THE RIVER LARK PROJECT

FINAL REPORT PREPARED FOR
THE NATIONAL RIVERS AUTHORITY
BY THE DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF BIRMINGHAM

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NATIONAL RIVERS AUTHORITY:

RIVER LARK PROJECT

PROJECT REPORT

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NATIONAL RIVERS AUTHORITY:

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PROJECT REPORT

1 Introduction

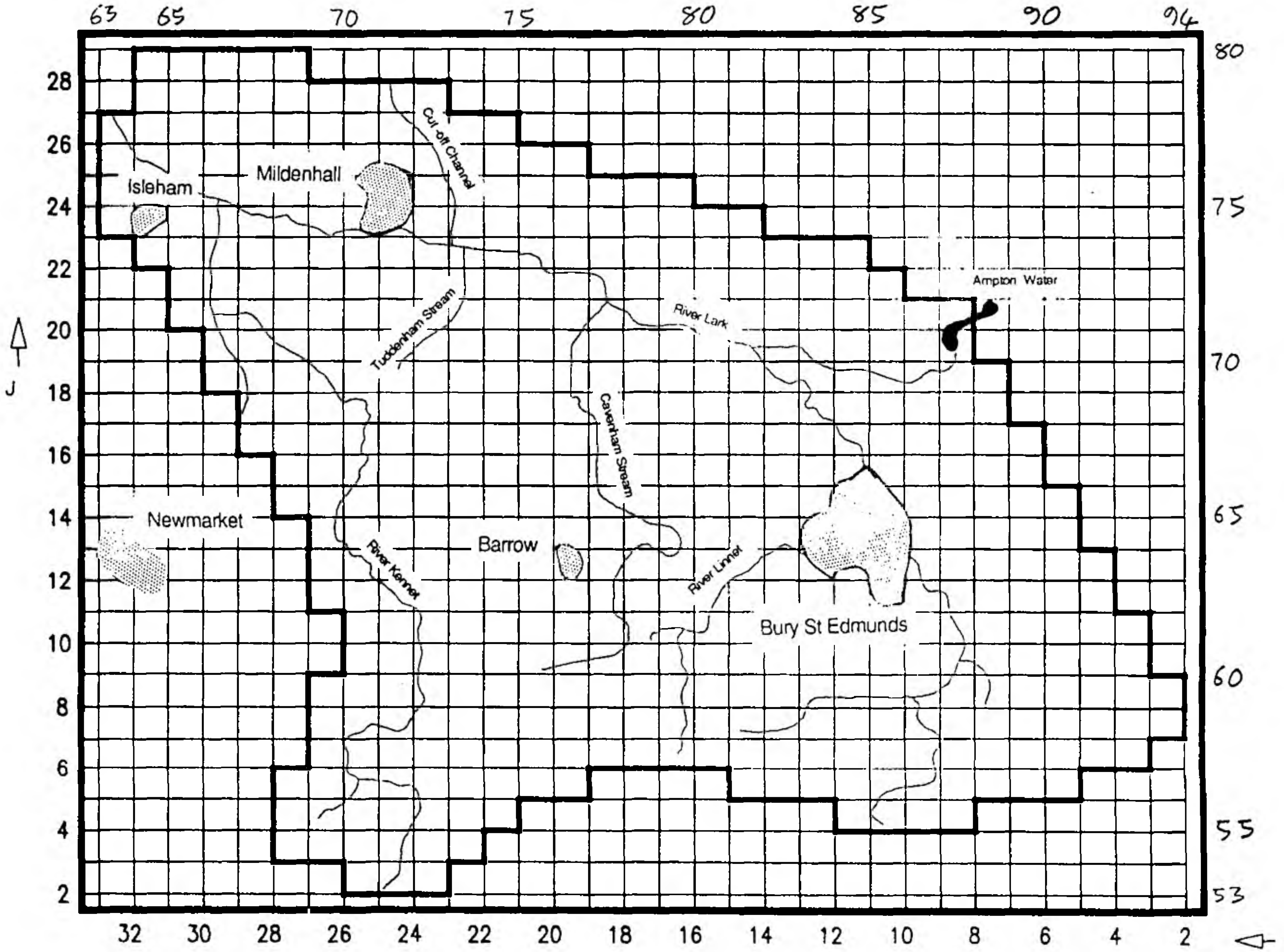
1.1 Reason for Study

This report to the National Rivers Authority describes the development of a digital groundwater model for simulating flow conditions in the River Lark catchment in Suffolk. The study was undertaken by the Department of Civil Engineering of the University of Birmingham between October 1988 and March 1991.

The investigation was initiated to improve understandings of regional groundwater flow behaviour and in particular, the interaction between the aquifer and the River Lark. Improved techniques for protecting local water resources are required because of increasing demands on the aquifer and the possibility of consequent conflicts with surface water usage.

1.2 Aims of Study

The overall aim of the study was to produce a groundwater model for use in predicting flow behaviour and storage distribution in the Chalk aquifer and also for interpreting the relationship of the aquifer with local surface waters. The model was to be developed in an appropriate form for use by NRA. To this end training was to be provided to enable NRA staff to continue any



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Mildenhall
Cut-off Channel
Tuddenham Stream
River Lark
Ampton Water
Cavenham Stream
Newmarket
Barrow
River Kennet
River Linnet
Bury St Edmunds

Fig 1.1

necessary model refinement and groundwater simulation, following the eventual transfer of the model to NRA computer facilities.

Implicit in the aims of achieving a clearer understanding of the resource, was the need to carry out any necessary field investigations and to perform the required analysis and interpretation of the field data. The resulting information was to be used in the development of a deterministic digital groundwater model.

1.3 Approach to Study in General Terms

The first stage of the study included a survey of all of the available data in the form of licence returns, hydrometric records and reported fieldwork. In areas where futher information was required - particularly for the development of certain aspects of the model such as the simulation of unconfined flow behaviour in the Chalk region - additional field study was carried out.

The model was based on a two-dimensional approach and the finite difference method scheme as described in Rushton and Redshaw (1979) although certain refinements to this approach were necessary. Features of the area that required special attention in developing the management model included the river-aquifer relationship and also the unconfined flow regions of the Chalk. In unconfined conditions the variation of transmissivity affects groundwater flow and the distribution of both head and storage - both major factors that influence aquifer management. Thus it was important for the model to be developed to accommodate a transient variation in transmissivity. Streamflow simulation is also important for management of the aquifer because of the need to maintain baseflows along the River Lark to preserve water quality. Routines were specially developed in the study for the model to simulate streamflows at specified sites along the River Lark.

Regional groundwater behaviour was simulated using a finite difference digital model coded in FORTRAN 77. Details of the model and the refinements necessary to improve the simulation of groundwater movement in the vicinity of the River Lark, are described in subsequent sections.

2 Model Development

2.1 Introduction

The value of a digital model in the protection and management of groundwater lies in the flexibility it provides in predicting the response of the aquifer to any external changes in parameters such as recharge and abstraction. This aspect of a model frees management from rigid approaches to controlling groundwater usage such as the safe yield concept. Safe yield is an indicator of the maximum possible pumping rate compatible with the stability of groundwater supply. Lee (1915) first defined it as the limit to the quantity of water which can be withdrawn regularly and permanently without dangerous depletion of the storage reserve. Similar definitions followed these, but all were eventually challenged by Thomas (1951) who suggested abandonment of the concept of safe yield which is too vague to encompass all considerations necessary in determining a yield limit.

Although a constant, single valued limit is attractive for regulating aquifer because of its simplicity, it makes no allowance for any uncertainties in the state of the resource - for example, any anomalies in the recharge behaviour. For this reason, any limit to the yield of an aquifer is best determined as a dynamic concept taking into account all possible variables within the system.

A groundwater model that has been successfully tested to reproduce field behaviour, provides a suitable framework for planning and controlling the development of an aquifer. The implications of developing a reliable model for interpreting groundwater flow behaviour in the Lark catchment are that in the long-term, the model can be used to produce more flexible and more responsive policies for protecting the resource. The model is a quick and efficient facility to help in revising abstraction licences as greater demands are placed on the aquifer and the need for more frequent revisions becomes necessary.

2.2 Digital Model

The model is based on the finite difference method and the point successive over-relaxation (SOR) scheme. The method is applied to a two-dimensional governing equation and permits transient simulation of regional groundwater flow behaviour and accommodates both time-variant transmissivity conditions and varying permeability profiles, and determines natural outflow from the aquifer to the River Lark.

Although the groundwater model was developed along the lines of the finite difference method as described by Rushton and Redshaw (1979), certain important changes were required to allow for the specific conditions of the Lark catchment which is dominated by aquifer-river interaction and has relatively large areas that are unconfined. Because these features affect the quantity and distribution of the available groundwater across the aquifer, they are important in policy formulation and must be represented in any management model developed for the Lark catchment area.

Unconfined conditions and springflow behaviour are each influenced by the variation of transmissivity both in time and in space. In unconfined flow conditions, any changes that take place in the groundwater head will have an effect on the current transmissivity. The reasons for this follow directly from the definition of transmissivity, i.e. the product of the integral of the permeability over a vertical line and the saturated depth. In an unconfined aquifer such as the exposed Chalk of the Lark catchment, permeability can vary significantly with depth and there is the potential for sharp variations in transmissivity and flow to occur as groundwater head alters. Rushton and Rathod (1980) examine the influence of permeability variation with depth on flow and demonstrate its importance in modelling unconfined regional conditions and in simulating springflow behaviour.

Most finite difference regional models capable of simulating unconfined conditions are based on the equation for saturated flow presented by Jacob (1950). The two-dimensional form derived using Dupuit assumptions, is

$$\frac{\delta}{\delta x}\left[k_x \frac{z\delta h}{\delta x}\right] + \frac{\delta}{\delta y}\left[k_y \frac{z\delta h}{\delta y}\right] = \frac{S\delta h}{\delta t} - q \qquad (2.1)$$

where

h = groundwater head [L]

q = Inflow or outflow per unit area [L/T]

S = storage coefficient [dimensionless]

t = time [T]

k_x, k_y = permeabilities in x, y directions [L/T]

x, y = space coordinates [L]

z = saturated depth of the aquifer [L].

Models of this type have been developed by Bredehoeft and Pinder (1970); Prickett and Lonnquist (1971); Trescott, Pinder and Larsen (1976) and Rushton, Smith and Tomlinson (1979).

Bredehoeft and Pinder (1970) describe a model developed to study leaky layers and unconfined flow in multi-layered aquifers. Trescott, Pinder and Larson (1976) describe a model that allows for leakage between surface water bodies and the aquifer. In a study described by Rushton, Smith and Tomlinson (1979), a simulation of flow processes in a Limestone aquifer is performed with both variable transmissivity and variable storage coefficients. Prickett and Lonnquist (1971) present a general model based on the finite difference method for simulating transient regional groundwater flow in situations that may include both confined and unconfined conditions, leakage between layers in multi-aquifer systems and interaction between surface water and groundwater within the system.

A detail that must be considered in any model developed to simulate unconfined flow conditions, is the treatment of the dewatered regions of the aquifer which may result from low recharge or large abstractions. Saturated depths and transmissivities in a dewatered zone of an aquifer are actually zero, because such a region is outside of the boundary to the saturated system of the aquifer governed by the Jacob's equation. For the purposes of simulating conditions in the vicinity of the River Lark, this factor can be ignored at present. However, it is possible that as the aquifer is further developed, so the likelihood of local dewatering will increase and the model will eventually have to be modified to provide a more accurate simulation.

The springflow calculated at a node is based on the difference between the groundwater head and an elevation representative of the outflow site as well as a leakage factor which is a measure of the resistance to flow through the river bed material. A routine in the program determines the total streamflow to a site along the water course by carrying out a flow balance calculation at each succeeding node upstream of the site.

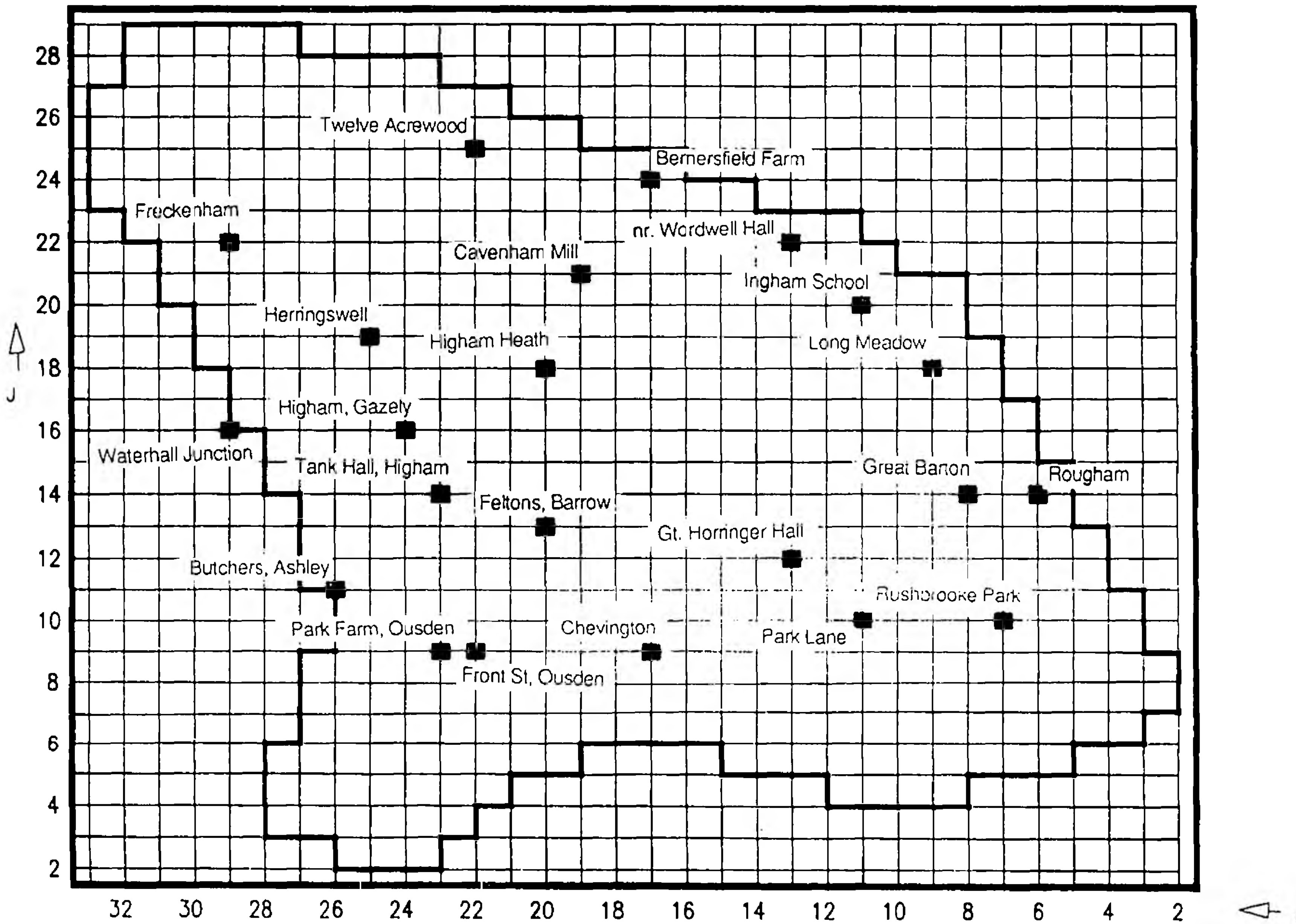
The model, complete with variable transmissivity and streamflow simulation features, is applied to the River Lark aquifer. Flow records are available for the past 21 years and the coverage of distributed properties of the aquifer is reasonable. There are 10 public water supply abstraction sites and 25 sites pumped by industrial and agricultural users that are significantly large for modelling considerations. The PWS sites are as follows:

Name	Model Node	Grid Ref.
Beck Row	(28,26)	TL 680773
Eriswell (1&2)	(24,26)	TL 730759
Twelve Acre Wood	(21,24)	TL 748755
Isleham	(32,22)	TL 641729
Moulton	(25,13)	TL 700646
Tuddenham	(22,20)	TL 751710
Risby	(20,17)	TL 773681
Barrow Heath	(19,14)	TL 779654
Bury St Edmunds	(10,13)	TL 850642
Rushbrooke	(8,11)	TL 874624

The location of the above sites as represented on the finite-difference mesh, are shown in Fig.(2.5).

The response of the aquifer to abstraction at these wells is determined from the simulated behaviour at any of the 22 observation wells and two springflow sites shown in Fig.(2.1). The reliability of these sites as indicators for evaluating management policy using the model, is tested by comparisons over prescribed periods between field data and historical simulations.

The aspects in which the Lark model differs from the finite difference scheme described in Rushton and Redshaw (1979) are outlined in sections 2.1.1 and 2.1.2.



Twelve Acrewood
Bernersfield Farm
Freckenham
nr. Wordwell Hall
Cavenham Mill
Ingham School
Herringswell
Higham Heath
Long Meadow
Higham, Gazely
Waterhall Junction
Tank Hall, Higham
Great Barton
Rougham
Feltons, Barrow
Gt. Horringer Hall
Butchers, Ashley
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Fig 2.1

2.1.1 Unconfined flow simulation

In nonsteady, unconfined flow situations, transmissivity may alter considerably as groundwater levels vary. Where groundwater levels are drawn down sharply, for instance in the vicinity of a pumped well, transmissivities decrease. This reduction in local transmissivities limits the possible inflow to a well from the surrounding aquifer.

A sloping aquifer bed may also have a significant effect on the phreatic surface of an unconfined aquifer. With no inflow to such an aquifer, transmissivity at a point decreases with time and it will also decrease in the updip direction.

Sharp transitions in the variation of permeability with depth have a significant effect on regional transmissivities over time as groundwater levels vary. This factor which affects the spatial and temporal variation of stored groundwater is not accounted for by simulations based on a constant transmissivity approach. Lower demands on computation and on the data required, have made constant transmissivity models a more favoured choice for regional flow studies. However, advances in computer hardware have opened up new possibilities for developing models that accommodate a transient variation in transmissivity.

The relevance of varying transmissivity to management lies in the ability of the approach to provide a more accurate simulation of the storage state of groundwater in unconfined regions and also to provide improved estimates of head dependent parameters such as river-aquifer transfers. Where aquifers feature both confined and unconfined flow zones - as in the case of the Chalk aquifer in the River Lark catchment - groundwater models that make no allowance for transmissivity variation tend to overestimate potentials in confined zones and underestimate heads in unconfined flow areas. Not only does this lead to less accurate predictions of the regional storage distribution, but it also has implications for the ability of the model to estimate such phenomena as the head dependent river leakages or the movement of contaminated water bodies around the aquifer. It was thus a desirable objective to develop a model of the River Lark Chalk aquifer that allowed for varying transmissivities.

The model accommodates variations in transmissivity by dividing the aquifer into two zones: a primary zone and a secondary zone. Smith (1979) describes the importance of rapid fissure flow in the regional behaviour of groundwater in the Lincolnshire Limestone in eastern England. The nature of the fissure system in the area suggests a sharp increase in transmissivity with water table elevation. To allow for the presence of a more permeable layer towards the top of the Chalk in the Lark area, the secondary zone in the model, which varies with the saturated depth, has a higher permeability than the primary zone below it. Groundwater head can never fall below the base level of the primary zone.

Permeabilities which remain constant for the duration of the model run are calculated from entered data for each zone at the start of the steady state calculation. These permeabilities are used in conjunction with the saturated depth - determined from the nodal head at the end of the previous time step - to calculate the transmissivity that apply to the node for the current time step. In this way, the transmissivity in the x and y directions are updated at each node for every time step of simulation.

Although it is possible to adapt the model to cope with a varying transmissivity, a major problem faced in the approach is that of the data requirements. It is difficult to obtain suitable data that represent the variation of permeability with aquifer depth. However as the volume of field work and analysis related to the normal activities of the NRA in the area continues, so it will be possible to include new data into the model to improve the quality of groundwater behaviour predictions.

2.1.2 Streamflow simulation

Introduction

Although, the responsibility for maintaining river flows is as much a concern of groundwater management as it is a surface water consideration, this fact is not always recognised. For example, in the United States, water beneath the surface of the ground was classed legally as a subject apart and separate from surface water supplies until 1960 (ASCE, 1961).

The importance of the interrelationship between surface and groundwater was recognised early on in management studies of the Chalk aquifer in the River Lark catchment. It is apparent that groundwater usage could eventually be carried out to the detriment of streamflows in the River Lark and the cut-off drain, where increases in abstraction are likely at sites such as Eriswell, near Mildenhall. It is possible that the River Lark and the cut-off drain are in hydraulic continuity with the aquifer in this area. Conflicts such as these can affect the requirements of either surface water or groundwater usage in the River Lark catchment.

In the interests of surface flow protection it is necessary to maintain the baseflows immediately downstream of Bury St Edmunds in order to dilute sewage discharged near Fornham St Martins; or in order to protect the groundwater storage, it may be necessary in the long-term to restrict outflows to the River Lark.

Approaches to streamflow modelling

One approach for including the influence of natural outflows in a groundwater model is to treat them as boundary conditions to be satisfied for each time step of solution. In other words, these flows would be entered as input data and would not be calculated by the model. There would be no possibility to use it to examine aspects such as the potential for conflict between surface and groundwater usage. Because of the importance of simulated baseflows to aquifer management, the Lark model has been developed to calculate the natural outflows at specified sites along the watercourse. These simulated flows are used to verify the model performance in comparisons with field data.

It is worth considering the other advantages of developing a model that determines natural outflow at every time step. The natural outflow from an aquifer can represent a significant proportion of the flow balance and so to use estimated flows in predictive simulation may leave a wide margin of error in the results. Furthermore, the model accuracy in predicting the distribution of stored groundwater across the catchment can be impaired if it is necessary to enter outflow data at the start of simulation, as these flows are not responding to aquifer conditions but are instead influencing local groundwater behaviour. For this reason, a model which predicts the response of natural outflows to changes in abstraction or recharge provides a more reliable interpretation of regional flow behaviour and groundwater distribution.

A further consideration in modelling springflow is that they are useful indicators of the state of aquifer storage. Reliable streamflow predictions from simulations can be related to the state of local groundwater storage determined by the model. Understandings of this relationship - gained through experience with the model - can be used eventually to provide rapid assessments of field conditions for policy formulation, on the basis of measured streamflows.

Because of the necessity to discretise an aquifer in digital groundwater models, the finite difference method is not always suitable for simulating streamflows. Streamflow can occur in a short period over a small area of the aquifer and yet for purposes of simulation, it must be represented in a model of an entire system, discretised into nodal elements of several thousand square metres and time increments of several days. An average head applying to the whole element and for the duration of each time step is the only parameter available for predicting the response of baseflow to changes in the aquifer. Consequently, it is often not possible or practical to represent the behaviour of baseflow accurately in a model. The method of modelling streamflow used in the Lark model overcomes many of these difficulties. The performance of the routine developed during the investigation is demonstrated in later sections.

Few generalisations can be made regarding the complex relationships that exist between surface and groundwater flow. This presents difficulties for developing modelling methods that use field measurements of aquifer characteristics to predict baseflow. The problem is demonstrated by a study carried out to establish the variables that influence natural outflow from an aquifer. Parizek (1969) attempts to relate 18 parameters to baseflows using linear regression. Of these variables, which include land use types, geological, physical and geomorphological parameters, few show an acceptable correlation with outflow.

