different artificial influence procedures into final system.

Activities on this task are scheduled for 1993.

KEY WORDS

Artificial Influences, Low Flow Estimation, Abstraction Licences, Discharge Contents, Gauged and Ungauged Sites, Abstraction scenarios, Mean Monthly Minima, Base Flow Index, Flow Duration Curve, MICRO LOW FLOWS Software, River Network, Residual Flow Diagrams, Groundwater Modelling, Aquifer Simulation Model.

1 Introduction

This report is the second annual Interim Report of the three year NRA R & D contract studying "Low flow estimation in artificially influenced catchments". This contract is aimed at the development of MICRO LOW FLOWS software so that artificial influences can be incorporated into design procedures.

MICRO LOW FLOWS for low flow estimation in natural catchments has been developed since 1988 and the sequence of development and the status of software installation in England and Wales are reviewed in Chapter 2. MICRO LOW FLOWS provides access to databases of gauged flow statistics and spot current meterings (Chapter 3) from natural and artificially influenced catchments to supplement the catchment characteristic based low flow estimation procedure.

As the basis for the estimation of low flows in artificially influenced catchments, MICRO LOW FLOWS possesses the facility to bulk load archives of abstraction, discharges and reservoir information (Chapter 4), with associated editing facilities.

Whilst MICRO LOW FLOWS is the vehicle for estimating artificially influenced low flows, there has been a need to develop design procedures and methods of incorporating artificial data. Chapter 5 describes procedures developed for evaluating the impact of groundwater abstractions upon low flows, expressed in terms of a Stream Depletion Factor, which distributes the abstracted volume as a monthly reduction in streamflow. Surface water abstractions, and adjusted groundwater abstractions upstream of an ungauged site can be combined to construct a monthly artificial influence profile (Chapter 6). Natural monthly low flow statistics are estimated at ungauged sites (Chapter 7), and these are combined (Chapter 8) with the monthly artificial influence profiles to estimate artificially influenced low flow statistics at ungauged sites.

In addition to the presentation of estimated low flow statistics at a single ungauged site, MICRO LOW FLOWS has been developed to construct residual flow diagrams for the more complex display of artificially influenced low flows (Chapter 9).

This project is due for completion in December 1993, and Chapter 10 contains forecast activities during 1993, and Chapter 11 presents long-term research activities which will not be achieved during this contract.

2 Micro Low Flows

This contract is aimed at the development of MICRO LOW FLOWS software so that artificial influences can be incorporated into design procedures. MICRO LOW FLOWS has been developed since 1988, and currently exists as Version 1.3.1. The sequence of development of the different versions is summarised in Section 2.1. Version 1.3.1 has been installed as an operational tool for low flow design in several regions of the NRA, and contracts to supply further regional copies are either under contract to supply, or are under negotiation. The status of installation of MICRO LOW FLOWS in England and Wales in summarised in Section 2.2.

2.1 SUMMARY OF VERSIONS

MICRO LOW FLOWS for natural catchments has two Versions, 1.3.1 and 1.4, which differ in the methodology used to construct catchment boundaries above ungauged sites. At the end of this contract in December 1993, Version 2.0 will exist, being a Beta Version for Artificially Influenced Catchments. At the end of a six-month trial period, the full Version 2.1 will be released.

Table 2.1 Versions of MICRO LOW FLOWS

Version	Date	Development
1.3.1	Current	
1.4	April 1993	DTM-generated catchment boundaries, subject to availability of DTM
2.0	December 1993	Beta Version of Artificial Influences
2.1	June 1994	Full Version of Artificial Influences

2.2 STATUS OF INSTALLATION IN ENGLAND AND WALES

During the Project Investment Appraisal, one risk that was identified was that the implementation of the artificial influence techniques would be contingent upon regions purchasing the MICRO LOW FLOWS software. Table 2.2 establishes the status of installation of the software.

Table 2.2 Installation of MICRO LOW FLOWS software

NRA	Version	Status	No. of copies
Anglian	1.3.1	Operational	4
Northumbrian			
North West			
Severn Trent	1.3.1	Operational	1
Southern			
South West	1.3.1	Operational	1
Thames	1.3.1	Under negotiation	1
Welsh			
Wessex	1.3.1	Under negotiation	1
Yorkshire	1.4	Under contract	1

It has been agreed that those NRA regions already in possesion of MICRO LOW FLOWS (either Version 1.3.1 or 1.4) at the termination of this contract in December 1993 will receive Version 2.1 as an upgrade. Version 2.1, based on the developments of this contract, is therefore likely to be installed in at least six of the NRA regions during 1994. This suggests that the risk identified in the Project Investment Appraisal can be considered to be diminished.

Those regions not in possession of MICRO LOW FLOWS at that time will be required to purchase Version 2.1 at the cost of either Version 1.3.1 or 1.4, depending upon the selection of method for catchment boundary definition.

3 Databases of gauged flow statistics and spot current meterings

3.1 GAUGED FLOW STATISTICS

MICRO LOW FLOWS provides access to archives of gauging station details through interaction with the screen icon. These include gauged low flow statistics, specifically mean flow, MAM(7) and Q95, extracted from the National Water Archive, and loaded into MICRO LOW FLOWS at the time of installation. Ultimately, an external input facility will enable users to load data from a predetermined format. The existing editing facility allows the user to update any of the loaded parameters, which should be utilised as more recent statistics are calculated. The full set of variables within the gauging station archive are summarised in Table 3.1. This database provides access to observed low flow statistics in artificially influenced catchments which are gauged.

Table 3.1 Gauging station archive variables

NO.	PARAMETER	DEFINITION	TYPE	FIELD LIMITS
1	NGRE	National Grid Reference Easting	num	min 4
2	NGRN	National Grid Reference Northing	num	min 4
3	MFLOW	Recorded mean flow	num	no limit
4	MAM	Mean annual minimum 7 day duration	num	no limit
5	Q95	Daily flow exceeded for 95% of the time	num	no limit
6	AREA	Planimetered catchment area	num	no limit
7	BEGYR	Start year of record	num	4
8	FINYR	End year of record	num	4
9	TITLE	Gauging station title	char	max 32
10	DESCRIPTION	Description of gauging station	char	max 32

where num = numerical
char = character

3.2 SPOT CURRENT METERINGS

MICRO LOW FLOWS provides the archive facility for spot current meterings. The variables within the spot gauging archive are summarised in Table 3.2. It is currently possible to archive up to 12 spot gaugings for any one river stretch, but this constraint will be removed in Version 2.1.

Table 3.3 Spot gauging archive variables

No.	PARAMETER	DEFINITION	TYPE	FIELD LIMIT
1	NGRE	National Grid Reference Easting	num	min 4
2	NGRN	National Grid Reference Northing	num	min 4
3	DATE	Date of reading	num	6 (DDMMYY)
4	PTILE	Percentile exceedance assigned to the flow reading	num	3
5	FLOW	Measured flow	num	7
6	LREF	Local reference text	char	max 10

where num = numerical
char = character

This facility enables measured flows to be archived, with an assigned percentile exceedance value assigned by the user to assist in the identification of either a Q95 value, or to contribute to the construction of a flow duration curve based on spot current metering data (to be developed later in this contract period). It is envisaged that the primary database of current meter gaugings will be held elsewhere. A facility for the regular bulk loading to MICRO LOW FLOWS will be provided.

4 Databases of artificial influences

MICRO LOW FLOWS offers the facility to bulk load archives of abstraction, discharges and reservoir information, as summarised in Sections 4.1.1 to 4.1.3 respectively. Once loaded the existing editor offers facilities to edit values, to update the database, to delete features and to move features around the river network database (Section 4.2). All databases can be edited by the user on a restricted access basis. Due to the complexity of abstraction licences, it is necessary to restructure the existing archive facility to be able to incorporate complex licences.

4.1 BULK LOADING OF DATABASES

4.1.1 Abstraction licence database

The required variables for each entry on the abstraction licence database are listed in Table 4.1.

Table 4.1 Abstraction Licence archive variables

NO.	PARAMETER	DEFINITION	TYPE	FIELD LIMITS
1	NGRE	National Grid Reference Eastings	num	min 4
2	NGRN	National Grid Reference Northings	num	min 4
3	LISMONTH	Start month of licence period	num	max 2
4	LIEMONTH	End month of licence period	num	max 2
5	LMAXDAY	Maximum daily licenced abstraction	num	no limit
6	LMAXHR	Maximum hourly licenced abstraction	num	no limit
7	TOTANP1	Total annual licenced for purpose 1	num	no limit
8	TOTANP2	Total annual licenced for purpose 2	num	no limit
9	TOTANP3	Total annual licenced for purpose 3	num	no limit
10	TOTANP4	Total annual licenced for purpose 4	num	no limit
11	ANLTOT	Total annual licenced abstraction	num	no limit
12	MRF	Minimum required flow	num	no limit
13	LINO	NRA Licence Number	char	max 13
14	OPERATOR	Licence holder	char	max 27
15	TYPE	Type of abstraction	char	1
16	SLOCATN	Source location of abstraction	char	max 27
17	LIPERIOD	Period of year to which the licence applies	char	6 or 7
18	PURP1	Abstraction purpose 1	char	2
19	PURP2	Abstraction purpose 2	char	2
20	PURP3	Abstraction purpose 3	char	2
21	PURP4	Abstraction purpose 4	char	2

where num = numerical
char = character

The variables TYPE, PURPx and LIPERIOD are allowed the following values:

TYPE:	N	-	Non tidal surface abstraction
	T	-	Tidal surface abstraction
	G	-	Groundwater abstraction
	R	-	Reservoir
	L	-	Pond/lake
	C	-	Canal
	S	-	Spring
	U	-	Unspecified
PURPx	SI	-	Spray irrigation
	CO	-	Cooling water
	IP	-	Industrial process water
	PS	-	Public water supply
	BW	-	British Waterways
	GA	-	General agriculture
	PW	-	Private water supply
	FF	-	Fish Farming
LIPERIOD	SUMMER		
	WINTER		
	SPECIAL		

This existing database structure will be modified to incorporate aquifer unit and distance to stream.

4.1.2 Discharge licence database

Discharge consent database:

The required variables for each entry on the discharge database are listed in Table 4.2.

Table 4.2 Discharge consent archive variables

NO.	PARAMETER	DEFINITION	TYPE	FIELD LIMITS
1	NGRE	National Grid Reference Easting	num	min 4
2	NGRN	National Grid Reference Northing	num	min 4
3	DESDWF	Design dry weather flow	num	no limit
4	CAVDAY	Consented average daily flow	num	no limit
5	CMAXDAY	Consented maximum daily flow	num	no limit
6	VDATE	Consent review date	num	4 (mmyy)
7	CONNO	Consent Number	char	max 27
8	OPERATOR	Consent holder	char	max 27
9	RECRIVER	Receiving river	char	max 21
10	LOCATION	Location of discharge	char	max 24
11	SOURCE	Source of discharge	char	2
12	TYPE	Consent type	char	3
13	CONTCOND	Special operating conditions	char	max 27

where num = numerical
char = character

The variable SOURCE is allowed the following values:

CS	-	Crude sewage
SC	-	Screened sewage
SS	-	Settled sewage (primary)
TS	-	Treated sewage (secondary)
SW	-	Storm water overflow
MD	-	Mine drainage
CW	-	Cooling water
FE	-	Farm effluent
TE	-	Trade effluent
FF	-	Fish farm effluent

4.1.3 Reservoir database

The data for reservoirs is derived from Institute of Hydrology (1987) "A study of compensation flows in the United Kingdom". The attributes for reservoirs on the database are summarised in Table 4.3.

Table 4.3 Reservoir archive variables

NO.	PARAMETER	DEFINITION	TYPE	FIELD LIMITS
1	NGRE	National Grid Reference Easting	num	min 4
2	NGRN	National Grid Reference Northing	num	min 4
3	TYPE	Primary function	num	min 6
4	DATE	Date of impoundment	num	4 (mmyy)
5	TOTAREA	Total area draining to dam	num	no limit
6	NYIELD	Net yield after provision for compensation flow	num	no limit
7	COMPCODE	Release policy category	num	2
8	COMPFLOW	Compensation flow	num	no limit
9	NETCAP	Net reservoir capacity	num	no limit
10	ADFMAP	Estimated mean flow	num	no limit
11	NATAREA	Natural catchment area draining to dam	num	no limit
12	GROSSCAP	Gross reservoir capacity	num	no limit
13	ADFREC	Recorded daily flow at the dam or maintained flow point	num	no limit
14	TITLE	Reservoir title	char	max 32
15	DESC	Description of reservoir	char	max 32

where num = numerical
char = character

4.2 EDITING LOADED DATA

It is envisaged that the primary databases of artificial influence data will be held elsewhere. A facility for regular bulk loading to MICRO LOW FLOWS will be provided. Once artificial influence data have been bulk loaded, the editor facility allows the user to modify archive data, as described in the following sections.

Edit archive

This option allows the editing of existing data by retyping data displayed in the display panel.

Update archive

If any editing has taken place which the user wishes to preserve, then this facility updates the artificial influence archive.

Add to archive

This facility allows the user to create a new feature by use of the mouse, providing a template which the user can fill with data in the same way as for editing existing features.

Delete from archive

This facility allows the user to delete any feature from the archive.

Move to new location

If the user detects that the location of a feature is in error, then this facility allows a feature to be moved to a new location on the river network.

5 Impact of groundwater abstractions on low flows

To develop simple procedures for evaluating the bulk impact of groundwater abstraction upon low flows it is necessary to quantify the dependance of the impact on:

i) Bulk aquifer hydrogeology
ii) Distance from the stream
iii) Seasonality of pumping
iv) Pumping rate
vi) Degree of hydraulic connection between the stream and aquifer.

Whilst it is appreciated that the impact on specific river reaches will also be dependent on very localised physical parameters, such as the distribution of spring lines, this is not being addressed in the current work as it is infeasible to incoporate these micro physical effects into the MICRO LOW FLOWS software.

The approach adopted has been one of a sensitivity analysis using a finite difference model of simple catchment configurations combined with re-analysis of modelling results from catchment specific studies.

The sensitivity analysis work has been concentrated upon the Chalk. Other aquifer configurations are being considered through collation of information regarding other modelling studies.

5.1 THE LAMBOURN MODELLING WORK

As discussed in the December 1991 interim report, a two dimensional finite difference model has been applied to the Lambourn catchment on the unconfined chalk in the Thames basin. The modelling work and sensitivity analyses performed are presented in detail in Appendix A. The model was calibrated on observed groundwater levels and stream flow. The calibrated values of hydraulic conductivity and storativity were found to be in accordance with values found from field measurements and calibration of other numerical models.

Abstraction scenario simulations have been evaluated in terms of the stream depletion factor which relates the stream depletion, at any point in time, directly to the pumping rate.

The analysis of the abstraction scenario simulations showed that the stream depletion due to a constant abstraction depends on the abstraction rate, the distance from the stream and discharge. The depletion of a seasonal abstraction depends on the abstraction rate, the distance from the stream and the duration of the abstraction, but not the time of the year. The influence of a seasonal abstraction on low flows depends on the factors cited above and the natural low flow variability.

For example, the modelling work in the Lambourn catchment has derived the Stream Depletion Factors in Table 5.1 for an abstraction of 1200 tcma from the Chalk, at 1km away from the stream, pumping at a constant rate during the April to September period only.

Table 5.1 Example Stream Depletion Factors

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
.12	.10	.06	.60	.79	.84	.88	.90	.91	.40	.22	.18

Using these Stream Depletion Factors, the impact of the abstraction of 1200 tcma upon streamflow will be distributed throughout the year as presented in Table 5.2.

Table 5.2 Monthly reduction in streamflow (tcm) using example Stream Depletion Factors

ABST 0 0 0 200 200 200 200 200 200 0 0 0

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
24	20	12	120	158	168	176	180	182	80	44	36

5.2 FURTHER WORK

The Lambourn work to date has shown consistent trends in the relative importance of the variables thought to control the bulk impact of groundwater abstraction. To corroborate the Lambourn work, model data from the Mott Macdonald groundwater modelling studies of the Wallop Brook and River Allen studies will be re-evaluated in terms of Stream Depletion Factors. The data available includes:

* Naturalised monthly flow data
* Current abstraction time series data (subject to NRA release)
* Modelled abstraction scenarios
* Spatial details of aquifer properties.

Data from pump testing of the Candover Augmentation Scheme will also be incorporated into these studies.

Once the response of the ASM model to groundwater abstraction has been validated, further abstraction scenarios will be run to extend knowledge about the model response to set abstraction scenarios under the modelled 1962-1990 hydrological time series.

A representative range of analytical solutions for predicting the impact of groundwater abstraction will be evaluated for the pumping scenarios considered in the numerical modelling. The effectiveness of the solutions will be evaluated with respect to the numerical modelling work and a solution selected for incorporation into the MICRO LOW FLOWS software.

A sensitivity analysis will be performed to ascertain the response of the selected solution for key abstraction scenarios under various aquifer types.

5.3 INCORPORATION OF THE GROUNDWATER ESTIMATION PROCEDURES INTO THE MICRO LOW FLOWS SOFTWARE

The final adjustment algorithms will estimate the 12 monthly Stream Depletion Factors for a given abstraction regime. Estimating the impact in this form will enable the annual flow duration curve adjustment procedures developed for the surface water abstractions to be utilised.

One of the key parameters in the adjustment algorithms will be hydraulic conductivity and storativity. At this point in time there isn't a digital database of the spatial distribution of aquifer parameters within the UK. The BGS are currently compiling a national map of T&S values for NRA. It is not clear yet whether this will be available in digital format. In the absence of such a database there are two approaches that can be taken to estimate these values:

i) To assign typical values of the aquifer properties to classes within the Hydrology of Soil Types database classification.

ii) To use typical values for the aquifer unit, as defined on the abstraction licence. Aquifer Unit shall be incorporated into the Abstraction Licence database.

Archived Features are indexed in MICRO LOW FLOWS on a stretch basis. Features are assigned to stretches using a closest distance algorithim. This algorithm will be modified to also calculate the distance to the nearest stretch.

6 Monthly artificial influence profiles at ungauged sites

At an ungauged site MICRO LOW FLOWS possesses the facility to construct a monthly artificial influence profile based on information archived within the Artificial Influence databases. This facility is based upon three steps:

i) the capability to identify all upstream occurrences of artificial influences upstream of the ungauged site, due to the structured river network database.

ii) the capability to total all upstream occurrences of a specific artificial influence parameter, eg. licensed abstraction rates. This is achieved at a monthly time unit, taking account of licence periods.

This sequence enables the construction of a monthly artificial influence profile at an ungauged site. This is illustrated for the simple case of a site with two upstream licences, one constant and the other summer only in Figure 6.1. In cases where groundwater abstractions occur, then the Stream Depletion Factors will be used to distribute the abstracted volume as a monthly reduction in streamflow. It is these reductions that will be incorporated into the monthly abstraction profile rather than the licensed abstraction volume on the database.

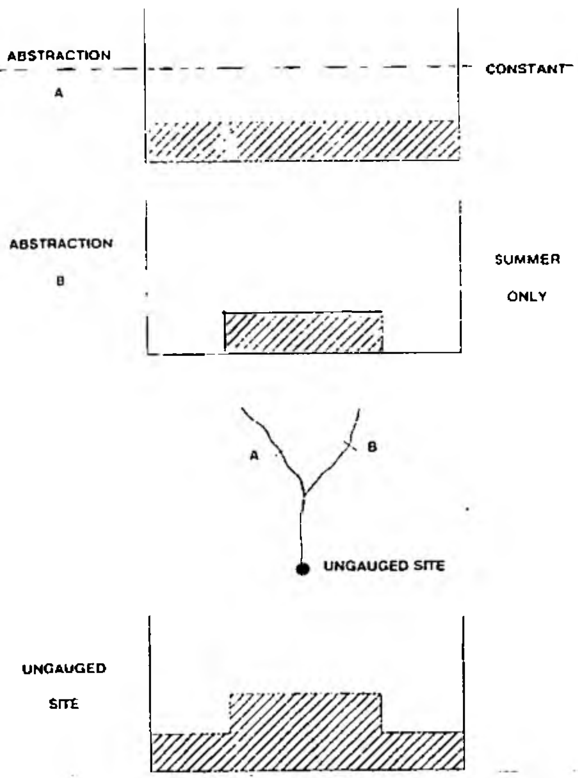


Figure 6.1 Construction of a monthly artificial influence profile

7 Estimation of natural monthly low flow statistics at ungauged sites

The objective is to estimate natural low flow statistics at ungauged sites, on a monthly basis, prior to combination with the monthly artificial influence profiles. Section 7.1 reports an investigation of the seasonality of low flows in the United Kingdom, which can be used for identification of the month of occurence of annual minima. Section 7.2 describes the methodolgy for the estimation of mean monthly minima for each of the twelve months. Section 7.3 describes the methodology for estimating seasonal flow duration curves.

7.1 SEASONALITY OF FLOWS

The work described in this section investigates the seasonality of annual minima in Great Britain, and provides a procedure for identification of the month of natural occurrence of lowest flows.

For each of n gauging stations, the seven-day minimum flow was identified for each year of record. Day numbers (1 to 365) were obtained for the centroid (4th day) of the seven-day minimum in each year of record. At a gauging station, the mean and standard deviation of the series of centroid day numbers were calculated.

Annual data may be represented using circular statistics (Mardia, 1972), as illustrated in Figure 7.1.

