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THE EFFECTS OF WATER RESOURCES MANAGEMENT ON THE RIVERS BURE, WENSUM AND NAR IN NORTH NORFOLK.

Final Project Report to the National Rivers Authority.

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The study has been undertaken by the University of East Anglia and has been commissioned by the National Rivers Authority.

This Report presents work carried out independently by the University.

The Effects of Water Resources Management on the Rivers Bure, Wensum and Nar in north Norfolk.

ABSTRACT

The River corridors of the Wensum and Bure have lost 20% and 25% of their bordering water meadows since the 1930s. Changes have been towards arable cultivation and have been most marked alongside tributaries. Land use change in the Bure valley has coincided with a 75% increase since 1904 in the intensity of the surface drainage network in the catchment. There has been a 40% increase in the Wensum.

Despite these changes in the catchment, the relationship between gross rainfall and flow over the period 1964 to 1992 has remained the same in all three Rivers. There has been no change since 1960 in the seasonal distribution of runoff from the surface catchment. Since 1960, there has been no evidence of a reduction in the baseflow (groundwater) component of flows. This indicates that, over the period, the amount of groundwater recharge has not changed. Flow volumes have thus closely followed temporal variations in rainfall since the flow record began in the early 1960s. Changes in the catchment since 1964 have not, therefore, had a significant influence on either flow volume or regime. This does not imply that changes did not occur before the 1960s.

Alongside changes in the catchments, the channels of the study Rivers have been engineered since Domesday times to provide the hydraulic heads needed to power water mills and to provide navigable waterway. The greatest change in water use this century has been the end of water milling. Although milling did not alter flow volumes, channel shape, water depth, flow velocity and sediment transport were all influenced greatly. Since the end of water milling, channels have narrowed, particularly during drought flows. This represents natural readjustment to former channel dimensions and is desirable because increases in local flow velocity will result.

Flow volumes have been altered by water use since the end of water milling. However, between 1971 and 1992, the average actual losses to seven-day mean flows due to net abstraction for all water uses have been no greater than 3%. Losses have been greatest during dry growing seasons due to spray irrigation, and especially during the 1989-1992 drought. Flows in the Nar have been the most affected by abstractions for spray irrigation, with a maximum loss of around 24% during the recent drought. Maximum losses in both the Wensum and Bure were about 15% in the 1989-1990 drought.

The relative sizes of loss to flow in the three Rivers due to spray irrigation are consistent with changes in the invertebrate communities of the Rivers. Since 1979, the invertebrates in much of the Nar have become more typical of silty and low-flow environments. There is no evidence of a similarly persistent change in either the Bure or Wensum, although short-term variations in community strucure, which do not necessarly relate directly to rainfall, have occurred.

In the Bure and Wensum, and on a catchment not local-scale, physical features of the River channels are more important in shaping the biology of the Rivers than either absolute water quantity or water quality. There are few past data on water plants, although those which do exist suggest improvements in the water quality of the River Wensum. Most of the fish species in the Rivers are less evenly distributed in the Rivers than in the early 1980s, particularly in the Bure and Nar. Fish density is lowest where there are the highest proportions of silty sediments in the channels. Increased external loading of these sediments will have occurred because of the changes in agricultural land use alongside the waterway. The present-day effect of this is most marked along tributary streams. No data on distributions of silt in the past exist. Less active transport of sediment since the end of water milling has presumably led to the deposition and retention of silty material over an increased proportion of the main channels. This will have reduced habitat variety and restricted the distribution of species which use clean gravel and other faster-flowing waters.

The priority for management to enhance the biology of the study Rivers should therefore be to prevent further consumptive water use in the Nar and, in all the Rivers, to prevent or to intercept inputs of sediment from agricultural land or from road runoff. This is particularly important in tributaries. Local variations in flow velocity, water depth and bankside cover are all desirable and should be maintained and created. Shoals which narrow the channel and thus increase flow velocity, should be allowed to form over much of the waterway. Equally, such features could be created as part of a programme to engineer narrower and more sinuous channels which drain, and, in suitable areas, flood, uncultivated land.

Project report by the University of East Anglia to the National Rivers Authority, 1994.

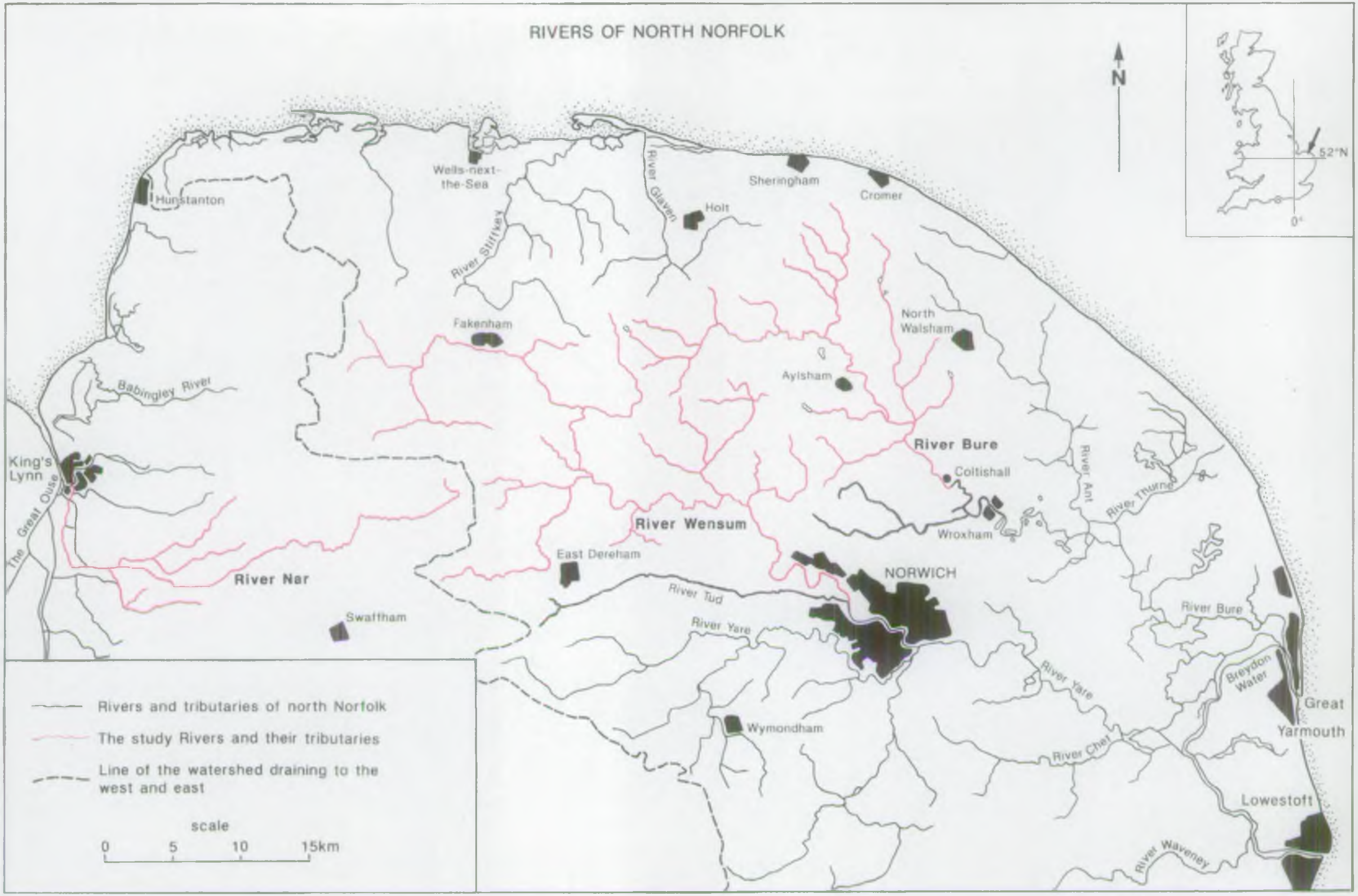
CHAPTER 1: INTRODUCTION TO THE PROJECT

CHAPTER 2: INTRODUCTION TO THE STUDY RIVERS

CHAPTER 3: CHANGES IN THE RIVER ENVIRONMENTS

CHAPTER 3:

RIVERS OF NORTH NORFOLK



Rivers and tributaries of north Norfolk

The study Rivers and their tributaries

Line of the watershed draining to the west and east

scale

0 5 10 15km

CHAPTER 1: INTRODUCTION TO THE PROJECT

CHAPTER 1: Section 1. Terms of Reference.

The full title of the project is *The Relationship between Water Resources Management and the Ecology and Hydrology of North Norfolk Rivers*. The project has a strong emphasis on applied research and its aims are specific to the non-tidal reaches of the Rivers Wensum, Bure and Nar in north Norfolk. The study Rivers, and also their tributaries, are shown in red on the introductory map. Funding for the work has come entirely from the National Rivers Authority (NRA) and this final Report is made to the Water Resources section of the NRA's Anglian Region.

The long-term aim of the NRA is to determine natural and artificial influences on the flow characteristics, water quality and ecology of the study Rivers. An important objective within this is to identify and investigate significant relationships between water resources management and ecological change. The NRA's major purpose in commissioning this study was to investigate claims of long-term ecological change in the study Rivers. This project has therefore, where possible, identified historical changes in biology and established the most likely causes of such change.

The specific objectives for the work, which were set by the NRA at the beginning of the project, were:

1. To locate and collect data on past and present land and water resources management, land drainage works, flow characteristics, water quality and ecology in the study Rivers and their catchments.

2. To appraise existing data for specific cases where probable cause and effect relationships between water resources, land management or any other factors and in-stream ecology have been identified.

3. To define the extent of change in the water environment of the Rivers.

4. To evaluate the information collected to meet Objective 1 and to select key investigations and data which will reveal circumstantial relationships between land and water management, catchment geology, hydrology, hydrogeology, channel morphology, water quality and ecology.

5. To structure multi-variate data sets (where data are available) fitted for search procedures which will identify variables, or groups of variables, most closely linked with historical change in the river environment.

6. To identify the interpretive and/or controlled experimental work required to define cause and effect relationships between land and water resources management, river flow and quality and ecological features.

7. To identify the deficiencies of existing data which constrain its interpretation for practical ecologically sensitive management of water resources.

CHAPTER 1: Section 2. Scope of the Project.

The central aim of the work is to examine the widely held belief that there have been long-term changes in the hydrology and biology of the study Rivers. If there is evidence that changes are long-term, then the project aims to identify likely causes and to scale their importance.

The catchment-scale approach of the work relies upon a range of environmental sciences to interpret a very wide range of information. The result is an evaluation of the relative importance for the Rivers of a large and well-mixed set of potential influences. The corollary of this is that detail at individual sites is masked if the relative importance of factors is different from the overall catchment-scale. Site-specific questions need to be answered in separate studies. Information from the project is relevant to the Yare Catchment Plan, which includes the catchments of both the Wensum and Bure, which has been presented recently by the NRA for public consultation (NRA, 1994).

Management of water resources is just one potential influence on the flow and biology of the study Rivers, though has been singled out by the NRA as a topic for special study in north Norfolk. This is because of public concern that demand for water in these catchments is satisfied at the expense of in-river needs. The project began during the 1989-1992 drought at a time of very low-flows in the East Anglian region. An important working objective of the project has been to calculate, on a catchment-scale, the relative effects on flow of low rainfall and of water abstraction.

Our approach to measuring the significance of water use for the Rivers' environment is to evaluate its effect against the scale of other, and perhaps longer-term influences. If any of these influences, for example: river engineering; land drainage; sediment loading or loading of treated sewage effluent, appear to be more significant than water resource management, then research and management should, at first, be directed at these. The scope of the project has to be wide and has taken account of reliable information recovered on all of the listed aspects of the Rivers and their catchments.

The time series of data for analysis is unusually long. The project involves looking for changes in the Rivers' environment which may have occurred since the 1930s, or earlier. This extends the interpretative part of the project to include the effects of water mills, which have, in the past, been an important feature of water resource management in the study Rivers.

The range of research tools used has been wide. Unstructured interviews of about sixty project consultees with long-term local interest in the Rivers, have been analysed. Most of the information used in the project is from data held in computerised form, though it has also been abstracted from the much older and more cryptic records of the NRA's predecessors. Archives of maps, films, photographs and herbarium specimens have been examined. Most of the historical information from old maps and from aerial photographs has been digitised using a geographical information system (GIS) which gives numerical data as well as visual output. Hydrological analyses have relied upon a number of computer modelling techniques and have included a resource model to naturalise the flow record of the Rivers. Part of the biological analysis relies upon computer association and ordination techniques known as TWINSPAN and DECORANA. Although the terms of reference for the project did not include field work to collect new data, sediment was collected from one of the study Rivers for biological analysis and for preliminary clay mineralogy using X-Ray defraction techniques.

CHAPTER 1: Section 3. Framework of the Report.

The major environmental features of north Norfolk Rivers and their catchments are introduced in Chapter 2. The first aim of this is to place the Rivers and their catchments in a regional and long-term context set by rainfall, geology and soils. The second aim is to describe the present day status (taken to be somewhere between 1988 and 1991) of the study Rivers. This is done using quantitative information, much of which has been extracted from routine NRA monitoring programmes. All the major research topics are covered. These are: flow; water use; water quality; channel dimensions and sediments; biology and land use in the River corridors. Project consultees' perceptions of today's status are summarised within most of the Sections.

Chapter 3 presents the main analytical output from the project. Emphasis is on time series of quantitative information. Time scales vary widely according to the availability of data: rainfall records go back to the 1860s; land use to the 1930s; water quality and hydrology to the 1960s and biology, usually only to the 1980s. Where time series are short, or where site continuity is unusually poor, other approaches are used to assess the likelihood of long-term change. Concluding statements are made at the end of every Section and have not, therefore, been added to the list of contents.

The interpretative part of the project is presented in Chapter 4. If persistent change in the hydrology or biology of the Rivers has been identified, then likely explanations are given. Explanations are, in the absence of quantitative data for the same sites or over the same time scales, based upon collections of correlative and any other strong, uncontradicted circumstantial evidence. Where persistent change has not been detected from robust data, then key relationships which, nonetheless, have implications for river management, are identified.

The main conclusions of the project are brought together in Chapter 5. The project is then appraised from the point of view of its interpretative, rather than experimental, approach. Constraints and reliability are set largely by availability of data. These constraints are described in relevant sections of the Report. Lastly, wider implications of the project in terms of further research, focused monitoring programmes and recommendations for improved river management are summarised.

Technical details on soil associations in the study area, analysis of rainfall records and flow naturalisation are given in Appendices. Line maps which show each of the study Rivers and the distributions of flow gauges and other monitoring stations are at the very end of the Report.

The NRA have commissioned the work to answer recent questions set by the public and by NRA managers of water resources, hydrology, biology, fisheries, water quality and river engineering. The Report will therefore be read by both specialists and non-specialists in each of the subject areas covered and will be available to organisations and individuals outside the NRA. Because of this, most of the technical terms used are explained in the main text. Where extra details and where common, as well as Latin, names might be useful, footnotes refer to information in Appendix 4.

A short summary of the project has been produced as a separate document. This contains some introductory information and the main conclusions made in Chapter 5.

CHAPTER 2: INTRODUCTION TO THE STUDY RIVERS

CHAPTER 2: Section 1. Introduction to Rainfall and Evaporation.

The study area lies in the east of England and so is prone to water deficit during summer. It is usual for considerable soil moisture deficit (SMD) to accumulate by the end of each growing season and, under normal circumstances, rainfall must eliminate this SMD before flow can be produced. The amount of water which remains after SMD has been satisfied is called effective rainfall, and it is this, and not necessarily gross rainfall, which eventually becomes part of total runoff (the river flow which leaves an area). Pathways of water movement and components of river flow are illustrated in Diagram 1.

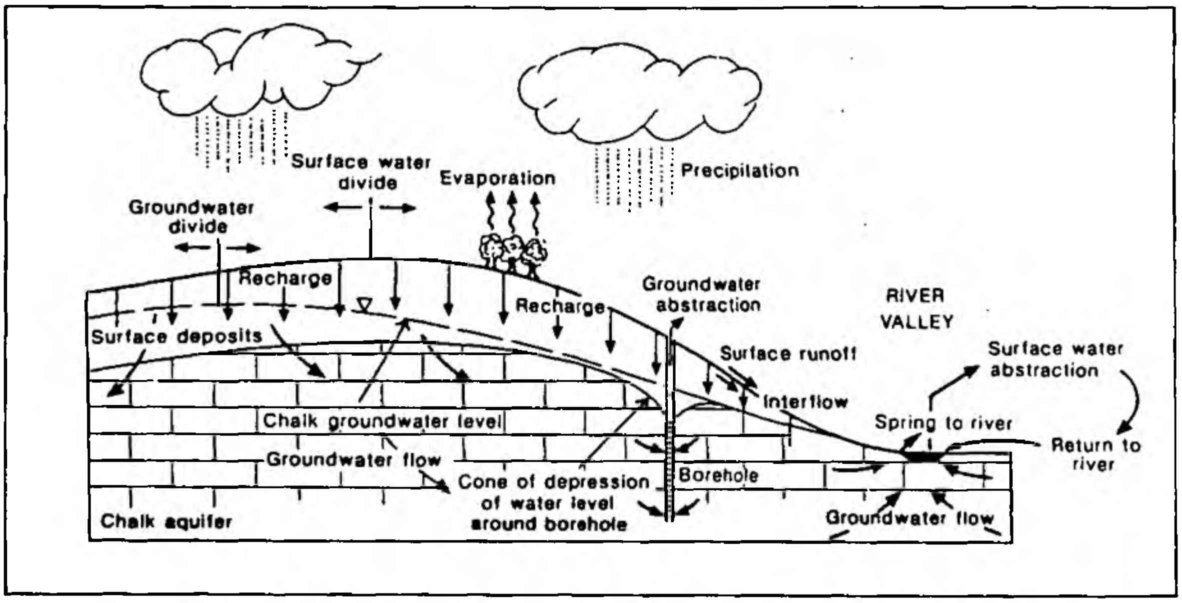


Diagram 1 Schematic hydrological cross-section for north Norfolk.

The average rainfall over the study area is calculated from gauges at Cromer, Sheringham and Wymondham. For the period 1930 to 1992, average annual rainfall was 648mm and annual amounts varied between 469mm and 827mm. Average monthly amounts for the same period were spread fairly evenly throughout the year with lowest values of around 44mm falling in late winter or early spring. The wettest part of the year is late autumn or early winter when average monthly values are over 60mm.

Rainfall in the region is distributed fairly evenly between seasons, though during summer losses of soil moisture to evaporation usually exceed replenishment. Potential and actual evaporation are calculated on an areal basis by the UK Meteorological Office who have applied their Meteorological Office Rainfall and Evaporation Calculation System (MORECS) to data that have been collected since 1961 (Meteorological Office, 1982). Mean annual actual evapotranspiration, which includes all evaporation from soils and transpiration from growing crops in the study area, is 460mm. Since mean annual rainfall amounts to 648mm, it follows that the annual effective rainfall in the study area is 228mm. This means that, on an annual basis, effective rainfall in the study catchments is substantially less than the area's gross rainfall.

Rainfall patterns in north Norfolk have been examined for any changes that may have occurred since 1930 and the results of this are given later in the Report. Relationships between gross and effective rainfall, groundwater and river flow in the three study catchments have also been described. Hydrological modelling and time series analyses have been used to show by how much these relationships have changed since the 1960s.

CHAPTER 2: Section 2. Introduction to Geology and Hydrogeology.

Section 2.1 Geology.

The geology of north Norfolk is simple, with Cretaceous Chalk dipping eastwards and north eastwards, overlain unconformably by Tertiary deposits dipping gently in the same direction. A geological cross-section along an east-west line, centred on Norwich is given in Figure 1.

2.1(i) Pre-Quaternary deposits.

The solid geology of Norfolk is shown in Figure 2(a). The Jurassic Kimmeridge Clay is the oldest deposit exposed within Norfolk, the outcrop being limited to isolated areas along the eastern margin of the Cambridgeshire Fens. Lower Cretaceous strata (including the Sandringham Sands, Snettisham Clay, Gault Clay and Red Rock) are described by Chatwin (1961) and Larwood (1961) and outcrop in west Norfolk, maintaining a width of 10km before dipping eastwards, at approximately the same angle as the underlying Jurassic strata, below the Chalk.

The Upper Cretaceous Chalk, a fine-grained, fissured limestone, attains a thickness of 430m on the northeast Norfolk coast and is exposed in west Norfolk and along the larger river valleys to the west and northwest of Norwich (Peake and Hancock, 1961). The upper surface of the Chalk reaches a maximum elevation of 95m above sea level about 10km from its western margin, declining to 154m below sea level at Great Yarmouth.

The Lower Tertiary Eocene Clay (London Clay) is present in east Norfolk attaining a maximum thickness up to 95m. This deposit thins westwards, resting directly on the Chalk at its feather edge at a maximum of 16km from the present east coast. No Upper Tertiary deposits occur in Norfolk (Baker, 1918).

2.1(ii) Quaternary deposits.

The succession of early Pleistocene deposits is described by Funnell and West (1977) and includes the Crag deposits which comprise coarse shelly marine sands with clay beds and gravelly horizons that occur in east Norfolk and range in thickness up to 30m. These deposits are shown on Figure 2(a).

The late Pleistocene deposits of Norfolk represent a period dominated by a major ice age. Temperatures began to fall about 700 000 years ago and the cycle of glaciations and interglacials continued until the end of the Devensian Stage, 10 000 years ago. Pre-Devensian glacial deposits are described by Perrin *et al.* (1979) and include the Chalky Boulder Clay (Lowestoft Till) and North Sea Drift. The Chalky Boulder Clay is a brown calcareous clay with clasts of chalk and flint and is generally between 15-30m in thickness. The North Sea Drift is a brown or grey non-calcareous sandy or silty clay with flint ranging in thickness up to 35m. The Chalky Boulder Clay is present in the upper Bure, Nar and Wensum catchments, and the North Sea Drift in the north and east of the Bure catchment. West of Norwich the boundary between the two glacial deposits is obscured by thick fluvio-glacial deposits that extend in a line from Norwich to Holt. The distributions of glacial deposits present in Norfolk are shown in Figure 2(b).

The principal effect of the last glacial stage, the Devensian, was the widespread development of permafrost conditions (Williams, 1969). At this time, thin but widespread near-surface windblown material, forming a uniform cover up to 2m thick, was deposited in eastern Norfolk and northeast Suffolk. This Coverloam, which is absent locally on steeper slopes, is mainly composed of silt and is mineralogically similar to the Devensian Till of northwest Norfolk, from which it is thought to derive (Catt *et al.*, 1971).

Major melting of the last Devensian ice sheet began about 11 000 years ago with the climate recovering during the present Flandrian interglacial. Recent deposits are shown in Figure 2(c) and include peats, clays and alluvium which occupy the lower reaches of the main rivers, and include the Nar Valley Clay and Nar Valley Freshwater Beds present in west Norfolk (West and Whiteman, 1986).

Section 2.2 Hydrogeology.

A detailed description of the hydrogeology and hydrochemistry of north Norfolk is given by Hiscock (1991 and 1993) with the salient features given here. The Chalk aquifer is the dominant hydrogeological unit, with the Chalk groundwater catchments corresponding approximately to the surface water catchments. In the east of the region the Chalk is confined by the Eocene Clay with no natural groundwater discharge from this part of the aquifer.

Different aquifer conditions are associated with the distribution of Quaternary deposits. Overflowing artesian conditions occur in the upper Bure catchment in regions of thick Chalky Boulder Clay. Unconfined (water-table) conditions occur in west Norfolk and also within the valley zones to the north and northwest of Norwich where either the Chalk crops out or there is a thin cover of Crag or glacial sands and gravels.

Chalk transmissivity values are also controlled by the distribution of Quaternary deposits. In valley zones values of 2000-3000 $m^2\ d^{-1}$ are possible, whereas in interfluve areas values of less than 100 $m^2\ d^{-1}$ are more typical. Aquifer storage coefficient values of 0.077 and 0.064 for the Bure and Wensum catchments (Toynton, 1983) are higher than expected when compared with an effective (fracture) porosity for the Chalk of about 1-2% and reflects the influence of the glacial deposits, particularly the North Sea Drift in the Bure catchment, in contributing to the overall storage of the aquifer system.

Other hydrogeological units include the Crag aquifer and the Eocene Clay. In the Crag, groundwater flow is intergranular, with groundwater yields dependent on the coarseness of the sand and gravel fraction. At its western limit, the Crag is in hydraulic contact with the Chalk. In contrast, the Eocene Clay is not water-bearing, forming instead an aquitard between the Crag and Chalk aquifers.

The hydrogeological behaviour of the glacial tills is important with respect to their potential for transmitting recharge, and also pollution, to the underlying aquifers. Some horizontal and vertical transfer of groundwater is expected through lenses of sands and gravels and joints within the more clay-rich till.

In describing the hydrochemistry of the Chalk aquifer of north Norfolk, a distinction is made between Chalk groundwater in valley zones and groundwater in interfluve areas. Unconfined Chalk groundwaters in the valley zones are calcium-bicarbonate in character and contain relatively high concentrations of chloride, nitrate and sulphate, mainly from agricultural sources. Tritium and carbon-14 data confirm that these groundwaters are modern in age.

In the interfluvial areas, groundwaters are again calcium-bicarbonate in character. Chalk groundwater from beneath Chalky Boulder Clay is distinguished from groundwater associated with North Sea Drift by a bicarbonate concentration of 300 mg l^{-1}, with higher values occurring beneath Chalky Boulder Clay.

Tritium and carbon-14 dating of groundwater in the interfluvial areas reveals that groundwater beneath the more impermeable, clay-rich Chalky Boulder Clay is of the order of 10 000 years old, and beneath the more permeable, sand-rich North Sea Drift is typically 1000-2000 years old. These old groundwaters do not contain nitrate and promote enrichment of the Chalk groundwater with magnesium, silica and strontium due to long groundwater residence times.

Chalk groundwater in the east of the Bure catchment shows evidence of a saline influence, with an increase in magnesium, sodium, potassium and sulphate concentrations, as the Eocene Clay boundary is approached. Where the aquifer is confined beneath the Eocene Clay, the chloride content increases to several thousands of mg l^{-1} where very old saline water is trapped in the Chalk.

All three study Rivers drain lowland, predominately rural, catchments. The Wensum above Costessey has the largest surface catchment with an area of 536 km^2. The surface catchment of the River Bure above Horstead covers 313km^2, and the Nar to Marham, 153km^2.

With a maximum catchment elevation of less than 100 mOD, channel gradients are gentle, particularly in lower reaches. The highest gradients occur in the upper Bure with values in excess of 2 mkm^{-1}. The lower part of the River Nar, which lies below Marham, is a typical fenland river and has a lower gradient than both the Bure and the Wensum which fall around 0.6 mkm^{-1}. Except where channels have been engineered for water milling, navigation or drainage, the Rivers and their tributaries are predominantly shallow and usually slow-flowing.

Flows are gauged at three points on the River Wensum which are in the upper, middle and near-tidal reaches. There are two gauges on the Bure which represent both upper and near-tidal reaches. The River Nar is gauged at Marham which is approximately mid-way between the source and the outlet to the Great Ouse at King's Lynn. Marham roughly marks the transition from a largely chalk fed stream to a fenland channel. The exact locations of the gauging stations are shown in Appendix 1.

Flow data since 1960, or before, are available for gauges at Costessey Mill on the Wensum, Ingworth Bridge on the Bure and at Marham. The gauge at Horstead on the Bure began operating during 1974. Close examination of Marham data reveals what appears to be non-continuous recording because stage readings at this gauge were taken manually before 1965. It appears that flow data from before 1965 are of a lower resolution than data from other stations. The flow velocity of the study Rivers has never been measured systematically and so description of this aspect of flow is beyond the scope of this study.

The mean flow of the Wensum at Costessey is 4.1 cumecs (m^3s^{-1}), of the Bure at Horstead, 2.2 cumecs and at Marham on the Nar, 1.1 cumecs. A cumec is a unit used to describe flow in terms of river discharge. Discharge is the volume of water (in cubic meters) which passes a fixed point in a river, for example a flow gauge, over a standard unit of time (per second). The size and shape of the channel control the speed of water movement. Since flow is monitored routinely by the NRA in terms of cumecs, flows described in this report refer to quantities of water and not to current velocity. The two variables are related, sometimes on very local scales, according to physical features of channels such as width, depth, the roughness of the banks and riverbed, the meander pattern of the river and the presence of artificial features such as buildings. Any changes in these physical features are emphasised in this study because of their effect on flow velocity and, thus, on river biology.

Flow (discharge) in the study Rivers is regulated naturally by the underlying chalk aquifer and overlying unconsolidated deposits of glacial and fluvial material. The degree of regulation is controlled by the extent and hydraulic properties of the aquifer and covering deposits. The degree of influence can be identified by the size and duration of the baseflow component of flow.

The baseflow index (BFI) calculates the percentage, on a gross volume basis, of the baseflow component of flow to total flow using the gauged daily mean-flow record (Institute of Hydrology, 1980). The BFI values for the period 1960-1992, ranged between 62% at Costessey to 83% at Marham. The regulatory influence of groundwater is therefore considerable in all of the study catchments.