All routines that simulate baseflow behaviour in digital groundwater models are based on some function of the potential difference between the river and the aquifer at a particular location. The type of function implemented is determined to a large extent by the flow conditions in the aquifer and also the nature of the connection between river and aquifer. For example, either a linear or nonlinear leakage mechanism are useful in situations where bed sediments of low permeability are present, whereas for some studies involving discharge from unconfined aquifers baseflows can be calculated directly from mass balance considerations as a loss of storage.

Several conclusions may be drawn from the various springflow routines that have been used in digital modelling by authors such as Oakes and Pontin (1976) and Miles and Rushton (1983). Miles and Rushton (1983), in a study of the river Worfe, describe a leakage flow mechanism which is applied in a coupled model of a partially penetrating river. It simulates flow between the aquifer and the River Worfe and includes a flow balance calculation to determine river flows across the aquifer. A different approach is used in a model described by Oakes and Pontin (1976). Outflows, which occur when groundwater heads exceed river levels, are determined as a direct loss of storage equivalent to the difference between the groundwater head and a specified topographical height for selected nodes. Disadvantages of this method are that the river is assumed to be fully penetrating and constant transmissivity conditions prevail throughout simulation. These factors limit the ability of the model to simulate groundwater flow behaviour in the vicinity of the river.

The variation of transmissivity with depth affects discharge behaviour in aquifers that are highly fissured in the upper layers, as in the case of the River Lark Chalk aquifer where pressure relief jointing from valley erosion has given rise to a high secondary permeability. The ratio of transmissivity to storage coefficient influences the range of possible discharges that may occur. Nutbrown and Downing (1972) recognise the effect of the relationship between local transmissivities and storage coefficients on natural outflow. They define a parameter, the aquifer response time, which is expressed as the ratio T/S which governs the range of flows encountered in a river sustained by a groundwater source. Higher streamflows result when ratios of T/S of the surrounding material increase. Thus if transmissivities rise sharply with increasing saturated depth, it is possible for the outflows to increase in a nonlinear manner. Rushton and Rathod (1979) describe a model developed to examine rapid recharge in the highly permeable upper layers of an unconfined aquifer. They confirm the importance of transmissivity variation with depth as an influence on springflow.

These factors have been considered in the development of the streamflow simulation mechanism described in the next section.

Streamflow simulation approach

The streamflow routine in the Lark model combines the runoff which is determined in the recharge model in a flow balance with the river-aquifer leakage flow calculated at each time step. The runoff component is balanced at the end of each time step and does not influence local groundwater heads, i.e. the river flow balance calculation is a post-processing routine independent of the simulation of groundwater movement. In other words the only natural outflow that affects the aquifer in the model, is the baseflow component of the streamflow.

The leakage flow is calculated from the following relationship during solution of the finite difference equations:

$$qra_{i,j} = r_{i,j}(h_{i,j,n} - g_{i,j}) \qquad (2.2)$$

where

$qra_{i,j}$ is the flow between the river and aquifer at node i,j

$r_{i,j}$ is the leakage factor

$h_{i,j,n}$ is the groundwater head at time step n

$g_{i,j}$ is the river stage

The routine using the above relationship to determine the river-aquifer leakage flows is capable of simulating sections of the

Lark that are are both influent and effluent along their course. The model can be used to calculate the baseflow at given sites on the Lark, i.e. it is the sum of the effluent flows along a specified reach of the river. Both the baseflow and the full streamflow can be produced as output from a simulation run.

The full streamflow is calculated from the following algorithm:

$$R_{i,r+1} = R_{i,r} + qnode_{i,r+1} + qra_{i,r+1} \qquad (2.3)$$

where

$R_{i,r+1}$ is the river flow for the current river node, r+1

$R_{i,r}$ is the river flow for the preceding river node, r

$qnode_{i,r+1}$ is the runoff component for the current river node determined from the recharge model and entered at the start of simulation

$qra_{i,r+1}$ is the river-aquifer leakage flow for the current node

If $R_{i,r} < 0$, only the entered runoff for the current river node constitutes the river flow before the water balance takes place. In the flow balance, the amount of water gained by the aquifer is controlled by the amount available in the river. The river is considered to be dry when the leakage into the aquifer is greater than or equal to the river flow.

The streamflow simulation capability of the Lark model is aided by the fact that the transmissivity can vary in time. This is especially important in areas such as in the Chalk immediately adjacent to the River Lark, where there is likely to be a marked permeability variation with depth.

Flow in the cut-off channel is accounted for by the diversion of a constant proportion of about 37% of the River Lark streamflow, simulated at a node corresponding to a site adjacent to Barton Mills immediately upstream of Isleham. This flow mechanism has been adopted following a trial and error approach in the early stages of the study. It is important that this situation should be corrected, as the cut-off flows in the vicinity of significant abstraction sites and any interaction between flow in the channel and the aquifer could be critical to developing future policy.

2.2 Data Requirements

Aquifer geometry

Aquifer geometry is represented in the Lark model by means of a rectangular grid. In finite difference models, the grid spacings in each direction (i.e. x and y directions) may be varied to concentrate nodes in areas of particular interest of the aquifer. These spacings are entered as data and remain constant throughout the simulation. In the case of the Lark model, the nodal intervals are all constant at 1 km and coincide with the National Grid. There are 27 intervals in the north-south direction and 31 intervals in the east-west direction.

Superfluous nodes occur on grid nodes where the aquifer geometry in plan is irregular. When array operations are performed, nodes that have no corresponding point in the aquifer are ignored throughout the simulation.

A primary saturated depth and a level of the base of the aquifer for each node are entered for calculating a secondary saturated depth from the groundwater head. These depths are then used to determine the inter-nodal transmissivity at the start of each time step.

The model boundary was determined from an inspection of the area and a study of local hydrogeological maps. The results of pumping tests carried out in the boundary areas of the aquifer were also used to determine the likely locations of the groundwater divides between the Lark and the surrounding catchments. The lateral limits to the aquifer are represented in the model as no-flow boundaries, except for the immediate area of the River Lark and its intersection with the model boundary at the downstream end of the catchment where fixed head nodes are used in simulating local conditions.

<u>Aquifer properties</u>

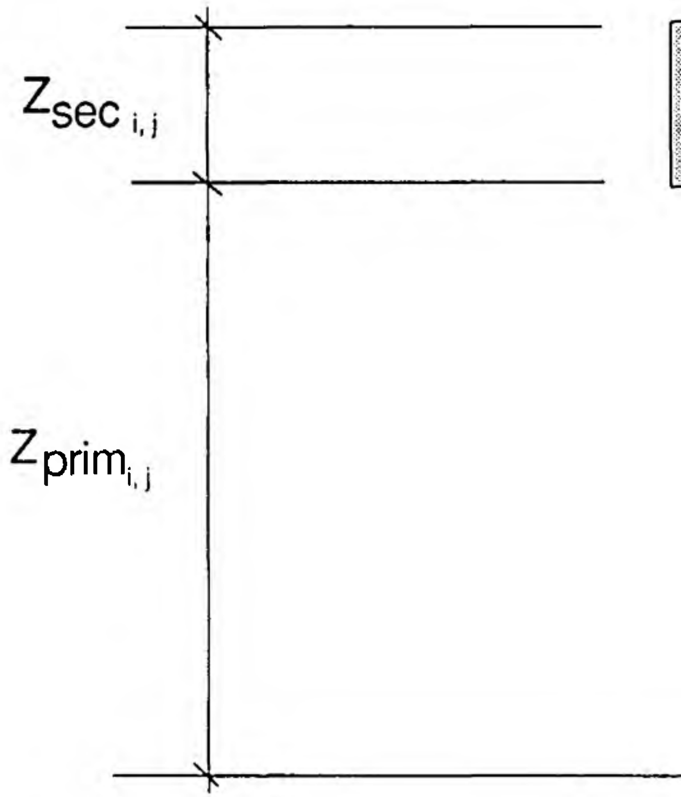
The model allows simulation of anisotropic, heterogeneous conditions. The physical parameters of the aquifer medium required for simulation are are the transmissivities (in the x and y directions) and the storage coefficients at each node. It is possible to incorporate any relationships between transmissivity and saturated depth into the model where suitable field data are available. Nodal storage coefficients remain constant throughout simulation. However, as data become available in time, particular in the area where groundwater flow may alter between confined and unconfined states along the boundary of the Boulder Clay, it may improve the accuracy of simulation to alter the model to cope with varying storage coefficients.

For the River Lark aquifer model, permeability is assumed to vary with saturated depth in the manner shown in Fig.(2.2). A transmissivity is entered at the beginning of the simulation based on field evidence. The primary and secondary permeabilities are then determined from the transmissivity entered for each node. These permeabilities are used to establish the relationship between saturated depth and transmissivity which then remains constant throughout simulation.

The distribution of transmissivities and storage coefficients that are entered into the model are shown in Fig.(2.4). These have altered during the course of the study to improve the simulated response of the aquifer to the historical flow records. The original distributions of these parameters are shown in Fig.(2.3).

Monthly flow data

The possible categories of flow data that may be included as



$Z_{sec\,i,j}$
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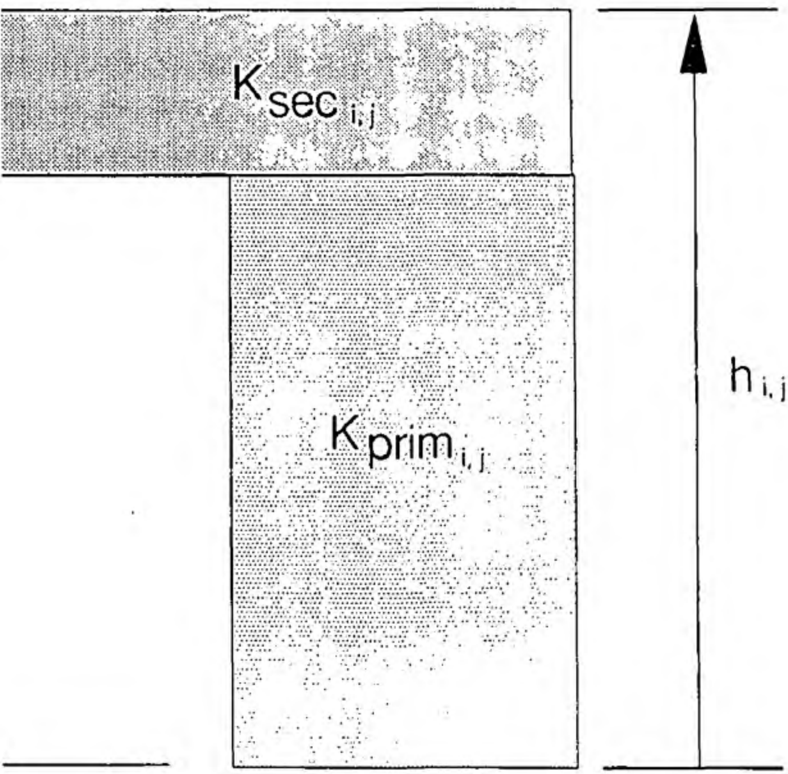

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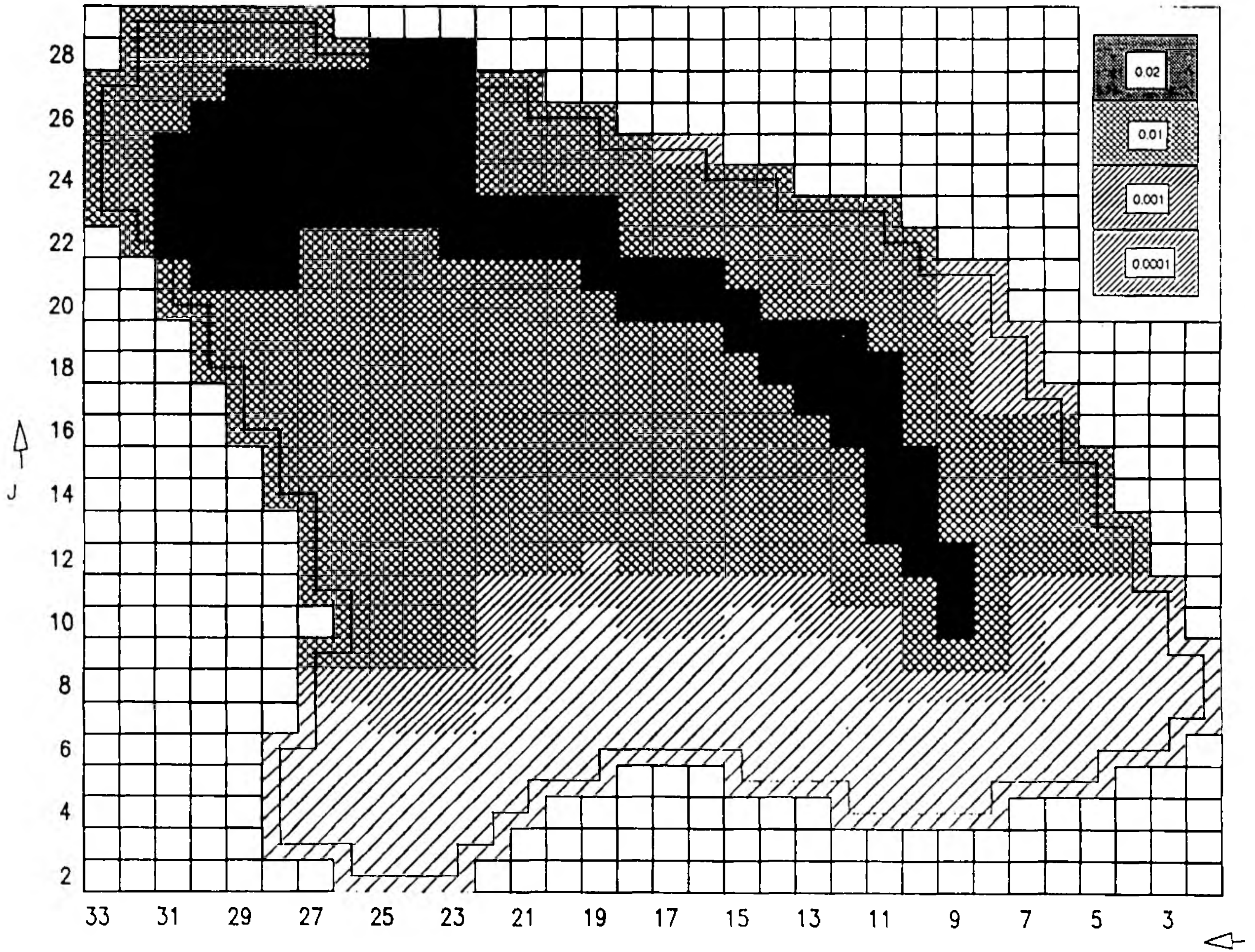

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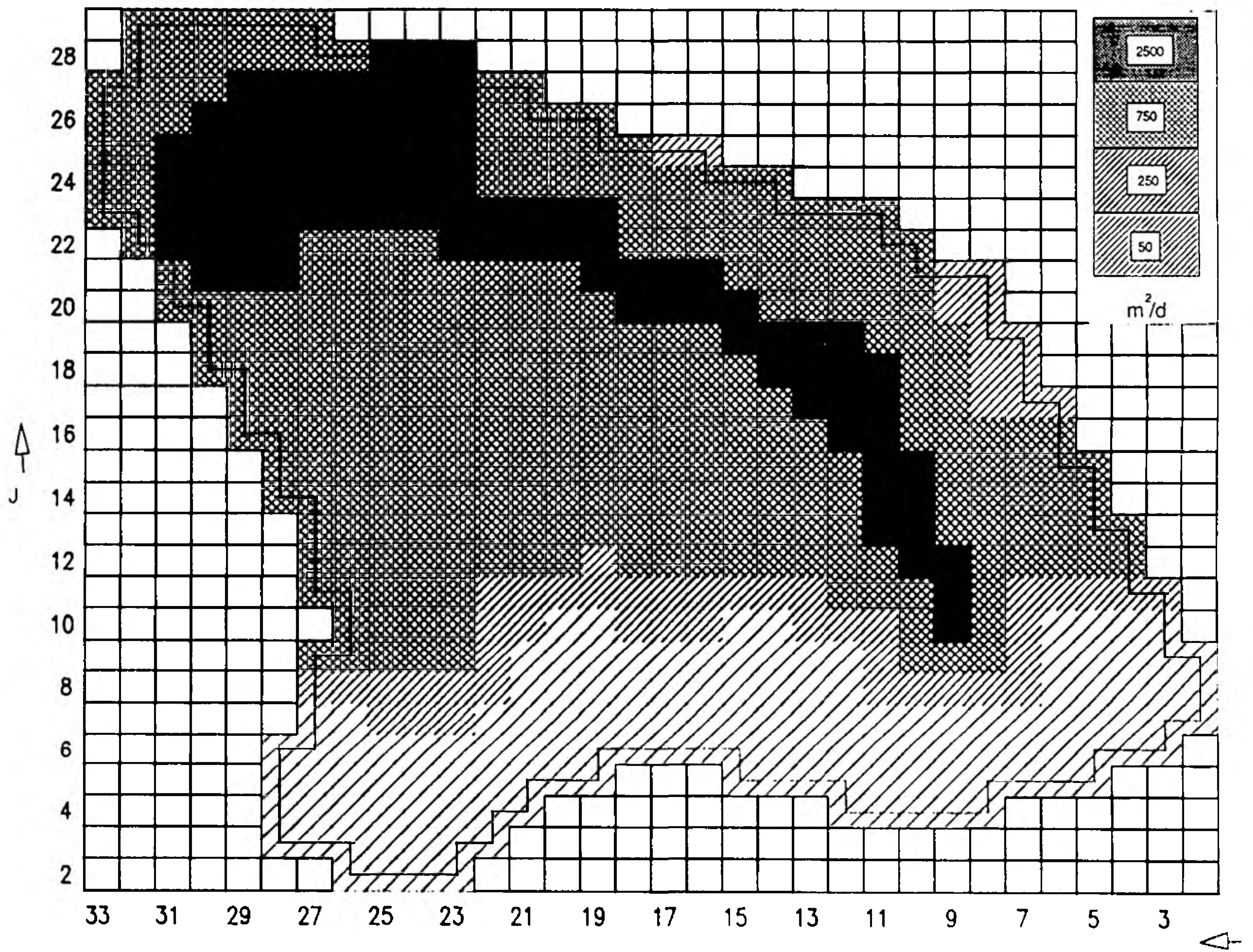
Fig 2.3(a)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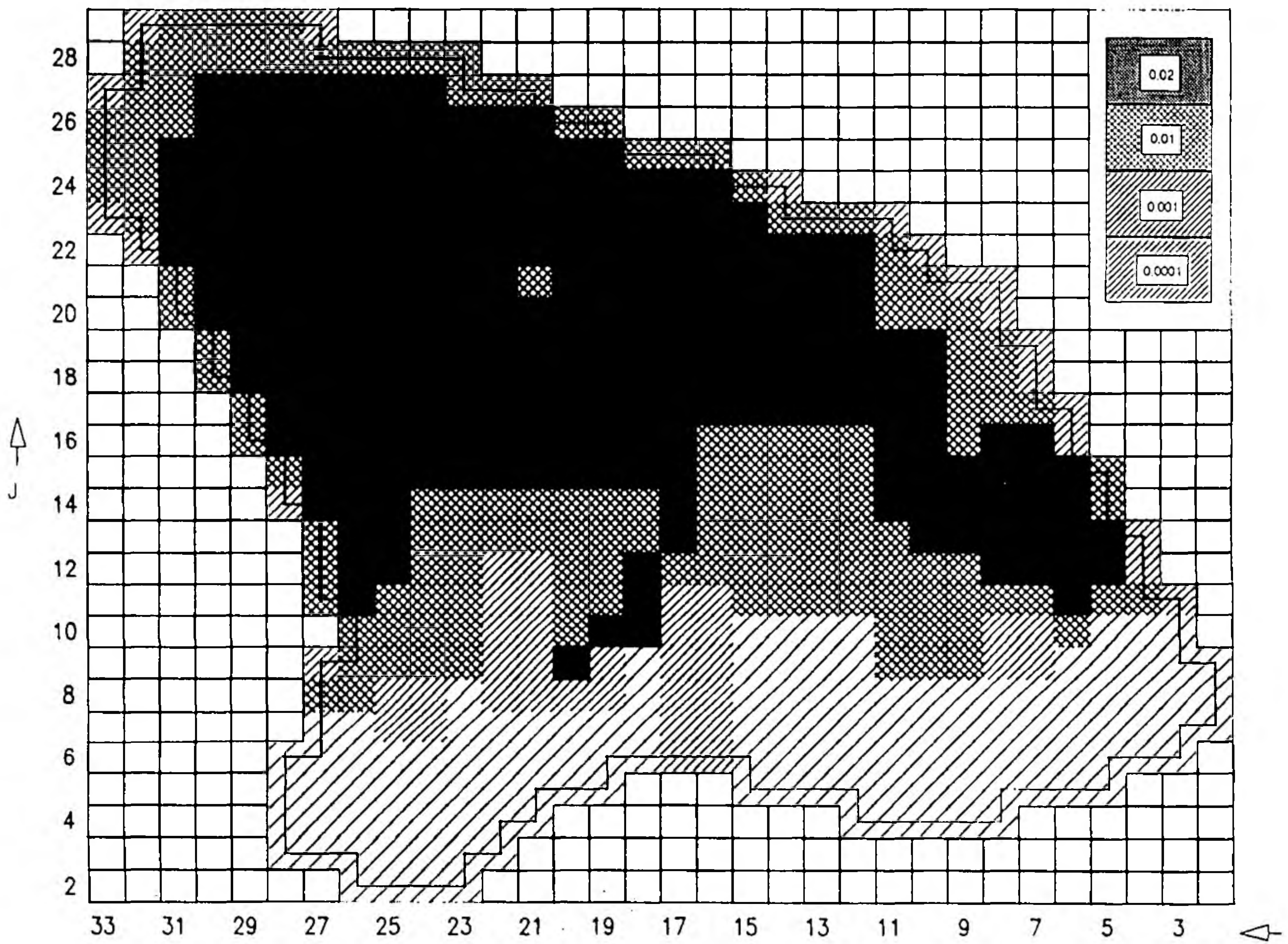
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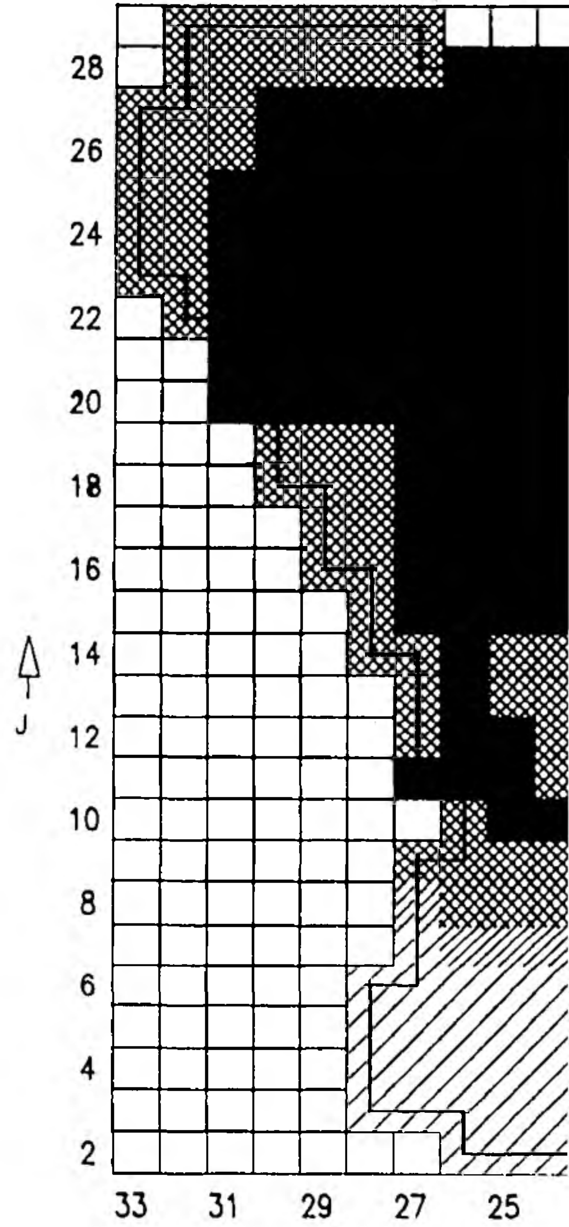
Fig 2.4(a)