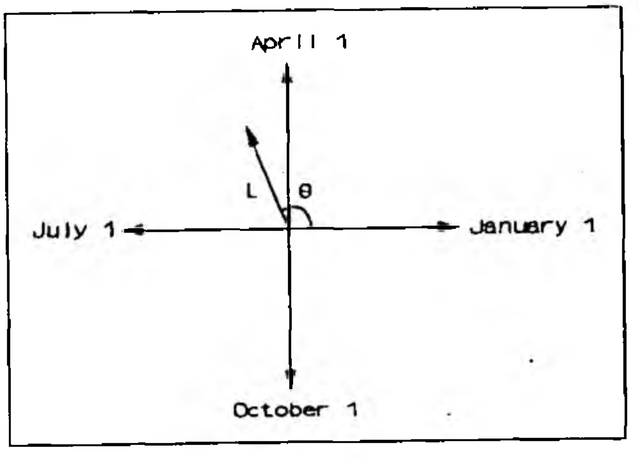


Figure 7.1 Representation of seasonality of low flows using circular statistics

Using this procedure, the mean day is defined by the direction of the arrow. The angle (in radians, measured from the horizontal) was derived from the equation;

$$\theta = \left[mean\ day\ number . \frac{2\pi}{365} \right] - \frac{1}{2} . \left[\frac{2\pi}{365} \right]$$

The length of the arrow is proportional to the standard deviation (in days) and appropriate to the scale of the plot.

This calculation is illustrated for a sample gauging station below;

Station 3002 - R. Carron
NGR NH 490921
Mean day number = 215; standard deviaton (days) = 51

For the direction of the arrow:

$$\theta = \left[215 . \frac{2\pi}{365}\right] - \frac{1}{2}\left[\frac{2\pi}{365}\right]$$

$$= 3.6924 \ rad$$

$$= (211.56°)$$

On a scale of 1:5 250 000, limits to arrow size are given as:

maximum = 80 000 m (equivalent to 111 days)
minimum = 10 000 m (equivalent to 19 days)

Therefore:

$$L = \frac{(51-19)}{(111-19)} . (80000-10000) + 10000$$

$$= 34348 \ metres$$

An arrow can be drawn:

From X=249000 Y=892100 (gauging station)
To X=219733 Y=874123

This procedure was applied to 687 good quality, relatively natural gauging stations to produce the map (Figure 7.2) depicting the mean day and standard deviation of day numbers of the centroid of annual seven-day minima in Great Britain.

This Figure can be used for the identification of the month of occurrence of annual minima, and offers guidance to the user in selecting appropriate months for low flow design in which the mean monthly minima (Section 7.3) should be estimated and adjusted for artificial influences.

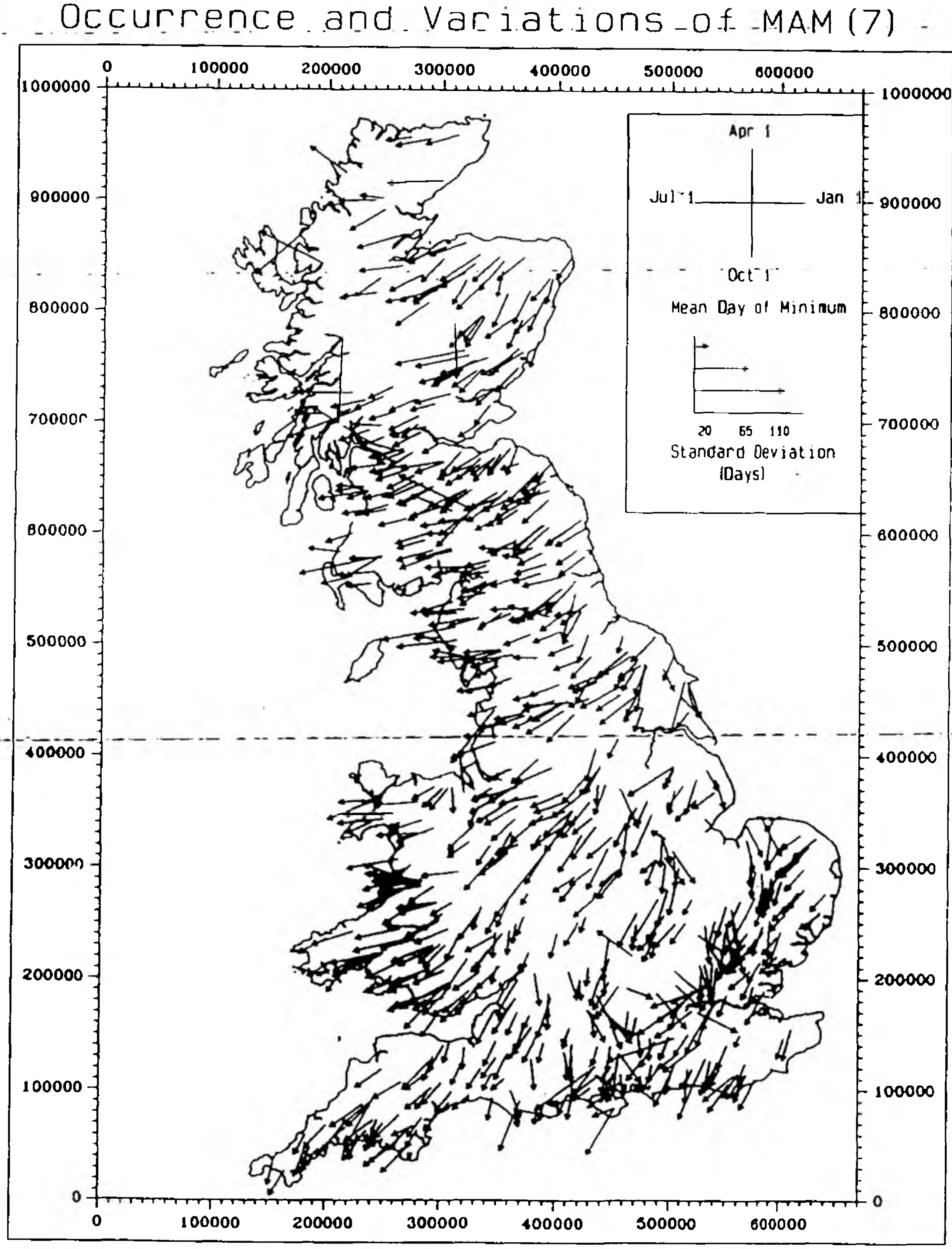


Figure 7.2 Seasonality of annual minima in Great Britain

7.2 MEAN MONTHLY MINIMA

This section describes procedures for the estimation of natural mean monthly minima at ungauged sites based on multiple regression with MAM(7) and catchment characteristics as independent variables. Analysis is based on 687 gauging stations with flow records in excess of ten years, and graded as usable for low flow studies in Gustard et al. (1992). The first step was to identify the improvement in error reduction of including different sets of independent variables. It was found that errors were reduced by the use of MAM(7), SAAR and AREA as independent variables, with log transformations.

This established that the general model for the estimation of mean monthly minima should be of the form

$$MMM(7) = a.\ MAM(7)^{b}.AREA^{c}.SAAR^{d}$$

For each of the twelve months. the general regression model was calibrated, and the regression parameter estimates are presented in Table 7.1, along with the percentage variance explained and the factorial standard error of estimate.

Table 7.1 Parameter Estimates for monthly minimum equations

	ERROR PARAMETERS		PARAMETER ESTIMATES			
			a	b	c	d
MMM	FSE	R^2	const	MAM(7)	AREA	SAAR
JAN	1.209	0.3606	152.61	0.144	0.012	-0.159
FEB	1.300	0.5269	997.57	0.215	0.001	-0.459
MAR	1.274	0.5570	432.95	0.259	-0.012	-0.358
APR	1.333	0.6930	628.30	0.433	-0.020	-0.523
MAY	1.311	0.7304	155.02	0.509	-0.019	-0.386
JUN	1.307	0.7998	42.53	0.667	-0.033	-0.302
JUL	1.288	0.8240	3.09	0.766	-0.031	0.007
AUG	1.260	0.7865	0.28	0.671	0.001	0.382
SEP	1.307	0.6946	0.07	0.608	0.014	0.619
OCT	1.252	0.5971	0.21	0.371	0.020	0.607
NOV	1.257	0.4776	0.60	0.268	0.033	0.526
DEC	1.224	0.3420	12.35	0.210	0.024	0.143
mean error	1.277			0.015	0.007	0.027

The parameter estimates associated with MAM(7), AREA and SAAR all display cyclical variability over the twelve months, but each out of phase with each other. The interdependency of parameter estimates in multiple regression procedures makes the physical interpretation of parameter estimates difficult. The overall percentage of variance explained by the regression equations displays a similar cyclical pattern, with higher explanation of variance in the summer and lower in winter. Indeed, the percentage of variance explained in winter months is low. However, the factorial standard error of the estimates from the regression equations remains relatively constant between 1.2 and 1.3, and mean monthly minima are estimated to within ±30% of observed values for 68% of the time by this procedure.

7.3 FLOW DURATION CURVE

The method for the estimation of artificially influenced flow duration curves is based first upon developing the capability to estimate natural seasonal flow duration curves. This is achieved by a procedure that has involved two steps, of which only the first step is complete.

The first step is to develop pooled monthly flow duration curves, based on groups of stations which have similar Q95 values. The second step is to construct Type Curves from the pooled monthly flow duration curves.

In achieving the first step, time series of daily flow data for 686 gauging stations were used. These gauging stations were assigned to groups according their gauged value of Q95, as summarised in Table 7.2.

***Table 7.2** Number of gauging stations used to develop pooled monthly flow duration curves*

Q95 group	Number of curves per group
0-2.5	12
2.5-7.5	87
7.5-12.5	156
12.5-17.5	146
17.5-22.5	98
22.5-27.5	71
27.5-32.5	37
32.5-37.5	30
37.5-42.5	18
42.5-47.5	13
47.5-52.5	3
52.5-57.5	3
57.5-62.5	3
62.5-67.5	3
67.5-72.5	0
72.5-77.5	1
Total	686

For each Q95 group, monthly flow duration curves were derived for the months of January, April, July and October. Figure 7.3 displays the sets of January and July flow duration curves for catchments with Q95 between 2.5 - 7.5% of mean flow.

For each of the 16 Q95 Groups, and for each of the four months, a single pooled flow duration curve was calculated. These pooled curves are displayed in Figure 7.4.

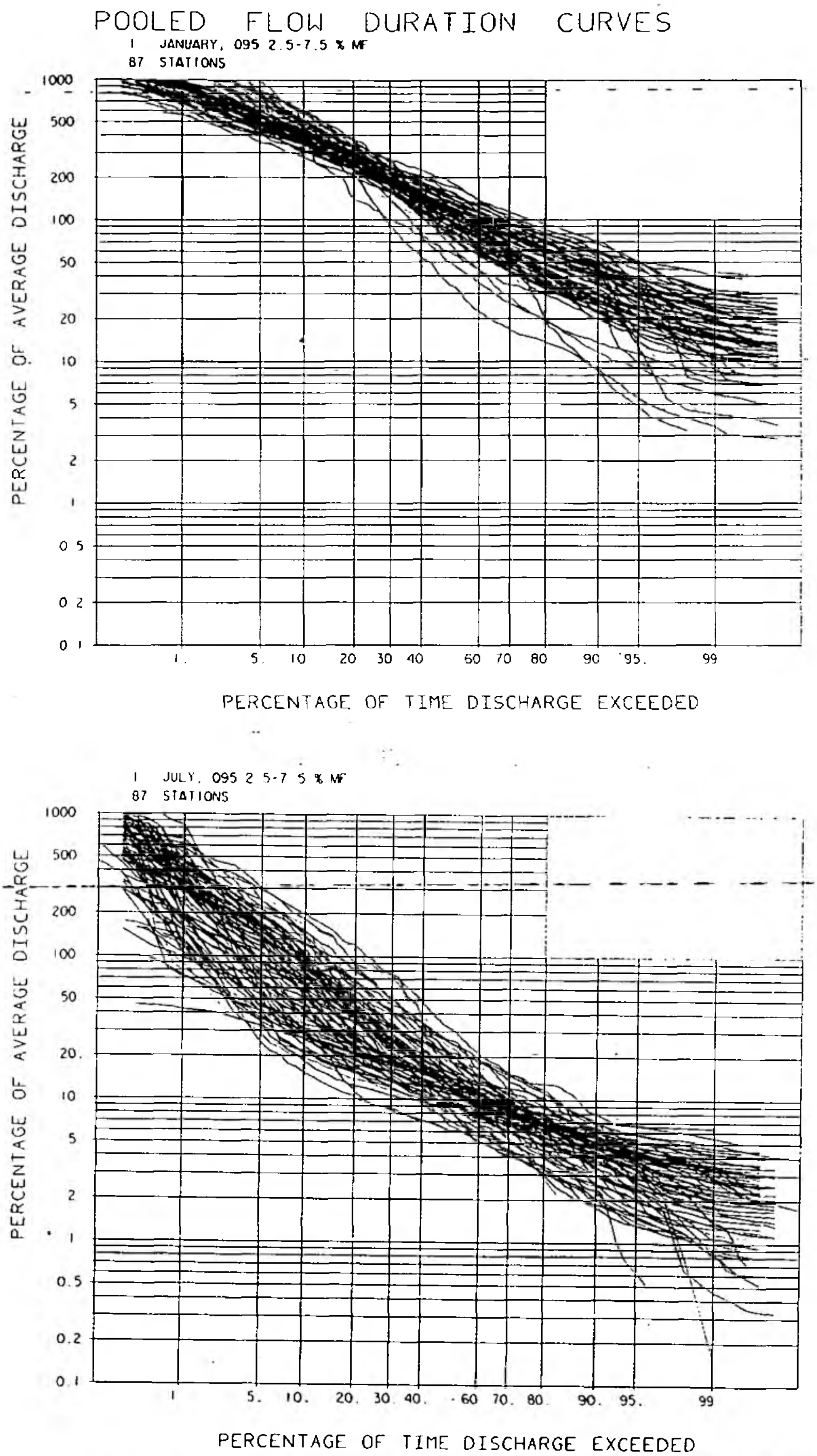
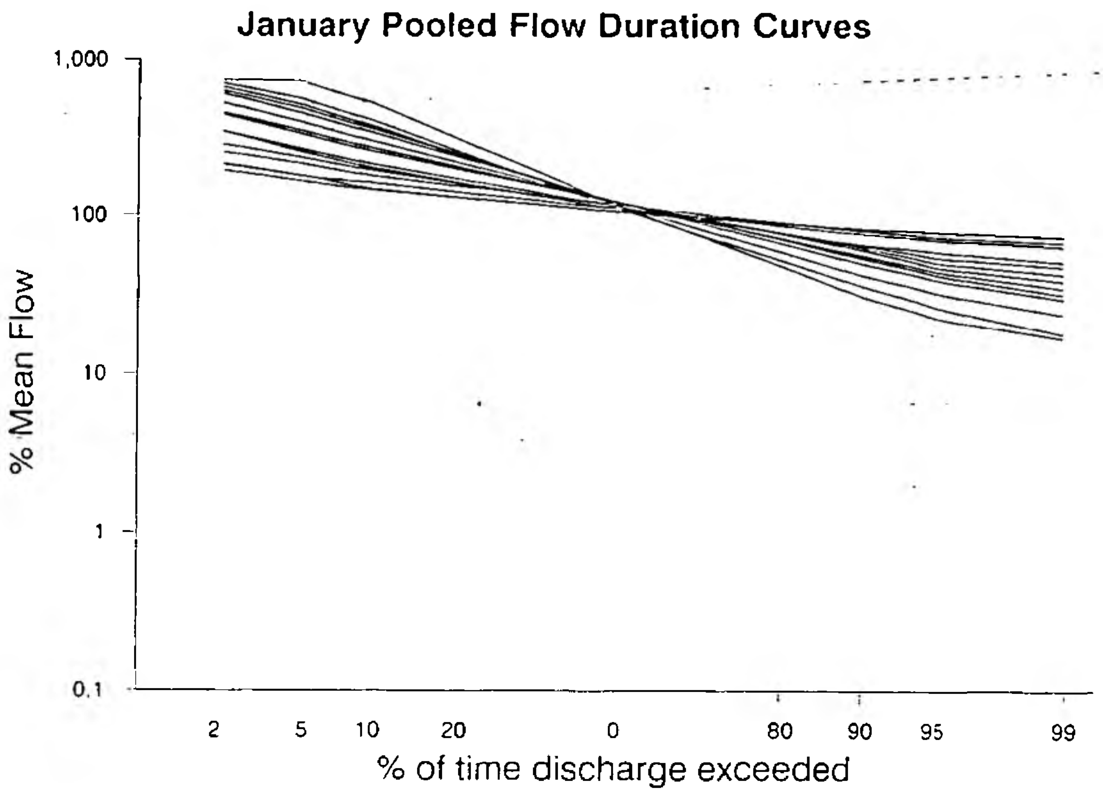


Figure 7.3 Sets of January and July flow duration curves for catchments with Q95 between 2.5 and 7.5% of mean flow.



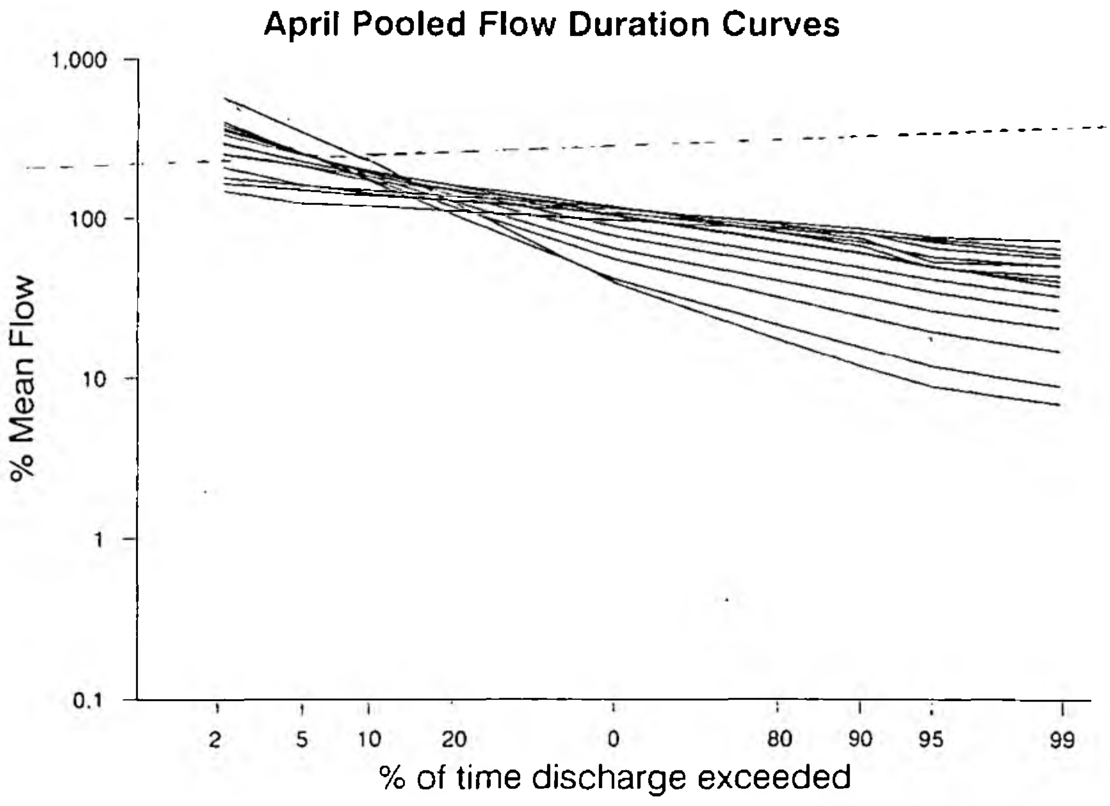
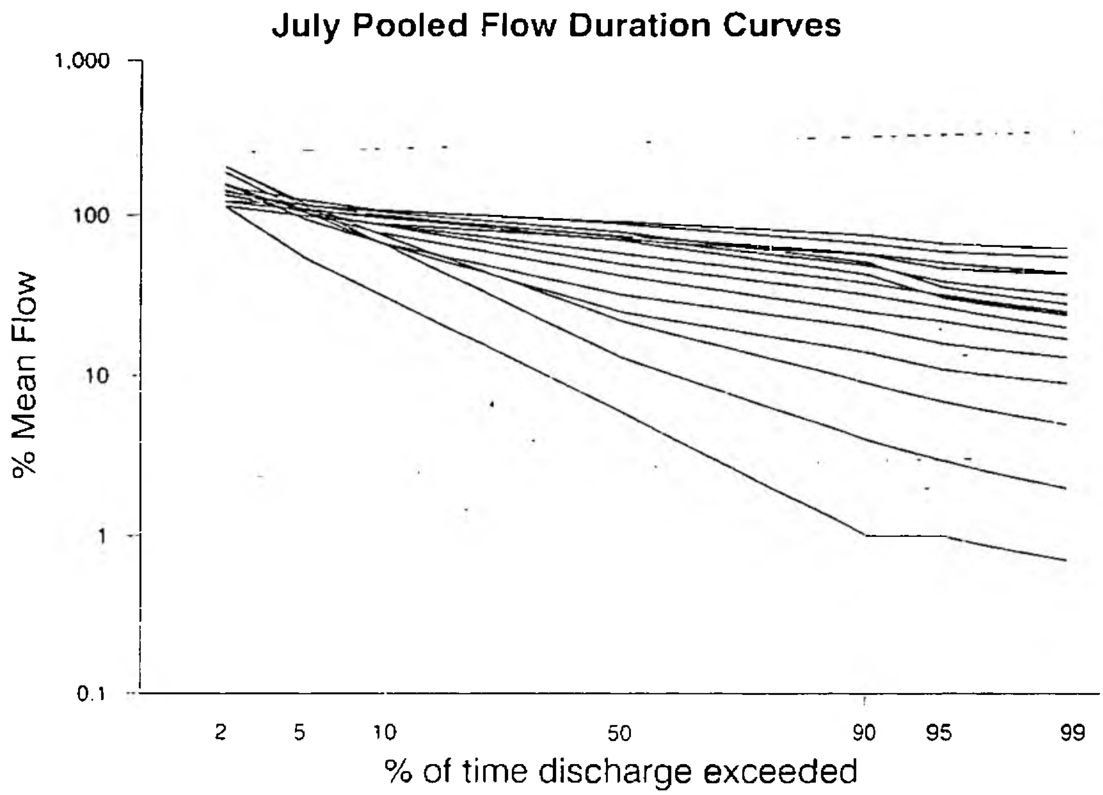