Flow behaviour can be illustrated by flow duration curves. These curves plot the recorded range of flows against their frequency of exceedence for a specified time increment, which is usually the mean daily flow. Figure 3 shows examples of flow duration curves for the study catchments which summarise flow regime over a much longer period of about 30 years. On these plots, the response of flows at Costessey on the River Wensum (Figure 3(a)) to rainfall can be compared with the responses of the Nar at Marham (Figure 3(b)) and the Bure at Ingworth, Figure 3(c). Allowing for the difference in drainage areas, a conclusion from examining these curves is that the Wensum is more flashy, with higher high-flows and lower low-flows. This is a reflection of the greater proportion of less permeable glacial deposits (boulder clay) in the Wensum catchment.

Flow duration curves are useful because they describe flow in terms of both its size and duration. They do not, however, reference time. The timing of specific fluctuations in flow is revealed by the hydrograph. The hydrograph plots flow against time and reflects catchment characteristics and the nature of preceding and prevailing meteorological conditions.

Description of the longer-term hydrology, that is the flow regime of the study Rivers, relies mainly upon flow duration statistics. The fluctuation of flow with time relies upon the hydrograph. The flow duration curve is not usually used as an analytical tool. Analysis to describe the fluctuation of flows and to test for change, has relied heavily upon flow time-series.

Historically, the flows of the study Rivers have been regulated to provide power for water mills and to provide navigable waterways. Navigation, primarily on the Bure between Aylsham and Horstead, was halted abruptly by the floods of 1912. For the purposes of this study, regulation for the provision of water power continued well beyond 1930, and had a significant effect on local flow velocities. The Wensum was by far the most exploited for water power. The Nar with two to three mills, was the least exploited.

By the early 1960s, water milling was in decline and most of the mills had ceased operating in the traditional manner. The flow analysis used throughout this study (post-1960) has therefore, through lack of data and likely impact, ignored the likelihood of occasional artificial regulation by sluice operation. Water abstraction and effluent discharge can be major influences on flow and both have increased in volume over recent decades. The use of the water resources in the study catchments is introduced in the next section.

By the end of 1991, the East Anglian region was in the third year of a severe drought. Average annual gross rainfall, shown in Table 2.1, had fallen to its lowest level since the beginning of the flow record in 1962.

Table 2.1 Rainfall statistics for the study catchments between 1962 and 1992. The average is of measurements from three gauges in north Norfolk.

YEARS	AVERAGE ANNUAL RAINFALL (mm)
1962-88	658 (Range 495-827)
1989	572
1990	546
1991	468
1992	687

During 1991, mean monthly summer flow, which is normally sustained by baseflow, also fell to its lowest value since 1962. A measure of the reduction in flow rates, seen against 1987 and longer-term antecedents, is given in Table 2.2. Even winter flows were much reduced, with rainfall satisfying catchment storage deficits before producing runoff.

Table 2.2 Monthly mean flows in the study Rivers between 1962 and 1986 and during the 1989-92 drought.

	MEAN MONTHLY FLOW (cumecs)					
	Costessey River Wensum		Ingworth River Bure		Marham River Nar	
YEARS	Jan	July	Jan	July	Jan	July
1962-86	6.69	2.31	1.51	0.78	1.49	0.89
1987	7.76	2.56	1.74	1.04	1.59	1.02
1989	4.03	2.78	1.08	0.70	0.95	0.48
1991	3.77	0.79	1.13	0.55	0.64	0.37

The high-flows of 1987 and 1988, over a time when catchment storage was unusually high, contrast sharply with the drought flows of 1989 and 1991. A major feature of the drought is virtual absence of high flows since 1989 and high frequency of low flows; data which describe flow behaviour during the drought are shown in Section 3.1.

Long periods of low-flow during the early 1990s precipitated the production by the NRA of a list of 'Forty-low-flow' rivers. Whilst none of the study Rivers feature in this report, our consultation exercise has revealed that low-flows are the major concern of those with a long-standing interest in the three study Rivers. The consultation process was undertaken during the late spring of 1992; consultees rightly identified that flows over the previous three years had been close to, or lower than, all minima recorded since 1962.

CHAPTER 2: Section 4. Introduction to Water Use.

Demands for water within the study catchments have increased since the 1930s when they were based only on the needs of scattered market towns and their farming hinterland. The increases are due to both newer demands and intensified use of the traditional ones. Present demands are domestic, from light industry, food processing industries, sand and gravel extraction and for irrigation of agricultural land. The greatest increases in demand have taken place since the Second World War, and more particularly, since the 1960s.

Between 1971 and 1991, per capita domestic water use rose from 128 to a peak of 156 litres day^{-1}. Historically, rural water use relied upon many, usually small, point sources. Discharge points were scattered similarly. Since the middle decades of the present century, towns and villages have been connected to both mains water supply and effluent disposal networks. Whilst farms and many rural properties, including some of the larger industrial users, have retained private supplies, a few large-capacity abstraction points now serve both the domestic and industrial needs of towns and villages. The use of trunk mains allows the distancing of abstraction and use. Similarly, the construction of rural sewage networks allows a concentration of discharges at points well removed from abstraction points.

Most non-irrigation uses produce minimal consumptive loss. This means that the major part of the water abstracted is returned to watercourses through effluent disposal networks. Increased use does not, therefore, necessarily pose a threat to catchment resources and thus river flows. Rather, abstraction from groundwater can regulate flows downstream of discharge points very effectively. However, the ability of water mains and sewers to carry water considerable distances, means that the discharge may be made far away from the point of abstraction. Flows may thus be reduced in one locality and augmented in another.

One special category of resource use is the provision of water power. This is entirely non-consumptive: water is retained within the river and none is lost from the system. It is also different because demand for water power for milling has fallen to zero over the time span considered in this project. In 1906 there were 72 working water mills in Norfolk; by 1956 there were 21; and by 1969, the last mill on the River Wensum at Elsing changed use, (Scott, 1993). The historic importance of water mills is great. Their many legacies, mainly in the form of channel modification, have a great bearing on the Rivers' environment to the present day.

Agricultural use for crop irrigation is, in contrast, totally consumptive. All of the related abstraction is eventually lost to the atmosphere during the growing season. Since abstraction for irrigation is a function of meteorological conditions, annual use varies markedly, with the highest consumption occurring during the driest years and during the driest times of year.

Data relating to quantities of water abstracted for different use categories are generally available from the mid 1960s. This coincides with the passing of the 1963 Water Resources Act and its implementation, through a licensing system by successive regulatory authorities. Under the Act, abstractors, for most use categories, have been obliged to complete returns giving the actual amounts abstracted (by month or year) within their licence conditions. These data, together with estimates of subsequent discharges have been used in analyses to determine the influence of water resource use on flows.

Table 2.3 gives the total licensed quantities for water abstraction for the study catchments for the year ending December 1991. Values are in thousands of cubic metres per annum (TCMA) and are divided into the main categories of water use in the catchments. Licensed quantities for abstractions from both ground and surface waters are included.

Table 2.3 Total annual licensed quantities for water abstraction from the catchments of the Rivers Wensum, Bure and Nar during 1991.

	ANNUAL LICENSED QUANTITY (TCMA)		
USE CATEGORY	River Wensum to Costessey	River Bure to Horstead	River Nar to Marham
Public water supply (PWS)	3764 (*)	2845	2554
Sand/Gravel works	1329	0	60
Agriculture: general	1126	379	200
Agriculture: spray irrigation	3876	3242	3494
Industry	1423	1	56

(*) Surface abstraction for PWS moved to a point above the Costessey gauge in 1987. Its present effect is along only a short stretch of River within the study area and is not included in this table. This treatment is consistent with other sections of this report. The PWS abstracted at Belaugh on the Bure is not within the study area.

The actual amounts abstracted are not necessarily the same as the total licensed quantities. For most water uses, percentage uptake does not vary greatly from year to year. The exception to this is uptake of amounts licensed for spray irrigation. Here, water use varies greatly according to weather conditions.

During the unusually wet summer of 1987, uptake for spray irrigation in the study area was approximately 12% of the total licensed quantity. This compares with a figure of 64% for the drought year 1990. In contrast to public water supply, which is largely returned to rivers as treated effluent, zero return from water used for spray irrigation is assumed. Since spray irrigation is potentially the largest actual use of water in the study catchments, variation in loss of resource between different years can be dramatic. The difference in the actual amounts abstracted from the Bure for spray irrigation between 1987 and 1990 was 1700 TCMA. This amount therefore represents the size of water loss from the Bure catchment due to spray irrigation during a drought year.

Abstraction for spray irrigation is a very public spectacle with abstractors spraying plumes of water over field crops. Delivery of water for other purposes is much more discrete. Of all comments about the Rivers' environment made during this project's consultation process, 27% related to river flows. Most parties held that, at the time, abstraction for crop irrigation compounded the effects of low rainfall on flow. During dry summers, which are often times of water shortage, many perceived large-scale resource losses at a time when the public are asked to conserve water. Some consultees viewed a change in overall flow as a longer-term process associated with groundwater abstraction and drainage of wetlands. Spray irrigation is certainly the largest use of water in all the study catchments and is wholly consumptive; the scale of the effect of abstraction on flow volumes and flow regimes during drought and over the longer-term, is the subject of the catchment-scale analyses reported in Chapter 4:1.

Quality of river water is controlled naturally by the geology, soils and vegetation of catchments. Although the catchments of the study Rivers are much influenced by humans, the Rivers should achieve and maintain **National Water Council** (NWC) -see footnote- river quality Class IA along most of the waterway. Class 1B is a realistic expectation for naturally slower-flowing reaches which are further downstream. Both Classes 1A and 1B can support diverse biological communities, though Class 1A will represent faster-flowing and more oxygenated water which carries little suspended material. At best, Class 1A waters will support breeding populations of trout. Class 1B is more likely to support coarse fisheries.

Artificial influences on the water quality of the study Rivers are largely from agricultural and sewage effluents with a few contributions from food processing industries. Occasionally, acute toxicity occurs after pollution incidents involving spillage of liquid ammonia. Discharges of effluents from point sources are controlled according to their compliance with NRA consents which detail limits to the quality and quantity of material that can be released legally. These consents take account of both the quality of the receiving water and its quantity and residence time because these determine scales of dilution. Results from NRA routine monitoring of treated effluents from all discharges are available from the Water Resources Act 1991 Register, which may be inspected by the public at the NRA regional headquarters at Peterborough.

The availability of phosphorus for uptake by water plants and algae sets the fertility of river water in the study area. Generally, the biological communities of the study Rivers are likely to become less desirable as water fertility increases. Treated effluent from sewage treatment works (STWs) contains phosphorus which is discharged into rivers, diluted, sedimented, taken up by plants or washed further downstream. Despite its ecological importance for plants, NWC river quality criteria do not include phosphorus. Changes in phosphorus concentrations since recording began for the study Rivers in the mid 1970s, are shown in Chapter 3. As a reference point, the natural background concentration of total phosphorus is likely to be less than or around $0.05mgl^{-1}$ which means that their natural fertility is moderate to high. Concentrations greater than $0.10mgl^{-1}$ are very high and usually indicate contamination by sewage effluents.

Concentrations of oxygen in water and underlying sediment are the major influence on the animal community. Oxygen concentrations increase with increasing flow velocity and are also affected by biological oxygen demand (BOD). A high oxygen demand by bacterial decomposers of organic material (either natural or suspended in effluents) removes oxygen otherwise available to fish and invertebrates. The upstream reaches of the study Rivers have a naturally low BOD of about $2mg\ O_2l^{-1}$ over 5 days. This value, which is similar in downstream stretches which are secluded from sewage treatment works, also gives an approximate background against which the scale of organic enrichment can be measured. Effective sewage treatment should reduce the BOD of crude sewage from around $600mgO_2l^{-1}$ to about $30mgO_2l^{-1}$, or less, in the final effluent.

During 1990, the National Water Council scores for the study Rivers all fell within Class 2 or above. The upper part of the Nar and most of the main channel of the Bure are classed as IB, and the lower Nar and most of the Wensum as 1A. The tributaries almost invariably have lower water quality than the main channel. None reached 1A status; most were 1B with short stretches of Class 2 water in the upper Nar and on the River Tat, which is the headwater tributary of the Wensum.

footnote: The NWC system is described in Appendix 4.

NWC Class 2 has a low threshold for BOD (<9mgl-1) and dissolved oxygen (40% saturation). Waterway falling into this category is likely to be slow-flowing with turbid water, underlain by organic sediments with few water plants and only invertebrates tolerant of low concentrations of oxygen. This is typical of the ecology of stretches of river which receive discharge from STWs. The Class 2 status of the top part of the Nar is obviously connected with effect from Litcham STW.

On each study River, biological oxygen demand, dissolved oxygen and ammonium concentrations have been measured at up to five stations since 1966. These routine monitoring stations are not necessarily close to effluent discharges. Although soluble phosphorus has been measured since 1975, total phosphorus, which includes algae, detritus and soil particles washed in from the catchment, has only been monitored on the River Bure since 1986 and at Marham on the River Nar since 1989. Variables of water quality which include major ions, trace elements, detergents and pesticides have been measured much more recently and only at harmonised gauging stations.

Table 2.4 shows how some features of water quality in the Rivers vary over one year and between upper and lower reaches. Of the variables shown on the Table, BOD, total phosphorus and water temperature are the most likely to affect the biology of the Rivers.

Table 2.4 Annual ranges of measures of water quality in upstream (u/s) and downstream (d/s) sites in the study Rivers during 1990. Values are in μgl^{-1} for phosphate and ammonium and mgl^{-1} for other determinands (there are 1000μg to 1mg). n.a.=not measured

	River Bure		River Nar		River Wensum	
	u/s	d/s	u/s	d/s	u/s	d/s
BOD	1-2.6	0.9-3.1	1-6.1	1.6-3.2	<1-3.0	<1-3.3
Orthophosphate	12-145	5-27	111-376	<60-140	<60-308	280-661
Total-P	46-273	26-7000	n.a.	n.a.	n.a.	n.a.
Ammonium-N	<40-240	<40-345	<40-160	<40-470	<40-106	<40-230
Oxidised-N	6.9-15	3.0-10	0.6-7.0	0.9-8.1	6.0-9.9	2.0-8.4
Chloride	30-79	43-81	35-50	33-49	30-41	44-55
Temperature (°C)	5.7-17.0	4.5-20.1	3.5-19.0	3.5-18.5	4.8-18.0	7.0-24

The values for nutrients show clearly that water receives effluents, though, except in the Nar, values for BOD are fairly low implying that the scale of dilution is generally high. Even the lowest BOD recorded in the Nar (at West Lexham) is much larger than the natural BOD of chalk streams. Water temperature is included in Table 2.4 because it is a key variable for fish populations. Temperature should be lower and more constant in rivers with high contributions from groundwater. The small difference in temperature between the upstream and lower site (King's Lynn) on the Nar is therefore surprising.

Only 4% of the comments made by project consultees involved water quality. Research on public perceptions of river quality and how this compares with actual chemical quality has shown fairly good agreement (House and Sangster 1991). However, because of the ecological importance of changes in water fertility or the frequency of pollution events, the quality record has been examined so that the relative significance of chemical and physical influences on the study Rivers can be scaled.

CHAPTER 2: Section 6. Introduction to Channel Dimensions and Channel Sediments.

Section 6.1 Channel Migration.

The Rivers of north Norfolk drain a lowland area where only small parts of the catchments are above 100m OD. The rivers have low gradients and meandering valleys draining areas of sandy and silty Quaternary and recent deposits. The Bure and the Wensum have strong meander patterns though the Nar has a much straighter course, particularly above Narborough. None of the Rivers are expected to be creating new meanders today. The courses of the Rivers are shown on the introductory map. Both the Wensum and the Nar follow large valley meanders, though channel migration does not occur today. Because of this, both Rivers are considered 'underfit' by geomorphologists (Richards, 1982). Their present valleys are thought to be either infilled fossil estuaries or, and more likely, to have been carved by glacial meltwater streams. These meltwater streams had much greater discharges than today's Rivers and this explains why the Rivers are small compared to the size of their valleys. The Nar valley has long attracted the interest of Quaternary geologists because glacial and interglacial climates can be inferred from its present-day features. The valley has been described in these terms by West and Whiteman (1986). Today, the study Rivers have very low stream power which makes natural bank erosion, channel migration and the formation of new alluvial meanders unlikely.

Section 6.2 Channel Widths and Water Fill.

Perception of low-flows is shaped largely by the water level in river channels and the proportion of the channel which is occupied by water. Over one quarter of the comments made by this project's wider consultees noted low-flows and around one fifth of comments made by consultees involved channel width. Many project consultees have reported decreases in channel width. Analyses of change in channel width have therefore formed part of the project. Relatively few consultees made explicit mention of changes in the proportions of sediments in the Rivers.

Estimates of widths from the NRA's river environment surveys (REDS) of 1990 are shown in Figure 4. Comparable information about the Nar is not available. Data for the River Bure are available for between 20km and 40km downstream. Figure 4 also shows widths of the wetted perimeter during 1990. These are the widths of the water surface which occupied the channel. The water fill, which is the percentage of the bankfull width occupied by water, increased with distance down the Bure though did not in the Wensum. In both Rivers, the wetted perimeter during 1990 was usually between 60% and 80% of the bankfull width. Variations in water fill between Rivers or with distance downstream may be due to variations in the cross sectional shape of the channel or could have been due to low flow. Information on water fill in both the Wensum and Bure is certainly consistent with this.

Since the REDS survey, the bankfull widths of the Wensum have been re-measured by the NRA in a much more detailed and accurate ground survey which was carried out during 1993, Figure 5. Figure 5 shows that generally the width of the Wensum varies on a local scale much more than with distance downstream. Local and large variations in bankfull width are also a marked feature of the River Bure.

For both of the Rivers, mills have been the major cause of local variations in channel width. Millponds immediately above sluice gates are three to five times greater than the widths of plunge pools beneath the gates. An example of this is at Bintree Mill on the upper Wensum, where the Mill pond is 25m wide and the width of the plunge pool is less than 5m. The influences of past river engineering for water milling are described in Chapter 4.

Section 6.3 Channel Depths.

Recent information on depths along the long profiles of the Rivers Bure and Nar is not available. The level against Ordnance Datum of the bed of the Wensum was surveyed during 1993 and the data are shown in Figure 6. In the upper part of the River around Sculthorpe Mill, the River bed is 40m OD; at two points is very slightly concave, which indicates slightly greater downcutting of the River in the upper reaches and greater sediment deposition in lower reaches. It is a long profile typical of rivers flowing in an area of low relief (Richards, 1982).

Between mills, each section of the Wensum appears to act as a separate system independent of the dynamics of the entire River. The overall pattern shows that immediately below mills, gradients are steeper than above the next mill. This is a partially engineered effect, though it is also due to erosion of a lower bed because of higher flow velocities below mill gates. In mill ponds above sluices, gradients are reduced slightly and the channel is wider.

Section 6.4 Sediments in the River Channels.

Sediments and their relative distribution within the channels of the Bure and Wensum were described in the 1990 REDS survey. Visual estimates were made for each of the 500m stretches surveyed. Table 2.5 summarises the information.

Table 2.5 Average % cover by silt, sand and gravel in the channels of the Wensum and the middle Bure during 1990.

	River Wensum Mean % cover n=38	The River Bure below Ingworth Mean % cover n=96
Silt	49	23
Sand	25	52
Gravel	26	25

The average proportion of silt in the Wensum was about 50% during 1990 and, over the 96 stretches surveyed, ranged between 0% and 100%. The percentage cover by gravel varied between 0% and 90%. Overall, the proportions of the different sediments in the Wensum did not vary with distance downstream. In the Bure however, the proportions of silt and sand in the channel increase significantly from Ingworth to the lower limit of the study area at Horstead Mill.

CHAPTER 2: Section 7. Introduction to Biology.

The present biological status of the study Rivers reflects conditions during drought, although low flows over at least the last decade have been supposed a major influence on riverine biology. The context of the project has largely been set by public perception of declines in fishery status and habitat quality that are thought related to artificially low flows. 21% of all the comments made by project consultees related to the fishery. This was second only to the emphasis given to river flows. Many comments linked the two.

The wider biological interest of all three study Rivers is the broad range of communities that are represented. Lower reaches are dominated by coarse fish (mostly roach, pike and eels) and plants common in moderately fertile water (water lilies, pondweeds, water milfoil and filamentous algae). These lower stretches generally have more species of water plant than many other fenland rivers. Where the upper parts of the Rivers are narrow, meandering and springfed there are low densities of native brown trout and higher densities of stocked trout and dace. Water crowfoot, water starwort and pondweeds may occur, though water plants typical of fast-flowing chalk streams are generally represented poorly. The distribution and species composition of the fish community has been influenced by introductions (trout, chub and barbel) and stocking (roach and dace) in both the upper and lower parts of the Rivers.

Both the Wensum and the Nar are designated River SSSIs, with part of the River Nar classed as a high quality chalk stream (Holmes et al., 1991). Despite their designated conservation value, naturalness is not a realistic expectation for the biology of the study Rivers. This is because their channels, flow and sediment transport regimes have been regulated for at least 900 years by water mills. The influence of working water mills on the river environment has been to alternate upstream and downstream type biological communities over distance downstream. This is reflected by benthic invertebrate communities, and, more recently, by fish communities. Invertebrates and fish do not show classic downstream continua from faster-flowing headwaters to slower, more silty and less oxygenated waters further downstream. The pattern is much less organised than this and reflects both artificial and more natural influences on the Rivers.

Over recent decades, riparian owners, managers and other river users have perceived changes in both river plant and fish communities. Of the comments on the fishery made by project consultees, most emphasised decreases in the density, condition or distribution of coarse fish, particularly roach. Catches of trout in all three Rivers are thought to have declined over the last few years. The reasons given involve flow, water quality and competition between game, coarse and introduced fish. 13% of the comments suggested declines in the biomass and species richness (which is the number of different species) of water plants. These were associated with river management, flow and water quality. The disuse of water mills featured very strongly in reports of change in riverine biology.

The present status of water plants in most of the study area is consistent with rather slow-flow and high fertility. Table 2.6 classifies a downstream series of river environments (Holmes, 1983) for each of the study Rivers and shows which water plants were dominant during summer 1990. Filamentous algae, usually *Enteromorpha*, dominate much of the River Wensum. The distribution of water crowfoot is restricted to the middle reaches of the River Nar (*Ranunculus pencillatus subsp. pseudofluitans*) and to fewer sites on the middle and lower Wensum (*Ranunculus aquatalis*).

Table 2.6 Downstream sequences of river environment and the dominant water plants identified in them during NRA biological monitoring (Bure and Wensum) and during the 1990-91 English Nature survey of the Nar.

	Dominant water plants in July 1990
River Bure	
Springfed in a clay catchment	
Small chalk stream Small chalk stream	*Callitriche Fontinalis*
Fen river	*Callitriche Myriophyllum Potomogeton Zannichellia*
Canalised, fenland clay, sand	*Myriophyllum Elodea*
River Nar	
Springfed in a clay catchment	Dry, no plants
Small chalk stream	*Callitriche Nuphar lutea Hippuris vulgaris Ranunculus*
Small chalk stream	
Fast-flowing on mixed substrata	*Callitriche Ranunculus Hippuris vulgaris*
Highly managed on unstable sand	*Callitriche*
Fast-flowing on mixed substrata	*Nuphar lutea Lemna Callitriche*
River Wensum	
Springfed in a clay catchment	*Callitriche Myriophyllum Potomogeton*
Fast-flowing, mixed substrata	*Enteromorpha Potomogeton*
Fen river, calcareous	
Highly managed, unstable sand	*Enteromorpha Myriophyllum Potomogeton*
Fen river, calcareous Fen river, calcareous	*Enteromorpha Myriophyllum Potomogeton*
Fast-flowing, mixed substrata	*Enteromorpha Myriophyllum Ranunculus Potomogeton*
Fen river, calcareous Fen river, calcareous	*Fontinalis Enteromorpha Myriophyllum*

The invertebrates recorded by the NRA during 1990 have been ordered into communities using TWINSPAN analysis. Overall, the invertebrate communities of the three Rivers were similar. The three Rivers together supported 71 families of invertebrates which divided into two separate communities that were represented fairly equally in each River. There is an ecological basis for the difference between the two communities. Community 1 is typical of faster-flowing waters and is dominated by insect larvae. Community 2 contains similar animals as well as some families which are more typical of slower-flow.

The fish community of each of the study Rivers has been described since 1983 by three intensive electro-fishing surveys. The survey of 1990 shows that average fish biomass is about $10gm^{-2}$ in the upper Wensum and $25gm^{-2}$ in the lower reaches. A **Class A fishery** -see footnote- supports a total biomass of more than $20gm^{-2}$. Biomass is, to a large extent, supported by stocking by the NRA: during 1988, for example, over 15,000 roach were stocked at Hellesdon Mill. Growth rates for roach are higher than national averages set by Hickley Dexter growth curves (Hickley and Dexter, 1979). The average density of introduced chub in the lower River Wensum is about $11gm^{-2}$ with strong year classes at six year intervals. Barbel have been introduced to a restricted area in the lower River though little recruitment to the adult population has occurred since 1976. Brown trout represent 3% of the fish stock in the upper River. Eels dominate the fishery of the upper Wensum (45% of the total biomass), the upper Nar (62%) and the River Bure below Aylsham (54% of the biomass).

The River Nar supports an average fish biomass of $22gm^{-2}$ with fast growth rates of roach, trout and dace. Dace represent 2% of this biomass. Roach account for 20% of the total biomass, though during 1990, were found aggregated at a single downstream site. The Nar has a reputation as a brown trout fishery which supports native fish. During 1990, trout were found at all six upstream sites and the average trout biomass in this part of the River was $3gm^{-2}$.

The upper reaches of the River Bure are managed as a trout fishery. Below Aylsham, the River is managed by riparian owners for coarse fish. Trout represent 59% of the average fish biomass of $13.25gm^{-2}$ in the upper River. The lower River supports $10gm^{-2}$ and is dominated by eels and pike. The growth rates of trout and dace are above average, though the growth rate of roach is below the average for the species.

The fishery status of the study Rivers depends upon climate, the quality and availability of spawning habitat, of food resources and of predator-free space. These aspects of the river environment involve: water plants as spawning habitat for coarse fish; clean gravel as spawning habitat for trout and barbel; invertebrates as a major food source and habitat complexity ("cover") as refuge from predatory pike, trout, chub or perch.

Most of the biological information used in this study is from routine monitoring or from special studies carried out by the NRA and its predecessors. Generally, quantitative information given in standard units of density or abundance for precise sites has only been available since the 1980s. Site continuity is poor for invertebrates because monitoring effort has shifted from a larger number of sites in the early 1980s to more intense seasonal sampling of fewer sites. Before 1990, the amount of information collected on water plants was small and restricted to a few special surveys and casual observations. Plant abundances are usually noted during routine biological sampling, though biological monitoring focuses largely on benthic invertebrates and does not involve skilled plant identification or accurate recording of percentage cover. Analysis of the water plant community made for this study therefore relies upon species lists only.

footnote: explanation in Appendix 4.

CHAPTER 2: Section 8. Soils and Land Use in the River Catchments.

Section 8.1 Soils Types and Land Capability.

The soils of the study area are sandy peats, loams or silts which generally have a high potential for arable agriculture. The soil associations of the area and their suitability for agriculture are detailed in Appendix 1. The key features of the soils which may influence the study Rivers are their permeability, the type of farming which they are capable of supporting and their susceptibility to erosion.

Although influenced strongly by soil texture, permeability is determined largely by underlying glacial deposits which may be clays, sands or gravels. Soils of the river valleys, particularly in the Wensum, where coarse loams occur on clay, are poorly drained. These areas tend to be used for grazing pasture. Where the soils have been drained for arable cultivation, materials dissolved in drainage water are likely to percolate easily to river channels. The upland soils, though relatively fertile, tend to be more sandy and so need to be irrigated to reach their agricultural potential.

The pattern in the study area is thus one of moderate to fairly high natural soil fertility. Differences in the permeability of underlying glacial deposits mean that the distribution of underlying deposits has a large effect on land use on the catchment. Cultivation of soils above sands and gravels implies a high demand for irrigation water, whereas soils overlying clay need to be drained.

The study catchments lie within the main arable area of England and Wales and irrigation and drainage have become a major feature of their use for agriculture. During the 1980s, 78% of Norfolk was in agricultural use, 6% was settlement and 5% woodland. Roads, airfields, open water and waste ground make up the remainder. These data suggest that agriculture in the catchments, and particularly in the River corridors, is likely to have a large effect on river environments. This is because rivers are the receiving waters for materials dissolved and suspended in water from their catchments.

Soluble agricultural effluents are likely to leach readily from ploughed land in the study area, particularly where the soils are sandy. If these areas are underlain by sands and gravels, the likelihood of percolation of effluent into groundwater is high. This is a particular, and predictable, problem in Norfolk. Where unimproved pasture borders waterway, soluble materials tend to be retained in the unploughed soils. The soil types around the tributaries of the upper Bure and in the lower Nar are particularly susceptible to erosion. Any changes in land use from meadow to arable cultivation therefore imply increases in sediment loading to rivers and their tributaries. Continuous cover by pasture grasses tends to preclude wind or gully erosion of exposed soils.