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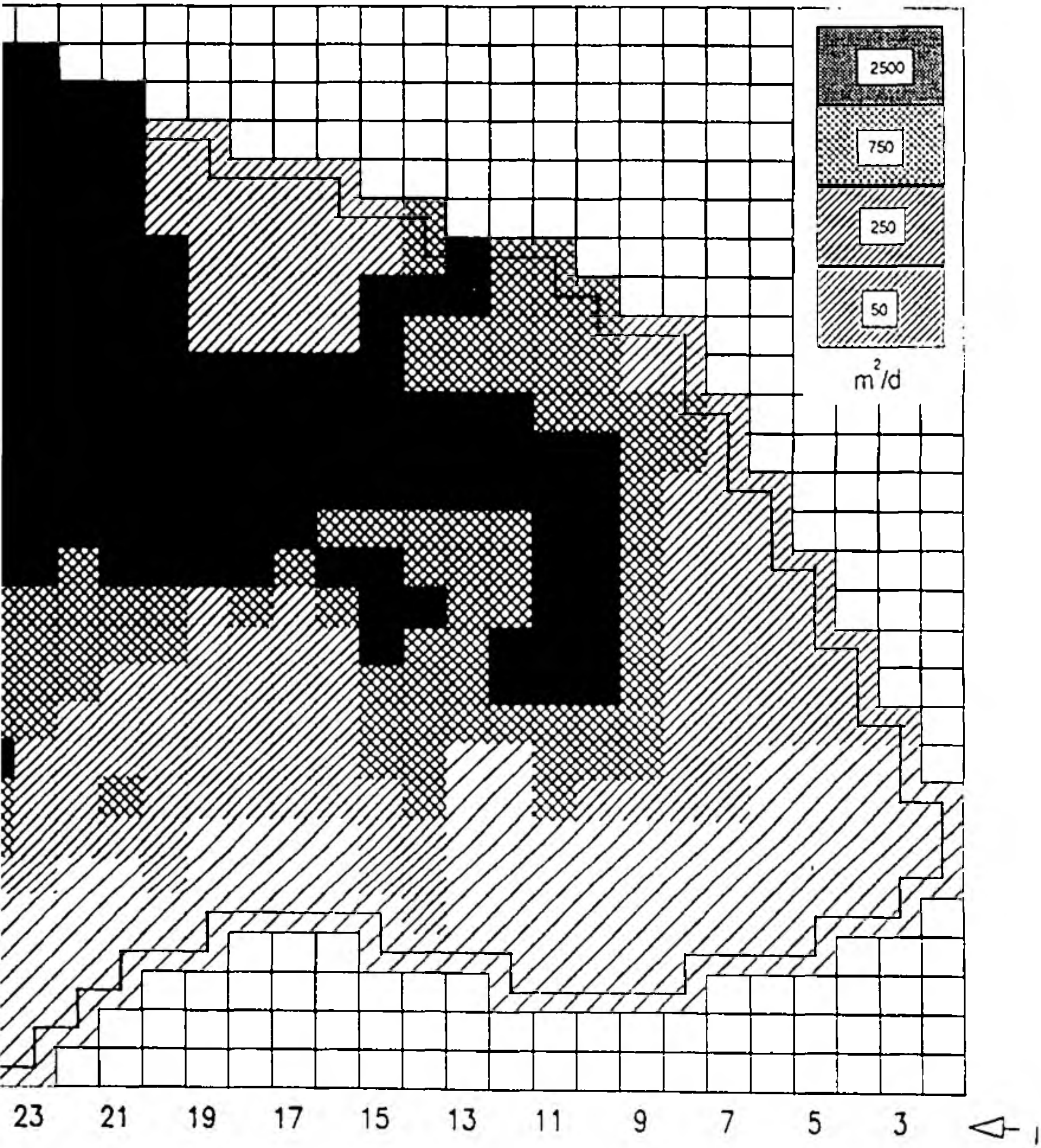


Fig 2.4(b)

input to the model are

> Recharge.

> Natural outflow.

> Abstraction.

The above data categories are entered as flowrates that remain constant over each calendar month. By treating the flows in this way, it is possible to divide time steps into periods with durations of less than a month.

Recharge.

The recharge estimation for the River Lark Chalk model is carried out according to the work of Penman (1949) and Grindley (1967) as modified by Spink and Rushton (1979). Penman (1949) introduced the notion of a root constant to define when actual evaporation is less than potential evaporation. The concept is important for use in soil moisture deficit models used to calculate recharge. These models determine recharge by considering a flow balance between the infiltration of precipitation and the saturated zone of the groundwater system. The amount of recharge that results from the infiltration depends on the state of the soil moisture store. This approach has been refined by further research and application of the basic theory to many different field problems. Grindley (1967) related vegetation and season to evapotranspiration improving the method suggested by Penman.

Two approaches are used for the recharge calculation, one for the area confined by Boulder Clay and the other for the unconfined Chalk. In the case of the Chalk, a more accurate estimate of the recharge can be obtained by allowing a fraction of the effective precipitation, i.e. the actual precipitation minus the evaporation, to enter the aquifer directly. The remainder is determined by applying Penman-Grindley theory to the balance of the effective precipitation. The recharge model used for the Lark aquifer allows direct infiltration of 6 % of the actual daily precipitation that exceeds 5.0 mm/d, followed by direct infiltration of 6 % of the effective daily precipitation.

Recharge to the Boulder Clay is modelled as a mechanism whereby on the elimination of the soil moisture deficit, 0.1 mm/d is allowed as recharge, delayed for 250 days.

The runoff calculated in these two approaches is allowed to contribute to the river flow in the flow balance calculation carried out at the end of each time step.

Details of the development of the recharge models and the related data are described in an interim report on the Lark Project (University of Birmingham, 1989).

Natural outflow.

The ability of the model to simulate natural outflow has been described in previous sections. If necessary, they can also be represented in the model as pumped wells, in which case the flows are entered at the start of the simulation. However, for most management studies of the Lark aquifer, it is most desirable to simulate natural outflow because of the dominance of the River Lark. Thus no baseflow data are required for entry into the groundwater model.

The runoff data produced by the recharge calculation are entered for the post-processing flow balance. These data do not affect the simulation of groundwater behaviour, but are only required - along with the baseflows output at each time step - to compute streamflows at specified nodes. Nodal factors are entered at the start of simulation to control the distribution of the runoff to the relevant nodes along the watercourse.

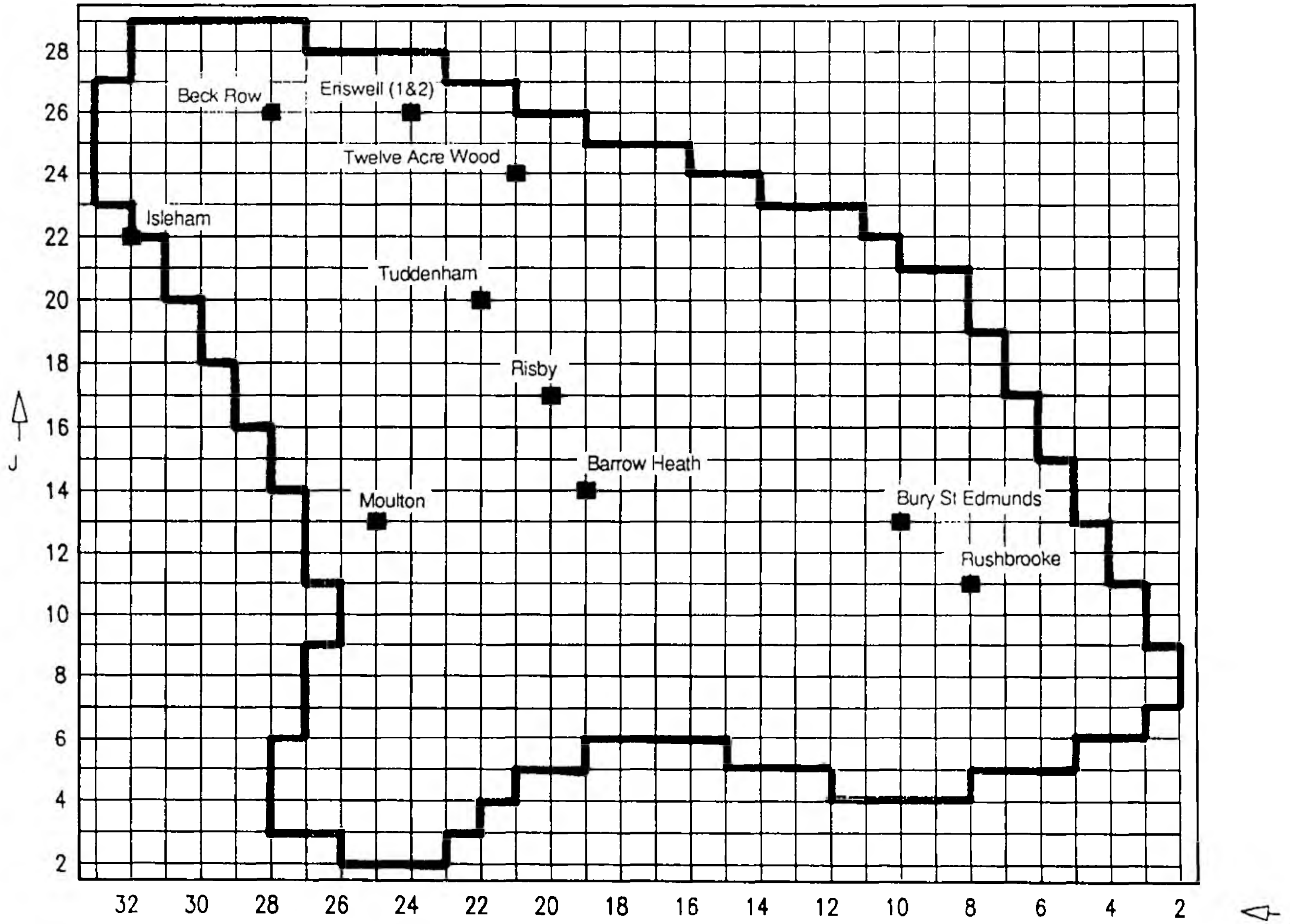
Abstraction.

Abstractions are included in the model at nodes that approximate to the field position of the pumped borehole sites. For the Lark catchment these include public water supply sites, spray irrigation wells and industrial abstractions.

The distribution of these sites is shown in Fig.(2.5).

Boundary conditions

The model is capable of including the three possible boundary conditions: fixed head boundaries, known inflow boundaries and impermeable boundaries. Of these types the Lark model only requires the use of impermeable boundaries and fixed heads. The impermeable boundaries limit the area described previously in the section on aquifer geometry, while the fixed heads which are set to a zero datum remain unchanged throughout simulation. Three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8
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I
Beck Row
Eriswell (1&2)
Twelve Acre Wood
Isleham
Tuddenham
Risby
Barrow Heath
Moulton
Bury St Edmunds
Rushbrooke

Fig 2.5

fixed head nodes are maintained at the downstream end of the River Lark on the north-west boundary of the modelled area.

<u>Data output</u>

The output requirements from a simulation are determined by the nature of the management exercise being carried out using the model. These requirements may also change according to the hardware and software available for presentation of simulation results.

Output may include the variation in both time and space, of groundwater heads, transmissivities and storage coefficients. Routines can also be incorporated into the model to determine regional variations in inflow, outflow and storage over the simulation period. Flow through the aquifer can be represented by vectors at each node, calculated from information about groundwater heads and transmissivities.

At present the Lark model produces output of groundwater head variation at the following sites:

Name	Model Node	NRA No.
Chevington	(17, 9)	TL 75/ 9
Front St, Ousden	(22, 9)	TL 75/19
Feltons, Barrow	(20,13)	TL 76/19
Higham Heath	(20,18)	TL 76/29
Rougham	(6,14)	TL 86/23
Great Barton	(8,14)	TL 86/22
Bernersfield Fm.	(17,24)	TL 77/ 4

Cavenham Mill	(19,21)	TL 77/46
Rushbrooke Park	(7,10)	TL 86/ 5
Long Meadow	(9,18)	TL 86/169
Park Lane	(11,10)	TL 86/170
Ingham School	(11,20)	TL 86/10
Butchers, Ashley	(26,11)	TL 66/ 4
Freckenham	(29,22)	TL 67/77
Park Fm, Ousden	(23, 9)	TL 75/68
Herringswell	(25,19)	TL 76/ 2
Higham, Gazely	(24,16)	TL 76/59
Tank Hall,Higham	(23,14)	TL 76/110
Twelve Acrewood	(22,25)	TL 77/53
Gt. Horringer Hall	(13,12)	TL 86/ 1
Waterhall Junction	(29,16)	TL 66/88
nr. Wordwell Hall	(13,22)	TL 86/114

Streamflow and baseflow predictions are also produced for Beck Bridge, Fornham St Martin, Isleham and Temple Weir.

2.3 Start-stop facility

An important feature has been added to the Lark model to allow simulations to be carried out between any two months within the period January 1970 to December 1989.

This is achieved using unformatted data files into which are written the model arrays that contain all of the relevant data that describe the state of the aquifer at any given month end.

This facility allows the model to be started from any given time provided that a dump file has been created with the necessary starting conditions. To create such a file, the model is run from steady state to the selected date and then the relevant data is output to a dumpfile. This file can then be used to initialize the model to carry out any number of simulations from this date without having to repeat simulation from steady state.

By using dump files it is possible to examine the impact of severe recharge sequences on proposed abstraction licences that have been implemented from the same date. The method can also be used to examine the consequences of a series of alternative policies that are implemented in the model and that start from a given month.
For example, the starting conditions for examining the impact of a drought may be suitably represented by those prevailing at the beginning of the drought of 1976. A dump file containing conditions in the Lark area for March 1976 will provide a suitable starting point to examine the impact of proposed abstraction licencing on the aquifer. A variety of different abstraction quantities can be imposed on the aquifer in a series of simulations of aquifer conditions throughout the ensuing drought of 1976 and the results used to decide on management requirements.

The start-stop option offers the possibility of rapidly updating the model too, and this will prove useful in implementing the Lark model in a regular operational role with the National Rivers Authority.

3 Model Adequacy

Sufficient data are now available to simulate conditions for any period between January 1970 and December 1989. The results of the model have been compared to historical observation borehole and streamflow hydrographs. These records were selected to provide a good coverage of the entire aquifer over the longest possible period.

The model was used to simulate historical conditions and the results are plotted with the relevant field records in Appendix A. These comparative plots indicate that the model provides a reliable simulation of the response of the aquifer to recharge and abstraction.

In determining the boundary, it has been necessary to strike a reasonable balance between providing a sufficient general limit to the areal extent of the aquifer considered and the need to avoid excessive processing time. However, the model boundary would benefit from continued refinement as more information becomes available from field evidence and also from experience of using the model. This is apparent along the northern boundary in the vicinity of Berners Field Farm, where it is likely from difficulties experienced in modelling local groundwater head variation that the influence of the aquifer extends further towards Thetford.

4 Model Implementation

4.1 Current Implementation

Model is currently implemented on a NEC microcomputer. The system is based on a 286 processor, with 640kB of memory and a 40 MB hard disk. An Inmos transputer card is installed to provide superior computation for the finite difference routines of the groundwater model.

4.2 General System Requirements

The compiled form of the recharge program together with the necessary data files for generating a recharge record from 1969 to 1989 requires 750 to 1000 kB of memory. In order to complete a simulation of groundwater conditions over this period, the minimum model memory requirements are 3.6 MB. The upper limit to this figure is determined by the nature of the simulations carried out and by the amount of output required from the model.

An important aspect of the system in current use, is the efficiency of the added transputer facility. The transputer card reduces the processing time to less than 1/15 of that normally required by the convential 286 microcomputer for a typical simulation of groundwater conditions in the Lark catchment.

5 Role of the River Lark Model in Management

5.1 Implementation

The model has been verified against field information. It provides a reliable interpretation of regional groundwater behaviour and has been developed to accommodate new information that may become available in the ongoing activities of the NRA, such as for example, the results of pumping test analyses. A "front-end" program has been developed in the study for preparing the model to carry out specific simulations. It allows the model to be altered to examine the impact of different recharge and abstraction sequences between any prescribed months from January 1970 and the present - the only limitation being the time taken to update its records with the most recent data available. For the model to be successful when used in such a capacity, it is important to have have a system which allows rapid feedback of field data. This is essential for refining policy and continuing improvement to the model.

It is clear that this offers wide scope and a high degree of flexibility in the nature of problems that can be examined using the model. In order to gain the maximum benefit from the model, it will be necessary to determine the constraints that apply to criteria used in assessing the impact of proposed changes - e.g. to abstraction licence amounts, in the River Lark catchment. Unlike a rigid approach to management which is constrained by a single valued safe yield policy, the flexibility of digital modelling allows greater freedom within constraints that ultimately can be applied not to abstraction, but to criteria such as the River Lark baseflows, regional groundwater heads or aquifer storage levels. The criteria to be used and the management constraints that apply to these simulated parameters will be determined by a range of factors including economic, legal and environmental considerations.

As stated in previous sections, the simulation data produced by the model can be presented in a variety of different forms for use as decision criteria over and above those already in use with the River Lark castchment model. Other forms of output may be useful to examine anticipated problems such as water quality and the movement of low quality bodies of water through the aquifer. These forms which depend on the type of study carried out and on the software and hardware available for presentation, include flow through specified sections of aquifer, leakage flows, flow vectors, volumes of stored groundwater and storage changes.

5.2 Present Role

The most important role of the model in the short-term is in reviewing abstraction licencing applications. This is carried out effectively in the following way. The model is used to simulate historical conditions in the aquifer over a representative period which includes extremes in recharge and baseflows to provide a suitable test of the proposed abstraction licence alteration. Two simulations are performed for the same representative time period. One is for the historical conditions, while the other repeats these historical conditions although it also includes the revised abstraction. The output of these two simulations are then compared according to the selected criteria to provide an assessment of the impact of the proposed change. Any significant changes that result from the revised abstraction will be apparent in the comparative plots of the simulated behaviour of the chosen criteria.

In this way the model can be used to review the feasibility of any new development to the aquifer. It can also be used to examine the impact of the existing abstraction licences, i.e. if they were all operating to their maximum permitted output. Through using the above approach either with historical data or with design drought sequences included in the recharge input to the model, it is possible to carry out a general examination of the existing licencing system. The results can be used to identify potentially critical areas of the aquifer and also to indicate regions that are suitable for further development should it become necessary.

5.3 Future Options

As data bases and data collection facilities improve in future, and as demands on water resources in the River Lark catchment rise, so the option of using the model in a more interactive role for examining short-term problems will become more likely. When the model is implemented in this way, it will require rapid updating of field data in order to simulate existing conditions, especially if the model is to be used in a predictive role to determine solutions in areas such as drought management or the control of groundwater quality. In these problems the definition of management constraints becomes increasingly important. It is desirable to define constraints for describing the deteriorating state of an aquifer. These constraints allow a critical condition to be anticipated in order to initiate remedial action.

For example, suppose that the baseflows at several sites along the River Lark were the selected criteria to indicate the state of the aquifer. Not only would they be useful for anticipating drought conditions, but they could also be used in simulations that investigate short-term policies for abstraction that would tend to minimize the impact of the drought on the behaviour of the selected criteria. By repeating simulations which start with the current aquifer state and which include a severe drought recharge sequence, the model could be used to test abstraction strategies designed to limit baseflow depletion at the sites in question. The question as to which criteria should be used will best be decided by NRA management after experience with the model.

As understandings of the river-aquifer interaction improve, both from field evidence and from model development, it will also be possible to define general control rules from modelling investigations, in order to prevent conflict between surface and groundwater abstractors. This will become particularly important in unconfined zones of the area of interest to this study where there is good hydraulic contact between the River Lark and the Chalk as demands increase.

6 Conclusions and Recommendations for Future Work

Various references have been made in this report to further work that is recommended for the continuing development of the model. The conclusions and recommendations emerging from this study are summarized below:

i) The model is adequate in all of the chosen criteria, which include 22 observation wells with long records that provide a representative indication of conditions over a wide area of the aquifer. In some cases, the simulated behaviour will benefit from further model refinement, e.g. Butchers, Ashley observation well which is located on the south-west boundary of the model. The model also provides reasonable simulations of the responses of the streamflows at Temple Weir, Fornham St Martin and Isleham.

ii) The model is suitable for use in its intended role to examine general management concerns such as licencing policy. It is also suitable for more specific and interactive use, should the need arise. It is possible to use the model in the solution of immediate problems such as drought management or the short-term redistribution of abstraction away from sites requiring protection during a critical recharge period.

iii) The aquifer boundary selected for modelling purposes is adequate from regional flow considerations. However, there have been difficulties in simulating conditions near Berners Field Farm in the north-east of the region and it is probable that this is due to the close proximity of the boundary in the area to the River Lark.

iv) The importance of continual updating with the best available data cannot be over-emphasized. As the essential data bases used in simulating regional conditions in the River Lark catchment are extended in time in their coverage, length and quality, so this information provides valuable feedback for improving the integrity of the model. Furthermore, attempts to simulate new field data emerging that relate to an extreme in weather such as a drought, may help to identify aspects of the model that require modification or further development. Eventually, it will be necessary to establish a framework for data collection that meets the specific requirements of continuing model development and policy revision, if the Lark model is to be implemented in regular service.

v) A further data requirement which affects springflow simulation, is continuous or more frequent recording of streamflow in the vicinity of the outflow sites. Only two sites in the area -Temple Weir and Fornham St Martin - have records that are reliable for purposes of continual verification of the model. Spot gaugings, which have been carried out at other sites in the past are also extremely useful.

vi) Work needs to be carried out to refine the simulation of flow in the cut off channel which is used to divert some of the flow in the River Lark near Mildenhall to Denver. Flow in the cut-off channel is approximated by allowing a constant proportion of about 37% of the River Lark streamflow to be diverted from a site immediately upstream of Isleham. This flow mechanism is based on the the results of a trial and error approach carried out in the early stages of the study. It is important that these cut-off flows should be simulated accurately as the channel crosses an area where there are major abstraction sites and any interaction between flow in the channel and the aquifer could be critical to developing future policy. Any streamflow data related to the cut-off channel would be useful in investigating local conditions and would improve simulation of the channel-aquifer interaction. This will be of great importance if the aquifer demand is to be increased in the Mildenhall area in order to raise local supply qualities.

vii) In the interests of improving the variable transmissivity simulation, more data are required to give information on permeability profiles. The model can be adapted to include other relationships - even more complex than that in current use - to describe the variation of nodal transmissivity with saturated depth.

viii) At present, the Chalk model does not allow the storage coefficients to vary as saturated depths alter. However, it can be modified to accommodate other relationships between storage coefficients and saturated depth. Field work and further model testing are needed to establish this relationship in areas likely to be affected by sudden changes in the storage parameters, e.g. in the vicinity of the boundary to the Boulder Clay and the Chalk. This refinement would improve the general simulation of unconfined conditions in the area and it may also have a significant effect on local groundwater storage predictions in areas such as Barrow Heath, Moulton and Bury St Edmunds.

ix) It is important to establish the criteria to be used in policy assessment. For example, in reviewing licencing applications it may be desirable to examine the effects on local baseflows as well as a range of observation sites. The criteria that are eventually selected, will best be decided upon by the National Rivers Authority management after experience with operating the model.

x) The model can be used to verify the adequacy of current abstraction limits in the manner described in section 5.2. It is interesting to note that abstraction in 1976 from the public water supply sites across the aquifer only reached 63% of the annual licence amount. By 1989 the proportion had risen to 87% of the annual amount, indicating the mounting pressure on the resource and also the need for the flexibility and efficiency that can be provided by the model, for reviewing abstraction limits.

xi) It is also possible to use the model to examine options for further development of the resource by carrying out a series of simulations with systematic increases in abstraction. The impact of the various increase on the selected assessment criteria can be used to identify potential problem areas as well as sites suitable for future development.