Figure 7.4 Monthly pooled flow duration curves



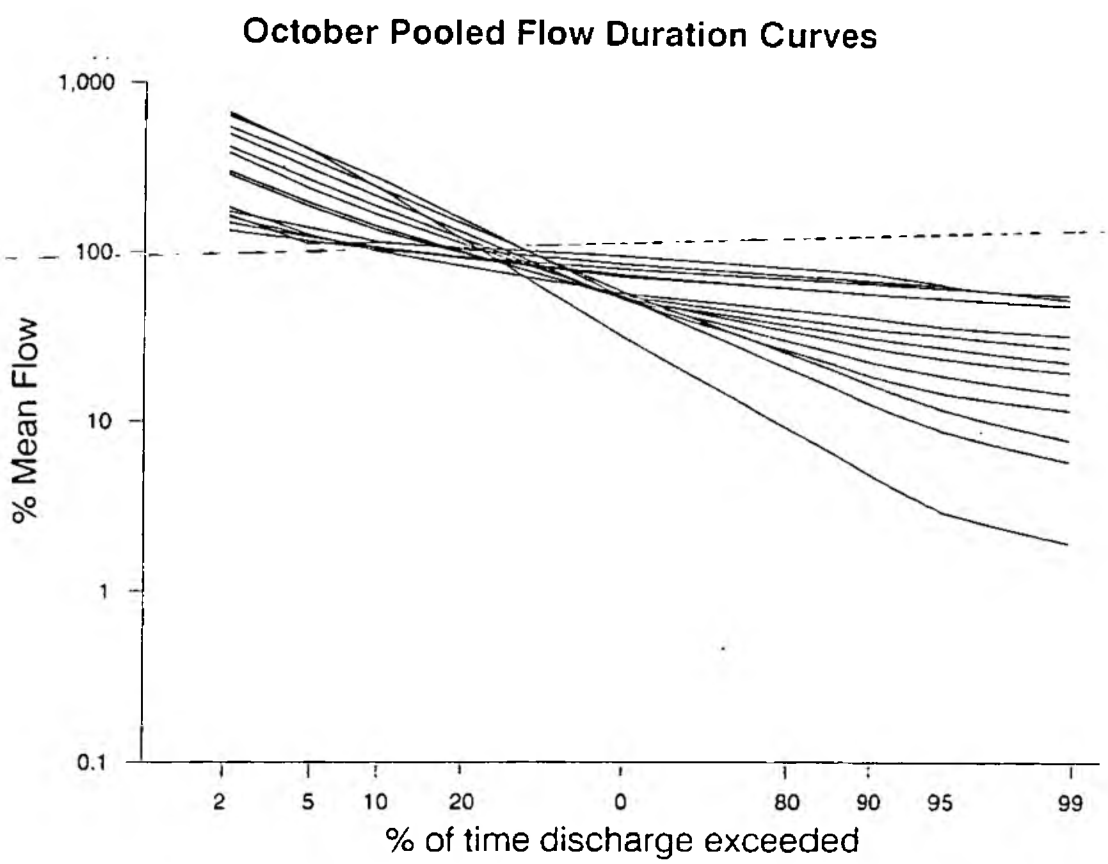


Figure 7.4 (cont.) Monthly pooled flow duration curves

The next step remains to convert the pooled flow duration curves into Type Curves, which has the effect of generalising and smoothing the pooled curves. The Type Curves developed for the estimation of annual flow duration curves in Gustard et al (1992) are unsuitable for generalising monthly pooled curves. The monthly pooled curves show greater variability in position, slope and shape, and will not be simple to generalise to Type Curves.

8 Estimation of artificially influenced low flow statistics at ungauged sites

8.1 MEAN MONTHLY MINIMA

The procedure for estimating artificially influenced mean monthly minima is based on two stages:

STAGE 1 Estimation of mean monthly minimum for the month of interest, as described in Section 7.3. The map showing the seasonality of low flows (Section 7.1) or local knowledge should be used to give guidance to the range of months in which the mean annual minimum could occur.

STAGE 2 Adjustment of the mean monthly minimum by combination with the monthly artificial influence profile to calculate the artificially influenced mean monthly minimum.

8.2 FLOW DURATION CURVE

The procedure for estimating artificially influenced flow duration curves is based on three stages:

STAGE 1 Estimation of 12 monthly Type Curves, as described in Section 7.2

STAGE 2 Adjustment of each of the monthly 12 curves by combination with the monthly artificial influence profile to create 12 monthly artificially influenced flow duration curves

STAGE 3 Reconstruction of the 12 monthly artificially influenced flow duration curves to produce a single annual artificially influenced flow duration curve.

Stage 2 combines the estimated Type Curve with the artificial influence profile for each month, as illustrated in Figure 8.1.

Stage 3 reconstructs a single annual artificially influenced curve from the twelve monthly curves. This is achieved by deriving, for specified flows, the 12 percentile values associated with that flow, and calculating a weighted average. The average is weighted by the number of days in each month. One point on the reconstructed curve is produced by plotting the weighted average percentile against the specified flow. This procedure is repeated for a range of flows to construct the whole curve. This procedure is illustrated for two seasonal (winter and summer) flow duration curves in Figure 8.2.

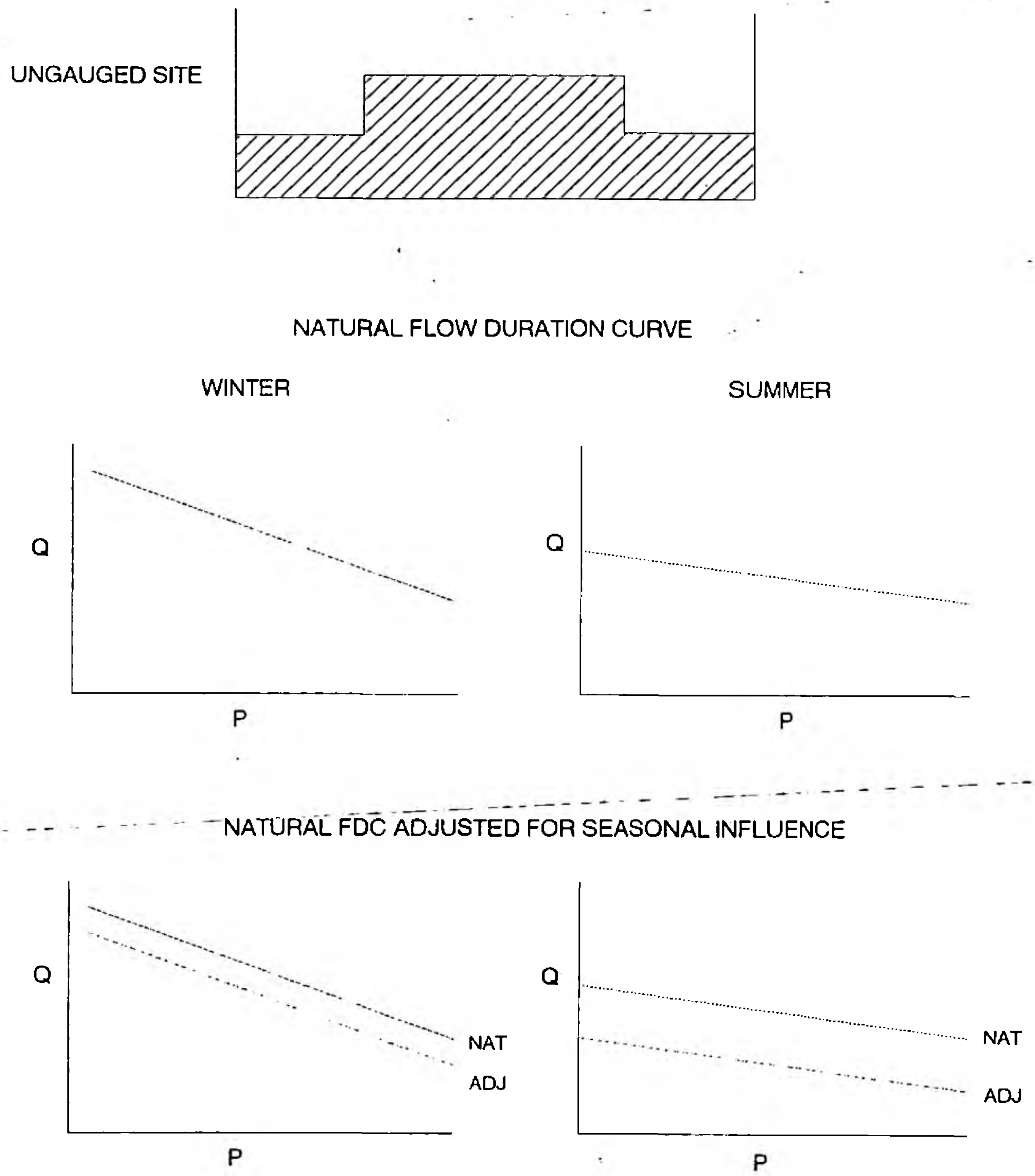
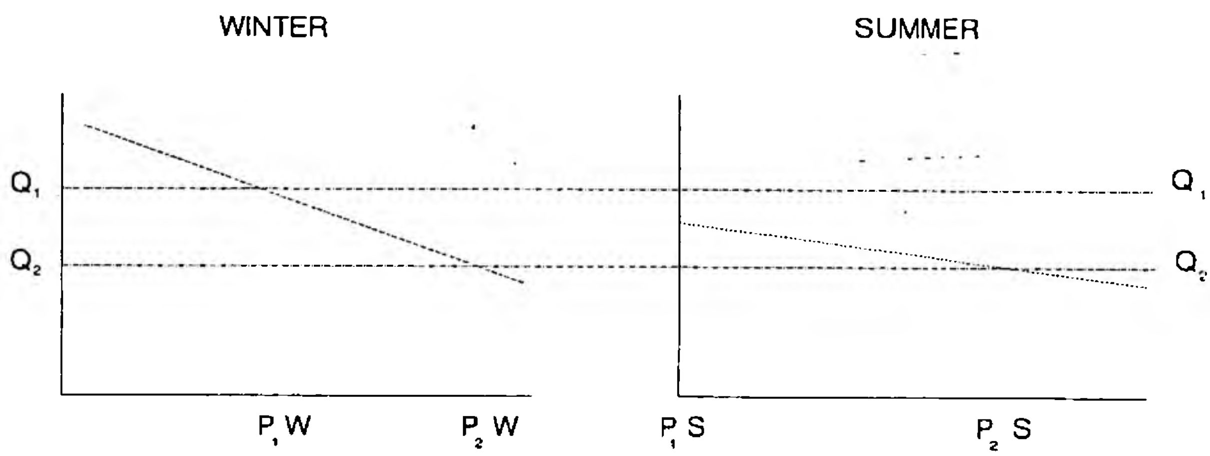


Figure 8.1 Combination of estimated Type Curve with monthly artificial influence profile

CALCULATION OF PERCENTILES FROM ADJUSTED MONTHLY FLOW DURATION CURVES



FOR Q_1 $\quad P_{1ADJ} = (P_1 W + P_1 S) / 2$

FOR Q_2 $\quad P_{2ADJ} = (P_2 W + P_2 S) / 2$

RECONSTRUCTED ADJUSTED ANNUAL FLOW DURATION CURVE

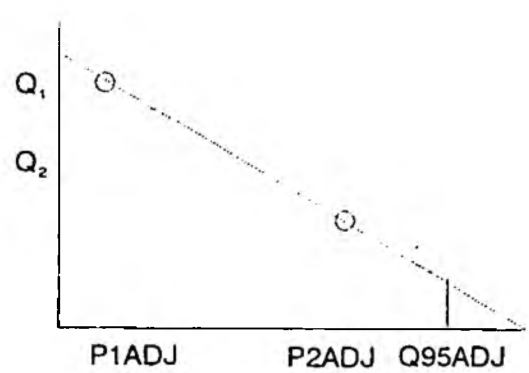


Figure 8.2 Reconstruction of single annual artificially influenced curve from monthly curves

9 Residual flow diagram

The residual flow diagram illustrates the total quantity of water in a river or stream for any location on the river at a single point in time for a chosen flow condition, assuming conditions are the same throughout the catchment. The first section describes the residual flow diagram which is based on the framework established by the Mersey & Weaver River Authority and adopted by the late John Pirt for studies of the Severn and Trent regions. The second section describes in more detail some of the features and modifications that are appropriate to the MICRO LOW FLOWS implementation of the diagrams.

9.1 KEY COMPONENTS

The key components of a residual flow diagram are as follows:

1. The vertical axis represents the line of the principal channel. Distance from source, or any other starting point, is measured downwards from the top of the axis in Km. The distance downstream from the source is annotated at evenly spaced distances.

2. The horizontal axis represents the rate of flow of the river measured in Ml/d, TCMD or m^3/s. The flow is separated into two components: the natural flow component is on the left of the vertical axis; the artificial component spans the full width of the axis with net gains (positive) on the right of the vertical axis and net losses (negative) on the left. The units used for the abstractions and discharges will be the same as for the natural flows.

3. The natural flow component is represented by natural flow statistics estimated using the IH methodology. In particular, the chosen flow conditions reflect the mean flow, a flow with a chosen flow percentile eg. Q95 or a minimum flow for a given duration e.g. MAM(7).

4. Incremental changes in the natural flows occur at the downstream limit of river stretches, as defined within MICRO LOW FLOWS. Tributaries are labelled with the names of the tributaries at the appropriate locations.

5. Discharges to the river which result predominantly from industrial effluents, sewage treatment works or other returns, but also from compensation flows, are plotted on the diagram increasing towards the right. A discharge consent may be represented by different measures and MICRO LOW FLOWS will allow a) design dry weather flow, b) consented average daily flow and c) consented maximum daily flow.

6. Reservoirs are represented in MICRO LOW FLOWS by a river stretch, including natural inflows, with a symbol at the location of the dam. Below the dam, the natural flow is assumed to be zero, therefore the compensation releases (discharges) will replace the natural flow until tributaries join the main channel.

7. Abstractions from the river are represented by lines which increase to the left. The length of line indicates the magnitude of the abstraction. An abstraction licence may be represented by different measures and MICRO LOW FLOWS will allow a) annual

licensed total abstracted quantities or b) daily licensed total abstracted quantities.

8. If an abstraction occurs that is greater than the residual flow of the river, the line is shown to extend across the vertical axis into the natural flow component and not be truncated at the axis.

9. Where abstractions and returns are made at the same location, a line drawn on the diagram indicates the magnitude of the total abstraction and total discharge, thus the flow downstream of this point is the net effect of abstraction plus partial return.

10. All major artificial influences will be labelled at the appropriate locations. The label will be the NRA licence number for abstractions and the name of the treatment plants, reservoirs, power stations etc for discharges.

The key components described above are illustrated in Figure 9.1.

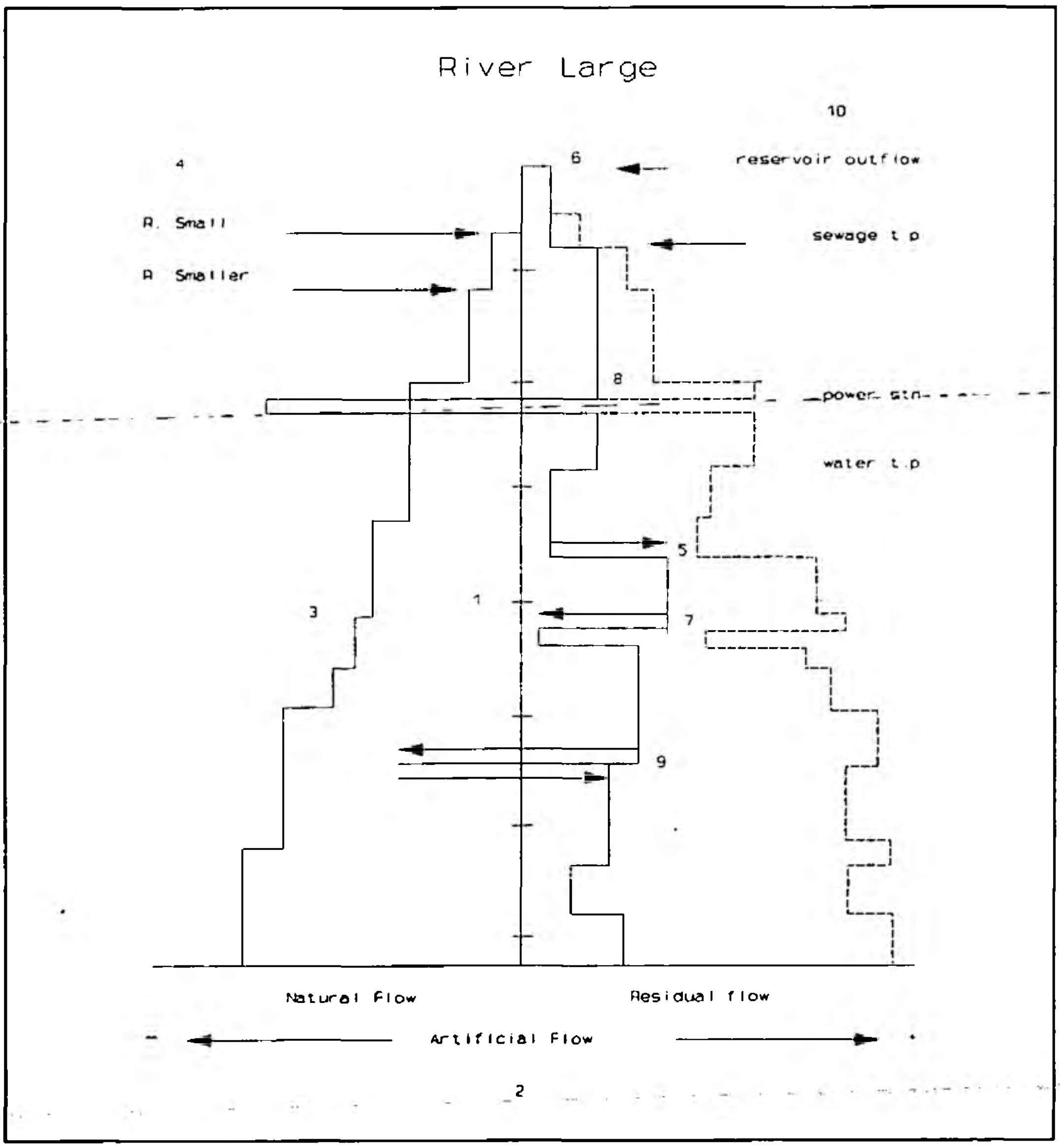


Figure 9.1 Idealised residual flow diagram

9.2 MICRO LOW FLOWS IMPLEMENTATION OF RESIDUAL FLOW DIAGRAM

1. The upstream and downstream locations of the river section of interest for the residual flow diagram can be defined by the user from the river network by using the mouse.

2. The appropriate statistics for representing the natural flows will be specified by the user from a list which may include a) mean flow, b) a selection of percentiles, for example Q95, Q80, Q50.

3. In addition to the natural and artificial flows, a line will be drawn on the right hand side of the axis to represent the sum of the natural and net artificial components i.e. plotting the residual flows.

4. There is the capability to write a title for the diagram which will be included in the output. The title will be specified by the user but should include the river name.

5. The introduction of labels for the names of tributaries, abstraction and discharge locations, accessed from a file, has been accommodated as far as possible. The options for labelling will be a) labelling the streams and artificial influences on the diagram (see Figure 1) or b) if there are a large number of labels, the names and cumulative distances downstream will be printed in a table, however, this table would not be displayed on the screen but would be printed out as part of the hardcopy.

6. The user is able to define the scale of the flow axis, specifying the maximum flows for both the natural and artificial components, which allow for diagrams to be overlaid. This may result in some large abstractions, for example gross cooling water, exceeding the limits of the graph and these will be truncated.

7. There is the capability to produce hardcopy output of the diagram and the associated list of stream names and influences, if appropriate, on A4 paper. In addition there will be some facility for saving data from the diagram to an external file for further analysis. The file would contain LID, grid reference (easting and northing), cumulative distance downstream from source, the natural flow and the net artificial flow. A line will be printed for the downstream end of each river stretch.

8. Control rules and hands off conditions will be difficult to incorporate. The initial solution will be to use the editor to change abstraction or discharge quantities manually to represent restrictions. These alterations will only be effective during the active session, enabling the master data base to remain unchanged. The capability could be developed to flag those licences to which conditions apply.

9. Within MICRO LOW FLOWS the adjustment procedure for calculating "artificially influenced" statistics will be applied on a stretch by stretch basis, accumulating to the point of interest. This will allow seasonal variations in abstraction licences to be considered. In addition to the residual flow diagram, the facility will be developed to plot these adjusted Q95 values against distance downstream for each stretch along the section. It is essential to note that the adjusted Q95 will be different, in many

- cases, from the sum of the natural and artificial components on the residual flow diagram.

N.B. There will be a disclaimer with the software to the effect that the NRA regions provided the information relating to the names and locations of the streams and influences which is assumed to be correct, but IH cannot accept responsibility where this information is mis-assigned within MICRO LOW FLOWS. Users external to the NRA must liaise with the NRA for bulk loading of artificial influence data and spot current meterings, and may thereby incur data handling charges.