The land capability of the study area for agriculture is high and has been exploited through widespread drainage works. These are on both field and much larger scales. Large scale works have involved widening, straightening and deepening of tributaries and parts of the main River channels. The effect of these engineering works is to simplify biological habitats. Engineering works have also been carried out for flood alleviation and, in the past, to allow navigation of cargo boats as far upstream as Aylsham on the Bure and Narborough on the River Nar. These past activities reflect the agricultural history of the area.

Section 8.2 Land Uses in the River Corridors.

Land uses alongside the Rivers Bure and Wensum have been classified from 1:10,000 colour aerial photographs taken during 1988. A GIS system has been used to digitise ten land uses (Table 2.7) to within a ground resolution of 50-100m on both sides of the River channels. The number of categories has been simplified for identifying the scale of changes in land use which are reported in Chapter 3, Section 6.

Table 2.7 Land use categories for GIS classification.

1. Arable on both banks
2. Meadow on both banks
3. Woodland on both banks
4. Arable and meadow on the opposite bank
5. Arable and woodland
6. Meadow and woodland
7. Housing on both banks
8. Arable and housing on the opposite bank
9. Meadow and housing
10. Woodland and housing

Table 2.8 shows the current (1988) pattern of land use in the corridors of the waterway of the Rivers Bure and Wensum. The waterway includes both the main channels and their tributaries.

Table 2.8 Land uses within 50-100m of the waterway of the Rivers Bure and Wensum during 1988.

	% of the length of the waterway	
	River Bure	River Wensum
Arable	30.5	29.3
Pasture	44.1	52.6
Woodland	23.3	16.3
Housing	1.8	1.7

Land use in the River corridors is very different to the pattern over Norfolk as a whole. Approximately half of the land next to the study Rivers is pasture, compared with less than 20% of land in the rest of Norfolk. The main channel of the Bure and its tributaries is largely uncultivated: about 44% of the waterway is either bordered by pasture/rough pasture or heath. The frequency of flooding in these areas probably precludes arable cultivation. Arable land accounts for about 30% of the land use over all the River corridor and woodland, for about 23%. Some sites on the main channel are wooded on one side only. Large proportions of the banks of the major tributaries, such as Scarrow Beck, are under arable cultivation within 50-100m of the channel. Woodland is also common on the margins of the tributaries, for example on King's Beck near Gunton Park. Around 2% of the length of the Bure system is bordered by buildings.

The main channel of the Wensum is also dominated by meadow on its margins, again presumably because of waterlogging and a risk of flooding. Approximately 29% of the land bordering the system is arable, 53% is meadow, about 16% is woodland and 2%, housing. The intensity of arable farming appears to be less on the margins of the Wensum than on the Bure, although the upper reaches of all the tributaries are dominantly arable on both sides. The more restricted distribution of arable land in the corridor of the Wensum probably reflects the poorer agricultural quality of the valley soils. The risk of flooding may well be greater in the Wensum valley because of the clayey soils.

Changes in land use in the River corridors between the 1930s and 1988 and the implications of change for soil erosion are given in the Section on land use in the next Chapter of the Report. Changes in the intensity of surface drainage networks between 1988 and the 1930s are also described.

CHAPTER 3: CHANGES IN THE RIVER ENVIRONMENTS

CHAPTER 3: Section 1. Hydrology.

The results given in this Chapter show if significant changes in features of the Rivers have occurred since the beginning of data collection. In this Section, data on rainfall and flow are used to look for long-term changes in flow behaviour, which is influenced by catchment characteristics, and in total flows. The effects of abstractions and discharges are dealt with in the next Section on water use. The questions which are addressed here are:

> Has the relationship between gross rainfall and effective rainfall changed ?
>
> Has the relationship between rainfall and flow changed ?
>
> Has catchment land use change altered flow response ?
>
> Have the characteristics of flow changed ?

Section 1.1 Background to Testing for Changed Flow Behaviour.

All flow in a natural system comes from precipitation falling over the catchment. There are, however, time lags between rainfall and the response in rivers. These are due to the storage properties and permeability of catchment soils and geology.

In the longer-term, flow (Q) is given by:

$Q=P-E-Na$ where:
- P is precipitation
- E is evaporative loss to the atmosphere
- Na is net abstraction from surface and ground water

In the shorter-term, flow (Q) is given by: $Q=P-E-Na \pm \delta S$
δS is the net change in catchment storage during the shorter-term.

Surface runoff and baseflow both contribute to riverflow in the study area, though they follow very different routes to the river channels. Detailed analyses of the shape of river hydrographs can indicate the relative importance for riverflow of baseflow and of surface runoff, including the water which permeates soils. The approach has been used here to show if the contributions of surface and of baseflow have changed over time. Rainfall which drains into tributaries and drainage networks or which permeates soils does not run directly to the river channel. The time lags between rainfall and its eventual contribution as baseflow, are even longer. The relationships between rainfall and flow are therefore complicated. Catchment storage may also rise and fall with time. This further compounds the complexity of the relationship between precipitation and flow.

1.1 (i) Relationships between rainfall and flow.

Relationships vary over both the short and long-term. Although it is difficult to define exactly what these time scales are, the difference is approximately between seasons and, over the longer-term, periods of years. Soil moisture status in the early spring, is usually at or around 'field capacity' following winter precipitation. This means that catchment storage in the soil is around its theoretical maximum. The soil's full reservoir of soil moisture is then subject to the losses through evaporation and transpiration, less the gains from rainfall throughout the growing season. For catchment soils therefore, the water year (April to March) becomes the transition from shorter to longer-term.

Following winter recharge, groundwater levels are usually at their annual maximum. However, these can vary markedly about the mean depending on net recharge, not just over one, but several years. In effect, groundwater levels can remain low during several years of below average rainfall. Conversely, they can remain high during wetter periods. The baseflow component of flow, which is important in sustaining summer flows, varies with groundwater levels and so can also fluctuate on a longer timescale. The transition from shorter to longer timescale here, implies a period of several years.

1.1 (ii) The difference between gross and effective rainfall.

Only part of gross precipitation subsequently becomes streamflow. This is because gross precipitation is depleted by any prevailing and stored evaporative demand. Rainfall normally satisfies soil moisture deficits, which may accumulate over several years, before it can either become runoff or enter groundwater systems. The net amount which becomes available is the effective rainfall.

It is the amount of effective rainfall which determine long-term gross flow volumes. The rates of flow are determined by the intensity of the rainfall event and the paths taken by the effective rainfall to reach the river channel. Relationships between gross and effective rainfall may therefore be affected over time by changes in soil moisture deficit in the catchment.

1.1 (iii) The effects of water resource management.

In areas where resource development involves large scale import or export of water or a large consumptive use of water (spray irrigation, for example), the effects of rainfall on water volumes or rates of flow will be affected significantly. A detailed assessment of the effects on flow of abstractions and discharges in the study Rivers is made in the next Section. Work reported in the present Section is concerned with the influences of rainfall and catchment characteristics on flow.

Section 1.2 Methods used to detect Change in Flow Behaviour.

Change in flow behaviour can have two explanations. Firstly, any long-term change in the quantity of effective rainfall received can affect flow volumes. Secondly, any mechanism which interfered with the paths taken by effective rainfall to become flow can affect the temporal distribution of flows. Flow behaviour can be predicted by looking at the distribution of effective rainfall and this is the approach used here.

The two main explanations for any change in effective rainfall are:

- Change in gross rainfall received (due to changes in climate)
- Changed loss to evaporation (due to changes in catchments or seasonal distributions of rainfall)

1.2 (i) Changes in flow due to climate.

Gross rainfall data for the study area have been available since before 1930. Thirty-year rainfall is the standard period for data analysis by the UK Meteorological Office. Catchment and other areal time-series with relevant statistics have been produced for the period 1930-92. This has enabled change in gross rainfall to be tested.

Finer details of rainfall data are available (British Rainfall Organisation, later the UK Meteorological Office publications) either in annual (January to December) or monthly form. From these, catchment/regional series have been produced back to 1930 both on an annual, and, seasonal basis. Only for those gauges which have always been reported in monthly form could water year or seasonal series be produced. Summer season includes the months of April to September, and winter, the months of October to March inclusive. Methods used to produce the rainfall series are given in the Appendix.

Effective rainfall has been more difficult to quantify. Monthly rainfall data have been used to infer the distribution of effective rainfall since 1930. In addition, the UK Meteorological Office (Meteorological Office, 1982) have produced areal data from MORECS method which is based on meteorological data since 1961. However, an unchanged distribution of seasonal rainfall does not guarantee that evaporative loss is unchanged.

Since flows are a function of precipitation, and therefore also the variability of this over time, long-term flow data have been tested statistically for any changes with time. The relatively recent nature of flow gauging in study catchments, generally since about 1960, does not allow the calculation of, for example, a series of thirty-year-mean flows.

1.2 (ii) Changes in flow related to changes in catchment land use.

Land use change has occurred in the study catchments. The scale and nature of changes is described in Chapter 4.6. Intensification of agricultural production, particularly since around 1940 has involved the increased use of inputs to enhance yields. Increased inputs include use of: fertiliser and other chemical treatments; heavy machinery; land drainage systems; and crop irrigation. The potential effects of catchment modification due to the intensification of farming would be largely in the direction of altering the lags between precipitation and flow.

Any mechanism which modifies infiltration characteristics and thus, the relative size of groundwater to other components of flow, has the ability to alter the seasonal distribution of flows. For example, if land use change produced a less permeable soil surface, then direct runoff would increase at the expense of baseflow, making high-flows higher and low-flows lower. Similarly, increased use of land drainage systems, for example, could well affect the paths or time taken for effective precipitation to reach the river channel and so affect the distribution of flows.

A possible exception to the effects of farming change on flow response to precipitation would occur if higher yields transpired more soil moisture. By reducing effective rainfall through higher soil moisture depletion during the growing season, effective rainfall and so gross flows would be reduced. This mechanism could operate within a stable longer term seasonal rainfall regime.

The questions addressed here are therefore:

- Has there been a change in the temporal distribution of flow ?
- Has there been an increase in evaporative loss to reduce gross flows ?

Riverflows have been reconstructed using gross rainfall data to test the constancy of the relationship between rainfall and flow. Mathematical modelling, which uses monthly increments of gross rainfall and mean seasonal loss to evaporation, is described by Jones (1984). The use of mean seasonal evaporative losses, which are subtracted from gross rainfall amounts, overcomes the lack of historic effective rainfall data.

By calibrating the model using data from the earliest period, the model can be run forward to predict flows from gross rainfall series. Any systematic divergence between predicted and observed flows is an indication of a changed relationship between rainfall and flow.

The calibration of any such model needs gross rainfall and flow data for a lengthy period which represents fairly the natural variability of climatic influence. In practice, optimal calibration is constrained by the availability of such data. In addition, wherever artificial influence in the form of abstraction and discharge have any significant effect on flows, naturalisation is a pre-requisite to calibration.

1.2 (iii) Change in the temporal nature of flow.

Rainfall-runoff modelling also allows testing for the longer- term aspects of the temporal distribution of flows. For example, if land use or farming change affected significantly the baseflow component of flow, there would be a change in the temporal distribution of flows on a seasonal level. This may be seen as a systematic divergence between predicted and observed monthly flows.

To complement and further test for change in the relative contributions of baseflow and surface runoff, a computerised technique has been used to estimate baseflow and non-baseflow components of flow and to compare them volumetrically.

1.2 (iv) Changes in annual flows since 1960.

To test for fluctuation in flow since 1960, standard measures have been used to describe the gauged daily-flow series for the study Rivers. From the statistics produced, a balanced view of the fluctuation of flow over the last three decades is obtained. In addition, any apparent trends with time can be used as indicators of change due to catchment modification. Conversely, lack of trend implies no change.

1.2 (vii) Wider perceptions of fluctuation in weather and flow.

Despite the distinction between artificially caused change and the natural variation possible within an unchanged climatic regime, it is necessary to connect the variability of weather patterns and their effect on river flows with human perception of what is normal.

The natural variability of weather pattern does not necessarily appear randomly on a yearly basis. Weather pattern trends often span several years and may have a return period of many decades. Inevitably, human perception of normality is coloured by the experiences of a finite lifetime. It seems likely that human perception with regard to changed weather-related variables will be heavily biased.

The description of flow data since 1960, using the various measures, should allow a balanced impression of the fluctuation of flow during what is a sizeable portion of living memory, to be formed.

Section 1.3 Results and Discussion of the results of Flow Analyses.

1.3 (i) Annual and seasonal long-term gross rainfall.

Flows are influenced by variations in climate and can be set in a wider context of natural variation in rainfall. This variability is illustrated in Figure 7 which shows that prolonged trends do occur.

There is no evidence of significant change in gross rainfall, since the 1930s, when rainfall is described in terms of thirty-year-means (Table 3.1). The statistics shown describe catchment series and are based on calendar years.

Table 3.1 Thirty-year-mean areal rainfall for the study catchments.

PERIOD	RAINFALL (mm)		
	Wensum	Bure	Nar
1931-60	677	677	678
1941-70	673	677	681
1951-80	678	668	694
1961-90	683	669	704

Figure 8 emphasises the variability of gross annual rainfall with gauged runoff for the Wensum above Costessey Mill. Units are millimetres of water falling on the catchment and time increments are water years. Gross rainfall values vary between 397mm in the year 1947-48 to 890mm in 1968-69. The mean value is 648mm with a standard deviation of $\pm$102mm. Thus shorter term variability within what appears to be an unchanged longer-term series is evident.

The correlation between gross rainfall and flow is very close. This is despite the fact that it is the amount of effective rainfall which is significant. For the period 1960/1-1991/2, the correlation coefficient was $r=0.83$, $p< 0.001$). However, the use of water year increments does favour correlation.

1.3 (ii) Long-term effective rainfall.

The possibility that the seasonal distribution of gross rainfall and thus, the proportion of effective rainfall has changed, has been tested by statistical analysis of long-term seasonal gross rainfall. If, for example, more of the annual rainfall were to fall in the summer season, it may be expected that loss to evaporation would be higher reducing overall flows.

Table 3.2 gives thirty-year-means for winter and summer gross rainfall in the study area. For the four periods, the mean seasonal rainfall is remarkably similar. This shows that seasonal distribution of gross rainfall has not changed.

Table 3.2 Thirty-year-mean winter and summer rainfall.

PERIOD	RAINFALL (mm)	
	Winter	Summer
1931-60	335	312
1941-70	332	325
1951-80	335	315
1961-90	333	317

There was a close correlation between gross rainfall and effective rainfall (MORECS data) over the period 1961/2 to 1991/2, $r=0.86$ $p<0.001$. The relationship is shown in Figure 9. Although the period of analysis is much shorter than for seasonal gross rainfall (1930-92), the close relationship between gross and effective rainfall on a water year basis suggests that, since 1961 at least, effective rainfall varies essentially with gross rainfall.

Even if seasonal gross rainfall is unchanged in the long term and effective rainfall fluctuates with gross rainfall, there is still the possibility that the proportion of gross rainfall that becomes effective rainfall has changed with time. This situation could arise if, for example, change of land use produced higher loss to evaporation.

Investigations by Olson et al.(1964) and Brown (1971), over many years, have suggested that the intensification of agricultural production has increased evaporative loss via increased vegetative transpiration. Higher agricultural inputs, mainly in the form of nitrogenous fertiliser, enables crops to establish more extensive root systems which are able to extract soil moisture more efficiently.

Brown (1971) found that the addition of 94 kg/N/ha to winter wheat, on soils with low fertility under rain fed conditions, produced an end-of-season soil moisture deficit 84 mm higher when compared with plots receiving no added nitrogen. Olson et al. (1964) note a less dramatic but still significant increase in soil water consumption with different crops at around 25mm.

Certainly, the use of nitrogen fertiliser has increased dramatically since the early part of this century. On a national scale, Figure 10 shows large increases in fertiliser use since 1910. It is not possible to judge the point where a threshold addition would have increased growing season transpiration at the expense of riverflow. It is feasible that such a point was reached before 1960, and thus before the availability of gauged flow data.

The hypothesis that crop fertilisation may have reduced flows is not tested easily. It is however, a plausible mechanism towards reduced flows within a long term stable climatic regime. An increased summer soil moisture deficit of 25mm over the area would reduce flows by about ten percent, where mean annual runoff for the study area for the period 1960-92 was 230mm.

The use of rainfall/riverflow modelling has a place here. This is because it helps to test further the relationship between gross and effective rainfall and for more than just the recent period. Its use is justified despite not taking account of artificial influences on flows during the calibration period (1964-74) which could invalidate model projections beyond that period. The naturalised flow record (see Chapter 4) for the Wensum above Costessey has shown that net abstractions were very small during the 1960s and early 1970s. On a seasonal basis, the maximum effect on flows over this period was estimated to be two percent. The flows used during model calibration were therefore, for all practical purposes, natural.

For the post-calibration period, that is the years 1975-92, the model has been run forward to predict flows from gross rainfall. A close relationship between observed and predicted flows is taken to mean that model calibration relationships between rainfall and runoff are valid. This is evidence of an unchanged relationship between rainfall and subsequent flow response, on an annual down to a monthly basis.

Following the naturalisation of observed flow data, (using 'lost-flow' series that are described in Chapter 4), predicted and observed monthly flows have been compared using the same methods used by Jones (1984). Figure 11 shows predicted and observed values for flow at Costessey Mill for the period 1962-92. Figure 12 shows the same information in the form of a plot of the cumulative predicted and observed series.

Figures 11 and 12 show that the model regression relationship has held reasonably well since the calibration period. This means that the relationship between gross and effective rainfall has probably remained costant since 1964. However, there is a degree of autocorrelation (shown by the Durban-Watson statistic) which occurs beyond the calibration period. Table 3.3 gives correlation (r) and Durbin-Watson (D) statistics from the calibration and post-calibration periods.

Table 3.3 Calibration and post-calibration period statistics from rainfall/riverflow modelling for Costessey Mill on the River Wensum.

Calibration (1964-74)				Post-calibration (1975-92)			
Logged		Untransformed		Logged		Untransformed	
r	D	r	D	r	D	r	D
0.97	1.65	0.96	2.14	0.93	1.03	0.93	1.40

Model performance has declined since the calibration period and this is probably due to the non-extreme nature of the weather during the calibration period. This has been followed by more extreme conditions in the post-calibration period. Ideally, the model requires a re-calibration exercise to take into account the more recent extremes of wet and dry weather. Following this, the model should be re-run, back in time, and the residuals (observed minus predicted) checked for any trend with time.

Checks using the cumulative error (observed-predicted flows) reveal that there has been a net over-estimation of flow by 4%. This can be seen on Figure 12. This means that observed flows have been larger than those predicted using the 1964-74 calibration period parameters. This contradicts any idea that effective rainfall and thus total flow, since 1962, may have been reduced.

1.3 (iii) Testing for change in the temporal distribution of flow.

Analyses so far indicate that long-term gross and seasonal rainfall have remained constant since the 1960s. This reduces the likelihood that the seasonal distribution of flows has been affected by any natural change in the balance between baseflow and non-baseflow components of flow. Flow data series are too short for statistical analysis which could distinguish with certainty between natural and artificial variability. However, catchment change has occurred and could affect the relative contributions to riverflow.

Flow data have been tested for any trend over and above the effects produced by variation in weather. Primary analysis here has involved the computerised separation of gauged flow into components of baseflow and non-baseflow. Institute of Hydrology baseflow index (BFI) techniques modified by Cook (Institute of Hydrology, 1980) have been used. The BFI is the calculated fraction of total flow volume which, during a specified period, has baseflow origin.

Figure 13(a) shows how BFI has fluctuated with time for the Wensum above Costessey. It has been calculated on a five-year-running mean basis. This smooths shorter term fluctuation which may be due to individual storm or snowmelt events when abnormal amounts of surface runoff may be produced.

During above average rainfall periods, it might be expected that more surface runoff would occur as soils became saturated. Conversely, in drier periods, aquifer storage declines and baseflow continues, albeit at a falling rate. Figures 13(b) and 13(c) show the variability of BFI with time for the Bure and Nar. No trend with time is obvious with BFI varying within a range of about $\pm 5\%$ of mean values. For a possible explanation of this variance, five-year-running mean BFI has been correlated with five-year-running mean rainfall. Correlation for the Wensum catchment reveals a statistically significant, though not a close relationship ($r=-0.443$, $p<0.05$). Similar analysis for the Bure at Ingworth shows a closer relationship between BFI and gross rainfall ($r=-.703$, $p<0.05$). There was no relationship for the Nar to Marham ($p=0.187$).

Five-year-running mean BFI values are determined partially by the distribution of gross annual rainfall, at least in the Wensum and Bure catchments. Regression analysis using five-year-running mean rainfall to predict five-year-running mean BFI, shows that, for the Bure at Ingworth, 49% of the variation of BFI is explained. For the Wensum at Costessey, 18% of variation is explained. Regression of the residuals with time, for Ingworth, reveals a small, though significant change in the relationship between BFI and gross rainfall ($r=0.54$, $p=0.002$). Similar analysis for Costessey is less conclusive.

There is no evidence of reduced baseflow component of flow with time. Indeed, the situation at Ingworth points in the opposite direction, that of a marginally increased baseflow component of flow.

The above analysis, while indicating that there is no reduction in the high baseflow component of flow, does not test the possibility that the make up of non-baseflow is changed. For example, if, through land drainage, the relative size of inter-flow and overland-flow components of surface runoff were altered, flows may become more or less responsive (in the short-term) to rainfall.

It has not been possible to compare detailed catchment hydrologic response to individual rainfall events over time. This technique which, from the detailed hydrograph, separates baseflow and non-baseflow components of flow, uses similar rainfall events with similar antecedent catchment conditions. The method therefore requires data relating to flow and areal rainfall intensity on a high resolution basis. The lack of suitable rainfall data requires alternative approaches to the testing for change.

Daily mean flows and their rainfall induced fluctuation, have been used to infer catchment response with time. From the post-1960 daily flow gauge series, a computer program has produced series of daily increments for the rising hydrograph. Threshold lower limits were set so that very small increases in mean daily flow, for example, within the accuracy expectations of the gauge, did not introduce bias. The incremental data have been described as annual subsets and the 'mean' values, (derived by log transformation), plotted as time series.

This technique groups together all situations of rising hydrograph and thus includes all possible combinations of catchment antecedent conditions with rainfall-event intensity and duration. The crudeness of this approach is mitigated by its ability to include all situations with minimal computing input. Possible seasonal aspects can be looked at by the separation of, for example, seasonal flows.

Figure 14(a) to 14(c) does not suggest any trend with time, when annual 'mean' incremental rise is plotted with time. Inevitably, the fluctuation of incremental data (measures of the increase in flow over that of the previous day) will be determined partly by the flow levels pertaining at the time of increase. In wet periods, flows will be high, catchments may have reduced storage; further rainfall will produce a rapidly rising hydrograph. Conversely, in dry periods, catchment potential storage will be high, thus the likelihood of modest hydrograph rise.

Correlation of mean incremental rise with study area annual rainfall, on a water year basis, confirms the connection between general 'wetness' and the tendency for higher daily rise of the hydrograph. The correlation coefficients were: $r=0.83$ for the Wensum, $r=0.66$ for the Bure and for the Nar $r=0.55$, $n=32$. All relationships are statistically significant at $p<0.05$. Variation in incremental rise was only explained partially by the variation in annual rainfall and this has posed problems for further statistical analysis.

The absence of any obvious variation of the above relationships with time can perhaps be seen to indicate that catchment change (for example, land use, farming practice and drainage), which may be assumed to have been relatively linear, has not had a significant effect on flow response. When flow series were split into seasonal subsets, no significant change to the above result was apparent.

1.3 (iv) Description of gauged mean daily flow series.

Flow in the study catchments over the period 1960/1 to 1991/2 is described for each water year (April to March) using:

- . Annual mean and running-mean flows
- . Annual maximum and minimum flow
- . Annual frequency of daily mean flow > threshold value
- . Annual frequency of daily mean flow < threshold value
- . Annual frequency of peaks over threshold value

Only one gauge in each catchment has been in place since 1960. Records for Ingworth (upper Bure), Costessey (lower Wensum), and Marham (mid Nar) have been analysed.

Figure 15(a) to 15(c) shows how annual mean flow has fluctuated since 1960. The running-mean plots effectively smooth the annual variability and emphasise the rather cyclical nature of wet and dry periods. Of particular note here, is both the extent and duration of the relatively wet ten-year period which began in the late 1970s. The extent of the late 1980s-early 90s drought period, which may eventually be seen to match in extent and duration the earlier wet period, cannot be seen from the running-mean plots.

Results have already shown that thirty-year rainfall has not changed. There is nothing to suggest that the observed cyclical nature of weather and resultant flow behaviour is not within the expected variability from an unchanged population of data. However, it is likely that prolonged trends which produce high or low flows will have great bearing on change as far as human perception is concerned.

Extreme high flow can be the result of a chance occurrence, for example a torrential storm during otherwise non extreme weather conditions. Equally, high-flow may result from a succession of rainfall events, none of particular note, but sufficiently close that hydrograph rise is cumulative. Extreme low-flow, on the other hand, results from a cumulative lack of rainfall, often over long periods. This is particularly so in catchments where baseflow influence is strong.

Extreme high-flow therefore has relatively short-term antecedents. Extreme low-flow is the product of longer-term meteorological conditions. However, ignoring the possibilities of artificial influence, the occurrence of extremes of flow are not necessarily the most useful indicators of flow-related process (for example, sediment deposition) within the river environment.

Figure 16(a) to 16(c) shows how very low flows and high flows can occur in the same water year, as in case of 1976/7. The effects of the extreme drought coupled with high temperatures during the summer of 1976 are well remembered and quoted. However, higher flows soon returned. Figure 15 has shown that the more prolonged, though less dramatic, period of low-flows in the early 1970s was potentially more significant for flow-related aspects of the river environment. The extremes of flow in the early 1970s were much less than those of the recent drought however.

Figure 17(a) to 17(c) shows the annual frequency of days when flow exceeded or fell below threshold limits. Threshold values were obtained from long-term flow duration curves for each gauging station, thus introducing a means of standardisation through the use of common exceedence limits. These limits were deduced from the flow duration curves shown in Chapter 2:3, with upper values set at 10% exceedence and lower values at 95% exceedence.

The cyclical nature of flow levels is re-emphasised and particular note should be made of the low incidence of low-flows during the period 1977-88 and the almost total absence of higher flows during 1989-92 drought period.

The distinction between annual frequency and extremes is primarily that of peaks versus duration of flows in excess of a given value. For example, a period of wet weather may produce prolonged high-flow which spans many days. Peaks-over-threshold analysis may only record one peak depending on the threshold set. The method is normally used to produce statistics of high-flows (thus high threshold, certainly less than 5% exceedence) at, or about floodplain inundation levels. Such flows would only rarely have a lengthy duration, and their significance would be related to the extent of flooding and possible morphological effects. Special significance is given to bankfull flows because of their potential to move and carry alluvial material (Harvey, 1969).

Bankfull flows (Institute of Hydrology, 1993) have been used to produce the statistics of peaks-over-threshold. Values for the Nar at Marham have been estimated from data given by Harvey (1969). Figure 18(a) to 18(c) illustrates, particularly for the Bure and Wensum, the cluster of flows which are likely to have removed and transported sediment during the period from the mid 1970s to 1987. It is likely that channels would have been particularly free of shoals during this high-flow period. Conversely, shoals would probably form again in the next drought period.

Conclusions on Changes in Hydrology

The conclusions on changes in flow that follow are based on unnaturalised flow data. This means that data have not been altered to take account of the net effect of abstractions and discharges. The reason for not naturalising the flow record is justified by the results of the next Section on Water Use.

The questions that have been asked in this Section are:

> Has the relationship between gross rainfall and effective rainfall changed ?
>
> Has the relationship between rainfall and flow changed ?
>
> Has catchment land use change altered flow response ?
>
> Have the characteristics of flow changed ?

1. Since 1931, there has been no change in the thirty-year mean gross rainfall over the study catchments. The seasonal distribution of gross rainfall for the period has also remained constant.

2. Gross rainfall and effective rainfall (calculated from MORECS data) correlate closely over the period 1961 to 1992. This shows that the proportion of gross rainfall that eventually becomes streamflow has not changed since the 1960s. This implies that there has been no change in evaporation from the catchment since this time. It does not imply that changes did not occur before the 1960s.

3. Modelling of the relationship between gross rainfall and river flow for the period 1964 to 1992 has shown that the relationship between the two has essentially remained the same. The conclusion from this modelling is that any changes in catchment characteristics that have occurred since 1964 have not had a significant influence on flow behaviour.

4. Since 1960, there has been no evidence of a reduction in the baseflow component of flow. Indeed, the situation at Ingworth points in the opposite direction, that of a marginally increased contribution from baseflow. This indicates that the amount of groundwater recharge and the discharge mechanisms are essentially unchanged despite any changes in catchment land use and farming practice.