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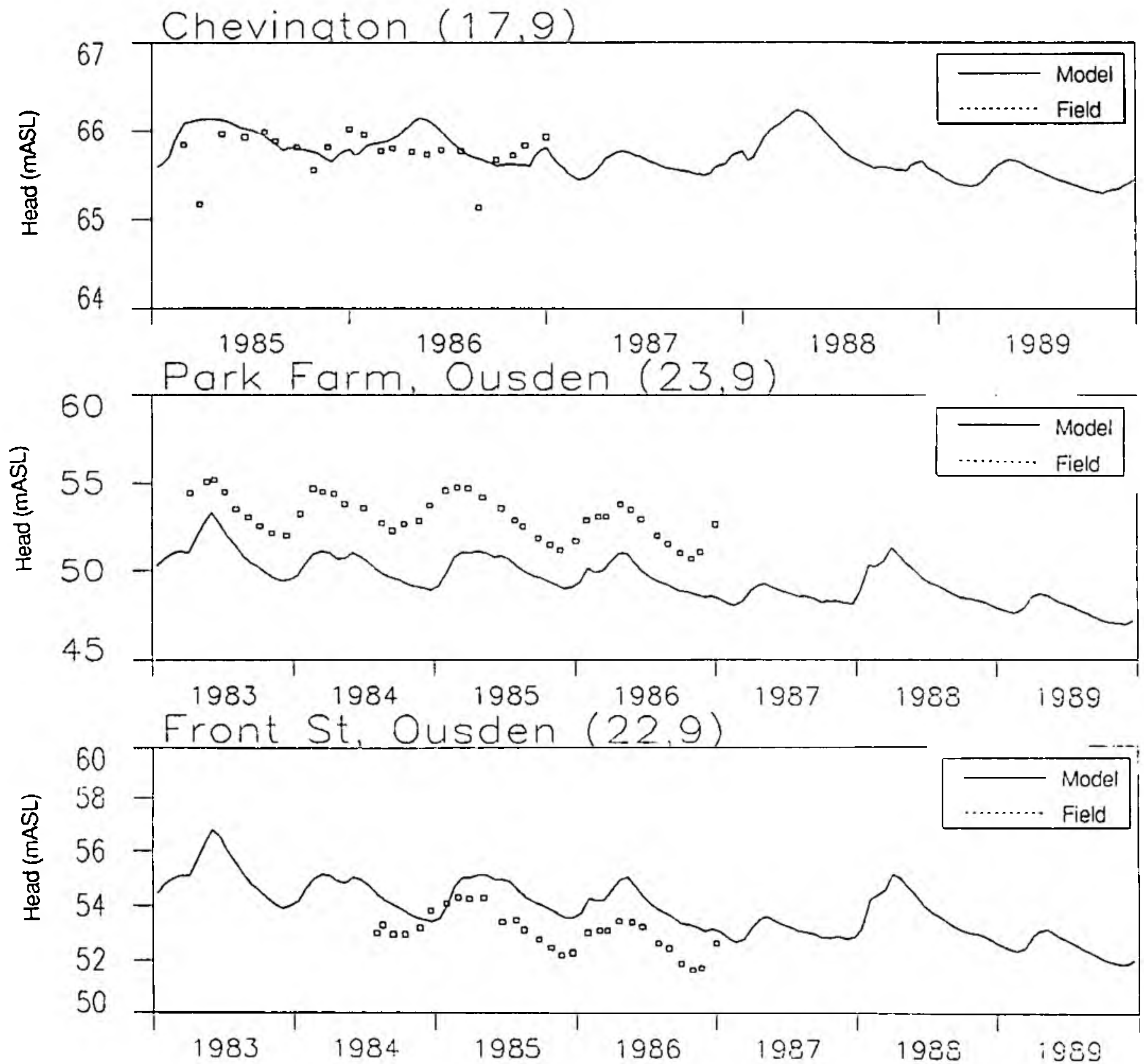
Appendix A

Comparative Plots:

Historical Data vs. Simulated Response

of Groundwater Head Variations

and Streamflow.


Chevington (17,9)
Head (mASL)
67
66
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Model
Field
1985
1986
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Park Farm, Ousden (23,9)
Head (mASL)
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Model
Field
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Front St, Ousden (22,9)
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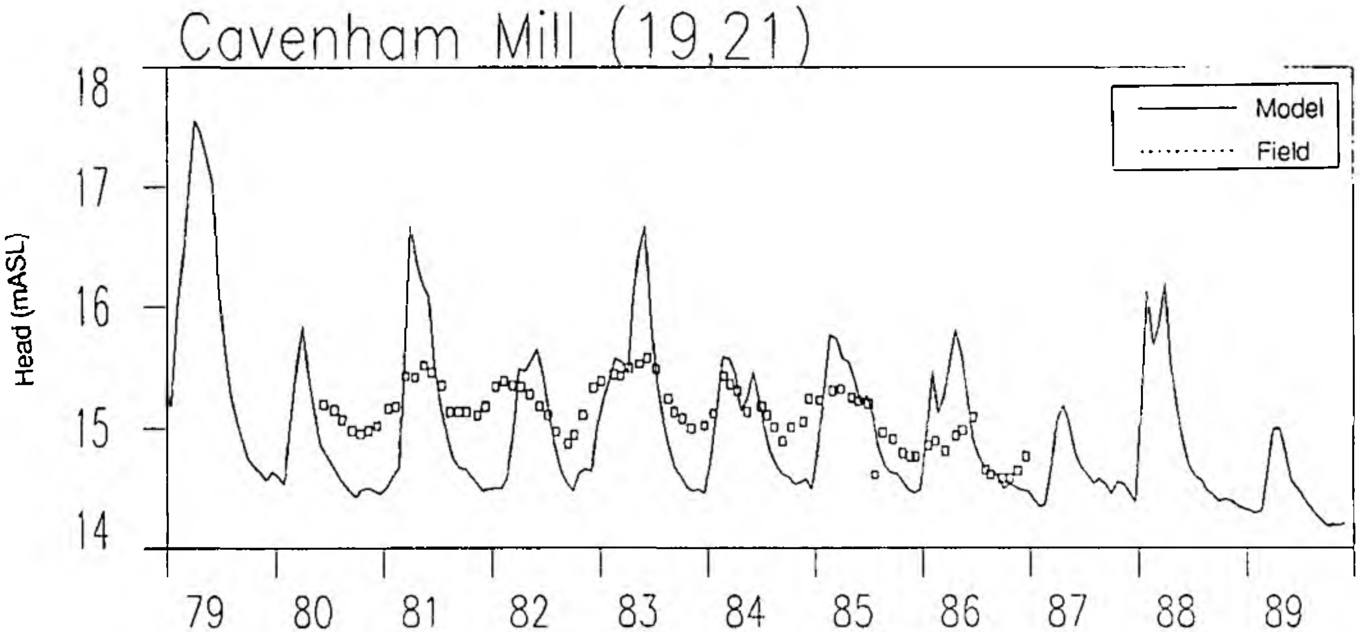

Cavenham Mill (19,21)
Head (mASL)
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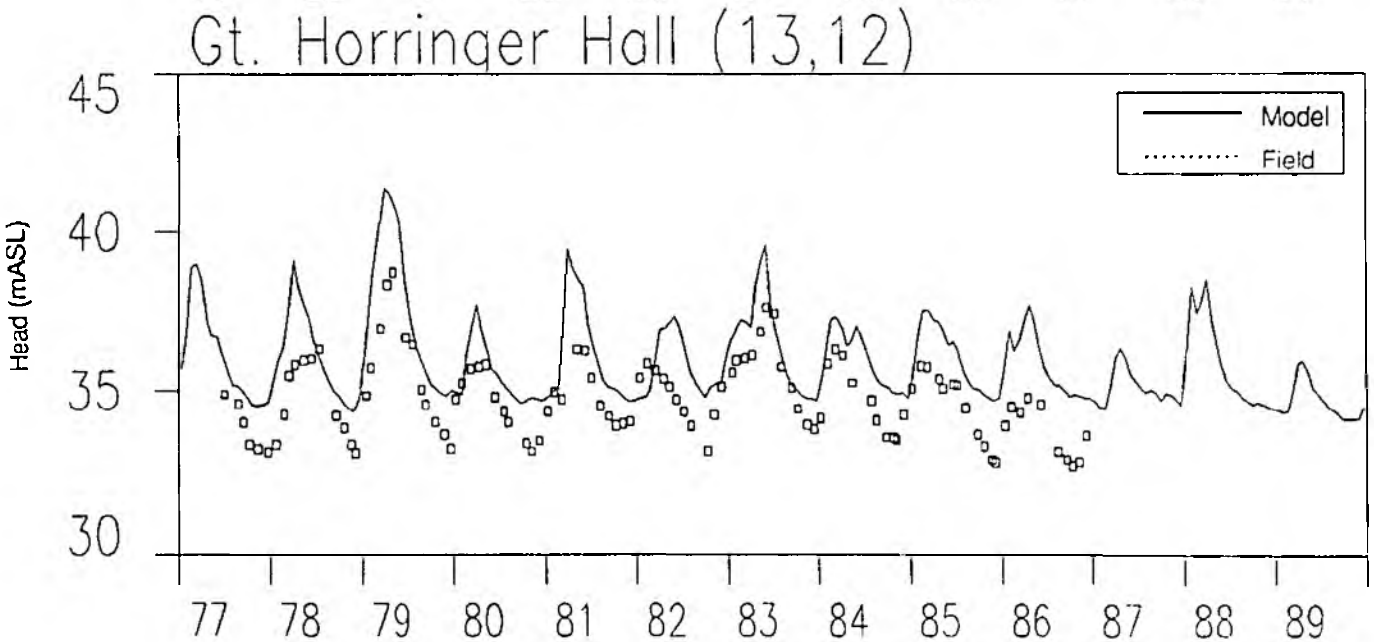

Gt. Horringer Hall (13,12)
Head (mASL)
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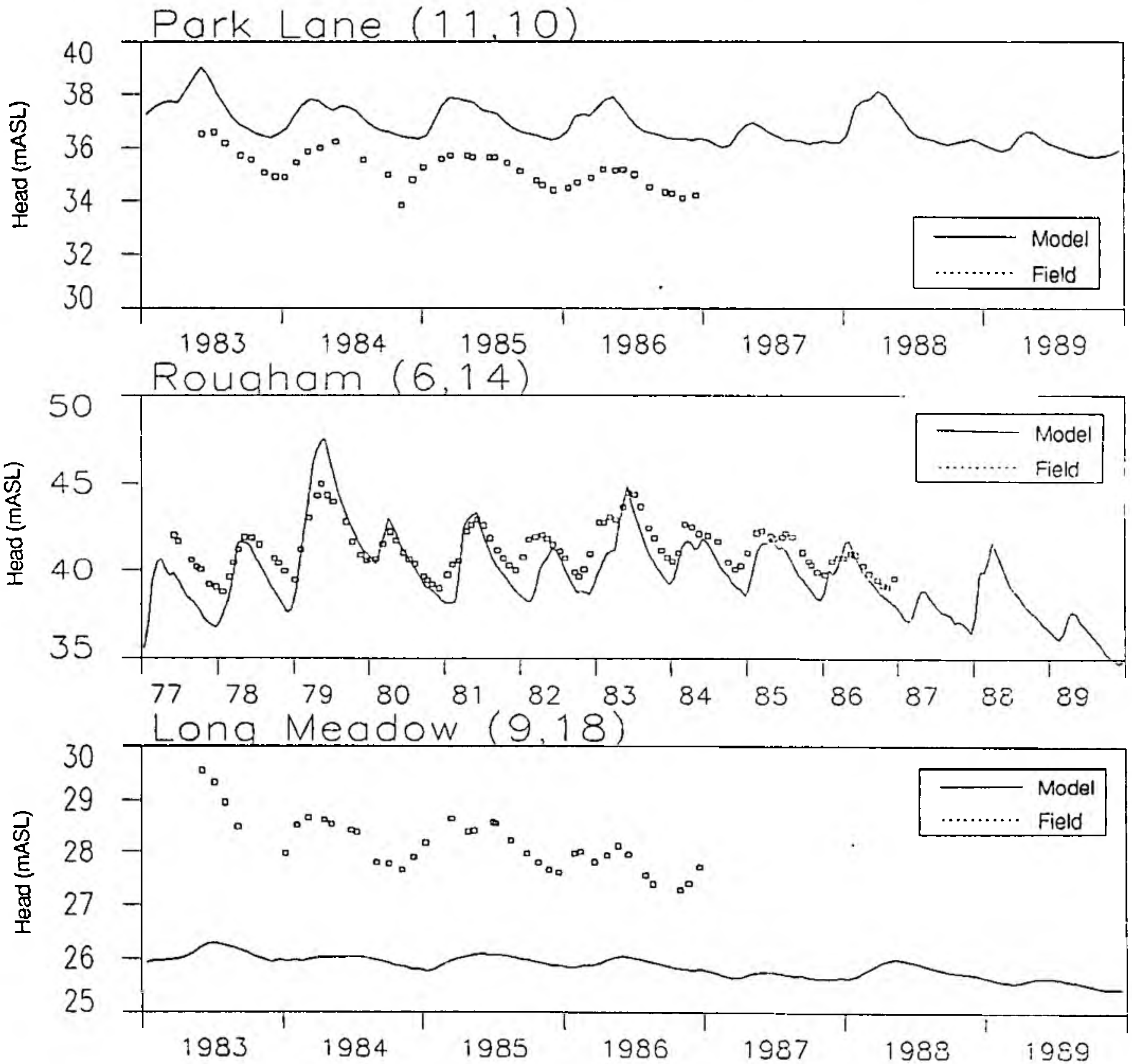

Park Lane (11,10)
Head (mASL)
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Rougham (6,14)
Head (mASL)
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Long Meadow (9,18)
Head (mASL)
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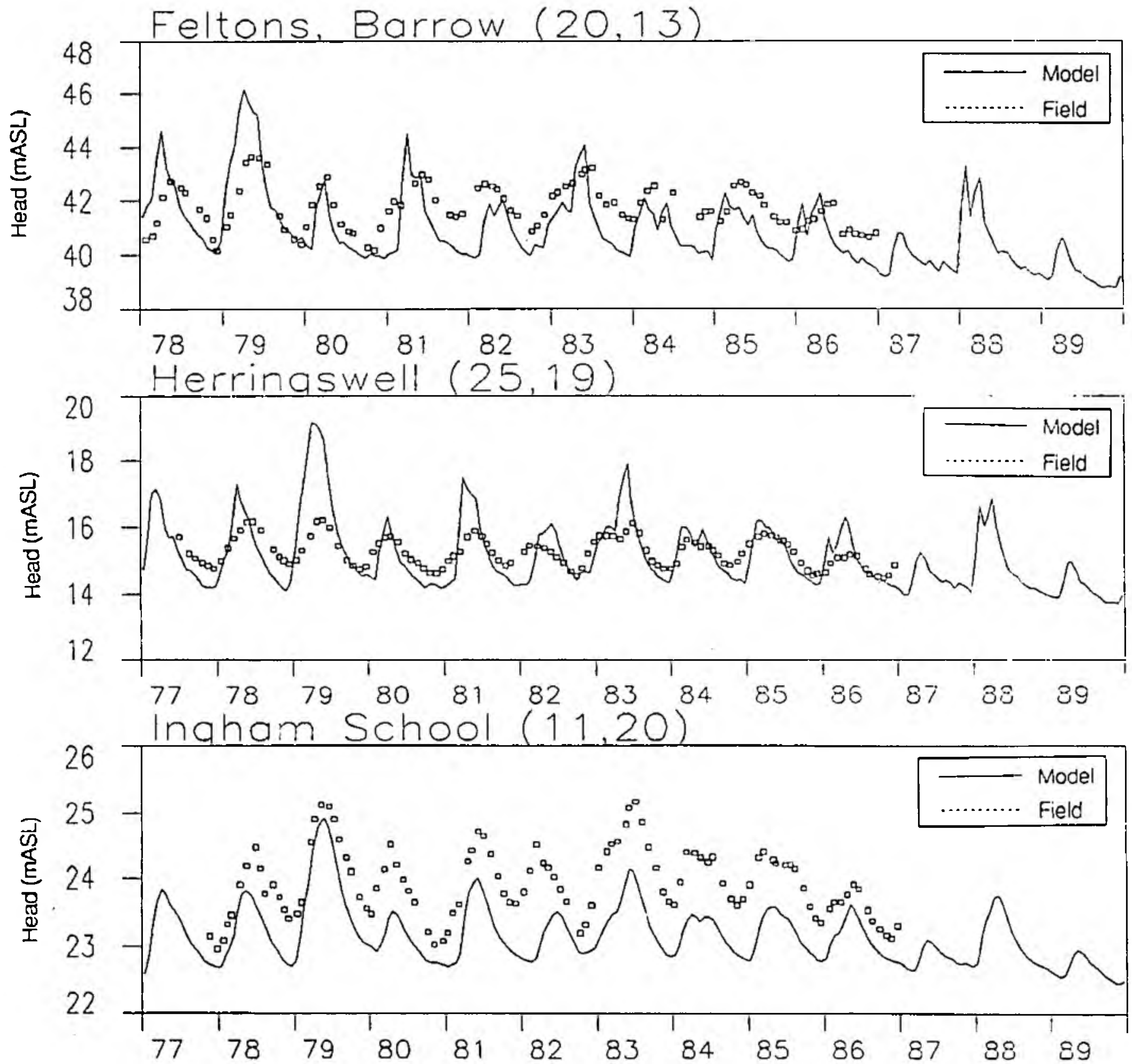
Feltons, Barrow (20,13)
Head (mASL)
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Herringswell (25,19)
Head (mASL)
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Ingham School (11,20)
Head (mASL)
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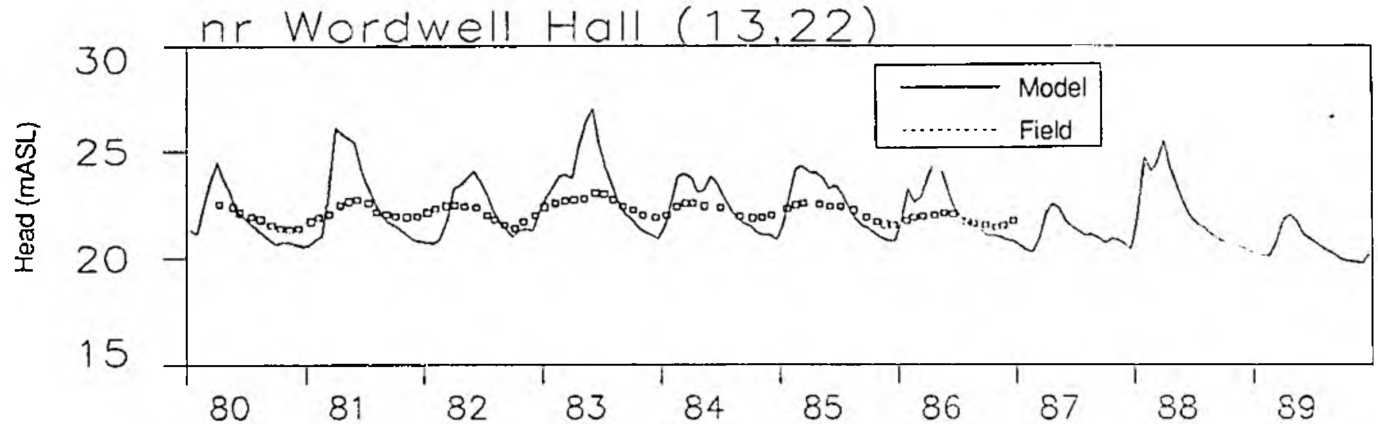

nr Wordwell Hall (13,22)
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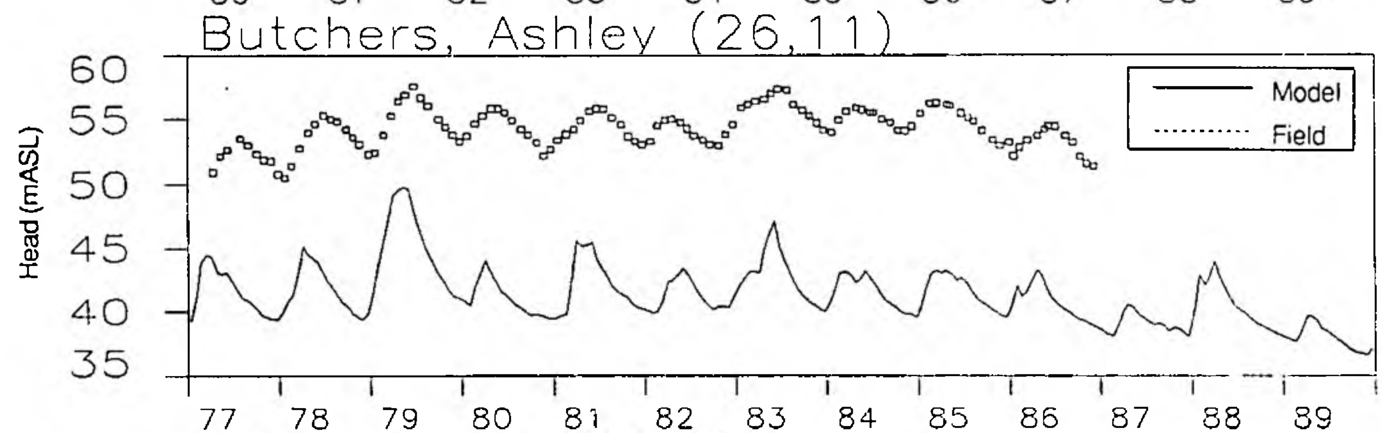