10 Forecast activities during 1993

The following activities are forecast for 1993 towards completion of the contract in December 1993.

i) Development and restructuring of MICRO LOW FLOWS editor to enable archiving of complex licence configurations.

ii) Development of capability to accommodate actual abstraction and discharge volumes.

iii) Identification of Type Curves for pooled monthly flow duration curves.

iv) ASM simulations to extend knowledge about the model response to set abstraction scenarios under the 1962-1990 hydrological time series.

v) Model data provided by Mott Macdonald groundwater modelling studies will be re-evaluated in terms of Stream Depletion Factors.

vi) Evaluation of analytical solutions for the impact of groundwater abstraction on streamflow with respect to numerical modelling work on the Chalk.

vii) Sensitivity analyses to ascertain the response of selected analytical solution for key abstraction patterns for other aquifer units.

viii) Establish how to assign appropriate aquifer characteristics for use in assessing the impact of groundwater abstraction.

ix) Development of procedures for incorporating spot current metering.

x) Development of procedures for incorporating the impact of coniferous afforestation/deforestation.

xi) Development of Beta Version (2.0) of MICRO LOW FLOWS for Artificial Influences.

xii) Quarterly progress reports and Final Report

11 Long-term research activities

At this stage, it is possible to identify activities which will not be achieved during this contract. These should be considered as longer-term research activities, beyond the completion date of this contract in December 1993.

i) A detailed regional analysis to estimate monthly flow-duration curves at ungauged sites.

ii) Development of procedures for the estimation of artificially influenced MAM(7). This should involve the estimation of monthly low flow frequency curves, and probability based simulation to combine monthly frequency curves to generate an artificially influenced annual low flow frequency curve. This can then be used for the derivation of estimates of artificially influenced MAM(7), or monthly frequency statistics.

iii) Investigation of the relationships between abstracted volumes, cropping patterns, soil moisture deficits and antecedent rainfall. This study should contribute to the more precise estimation of actual abstracted quantities.

iv) Development of access through MICRO LOW FLOWS to HYDATA to provide access to artificially influenced gauged flow series.

v) Extension of low flow analysis to the impact of other land use types.

vi) Development of groundwater pumping impacts concentrating on determining the importance of local parameters such as springlines and development of regional databases of aquifer properties, streambed permeabilities and properties of confining layers.

Appendix A The Lambourn Catchment Modelling work

A.1 INTRODUCTION

The objective of this part of the study has been to develop a simple numerical model of a typical chalk catchment which could be used for a sensitivity analysis of the impact of groundwater pumping on stream flow with respect to abstraction regimes and aquifer configuration.

The Lambourn catchment is on the Berkshire Downs, which lies on the unconfined Chalk aquifer. This aquifer is the major aquifer in the UK both in areal extent and in the quantity and quality of water extracted from it. The Lambourn catchment was investigated intensively during the 1960s and 1970s for the purposes of the West Berkshire Groundwater Scheme, which had the objective of maintaining downstream river flows during dry periods through augmenting the River Lambourn by groundwater pumping (Hardcastle, 1978).

The Lambourn catchment was chosen for the chalk catchment because of its extensive groundwater and river flow monitoring network developed as part of the West Berkshire Groundwater Scheme. Furthermore, except for short periods when the abstraction scheme was operated, the catchment is relatively natural with only 3 % of the mean flow abstracted for local supply.

The aquifer in the Berkshire Downs has been extensively modelled in the past (Oakes and Pontin, 1976; Connorton and Hanson, 1978; Morel, 1980), and most recently by Rushton *et al.* (1989), who developed a three dimensional model of the complete River Kennet basin for estimating the groundwater resources of the aquifer.

The numerical basis and the assumptions of the model are described. The calibration procedure is discussed, and the calibrated values are compared to values used in other models which have previously been applied to the catchment. Finally, the sensitivity of the catchment low flow response to groundwater abstractions is estimated.

A.2 HYDROGEOLOGY OF THE STUDY AREA

The study area is the 234.1 km^2 catchment of the River Lambourn gauged at Shaw in Newbury (Fig. 1). The Lambourn is a tributary of the River Kennet, which drains the Berkshire Downs to the Thames. The only streams within the catchment are the Lambourn itself and the Winterbourne, a northern tributary which joins the Lambourn just upstream of Newbury. The bourne head of the Lambourn varies by up to 7 km downstream from the source shown in Fig. 1. Similarly the bourne head of the Winterbourne varies by about 5 km depending on the groundwater table.

The catchment topography rises from 76 m to 226 m above sea level and has a general slope towards the south east (Fig. 1). The irregularly shaped contour lines show the existence of several dry valleys. The topography and drainage of the region are strongly controlled by geological structure. The region is situated on the northern flank of the London Basin, which is an asymmetrical syncline, dominated by Cretaceous Chalk (Fig. 2). The Chalk has a thickness of more than 200 m and with its northern escarpment forms the catchment boundary with lower ground on the older Greensand and clays to the north. In the central part of the catchment the Chalk is overlain by more impermeable deposits of clay with flint.

The Chalk is a porous, micritic, white limestone divided into a lower, middle and upper zone. Results of geophysical well-logging and pumping tests have shown that groundwater movement is related to fissures mainly parallel to the bedding, and that fissure development is dependent on depth rather on stratigraphy (Owen *et al.*, 1977, Owen and Robinson, 1978). The effective saturated thickness is about 30-50 m.

The transmissivity (T) and storativity (S) vary laterally as well as vertically, the lateral variation having an apparent correlation with topography. Based on four parameters (distance from a main valley, depth to water table, saturated thickness and the proportion of the effective aquifer in the lower Chalk) a hydrogeological model was developed (Owen and Robinson, 1978). According to this model the T value varies horizontally as shown relatively in Fig. 3. The base value for average groundwater levels is $T = 2x10^{-2}$ m^2 s^{-1}. The storativity varies in a similar way from 0.4 % to 3 %. In addition to the horizontal variation, the transmissivity decreases with decreasing water levels (Connorton and Reed, 1978) due to a reduction in saturated depth and in the hydraulic conductivity (K).

A.3 NUMERICAL BASIS OF THE ASM MODEL AND REPRESENTATION OF THE AQUIFER PROPERTIES

The ASM model (Aquifer Simulation Model) was applied to the catchment. This is a two-dimensional, finite difference, numerical model, developed by Kinzelbach and Rausch (1989). The model includes a leakage flow term, which is used to simulate the exchange flow between the aquifer and surface water. The program uses the IADI (Iterative Alternating Direction Implicit) method described by Prickett and Lonnquist (1971) to solve the differential, heterogeneous, isotropic, transient groundwater flow equation:

$$T\left(\frac{d^2\theta}{dx^2} + \frac{d^2\theta}{dy^2}\right) = S\,\frac{d\theta}{dt} + q \qquad (1)$$

where x and y are orthogonal space coordinates, t is time, θ is the water table and q a general flow term including fixed boundary flows, recharge, leakage to/from streams and abstractions. For each iteration T is calculated as K times the saturated depth of the unconfined aquifer. The IADI method is stable for large time steps, which allows monthly data to be used.

A rectilinear mesh was superimposed over the study area such that the grid lines lie parallel to the major valleys (Fig. 4). The grid size was selected to be 500 m in both directions. The boundary was defined as a non-flux boundary following the groundwater divide determined on the basis of the groundwater potential map marked in Fig. 5. The map is based on mean values of the maximum groundwater level (February-March 1988) and the minimum level

(December 1990) observed during the period 1966-1990 in those wells shown in Fig 5. These mean values are found to be close to the average groundwater levels. The groundwater catchment area was estimated to be 210 km^2, which corresponds to 90% of the topographic catchment area. The bottom of the aquifer in each cell is defined to be 40 m below mean groundwater level. This corresponds to the estimated depth of the major aquifer as published in the literature.

The stream cells, shown in Fig.4, differ from the remainder by including a leakage rate (q_{lea}) between the aquifer and the stream. When the hydraulic head is higher in the aquifer than in the stream the leakage rate is directly proportional to the head difference (θ-h) between that of the aquifer potential head (θ) and the stream surface water level (h), and the hydraulic conductivity of the streambed (p'), and is inversely proportional to the thickness of the streambed material (m'). The constant of proportionality termed the leakage coefficient λ is defined as p'/m'. The leakage rate can thus be calculated as:

$$q_{lea} = \frac{p'}{m'}(\theta - h) = \lambda(\theta - h) \quad . \qquad (2)$$

However, when θ becomes lower than the bottom of the river bed (h_b) the stream cells are represented as a series of tanks draining through the resistance of the streambed. In this case the leakage rate is proportional to the potential head in the stream and can be calculated as:

$$q_{lea} = \lambda(h - h_b) \qquad \text{for } \theta < h_b \quad . \qquad (3)$$

The intermittent nature of the bourne sections of the stream was simulated by defining the stream depth as zero ($h = h_b$) for the stream cells corresponding to the bourne section. Under the condition θ is less than h_b the leakage rate, as defined by equation (3), is zero. Flow routing in the stream cells is achieved by summing cells to the four gauged points in the catchment. While this is sufficient when working on a monthly time step, it does assume the bourne stream cells dry up sequentially from the head waters downstream.

The leakage coefficient is set to 1.0×10^{-7} s^{-1} for all stream cells. This value was estimated from Eq. 2 by inserting simultaneously observed head differences and flow values for each of the four reaches shown in Fig. 4. Both the average situation (mean flow and average groundwater level) and the minimum situation (the Q95, which is the discharge exceeded 95 % of the time, and the minimum groundwater level) were used to estimate the leakage coefficients.

A.4 ESTIMATING GROUNDWATER RECHARGE

The series of monthly streamflows used for the modelling study were the 29 years from 1962 to 1990. During this period four gauging stations were operational (Fig. 1). Their names and the most important flow statistics are given in Table 1. The mean flow (MF) from the catchment at Shaw is 1.72 m^3 s^{-1}, equivalent to 258 mm $year^{-1}$ using the groundwater catchment area.

The mean precipitation (1941-1970) varies from 700 mm $year^{-1}$ in the valleys to 760 mm year^{-1} on the Downs. The mean recharge to the aquifer was set equal to the recorded mean flow (258 mm year^{-1}). Based on the distribution of rainfall and catchment geology the mean recharge was assumed to be 235 mm year^{-1} in the eastern area and 280 mm year^{-1} in the western area (Fig. 6), where the precipitation is higher and there is no cover of clay with flint.

The seasonal variation of infiltration from the root zone was derived from time series of the effective precipitation for grassland calculated using MORECS (Meteorological Office Rainfall and Evaporation Calculation System). The land use in the Lambourn catchment is dominated by grassland and arable farming, with a limited area of woodland. The root constant for grass is 75 mm, and 100 mm for arable areas. The mean value of the effective precipitation for grassland (1962-1990) calculated from MORECS is 212 mm year^{-1}. This is lower than the value of 258 mm year^{-1} calculated from long term gauged flow records at Shaw. The mean effective precipitation calculated from flow records was used for the study as it was deemed to be more representative of the catchment than the MORECS estimate. The MORECS monthly values were used to temporally distribute the gauged value of mean effective precipitation.

The Base Flow Index (Gustard *et al.*, 1992) is very high at all four gauging stations (Table 1) indicating that rapid response runoff is very limited, a feature which is supported by Morel (1980). This is represented in the model by assuming that all streamflow is derived from groundwater, that is the mean infiltration is assumed to be equal to the mean flow, and infiltration is equal to effective precipitation. To derive values of monthly recharge the monthly values of effective precipitation were multiplied by a factor of 1.32 (280 mm year^{-1}/212 mm year^{-1}) for the western area and 1.11 (235 mm year^{-1}/212 mm year^{-1}) for the eastern area.

The final step in estimating the recharge times series was to estimate the transit time of the infiltration through the unsaturated zone. The catchment transit times were optimised during the calibration procedures.

A.5 CALIBRATION OF THE ASM MODEL

The parameters of the ASM model were optimised against observed groundwater levels and observed streamflow. The hydraulic conductivities were calibrated from steady state simulations, while the storativities and the transit times for the unsaturated zone were calibrated from dynamic simulations.

The simulated groundwater levels, derived from using K values calculated from the T values in Fig.3 (K equals T divided by 40 m) in a steady state simulation, ranged from about 80 m at the lowest point to more than 200 m in the north west. These are much higher than the observed mean values; this is shown in Fig.5. The distribution of steady state mean stream flow for various calibration methods is shown in Fig.7. From Fig. 7 it can be seen the mean flows from the upper western catchment are higher than the observed values whilst the flows in the south east of the catchment are lower.

The first approach to calibration was to calibrate K values by optimising the simulated groundwater levels based on the observed values, using an automatic least squares approach, the simulated average groundwater potential map is given in Fig 8, which shows a good fit between the observed and simulated maps. The optimized K values, found by minimizing the sum of squared deviation between the simulated and observed groundwater levels in each grid cell, vary from $4x10^{-5}$ m s^{-1} (T = $1.6x10^{-3}$ m^2 s^{-1}) near the periphery of the catchment to more than $3x10^{-3}$ m s^{-1} (T = $1.2x10^{1}$ m^2 s^{-1}) in the valley, which are an order of magnitude higher than the values shown in Fig. 3. The flow distribution was, however, still erroneous, with insufficient water flowing from the upper western catchment. This distribution was unaffected by any variation of the leakage coefficient. The erroneous flow distribution could either be due to uncertainty in defining the average groundwater levels or wrong model assumptions.

By manual calibration simultaneously based on both flow values and groundwater levels a final conductivity distribution was found. These values range from $2x10^{-5}$ m s^{-1} (T = $8x10^{-4}$ m^2 s^{-1}) to $1x10^{-3}$ m s^{-1} (T = $4x10^{-2}$ m^2 s^{-1}), which are 2-5 times higher than the values shown in Fig. 3 (the highest multiplication factor relating to the peripheral areas). Similar values were found by Morel (1980), who also used a finite difference model calibrating the transmissivity by an inverse method. The resulting groundwater levels using the K values from this manual calibration exceed the groundwater levels in Fig.5 by 5-10 m in the western areas, Fig.9., however the mean flow distribution was deemed to be the closest fit to the distribution of observed mean flows within the catchment (Fig. 7).

With the calibration of the hydraulic conductivity completed, the transit time in the unsaturated zone and the storativity values were calibrated from non steady state simulations. The amplitude of the seasonal variations in streamflow are influenced by both parameters, whereas transit time only determines the phase of the flows.

Good results were found by introducing a transit time of two months in the peripheral areas, one month in the middle area, and no delay in the valleys. The calibrated storativity was 1.5 % in the peripheral area above approximately 160 metres and 3 % in the remaining area. The boundaries between the areas follow the contour lines of the topography. Comparisons between the simulated and observed streamflows are presented in the form of the annual flow duration curve and a part of the simulated hydrograph for the station at Shaw in Figs.10 and 11 respectively.

Well hydrographs were monitored for three wells in the catchment; SU38/51 up on the Downs, SU37/24 in the Lambourn valley and SU47/17 on the periphery of the catchment at the top of the Winterbourne, Fig. 12. Examples of the hydrographs in Figs. 13 to 15 show little difference in the quality of fit to the observed data between the two calibration approaches.

A.6 PREDICTING THE LOW FLOW RESPONSE OF GROUNDWATER ABSTRACTIONS

The long term flow response was investigated by simulating constant and seasonal abstractions in different locations and with different abstraction rates. It took approximately four years for the model to reach equilibrium, and so the first four years of simulation were omitted from the analysis.

The locations of the hypothetical abstractions are shown in Fig. 4. The distances from the stream are 0.5 km, 1 km, 2 km and 3 km. The transmissivity decreases with increasing distance from the stream.

For each simulation the monthly stream depletion factor (SDF) was calculated as

$$SDF = \frac{\Delta q_d}{Q} \quad , \qquad (4)$$

where Δq_d is the difference between the simulated natural flow and the flow influenced by the abstraction, and Q is the pumping rate. For seasonal abstractions the monthly pumping rate is used to define the SDF even in those months when pumping ceases.

The results of the analysis have shown that:

1. The SDF is independent of the pumping rate up to at least 500 $m^3 hour^{-1}$.

2. A constant continuous abstraction results in seasonal variation of the SDF, (Fig. 16). lines have been drawn between the monthly values to illustrate the different SDF regimes more easily. The variation is small for abstractions near the stream. For the abstraction 3 km from the stream the monthly mean SDF varies from 0.89 to 1.13, (Fig. 17). The SDF is largest when the groundwater levels and the stream flows are high, which is due to a more rapid flow routing (large hydraulic gradients). The Figure also illustrates the relative decrease in aquifer storage in the summer to supply the excess of groundwater abstraction over stream depletion. Conversely in the winter there is a relative increase in storage when the streamflow depletion is greater than the abstraction.

3. The introduction of a seasonal abstraction results in a seasonal depletion. The seasonal depletion depends primarily on the duration of the abstraction and the distance from the stream, not the time of year when the abstraction occurred.

The dependence on distance is illustrated in Fig. 18, which shows the monthly variation in SDF for a six month abstraction period from April to September at the four abstraction locations. From Fig. 18 it is seen that as the distance from the stream increases the damping of the amplitude of the monthly variation in SDF. As a result, although the total mass depleted from the stream is independent of the distance from the stream, the monthly SDF is more evenly distributed throughout the year.

The monthly variation in SDF for abstraction scenarios of two months durations are illustrated in Fig. 19 for the locations at 0.5, 1 & 2km from the stream. For the location at 0.5 km from the stream the monthly variation in SDF is plotted for three seasonal scenarios; when the 2 month period occurs in December-January, April-May & August-September. From these scenarios it can be seen the magnitude and variation of the monthly SDF is independent of the seasonality of the abstraction. For clarity, only the variation in monthly SDF for the abstraction occurring in April-May is shown for the locations at 1 & 3 km from the stream. As the distance form the stream is increased the variation in SDF is damped, as seen for the six month abstraction scenarios in Fig. 18, however for the shorter 2 month abstraction scenario there is a shift in the occurrence of the peak SDF from June to July, ie to the month after the abstraction has stopped.

It should be noted that the definition of SDF, whilst enabling easy calculation of the numerical impact on the stream, does not conserve mass for intermittent pumping scenarios and thus does not allow for easy numerical comparison between scenarios.

The modelling work of Rushton *et al.* (1992) considers the impact in August 1976 of target abstraction regimes at three sites (the sum of the three constituting a continuous time dependent abstraction, peaking in the summer months) on the Oolitic Limestone headwater rivers of the River Thames. The abstraction points were at least 3 km from the nearest stream. Adjusting for vertical flow from a minor aquifer the presented results indicate an overall approximate SDF of 0.85 during the August low flow period. Whilst the hydrology of the Oolitic limestone is very different to that of the Chalk, it is interesting to note that this SDF is very similar to the 0.89 SDF observed for a continuous abstraction at 3 km from the Lambourn stream in this study.

During the 1976 test period of the River Candover Groundwater Augmentation scheme (Giles *et al.*, 1988) a group of six wells at a distance of 7 km from the Candover headwaters were pumped at a combined rate of 1155 m^3/hr for a period of six months from May to October. By August the nett gain to the stream had been reduced to 70%, giving an SDF of 0.3. However, 20% of the total nett gain had been derived from an adjacent catchment. Assuming this occurred during the last three months of pumping the approximate adjusted SDF would be 0.6. The Candover is a chalk catchment with a higher transmissivity and a lower storativity than the Lambourn catchment. Thus, for a given distance the impact of a specific transient abstraction regime on a stream would be observed earlier and would be less diffuse (Oakes & Wilkinson; 1972) in the Candover catchment compared with the Lambourn catchment. In view of this the results from the Candover scheme are not inconsistent with the results obtained for the 6 month abstraction period during this study.

Based upon the impacts described it is possible to summarize the impacts on river flow regime as follows:

A constant abstraction will result in a minor seasonal variation in the amplitude of stream depletion. The amplitude increases with the distance from the stream. For a given distance from the stream, the smallest depletion rates occur during periods of low flow. The degree of influence that a constant continuous abstraction exerts on the stream at any point in time is inversely proportional to the stream flow at that point in time, although this variability is relatively small in comparison to the pumping rate. This means that low flow measures such as the 95 % exceedance and the annual minimum discharge will be reduced by the abstraction rate multiplied by the SDF, which is less than but close to 1.00. Fig. 13 shows the flow frequency curve of the annual minima for the natural stream flow and the stream flow influenced by constant abstraction rates of 500 m^3 hr^{-1}. The effect on the annual minima is greatest for the abstraction nearest to the stream. This is illustrated in Fig. 20 which also shows the almost constant influence from year to year.

The impact of a seasonal abstraction will depend primarily on the abstraction rate, the distance from the stream and the time of the year the abstraction takes place. In contrast to a constant abstraction, the influence of a seasonal abstraction on low flow statistics is more dependent on the year to year variability of low flows in both their timing and magnitude and how they relate to the timing and magnitude of the depletion.

As the distance from the stream increases the monthly variation in the SDF for a annual periodic, intermittent abstraction is damped by the storage properties of the increased aquifer volume between the abstraction location and the stream, as the distance tends to infinity the influence on the stream will tend to that of a constant abstraction at a rate equal to the mean abstraction rate over the whole year.

In the case of annual minimum discharges the month of the minimum is critical in terms of the direct effect of depletion. Annual minima will be reduced more severely when the month with the natural minimum is coincident with the month of the maximum depletion, (Fig. 21). Thus in Chalk streams such as the Lambourn where the minimum flow normally occurs in October or November the maximum impact of a seasonal abstraction would be from a borehole close to the stream with a maximum abstraction in September and October.

A.7 CONCLUSIONS

The influence of long term groundwater abstractions on a natural flow regime has been investigated using a two dimensional regional groundwater model. The model was calibrated on observed groundwater levels and stream flow. The calibrated values of hydraulic conductivity and storativity were found to be in accordance with values found from field measurements and calibration of other numerical models. After the model was calibrated it was possible to simulate the natural flow at the gauging stations.