5. There have been no changes in the timing or amounts of the non-baseflow components of flow since 1960. There has been no significant change in either the longer-term or seasonal distribution of the flows. Again, this has been despite any changes in land use and land drainage intensity that may have occurred in the catchment. The timing and quantities of all components of flow, having regard to rainfall distribution, therefore appear unchanged.

6. The prolonged, though undramatic, period of low-flows in the early 1970s was potentially very significant for flow-related processes involving river sediments. The low flows of the period would have deposited sediments and shoals probably formed in the channels. The low-flows of the period were much less extreme than those of the recent drought. There was cluster of high-flows between the mid 1970s and 1987. Over this period, channels would have been particularly free of shoals.

7. Even during long-term climatic stability, there is much scope for variation in streamflow. The time scales of variation in flow due to climate may be seasonal or may span several years. It is likely that the most prolonged trends, which in the study Rivers have led to periods of both high and low-flows, have had a large influence on human perception of change.

CHAPTER 3: Section 2. Changes in Water Use.

Section 2.1 Background to Use of Water Resources.

Since the adoption of an abstraction licensing system under the Water Resources Act of 1963, there has been a steady increase in water use. There is no reason to assume that increases had not occurred before the 1960s, though this is before licensing records became available. It seems reasonable to expect that, whilst probably increasing since 1930, the rate was much lower before 1960 than since.

The provision of water power, which does not involve abstraction or discharge in the conventional sense, stands apart from other use categories. This type of water use involved the creation of artificial river channels and use of control structures to produce hydraulic heads by impoundment. The release of impounded water powered mill machinery. The process of water milling has profound effects on many aspects of the river environment.

The period of enquiry for this study pre-dates comprehensive licensing systems. An assessment of change in resource use for the period 1930-92 has been split accordingly.

Section 2.2 Changes before the 1963 Water Resources Act.

2.2 (i) Main uses of water before 1963.

Unfortunately, due to lack of information before 1963 it is only possible to infer the extent of change using proximate data. For example, local changes in population or the provision of mains water and sewerage services provide an estimate of resource use. The approach requires caution because relationships between these data and domestic or industrial use do not necessarily remain constant over time.

The main water use categories before 1963 were public water supply (PWS), sand and gravel working, agricultural (general), agricultural (spray irrigation), industrial and the provision of water power.

PWS demand is a function of population size and the need, and ability, to use a public supply system. Demand for PWS also reflects the demands of other users, usually light industry, though there is little of this in the study area. A notable feature of PWS is the possible geographical separation of abstraction, consumption, and discharge points through the use of trunk mains. This is relevant to the effects of PWS use on the river environment and is dealt with further in Chapter 4.

2.2 (ii) Population change between 1931 and 1961.

Population statistics on a county, district, or parish level are available from Census records published by HMSO. To correct for the possible fluctuations of population between individual parishes, population change on a district level has been examined. The districts used are the old town and rural district council areas which predate local government reorganisation in 1974. Boundaries do not coincide well with the project area though a reasonable estimate of population change has been gained.

The general trend has been of small increases in population between 1931 and 1961. The exception to this was a large increase in the St. Faiths and Aylsham Rural District, said to be overspill from Norwich (Norfolk County Council, 1952). Table 3.4 shows the urban and rural districts which cover most of the study area, their populations in 1931 and 1961, and the percentage change between the dates.

Table 3.4. Populations of Urban and Rural District Council areas and their percentage change between 1931 and 1961.

DISTRICT	POPULATION 1931	1961	%Change
East Dereham UDC	5643	7199	27.6
Erpingham RDC	17659	18479	4.6
Freebridge Lynn RDC	10270	11940	16.3
Mitford & Launditch RDC	17107	17651	3.2
St. Faith's & Aylsham RDC	25648	46003	79.4
Smallburgh RDC	15690	17376	10.7
Walsingham RDC	18119	20890	15.3

2.2 (iii) Change in per-capita consumption.

Per-capita consumption would undoubtedly have changed, particularly as mains water supplies reached new areas. This would become pronounced as mains sewage or other efficient means of effluent disposal (such as flush toilets) became available. It is difficult to assess the size of increase in this type of water use, though it was presumably large. Even properties which had enjoyed water on tap since 1930, would tend to use more water with time because of increased use of domestic plumbing and water-using appliances. Again, it is difficult to assess likely effects on resource use in this earlier period.

2.2 (iv) Evidence for increased water use.

Per-capita consumption in rural areas of Norfolk during the later 1940s in properties with piped water and without sewage schemes, is given as 85 litres day^{-1}. For areas with sewage systems, the figure increases to 89 litres day^{-1} (Norfolk County Council, 1947). A per-capita consumption of 128 litres day^{-1} in 1971 is used currently in NRA resource calculations. This illustrates the relative size of increased resource use without the above 'coming-on-stream' effects.

Full details of the spread of mains services since 1930 have not been located. However, an insight into the relatively recent nature of their arrival in many of the rural areas of Norfolk, comes from a 1944 House of Commons statement by the then Minister of Health. The statement put Norfolk at the 'bottom of the league' with respect to the number of rural parishes having public piped water supply. Out of 523 rural parishes, 383 were still awaiting provision in 1944 (Norfolk County Council, 1947).

Table 3.5 uses Norfolk County Council data from 1952 for Rural District areas and so updates information on the availability of piped water supplies in and around the study area.

Table 3.5 The number of rural parishes with and without piped water supply (by Rural District area, December 1951)

RURAL DISTRICT	PIPED WATER SUPPLY	
	WITH	WITHOUT
Erpingham	10	34
Freebridge Lynn	7	16
Mitford and Launditch	0	47
St. Faith's and Aylsham	18	30
Smallburgh	7	27
Walsingham	14	24

If all the Rural Districts in Norfolk are included, then 323 parishes were still without piped supply in 1951. Sixty rural parishes received piped supplies between 1944 and 1951. The provision of water borne sewerage systems for the same Rural Districts is shown in Table 3.6. Clearly, the provision of sewage schemes was well behind that of piped water supplies.

Table 3.6 The number of rural parishes with, or awaiting approved sewage systems (by Rural District area, December 1951).

RURAL DISTRICT	WITH	FORTHCOMING
Erpingham	4	3
Freebridge Lynn	0	3
Mitford and Launditch	0	1
St. Faith's and Aylsham	2	7
Smallburgh	1	3
Walsingham	3	3

Within the Study area, likely causes of increased demand for PWS during the period 1931-61 were:

i) from the increased provision of utilities
ii) from the increasing availability of water-using appliances and facilities
iii) from increased population density.

2.2 (v) Sand and gravel working.

Sand and gravel working saw a sharp increase over the same period. The construction of Ministry of Defence airfields and other installations in the run up to, and during, the Second World War provided large increases in water demand. The momentum of increased extraction was maintained during the post-War development era.

Abstraction is normally from water filled workings and discharges are to the same reservoir (East Suffolk and Norfolk River Authority, 1971). Loss or export of resource is confined to that transported away with the sand and gravel plus the 'open water body' evaporation from the water filled workings. Losses are generally less than five percent.

2.2 (vi) General agricultural use.

This category of use includes all purposes other than spray irrigation. Livestock watering, washing-down and the application of agrochemicals are perhaps the main uses. Quantities abstracted for these uses, though increased, are generally small with substantial return to ground or surface resources.

2.2 (vii) Agricultural use for spray irrigation.

Abstraction for this highly consumptive purpose is relatively recent. In 1950, nationally there were less than 1000 ha of irrigated crops (Ministry of Agriculture Fisheries and Food, 1963). The local growth of crop irrigation practice has been seen since the mid-1960s. Full details concerning the post-1960 growth of irrigation practice and its implications are given in the Section on flow naturalisation.

2.2 (viii) Industrial abstractions.

The study area has never supported industrial activity which requires significant quantities of water. As mentioned previously, the main local industrial uses are those allied to local agricultural production. These, with the possible exception of the brewing industry, are largely post-War developments.

2.2 (ix) Use to power water mills.

There are at least twenty sites on the Wensum and its tributaries where water power was once used (Scott, unpublished). The upper Bure and its tributaries have supported about fourteen mills and five sites are known on the Nar. Some of the mills are extremely old: Buxton and Corpusty Mills on the Bure were both mentioned in the Domesday Book. Most of today's structures and remains date back to the second half of the 18th and into the early part of the 19th Century and this probably represented the period of greatest use.

Most of the 302 water mills recorded in the Domesday survey of Norfolk continued working until the middle of the 19th century. By the early 1930s, the use of water power was in marked decline. Scott (1993) noted that in Norfolk, there was a reduction from 72 to 21 working mills between 1906 and 1956. The decline affected the study Rivers, though there were probably still seven working mills on the Wensum, six on the Bure and one or more on the Nar during the early 1930s. By 1969, only Elsing Mill on the River Wensum was using water power. The effects of mill working on local hydrology are described in Chapter 4.

Section 2.3 Changes in Water Use since the 1963 Water Act.

2.3 (i) Total water use.

Using data on licensed abstractions for the study area and their change with time, it is possible to produce totals according to use-category and sub-catchment. Some abstraction and discharge estimates were given in Ministry of Housing and Local Government Reports (Ministry of Housing and Local Government, 1960 and 1963) and these have been used as 'base points' for analysis. Care has been taken where licenses have been revoked, cancelled, or amended or where new ones have been granted. Summary data for hydrometric areas 33 and 34 were obtained from relevant NRA offices.

Table 3.7 shows main water uses for the whole study area, their expected return and how they have changed since 1960. The dates are approximate and licensed quantities are given in thousands of cubic metres per annum (TCMA). Tables 3.7(a), 3.7(b), and 3.7(c) give the individual catchment contribution to the totals that are in Table 3.7.

Table 3.7 Water use in the study area between 1961 and 1991.

USE CATEGORY	RETURN(%)	ANNUAL QUANTITY (TCMA)(**)			
		1961 (#)	1971	1981	1991
P.W.S. (*)	90%	1913	6651	6910	9163
Sand/gravel works	95%	53	1570	1665	1389
Agricultural-general use	90%	1297	1331	1518	1705
-spray irrigation	0%	2319	3342	5692	10612
Industrial	80%	256	790	1007	1480

Table 3.7(a) Water use in the Wensum-to-Costessey catchment between 1961 and 1991.

USE CATEGORY	RETURN(%)	ANNUAL QUANTITY (TCMA)(**)			
		1961 (#)	1971	1981	1991
P.W.S. (*)	90%	495	1617	2155	3764
Sand/gravel works	95%	53	1467	1561	1329
Agricultural-general use	90%	798	840	1000	1126
-spray irrigation	0%	1111	1571	1774	3876
Industrial	80%	206	781	948	1423

Table 3.7(b) Water use in the Bure-to-Horstead catchment between 1961 and 1991.

USE CATEGORY	RETURN(%)	ANNUAL QUANTITY (TCMA)(**)			
		1961 (#)	1971	1981	1991
P.W.S.	90%	930	2267	2180	2845
Sand/gravel works	95%	0	46	45	0
Agricultural-general use	90%	322	314	322	379
-spray irrigation	0%	740	1037	2247	3242
Industrial	80%	0	3	2	1

Table 3.7(c) Water use in the Nar-to-Marham catchment between 1961 and 1991.

USE CATEGORY	RETURN(%)	ANNUAL QUANTITY (TCMA)(**)			
		1961 (#)	1971	1981	1991
P.W.S.	90%	488	2767	2575	2554
Sand/gravel works	95%	0	60	60	60
Agricultural-general use	90%	177	177	196	200
-spray irrigation	0%	468	734	1671	3494
Industrial	80%	50	6	57	56

* the large PWS abstraction from the Wensum near Norwich is excluded. PWS abstractions at Belaugh on the River Bure are outside the study area.
** licensed quantity as opposed to actual quantity.
# these are estimates. Most use-categories not yet subject to licensing (e.g. spray irrigation). Data apparently refer to estimated abstractions, not licensed amounts.
Data are from Ministry of Housing and Local Government (1960 and 1963), and National Rivers Authority unpublished material.

2.3 (ii) Abstractions and their increase since 1960.

The apparently large increase of 348% in licensed PWS use for the period 1961-71 is highly misleading. This is because mains services, which are included in 1971 data, replaced many diffuse, and previously unreported sources of supply over the period. The 1961 PWS abstraction data were also estimated abstractions, not licensed quantities.

There have been steady increases in demand for water for all uses. The increase of 358% in the licensed total for spray irrigation has been by far the most extreme. The increase has added significance because the use is wholly consumptive. Crop irrigation is needed most during the driest time of the year, with the greatest demand occurring in the driest years. Demands are thus greatest when catchment reserves are depleted naturally. Pronounced seasonal effects on flow and flow-related aspects of the Rivers are feasible.

Annual licensed totals for spray irrigation are larger than those for PWS. It is important to note, however, that uptake of the licensed total is often low. This growing season, weather-related variable fluctuates markedly about its mean value of 31%. Figure 19 shows the range of values for the annual uptake of spray irrigation for hydrometric area 34 during the period 1961-92. Equivalent data for area 33, the Nar, are not available so the same values have been assumed. The variation in uptake for irrigation and other uses makes licensed total an unreliable guide to actual abstraction and subsequent effects on the Rivers' environment.

The availability of actual abstraction data under the 1963 Act, allows a quantitative assessment of the actual changes in resource use. From these any effects on different aspects of the Rivers' environment can be calculated or inferred. The appendix gives a detailed description of methods used to assess actual abstraction and discharge amounts by sub-catchment. Information relating to actual amounts used during this period has been obtained from material supplied by NRA licensing sections.

Due to concern during the early 1960s about depletion of surface flows by increased surface abstractions, particularly for spray irrigation, (East Suffolk and Norfolk River Board, 1962; O'Riordan, 1970), there was a move by the East Suffolk and Norfolk River Authority to limit further licensed quota to groundwater sources. The vast majority of the increase in licensed abstraction since that time has come from groundwater (Figure 20). Abstractions from groundwater greatly outweigh those from surface waters in all of the study River catchments. The exception to this is the public water supply (PWS) abstractions from the Wensum near Norwich and from the Nar at Marham. Similarly, discharge to surface water is usual, the exception here being that from sand and gravel workings which, in recent times, is discharged mainly to ground.

For the use-categories which produce discharge, that is PWS, sand and gravel working, general agricultural, and industrial use categories, their increase in use may be more significant from a water quality rather than a flow perspective. Their high rates of relatively direct return (see Table 3.7), make them potential influences on water quality.

Conclusions on Changes in Water Use before the 1960s.

1. Apart from the beginnings of spray irrigation, there have been no new categories of water use since the 1940s. The only change has been in the opposite direction. This was due to the end of instream resource use by water mills. After many centuries of water use, a decline in water milling occurred over a few decades and was almost complete by 1960.

2. Increases in other uses during the 35 years from 1930 were sustained, though small. The exception was for PWS. Increasing living standards, especially during the post-War period, increased domestic water consumption beyond the very low levels of earlier times. The amounts used at the end of the period were still very modest.

Conclusions on Changes since the 1963 Water Act

1. Since 1960, growth in spray irrigation capacity has been a significant change in water use in terms of potential loss to flow. Over the whole study area, the increase in the total licensed quantity from 2319 TCMA in 1961 to 5692 TCMA in 1981 was 44% compared with the increase of 86% from 1981 to 10,612 TCMA by 1991. During 1990 uptake of the total licensed quantity was 64% and during 1991, 54%.

2. The effects on flow of PWS abstraction, which is the other major use category, are mitigated to a large extent by STW discharges, although these may be made much further downstream. Other discharges tend to be made near the point of abstraction thus reducing the effects of abstraction.

3. The significance of changes in water uses which produce discharges cannot be assessed completely without using data on discharge location, quantity and quality. Here, the assessment of the volumes and locations of return after PWS-use poses many problems, given the ability of water supply and sewage networks to transfer resources.

CHAPTER 3: Section 3. Changes in Water Quality.

Changes in water quality are inevitable where drinking water is returned to rivers as treated effluent. During 1989, the year that the NRA was formed, Anglian water operated 1091 sewage treatment works (STWs) and estimated that approximately 81% of the effluent received by them was processed by these works. The remainder of the effluent received primary treatment only or was discharged to sea untreated. Anglian Water Services operate 159 sewage treatment works and three sea outfalls within the catchments of the Yare, Wensum, Bure and Waveney (NRA 1994). Discharges from STWs must comply with conditions set out in consents. These conditions are set, or revised, according to EC Directives and local standards and take account of the dilution available in the receiving water.

Few industrial effluents are discharged into the study Rivers, though effluents from agricultural land diffuse into water courses. These diffuse sources are much more difficult to trace, to identify and to control than effluents from point sources. Pesticides may enter the study Rivers though have only been measured very recently in the study area. Their effects are unlikely to be significant when set against other larger and better documented changes in the Rivers. Major contamination of surface and groundwaters by nitrate occurs in the area. This is of most relevance to the quality of drinking water and would not have direct biological effects that could be separated in this project from the influence of phosphorus from sewage effluents. High loadings of nitrate can disadvantage bankside plants in lakes (Boar et al. 1989) though it is unlikely that the same mechanism has a significant influence on the plant communities of the study Rivers.

This Section answers questions about aspects of water quality which are likely to affect the biological community and for which there is a reasonably long monitoring record. This record goes back to 1966 for some aspects of water quality though is more recent for suspended solids and phosphorus.

The questions are:

- Has there been a change in the biological oxygen demand in water?
- Have concentrations of suspended sediments changed ?
- Have concentrations of phosphorus in the Rivers changed ?
- Has there been a change in the ammonium concentration in water ?
- How have water temperatures in the study Rivers changed ?

Section 3.1 Biological Oxygen Demand.

The amount of oxygen used by bacteria and other micro-organisms, depends upon the amount of decomposing organic material in water. Even in silty downstream type environments, the natural BOD of the study Rivers is probably between $1mgl^{-1}$ and $2mgl^{-1}$ over a standard 5 day incubation. Values above the natural background may be due to decomposition of organic matter in effluent discharges; water plants not removed from the Rivers after cutting or, to a smaller extent, added oxygen demand for decomposition of increased water plant or filamentous algal growth. Very high BOD can deoxygenate water enough to cause the death of fish and invertebrates.

The annual maximum BOD in the Rivers Bure and Wensum between 1966 and 1990 is shown in Figure 21. The early values are from summary statistics given in the yearly reports of the Norfolk and Suffolk River and Water Authorities. Maximum values in the Rivers were usually between $2mgl^{-1}$ and $4mgl^{-1}$. Figure 21 shows the frequency of extreme events. In the four sites on the Bure (Figure 21(a)), the highest BOD has been about $3mg\ l^{-1}$ each year since 1966. The average has been around $2mgl^{-1}$, though periodic pollution by organic effluents and ammonia, detected particularly at Horstead Mill, have contributed to the placing of the River in NWC Class 1B. Maximum BOD has, on average for all four sites, increased by $0.06mgl^{-1}$ per year ($r=0.4567$ $p<0.02$) over the 25 year period. Although the rate of increase has been low, the overall size of the increase since 1966 has been relatively large at $1.5mgl^{-1}$. The low figures for correlation coefficients (r) show that short-term variations in BOD have been large. The pattern for different sites also varied. The BOD at Saxthorpe and Buxton Mills has fluctuated, though has not changed significantly, though the size and frequency of high BOD at both Ingworth Bridge ($r=0.4302$ $p<0.05$) and at Horstead Mill ($r=0.4649$ $p<0.02$) has increased.

The BOD at Ingworth and Horstead was low during the drought years 1989 and 1990. When these two years were excluded from regression analyses, the increase over time (to 1987) was $0.10mgl^{-1}$ per year ($r=0.6961$ $p<0.001$). Low BOD during the drought could have been because sediments settled out of suspension onto the River bed. Loading of sediments eroded from the catchment must have been negligible during the drought, and sewage treatment works would have contributed very little, or no, material from urban runoff.

In contrast to the Bure, there has been no long-term change in the annual maximum BOD at any of the monitoring sites on the Wensum (Figure 21(b)). Maximum values have been around $3mgl^{-1}$, which is similar to the Bure. The drought made little difference to BOD. This probably means that either the proportion of sediment that remained in suspension during the early drought, or that contribution of sediment from the catchment, did not change. Pollution incidents involving effluent from food processing works and a large malting at Great Ryburgh, probably explain most of the short-term fluctuations of BOD in the Wensum.

During 1986, the maximum BOD on the data record was $>13.2mgl^{-1}$ at Hellesdon. This value does not appear on Figure 21(b). Against an annual mean value of twelve samples for the year of $2.13mgl^{-1}$, and without any correspondence with oxygen saturation, phosphorus or suspended sediment, the value has been excluded from analyses as a probable recording error.

Section 3.2 Suspended Solids.

The high maximum BODs in the Bure during 1984, 1987 and 1988 corresponded with extremely high concentrations of suspended solids, Figure 22. The overall relationship was not, however, as close as expected at the sites involved (Horstead $r=0.43$ $p<0.15$; Ingworth $r=0.31$). This may imply that the BOD of water was influenced as much by the oxygen demand of sediment on the river bed as by sediments suspended in the water. It may also imply that suspended material was not necessarily organic and was, at times, composed of clay or other mineral particles which have a much lower oxygen demand.

The concentration of suspended solids in water at Horstead Mill has increased steadily since measurements began ($r=0.5479$ $p<0.05$). Surprisingly, during 1990 the River at Horstead appeared to carry more, rather than less, suspended material than before the drought. The opposite occurred at Ingworth. Here there were large increases in the concentration of suspended material, though only until the drought. Maximum concentrations during 1988 and 1989 of about 150mgl^{-1}, which are extremely high, dropped to around 30mgl^{-1} during 1990. Low winter flows at Ingworth must therefore have corresponded with either a reduction in external loading of sediment, its deposition closer to source or its deposition at the site.

Field observations at Ingworth, made during summer 1991, showed that net deposition was occurring in the middle of the channel. Local information suggested that this has been a feature of the site for at least the last twenty years. Substantial amounts of ochre (orange particles of iron oxide) were observed at the site in the mid 1980s (D.Clarke, personal communication). These particles would have been formed by chemical changes in soils during 1985 and after deep drainage of the Scarrow Beck tributary by the Internal Drainage Board. Further work was carried out in Scarrow Beck during 1990. This type of drainage activity in tributaries remains outside the direct control of the NRA.

Large changes in the concentration of sediment in water appear to have occurred in the Wensum at Hellesdon. Figure 22 suggests that annual maximum concentrations of suspended solids increased to over 100mgl^{-1} until the drought (0.6503 $p<0.05$), and then returned to about 25mgl^{-1}. The lower value still represents turbid water where a river bed may not be visible below about one metre of water. During 1987, sampling at Hellesdon increased from monthly to weekly intervals. A high sampling frequency is likely to detect extreme events. It is therefore plausible that higher values simply reflect increases in sampling effort. This is likely because the apparent increase between 1986 and 1987 of 28mgl^{-1} to 118mgl^{-1} was not paralleled by an unusually high BOD during 1987, which at about 4.5mgl^{-1}, was similar to preceding years. This suggests that the lower frequency of sampling before 1986 substantially underestimated loads of suspended solids in the River. Analyses of annual means to some extent moderate the difference between sampling regimes, though, with the exception of nutrients, average conditions in rivers have a great deal less biological relevance than extreme events.

Section 3.3 Phosphorus Concentrations.

Large changes in the availability of the nutrient phosphorus are more likely to affect the plant community than almost any other chemical variable in the study Rivers. Only phosphorus that is dissolved in water can be taken up as a nutrient; particulate phosphorus is already bound in algae, other micro-organisms or in sediments. Of the three main plant nutrients, phosphorus is naturally the most scarce because it is fairly insoluble and so weathers slowly from catchments. Small inputs of dissolved phosphorus from sewage treatment works therefore have large effects on plant growth.

The record for dissolved inorganic phosphorus, which is measured as its chemical form orthophosphate, began during 1975. The concentration of total phosphorus, which includes both dissolved and particulate forms, has only been measured since the mid 1980s. The timing of the start of these programmes reflects awareness of the ecological importance of phosphorus. Dissolved phosphorus had not been measured before 1975 because its concentration does not have a direct effect on the quality of drinking water. The ecological importance and the usefulness of information about particulate phosphorus has only been reflected in routine monitoring programmes, and only at a few sites, since the mid 1980s. In their study of river eutrophication, Stansfield and Moss (1989) found that the monitoring programmes of most Water Authorities collected too little information for reliable estimation of the phosphorus loads in most UK Rivers.

Sewage effluent is the major source of dissolved phosphorus. It is also possible that at times of high rainfall, STWs contribute significant amounts of particulate phosphorus from catchment and urban runoff. The size of these contributions is not usually measured directly in budgeting work. For the Bure, Moss et al. (1989) estimated that phosphorus from soil washed into the River directly from the catchment above Hoveton (about 8km below Horstead Mill), contributed about 22% of the total phosphorus measured in the River. The remainder was from sewage effluent.

Phosphorus, and its control has received much attention in the Bure because of its significance for the Norfolk Broads, which are further downstream. Phosphorus in the Wensum has received much less attention, perhaps because it must have relatively little significance for the Yare Broads compared with the size of STW discharges below the City of Norwich. Phosphorus loading to the River Bure, and to a much smaller extent, the River Nar, have been well described. Loadings to both Rivers are known to be large enough to justify management to reduce the concentration of dissolved phosphorus in sewage effluent. The NRA and its predecessors have produced five annual reports since 1987 detailing the size of contributions of phosphorus from treatment works in the Bure catchment. These documents report the effectiveness of ferric sulphate dosing of final STW effluent to reduce phosphorus loading to the Bure. Such phosphate stripping is carried out by the Water Authority at some of their works, and particularly on the Bure at both Briston and Aylsham. A phosphorus budget for the River Nar has been produced as part of an NRA special study of eutrophication in the River (Lister and Boar, 1993).

Concentrations of dissolved inorganic phosphorus in the Nar at Marham (Figure 23(a)) show an expected pattern of winter highs and summer lows. Low summertime concentrations are because of nutrient uptake by plants. Summer concentrations have been below 0.10mgl^{-1} since 1979. This is low when set against an annual load of dissolved phosphorus in the upper River at Litcham of about 5000kg in 1989. Dissolved phosphorus from the STW at Litcham is taken up rapidly by water plants further downstream, especially by the invasive *Apium nodiflorum*, and may also be adsorbed by exposed chalk on the bed in middle and upper reaches. This chemical process is described in soils by Mott (1981) and Freeman and Rowell (1981) and has been used by Jickells et al. (1988) to explain low concentrations of phosphorus in water in a chalk aquifer. Retention of phosphorus in invading plants or sediment is not desirable, particularly in the upper reaches of the River. Figure 23(a) also shows concentrations of particulate phosphorus, which, with dissolved orthophosphate, makes up the concentration of total-phosphorus shown on Figure 23(b). Particulate phosphorus made an important contribution to the total amounts, particularly during winter. Part of the particulate load during winter may have drained or been washed into the River by winter rainfall.

The annual mean dissolved phosphorus record for four sites on the Bure (Figure 24(a)) illustrates a complicated pattern of variation between sites and variation at each site. The only site where there has been no change since 1975 is Saxthorpe Mill. Here the River drains only a small part of the upper catchment though it has received effluent from sewage works at Briston and Hindolveston. The annual average concentration at Saxthorpe has been around $0.08mgl^{-1}$. Over all the four sites shown, there was no net change in dissolved phosphorus concentrations between 1975 and 1990 ($r=0.14$). There were, however, large increases in the three lower sites until 1985 (0.7548 $p<0.001$) with decreases since 1986 and again over the drought years 1989 and 1990. The introduction of phosphate stripping of effluent from Briston and Aylsham during 1986, explains the earlier reductions. This is shown clearly in time series for total phosphorus given in Phillips and Chilvers (1991). These series show reductions between 1986 and 1987 in the load of phosphorus in effluent, as well as in the River water. Further reductions in the concentrations of dissolved phosphorus in the River water over 1988 and early 1989 were probably due to improved efficiency of phosphate stripping.

Load calculations are essential for describing real change because they correct for variations in dilution between the different years. Calculations of the phosphorus load carried by the River Bure at Ingworth have been made for this project from monitoring data on flow and on total phosphorus concentration in river water. Phillips and Chilvers (1991) have calculated loading from the point of discharge at the Briston treatment works as well as loads in the River at Ingworth and other monitoring sites. External loading was estimated from direct measurements of phosphorus concentrations in effluent and values for the volumes of effluent discharged from the works. These measurements were made by Anglian Water. The two estimates of loads at Ingworth between 1987 and 1989 made by Phillips and Chilvers and made for this project have been compared. The two estimates were very close, falling within 5% of each other. However, during 1990, when annual rainfall on the catchment was 546mm (rainfall over the drought is given in Table 2.1), there was a larger difference between the two estimates.