Butchers, Ashley (26,11)
Head (mASL)
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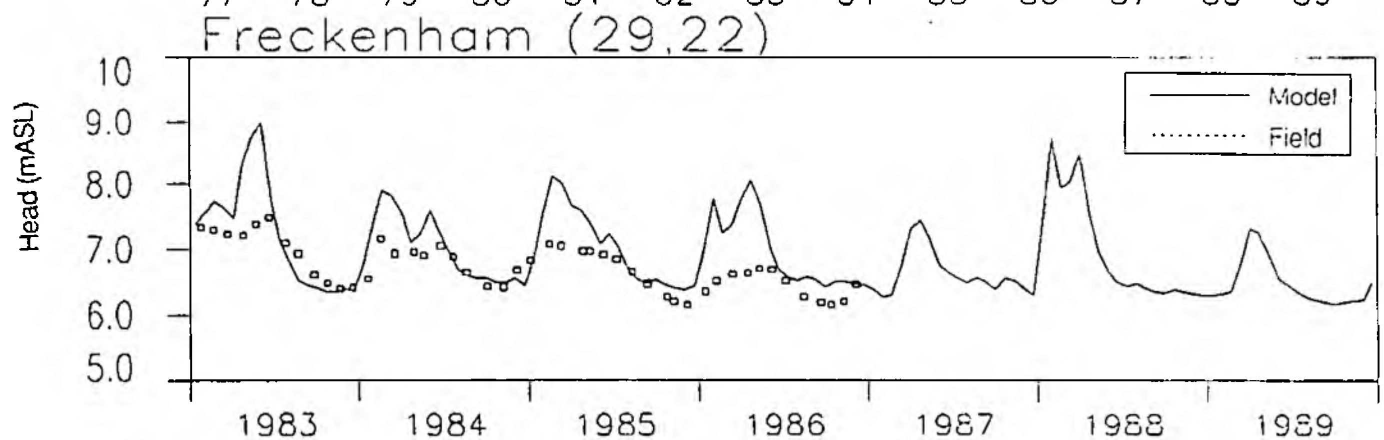

Freckenham (29,22)
Head (mASL)
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8.0
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Model
Field
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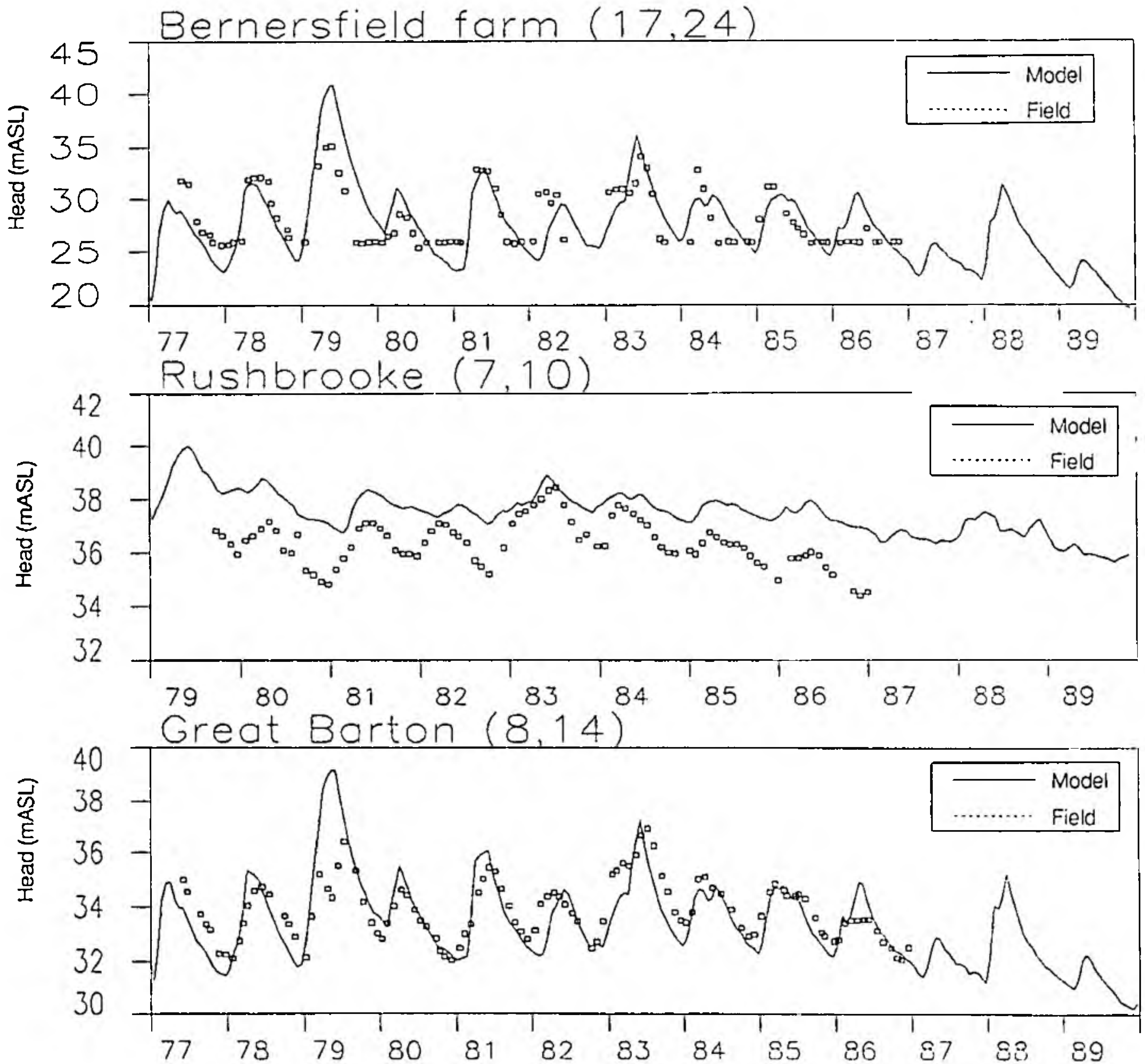
Bernersfield farm (17,24)
Head (mASL)
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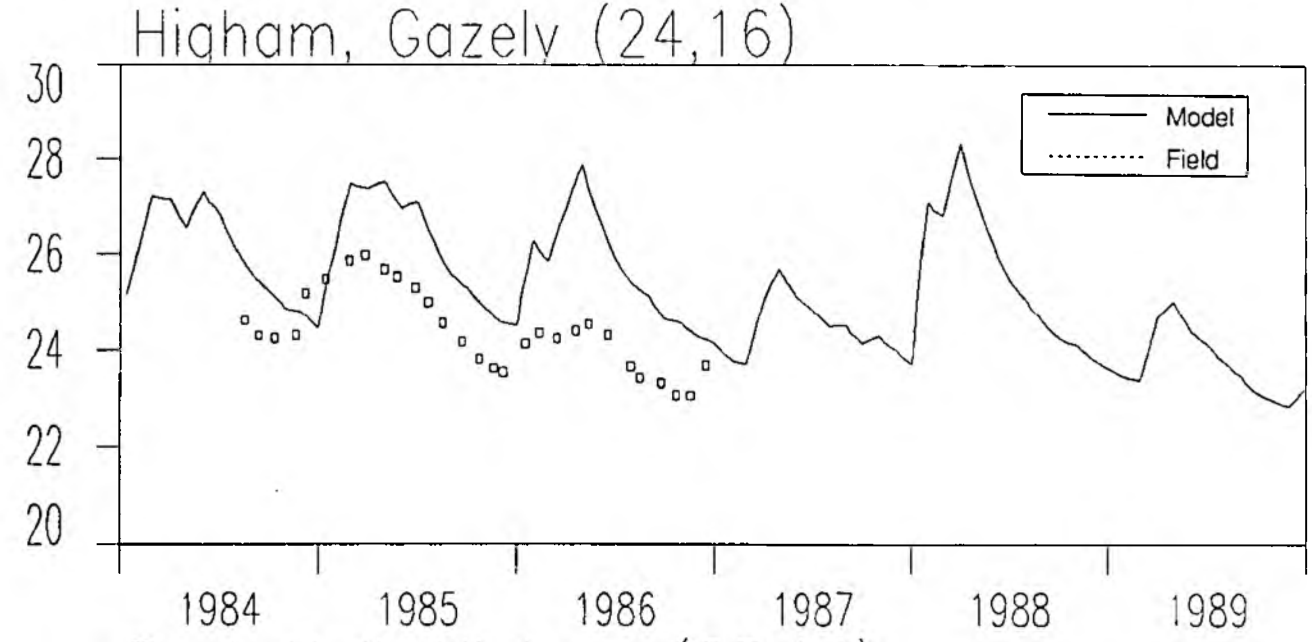
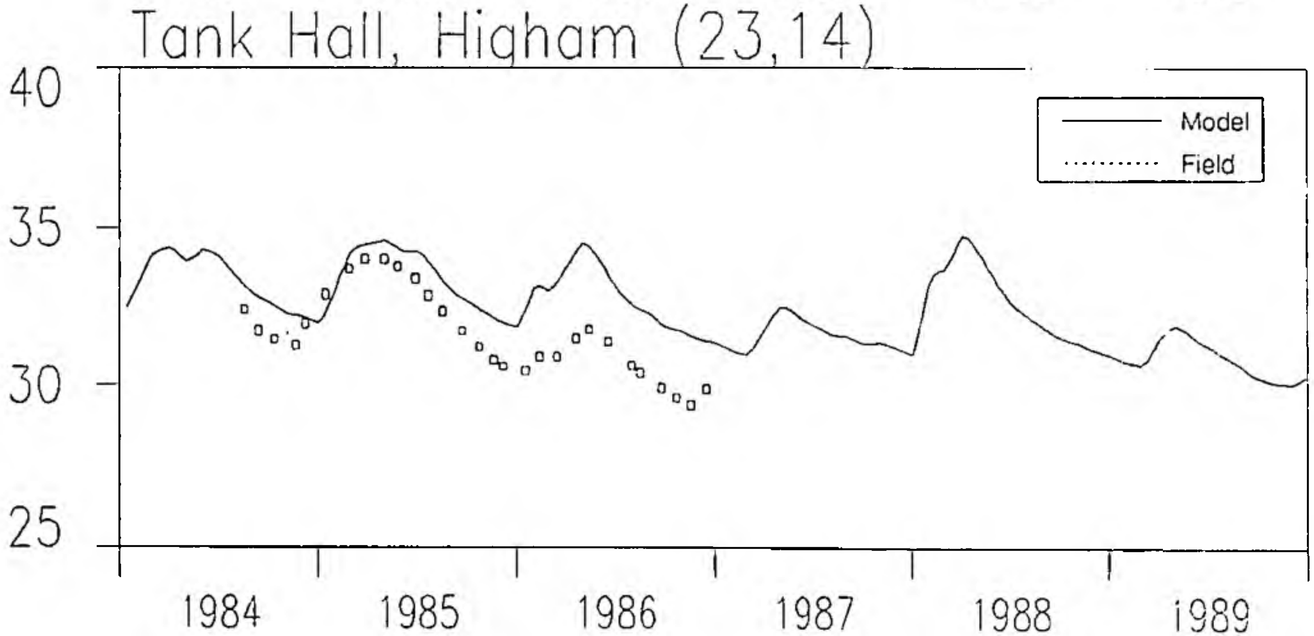
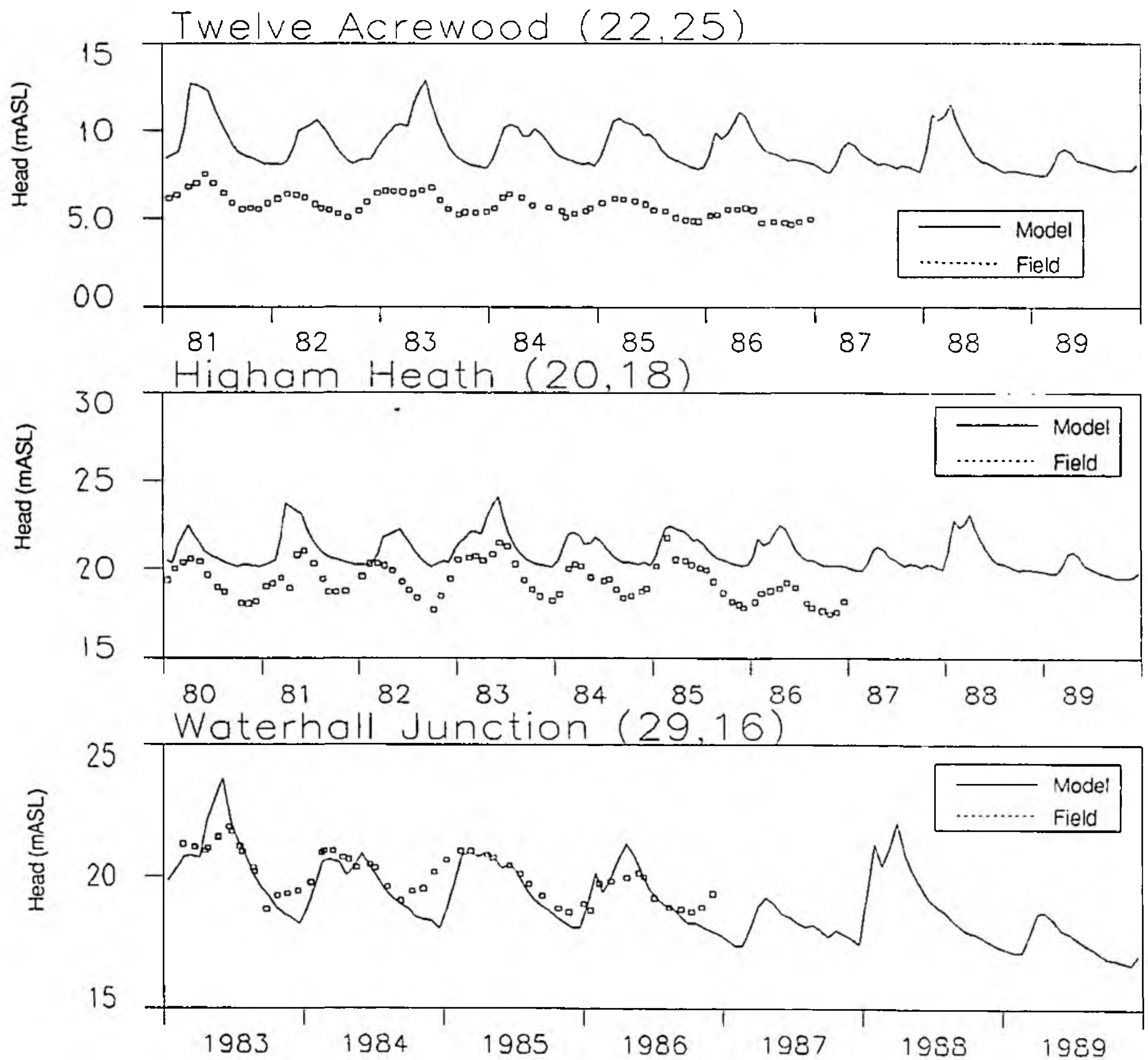
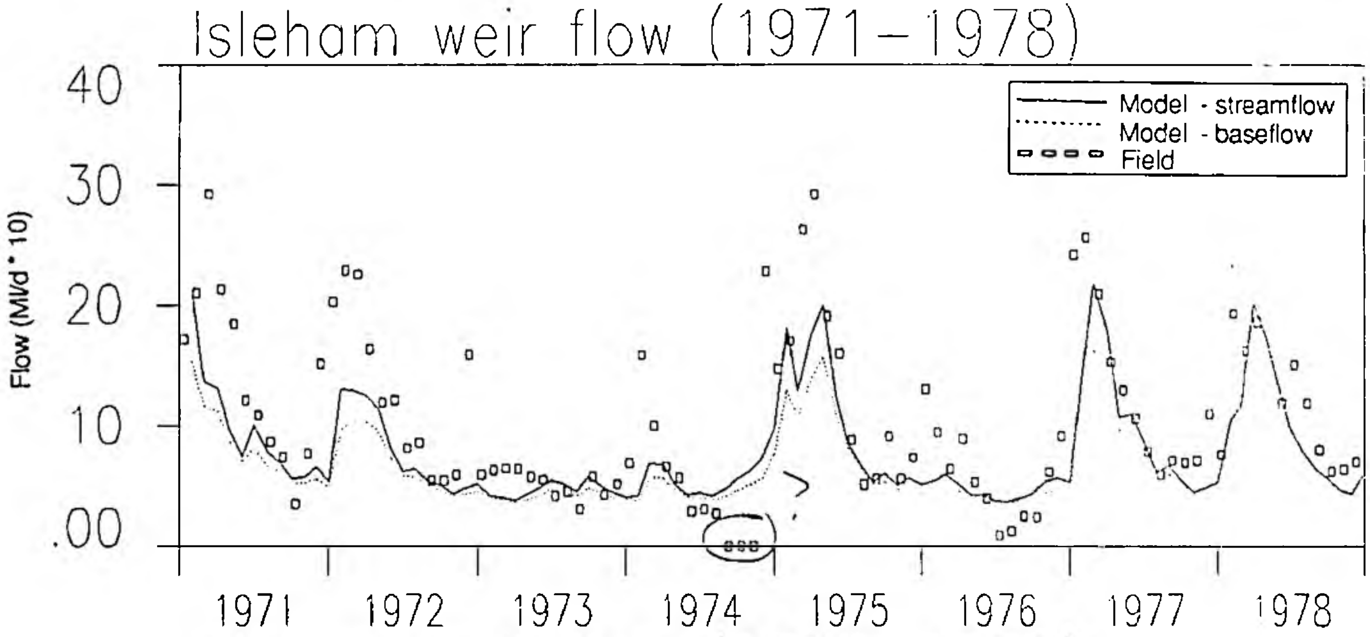
89
Rushbrooke (7,10)
Head (mASL)
42
40
38
36
34
32
Model
Field
79
80
81
82
83
84
85
86
87
88
89
Great Barton (8,14)
Head (mASL)
40
38
36
34
32
30
Model
Field
77
78
79
80
81
82
83
84
85
86
87
88
89

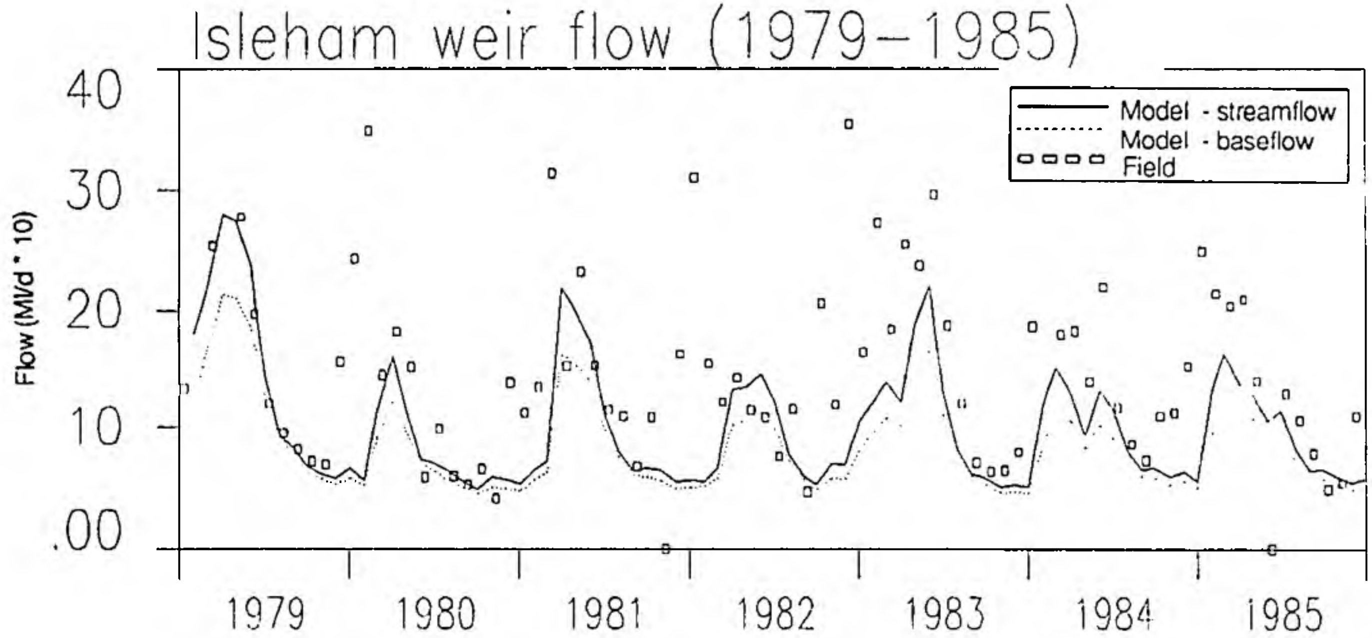

Higham, Gazely (24,16)
30
28
26
24
22
20
Model
Field
1984
1985
1986
1987
1988
1989