The analysis of the simulations showed that the stream depletion with a constant abstraction depend on the abstraction rate, the distance from the stream and discharge. The depletion of a seasonal abstraction depends on the abstraction rate, the distance from the stream, the duration of the abstraction, but not the time of the year. The influence of a seasonal abstraction on low flows depends on the factors cited above and the natural low flow variability.

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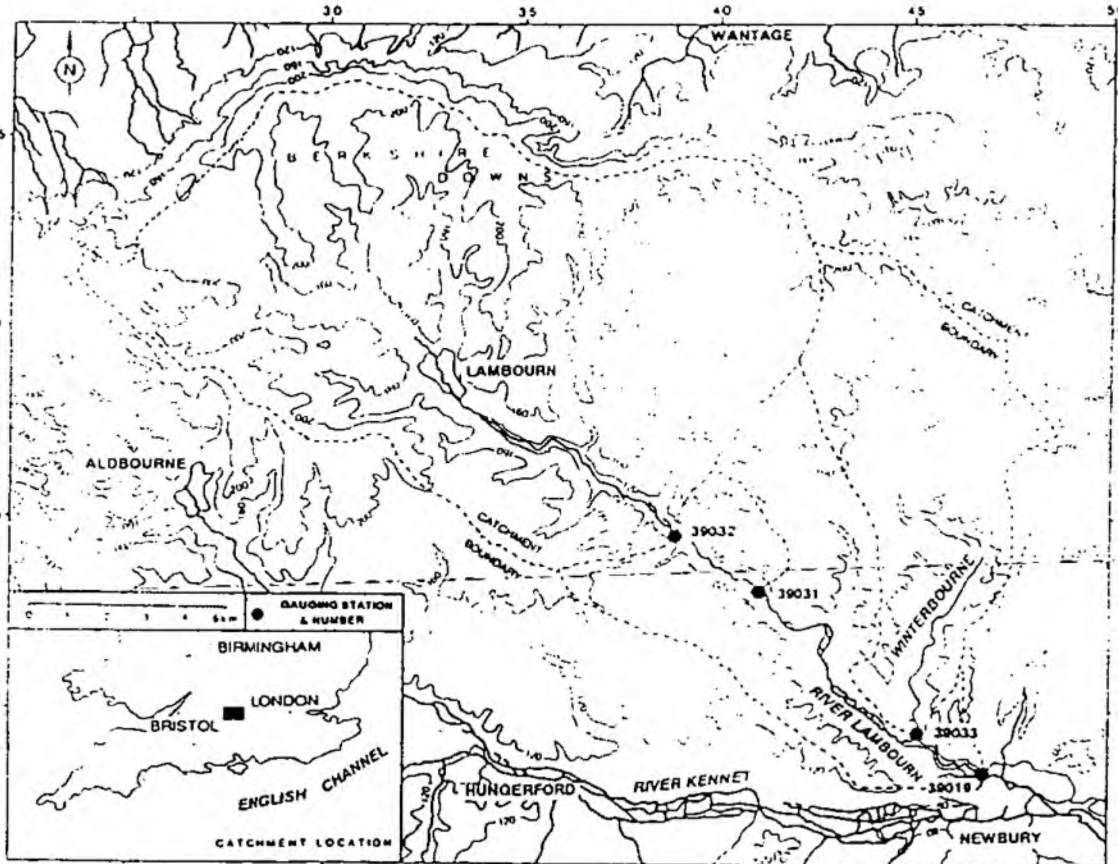


Fig. 1 The topographic catchment of the River Lambourn.

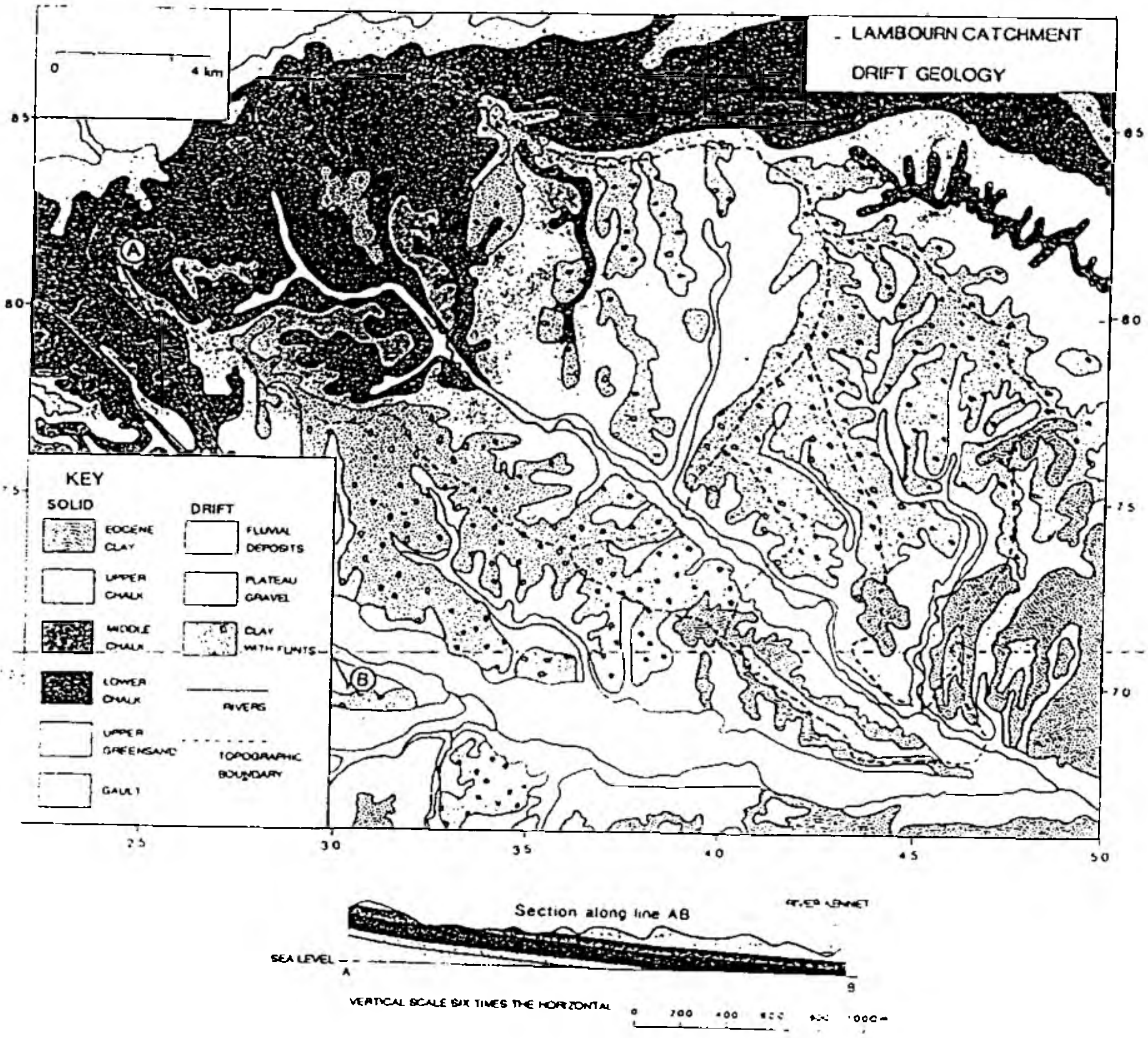
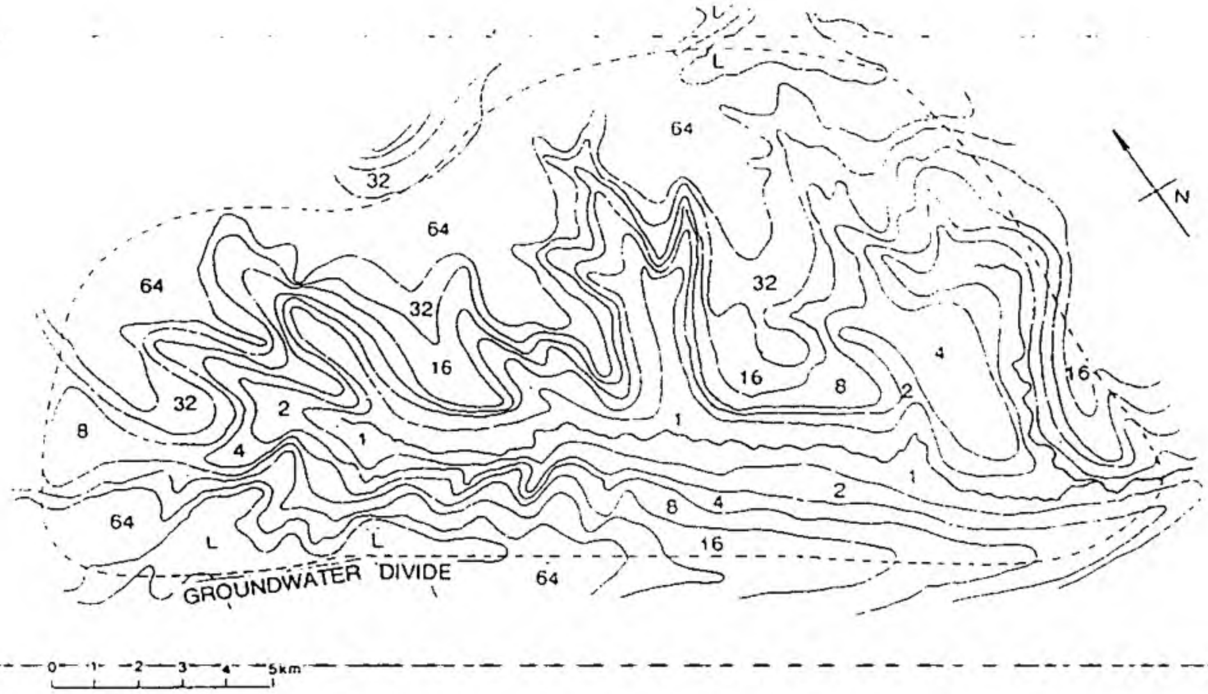


Fig. 2 The geology of the Lambourn catchment.

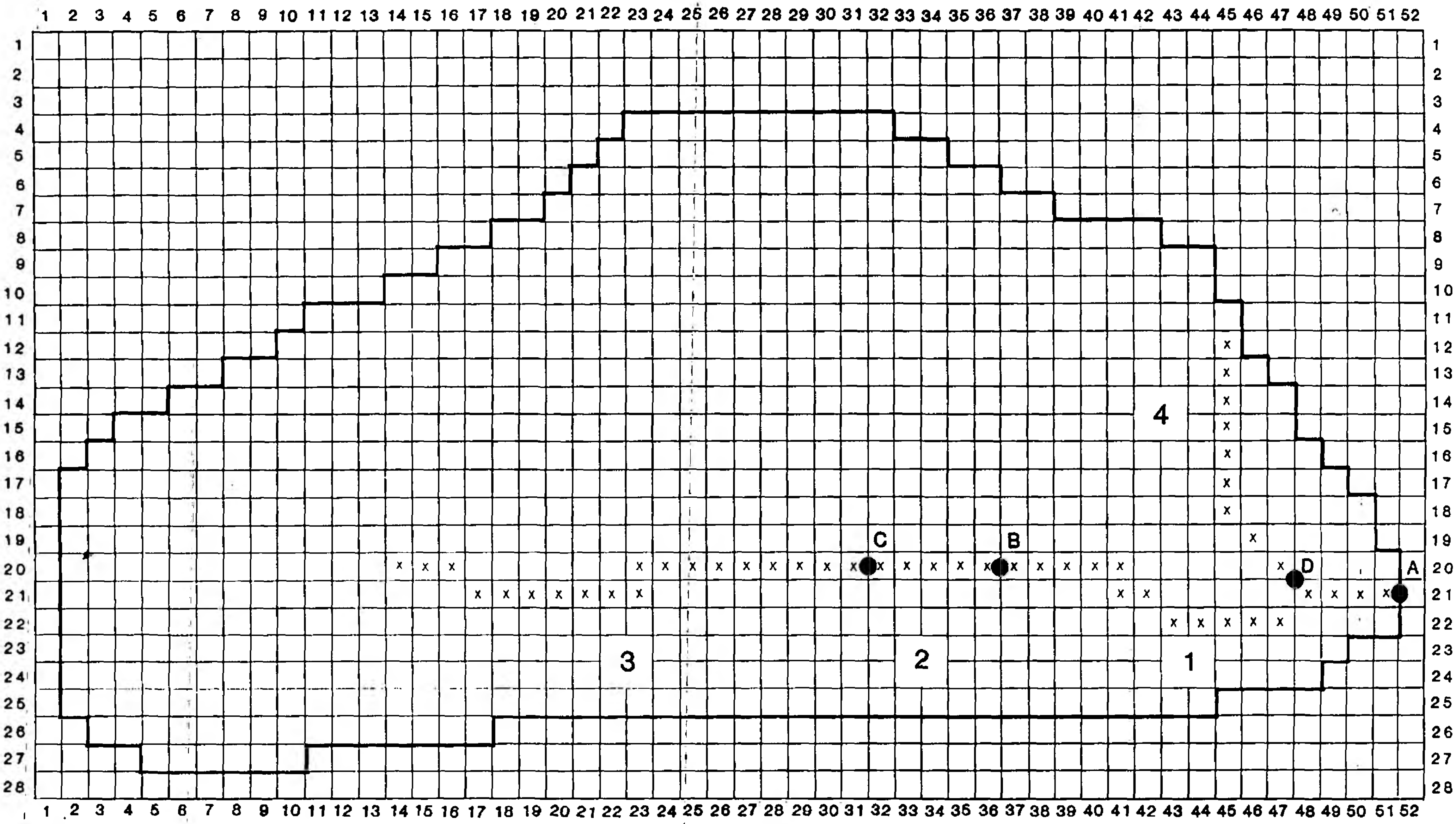


KEY

1 - T	4 - T/4	16 - T/16	64 - T/64
2 - T/2	8 - T/8	32 - T/32	L - <T/64

Fig. 3 Relative transmissivity distribution (after Owen and Robinson, 1978).

Fig 4. Model Representation of the Lambourn Catchment



☐ 0.5km x 0.5km ● Gauging Station A. Shaw C. East Shefford

x Intermittent Stream B. Welford D. Winterbourne

Fig 5. Simulated and Observed Groundwater Potential Observed Hydraulic Conductivity (K).

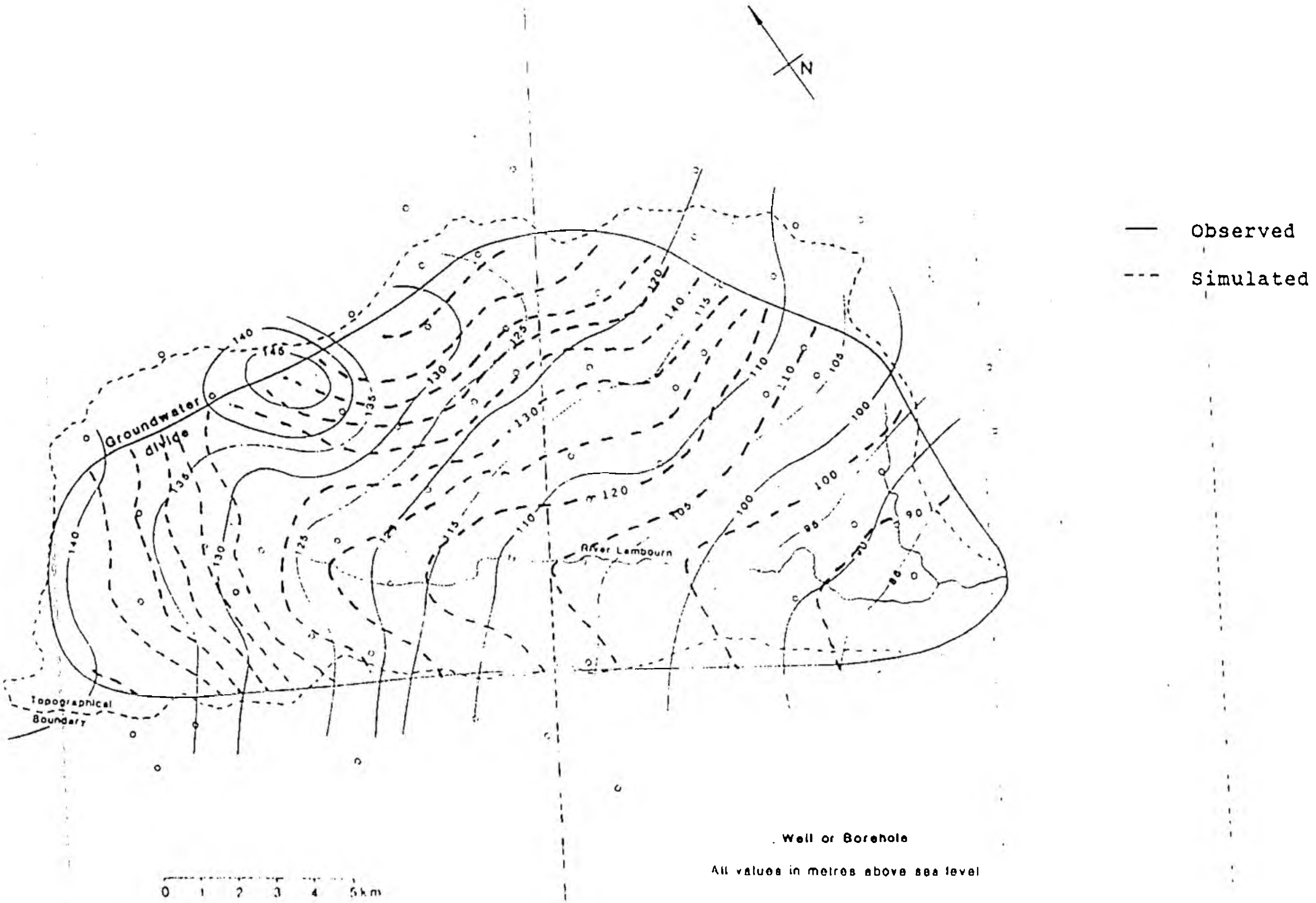
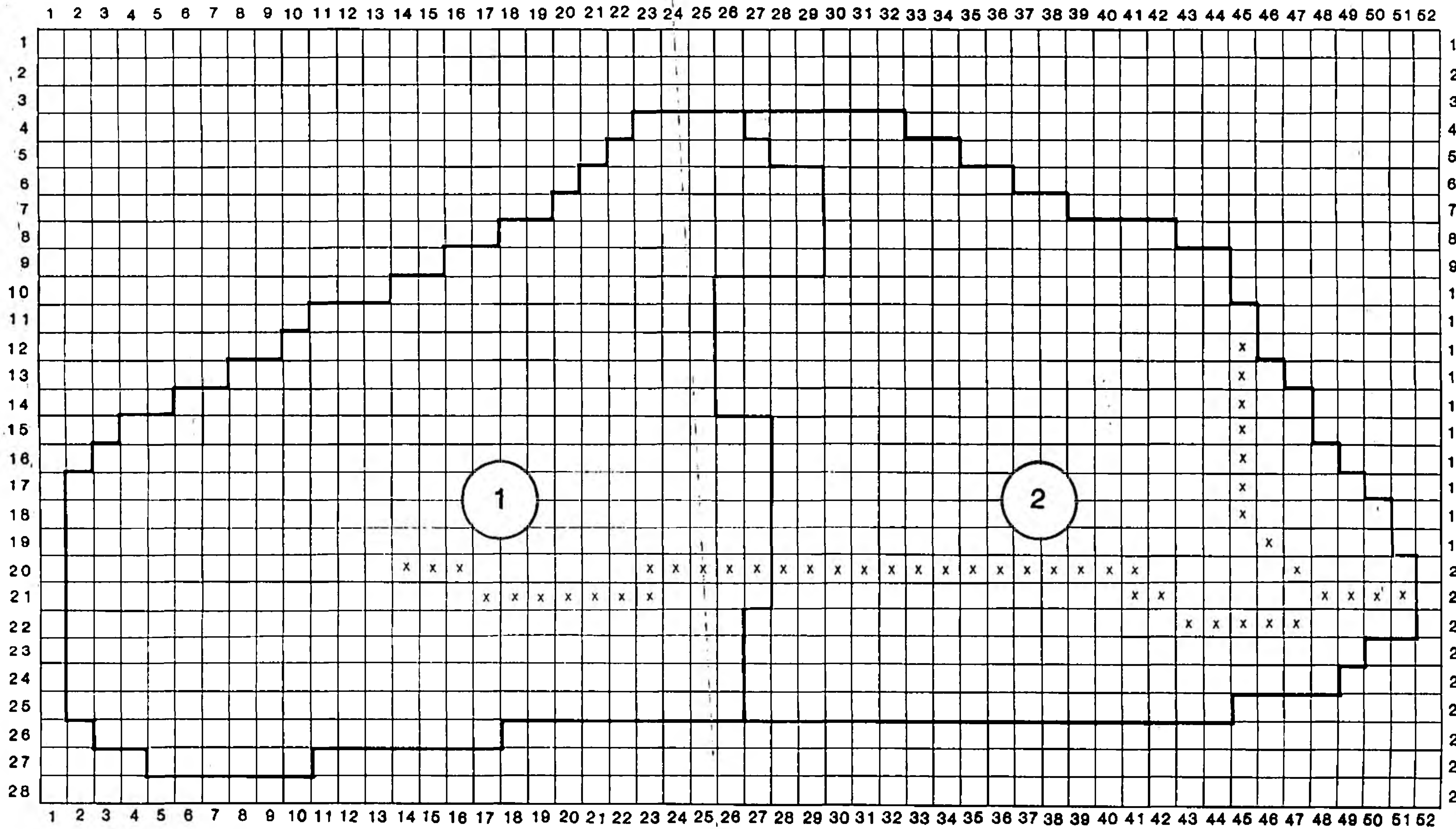