Further calculations have been made from data given by Phillips and Chilvers. The aim of this was to scale the importance of diffuse inputs from the catchment by examining the effect of low rainfall during 1990. Calculations have enabled comparison of the size of phosphorus loading from Briston with the amount of phosphorus actually found in the River further downstream at Ingworth. The results show that in wetter years (1986 to 1988), about 88% of the phosphorus at Ingworth cannot be explained by contributions from Briston. Inputs from other discharges were not included and are not likely to make up the difference. When the lower of the two estimates of the annual phosphorus load at Ingworth in 1990 was used in the calculations, the catchment contribution in this very dry year dropped from 88% to 54%, a reduction of 34%. This suggests that in the upper part of the Bure, runoff from the catchment or contributions of particulate material from underdrainage, contribute at least one third of the total phosphorus which enters the main River. This is somewhat higher than previous estimates of the size of diffuse inputs. Previous budgeting work, which suggested a contribution of 22%, did not benefit from a period of low rainfall when such rainfall made up large soil moisture deficits rather than contributing surface runoff. Recent work on Scarrow Beck (Turner, 1993) has shown that sources other than sewage effluent contributed 27% of the load of total phosphorus to the Beck during summer 1993. An irrigation ditch made an important contribution to this summertime input. Management of the riparian zone along Scarrow Beck to intercept phosphorus inputs from the catchment, which are likely to be largest during winter, is therefore an appropriate recommendation from both Turner's work and the results of this study.

Load calculations have not been made for the Wensum, though annual mean concentration of dissolved phosphorus in most of the Wensum has increased since 1975 ($r=0.8512$ $p<0.001$), Figure 24 (b). There has been no change from around $0.15mgl^{-1}$ at Sculthorpe Mill, which is the site furthest upstream. The increases at other sites have been large, with concentrations in the lower sites at around $0.5mgl^{-1}$ during 1990. The most persistent increases have been at Billingford Bridge ($r=0.7363$ $p<0.001$) and at Great Witchingham ($r=0.8497$ $p<0.001$). In contrast to the Bure, drought flows have not influenced the concentration of dissolved phosphorus. When 1989 and 1990 were excluded from regressions between time and the average concentration for all of the sites, the correlation coefficient increased to 0.9104 $p<0.001$. This shows that increases in dissolved phosphorus in the Wensum have persisted over the decade and that there has been little annual variation around the upward trend.

The concentrations of chloride in the Rivers should follow the same pattern as changes in the loading of phosphorus from sewage works. This is because STW effluent is the major source of chloride in non-tidal rivers. The average annual mean dissolved phosphorus and annual mean chloride concentrations for the six monitoring sites on the River Wensum varied together closely ($r=0.7169$ $p<0.0001$). The closeness is quite surprising because uptake of dissolved phosphorus by higher plants should complicate the relationship. Unfortunately, data on total phosphorus are not available for most sites.

The average annual mean chloride for all six monitoring sites on the Wensum has increased since 1979 ($r=0.7196$ $p<0.0.001$), Figure 25. The largest changes were at Hellesdon ($r=0.6254$ $p<0.01$) and at Great Witchingham ($r=0.6293$ $p<0.01$), with no change at all at Sculthorpe Mill. Chloride is not taken up by water plants or algae, adsorbed by chalk or contributed by the catchment. Chloride will therefore become more concentrated in lower-flows and more dilute in high-flows. The low rainfall of the drought years did not, however, make a large difference to the mean chloride concentration of about $18mgl^{-1}$. Short-term variation in the annual range of chloride concentration (the difference between the maximum and minimum values) during the beginning of the drought, was no different from the variation in annual ranges over the longer-term. This tends to suggest that concentration in lower-flows was not a major effect of the 1989 drought and that changes in the loading or transport of STW effluent were the main influence.

Section 3.4 Ammonium concentrations.

Background concentrations of ammonium depend upon the amount of organic matter in a river. This is because ammonium compounds are released during decomposition of organic matter, though they are usually taken up again rapidly by plants. Rainfall may deposit unusually large amounts of ammonium in areas of intensive animal farming, particularly where there are housed livestock units. Amounts as high as about 120kg Nitrogen ha^{-1} $year^{-1}$, of which 83% is ammonium, have been reported in rainfall in the Netherlands and these equate with amounts deposited in some areas of this country (Ineson, 1994). The scale is large and compares with an average fertiliser application in Great Britain of 130kg N ha^{-1} $year^{-1}$ during 1988 (Chambers et al. 1990). Ammonium is also contributed directly by sewage effluents, by liquid effluents from livestock units and by spillages of liquid ammonia. The importance of ammonium is that, under certain physical and chemical conditions, contamination may be great enough to cause fish kills and the death of benthic invertebrates.

Annual mean concentrations of ammonium in the Wensum increased between 1966 and 1990 ($r=0.5757$ $p<0.01$), Figure 26(a). Concentrations increased only until 1989 ($r=0.6954$ $p<0.001$) by, on average for the four sites, about $0.1mg^{-1}$ ($y=0.05+0.003x$). This is a large increase, although during 1990 concentrations dropped to levels typical of the mid 1970s in all four sites. Annual maximum concentrations were often much higher and Figure 26(b) shows the frequency of extreme events at Great Witchingham. The record shows that the frequency of contamination has not changed since 1966. Contamination has been particularly extreme at Great Ryburgh where maximum concentrations during 1983 and 1984 reached $0.96mg^{-1}$.

Because of the greater ecological significance of extreme events, Figure 26(c) for the Bure, shows annual maximum concentrations. These have tended to be higher than in the Wensum. Between 1966 and 1990, there was an overall increase in the average for the four sites ($r=0.4053$ $p<0.05$), although short-term variations have been large. For example, the maximum concentrations during 1966 and 1967 were greater than concentrations throughout most of the 1970s and 1980s. Maximum concentrations in the two downstream sites fell during the first year of the 1989 drought. Most of the River Bure is classed in NWC Class 1B; this represents water quality which will support a coarse fishery.

Thresholds for ammonium concentrations are set by the NRA according to the sensitivity of the fishery. Relationships between ammonium concentration and the behaviour of fish are not at all straightforward. This is because concentrations of free ammonia need first to be predicted from principles of physical chemistry. The calculations involve temperature and pH; in the study Rivers, both temperature and pH tend to favour the dissociation of ammonium to free ammonia. The NRA have commissioned a study to predict ammonia toxicity to freshwater fish and its results are expected during 1994. Working thresholds that relate ammonium concentration to the fishery do, however, exist. The threshold for a F_2 fishery (which supports cyprinid fish) is that 1.5mg ammonium l^{-1} should not be exceeded for more than 5% of the time. The limit is lower at $0.75mgl^{-1}$ for F_1 fisheries (which support breeding populations of trout or salmon). Higher limits of $2.5mgl^{-1}$ and $1.25mgl^{-1}$, which should not be exceeded for more than 1% of the time, are a further guide. These high limits are at concentrations where fish kills are almost inevitable, particularly for younger fish.

Over the period of records for maximum ammonium, only once have concentrations been high enough at more than $1.25mgl^{-1}$, for lethal effects on trout. This was on the Bure at Ingworth during 1977 when liquid ammonia spilled into the River. Concentrations have been close to, or have exceeded, the 0.75mg limit for trout on two other occasions though. The data record does not suggest that lethal effects on coarse fish in the Bure are probable, though maximum concentrations may be high and occasional behaviour effects linked to pollution events are plausible.

Mean ammonium concentrations in the Wensum have remained well below thresholds for effects on either salmonids or coarse fish. Maximum concentrations exceeded the 5% threshold for trout at Sculthorpe Mill during 1980, 1981 and 1983, at Great Ryburgh in 1983 and 1984, and have approached the limit of $0.75mgl^{-1}$ at Great Witchingham. Similarly, maximum concentrations at Hellesdon have increased significantly since 1966 ($r=0.5888$ $p<0.01$) and, until the drought, were approaching annual maxima of around $0.5mgl^{-1}$. Occasional contamination of the River Wensum by ammonia may thus have an effect on trout as far downstream as Great Witchingham. Lethal effects on coarse fish are very unlikely in the Wensum. Before the drought, maximum concentrations were around 30% of the F_2 limit. Sub-lethal effects, or the particular sensitivities of young fish, are unknown and are the subject of current research elsewhere. It would take several decades of continuing upward trends in the lower River for potential effects to occur.

Section 3.5 Water Temperature.

Figure 27 shows mean monthly water temperatures at pairs of sites which are in the upper and downstream reaches of the study Rivers. The headwater sites have been chosen because they are close to springs. For useful comparison, sites should be similar distances from groundwater inputs and the time of day when measurements were made should be known. Water temperature is an important variable because it has a direct relevance for the recruitment success of coarse fish. Greatest success occurs in years of relatively high temperature. Recruitment of roach in the River Ouse has, for example, been strong over the hot summers of the recent drought. The relevance of water temperature for game fish has the opposite emphasis. Trout are likely to suffer physiological stress at temperatures around or above 20°C and competitive abilities are likely to be reduced at temperatures above 15°C. Temperatures suitable for spawning and egg development for trout lie between 0°C and 10°C, with variations in development time according to temperature. The long development time for trout eggs gives prolonged vulnerability to variation in temperature, siltation or to dislodgement of eggs during winter floods.

Changes in the relative contribution of cold groundwater to surface runoff can be inferred from records of water temperature. Ideally, the record should be standardised against air temperature. Figure 27 shows a difference of up to 5°C between the spring-fed headwaters of the study Rivers and lower reaches where surface runoff from the catchment has a much larger influence on winter flows. The difference between temperatures at the two sites on the Nar was smaller than in the other two Rivers. This is because flow throughout the Nar is much more influenced by groundwater than in the Bure or Wensum. If the contribution of baseflow to the study Rivers has not changed, there should be no change in the relationship between water and air temperature in upper reaches. Unfortunately, local air temperatures have not been recorded. There has not, however, been a persistent change in the temperature of the Bure or Wensum over time. This tends to suggest that the relative importance of baseflow contributions to flow in the Bure and Wensum has not changed. Summer temperatures of spring water in the upper Nar were generally about 4°C higher than in water from the upper Bure or Wensum. This may reflect natural differences between the hydrology of the upper catchments of the Rivers.

Temperature data are consistent with the results of hydrological analyses: the effect of low rainfall during drought is clear. During 1991 and 1992, when catchment runoff made a much smaller contribution to winter flow, water temperatures were similar in upstream and downstream reaches in all three Rivers. The record for the Nar is patchy and short and does not illustrate this well. Although only three years of continuous data are available for the Nar, maximum temperature at Marham increased between 1989 and 1991 and did not in lower sites on the Rivers Bure and Wensum. This may relate to the larger impact of water abstraction from the Nar catchment causing less volume of flow in the River. It is not unreasonable that water temperature has been a recent influence on trout in the upper Nar; temperatures at Castle Acre, which is an important native trout fishery, were 3°C to 5°C warmer in the summers of 1989 and 1990 than during 1985.

Conclusions on Changes in Water Quality.

1. High biological oxygen demand (BOD) in water may compete with the oxygen requirements of fish and invertebrates. Records of the BOD in the River Wensum since 1966, show that there has been no significant change in annual maximum values which have been between 2mg and 4mgl^{-1}5 $days^{-1}$. The record for the Nar is sparse, though from it there is little evidence of a change since 1983. The effect of the drought was to decrease BOD in the Bure from about 3mgl^{-1} to about 2mgl^{-1}. The influence of periodic pollution is reflected clearly in the data record for the Rivers.

2. Annual maximum concentrations of suspended material in the Rivers Bure and Wensum appear to have increased from about 30mgl^{-1} since recording began in 1977, to over 100mgl^{-1} in the late 1980s. Increases in sampling frequency in 1987 suggest that earlier concentrations were underestimated and may have been as high as 100mgl^{-1} throughout the 1980s. Concentrations increased or decreased at different sites during the early period of drought.

3. Since records began in 1975, annual mean concentrations of dissolved phosphorus have increased markedly in the Wensum to values of around 0.55mgl^{-1} in all but the upper site on the River. These increases are due to the influence of sewage effluent. Changes have been less marked in the Nar and in the Bure, where phosphate stripping from STW effluents since 1986 has been effective. The record for particulate phosphorus is short, though a change in the load of total phosphorus (which includes particulate material) in the upper Bure during the low rainfall year of 1990, suggests that diffuse sources of phosphorus may contribute as much as one third of the total phosphorus load in the middle Bure. Diffuse sources may be: material eroded from agricultural land; sediment from field drainage systems or disturbed river banks; runoff from roads or overflow from septic tanks.

4. Annual mean ammonium concentrations in the Rivers Wensum and Bure increased from about 0.1mgl^{-1} in the late 1960s to about 0.2mgl^{-1} in 1987. These increases are probably associated mainly with effluent from sewage treatment works, though effluents from livestock units and food processing works are involved also. Concentrations fell during 1989 and 1990 and, since these were years of low rainfall, this suggests that contributions from the wider catchment are important. Although increases in both Rivers are large, present-day maximum concentrations are not generally high enough to have a significant effect on the success of the coarse fishery. The frequency of contamination of the Rivers has not changed since 1966, though occasional contamination events in both Rivers have been sufficient to affect trout fisheries and it is plausible that there have been sub-lethal effects on the coarse fishery.

5. Records of water temperature in the study Rivers are consistent with the results of hydrological analyses which show no change in the baseflow component of flow in the Rivers Bure and Wensum. Temperatures in upper reaches are typically between 10°C and 15°C, with the lower Rivers reaching annual maxima of around 18°C to 20°C. Temperature changes during the 1989 drought were consistent with low contributions of surface runoff in the lower Rivers. This was because maximum water temperatures in the lower sites during summer were about 5°C lower than in previous years. The difference was larger at about 10°C in the Nar at Marham. There was clear temperature separation between habitats which support trout and which support coarse fish. Temperatures in the upper and middle Nar may have increased since 1989; if this trend continues the trout fishery could be affected.

CHAPTER 3: Section 4. Changes in Channel Dimensions.

Of the study Rivers, the Wensum has supported the largest number of mills and has probably been the most engineered for land drainage and flood alleviation. The distribution of the water mills on the River Wensum is shown on Colour Map 1. The history of water use for milling and its recent disuse, alongside the continued effect of other engineered features, imply that the physical structure of the channel has simplified. This would moderate flow patterns and distribute silt more equitably throughout a river. If changes have been in the direction of a straighter, wider or deeper channel then the biological community will almost certainly have simplified also. Simplification here means comparatively little biological variation between sites, fewer unusual species and restrictions of species which use faster-flowing waters to only a few sites.

The Wensum has been chosen as a case study because of its history of intense river management. This history is not recent. It extends as far back, and perhaps further, than Domesday times when the River was first engineered for water milling.

Section 4.1 Changes in Channel Position.

4.1 (i) Introduction to the effects of changes in channel position.

To provide a sufficient gradient for water power, the river course above mills must be altered. A change in channel position away from the valley bottom to the margins of the flood plain, can artificially produce a greater drop to the mill. The effect of this is to shorten the length of the watercourse.

Repositioning a channel has significant effects on both surrounding land and on the channel itself. If a river is raised above the level of surrounding land its floodplain is drained much less effectively. This has happened at Hempton Fen in the upper Wensum valley. The raising of the channel at Hempton created large areas of marsh, which are shown on Photograph 1, to which a new drainage network was added. These drains lay parallel to the channel, draining back into the River below the next mill site, and were a common feature of the valley. Water was always flowing, irrespective of mill operation. This secondary system of drainage is still in evidence today.

Complicated drainage networks were created at Fakenham, Ryburgh and Costessey Mill. In response to its new position, the River must have adjusted to re-establish its place in the lowest part of the floodplain. This process involves bank erosion. There is evidence of this having occurred before the 1950s: wooden hoardings were constructed on the north bank at Sculthorpe Fen to prevent new meanders from further erosion. The hoardings are still visible today. Any channel deepening by dredging would, however, have tended to reduce the erosive force of the River. The River would, though, continued to readjust laterally in reponse to the initial change in channel position. This implies that dredging of sediment is a commitment which will continue until a new (or probably the former) equilibrium channel position is reached.

Sediment transport rates are affected by channel form. Thorne (1991) considered streams draining bluff hills in the United States and noted that the sediment transport rates increase two to five times in response to the steepening of bedslope due to shortening of the watercourse. However, when reduced resistance to flow and increased channel capacity were also taken into account, sediment transport rate was estimated to be fifty times more than in the former natural channel (Schumm et al., 1984).

4.1 (ii) Changes in the position of the River Wensum.

The position of the main channel of the River Wensum over a period of 800 years has been determined. The earliest information has been deduced from the position of parish boundaries on 1:10,000 Ordance Survey maps. The parish boundaries were established before Domesday and finally confirmed in the early 12th century. The channel position in 1797 has been taken from Faden's map of Norfolk; this is the least reliable of all the sources of data because of the inaccuracy of the original map. The position of the channel at the beginning of this century has been taken from County Series 1:10,560 maps, and the most recent position, from 1970-1980s 1:10,000 Ordnance Survey maps.

Colour Maps 2(a) and 2(b) show channel positions during the different periods. The courses during the 12th century and of the River today are marked on the map. Only areas where the channel followed a new course between 1797 and 1898 are indicated. The course of the River appears to have changed relatively little since the 12th century. The main changes between the 12th century and 1797 were the shortening of large meander loops. These were all related to mill sites, for example at: Sculthorpe; Fakenham; Great Ryburgh; Elsing; Lyng and Lenwade. It is possible that these channel deviations were natural, though because they all appear to be associated with mills, it seems more likely they were the result of engineering. Smaller deviations at Attlebridge were possibly related to a sawmill (now demolished) at Morton Hall or to maintenance of better flows in the main channel.

A major deviation in the course of the River occurred near Tatterford between 1797 and 1898. This change was probably related to a water mill at "Southmill Farm". Other changes in the upper reaches of the Wensum also occurred over the period. Examples are shown on Colour Map 3. The straightening of many small meanders between Tatterford and Sculthorpe, together with a major diversion immediately above Fakenham in the area of Sculthorpe Fen, were probably related to the three Mills immediately downstream. These Mills were at Sculthorpe, Hempton (Gogg's Mills) and Dewing and Kersley's Mill below Fakenham. The straightening of meanders at Little Ryburgh, Great Ryburgh and Sennowe Hall, with smaller changes above North Elmham and near Billingford Common, also occurred at this time. During the latter part of the period, there was a greater awareness of land drainage requirements and it is probable that some of the channel straightening, especially the removal of smaller meanders, was related to flood alleviation.

Only minor changes in the course of the River have occurred during the last 90 years. Between Tatterford and Tattersett, many small meanders and a lake have been removed. Small meanders have also been removed above Fakenham in Sculthorpe Fen, at Great Ryburgh Common, Great Ryburgh Carr, below Bintree Mill, above North Elmham, near Attlebridge, Ringland and Drayton. All these changes are associated with land drainage, often with dredging. Such changes mainly occurred in the period 1953-1957 as part of a *"policy to remove unnecessary bends and ox-bows"* (Rose, 1990) to improve drainage.

Conclusions on Historical Changes in Position of the Wensum.

1. Since the 12th Century and before the end of the 1800s, there were local changes in channel position where large meander loops were shortened for water milling. These occurred at Sculthorpe, Fakenham, Great Ryburgh, Elsing, Lyng and Lenwade.

2. Channel position changes which occurred this century have been on a small-scale and related to land drainage and flood alleviation. The decline of the milling industry and conversion of pasture to arable cultivation changed the emphasis from maintaining the waterways for milling to the interests of land drainage.

Section 4.2 Changes in the Width and Depth of the Wensum.

4.2 (i) Methods used to assess changes in channel width.

Local observations by project consultees have suggested that the channel of the Wensum is narrower than in the 1950s. The aim of this analysis is therefore to discover if the present width of the Wensum is significantly different from in the past. The approach has been to predict River bankfull widths from equations which relate the curvature (arc length) of meanders shown on old maps. Meander arc length and channel width are related closely (Hey, 1976; Hey and Thorne, 1986). One of the main assumptions of the method is that the meanders are no longer undergoing lateral movement. This holds for unengineered parts of the Wensum. Such meanders may represent conditions which existed hundreds, or thousands, of years ago though their shape has remained the same. Some of the larger meanders, such as those of the Wensum at Ringland and Costessey were formed during a period of much greater discharge, probably from melt waters during the last glacial period. Such meanders are not included. The definition of the term "bankfull" is important. The term represents the bankfull situation in times of regular flood and is defined by reference to floodplain level. It is not the level of water usually seen in the River. This has some significance since river width (bankfull) is determined by flows which occur only several times a year.

The following equation from Hey (1976) describes the relationship between channel width and meander arc length:

$$z = 2 \pi w$$

where z = meander arc length and w = bankfull width

By measuring arc length directly from present day (1970-1980s) 1:10,000 O.S. maps, the expected channel widths have been calculated. These are the widths that are in equilibrium with the flows which formed the meanders. Areas where the channel has been engineered into a different position have not been used. Most parts of the present river have been engineered to some degree so relict meanders, which appear on old maps in the position of the parish boundaries, have also been used.

Equilibrium widths have been compared with very accurate measurements of present day bankfull widths made under commission to the NRA during 1993.

4.2 (ii) Historical changes in the bankfull width of the Wensum.

Figure 28 shows differences between predicted and observed bankfull widths. In the middle stretches of the River between Billingford Bridge and Lenwade, the channel is up to around 10m wider than predicted from the relatively few meander arcs which have been assumed natural. In the lowest part of the River, the channel is the width expected from meanders (the analysis did not include the very large meander loops which are in this area). Around Costessey Pits, the River is narrower than expected. In the upper part of the river below Fakenham, calculations from relict meanders suggest that today the River is probably about the same width as it was around the year 1200. Widths predicted from the present-day meander pattern suggest that, since this time, the River has passed through a stage of being 2-3m wider than today.

Results suggest that it is the middle part of the River which is still generally wider than when the meander arcs were formed. This reinforces observations on channel engineering. The tendency of an over-widened river is to return to equilibrium with its flow. This will occur naturally either through narrowing due to sediment accumulation at bank margins, or more likely, by accumulation of sediment on the River bed. Accumulation of sediment in the middle of the Wensum is probably, therefore, part of a natural process of return from a highly engineered channel to narrower and more natural dimensions.

Photograph 2 illustrates channel readjustment at Hempton Fen where a sharp bluff has formed. This bluff represents the former margin of the channel from a period when the River was dredged and over-deepened. In a present day survey, bankfull would be at the level of the bluff.

4.2 (iii) Evidence of channel narrowing from maps and photographs.

At several sites, channel narrowing is evident from comparisons of County Series maps from 1890 and the Ordance Survey 1:10,000 maps from 1970-1980. Change has been in the order of several metres in some places, particularly at disused mill pond sites. Examples of this are at Dewing and Kersley's Mill, the site of the now demolished Gogg's Mill, and at mill ponds in North Elmham, Lenwade and Taverham. Other areas of channel narrowing are also related to mill sites, downstream of Lyng Mill for example. Following the abandonment of mill working, accumulation of sediment at the sites is inevitable in areas engineered to artificially dam large volumes of water. Approximately 5ft heads of water were stored in 12ft deep mill ponds and as a result, the River may have been 25-30ft wide in some areas. Visual evidence of changes in channel width close to mills and the importance of mills in shaping the former character of the River is shown in Photographs 3 to 5.

Photograph 3(a) shows the Wensum above Gogg's Mill and is an example of the influence of mills on river width. Gogg's Mill was at Hempton on the site of the A1065 road bridge. The Mill was demolished in 1957 by the East Suffolk and North Norfolk River Board *"in the interest of drainage and agriculture"*. The photograph is from shortly after the turn of the Century and shows a river more than 10 metres wide. Photograph 3(b) shows that by 1993, the same stretch of river had narrowed to some 2-3 metres. Most of this narrowing has occurred on the naturally accreting slipoff slope on the inner bend of the channel. The removal of the Mill stopped the damming up of water in an artificial watercourse and, with no need to maintain the channel at its former width, natural accretion of the river margins has occurred.

Photographs 4(a) and 4(b) show the difference between Gogg's Mill in 1914, with its large mill pond some 20 metres wide and the same site during 1993, since the demolition, with the River only 3 to 4 metres wide.

Photographs 5(a) and 5(b) illustrate gradual encroachment of vegetation in the mill pond at Dewing and Kersley's Mill between 1905 and the 1990s. Photograph 5(a) shows the size of the pond in 1905. At this time, water power only supplemented steam power. It is probable that before the introduction of steam engines, the Mill pond was wider. By around 1940, gas or diesel engines were used to power the Mill and a photograph of the time shows that the pond was significantly narrower and infilling with vegetation. The Mill has now been converted into housing and the channel has narrowed to the proportions shown on Photograph 5(b).

Some areas of channel narrowing have not been connected with mills. In these, the land drainage engineering works which began in the 1950s deepened the channels, for example at Ringland. In places, over-deepening of the channel for land drainage has caused the River to adjust its sediment carrying capacity to its flow by sediment deposition in channel margins. This, together with the encroachment of bank vegetation, has narrowed channels.

Photographs 6(a) and 6(b) show effects of dredging on sedimentation and river flow at two adjacent sites at Sculthorpe Woods on the Wensum. Photograph 7(a) shows accretion following dredging in the 1950s which probably increased channel width to about 3m. In the photograph, flow appears to be rapid and the River is probably in equilibrium with its discharge. Photograph 6(b) shows the River immediately downstream. This area was also dredged in the 1950s and again in 1989. Water velocity has been reduced and flow appeared sluggish.

Conclusions from Observations on Channel Widths.

1. The middle reaches of the Wensum are wider by about 5 to 10 metres than the bankfull width when meanders were originally formed. This has been deduced from calculations of equilibrium widths from patterns of unengineered meanders shown on old maps. Increases in width have been attributed to channel engineering.

2. The lower reaches of the Wensum around Costessey are slightly narrower than expected from todays meander pattern. Nearby at Ringland Hills, widths are probably about the same as during the 13th century.

3. Recent channel narrowing appears to be a natural process of channel adjustment back to its former width. The distribution of silt in the channel may be related to the process.

4. Observations from 1890 maps and from old photographs illustrate clearly that channel narrowing has progressed since the end of traditional mill working.

5. Channel narrowing is not linked invariably with mill closure. In some places where dredging occured during the 1950s, it is probable that water velocities were reduced enough to create depositional environments. Sediment accumulation in these areas has narrowed the channel and favoured colonisation by bankside plants.

Section 4.3 Influences of River Maintenance on Channel Dimensions.

4.3 (i) Changes in the intensity of weed cutting and dredging.

Assuming from the Wensum case study, that parts of the other two study Rivers are not in equilibrium with their natural form, then all will require constant maintenance. It is possible though that some of the recent changes in the channels are because of changes in intensity of river maintenance. Changes in the intensity of river maintenance are described here.

Earliest records are from the East Suffolk and Norfolk River Board Annual reports (1954-1966). In these reports, annual costings for the maintenance of waterway in Norfolk and Suffolk are given. The costs of weed cutting, shoaling, bank clearance, damage repair and other general maintenance procedures (some relating to coastal sections) are grouped together. However, large-scale dredging works were costed separately. Between 1966 and 1974, the costs of maintaining the tidal and non-tidal sections of rivers were recorded separately in the East Suffolk and Norfolk River Authority Annual reports. For this study, the data used include costs of shoaling, weed cutting, bank cleaning and damage repair, though not major dredging events. After 1974, more detailed descriptions of the type of work carried out are given in the Anglian Water Authority Norfolk and Suffolk River Division Annual reports (from 1978, the Anglian Water Authority Norfolk and Suffolk River Division Local Drainage Committee). Individual rivers are not usually mentioned. The expenditure for this period includes weed cutting, shoaling and dredging. The Annual reports of the NRA (1989 onwards) contain similar details to reports from the Local Drainage Committee. From 1974/75, details on the amount of weed cutting and dredging in the whole waterways have been included.

The format of the accounts changed between periods of different management, so it is not possible to compare expenditure on river maintenance between 1954 and 1991. Three separate periods have therefore been compared after correction for inflation at the beginning of each period.

Figure 29(a) shows that during the 1950s and most of the 1960s, expenditure on river maintenance was fairly constant. Weed cutting effort was probably constant also. However, Capital Costs between 1953 and 1957 show that substantial dredging was carried out in these years. Rose reported that a 5-mile stretch of the Wensum between Shereford and Sennowe Park was drag-lined during the period.

Figure 29(b) for 1966 to 1974, shows a reduction by almost 50% in amounts spent on maintaining the upper waterways. This was possibly related to the introduction of mechanised weed cutting and a real reduction of costs. The change could equally represent a change in maintenance policy for the non-tidal rivers. Following the initial decrease in expenditure, the amount spent on river maintenance increased steadily during the late 1960s and early 1970s.

Figure 29(c) for 1975 to 1991, shows that during the mid to late 1960s, expenditure on river maintenance was fairly constant. A small increase in expenditure occurred during the early 1980s then reduced dramatically between 1983/84 and 1989/90. The amount of weedcutting and dredging during this period is shown in Figure 30 (a) and 30(b).