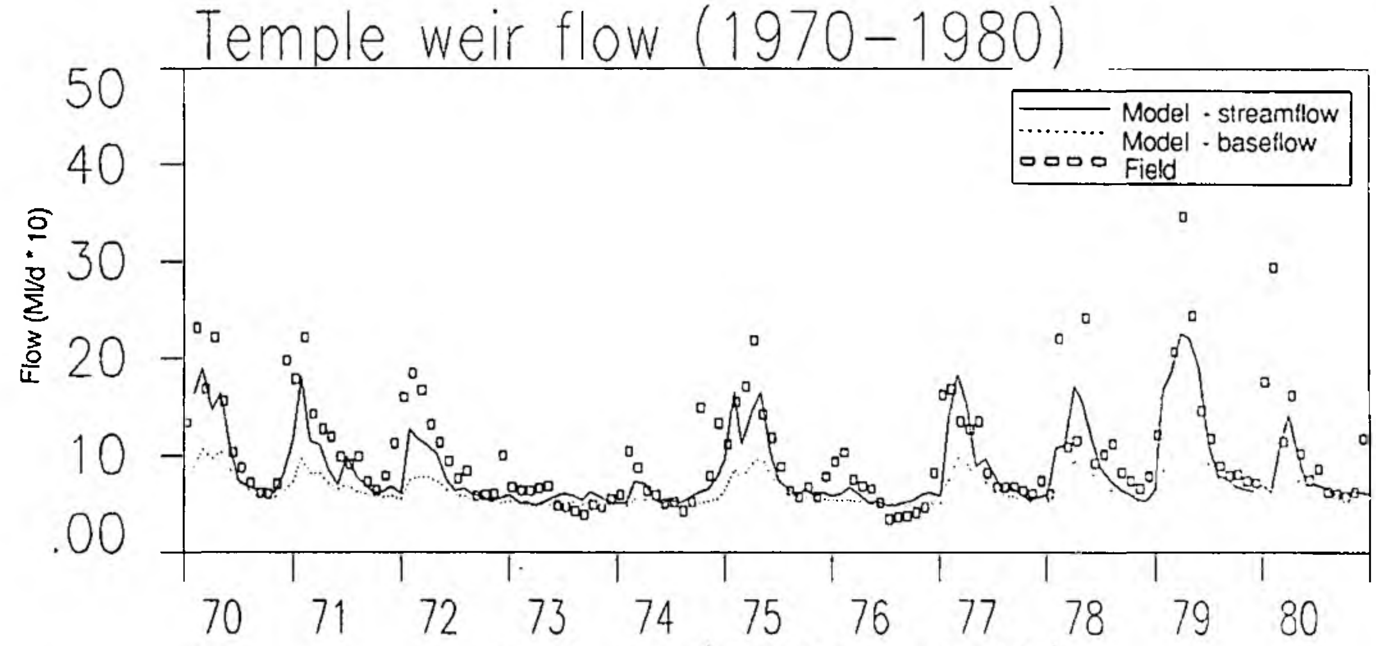

Tank Hall, Higham (23,14)
40
35
30
25
Model
Field
1984
1985
1986
1987
1988
1989

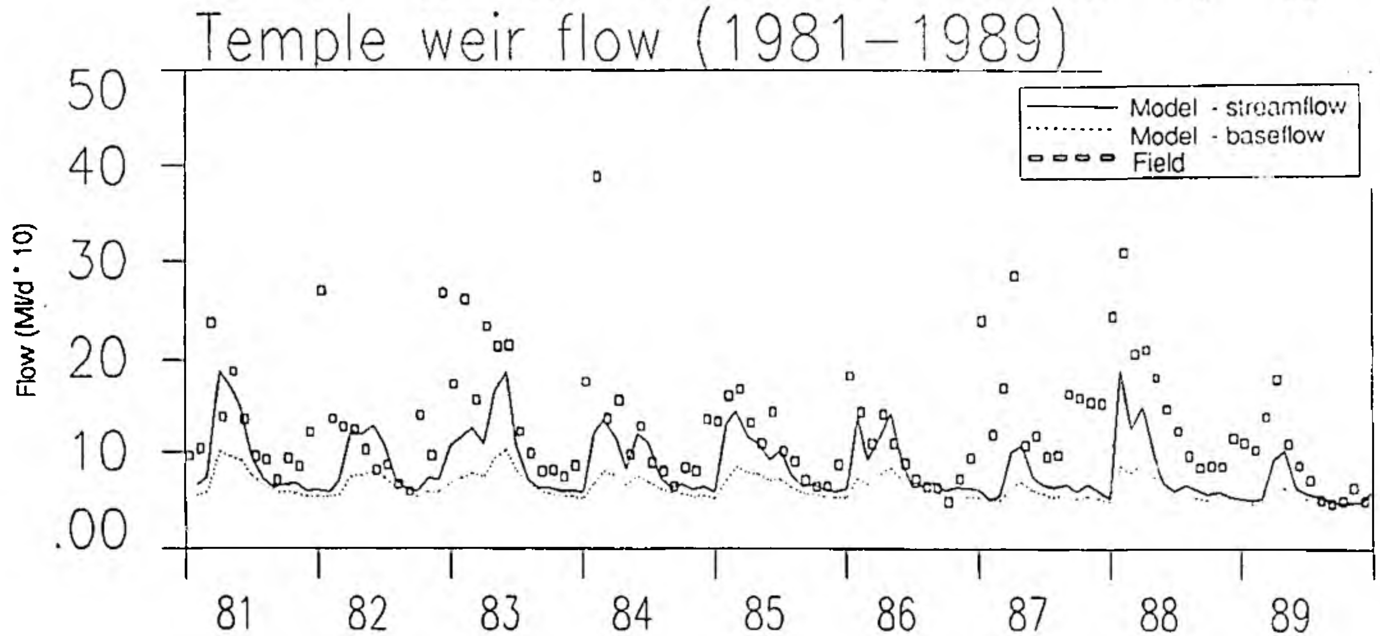


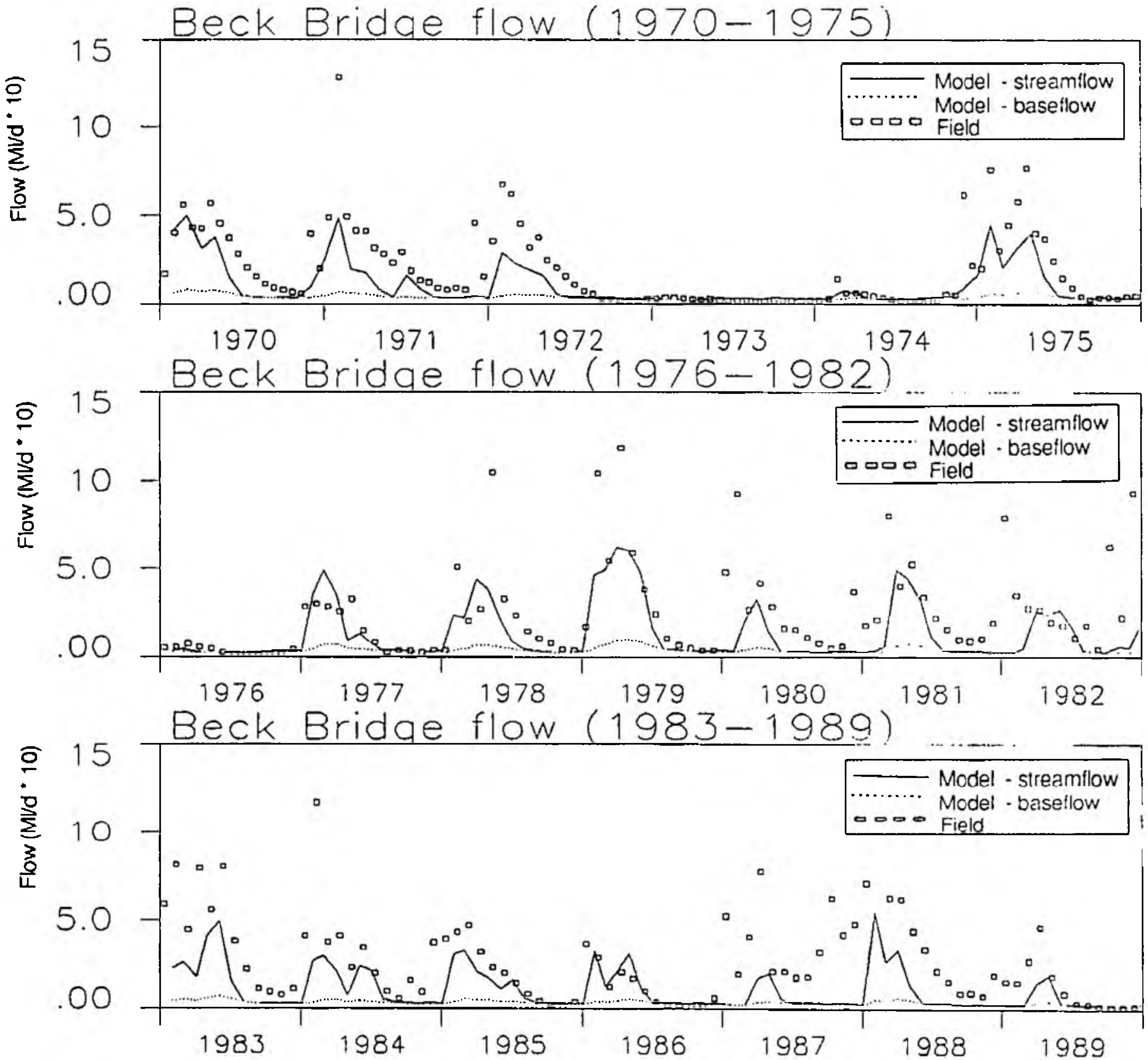
Twelve Acrewood (22,25)
Head (mASL)
15
10
5.0
00
Model
Field
81
82
83
84
85
86
87
88
89
Higham Heath (20,18)
Head (mASL)
30
25
20
15
Model
Field
80
81
82
83
84
85
86
87
88
89
Waterhall Junction (29,16)
Head (mASL)
25
20
15
Model
Field
1983
1984
1985
1986
1987
1988
1989

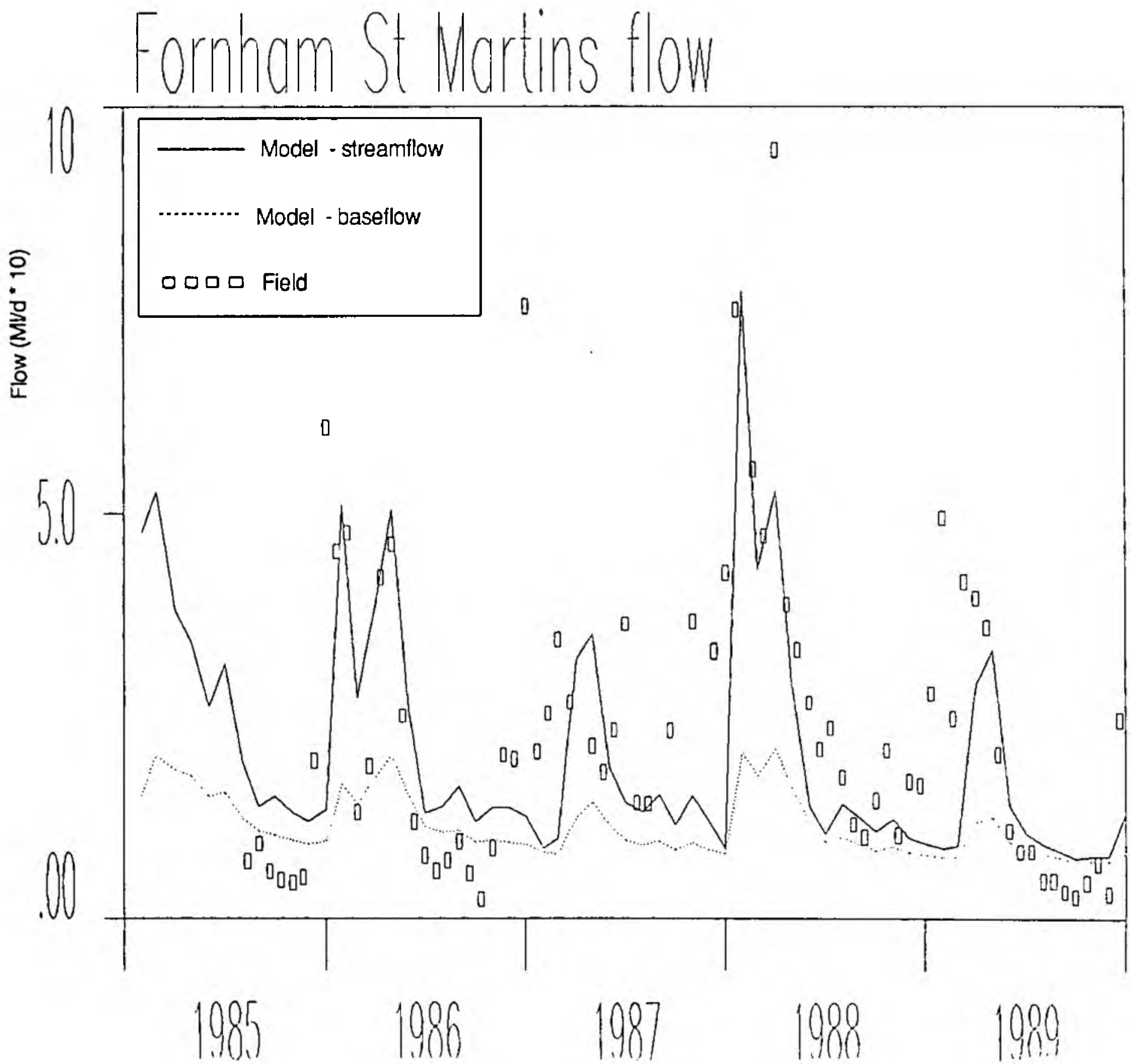

Isleham weir flow (1971–1978)
Flow (Ml/d * 10)
40
30
20
10
.00
Model - streamflow
Model - baseflow
Field
1971
1972
1973
1974
1975
1976
1977
1978


Isleham weir flow (1979–1985)
Flow (Ml/d * 10)
40
30
20
10
.00
Model - streamflow
Model - baseflow
Field
1979
1980
1981
1982
1983
1984
1985

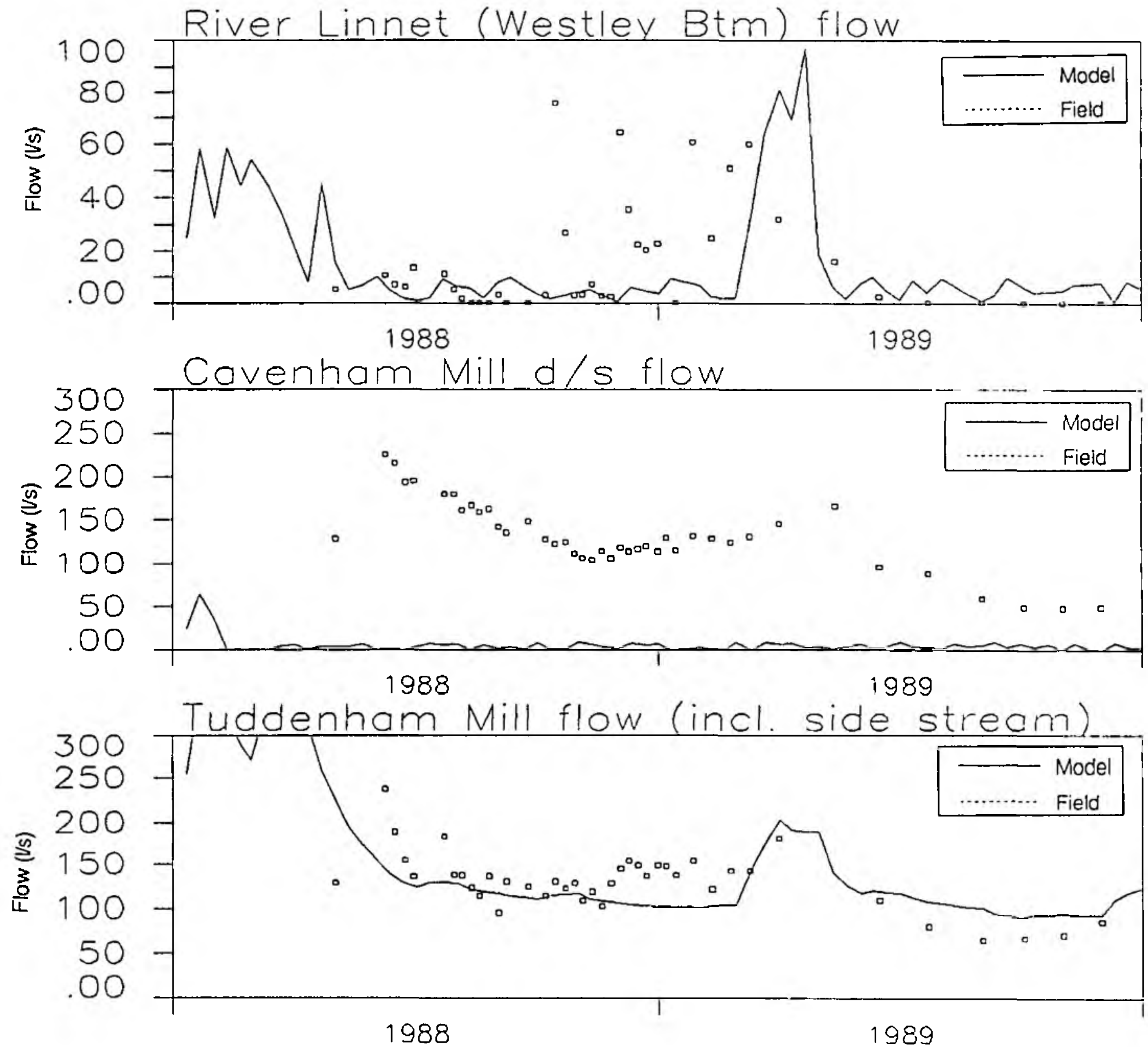

Temple weir flow (1970-1980)
Model - streamflow
Model - baseflow
Field
Flow (Ml/d * 10)
50
40
30
20
10
.00
70
71
72
73
74
75
76
77
78
79
80

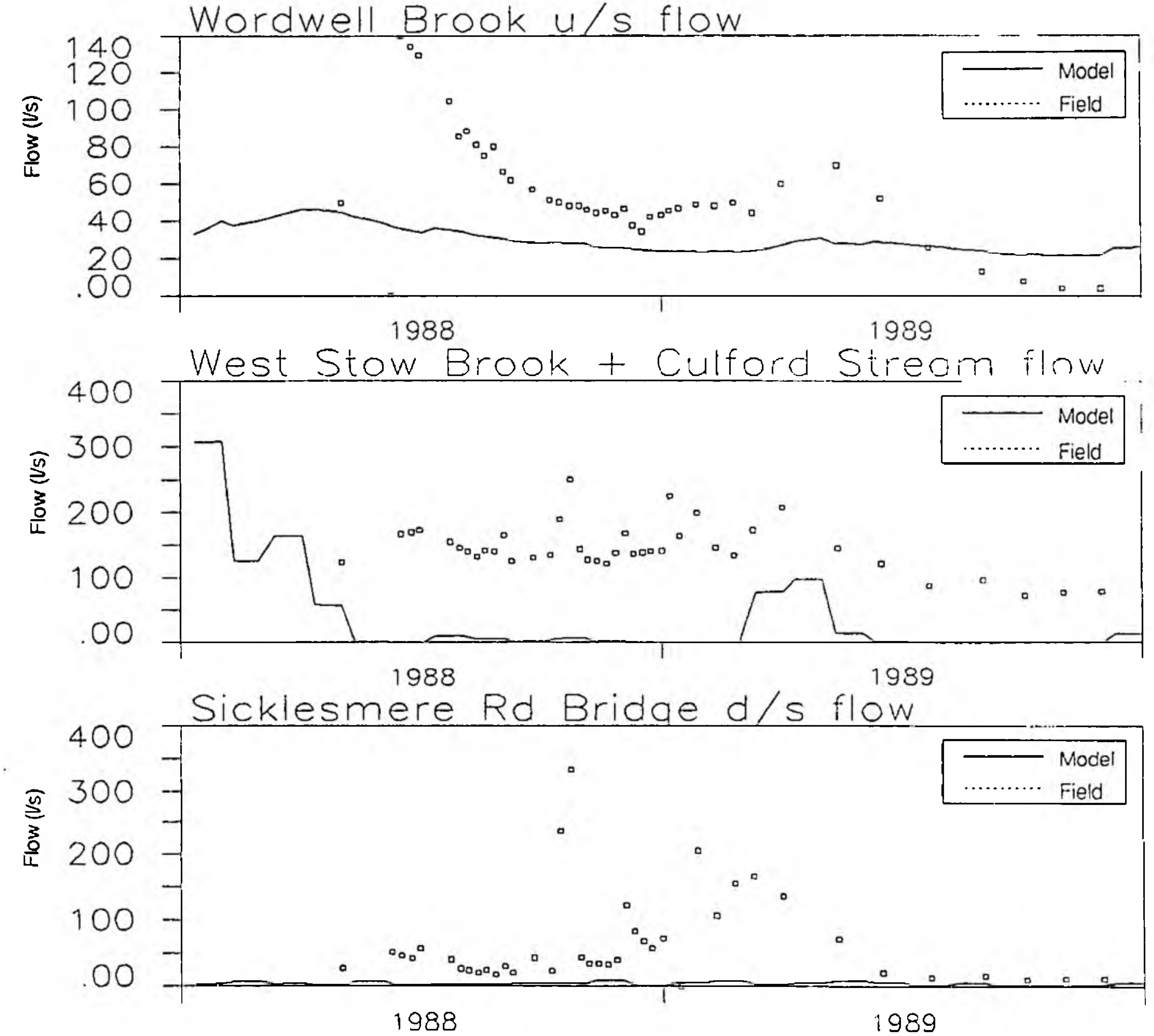

Temple weir flow (1981-1989)
Model - streamflow
Model - baseflow
Field
Flow (Ml/d * 10)
50
40
30
20
10
.00
81
82
83
84
85
86
87
88
89


Beck Bridge flow (1970-1975)
Flow (Ml/d * 10)
15
10
5.0
.00
Model - streamflow
Model - baseflow
Field
1970
1971
1972
1973
1974
1975
Beck Bridge flow (1976-1982)
Flow (Ml/d * 10)
15
10
5.0
.00
Model - streamflow
Model - baseflow
Field
1976
1977
1978
1979
1980
1981
1982
Beck Bridge flow (1983-1989)
Flow (Ml/d * 10)
15
10
5.0
.00
Model - streamflow
Model - baseflow
Field
1983
1984
1985
1986
1987
1988
1989



Fornham St Martins flow
Model - streamflow
Model - baseflow
Field
Flow (Ml/d * 10)
10
5.0
.00
1985
1986
1987
1988
1989


River Linnet (Westley Btm) flow
Flow (l/s)
100
80
60
40
20
.00
Model
Field
1988
1989
Cavenham Mill d/s flow
Flow (l/s)
300
250
200
150
100
50
.00
Model
Field
1988
1989
Tuddenham Mill flow (incl. side stream)
Flow (l/s)
300
250
200
150
100
50
.00
Model
Field
1988
1989


Wordwell Brook u/s flow
Flow (l/s)
140
120
100
80
60
40
20
.00
Model
Field
1988
1989
West Stow Brook + Culford Stream flow
Flow (l/s)
400
300
200
100
.00
Model
Field
1988
1989
Sicklesmere Rd Bridge d/s flow
Flow (l/s)
400
300
200
100
.00
Model
Field
1988
1989

Appendix B

Longitudinal Sections of the Simulated Streamflow in the River Lark and its Tributaries.