Fig 6. MEAN RECHARGE



1. 280mm/year
2. 235mm/year

□ 0.5km x 0.5km

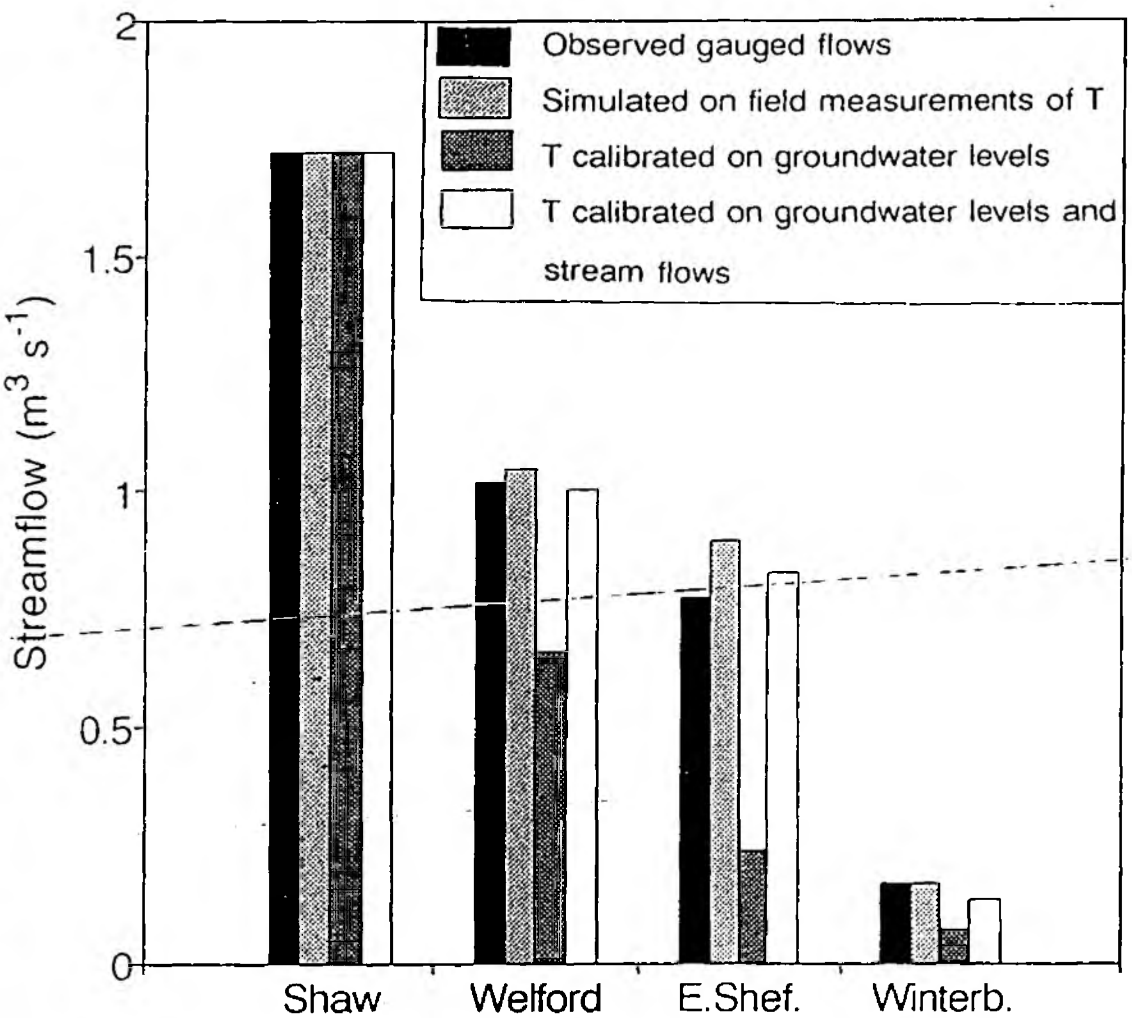


Fig 7. Observed and simulated mean flow distribution obtained from steady state simulations.

Fig 8. Simulated and Observed Groundwater Potential K
Calibrated on Observed Groundwater Levels.

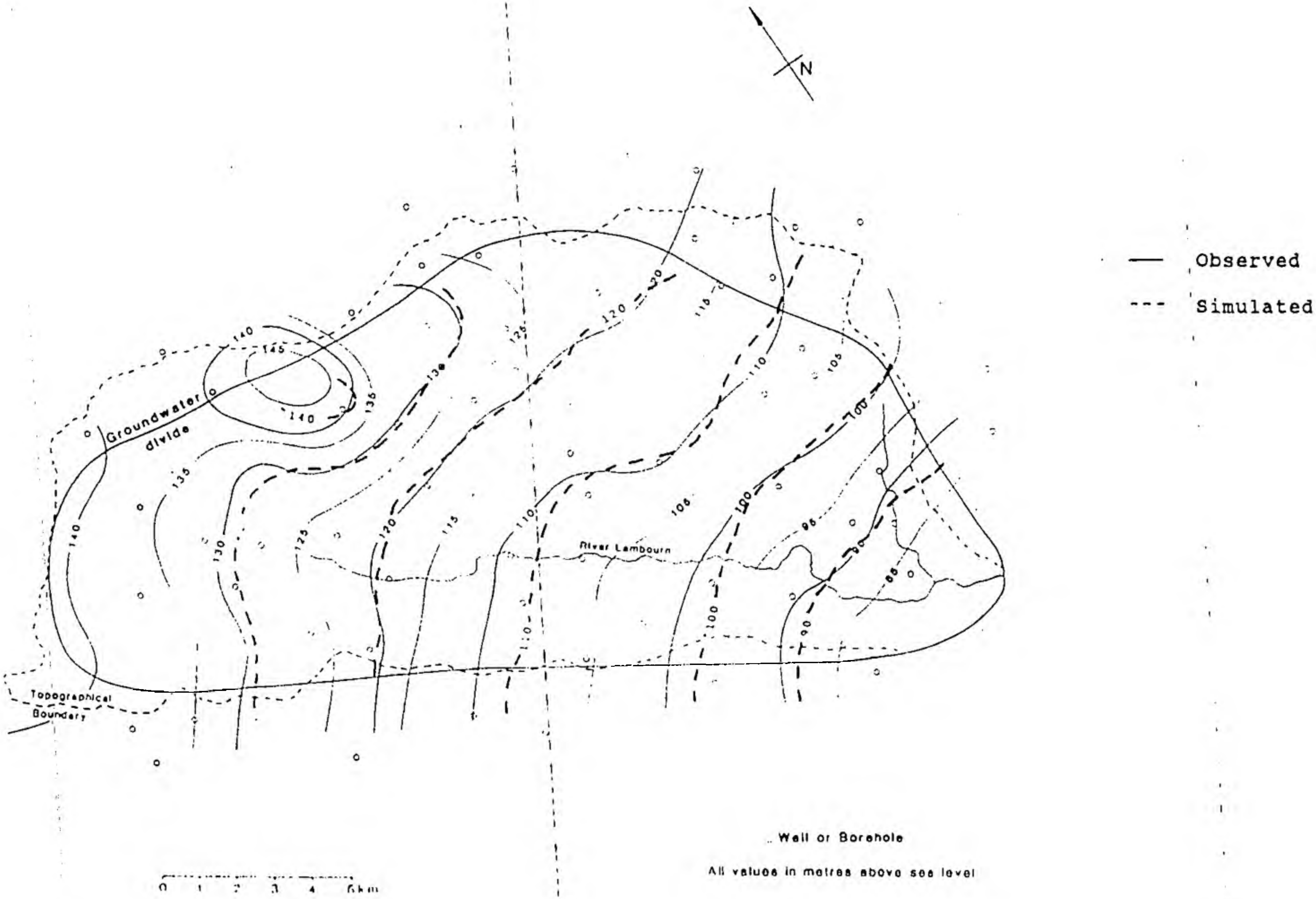
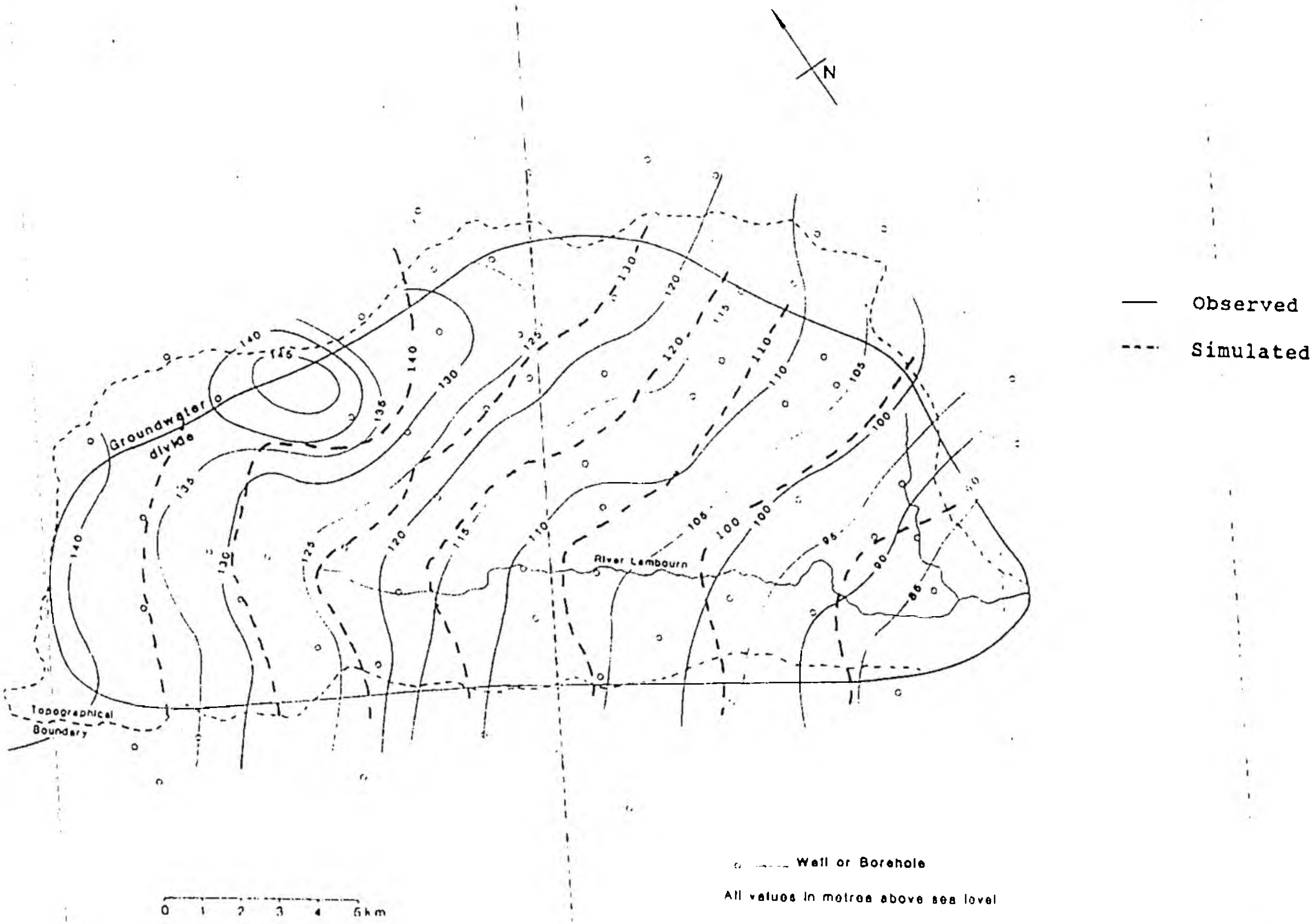


Fig 9. Simulated and Observed Groundwater Potential K calibrated on Groundwater Levels & Streamflow.



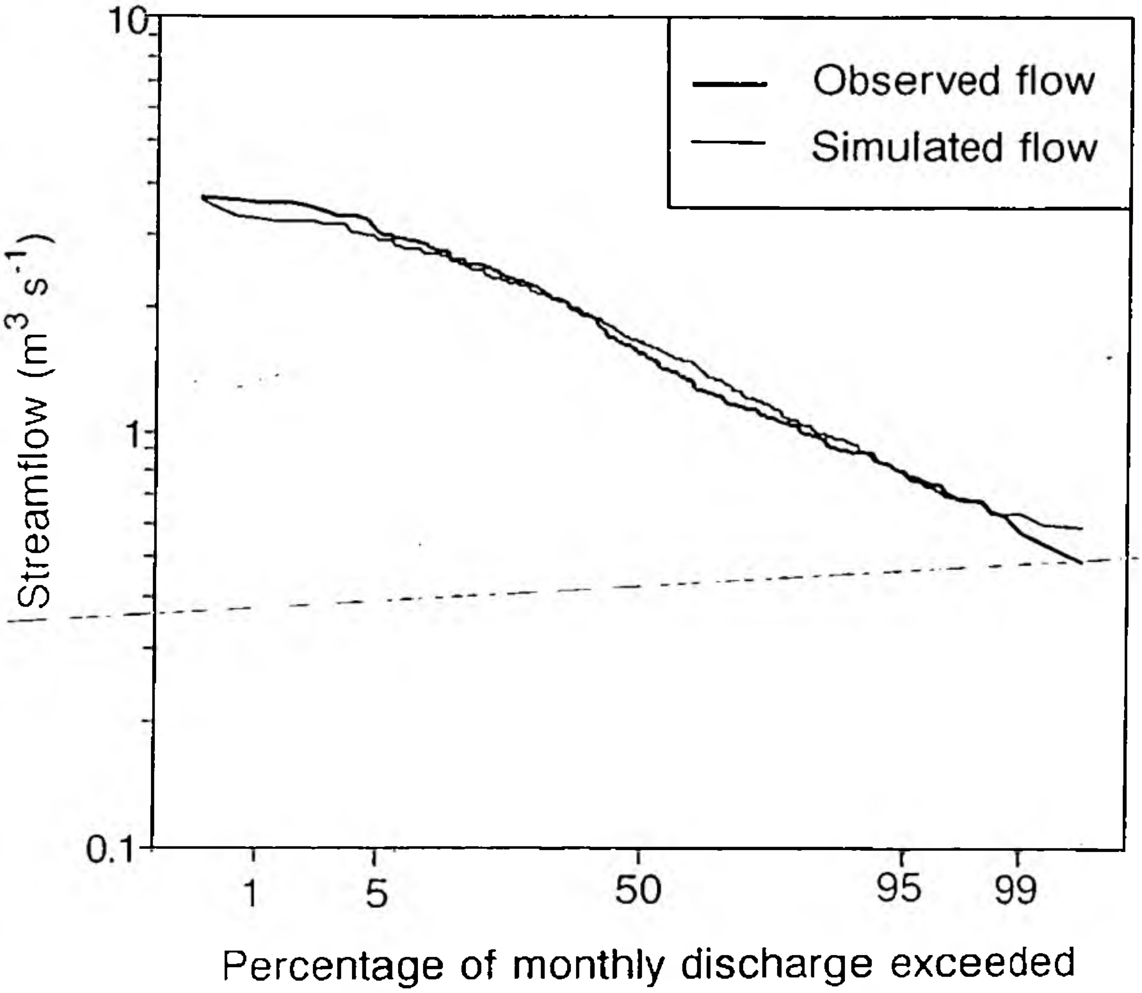


Fig 10. Observed and Simulated flow duration curve at Shaw.

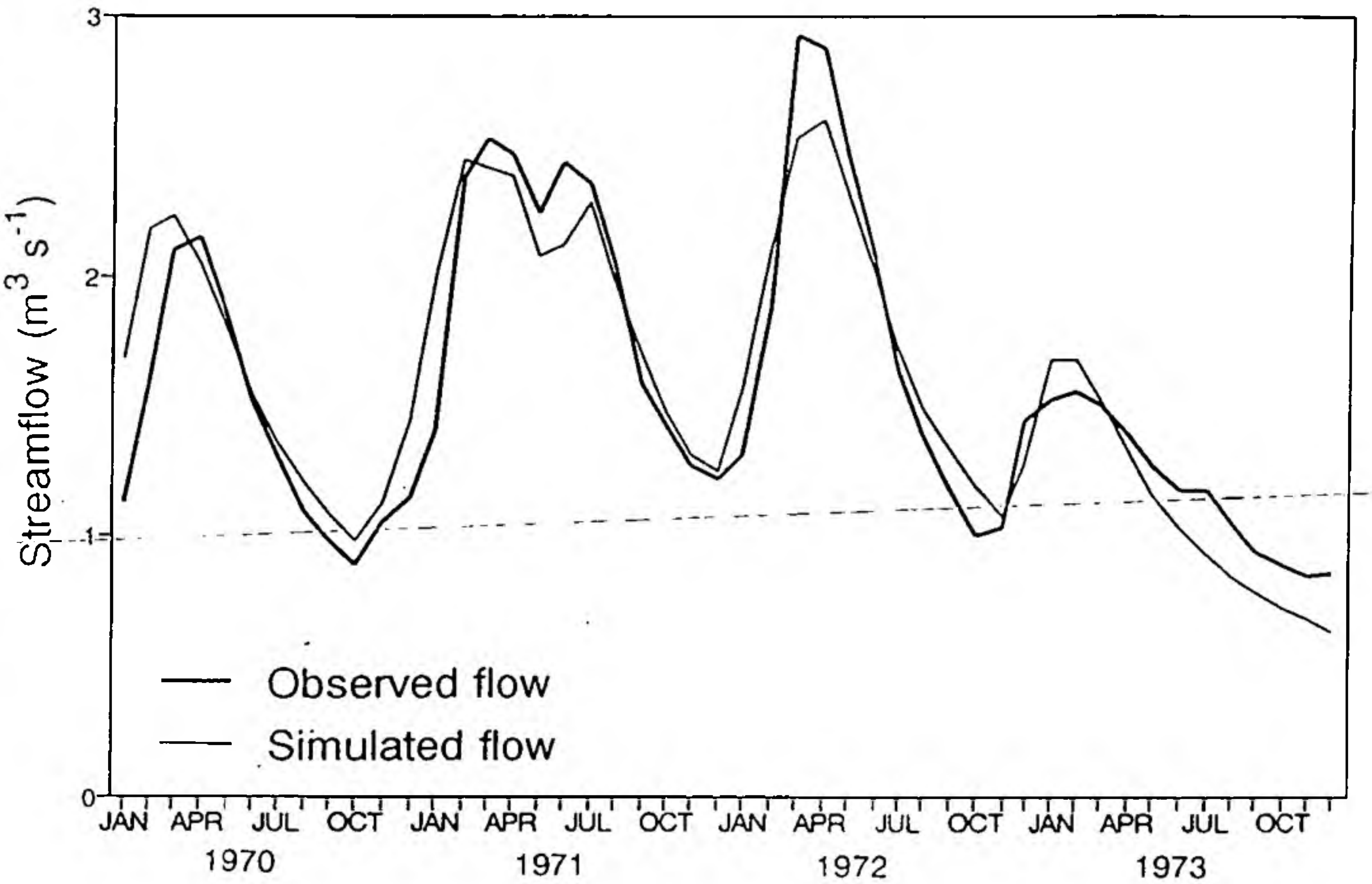


Fig 11. Observed and simulated hydrograph at Shaw for 1970-1973.

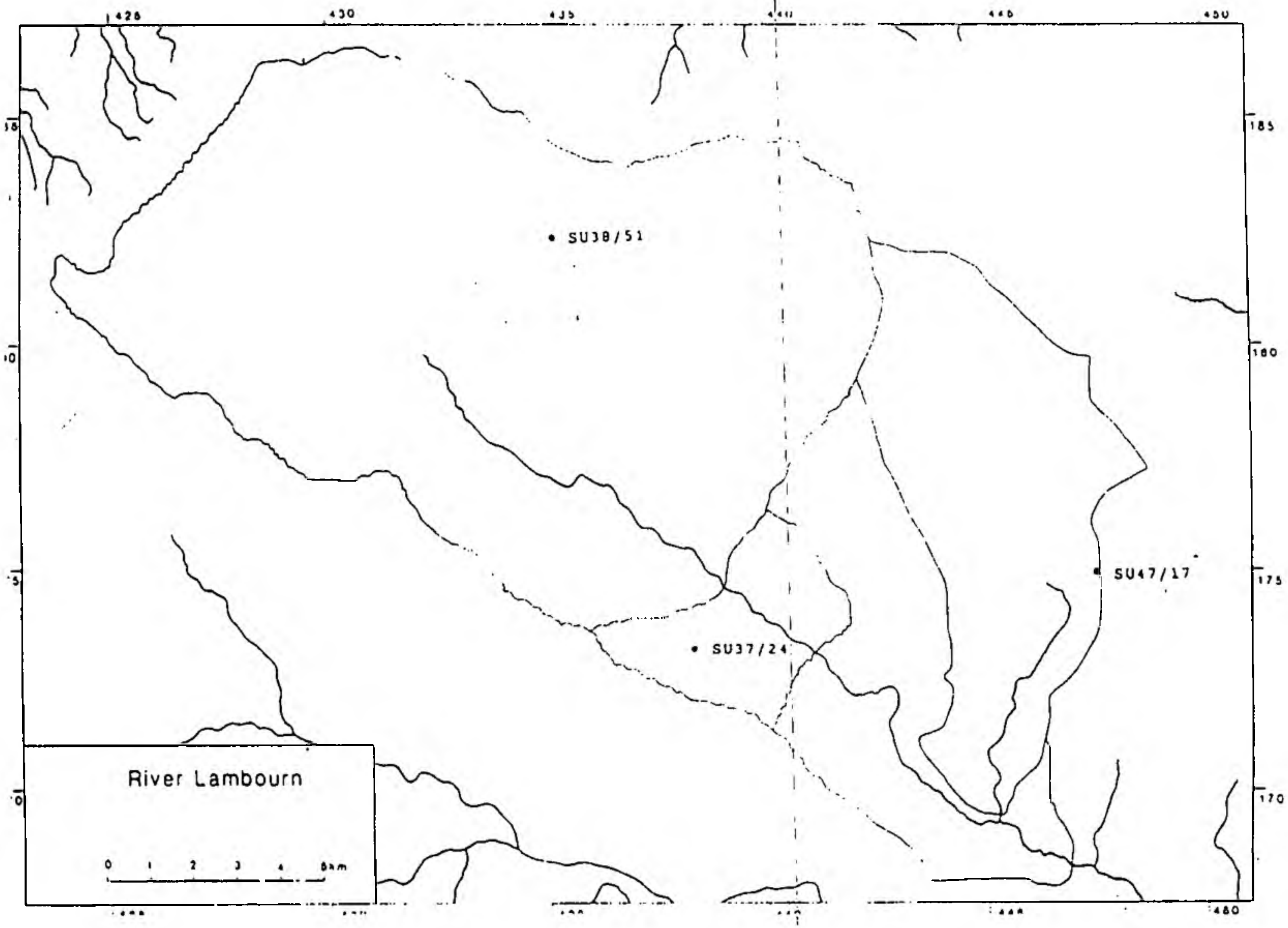


Fig 12. Location of the observation wells.