Figure 30(a) shows that during the late 1970s, dredging of all parts of the system (tidal and non-tidal) fluctuated little, with an average of 30km of river being dredged each year. In 1981/82 there was a large increase in total dredging effort from about 32km per year in 1980/81 to over 70km. The following years saw a considerable reduction. In 1983/84, grants for river maintenance were reduced from 75% to 35%. The following is taken from the operations report for 1984/85 *"The committee are extremely concerned over the reduction in maintenance and reconstruction works now being carried out, compared with what is considered to be the absolute basic necessity to at least maintain standards"*. Severe restrictions continued until 1987, when it was considered that standards of flood defence were unacceptably low. Emphasis has changed from land drainage to flood defence. During 1987/88, Government grants were increased to 45%. The establishment of the NRA in 1989 introduced a new period of maintenance activity. The annual report of 1988 suggests a greater sensitivity to environmental issues in maintenance policy. It is the NRA's duty *"to preserve, and where possible to enhance, the river environment"*. Now, all main river dredging operations are preceded by a biological study. It appears that the financial constraints which reduced the amount of weed cutting and dredging during the 1980s had become desirable for ecological reasons by the 1990s.

Conclusions on Changes in River Maintenance.

1. Changes in rates of sediment accumulation or productivity of water plants cannot be inferred reliably from official records of river maintenance. The history of dredging and weed cutting in the area appears to have depended largely on the availability of money to carry out these works.

2. Since the formation of the NRA in 1989, there has been an increase in dredging activity. It is absolutely essential that operations remove only finer material from the River channels and do not remove underlying coarser material or disturb river banks. This environmental sensitivity is the current NRA policy which is followed by river managers. Field operations must reflect it also.

Overall Conclusions on Changes in Channel Dimensions.

1. Before the 1800s, there were substantial local changes in channel position of the River Wensum to create the gradient needed to power water mills. By comparison, the scale of changes in channel position due to land drainage and flood alleviation has been small.

2. The width of the Wensum today is generally similar to estimates of its width made from 13th maps. A long history of water milling, which was particularly intense during the 18th century, has increased River widths above sluice gates. Since the end of the working regimes of mills, natural processes of accretion have tended to reinstate former channel dimensions.

3. In the upper Wensum, channel narrowing is likely to be an indirect result of engineering works for land drainage carried out during the 1950s by the old River Boards. Where channels were deepened or widened, water velocity must have decreased and depositional environments thus created. Such areas may well accumulate sediments. Where straightening of the channel has occurred, natural processes of bank erosion will tend to return the channel to its former shape. This process implies that sediments from banks have entered the channel.

4. Predictions of equilibrium channel widths made from the shape of unengineered meanders, show that the middle reaches of the Wensum in particular are still wider than expected. This implies that removal of sediment will be a continuing commitment if present River widths are to be maintained artificially.

5. Changes in expenditure on river maintenance since the 1950s do not give information precise enough to infer timing or rates of change in sediment deposition and accumulation.

CHAPTER 3: Section 5. Changes in Biology.

This section address the following questions:

> Have there been changes in the composition of water plant communities ?
>
> Has the composition of benthic invertebrate communities changed ?
>
> Can biological changes be detected in river sediments ?
>
> Has the biomass and distribution of fish changed ?

Section 5.1 Water Plants.

5.1 (i) Information and methods used to detect change.

Water plants of the Wensum were surveyed properly in 1976 (Driscoll 1981; Baker et al., 1978), again in 1985 along part of the lower River (Phillips 1988) and, most recently, in the REDS survey (NRA, 1990). Plants in the Nar were recorded during 1989 for an English Nature river corridor survey. Surveys of the Bure are also recent, with information from 1988 (Anglian Water, 1988) and REDS. Casual observations of plant cover have been made at NRA biological monitoring points since around 1988. Combinations of data from these surveys and observations have been examined. Sites rarely correspond over more than two of the survey dates; this limits interpretation because short-term variations could be interpreted easily and mistakenly, as longer-term change.

There are very few plant data from the past. Analysis has therefore included a comparison between the species richness of the study Rivers and the number of plants which are normally found in the same, or similar, type of environment. The approach aims to discover if the study Rivers support the number of water plants expected for their flow regime and sediment composition. Water plant communities were matched to different types of environment from surveys of over 200 rivers made during the early 1980s (Holmes 1983).

Another approach, which uses water plants as ecological indicators, has been used to detect changes in the plant ecology of the Wensum between the 1976 and 1990 surveys. Numeric 'Trophic Scores', which rate the nutrient status of the usual growing environment of different plants, have been given by Newbould and Palmer (1979). The principle is similar to BMWP scoring for invertebrates, though biotic scores for water plants have never been used for ecological monitoring. Here, Average Trophic Scores per Taxon (ATST) have been calculated for plants at each of the sites surveyed in the Wensum. Values from 1976 are compared with present-day scores calculated from 1990 REDS data. The approach should show if a change in nutrient status has had an influence on the composition of the water plant community. A change in ATST could relate equally to changes in the amount of organic sediment in the River or to annual differences in river discharge or flow velocity.

Unfortunately, plant surveys of the study Rivers cannot help to show if there have been changes in the abundance of plants. They show only if species have been lost or gained. Previous records are often from the casual observations of riparian owners and managers or the observations made by the NRA during invertebrate sampling. These records are unlikely to be complete and probably include only the most obvious species.

5.1(ii) Changes in plant species lists.

The upper reaches of the River Bure have not lost any species of water plant since the early 1980s, and have regained *Zannichellia* since its last record during 1981 (Barham 1981). This plant occurs in nutrient-rich and slow-flowing water. The lower reaches of the River appear to have lost *Ranunculus*, which occurs in fast-flowing clear water, and stands of *Sagittaria sagittifolia* and *Potomogeton pectinatus*. The loss of *Ranunculus* usually occurs if silty sediments accumulate, or if water clarity and flow are reduced over several years. The loss of *Sagittaria* and tolerant species of *Potomogeton* is surprising. These are robust plants which are typical of slow-flowing or nutrient-rich water. Losses of more tolerant water plants suggest that physical disturbances or exclusion by taller emergent plants such as reed and nettles, or bankside trees, are involved.

In parts of the upper Bure, the channel has been colonised by plants which are typical of drier bankside communities. This appears to have begun before the drought flows of 1989. *Phragmites australis* (Norfolk reed), *Apium nodiflorum* and *Sparganium erectum* were recorded in 1989 during routine sampling of invertebrates. A previous record of *Phragmites* in the main channel of the upper Bure at Ingworth Bridge was made during 1976 (Seymour 1976). This shows that, although channel encroachment has been a feature of the recent drought, the same changes probably occurred during the 1976 drought flows.

During 1992, sites in the middle Bure were visited to check observations on channel encroachment. Blickling was chosen because this part of the River appears unaltered by the channel widening typical of the Bure below Aylsham. The extent of channel colonisation by emergents was surveyed and showed that up to 30% of the average bankfull width of 9m was colonised by *Phalaris arundinacea*. This is a tall emergent grass which looks very similar to *Phragmites*. *Ranunculus* was not found at the sites visited, although it certainly occurred during the early 1980s (Barham 1981).

The most reliable comparisons between past and present are for the Wensum between 1976 and 1990. Figure 31 compares species lists for Swanton Morley, which was surveyed in 1976 and Hellesdon Mill. Each site has lost both sensitive and robust species, with few gains. Species lists for all sites and survey dates have been compared and there is no obvious pattern. There have been local gains and losses of *Ranunculus* since the 1970s. This plant was not distributed widely during 1976, perhaps because of drought flows. *R.aquatilis, R.peltatus or R.fluitans* occurred at only three of the sites between the headwaters at Wissonsett and Lyng. Although *Ranunculus* was more widely distributed in 1990 than in 1976, it is still surprising that its present (1990) distribution is restricted to only seven sites upstream of Lyng. The loss of *Zannichellia* from sites in the upper Wensum is surprising since this plant gains a maximum trophic score of 150 on Newbould and Palmer's scale of tolerance to nutrient enrichment. Gains in filamentous algae, particularly *Enteromorpha*, are a feature of most of the Wensum.

Channel encroachment by tall emergent plants has occurred in the middle reaches of the Wensum around Great Witchingham. Local information suggests that this is recent. Encroachment of the channel, particularly by *Apium nodiflorum* (a low-growing spreading plant which looks like watercress), has been widespread in the upper Nar. Figure 32 shows that water plants were absent from two sites in the upper reaches of the Nar during 1990 and that elsewhere, bankside plants dominated the flora of the channel.

Photograph 7 shows *Apium nodiflorum* overgrowing the headwaters of the Bure at Briston during 1992 and the tall grass *Phalaris arundinacea*, enroaching the channel of the upper Bure at Blickling during 1992.

The earliest biological monitoring record for the Nar shows that, during November 1969, *Ranunculus* was growing at Setchey Bridge, which is about 37km downstream. It was recorded in 1973 with *Fontinalis*, though not in 1977 when the water was *"deep and muddy, possibly after weed cutting"*. *Elodea* was noted in 1979 and *Sagittaria* in 1980. *Ranunculus* was recorded again in 1981 and 1982, though there was a note that no vegetation was present in October 1983. After almost continuous notes of gravel and stones until 1984, during 1985 it was noted that very little gravel was exposed and that filamentous algal growth was excessive. The last record of *Ranunculus* was therefore during 1982. The 1990 river corridor survey records *Callitriche stagnalis* as the only water plant at the site with *Apium*, *Glyceria fluitans* and bankside plants. The ecology of these plants is so different to *Ranunculus* that its loss is certain to be permanent or, at least, long-term. *R. pencillatus* still ocurrs around Narborough, which is about 24km downstream.

The loss of *Ranunculus* from Setchey Bridge seems associated with accumulation of sediment. This could have been due to bank disturbances during channel widening for flood alleviation. Information on the fishery of the Nar shows that between 1983 and 1985, there was a very large change in the distribution of roach in the River. This was associated, by fisheries staff, with channel widening near King's Lynn. The early 1980s was also, however, a period of decline in the frequency of high-flow events (measured as the number of days when flow exceeded the long-term Q10). This means that the River's sediment load may not have been flushed downstream as effectively as during the middle 1970s. Instead, sediments would have accumulated and this would have exaggerated the biological consequences of any upstream engineering.

5.1(iii) Comparisons with species richness in similar rivers.

The species richness of river plants (which includes bankside and water plants) in each study River is compared with the richness typical for their particular river environments in Figure 33. The river environments have been classified by Holmes (1983). During the 1980s, the headwaters of the Bure and Wensum had fewer in-stream plants than comparable rivers. The largest deviations between the observed and expected number of species were in spring fed reaches, small chalk stream type environments and fast-flowing stretches on mixed substrata. This shows that, even in the early 1980s, the plant communities of the upper reaches were below their potential species richness. If any long-term change in community composition of water plants has occurred in the Wensum and Bure, it happened before the decade of the 1980s.

The pattern is different for the Nar. Here the upper reaches supported as many species as typical spring fed streams on clay, and, in the next stretch, more species than a typical chalk stream. The plant community of the River Test in Hampshire had an important influence on the definition of typical. The next stretch, which is the third river environment shown on Figure 33, is also classed as a small chalk stream. This is probably the middle reach above Marham. Here, water plants were less well represented than in comparable rivers. The pattern in the Nar thus suggests that, if the plant community in the middle reaches has changed, this occurred before the 1980s and before information on the former community exists. The plant community of the upper Nar was probably intact during the early 1980s.

The lower parts of all three Rivers are classed as fen, canalised or highly managed (Holmes, 1983). In the early 1980s, almost all these stretches had richer than average plant communities. During 1985, water plants typical of fenland rivers were still well represented between Taverham and Norwich (Holmes, 1985; Phillips, 1988).

5.1(iv) Changes in trophic scores of water plants in the Wensum.

The Average Trophic Scores per Taxon (ATSTs) of water plants recorded in the Wensum during 1976 and 1990 are shown in Table 3.8. These values are the total of the trophic scores for each plant at the site divided by species richness (the number of different species there). The mean ATSTs for several sites show that there has been no significant change since 1976. A possible reduction in ATST ($p<0.10$) between Fakenham and Bintree Mill was due to a new record for *Ranunculus aquatilis* at Sennowe Hall. There was no change in the rate of downstream increase in cumulative ATST between 1976 and 1990. The shape of the curves implies that the influence of water quality or sediments does not vary greatly with distance downstream. This pattern probably reflects the remaining influence of mills on water depth, channel width, water velocity and sediments on the usual downstream succession of plants.

Table 3.8 The mean±s.d. Average Trophic Scores per Taxon (ATST) and species richness of water plants in the River Wensum during 1976 and 1990.

Reach	Number of sites		mean ATST		mean species richness	
	1976	1990	1976	1990	1976	1990
U/S Fakenham	4	4	129±3	121±8	5.8±2.3	6.5±1.7
Fakenham to Bintree	5	5	124±2	115±12	6.4±1.5	4.2±1.3
Bintree to Billingham	5	5	125±5	118±6	7.0±2.7	7.4±2.1
Billingford to Lyng	6	6	125±12	121±11	5.3±3.6	4.0±1.7
Overall the Wensum	20	20	125±7*	119±9*	6.1±2.6	5.4±2.2

* Difference significant at $p<0.05$

Generally, changes in the trophic scores of plants in the Wensum show that the plants of 1990 reflect a lower nutrient status than in 1976. This suggests that neither flow nor water quality have been major influences on the species list in any of the four sections of the River. The similarity may also be because both surveys were carried out in drought years. If short-term drought has influenced both species lists, then it follows that the effect on the water plant communities was similar during both droughts.

Conclusions on Changes in Water Plants.

Interpretation of plant data relies upon species lists and not on information about plant density, biomass or productivity. Data useful for assessing changes in plant performance do not exist.

1. Water plants typical of the lower reaches of comparable rivers are well represented in all three study Rivers. There is some evidence of change in the plants communities of the middle and lower Nar; this probably occurred during the 1980s.

2. Since the mid 1970s, some Wensum sites have lost plants which normally tolerate nutrient enrichment. This suggests that other factors, such as physical disturbance, are involved in local losses.

3. Changes which have occurred in the species lists of the upper Bure and upper Wensum are consistent with the ecological effects of sediment accumulation.

4. Bankside plants colonised channels during 1989 and 1990. This appears to be a feature of recent drought. Invasion by bankside plants has been particularly marked in the upper 13km of the Nar, in the middle stretches of the Bure at Blickling and at Great Witchingham in the middle Wensum. Such changes in the upper Nar are undesirable because they are at the expense of in-stream plants which have a very high conservation value.

5. Colonisation of the channel in parts of the Bure and Wensum are ecologically desirable. This is because channel narrowing results in local increases in flow velocity and thus, in habitat diversity. Shoals which form after periods of low-flow should not necessarily be removed.

Section 5.2 Benthic Invertebrates.

5.2 (i) Information and methods used to detect change.

Biotic scoring of invertebrate samples can be used to summarise community response to environmental conditions (Hellawell, 1986; Frogley, 1991). High BMWP scores usually describe communities which are sensitive to deoxygenation. Sensitive communities tend to be replaced by groups of more tolerant animals when the organic or nutrient content of water rises, or when there is less oxygen in water because of lower flow velocities. Communities most able to tolerate low concentrations of dissolved oxygen (and so are typical of silty reaches) usually have lower BMWP scores.

Detailed invertebrate records for four sites on the Bure, five sites on the Wensum and five sites on the Nar have been made since at least 1980. Time series of BMWP scores, Average Scores Per Taxon (ASPT) and the abundance of a set of indicator invertebrates, which cover a range of scores, have been produced. Indicator species are from groups which are found over a range of flows from fast to the slower-flow environments where organic sediments are likely to accumulate. The results are able to reveal changes in the composition of the benthic communities at the monitoring sites; they cannot be used to detect changes in the extent or distribution of different communities in the study Rivers as a whole.

TWINSPAN analysis has been used as a further tool to identify changes in invertebrate communities. The analysis can only describe changes at the sites where information has been collected. It cannot show if there have been changes in the distribution of different animals in the Rivers. The approach can be used to group sampling sites according to the similarity of their invertebrates and has been used fairly widely in the Anglian Region (Harper et al., 1992; Petts and Bickerton, 1992). The programme has been run for the study Rivers with species information from all sites on all sampling dates, then separately for the three Rivers and finally with information between 1980 to 1988 for comparison with a separate run for 1989 to 1990. The results of these three treatments describe the composition of the most widespread communities in the study Rivers and then show if there are differences between Rivers or over time. Inferences about environmental conditions can then be made from the types of animals which are most representative of the different communities. These inferences are tested in the next Chapter of the Report using detrended correspondence analysis (DECORANA).

5.2 (ii) Changes in BMWP scores.

The BMWP scores for all the monitoring sites in the study Rivers on all sampling occasions since 1979, are shown in Figure 34. Only 5% (since $r^2=0.05$) of the variation in BMWP can be attributed to a variable which has changed consistently over time. For the Rivers Bure and Wensum, there is a trend of slight increase until 1987 and then decrease. This is similar to the trend found in the River Glen (Petts et al., 1992) and may be due to changes in sampling programmes that occurred around this time.

The pattern has not been the same for the three Rivers. This suggests that the overall influence of climate-related changes in temperature, drought or flooding is not the most important influence on the composition of invertebrate communities.

The BMWP scores in the Nar have varied with time more closely. Scores have decreased significantly since about 1983. About 30% of the change in BMWP score varies with a time-related variable. This implies that most (70%) of the variation is linked with short-term events. In the Bure and Wensum, all of the variation over the 1980s was short-term.

Although BMWP scores provide a useful biological summary, the results of time series analysis cannot be interpreted precisely. An unchanged score in the Bure or Wensum could, for example, reflect increases in the variety of average-scoring animals at the expense of a few highly sensitive animals. Changes in populations of the most sensitive animals, for example the mayfly, *Ephemerella ignita*, are a much better indicator of both long-term and shorter-term environmental change. Figure 35 shows changes in the abundance of *Ephemerella ignita* at Ringland Bridge on the River Wensum. Other taxa which have different environmental tolerances are also shown. Assuming that the actual number of animals in each sample was the minimum number in each abundance class, regression analysis of data in Figure 35 shows that the number of mayflies at Ringland Bridge has not changed significantly over the last ten years. However, their abundance during 1989 and 1990 was lower than in preceding years by up to two orders of magnitude. This is evidence of a short-term ecological change. Annual variations in other taxa have certainly occurred, though are superimposed on time-series for the decade which have invariably shown no significant change.

footnote:
notes on the ecology of animals used
as habitat indicators are in Appendix 4.

Table 3.9 shows that BMWP scores in the Nar have reduced significantly ($p<0.05$) since 1979 in three of the four sites shown. In these three sites, sampling month did not relate significantly to the score, though there were very weak ($p<0.15$) direct relationships. This means that BMWP scores tend to increase during the year and inclusion of samples from every month in the analysis has therefore tended to exaggerate any decline. Decreases in BMWP score since 1979 have been large and fairly consistent though and are likely to have overridden seasonal effects on scores. There has been a recent change in NRA sampling regime where each site is sampled more often although fewer sites are sampled. This will improve the basis for comparisons between years. The sampling site at Litcham was unusual in that BMWP scores have not changed significantly since 1979 and have tended to decrease ($r= -0.56$, $p<0.10$) rather than increase towards the autumn.

Table 3.9 BMWP scores for the invertebrates sampled from four sites in the River Nar since 1979. Sites have been chosen to represent most of the length of the River. Correlation coefficients (r) are between BMWP score and time in years and month.

		Setchey Bridge	Marham Intake	West Acre	Litcham
		BMWP score			
Sept	1979	117	184	145	95
	1980	140 (Nov)	166 (July)	166 (July)	74 (Nov)
	1981	138 (Sept)	167 (July)	162 (July)	85 (July)
	1982	132 (July)	195 (July)	153 (July)	118 (June)
	1983	92 (Oct)	160 (Oct)	152 (Sept)	-
	1984	162 (July)	184 (July)	185 (July)	66 (Oct)
Sept	1985	91	142	177	-
	1986	84 (Sept)	-	191 (July)	-
	1987	121 (May)	180 (May)	129 (March)	180 (May)
Feb	1989	57	149	132	149
March	1990	85	89	110	89
	1990	85 (June)	146 (June)	104 (July)	146 (June)
Oct	1990	92	117	122	117
May	1991	68	114	133	114
		$r=-0.7086$ $p<0.01$	$r=-0.7524$ $p<0.01$	$r=-0.5975$ $p=<0.05$	$r=-0.4809$ N.S.

There has thus been a change in the invertebrates of much of the Nar. Reductions in BMWP suggest a shift in the invertebrate community toward increasing tolerance to lower oxygen concentrations in the sediment on the river bed. Because of the relatively high BOD of organic sediments this is consistent with accumulation of these sediment on the River bed.

Similar analyses for the Rivers Bure and Wensum shows that since 1980 the invertebrate ecology of these Rivers has not generally changed. These results do not however imply that there have been no changes in the distribution of the communities or in the total abundance of animals in the Rivers. The results can only show that changes have not occurred at the sampling sites.

5.2 (iii) Definition of invertebrate communities using TWINSPAN.

TWINSPAN analysis has identified two major community types over all three Rivers, Table 3.10. Of all the twenty-four sites, which are represented by 176 samples between 1980 and 1991, about half supported community 1. Community 1 is dominated by insects, mostly caddis flies and community 2, by snails associated with either plants or stones. The habitat notes on Table 3.10 show that the communities tend to be typical of either faster-flowing or slow-flowing river environments. Damselflies belonging to the family *Coenagriidae* were the strongest indicator group: they hardly ever occurred in community 1, which is typically found in more upstream-type environments and were almost always present in community 2, which is typical of more silty downstream reaches. Damselfly nymphs are invariably associated with the emergent leaves or stems of water plants or bankside vegetation which are most typical of lower reaches.

The same two community types are found in each of the study Rivers. In the River Bure, the 'upstream' community occurs at all monitoring sites except Horstead Mill and is well represented in the upper Nar between Mileham and Marham. Only Sculthorpe Mill and Billingford Bridge, which are the two upper sites on the Wensum, support community 1. This shows that during the 1980s, habitats in the lower Nar and in most of the Wensum have generally supported invertebrates typical of slower-flowing water emergent, probably mostly bankside plants.

Table 3.10. Classification of the benthic invertebrate communities of the Rivers Wensum, Nar and Bure using biological monitoring data collected during the 1980s.

Community 1		Community 2	
Family	Usual habitat	Family	Usual habitat
Hydropsychidae (5)	fast running water	Coenagriidae (6)	still or flowing water
Rhyacophilae (7)	running water	Lymnaeidae (3)	still or flowing water
Ecdyonuridae (7)	running water	Neritidae (6)	rivers and lakes
Ancylidae (6)	rivers and still water	Physidae (3)	widespread
		Valvatidae (3)	still or flowing water
*Tipulidae (5)	widespread	Ascellidae (3)	stagnant or slow-flow
*Simuliidae (5)	fast running water	Planaridae (5)	still or slow-flowing
*Leuctridae (10)	stony streams		
*Polycentropidae (7)	still or flowing water		
*Leptoceridae (10)	still or flowing water		

* Present occasionally BMWP scores on the standard scale of 1-10 are shown in brackets

Invertebrate data for the Bure and Wensum from the drought years 1989 and 1990 were pooled and analysed separately. The upstream community-type 1 occurred no less frequently between 1989 and 1990 than between 1987 and 1988 or between 1980 and 1986.

footnote: Common names for the families shown on Table 3.10 are in Appendix 4.

5.2 (iv) Changes in the abundance of indicator invertebrates.

The pattern of annual abundance of indicator invertebrates that were shown in Figure 35 showed little similarity between the Rivers Wensum and Bure. Each year there was, however, a weak, though direct, correspondence between the numbers of invertebrates in the upstream and the downstream site on the Wensum. Although none were more than 85% significant, correlation coefficients for all five taxa found in both sites on the Wensum were between 0.45 and 0.55. In the Bure only two of the six taxa, the Haliplidae ($r=0.81$) and Tubificids ($r=0.50$), varied together. This may reflect the larger diference in water temperature between up and downstream reaches of the Bure. It may also imply that habitat features other than water temperature vary more over the length of the Bure than over the Wensum. The pattern of correlations implies that in the Wensum, about half of the variation in the community is due to habitat features that are similar in upstream and downstream environments.

A conclusion from this is that habitats in the Wensum vary less with distance downstream than in the Bure. This is probably true, though it is in part a natural difference between the Rivers. The upper parts of the Bure are naturally chalk stream type environments. Although the upper Wensum is naturally springfed, the catchment is underlain by clay. An outcome of this may be that invertebrates in the Wensum are the more sensitive to short-term changes because a smaller variety of habitats is represented. This is because different habitats have different sensitivities to environmental change.

Conclusions on Changes in Invertebrate Communities.

1. There has not been a persistent change in BMWP scores in the Bure or the Wensum over the 1980s. This means that, in general, any changes in the types of animals present do not reflect ecological changes which have persisted over the decade.

2. Over the same period, there has been a reduction in the BMWP scores at monitoring sites in the Nar. The direction of change suggests that organic sediments have accumulated over the recent decade or that nutrient enrichment has occurred. Both of these changes are likely to be associated with flow velocities or periods of low river discharge.

3. In the Bure and Wensum, the abundance of taxa most sensitive to environmental change was low during 1989 and 1990, even though there was no significant change over the decade. This shows that the community was sensitive to short-term changes associated with drought, though not to any underlying trend in flow.

4. Animals in the Wensum are more prone to short-term changes than in the Bure. Variations in the abundance of animals were similar in upstream and downstream sites in the Wensum. This was more marked than in the Bure and so implies a greater similarity of habitats throughout the Wensum.

5. There was no correspondence between the Wensum and Bure in patterns of annual abundance in downstream reaches. This means that local factors, which are probably related to physical habitat structure, rather than climate-related changes in temperature or flow have the greater effect on community composition.

Section 5.3 Tracing Biological History from River Sediments.

5.3 (i) Principles of the approach.

Ecological history can be inferred from changes in the types of biological remains found at different depths in relatively undisturbed sediments. The approach is only reliable if any layering of remains really does represent a time series, and is not because of mixing by burrowing animals or any other physical disturbance. Although the approach is often used to trace past changes in lake ecology, it is not very promising for disturbed riverine environments. Nonetheless, it is possible that in the study Rivers, sediments which have accumulated above water mills and have not recently been dredged, contain an interpretable record. Cores of material from above the Mills at Bintree and Hellesdon and at Ringland on the River Wensum have been examined. Microscope work has shown how the relative abundances of plant, diatom, insect, snail and ostracod remains change with depth. Pollen was not found in any of the samples. The outer cases of diatoms (which are a type of algae), preserve well in sediments. Pennate forms of diatom and molluscs are usually associated with plant beds. Insect larvae, apart from Chironomids, often have higher demands for oxygen than other invertebrate taxa. Large changes in the density of their remains can therefore imply changes in water oxygenation perhaps as a result of changes in flow velocity.

5.3 (ii) Changes detected in the sediment record of the three sites.

Bintree Mill

Of all sites on the study Rivers, Bintree Mill (19km downstream) was the site most likely to have retained an interpretable record. The sediment immediately above one side of the Mill gates had not been dredged for about 50 years (P.Seaman, personal communication). Despite evidence of layering, particularly of insect remains (Figure 36), the pattern did not represent an undisturbed time sequence. Sediment was oxidised to the bottom of the 40-cm core and living chironomid larvae and oligochaetes were present throughout. This suggests vertical mixing of the sediment. Plant remains were abundant at all depths and there is no evidence from the core that there has been any change in the density of water plants. The casual observations of the Mill owner also suggest that plant cover at the site has not changed.

Ringland Hills

The stretch of the River sampled at Ringland (about 52km downstream) had not been dredged for around 30 years (R.Francis, personal communication). The substratum is coarse sand with a surface film of fine silt. Until the late 1970s, the sampling area was noted by anglers as a good roach fishery. A supposed decline in the fishery began after this and has been associated locally with sudden influx of large amounts of sand which is thought to have caused losses of water plants.

Organic content of sediment from the site increased with depth, and water plants and their associated molluscs appear to have been more abundant in the past. The top 30cm of the sediment contained only sand with no insect, ostracod or plant remains. Plant, snail and plant-associated diatom remains were present below this and so suggest that water plants were more abundant in the past. It is probable that large quantities of sand were disturbed and deposited in this part of the River about 10 to 15 years ago. This corresponds approximately with 1976 so could have been associated with the high frequency of high-flows which followed the drought. Local engineering to stabilise banks has been a feature of this part of the River. Evidence from the core is certainly consistent with an influx of sediment from physical disturbances to the River.

Hellesdon Mill

Sediment retained by the sluice gates of Hellesdon Mill (62km downstream) had not been dredged for at least nine years. The rate of net accumulation, averaged over this period, may therefore have been around 3cm per year. Living oligochaetes were common at all depths, so the sediment was probably fairly well-mixed, though there was evidence of layering of plant remains and snail shells. If these layers represent a time-sequence, then an increase in the abundance of plants has occurred over the last ten years. The proportion of organic carbon decreased with depth and algal filaments were the most abundant remainder of former plant communities. These lower layers contained the highest proportions of sand and few, if any, animal remains. Evidence from this core, which was taken about 7km further downstream than Ringland, was thus consistent with the local observations of high loads of sandy sediment made further upstream. Fragments of brickwork occurred in an undisturbed layer between 20cm and 25cm and coincided with declines in the numbers of both plant and mollusc remains. Small fragments of copper were found at the same depth.