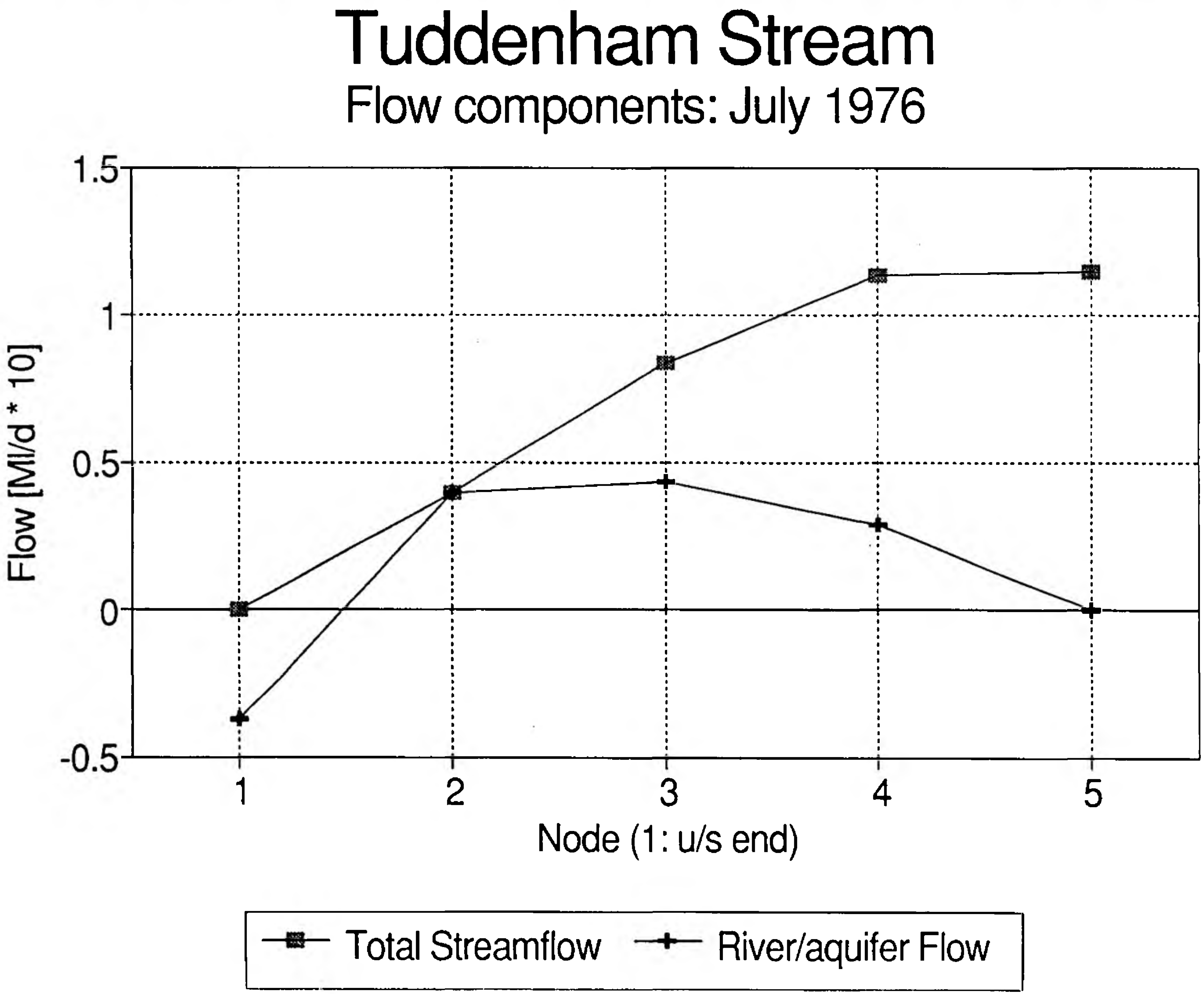
The figures in this appendix show the simulated flows along four major water courses in the area:

> Cavenham Stream
> Tuddenham Stream
> River Kennet
> River Lark

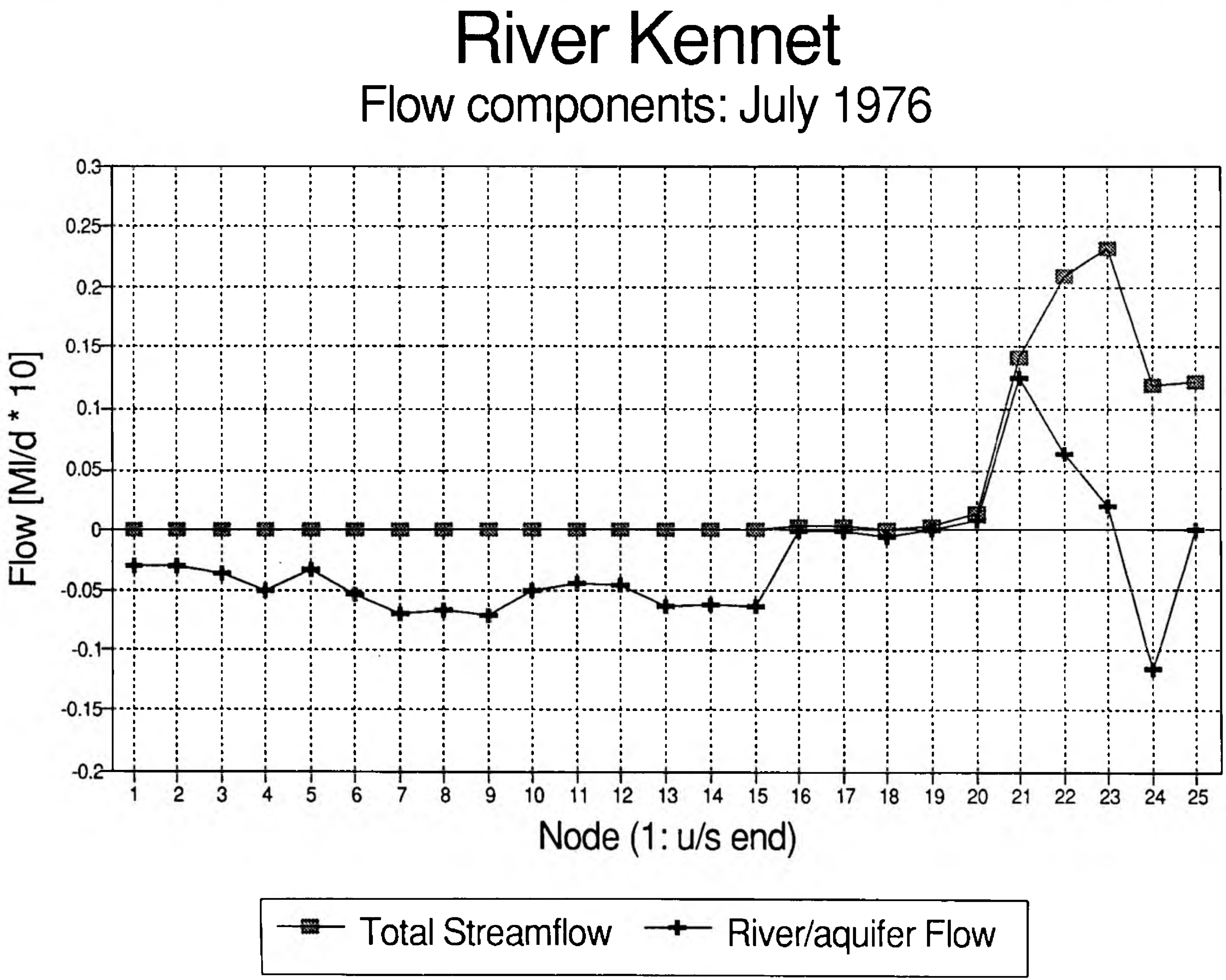
Each figure contains the plot of two series, the **total streamflow** and the river/aquifer **interchange flow**. The **total streamflow** refers to the model estimate of the streamflow that would be gauged at each node, i.e. it is the cumulative flow of all components - runoff, river/aquifer interchange flow, effluent discharges, etc. - for all of the upstream nodes to the site in question. The series plotted for the **river/aquifer interchange flow** refers only to the nodal flow, i.e. unlike the total streamflow series plot, it takes no account of conditions upstream and is only a single component of the total nodal streamflow. Negative river/aquifer interchange flows shown in these figures indicate losses from the river to the aquifer, and vice versa.

The record was examined on the basis of four month antecedent flows to determine maximum, minimum and average recharge conditions. These conditions are represented by the following periods from the simulation record:

> Minimum recharge flows - July 1976.
> Average recharge flows - May 1989.
> Maximum recharge flows - April 1979.

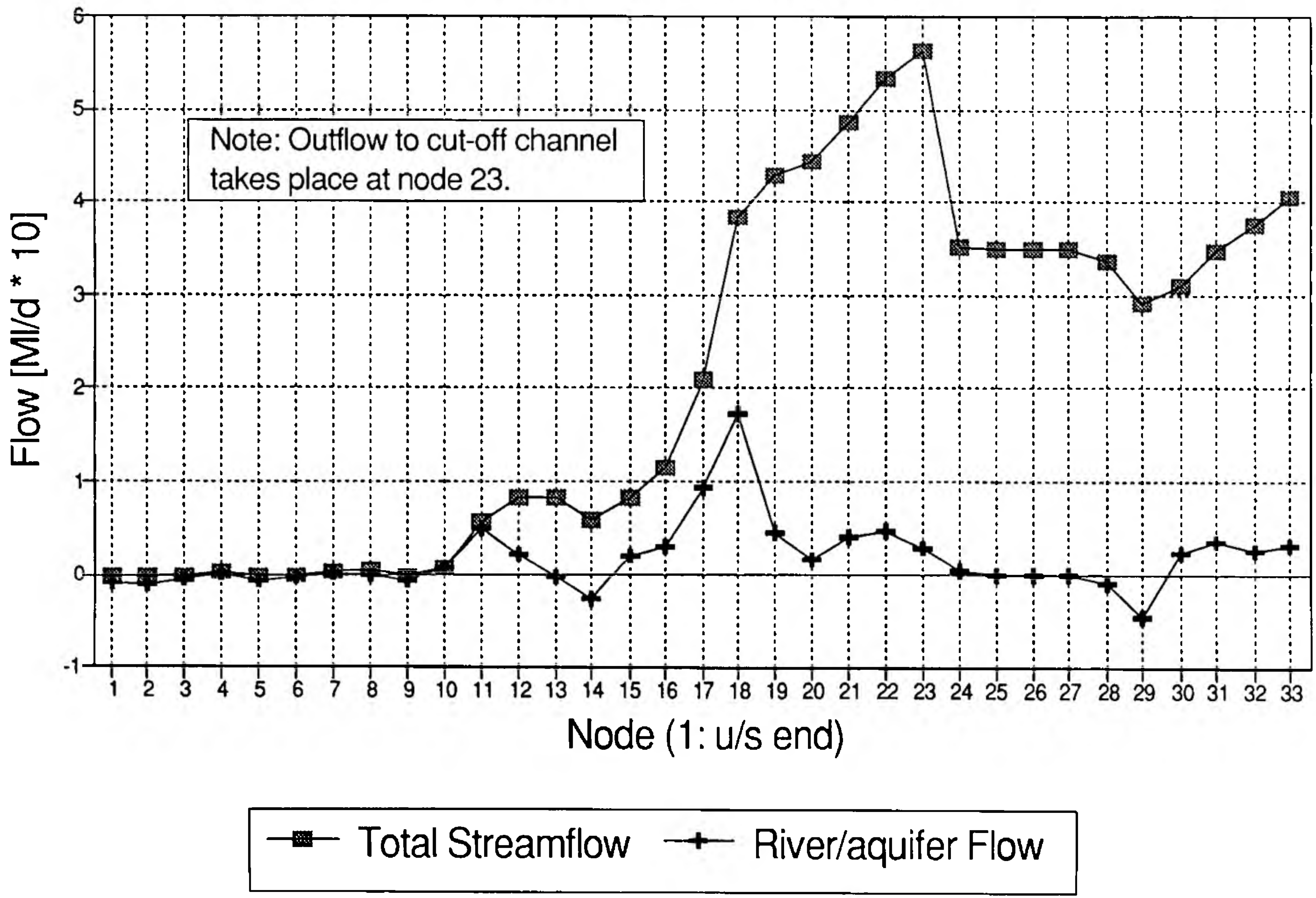


Tuddenham Stream
Flow components: July 1976
1.5
1
0.5
0
-0.5
Flow [Ml/d * 10]
1
2
3
4
5
Node (1: u/s end)
Total Streamflow
River/aquifer Flow


River Kennet
Flow components: July 1976
Flow [Ml/d * 10]
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Node (1: u/s end)
Total Streamflow
River/aquifer Flow