Fig 13. Water Levels at Down End Cottage - Chievley Well No: SU47/17.

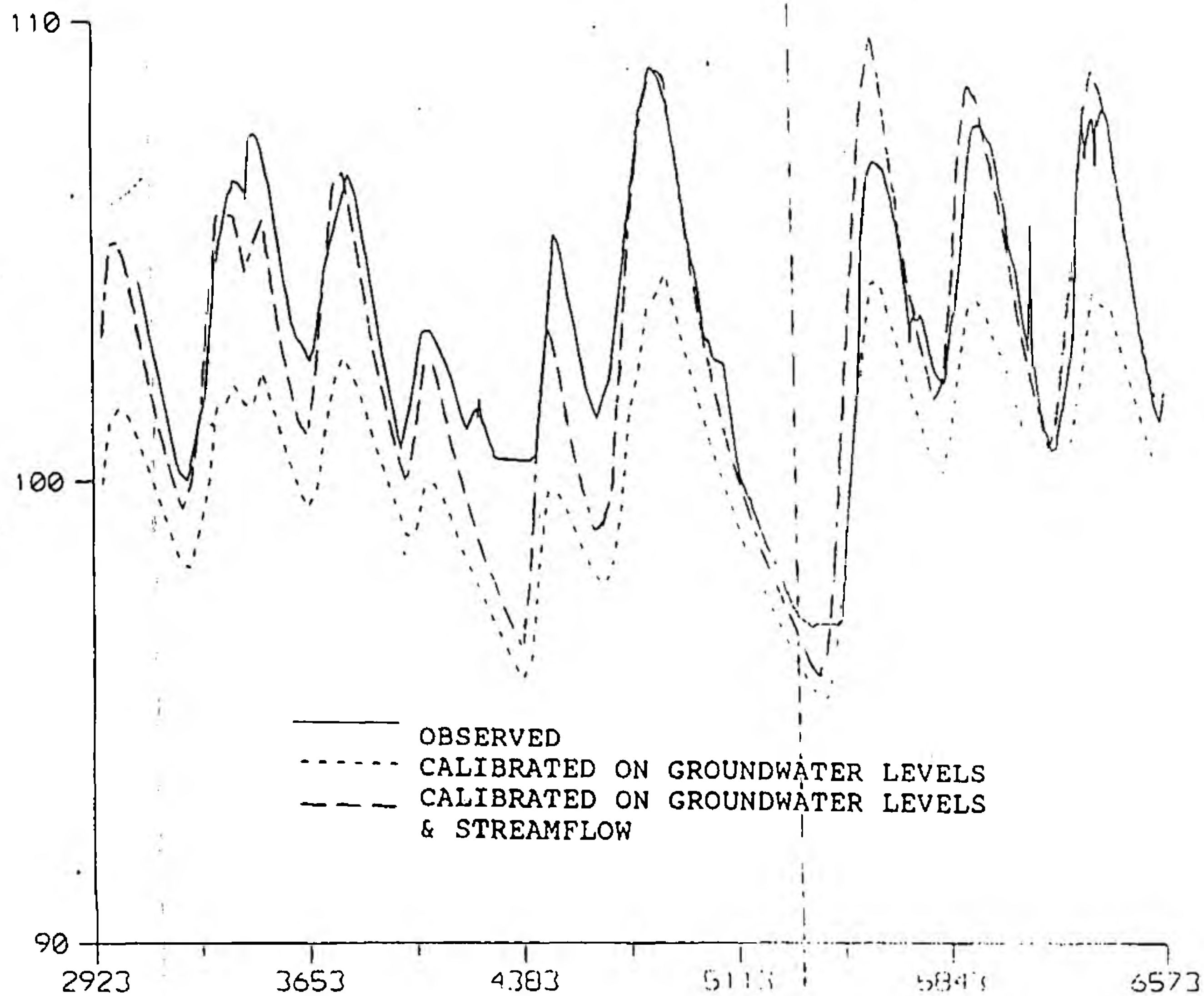


Fig 14. Water Levels at Oakhanger Park - (Disused) Well no: SU37/24.

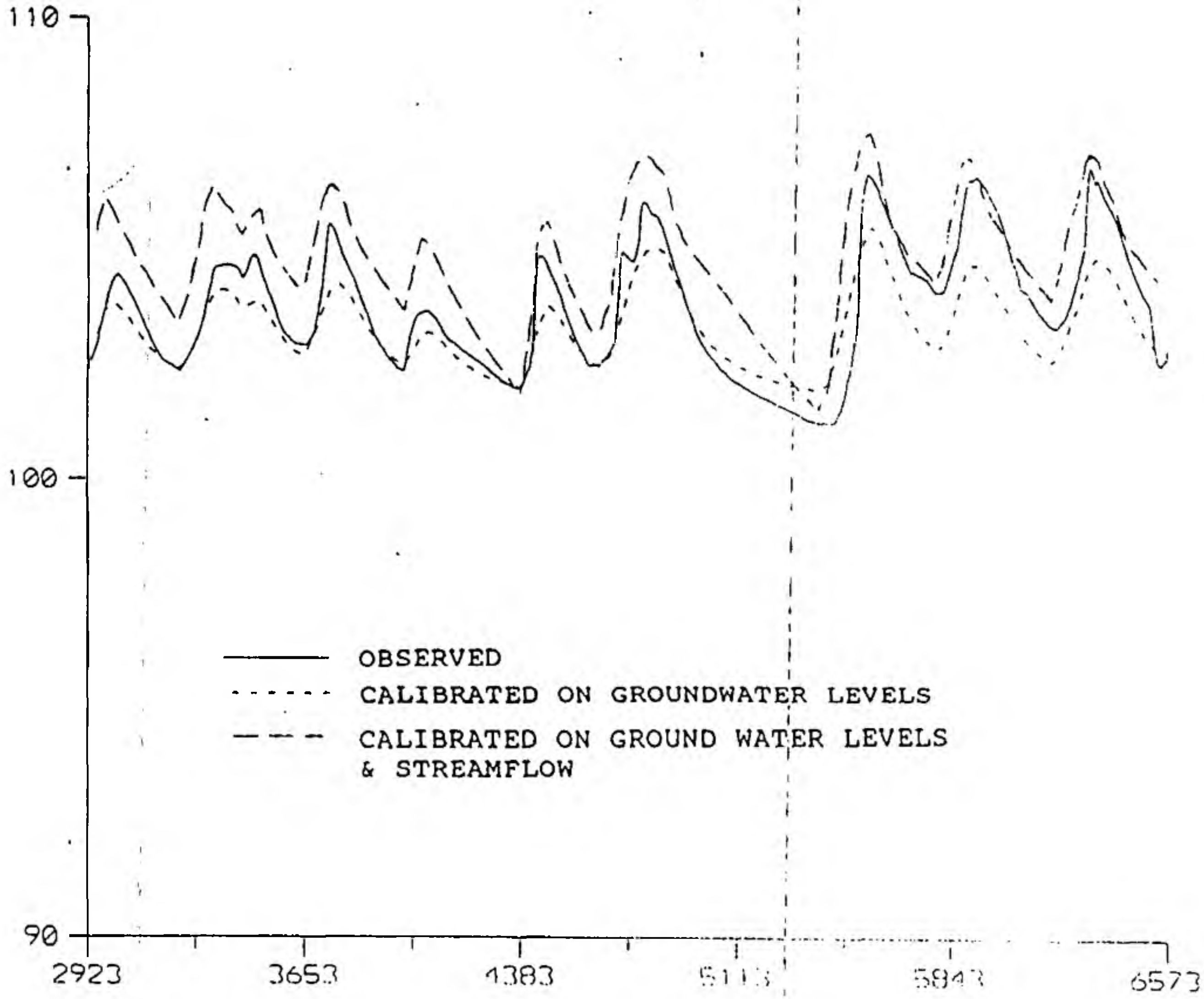
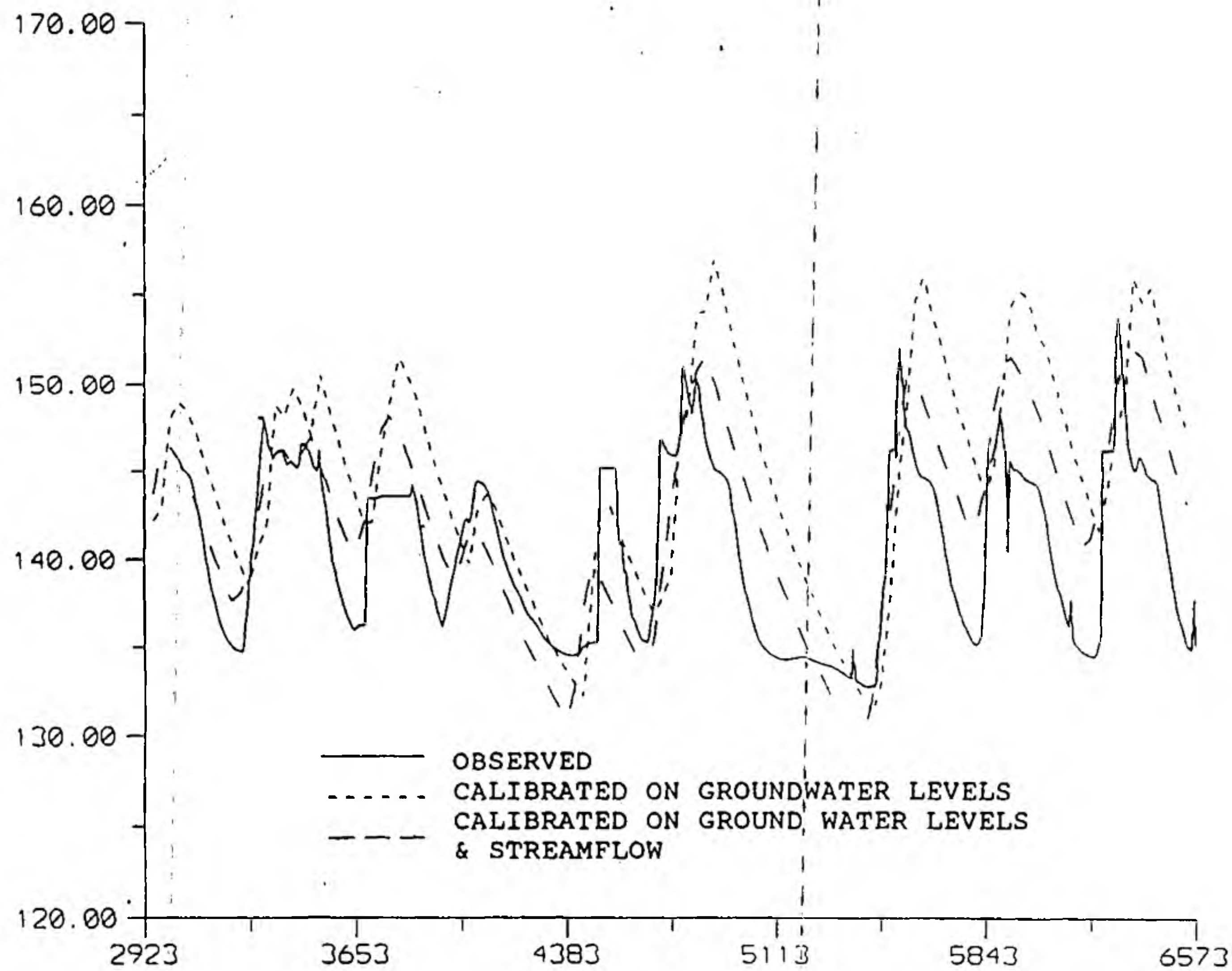


Fig 15. Water Levels at Stancombe Farm - Lambourn Downs Well No: SU38/51.



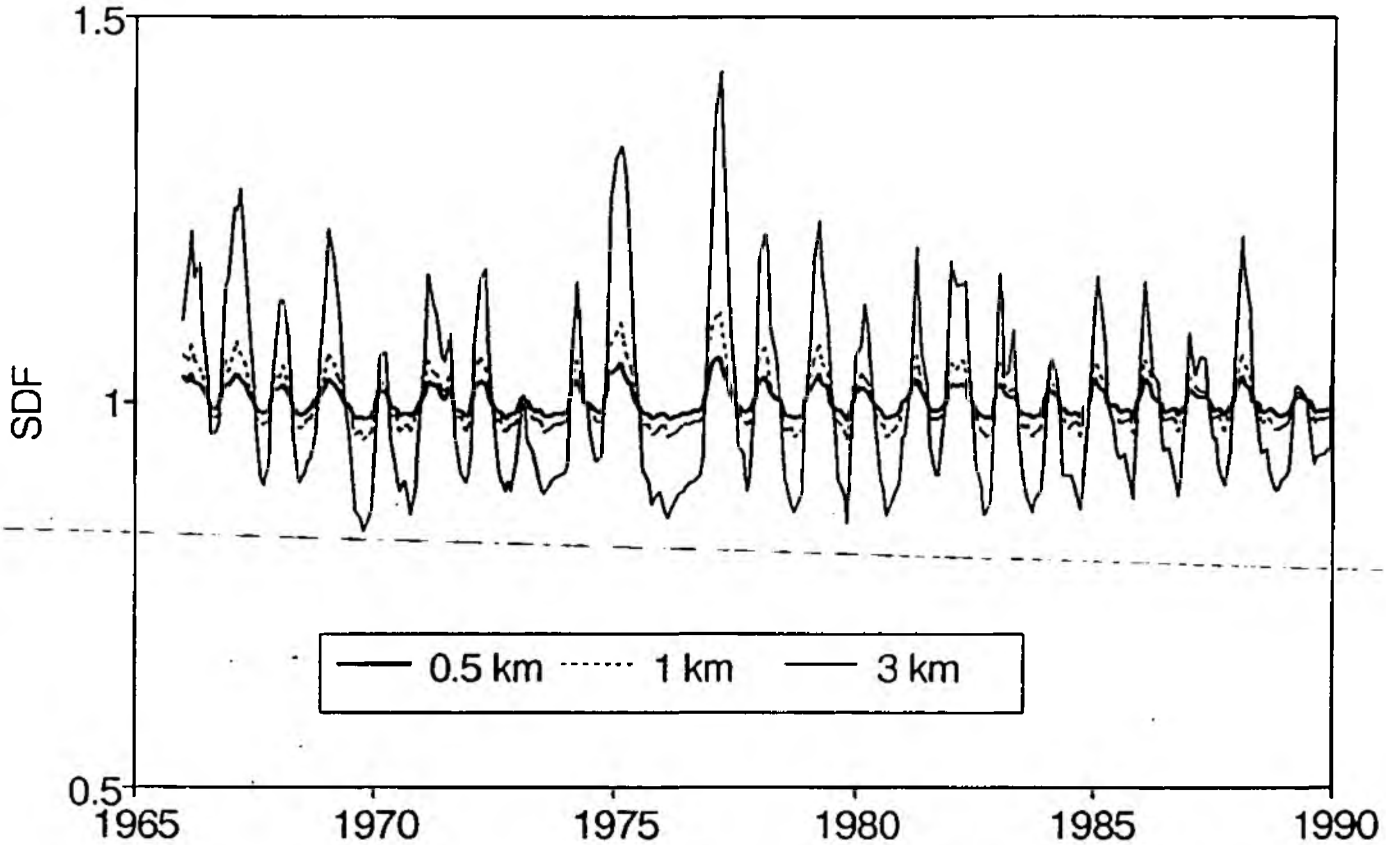


Fig 16. The variation of the stream depletion factor (SDF) for different locations with constant abstractions.

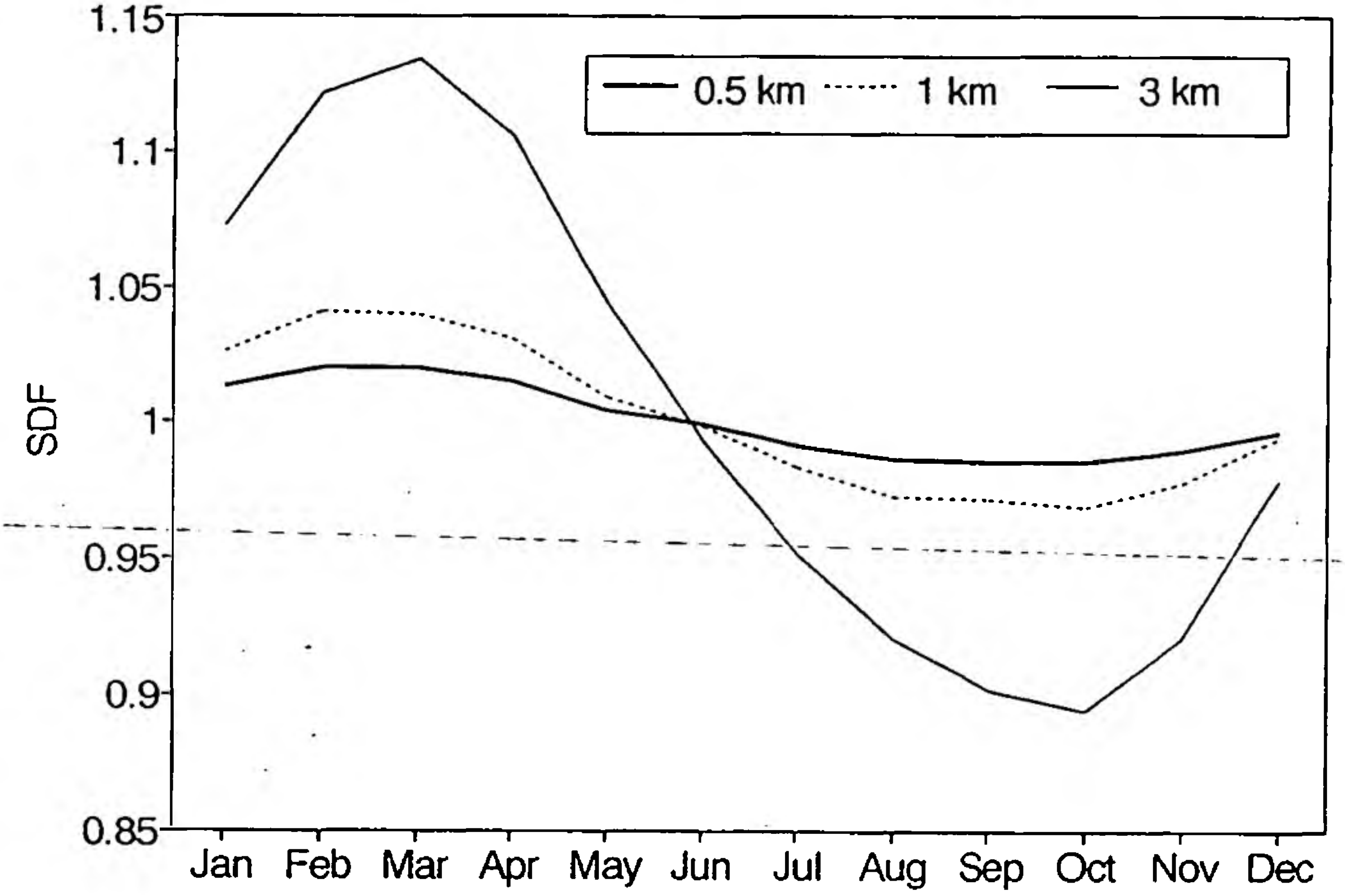


Fig 17. The mean monthly stream depletion factor (SDF) for different locations with constant abstractions.