Conclusions from Analysis of Sediment Cores.

1. Biological remains in sediments trapped above water mills cannot provide an accurate record of biological change because shallow organic material is mixed by living invertebrates.

2. Changes in the particle sizes of sediment with depth seem to provide a reasonably accurate history of ecological change caused by physical disturbance. These disturbances may be due to bank engineering, to dredging of the channel, or perhaps to removal of sluice gates or other flow retaining structures. Evidence suggests that during the mid to late 1970s, coarse sand was disturbed and was deposited in the channel at Ringland and transported as far downstream as Hellesdon Mill. This sandy phase was not well-mixed and, since it contained few plant or animal remains, suggests that a single event reduced the species richness of the site.

Section 5.4 Historical Records of the Fisheries of the study Rivers.

Historical information is from the notes, memoirs and published works of local naturalists. Unfortunately, the work of Paget, one of the best known naturalists of Norfolk, deals exclusively with marine fish. More recent information is from a newspaper archive from 1953 to 1957 and 1966 to 1983 which was begun by Mr Quentin Bitten a regional fisheries officer, trout returns made to the NRA, minutes of the Fisheries Liaison Committee, annual reports of the River Boards and River Authorities and personal records of fly fishers. Both anglers and fly fishers have been interviewed. These interviews provide valuable observations, though few written long-term records of catches are described using standard units. It is difficult to make reliable comparisons between years that are based on observations made by different fishermen.

Data have been collected in standard form by NRA and Anglian Water electro-fishing surveys which have been carried out routinely since 1981. The method involves stop netting and fishing successive stretches according to successive depletion models. Fish are identified, counted and weighed. The length of individuals from different size classes is measured and later plotted against the age of the individual calculated from samples of scales. From this information, growth rates and the relative proportions of different age classes can be deduced. Each of the study Rivers was surveyed three times during the 1980s.

The results of the surveys have been examined here to find out if there has been a persistent change in fish biomass over the decade and if the downstream distributions of fish have changed. Changes in downstream distributions of the different species are particularly interesting because they may well relate to changes in the extent of usable habitat.

One of the problems with interpreting data for the study Rivers is that roach, dace, chub, trout and barbel are stocked artificially. Stocking location or the number of fish added are not documented in fisheries reports. Gudgeon are not stocked and few are removed by anglers; this species should therefore be a reliable indicator of habitat change. Gudgeon use faster-flowing water and usually spawn on clean stony substrata. Patterns for the other species are compared with patterns for gudgeon. Changes in the biomass of eels are compared with other species because, unlike all the other fish, eels do not depend on rivers for spawning habitat. A persistent reduction in the biomass of eels might indicate restrictions in food supply or possibly obstructions to their upstream migrations. An increase in eel biomass, though not in other species, suggests either low spawning opportunity or poor recruitment of the other species. Increases in eel biomass relative to other species, can also suggest decreasing habitat variety since eels have more flexible habitat requirements than most other species.

5.4 (i) Earliest records of the fish communities.

Sir Thomas Browne (1605-1658) noted that *"the trout is but scarce in our* [Norfolk] *rivers, but frequently taken in the Bure or north river and in the several branches thereof and very remarkable crawfishes to be found in the river which runs by Castleacre* [the Nar]."

Sir Thomas did not mention the Wensum, nor the reputation that Nar trout had gained by the turn of the seventeenth century, though an interesting comment on salmon appears in the same memoir. Salmon were *at one time* visitors to Norfolk's rivers. The Norwich Court of Mayoralty book records that, in 1667, in an effort to conserve salmon populations, a close season was ordered. This shows that human impacts on fisheries ecology of Norfolk rivers were of concern, even during the 1600s.

The next significant records are from 1905 by Arthur H. Patterson. A manuscript for Patterson's 'Fishes of Norfolk' contains the many species lists which he contributed to the Proceedings of the Norfolk and Norwich Naturalists Society. Fresh water species are often recorded, though almost invariably from the Norfolk Broads and tidal reaches of the Rivers. Upstream, though unnamed, sites were mentioned only once in the manuscript. He recorded that the Rivers Bure and Yare supported *"notable populations of native trout"*. The reference to the Yare is puzzling. It is plausible that this referred to the Yare (Wensum) above Norwich.

The next useful information is in E.C. Keith's book on 'Trout Streams in Norfolk' (1936). This is a narrative documenting the channel widening, dredging and stocking of a three mile stretch of the Whitewater tributary of the Wensum during the 1920s. The introductory chapter comments on the general status of trout in Norfolk. *"So far as I know there are only two trout-breeding rivers in Norfolk, and by that I mean rivers which require no artificial stocking. One is the Nar ... and the other the Bure... It is only above Aylsham that the trout fisherman comes into his own. Here it is all good clean trout water and perhaps the most prolific stream we have ..... In the breeding streams trout generally run small, but in those which rely on artificial stocking they grow faster and to a much greater weight."*

A second interesting set of comments by Keith compares Norfolk's rivers with the well known trout rivers of Hampshire. *"The growth of trout in the Itchen or Test is out of all proportion to that in Norfolk or perhaps any other county, although, as far as I can see, the food is very much the same and there is ample supply of it in both cases. It has been stated on excellent authority that the characteristics of the Nar are very similar to the Test, but the growth of trout, or their ultimate weight, is in no way comparable"*

The comparison of the Nar and the Test does not take into account that the Nar is a much smaller river, even compared with the uppermost reaches of the Test. Keith goes on to suggest iodine deficiency (a fashionable explanation for many ills at the time) and inherent features of the native fish as plausible explanations for differences in growth rates between the Wensum and Hampshire rivers. Predation of trout by pike was stated as the largest, though manageable, problem in the Whitewater.

Comment on coarse fish in the study Rivers is almost non-existent. This perhaps reflects on the interests of gentlemen naturalists. The first record of chub in the Wensum dates back to its introduction in 1943. Lubbock states that *"Chub is entirely unknown in the Bure, Yare and, I believe, the Waveney and is very large in some Norfolk rivers ... the Ouse, the Thet and the Wissey"*. Other than this, there is little historical evidence of the past distribution and productivity of coarse fish.

Conclusions from Early Fishery Records.

1. The earliest records of fish in the study Rivers suggest that, although the upper reaches certainly provided spawning habitat, they did not have a reputation as important trout fisheries. Native populations appear to have been strongest in the Bure above Aylsham and in the Nar around Castle Acre, though not in the Wensum. It seems that the Wensum attracted development as a trout fishery from around the turn of the Century.

2. Early records suggest, especially for the Wensum, that the Rivers' natural trout stock would not have satisfied the demands of fishing syndicates who, around the turn of the century, focused on the study Rivers as under-exploited fisheries.

3. Patterns of fish distribution today are broadly similar to the relative distributions in the past. Populations intended for organised fly fishing seem always to have been sustained by stocking.

5.4 (ii) Fisheries records from newspaper archives.

Local and angling newspapers refer to the Wensum much more often than the Bure, where there were only twelve records nearly all for roach, and to the Nar hardly at all. This, to an extent, reflects public access to the Rivers. Very few specimen or winning weights have been recorded from the Bure, and only a single reference to the Nar was made when it was described as a trout stream. The best weights for the year have been selected and are shown for the Wensum in Figure 37. No archived material was found for the years 1958 to 1966, so there is no information at all for the early 1960s. Over the period that is described, eight species of coarse fish were recorded from the Wensum and five from the Bure. About 35% of all the records of individual weights were for roach.

Reports from the late 1960s show the lowest weights of roach. This might be expected during a period still affected by the diseases that were widespread earlier in the decade. During both the 1960s and 1970s, roach weights were lower in the Bure than in the Wensum; the best weight recorded in the Bure over the period was in 1978 at 2lb 15oz. By the mid 1970s, specimen roach of 3lb and over (3lb 2oz) were fished from the Wensum and best weights of roach appear to have increased ($p<0.06$). There were usually more reports in years when the largest fish were caught. This is not surprising. The observation suggests that angling pressure at the time did not alter the size class distributions of the fish.

Dace in the Wensum have reached specimen weights, with records of 1lb 2oz and of 14oz in 1972 and 1973. The small number of dace compared with roach records may reflect the greater 'trophy' value of roach.

From around the mid-1950s, bream of around 6lb were found in the Bure. There were no records of bream from the Wensum until 1977. During the mid-1970s, best bream in the Bure varied between 10lb and about 3½lb in successive years and a similar scale of variation occurred in the Wensum during the early 1980s. In all, only four records, spanning a period of thirty years, were found for the Bure. The bream stock is therefore likely to have been small. Project consultees have described loss of bream from the middle to lower Bure. Bream have certainly not been found in the middle Bure since quantitative surveys began in 1981. Bream tend to use deeper waters on the outside of meanders and above mill gates. In the past, fishes from Gunton Lake used to migrate to the Bure at Buxton Mill at times of flood. During the early 1970s, sluice gates were opened on the Bure whilst works were being carried out at a mill not far above Horstead in an area known as Bream Corner (Wilson, 1974). A stretch of the River was drained and any fish which survived were washed out of the River. Their population has not re-established.

Weights of barbel, which were introduced to a short stretch of the lower Wensum during the early 1970s, increased steadily over the 1970s. It is very likely that these weights, which span ten years, are for successive age classes of the original stock. It seems that the reputation of the Wensum for barbel has always been based on a very small number of fish. A few young fish were found in the River during the 1980s; unless these fish were stocked illegally, spawning did occur in the River during 1976 (a drought year) and 1982/1983. It is of some interest that barbel stocked into the Severn during the 1950s, became dominant within ten years. In contrast, barbel have shown very little reproductive capacity in the Wensum. This suggests that spawning habitat was restricted in the 1970s and that any change that this represented cannot, therefore, be a recent feature of the River or a result of its recent management.

Best weights of chub peaked during the mid-1970s and, although individual weights varied between 3lb 10oz and 5lb 5oz in the early 1980s, there has been no longer-term change.

Weights of the native predators perch and pike, show marked contrast. There have only been five reports of perch catches from the Wensum and only until 1978, when the best weight was 2lb 12oz. The few weights of perch that are reported have not changed over time. Public consultation has suggested that perch numbers have declined. This probably reflects outbreaks of perch disease. Numbers have not since recovered. In contrast, weights of the largest pike caught have increased fairly consistently since the 1960s. A 29lb fish was caught in the Wensum during 1977/78. The two largest pike caught in the Bure in 1982 (30lb) and 1983 (24lb 8oz) were comparable with the weights of Wensum pike.

No records of Bure trout were found in the archive. Wensum trout varied between 4½lb in 1953 and 1968 and 7lb 15oz in 1971 and the weights show a weak trend of increase ($p<0.15$). Large trout have been recorded consistently and this suggests that feeding opportunity was not restricted over the period. A weight was last reported in 1976. Presumably, weights since 1976 have not been newsworthy. Information from elsewhere (the records of John Wilson) certainly shows that large trout still occur.

Conclusions from Newspaper Archives.

1. Newspaper articles since the 1950s have continued to emphasise the importance of the Wensum as a coarse fishery, particularly the stretches around Ringland, Costessey and Hellesdon where access is public. Apart from during the 1960s, when there were national epidemics of roach disease, the best weights of roach from the Wensum have been over or around 3lb. Best weights of Wensum roach have tended to increase since the 1970s.

2. Since the mid-1950s roach have been consistently smaller in the Bure than in the Wensum. Next to no information about other species in the Bure has been recorded. This shows that either the Bure did not support a notable fishery in the 1950s or 1960s or it may reflect the generally private land ownership pattern in the middle Bure.

3. The best weights of barbel, pike and trout in the Wensum have increased through the period and there has been no significant change in the weights of chub.

4. Noteworthy perch were recorded in the Wensum and large bream were found in the Bure until the mid-1970s. There have been losses of perch and bream, though the fish were not distributed widely in the Rivers during the 1950s and 1960s. There has been a recorded case of loss of bream from the Bure due to improper opening of mill gates. This case illustrates just one aspect of the powerful influence that mills have had on fisheries.

5. Loss of water plants has not been an important theme in newspaper reports. Instead, excessive plant growth, which is a problem for anglers, was referred to often. High plant productivity is a usual feature of the early stages of nutrient enrichment of water. It is not possible to infer from the records whether or not this represented a change from former conditions.

5.4 (iii) Information from club and personal records.

Figure 38(a) shows records from the Castle Acre Fly Fishing Club on the River Nar. Trout are not stocked at Castle Acre, which contrasts with Abbot's Hall Fishery at Ingworth on the Bure (Figure 38(b)), where between 400 and 800 trout have been added every year since 1981.

There have been declines in both the numbers and individual weights of wild trout in the Nar since the late 1970s. The size class distribution of fish caught between 1977 and 1991 has changed with a convincing shift toward smaller sizes. The numbers of fish caught per unit effort by the same fisherman has decreased from five to two from 1977-1983 and to one fish of less than 1lb in each of the last two years. The number of fishing visits made by Club members has decreased markedly since the early 1980s which could reflect social change as much as any change in the fishery. The pattern of decreases in the number of larger fish caught is consistent with feeding stress, although it is also a classic effect of over-fishing. Restriction of spawning habitat or low recruitment of younger fish would instead tend to decrease the relative proportion of smaller fish. If over-fishing is involved, weights might be expected to recover in years after a decrease in fishing intensity.

The pattern at Abbot's Hall on the River Bure (Figure 38(b)) is easier to interpret: the number of fish taken depends upon the number stocked. An interesting feature of the results is that, since 1985, there has been an increase from about 50% to about 75% in the proportion of the stock that is caught. Since the relationship between stocking and the number of visits made has not changed, this is evidence that either fish are easier to catch or that fewer emigrations to either up or downstream have occurred.

Field visits made to Ingworth during this project have shown that this stretch of River is structurally simple with very few water plants and little bankside cover. Local information and an independent study commissioned during 1976 (Seymour, 1976), suggest that there were losses of *Ranunculus* and *Callitriche* before 1976 and replacements of these fast-flow indicators by filamentous algae (*Enteromorpha*) and pondweed (*Potomogeton spp.).* Minnows must have been common since they were noted as one of the features of the site. Changes at Ingworth, which have not since reversed, have thus further simplified short stretches of the River which appear to have been widened (and thus simplified) artificially. Silt accumulation was a problem in 1976 and local opinion has associated this with closure of sluice gates at Aylsham Mill.

Conclusions from Club and Personal Records.

1. Case studies of two sites at Castle Acre on the Nar and Ingworth on the Bure have shown decreases since about 1980 in either the size or number of trout caught. Shifts toward smaller trout in the wild populations of the Nar are consistent with increased fishing intensity. If this is so, then results of NRA fisheries surveys made during the 1980s and after presumed decreases in fishing intensity, should show increases in the densities of trout.

2. Changes at Ingworth occurred before 1976. Silt accumulation and plant loss which were documented at the time and local opinion associates these changes with changes in mill use at Aylsham. Any effects of mill gate closure on silt accumulation may well have been exaggerated during the 1976 drought. It is possible that channel widening, as part of the early development of this private trout fishery, contributes to low-flows and thus silt retention.

5.4 (iv) Records of fish introductions and stocking.

Figure 39 shows the intensity of trout stocking to the Wensum in the mid 1950s. These data are from River Board and River Authority annual reports. Figures for best weights of trout are given for most years and are plotted alongside values for the same years taken from newspaper reports. For the three years when dates coincided, there was clearly no correspondence at all between the best weights from the two different sources. Newspaper-reported weights were at least 2lb greater than the reports quoted by the River Boards.

Using officially quoted values only (because there are more of these), the weights of the largest fish have varied closely with stocking intensity, with a lag of around four years, which is presumably the maximum residence time of trout after stocking. Both best weights and stocking intensity decreased during the 1950s and 1960s. This suggests that over-stocking occurred during the 1950s and that either competition for food or over fishing depressed maximum weights. Best weights stabilised during the 1970s which is consistent with the pattern interpreted from the newspaper archive.

Chub, which are predatory and highly competitive fish, were introduced to the Wensum during the 1940s, though have not colonised the river as rapidly as expected. Between 1955 and 1966, over 1800 chub, mostly from Wales, were stocked into the Wensum between Hellesdon and Costessey Mills. Over the same period, 930 were introduced to the Bure between Oxnead and Horstead Mills. Chub have slowly colonised about 35km of the Wensum from their initial stocking area, but are not in the upper reaches, presumably because of effective barriers such as Bintree Mill. In the Bure, chub occur between Buxton and Horstead Mill, a stretch of less than 10km. Chub are gravel spawners and spawning starts at water temperatures of around 15°C. This would cause a natural restriction of their distribution to more downstream waters. The high baseflow component of flow in upper reaches probably means that waters are not warm enough to support a successful chub fishery. In common with other coarse fish, fry survival varies markedly between years and is high when water temperatures are above average.

Chub feed on a very wide variety of prey, including filamentous algae, higher plants, and, for older fish, crayfish, small mammals and other fish. The feeding niches of chub, trout and other coarse fish, particularly roach, overlap (Smith, 1989) and chub have also been seen taking roach fry in the Wensum (R.Francis, personal communication) There is thus potential for competition between introduced species and native fish. The effects of competition and predation are most intense in structurally simple habitats. In these habitats, opportunities for foraging and cover from predators are the most restricted. A detailed study of the requirements of chub in the lower Wensum has shown that physical attributes of habitats are the main influence on their distribution (Smith, 1989). Increase in the weights of pike taken from the Wensum during the 1970s provides some evidence that predation by these natives may have had an influence on other coarse fish. Pike removal is an essential part of management of a trout fishery. No information on pike removals is available, though it seems likely that efforts are now less intense than in the past.

Conclusions from Records of Fish Stocking to the Rivers.

1. The upper Wensum was stocked artificially with between 2000 and 7000 trout per year between 1954 and 1962. This intense stocking was linked to a decline in the size of the largest trout caught and may have been the cause. Different sources of information show different trends. Weights reported in newspapers indicate that best weights were greatest at lowest intensities of stocking whereas best weights given in river board and water authority reports, suggest that declines continued into the early 1980s and despite decreases in stocking intensity.

2. Although no quantitative information exists, it is probable that increases in predation by pike and introductions of trout and chub have had an influence on the native fish community. It is possible that fewer pike are removed today than in the past; this would be consistent with increases in the best weights of pike reported in the newspaper archive.

3. It is highly likely that expectations of the trout fishery are shaped by artificial standards and not by the actual carrying capacity of the Rivers. This is a theme which underpins most of the observations made. Earliest information suggests that the carrying capacity of the study area has always been low compared with better known trout rivers. Nonetheless, the upper reaches of the Rivers and their tributaries are, and should, be capable of sustaining wild populations.

4. The River Quality Survey results of 1990 show that the River Tat, which is a head-water stream of the Wensum, has fallen from NWC Class 1B to Class 2. Past changes in NWC class have related to the success of trout in the upper River. The significance of the stream is probably great. Removal of gravel, channel widening or deepening, low flows or new inputs or accumulation of silt are likely to reduce the stream's potential for trout spawning greatly.

Section 5.5 Analysis of Recent Electro-fishing Survey Data.

5.5 (i) The scope and methods of the surveys.

The results of fishery surveys will reflect changes due to natural cycles of recruitment. Water temperature is a major influence on these cycles. The survey results will also reflect the combined influences of stocking, angling, predation and competition, pollution, flooding, migration toward mill pools and any changes in the quality or extent of spawning or feeding grounds. Inferences made from the data will help to separate the importance of artificial from natural influences on the fishery. Survey data will be examined for changes which have persisted over the decade. Any changes which have persisted over this time scale are likely to be long-term.

The questions that are addressed are: has there been a persistent change in fish biomass over the 1980s; how important are natural variations in temperature; has the distribution of fish in the Rivers changed; how does the growth rate of the different species compare with standard rates ?

To answer these questions, data from each of the three or four years are summarised as the biomass of the major species. Only the biomass of fish longer than 10cm is included. Estimates of smaller fish are unreliable because these usually escape the sampling method. Data are presented as changes in fish biomass with distance downstream and not the actual values, which vary greatly from site to site. This means that at each site, biomass is added to the total value sampled from further upstream. This gives cumulative amounts on a curve which increases gradient when fish were found and does not change when no fish were recovered from the site. This is a useful way of summarising a complicated set of data because it shows downstream distributions very clearly. The final accumulative value can also be compared between years, between species and between Rivers.

Fish tend to migrate and aggregate during winter. Variation in the time of year in which surveys were carried out could therefore affect survey results. The densities of all species in the Rivers have been plotted against the month in which sampling began. The result ($r=0.22$) shows that sampling time did not have a significant effect on the results. This is an important result. Had the relationship been close, changes in downstream distributions between years could not be interpreted as an effect of changes in the distribution of usable habitat.

5.5 (ii) Analysis of electro-fishing data for the River Bure.

During 1981, pike were distributed fairly evenly along the River (Figure 40(a)). Other species were not. Roach, dace, chub and, to some extent, trout were highly aggregated in few sites. Almost all roach were aggregated above Itteringham Mill, which is about 13km downstream, and where the surveys begin. The high gradient of the line for trout between Itteringham and Blickling on Figure 40(a) is due to stocking of these waters. By 1985, fish were distributed more evenly in the River. The biomass of both roach and dace in the River had increased by 1985 and the biomasses of trout and chub decreased. There was little change in the distribution or biomass of pike, the species least likely to be managed. During 1988, dace and roach were still concentrated at Itteringham Bridge, Oxnead Mill (28km downstream) and at Mayton Bridge (34km downstream). The pattern of distribution was similar for both species. This is surprising and shows that fish which usually occupy different habitats, though for dace and roach with some overlap, were invariably congregated in the same sites. Chub remained close to the areas in which they were introduced. By 1993, almost all roach were at Itteringham or Mayton and the biomass of both dace and trout had decreased greatly. During 1992, the growth rate of individual roach in the lower River was lower than average, which at low population density, is almost certainly a result of low feeding opportunity during the third year of drought. Chub had migrated further upstream and both their biomass and the biomass of pike had almost doubled since the last survey.

The most striking features of the Bure fish community over the period are thus extreme clumping at few sites, a large reduction in the number of trout, which probably reflects decreased stocking, and the widespread distribution and recent increase in the biomass of predatory fish.

Figure 40(b) compares time series for roach and dace with the patterns for gudgeon and eels. During 1985, the downstream distribution of gudgeon was almost a model pattern for a river with a high diversity and mixed distribution of usable habitat. The rank order of gudgeon biomass in the different years (1985, 1988=1981, 1993), was similar to roach, though not to the other major species. This suggests that factors other than temperature and flow, most probably artificial stocking, had the greater influence on biomass of dace during the 1980s. Feeding opportunity is unlikely to have been an important factor over all the decade since the biomass of eels has increased steadily and significantly since 1981 ($r=0.9688$, $p<0.05$).

The biomass of all species, except eels and pike which tend to use slower-flowing more silty habitats as well as faster-flowing waters, was lowest during 1993. This suggests that conditions in the River during 1992 and the few years before, restricted recruitment and subsequent survival of the other species. The biomass of both eels and pike suggest that food present in organic sediments and as prey for predatory fish, was not restricted. The relative success of pike which spawn on plants, suggests that predation pressure increased during the drought period. Gudgeon and trout spawn on gravel in well-oxgenated riffles. This habitat is the most sensitive to low-flow and restriction of it would be one of the earliest effects of drought.

One of the interesting features of the results is increasing aggregation of all schoaling species which is probably related to reductions in the availability of usable physical habitat. Pike and eels have both been relatively successful and both have less specific habitat requirements than the other fish. Their numbers are the least likely to change if habitat diversity, particularly the distribution of riffles, is reduced. Increases in the biomass and distribution of eels may though be a symptom of a much wider picture, which may well have long-term implications for the study Rivers. Eels depend on marine conditions as well as conditions in rivers. There is now evidence of thirty-year cycles of temperature change in the Atlantic (Dickson 1993) and these are thought to affect commercial fisheries. The period of increase in eels in the study Rivers corresponds almost exactly with the rising part of temperature curves.

Conclusions from Electro-fishing Data from the Bure.

1. After the drought, the biomass of all fish except eels and pike was the lowest of the four fisheries surveys which have been carried out since 1981.

2. The recent effects of drought on biomass are super-imposed on a trend of increasingly patchy distributions of fish. Animals with different habitat requirements now co-exist. This implies low habitat diversity and increasing predation pressure on young fish.

3. The effects of drought on food supply are ambiguous. The individual growth rate of roach, though not dace, decreased in the lower River whilst the growth rate of predators such as pike, trout and chub did not change. Roach are the least likely of the sport fish to have been affected by silt accumulation in the River.

4. The distribution pattern of one of the most successful fish, pike is the least likely to be affected by flow velocity or silt accumulation. Eel distribution has not changed and total biomass has increased. This may be related to tolerance to increasing simplicity of physical habitat or to cycles of success during the marine part of their life cycle. There is evidence that relatively high ocean temperatures occurred during the 1980s and these may well have favoured eel survival.

5. Fish in the Bure tend to aggregate around artificial structures such as mills and bridges. These buildings restrict flow. This results in higher current velocity and eventual down cutting of deep pools. Both of these features enhance fishery habitat, even though they are not necessarily natural features of the River. The closure of mills and loss of their influence on flow and distribution of sediment is very likely to have had a major effect on habitat diversity in the main River channel.

6. Distributions of fish suggest strongly that the effect of artificial structures on flow regimes have as great an effect on the fishery as annual variation in river discharge.

5.5 (iii) Analysis of electro-fishing data for the River Nar.

The Nar has been surveyed three times. Eels, dace and pike dominated the lower slower-flowing and least diverse part of the River during 1982 (Figure 41(a)). The whole of the River was surveyed during 1985 so the upper faster-flowing chalk stream stretches were included also. Dace dominated the top 5km of the River with eels and wild trout distributed evenly throughout the rest of the upper 23km. The River's entire population of roach was congregated above the sluice gates at King's Lynn giving a roach biomass of $221 gm^{-2}$ at the site. There was little change in either the biomass or distribution of trout or pike between 1985 and 1990 though the biomass of dace, which tended to occur further downstream than before was much lower (Figure 41(b)). The biomass of roach had dropped to about 25% of the value in 1985, though was still higher than in 1982.

Gudgeon occur rarely in the Nar, contributing less than 1% of the total fish biomass. The fish least likely to be stocked are trout. There was little change in the biomass of trout between 1985 and 1990, their distribution in the River was similar to 1985 and individual growth rates in 1985 were fast. The size distribution of the trout caught in the survey indicates that a viable breeding population does exist in the River, though fish are rarely older than three years.

There was a small increase in the biomass of eels between 1985 and 1993 when they were distributed more evenly throughout the River.

Roach distribution in the Nar is restricted to the most downstream reach. This is not surprising because maximum annual water temperature further upstream, at West Acre (19km downstream) for example, is only around $15^{\circ}C$. An extra site was sampled during 1985 though, so fish at this site probably contributed to the apparently large increase in roach between 1982 and 1985. Widening of the River above the sluice gates at King's Lynn is likely to have created favourable habitat for the species.

Since the growth rate of both dace and trout in the upper reaches was fast, food supply in the Nar does not appear to be restricted. Changes in invertebrates represented by reductions in BMWP scores do not, therefore, relate to individual growth rates of the coarse fish or trout in the River.

Conclusions from Electro-fishing Data from the Nar.

1. Changes in roach biomass dominate the pattern of variation in total fish biomass over the decade. During 1990, roach and eels accounted for 82% of the biomass of the fishery. This suggests that habitats are more likely to be silty than fast-flowing and underlain by gravel.

2. Variations in biomass between survey dates show decreases in the biomass of dace, and restrictions in the distribution of roach. This suggests that habitats have become generally more silty, are more nutrient enriched or are slower-flowing.

3. The lower part of the River below Narborough has been engineered since the 16th century. Roach are not well represented along the lower straightened part of the River. This probably reflects a low diversity of physical habitats.

4. The biomass of trout in the upper part of the River was similar in 1985 and 1990. Young fish were represented well in the population during 1990 which suggests that spawning habitat was not restricted in 1989. Fish older than three years were not found. This tends to support earlier conclusions, based on fishers' records, that over fishing has had an influence on the population.

5. The growth rate of individuals of the different species compare well with standard growth rates. The fast growth rate of trout between 1987 and 1990 implies that low trout weights in the middle reaches of the Nar are linked to over fishing. It is improbable that food supply is generally restricted. This is consistent with the consistently high biomass of eels in the River.

6. Changes in the invertebrate community of the Nar during the 1980s may be reflected in declines in the dace population and restriction in the distribution of roach. The individual growth rates of neither species were affected. Changes in food quality are the least likely to affect the distribution of eels, which have been successful, and are the most likely to affect trout.

7. The last fishery survey corresponded with the first winter after the beginning of the 1989 drought. Any effect of the drought on recruitment or distribution of fish should be detectable from the next survey.

5.5 (iv) Analysis of electro-fishing data for the Wensum.