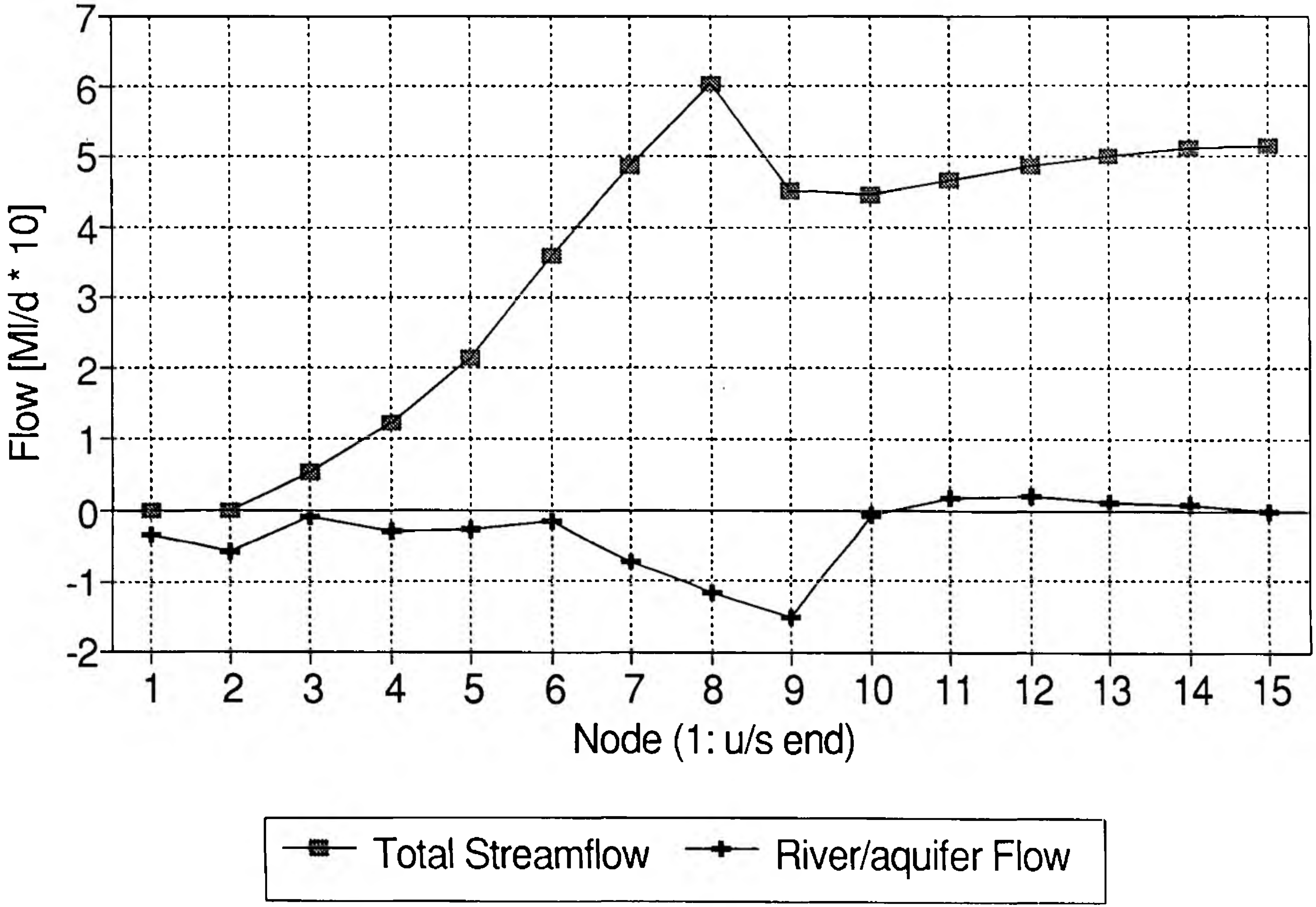
River Lark

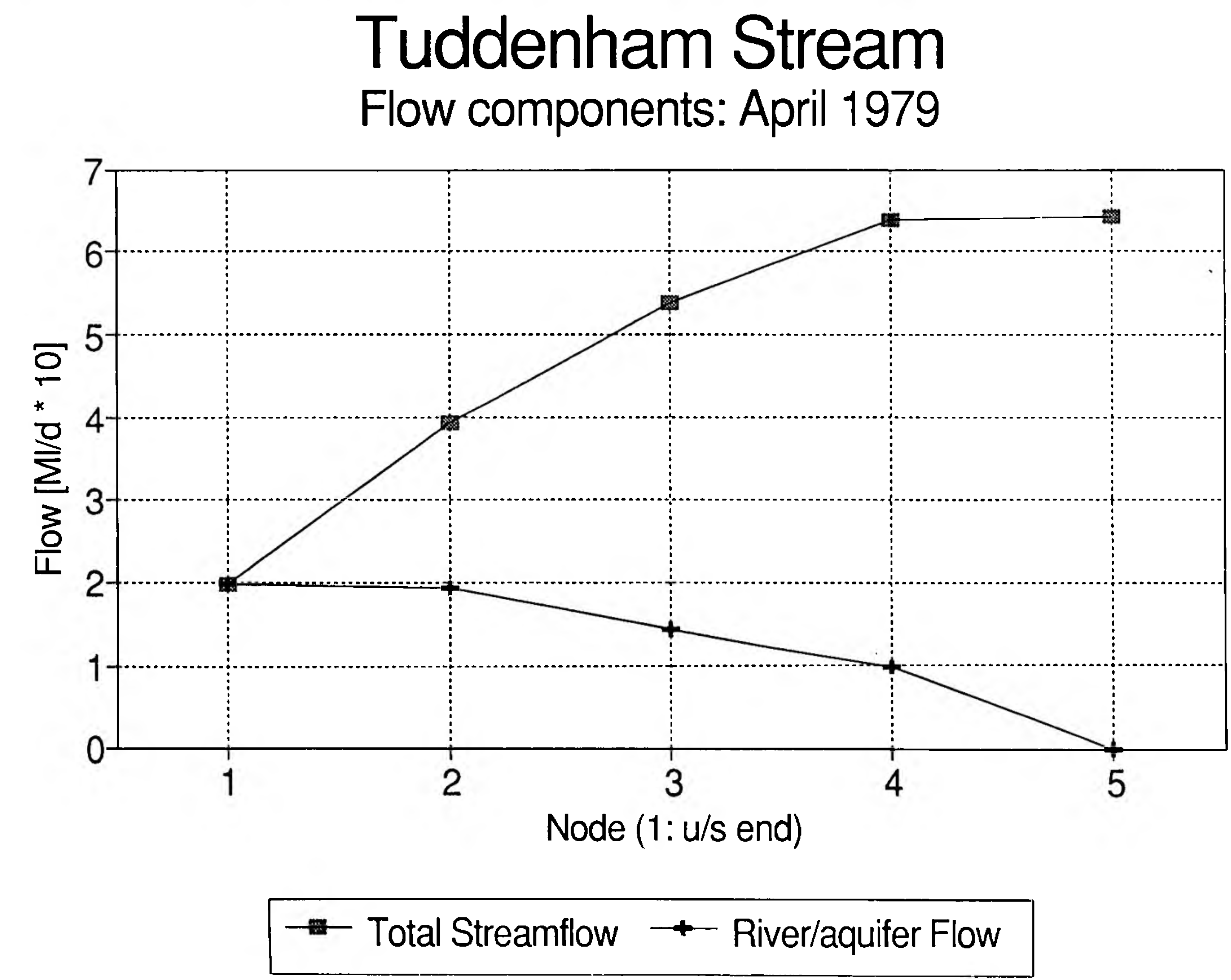
Flow components: July 1976



Cavenham Stream

Flow components: April 1979

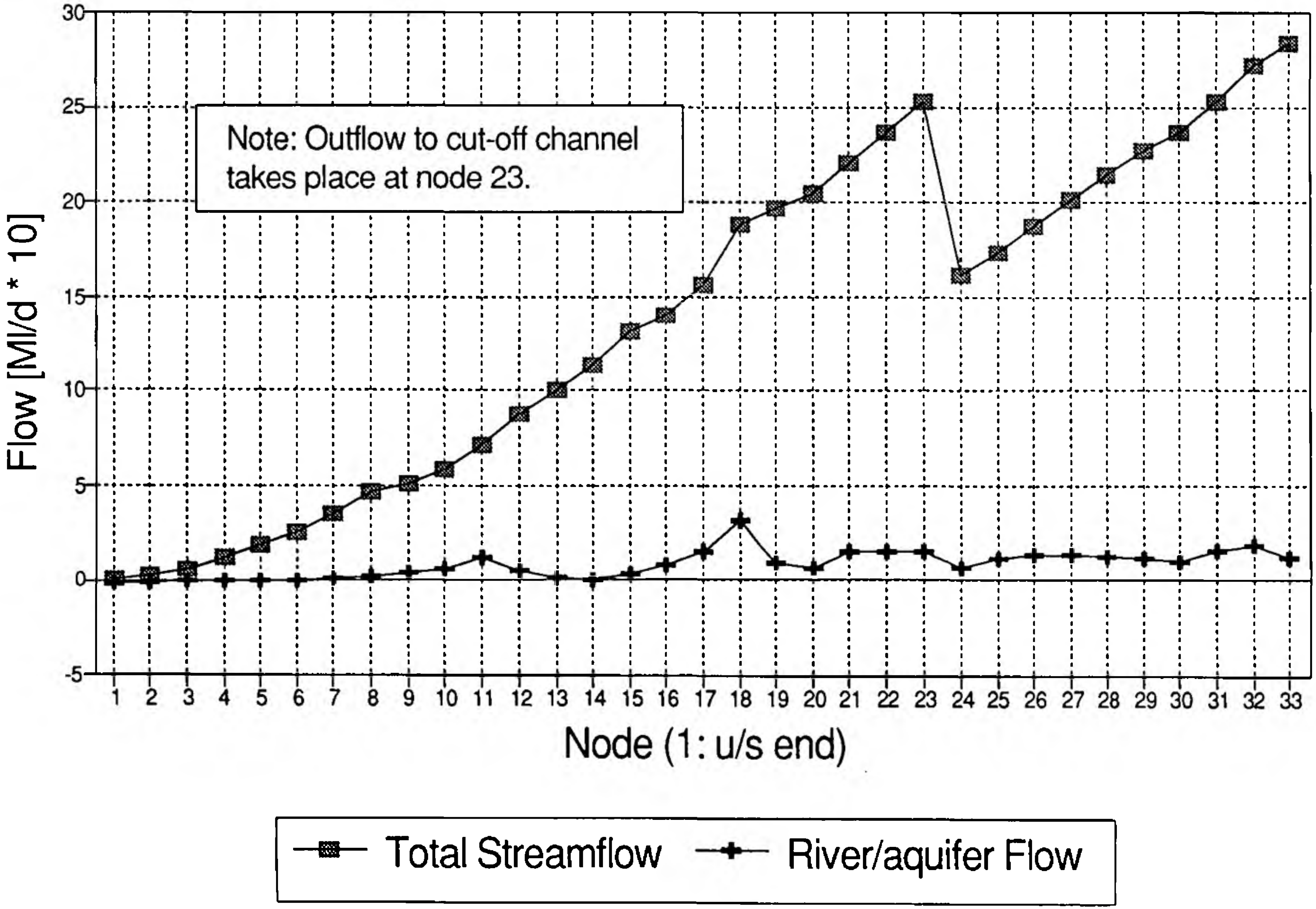


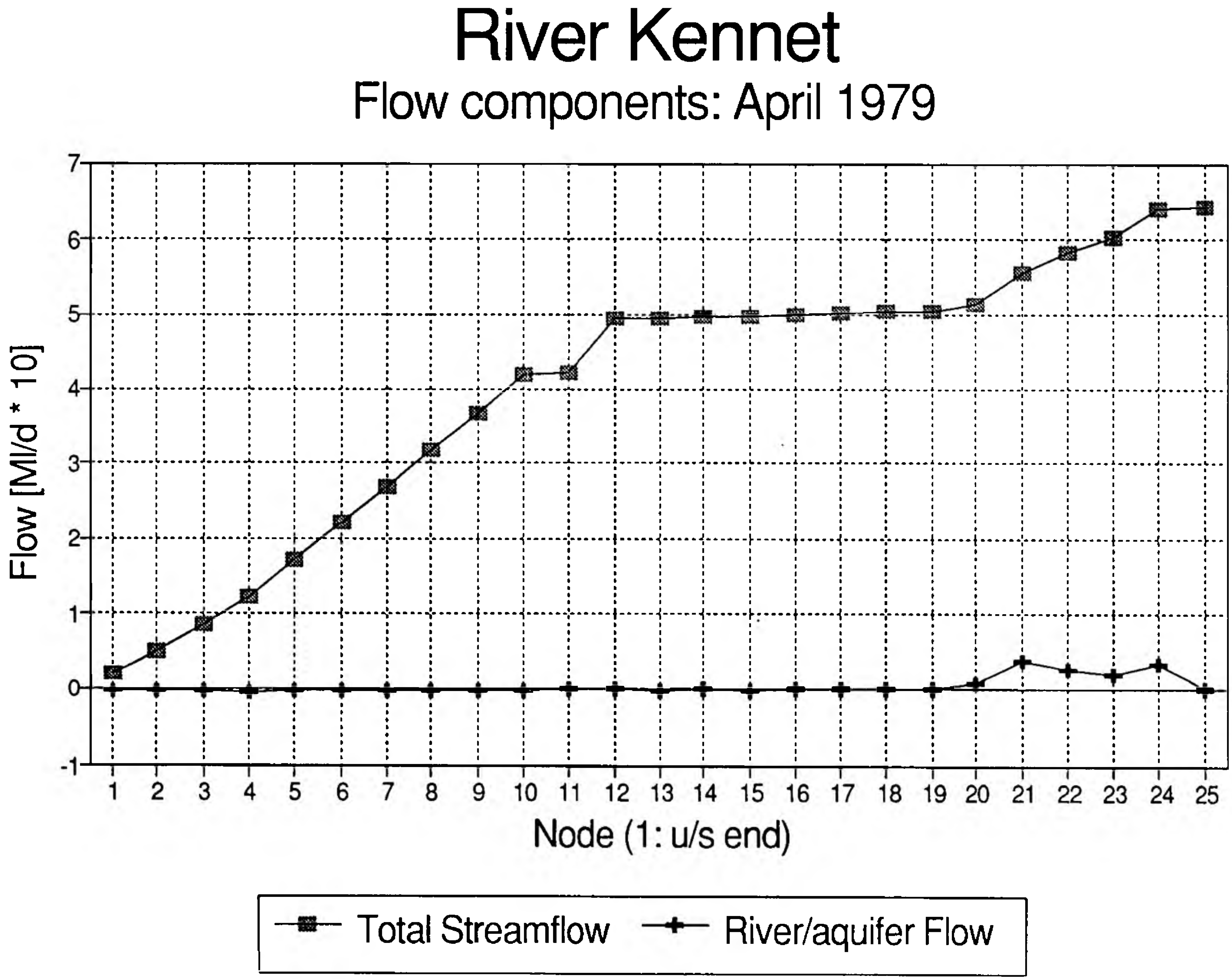


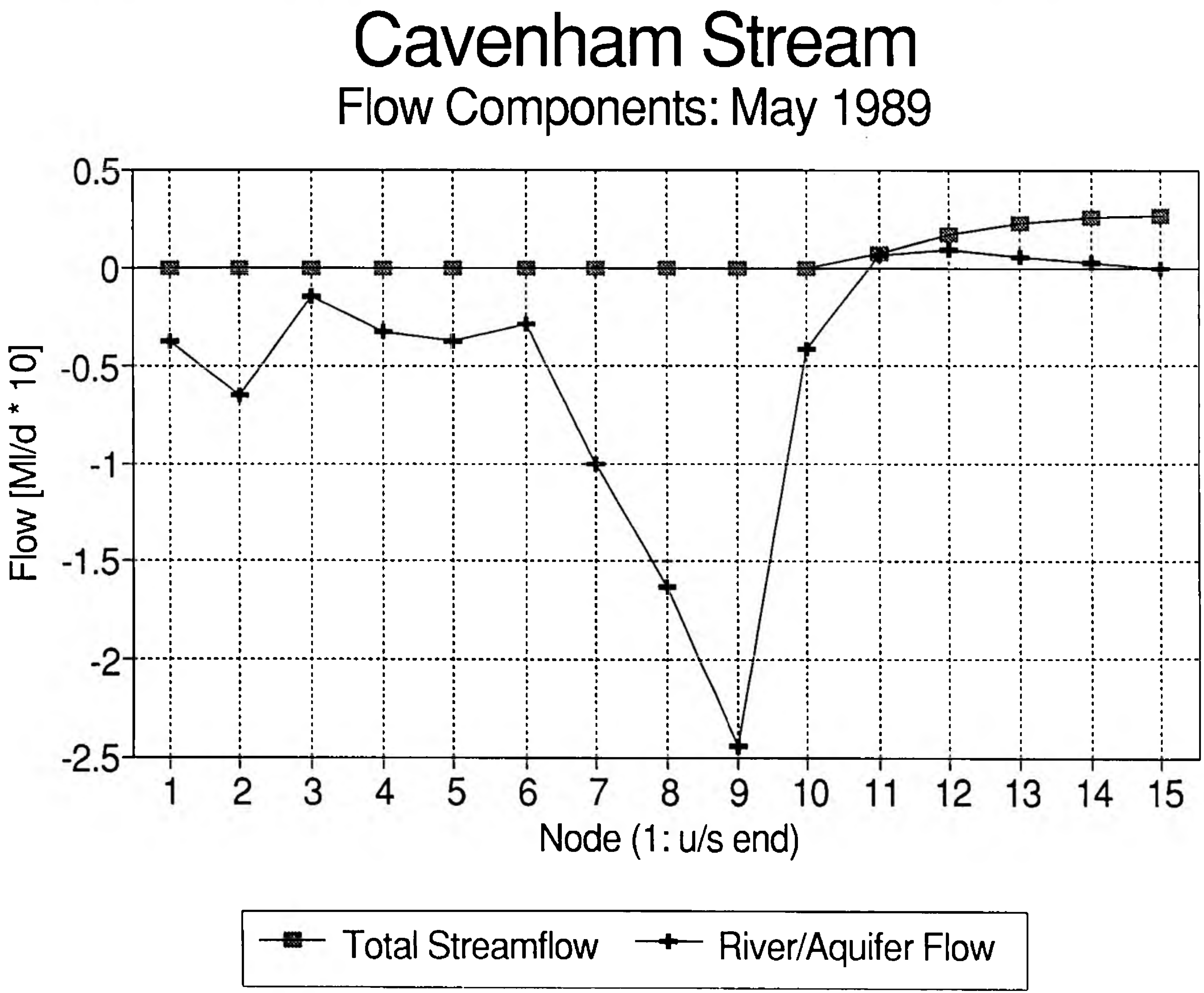
Tuddenham Stream
Flow components: April 1979
Flow [Ml/d * 10]
0
1
2
3
4
5
6
7
1
2
3
4
5
Node (1: u/s end)
Total Streamflow
River/aquifer Flow

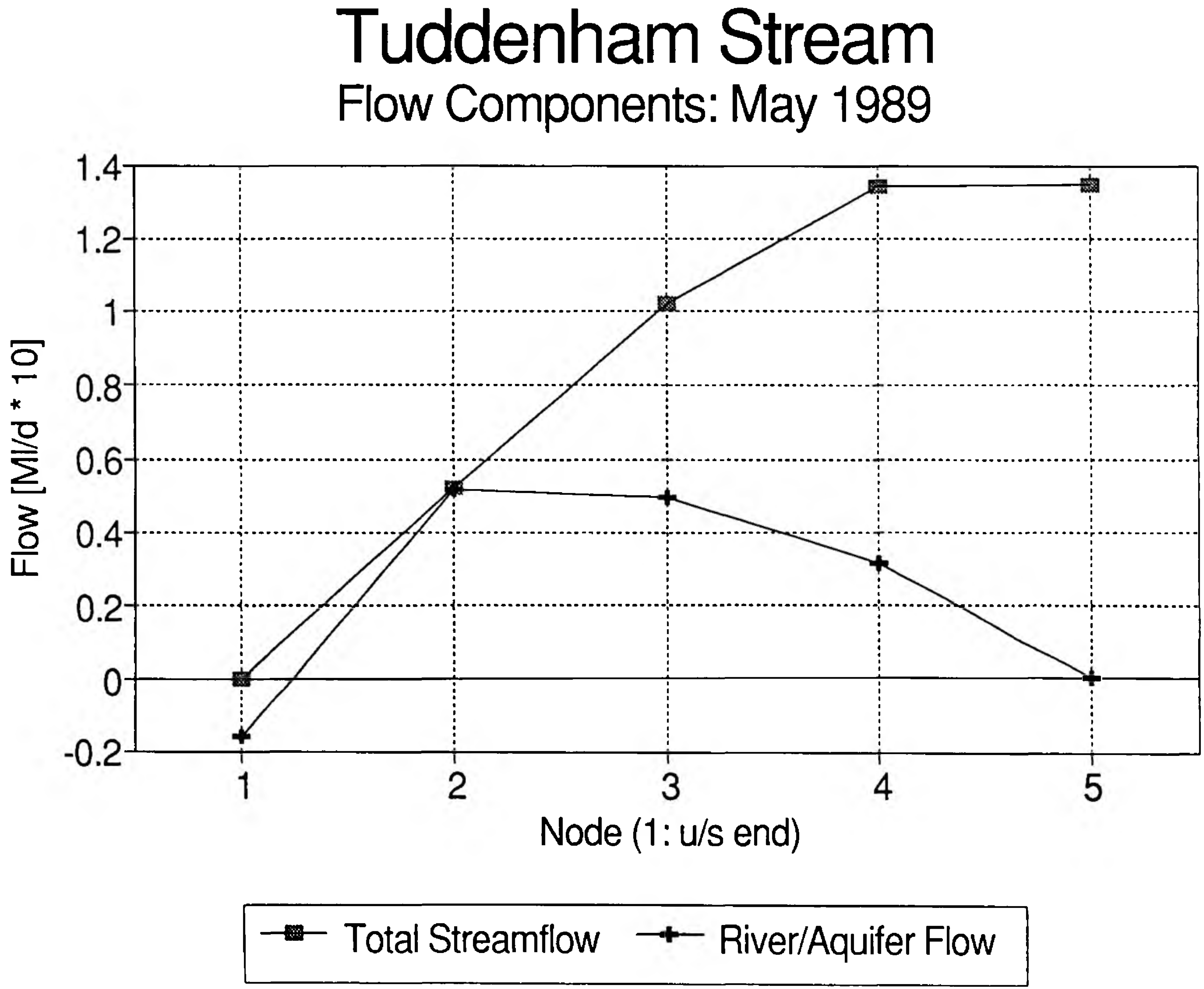
River Lark

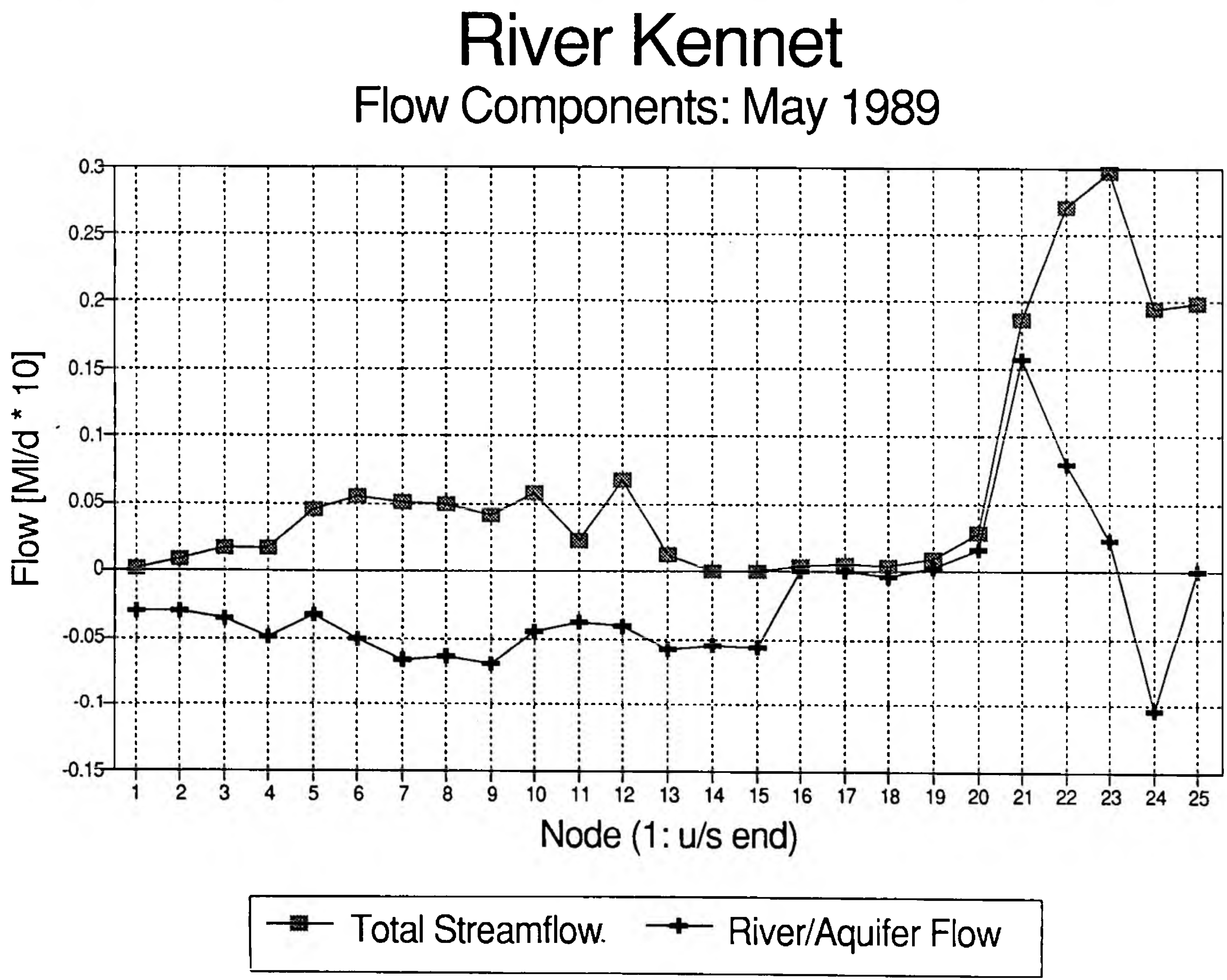
Flow components: April 1979



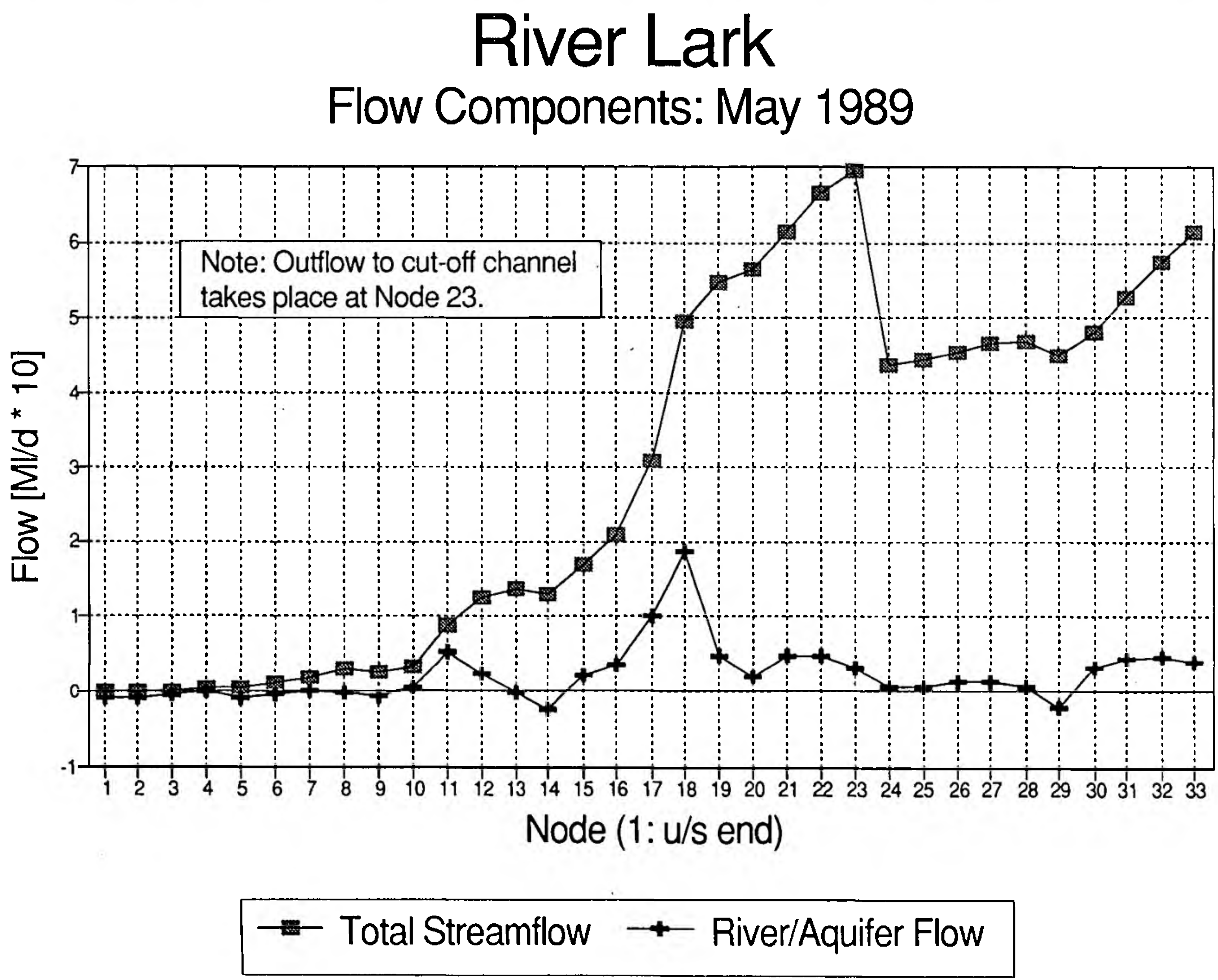

River Kennet
Flow components: April 1979
Flow [Ml/d * 10]
7
6
5
4
3
2
1
0
-1
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Node (1: u/s end)
Total Streamflow
River/aquifer Flow


Cavenham Stream
Flow Components: May 1989
0.5
0
-0.5
-1
-1.5
-2
-2.5
Flow [Ml/d * 10]
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Node (1: u/s end)
Total Streamflow
River/Aquifer Flow


Tuddenham Stream
Flow Components: May 1989
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
Flow [Ml/d * 10]
1
2
3
4
5
Node (1: u/s end)
Total Streamflow
River/Aquifer Flow



River Kennet
Flow Components: May 1989
Flow [Ml/d * 10]
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Node (1: u/s end)
Total Streamflow.
River/Aquifer Flow


River Lark
Flow Components: May 1989
Note: Outflow to cut-off channel takes place at Node 23.
Flow [Ml/d * 10]
Node (1: u/s end)
Total Streamflow
River/Aquifer Flow

Appendix C

Copy of River Lark Project

Memorandum of Agreement.

MEMORANDUM OF AGREEMENT made the 16th day of November 1987 BETWEEN ANGLIAN WATER AUTHORITY of Ambury Road Huntingdon in the County of Cambridgeshire (hereinafter called 'the Client') of the one part and THE UNIVERSITY OF BIRMINGHAM (herinafter called 'the University') of the other part.

WHEREAS the Client has requested the University to provide professional services as described in the Appendix hereto in connection with a study of the water resources of the exposed and concealed chalk aquifer within the catchment of the River Lark (referred to in this Agreement as 'The Task')

NOW IT IS HEREBY AGREED as follows:-

1(a) The Client agrees to engage the University subject to and in accordance with the Association of Consulting Engineers Conditions of Engagement (ACE Agreement 1) modified as hereinafter appearing (hereinafter called the 'Conditions of Engagement') and the University agrees to provide professional services subject to and in accordance with the Conditions of Engagement modified as aforesaid.

1(b) In the Conditions of Engagement the words "the University" shall be substituted for the words 'the Consulting Engineer' wherever they appear.

2. This Memorandum of Agreement and the said Conditions of Engagement modified as herein provided shall together constitute the entire Agreement between the Client and the University.

3. In the said Conditions of Engagement:-

(a) the rate or rates referred to in Clause 9.1(a) shall be nil

(b) the multiplier referred to in Clause 9.1(b) shall be nil

(c) the multiplier referred to in Clause 9.1(c) shall be:-

for field staff who are permanent employees of the University nil

for field staff who are recruited specifically for the Task nil

(d) the fee referred to in Clause 9.2(a) shall be nil

(e) the sum referred to in Clause 9.3(a) shall be £43,400

(f) the said lump sum is agreed by the parties hereto to include all disbursements that the University may incur and which would otherwise fall to be dealt with under Clause 11 of the Conditions of Engagement

(g) the said lump sum shall be payable by the Client to the University by three installments of £10260, £10700, and £11220 payable on delivery by the University of each of the six-monthly progress reports referred to in the Appendix hereto together with the balance of £11220 payable upon delivery of the final report on completion of the Task

(h) the University's Principal Bank referred to in Clause 14.3 of the Conditions of Engagement shall be Lloyds Bank PLC.

4. The method of payment for services under Clause 6 of the said Conditions of Engagement shall be that described in Clause 9.3 thereof.

5. In addition to the above mentioned lump sums the Client shall reimburse the University at the rate of one hundred and forty percent of:

(i) any increase in salaries arising from national academic awards so far as they increase the salary payable to the Research Fellow or Associate appointed by the University to carry out the Task together with

(ii) any increase in National Insurance Contributions or Superannuation Payments made in consequence of any pay award under sub paragraph (i) of this paragraph.

Such additional sum to be calculated on a day to day basis during the time that the University is engaged on the Task.

6. The Client shall not be entitled to require the University to carry out all or any of the Additional Services mentioned in Clause 7 of the Conditions of Engagement.

7. In the event of the Client terminating or suspending the Task pursuant to Clause 2.3 of the Conditions of Engagement, the Client shall repay to the University on demand the amount of any monies paid or payable to the said Research Fellow or Associate by reason of the termination of his or her employment to the extent that the same shall not otherwise be recoverable by the University under the terms of Clause 12 of the Conditions of Engagement but so that in no case shall the Client reimburse the University as aforesaid under both this Clause and Clause 12 of the Conditions of Engagement.

As WITNESS the hands of the parties hereto the day and year first before written

Duly authorised representative of	Duly authorised representative of
the Client..............................	the University..............................
	Assistant Finance Officer University of Birmingham
Witness......E. J. Smith..........	Witness..............................

APPENDIX TO THE MEMORANDUM OF AGREEMENT

Part 1

The services to be provided by the University shall be as follows:

1. To formulate a mathematical simulation model to represent groundwater flow within the chalk aquifer of the River Lark catchment.
2. To provide training for a hydrologist employed by the Client to enable the hydrologist to use refine and calibrate the model.
3. To produce progress reports at six-monthly intervals.

These services shall be undertaken with regard to the details of the project as stated in Part 2.

These services shall be completed within a period of two years from the date upon which the Research Fellow or Associate appointed to support the project takes up his appointment with the University or be completed by the first day of January 1990, whichever is the earlier.

Part 2

The details of the project are as follows:-

a) Objective — The model will be used to improve the understanding of groundwater flow and storage in the chalk aquifer, and its hydraulic relationship with contiguous surface waters.

b) Project Area — The total study area shall comprise the main tracts of the exposed and concealed chalk aquifer within the catchment of the River Lark.

c) Programme — The work on the project as a whole shall comprise three parts which may overlap in time or implementation:-

Part 1 — Field Studies and Investigations

Part 2 Interpretation of Field Data

Part 3 Model Development

(i) In the first part of the project (Field Studies and Investigations) the Client shall in consultation with the University carry out field investigations either using his own staff or by contract and obtain the necessary data

(ii) In the second part of the project (Interpretation of Field Data) the Client shall generally interpret geological, hydrogeological, hydrological and associated data. The University shall in consultation with the Client undertake the analysis and interpretation of field data to aid the development of the groundwater simulation model.

(iii) In the third part of the project (Model Development) the University shall in consultation with the Client develop a mathematical groundwater simulation model of the chalk aquifer. During this part of the project the University shall provide training for a member of the Client's hydrological staff with the objective that he shall undertake further model refinement and calibration after the project terminates.

d) Reports The University shall submit to the Client on the first day of April 1988 an interim progress report on the project under the general part headings (1 to 3) listed above and shall submit further interim progress reports at intervals (in each case) of no greater than six calendar months from the date of submission of the immediately preceding such report during the period of this Agreement. The final project report should be submitted to the Client by the University no later than the first day of January 1990.