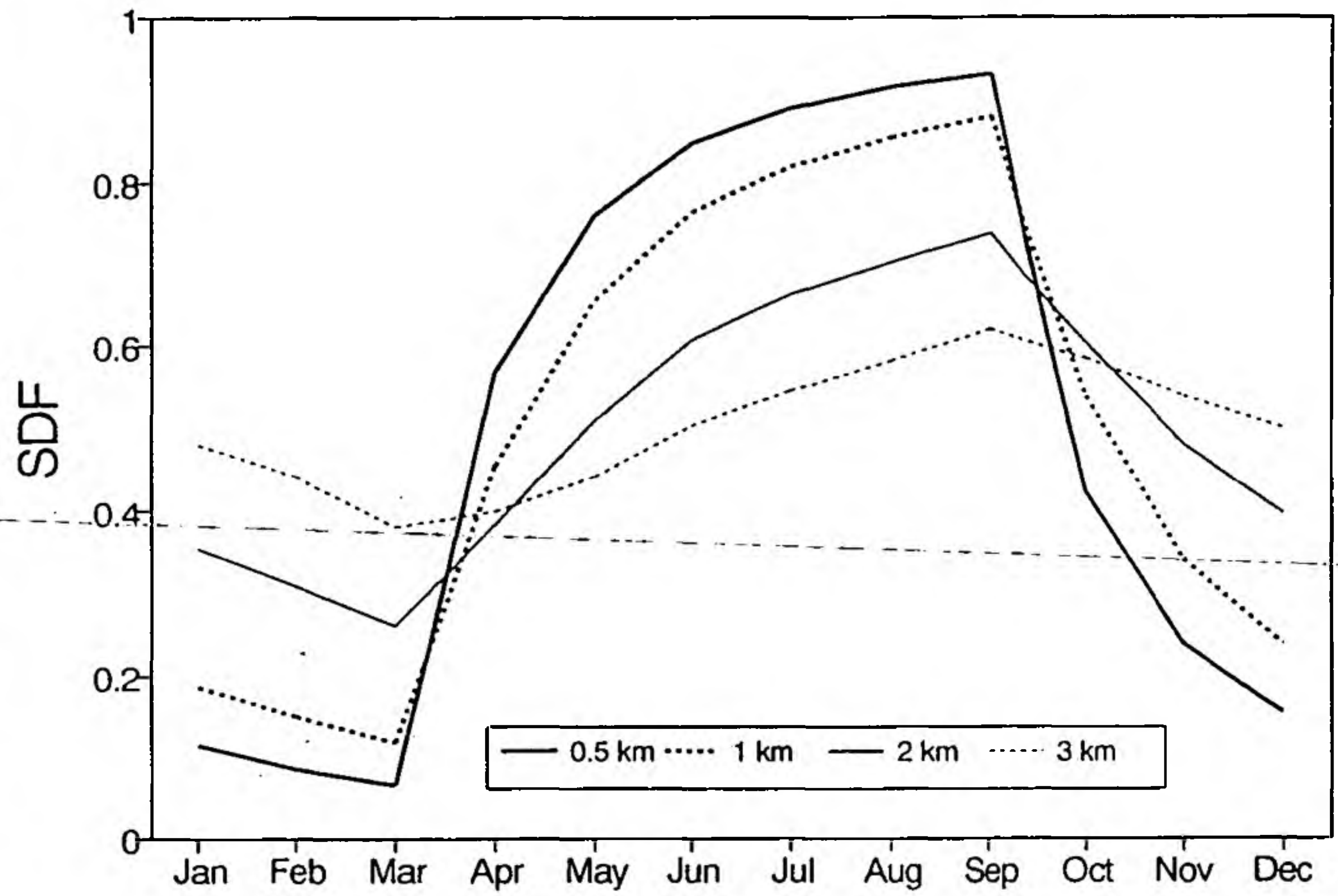


Fig 18. The mean monthly stream depletion factor (SDF) for different locations for six month (April-September) abstractions.

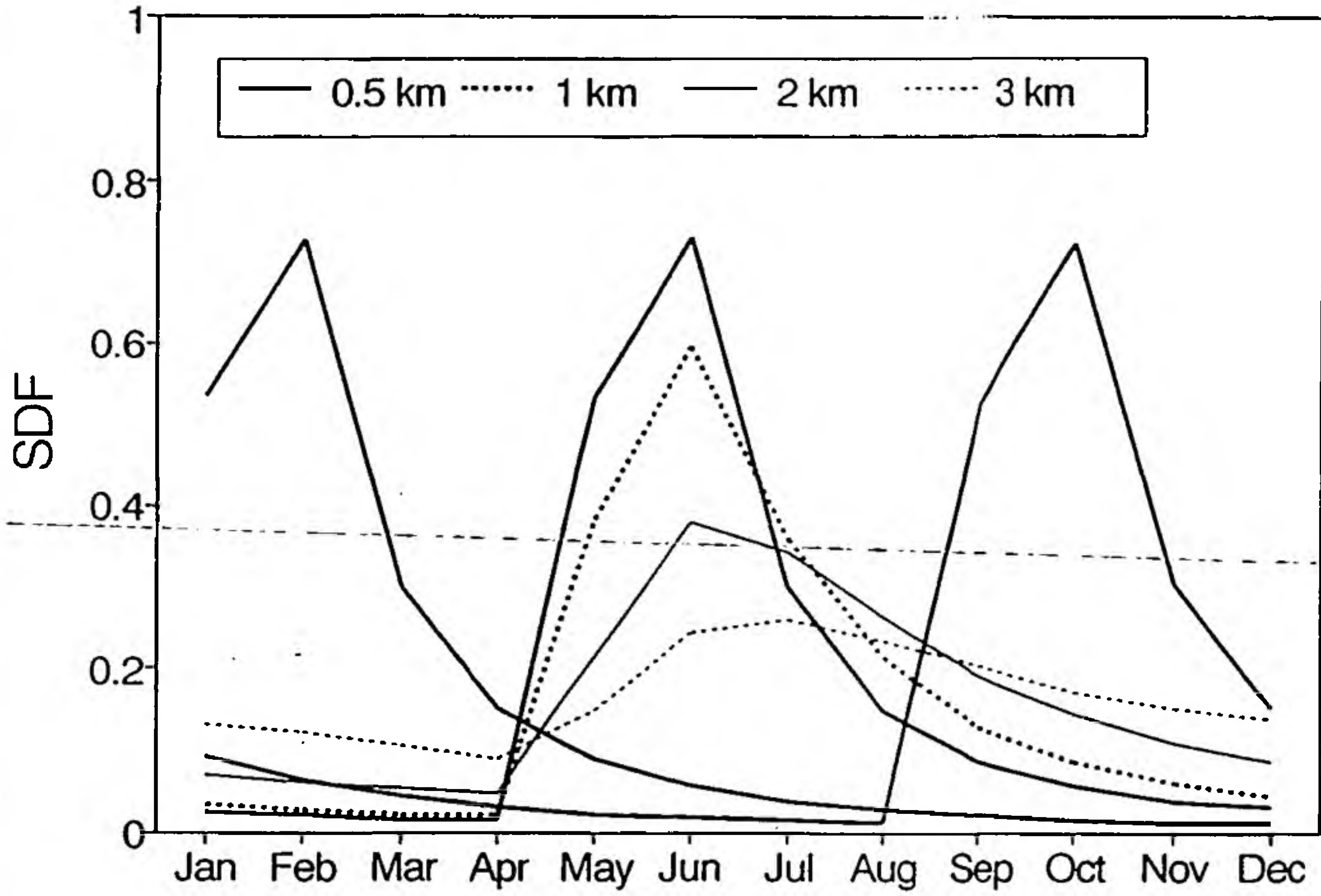


Fig 19. **The mean monthly stream depletion factor (SDF) for different locations for two month abstractions. The middle peak results from abstracting in May and June.**

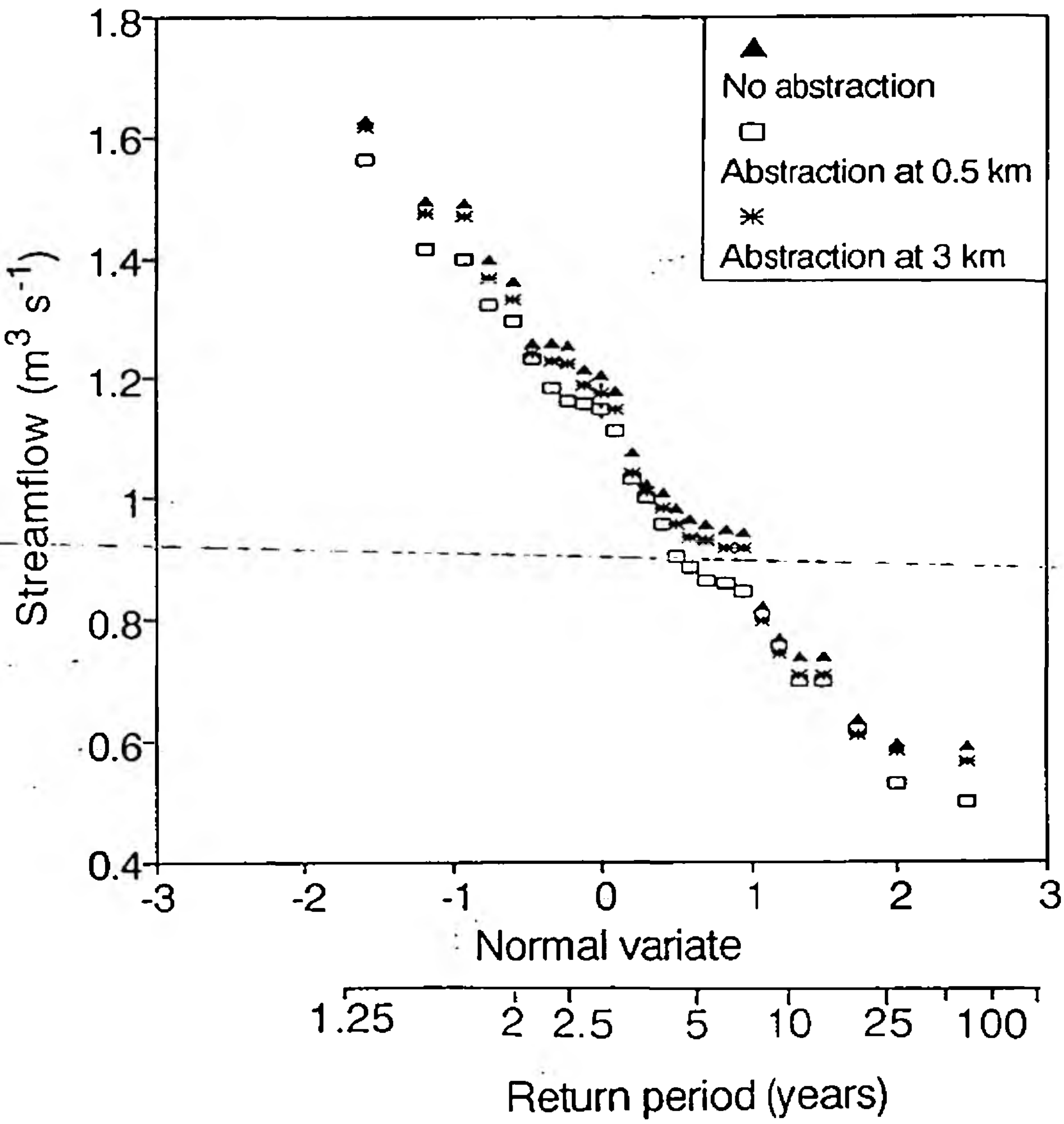


Fig 20. The effect of constant abstractions (500 m^3 s^{-1}) on the one month annual minima series.

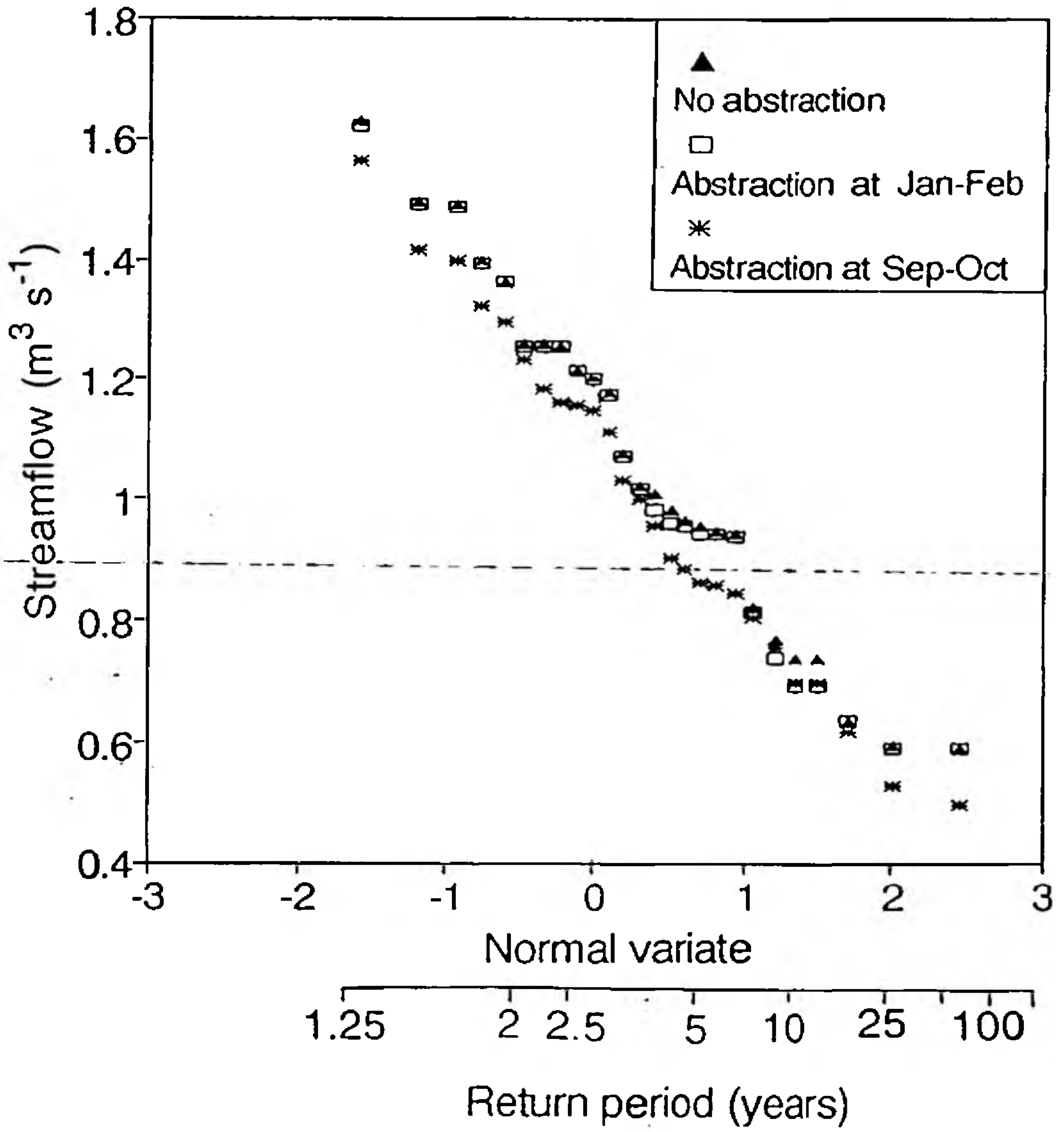


Fig 21. The effect of two month abstractions (500 m^3s^{-1}) on the one month annual minima series.

Station name & number	Lambourn at Shaw 39019	Lambourn at Welford 39031	Lambourn at E.Sheff. 39032	Winterbourn at Bagnor 39033
Topographic catchment area (km^2)	234.1	176.0	154.0	49.2
Mean flow (m^3s^{-1})	1.72	1.02	0.77	0.17
Q95 (m^3s^{-1})	0.811	0.409	0.097	0.056
BFI	0.96	0.98	0.97	0.96

Table 1 Key variables for the four gauging stations in the Lambourn catchment.

Appendix B Dates of Advisory Committee Meetings

1st meeting:	30 January 1991, Institute of Hydrology, Wallingford.
2nd meeting:	26 June 1991, Institute of Hydrology, Wallingford.
3rd meeting:	31 January 1992 at Kingfisher House, NRA Anglian Region, Peterborough.
4th meeting:	16 July 1992 at Kingfisher House, NRA Anglian Region, Peterborough.
R & D meeting:	14 September, 1992, Institute of Hydrology, Wallingford.

Appendix C Project Investment Appraisal

LOW FLOW ESTIMATION IN ARTIFICIALLY INFLUENCED CATCHMENTS

Commission: B Water resources

Topic: BO2 Flow regimes

Proposal no: BO2.03.90

Project no: 0257

R&D classification: D

Primary purpose:

Project Leader: Mr N Fawthrop

Post title: Principal Hydrologist
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Research Contractor: Institute of Hydrology

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Oxfordshire
Postcode: OX10 8BB
Telephone: 0491 838800
Fax: 0491 32256

Contract signatory: Mr D M L Rampton

Project manager: Dr Alan Gustard

CONTRACT DETAILS

Type: Sole Source Tender

Start date: 12/90 Reference: INITIAL CONTRACT
End date: 11/93 Reference: INITIAL CONTRACT

OBJECTIVES

To develop procedures for estimating low flows on catchments where processes are artificially influenced.

Specific Objectives

To produce methods of flow estimation in ungauged or partially gauged catchments which are subject to artificial (man's) influences.

The project will extend the existing Micro Low Flow software (currently commercially available through the Institute of Hydrology) to produce estimation procedures which account for the following:

i) 'Artificial' surface water influences including abstractions, discharges, reservoirs and implicity, existing urbanisation.

ii) Bulk effects of groundwater abstraction.

iii) Land-use change in the form of afforestation/deforestation.

The project will incorporate best practices currently applied in the NRA regions and optimise the use of all relevant data archives.

BACKGROUND

A major component in the determination and review of prescribed flows, abstraction licences, levels of compensation releases and discharge consents is the estimation of statistics of low river flows. Three methods are currently in use in the NRA regions:

1. Estimation from continuously gauged flow data.
2. Measuring flow by carrying out 'spot' current meterings.
3. Estimation of low flows using hydrological models-generally multi-variate models which relate low flows to catchment characteristics.

Where continuous flow data are available at the site of interest then method 1 is the most accurate and the preferred technique. However most information is generally required at ungauged locations and method 2 or more commonly, method 3 must be used. Commercially available low flow estimation procedures, developed at the Institute of Hydrology, have been almost exclusively developed on natural catchments. This contrasts with the most frequent applications of estimation procedures; ie in catchments where the flow regime is influenced and often dominated by a range of human influences.

Context

This proposal seeks to address the problem of assessing artificial influences on low flows and develop practical design techniques for low flow estimation in affected catchments. The opportunity will also be taken of formalising existing adjustment techniques used in some NRA regions so that they can be used more easily and to facilitate the adoption of standard procedures across the NRA. The focus of the research will be to provide either generalised estimation procedures or where this approach is not feasible to recommend particular models.

The project will develop the Micro Low Flow (natural rivers) software (previously funded by NERC) so that the most important artificial influences can be incorporated into low flow design.

STRATEGY

Method

1. Review procedures currently used by the NRA for adjusting low flow estimates.

2. Using low flow records from the Surface Water Archive and different combinations of artificial influences investigate the impacts of different scenarios of surface abstraction and discharges on standard low flow measures.

3. Develop and apply simple method(s) for estimating the bulk impact of groundwater abstraction on low flows for major aquifer management units in the NRA.

4. Develop software for deriving residual flow-type diagrams and use to test method on three example catchments in the NRA. The software will be capable of assimilating spot current meter gaugings of known or assumed return frequency.

5. Using conceptual models (eg HYRROM) estimate the regional impact of forestry management on low flows in England and Wales. Develop software for incorporating model results in an estimation procedure.

Monitoring

A six man advisory group will monitor the progress of the project. The group will consist of the project leader and two representatives from other NRA regions, plus a representative from a water company, a consultant and a university. The group will consider:

i) Three monthly short progress reports by correspondence.

ii) Annual 'interim' reports, at annual progress meetings.

TARGETS

	Work Item	To be completed Month
1.	Review NRA procedures for naturalising low flow statistics and residual flow diagram production.	6
2.	Simulate impact of artificial influences on low flow statistics	12
3.	Interim report.	12
4.	Develop software for automatic naturalisation of low flows and production of residual flow diagrams.	18
5.	Review/develop simple procedures for estimating the impact of groundwater abstraction on low flows at the catchment scale.	24
6.	Develop procedure for incorporating spot current meterings into low flow estimation procedure.	24
7.	Interim report.	24
8.	Apply simple conceptual model to estimate impact of forestry management on low flows for catchments with different soil type and climate.	30
9.	Combine different artificial influence procedures into final system.	33
10.	Draft final reports.	33
11.	Final Report.	36

OUTPUTS

	Type of Report	Required by	No. of copies
1.	Quarterly progress report	Quarterly	5
2.	Interim 12 monthly reports	+12, +24	15
3.	NRA Research Report including estimation manual	+36	50
4.	Micro low flow (artificial influences) User Guide	+36	On demand

BENEFITS:

1. Extension of low flow estimation procedure to artificially influenced catchments.

2. Improved accuracy of flow estimation, and ability to reliably set prescribed flows, abstraction licences, compensation flows or consent to discharge.

3. Reduce NRA staff time for low flow estimation.

4. Consistent methodology available over time and between NRA regions.

5. Potential to simulate change in artificial influence in order to estimate change in low flow regime.

6. Royalties from sale of package to consultants, research institutes and water companies as detailed in the Research Contract.

ASSUMPTIONS/RISKS:

1. Uniformity of frequency within low flows response.

2. The accuracy of simple groundwater and afforestation/deforestation models will be adequate in assessing low flow impact.

3. That there will be up-take by NRA regions of proposed technique. Implementation will be contingent upon regions purchasing the existing Micro Low Flow software.

4. That errors of artificial influence data and assumptions concerning the ratio between actual and licensed abstractions is adequate.

OVERALL APPRAISAL:

Measures of low river flow are required for many purposes by the water industry. In some cases data can be obtained from gauging station networks, but often flows have to be estimated. There are several methods by which the natural component of flow of specific duration or frequency can be calculated, but stream flows often have an artificial component. Both components are susceptible to change, but in the artificial case, change can be both sudden and marked. Change may be due to variations in industrial practice or alterations to abstraction and discharge policy. For example, in the Severn-Trent region the value of some Dry Weather Flows have been shifted by 25% in the last 5 to 10 years due to changes in the artificial component of flow. This research will give a greater understanding of low flow regimes, their susceptibility to change and lead to more reliable flow estimation techniques for use in the water industry.