Compared with the Bure, the Wensum supports a large biomass of coarse fish. This is likely to be because of the higher water temperature of the Wensum; both the upper Bure and upper Nar have summer maxima of around 15°C, several degrees lower than in the upper Wensum and the lower parts of all three study Rivers.

The large and aggregated biomass of trout between Sculthorpe Mill and Fakenham (5 to 10km downstream) during 1983 was lower in successive years, though the biomass remained similar between 1986 and 1990 (Figure 42(a)). The pattern may, to some extent, be influenced by stocking. Age class distributions calculated from the fisheries data, suggest that part of the population had bred, probably from earlier introductions, in the River. The annual pattern of trout biomass corresponds with environmental changes in the Tat, which is the main headwater tributary of the Wensum. This suggests that the Tat is a very important trout spawning area. The River was in NWC river Class 2 during 1985, 1B during 1989 and is now Class 2. The next survey results may therefore show a decline in the number of trout that relates to environmental change in the Tat.

Over the survey period, downstream successions of species generally reflected natural differences in their ecology. Over all the survey years, relatively few fish, except pike and eels, were recorded between 30 and 45km downstream. This is the stretch between Swanton Morley and about 5km below Lyng. Pike and eel are species with the least exacting habitat requirements which suggests that habitat variety may be low in this stretch. If this represents a change from former conditions, the change must have occurred before 1983.

Overlaps in the distribution of chub and roach occurred during 1983, though since then there has been greater separation between the species. Although the biomass of chub below Costessey (about 55km downstream) decreased greatly between 1986 and 1990, their general distribution throughout the River has remained fairly even. The distribution of roach has become progressively more restricted which could reflect the distribution of usable habitat, or perhaps competitive exclusion by chub or predation by either chub or pike. The biomass of pike has increased only slightly over the decade. Its distribution in the River has remained the same over the decade which, because this is a species that is not exacting in its habitat requirements during most of the year, is fairly strong evidence that habitat variety, which should include backwaters and washlands, restricts the distribution of other coarse fish.

Evidence from age-length relationships suggests that individual growth rates of roach from the 1989 and 1990 age classes were high compared with fish from between 1983 and 1988. Roach from 1989 were very well represented in the age profile of the population. The results of the next fishery survey should thus show an increase in roach biomass in the River.

The rank order of cumulative biomass for the different years is similar for roach, dace and gudgeon (Figure 42(b)). This suggests that, despite different habitat requirements and differences in habitat variety in different parts of the River, the success of these fish depended upon the same factor, which was probably temperature. The biomass of roach during 1990 appears to contradict this, though this was not a natural feature of the fishery. The very large increase that appeared at about 54km downstream during 1990 was due to stocking. In December 1986, which was a few months after the 1986 survey, 570 15 to 25-inch fish were stocked at Costessey, 1000 6-inch fish were added in November 1988 and at the same time, 15,156 6-inch fish were added at Hellesdon Mill. The intensity of this stocking has probably obscured a reduction in biomass that would probably have been similar to that further upstream.

The effect of this stocking led the Fishery Survey Report of 1991 to conclude that there had been no major change in the Wensum fishery since 1983. Increases in the biomass of eels and increases due to artificial stocking make a large contribution to the figures from which the conclusion was drawn.

Although not a significant trend, the biomass of gudgeon may have decreased since 1983. If the trend continues into the 1990s it will indicate that riffles, which are their main feeding areas and spawning grounds, are probably accumulating fine organic sediments steadily over time.

Conclusions from Electro-fishing Data from the Wensum.

1. There have been no persistent changes in the Wensum fishery during the 1980s.

2. The biomass of fish, apart from eels, was generally low during 1990, though usually higher than values in 1986. This shows that variations in the Wensum fishery that occurred during the 1980s are likely to be short-term. Changes in the biomass of gudgeon suggest that there may be an underlying trend in habitat quality which can only be tested further with data from a fourth survey.

3. Similar patterns of annual variations in biomass for the different fish species suggest that a common factor, which is almost certainly temperature, is the most important cause of annual variation. This contrasts with the Bure.

4. Pike maintained high biomass and an even distribution throughout the River during the 1980s. It is therefore unlikely that there has been a significant increase in predation pressure from pike during the 1980s. The ranges of roach and chub overlap and it is plausible that chub influence the distribution of roach.

5. Other fish are less evenly distributed than pike. Apart from the local effects of stocking, patterns of downstream distribution of most species have remained similar over the decade.

6. On a broad scale, physical variations in habitat structure do relate to fish distribution. Fish are most likely to aggregate in parts of the River where flow velocity and channel depth are most variable. This occurs in stretches of the River which have the most sinuous meander pattern and not where the channel is relatively straight or widened artificially. On a local scale, fish do tend to aggregate around artificial structures, though this is less obvious than in the Bure.

7. Gudgeon are not stocked and thus reflect the distribution of physical habitats fairly closely. Habitat variation appears least between about 30km and 40km downstream. If this represents a change in habitat, then this must have occurred before 1983.

Conclusions from Fisheries Data for all three Rivers.

1. Year to year variations in biomass of different species have been large. The broad similarity between the patterns for different coarse fish in the Wensum suggests that variations are linked to the same or a closely-related factor. This factor is most likely to be water temperature. The precise effect of water temperature has been obscured by the effects of artificial stocking.

2. During the 1980s, distributions of roach, dace and gudgeon in the Bure were restricted to progressively fewer sites. This probably reflects progressive narrowing of habitat variety.

3. Changes in the Nar fishery have generally been consistent with decreased habitat variety and accumulation of organic sediment. Improvements in the trout fishery are an exception to this general conclusion which is based on changes in invertebrate and plant communities as well as changes in the populations of dace and roach in the River.

4. Species which are least exacting in their habitat requirements have been the most successful in terms of biomass and distribution in the Rivers. These species are pike and eels. Relative success of pike and eels is a feature of all the study Rivers. This implies a common cause. For pike, this may be recent decreases in pike removal. A common cause for changes in eel biomass may lie outside the Rivers and be linked to cyclic variations in ocean temperature.

5. Artificial stocking is an important and by no means recent feature of the Rivers. A main conclusion from historic data is that a high natural carrying capacity for trout is a recent expectation of the Rivers. The natural carrying capacity may be much less. This means that the high expectations of trout fishers must continue be met by artificial stocking.

6. The species richness of the Rivers is less than in the 1960s. There are probably fewer perch, bream and perhaps minnows, than in previous decades. This is an important indication that habitat variety, particularly in terms of flow velocity and water depth, is less than in former times.

7. Fish aggregate around artificial structures, especially in the River Bure. This implies that, in the past, the effect of mill working on habitat diversity enhanced the fishery. The major effect of mill working was to vary flow velocity and water depth and to maintain a patchy distribution of gravel and silt throughout the Rivers. These effects have been lost. Present day distributions of fish suggest strongly that re-instatement of such large-scale structures would considerably enhance the fishery.

8. Distributions of fish suggest strongly that the effects of artificial structures on flow regimes have at least as great and perhaps a greater effect on the fishery as variation in river discharge over the 1980s.

Section 5.6 Overall Conclusions on Biological Change.

This section has addressed the following questions:

Has there been a change in the composition of water plant communities ?

Has the composition of benthic invertebrate communities changed ?

Can biological changes be detected in river sediments ?

Has the biomass and distribution of fish changed ?

The overall conclusions are:

5.6 (i) Water plants.

At the beginning of the 1980s, species richness of the upper Bure and upper Wensum was lower than in rivers elsewhere in Great Britain. The richness of the upper Nar was higher. The lower reaches of all three Rivers had species richness that was typical, or better, than in comparable rivers elsewhere.

Since the early 1980s, there have been local gains and losses of water plant species in the study Rivers. This is not surprising. The pattern does not relate to any overall change in the ecology of the Bure over the decade. In the Wensum, changes in plants between 1976 and 1990 suggest an improvement in water quality. Changes in the lower Nar indicate deterioration of habitat variety since 1980 and this is probably linked to recent accumulation of organic sediments.

The time scales of change in the study Rivers are different. The Nar has shown change during the 1980s; in the other Rivers changes in plant communities of the upper reaches probably occurred before the early 1980s.

All three Rivers have areas where bankside plants have recently colonised the main channel. This change occurred during recent drought flows and it probably occurred in 1976 also. The effect has been local increases in flow velocity. This change is desirable in all stretches of the study Rivers which have a history of artificial channel widening. Channel encroachment is not desirable in the natural channel dimensions of the upper 12km of the Nar. Here channel encroachment by tall plants would reduce conservation value.

Water plants do not receive serious attention in NRA monitoring programmes. Very few data have been collected in the past. Since water plants provide cover and essential spawning habitat for fish species which are of major importance in the study Rivers, plant distribution should be described routinely. Information on changes in water plants, especially in the upper Rivers, could have helped to provide a reliable, reasonably precise and long-term indication of changes in the ecology of the study Rivers.

5.6 (ii) Benthic invertebrates.

The composition of communities in the Bure and Wensum has not changed over the decade, although there has been change in most sites on the Nar. Since the late 1970s, the invertebrates of the Nar have become more typical of slow-flowing and silty environments. Patterns are generally consistent with information about water plants.

Features of the invertebrates of the Wensum and Bure correspond with local variations in habitats. Short-term changes are probably due to variations in flow velocity and patterns of sediment deposition, rather than to any progressive change through the decade.

The invertebrates of the three study Rivers divide into two groups which are broadly typical of either faster-flowing or slower-flowing and more silty environments. The overall biological similarity between Rivers is surprising and does not generally follow differences in their natural features. Similarity suggests that the Rivers are influenced by common factors. Common factors may be natural, such as rainfall, or they may be artificial, such as the direct influence of physical changes in channels or the indirect influences of catchment land use. If the causes are artificial, then natural biological differences between the Rivers are bound to become progressively less over time.

5.6 (iii) Biological remains in sediments.

The sediment record has not provided reliable information about the ecological history of the River Wensum. Even in sediments trapped above mill gates, biological remains are mixed by living invertebrates and are therefore too disturbed to give an accurate time sequence.

Different sizes of sediment particles were stratified. Changes in sediment deposition in one site in the lower Wensum have been inferred from the pattern of layering, though the timing and causes of movements of bed load are unknown. Local opinion has suggested that banks were disturbed during maintenance works in the mid 1970s and that the deposition of new sandy sediments within the channel reduced biological variety further downstream. Work on sediment cores did not identify sources, though evidence from the material did not contradict local opinion. Sophisticated analytical methods for tracing sources of sediment do exist.

5.6 (iv) Changes in the fisheries.

The natural influences of water temperature are reflected in fish distributions and in annual changes in the fisheries of the study Rivers. Links were weakest in the Nar, where undesirable changes in the fishery are consistent with changes in both plants and invertebrates.

Fish have generally become less evenly distributed, particularly in the Bure. This has seemed to be due to increasing restriction of physical variety in habitats, rather than to restrictions in food supply. This is consistent with observations on invertebrates and the generally high individual growth rates of fish. Fish with the most flexible habitat requirements have invariably maintained their biomass and equitable pattern of downstream distribution.

A contradiction exists in that invertebrates suggest that habitats are least variable in the Wensum and fish suggest that they are the least variable in the Bure. Physical habitat features and water quality would tend to have similar effects on fish and invertebrates. This suggests that a different set of factors may be involved also. These may be biological interactions such as competition between fish and predation. The point is made here because pike and stocked predatory fish such as trout and chub are relatively abundant in both Rivers. Pike and chub have both been particularly successful over the decade.

Fish distributions still reflect the distribution of mills and any other artificial structures which provide cover or increase local flow velocity or water depth. The work of mills undoubtedly enhanced the fishery, invertebrate and plant communities of the study Rivers. Management to re-instate of the effects of mill working on sediment transport and deposition, flow velocity and water depth would presumably enhance the biology of the Rivers greatly.

CHAPTER 3: Section 6. Changes in Land Use and Land Drainage.

Section 6.1 Methods used to measure Changes in Land Use.

Land use within a corridor of about 50m on both sides of the Rivers Bure and Wensum has been determined from old land use maps and recent aerial photographs. Information for the earliest maps was surveyed by Dudley Stamp and one-inch maps describe land use in the two catchments during 1929. The ten land uses shown on Table 2.7 have been classified, traced and digitised from the maps using TOSCA and IDRISI geographical information systems. Land use maps at a scale of 1:10,560, are available from the 1960s for the Bure catchment only. Most recent information on land use in the River corridors, which has already been described in Chapter 2:8., was interpreted and digitised from 1:10,000 aerial photographs taken during 1988.

6.1 (i) Changes in the Bure valley.

The ground area covered by maps from each of the three periods studied differs slightly. Maps from the 1960s cover only part of the whole catchment, so statistics which compare the three periods are all based on this standard area. Changes in land use are summarised in Table 3.11.

Colour Map 4 shows the dominance of meadow land in the corridor of the River Bure during the 1930s; 70% of the length of the waterway (which includes the main channel and its tributaries) was meadow. About 16% of the land area was under arable, mainly in the headwaters of the Bure and along the Blackwater tributary (these are in Area 1 of the map). Isolated pockets of arable land occurred along Scarrow Beck around Bessingham and Sustead (Area 3). Woodland predominated in the upper part of King's Beck at Gunton Park (Area 4), with small areas above Buxton and near Aylsham. During the 1930s, housing bordered approximately 4% of the River; this represented the greatest settlement within the River corridor over the period covered by this study. It has been possible to distinguish between the proportions of the different land uses in the main River and in the tributaries. In general, arable land occupied slightly more (18%) of the valley of the main channel than of the tributaries (13%). Meadowland was also more common along the main channel (75%). Woodland was more important on the tributaries, where there was 16% cover, compared with 6% along the main channel.

The land use of a slightly smaller area of the Bure is shown for the 1960s on Map 5. By this time, arable land had increased to about 21% of the length of the waterway, meadow had fallen to 65%, woodland had increased slightly to about 11% and housing had reduced to the same levels as today, which are around 2%. Land use change appears to have been mostly in the headwaters of the Bure and the Blackwater around Briston, Melton Constable and Hindolveston, (Area 1). In this Area, arable cover was about 15% during the 1930s and had risen to 24% by 1960. Other areas where similar changes took place, but to a much smaller extent, were on Scarrow Beck between Aldeborough and Matlaske and above Oulton (Area 3).

The greatest change in land use alongside the waterway occurred between 1960 and 1988. Map 6 illustrates the present day (1988) land use pattern for the Bure. The main difference between the land use in the 1960s and the present day is the increase in arable land (to 31%) and woodland (to 23%) and the reduction in meadowland (to 44%). The difference between land use along the main channel and tributaries is more pronounced than in the 1960s. There is approximately three times more arable land bordering the tributaries (33%) than the main channel (12%). Woodland is also more dominant on the tributaries, where values are 33% and 18%. To a lesser extent, the difference applies to housing, where the relative proportions are 1% and 2%. Meadowland now occupies 31% of the corridors of the tributaries compared with 67% along the main channel. One of the areas of greatest change has been along King's Beck, where arable land has increased from 4% to 40% and woodland has increased from 8% to 21%, mainly at the expense of meadowland. Other areas of change include the upper Bure (Area 1), where 43% of the land is now arable compared with 24% in the 1960s. Similarly, in Scarrow Beck (Area 3), meadowland has reduced in area in favour of arable cultivation. Arable is presently at 42% in this Area compared with 27% in the 1960s. Woodland has increased in extent, especially around Gunton hall (Area 4), where, at present, it represents 63% of the land compared with 32% in 1960s. Only main channel Areas such as Area 5, appear not to have changed land use. Area 5, which is mostly above Aylsham, contains a proportion of estate land which is now managed by the National Trust. The River around Blickling has not been engineered and so retains a natural meander pattern and is bordered by wetlands.

Table 3.11 Proportions of different land uses within 50-100m of the waterway of the River Bure. This includes tributaries.

Land Use	1930	1960	1988
Arable	16	21	31
Meadow	71	65	44
Woodland	9	11	23
Housing	4	2	2

6.1 (ii) Changes in the Wensum valley.

Colour Map 7 shows land use in the corridor of the Wensum during the 1930s. The information is also shown on Table 3.12. The distribution of land use shows that woodland was widespread in the upper parts of the catchment (Areas 1 and 3) and around Haveringland Hall, which is in Area 13. Similarly to the River Bure, meadow was the dominant land use throughout the corridor in the 1930s and bordered 71% of the waterway. Meadow was more widespread along the main channel, with 78% compared with 69% in the tributaries. Arable land was distributed fairly evenly throughout the whole area, occupying 23% of the tributaries and 16% of the main channel. At this time, the Bure valley had a slightly higher proportion of woodland and housing and less arable land and meadow than the Wensum.

Map 8 for the 1980s shows how land use in the Wensum River corridor has changed. For the waterway as a whole, arable land has increased to 29% from 22% in the 1930s. This represents a lower conversion rate than in the Bure.

By 1988, there was greater differentiation of land use between the main channel and the tributaries. The main channel was apportioned into 17% arable, 65% meadow, 13% woodland and 2% housing. The proportions in tributaries were: 37% arable; 41% meadow; 19% wood and 2% housing. The extremes of the tributaries, particularly upstream of Helhoughton (Area 2) and around Reepham and Heydon (Area 11), have had the most widespread conversion to arable cultivation. Areas where woodland was important in the 1930s had even higher proportions of woodland in 1988. Examples of this are in Areas 6, 8, 10, 11 and 13. In the regions immediately above Norwich (Areas 12 and 14), woodland has expanded at the cost of both meadow and arable land.

Table 3.12 Proportions of different land uses within 50-100m of the waterway of the River Wensum. This includes tributaries.

Land Use	1930	1988
Arable	22	29
Meadow	71	53
Woodland	5	16
Housing	2	2

Conclusions on Changes in Land Use in the River Corridors.

1. Between the 1930s and the 1980s, the length of the River Bure waterway (which includes tributaries) bordered by meadow fell from 71% to 44%. In the Wensum valley, the change was from 71% to 53%. Changes have tended to be larger in the tributaries than in the main channels.

2. Arable cultivation in the corridor of the Bure increased from 16% in the 1930s to 31% during the 1980s. In the Wensum, the change was from 22% to 29%. Again, changes were more marked in the tributaries and particularly in the upper part of the Bure.

3. The period of greatest land use change was between 1960 and 1988. The changes may have been encouraged by drainage incentives and pressure to produce crops on marginal land.

4. The possible consequences for the Rivers of these changes are:

Changes in evaporative demands and therefore changes in effective rainfall.
Increased sediment loads to the Rivers from surface erosion.
Bank erosion.
Increased loading of soluble agricultural effluents from arable land.
Increased land drainage in the river corridors with potential effect on hydrology.

Section 6.2 The Risk of Soil Erosion in the Bure and Wensum catchments.

6.2 (i) Erosion risks in the Bure valley.

The main channel of the Bure and most of the tributaries occur within floodplain soils. The floodplain soils in the upper part of the catchment, where substantial conversion to arable has occurred in the last 30 years, are sandy and peaty and this makes them vulnerable to wind erosion. Within Area 1 on the land use maps of the Bure, substantial amounts of sediment could enter the River directly. The majority of the rest of the catchment is dominated by more silty floodplain soils which, when drained, provide excellent arable land and are less vulnerable to erosion than the soils of the upper part of the catchment. In the tributaries to the north and south of Saxthorpe (Area 2), conversion to arable has taken place upon soils susceptible to gully erosion.

6.2 (ii) Erosion risk in the Wensum valley.

The Wensum and its tributaries mainly lie within flood plain soils with similar characteristics to those in the upper Bure. Such soils are liable to wind and water erosion when cultivated. The risk is high in areas such as: upstream of Tatterford (Area 1); near Fakenham (Area 4) and near Heydon and Reepham (Area 11).

Photograph 8 shows gully erosion from winter cereal fields near Sparham (Area 14). Photograph 9(a) shows surface runoff at Pear Tree Corner, and runoff from a maize field at West Raynham is shown in Photograph 9(b). Both 9(a) and 9(b) are in Area 2.

Many of the arable areas in the Wensum have slowly permeable loamy or clayey soils which are not prone to wind or water erosion. Examples of areas of low risk are Kettlestone (Area 5), upstream of East Bilney on the Black Water (Area 8), Wood Norton (Area 7) and on the tributary near Billingford (Area 10).

Area 14 is represented by a semi-fibrous peat soil which, when drained, can support some cultivation but is prone to wind erosion and is agriculturally fairly poor. Together with an increase flood risk in the lower part of the River, this explains why grassland is the dominant land use in the area.

Conclusions on Risks of Soil erosion in the Bure and Wensum Valleys.

1. The risk of erosion from soils under arable cultivation in the study area is large. The risk is large enough to suppose that substantial contributions of sediment are made to parts of the main channels, and particularly the tributaries.

2. The soils of the River Bure corridor are more at risk of wind and water erosion than soils of the Wensum. This is due to the higher proportion of light sandy soils that are cultivated alongside the Bure.

Section 6.3 Methods used to measure Changes in Land Drainage.

Over the last century, land drainage has been the responsibility of several succeeding organisations. Today, responsibility falls to Internal Drainage Boards (IDBs) and the NRA. The tidal sections of the Rivers, which are not part of this project, presently fall under the auspices of the Port and Haven Commissioners. Information about any changes in intensity or method of drainage depends very much upon the resolution of records kept by the organisations involved.

Since the 1930's, agricultural land drainage, other than that associated with main river channels, has been the responsibility of IDBs. Unfortunately, quantifiable information about changes in drainage patterns is not available from IDB records for the study catchments. Main channels are maintained by the NRA which has inherited the responsibility from Anglian Water and before that, the former Water Authorities and River Boards. Anglian Water Annual Reports describe, in varying degrees of detail, the works carried out on the main Rivers. Works on main rivers involve dredging and weed clearing. Changes since 1954 in the intensity of these activities in the study area have been described in Chapter 3: Section 4.

Since the 1940s, field drainage works carried out by farmers have been recorded as amounts of drainage grant allocation. Data are available from the Agricultural Development Advisory Service (ADAS). The information was published by MAFF in 1979 and 1981 in technical reports produced by their Field Drainage Experimental Unit.

Ordnance Survey maps at scales of 1:10,560 and 1:10,000 are useful for identifying the change in drainage ditch networks between the turn of the century and the 1970-80's. Of the sources listed, MAFF statistics and Ordnance Survey maps have provided the only quantifiable drainage data.

For this project, data on drainage intensity has been gained from mapping the open ditch component of the drainage system. Open drains are needed for flood defence and to receive underdrainage water. Thus, except in areas of exceptionally high water table where underdrainage is not feasible, changes in cover by open drains are a general indication of change in total drainage intensity. The exceptions to this may be in areas where some open drains were originally too large for their purpose and have not needed extension or deepening as underdrainage has increased (Ken Buckley, personal communication).

Land cover by drainage ditch networks in the Bure and Wensum valleys has been determined from 1:10,560 and 1:10,000 Ordnance Survey maps. Data have been obtained for periods both before and after drainage expansion. The earliest information is from the late 1950s (1957-59) maps. These show the drainage network based on a 1904 ground survey. The Ordnance Survey office in Norwich have confirmed that this is because the drainage network was thought not to have changed significantly between 1904 and the 1930s and so was not resurveyed for the 1930 revision. It was not until the late 1960s and 1970s that the drainage network was resurveyed. This most recent information has been drawn up at 1:10,000 scale and compiled from 1:2,500 maps. These maps were surveyed between 1965 and 1980 with an average date of around 1975. The drainage network of the Bure and Wensum valleys has been reproduced for both time periods by tracing the network from the corresponding maps.

Drains are difficult to identify from black and white maps because they look similar to field boundaries. Because of this, coloured 1:25,000 maps were used as a guide for tracing the most recent drainage network and the earlier network traced with reference to the later network. Occasionally the word "drain" is used on the maps and more particularly on the earlier versions. Arrows indicate flow on streams on the earlier 1:10,560 scale maps but not the more recent 1:10,000. Careful consideration of form was therefore required for accurate differentiation between streams and ditches shown on the later maps. Other clues to the positions of ditches are bridges marked by double hachure and in the earlier maps, some ditches were marked as a double line with regular crossing points. Once identified, the drainage system was digitised using the GIS system that was used for land use work and changes in network area finally calculated using IDRISI programmes.

6.3(i) Changes in the Bure valley.

The drainage ditch network of the Bure valley during 1904 is shown in red on Colour Map 9. The network was well established in 1904, though confined to the flood plain of the main River and its tributaries. The main purpose of the drains was to prevent flooding and to improve meadows. The drainage pattern is therefore a close reflection of where high water tables occurred the area. Additions made to the network between 1904 and 1980 are shown in blue on Map 9. Between 1904 and 1970-80, there was a 75% increase in drainage density in the Bure catchment, Table 3.13.

The increase has mostly been in the upper reaches of tributaries. Changes have been most marked on the flood plain of King's Beck above Banningham and Felmingham, on the flood plain of Scarrow Beck around Gresham, Aylmerton and above Hanworth and in headwaters around Swanton Novers and Melton Constable. The areas of drainage expansion are related closely to soil type (soils were introduced in Chapter 2:8 and are described in more detail in Appendix 1). The soils in the floodplain are fertile once drained, though are prone to flooding. There has been little need for substantial drainage of soils away from the channel and close to tributaries in most of the catchment because soils are generally permeable coarse or fine loams. The exception to this has been in the headwater catchment where soils away from the flood plain tend to have impermeable subsoils.

Table 3.13 The percentage change in cover by drainage ditches in the Bure valley between 1904 and 1980.

	Number of GIS cells	% change
1904	4755	
1980	8325	75

Personal communications (1994) with Ken Buckley of the Upper Bure IDB, suggest that little or no increase in surface drainage has occurred in the flood plain of the Upper Bure since at least 1974. "Routine maintenance" is carried out though and it appears that some drains may have fallen into disrepair recently. Grants for new drainage work are still available. However, reduced agricultural needs and more powerful environmental protection policies limit such activity to very unusual events. The possible exceptions are schemes to alter water flow within channels. If development for purposes other than agriculture require these works, then developers have to pay the costs of the project (K. Buckley, personal communication).

6.3(ii) Changes in the Wensum valley.

In 1904, land drainage in the Wensum catchment followed a pattern similar to the Bure in that ditches were confined mostly to floodplains. The ditches at the time are shown on Colour Map 10. The most drained areas were just above Norwich, around Fakenham and Tatterford, between Lyng and Lenwade and between North Elmham and Guist. Land drainage was probably for flood defence and maintenance of water meadows.

By the late 1970s, both the amount and distribution of the drainage network had changed. Between the late 1970s and 1904 there was a 40% increase in ditch density, Table 3.14. Emphasis was still on draining floodplains though new drains appeared in all sections of the system. Of particular note are new systems Ringland and Taverham and along the upper sections of Wendling Beck towards East Dereham. Ditches in areas away from the floodplain provided drainage for soils which are dominantly coarse or fine loam over impermeable clay. In these areas, underdrainage has probably occurred also.

Table 3.14 The percentage change in cover by drainage ditches in the Wensum valley between 1904 and 1980.

	Number of GIS cells	% change
1904	7365	
1980	10,290	40

Conclusions on Changes in Land Drainage Intensity.

1. Land use change in the Bure valley, particularly the change from 71% to 44% meadow between 1930 and 1980, has been mirrored by a 75% increase in the intensity of the surface drainage network in the catchment since 1904.

2. There have been fewer losses of meadow in the corridor of the River Wensum (from 71% in 1930 to 53% in 1980) than in the Bure. A 40% increase since 1904 in the intensity of land drainage in the Wensum catchment corresponds with the loss of bordering wetland. The difference between the two catchments reflects differences in soil types.

3. If rates of change in Norfolk have followed national trends, then the greatest increase in drainage activity happened during the 1970s. Substantial increases began to occur from about 1952 and this presumably marks the beginning of potential changes to the Rivers.

4. The major implication of large increases in drainage of riparian wetland in the two cases studied, is an increase in external loading of soluble and particulate materials to the River Wensum and, particularly, to the River Bure. The combination of soil texture, change in land use, susceptibility to soil erosion and increase in land drainage close to the River Bure and particularly its tributaries, make increases in external loading of sediment to the waterway highly probable.

Section 2 of the next Chapter reports on the biological implications of these conclusions.

CHAPTER 4: CAUSES OF CHANGE AND IMPLICATIONS FOR MANAGEMENT

CHAPTER 4: Section 1. Causes of Variations in Hydrology.

The main results from analysis of change in flows were:

> No change since 1931 in thirty-year mean rainfall.
>
> No significant change in effective rainfall since the 1960s.
>
> No significant change since 1964 in the relationship between gross rainfall and flow.
>
> No evidence for a reduction in baseflow since 1960.
>
> No evidence for changes since 1960 in the seasonal distribution of flow.
>
> On a catchment scale, natural flow responses to periods of low rainfall lasting for several years, are likely to be perceived as artificial effects of water abstraction.

Superimposed on the natural effects of rainfall on flow, there are artificial influences on the hydrology of the study Rivers. These influences may work on both local and catchment scales.

Flow data are collected by the NRA from a gauging network designed for catchment-scale monitoring. This means that artificial effects on hydrology at local scales cannot be detected and quantified from available data. Measuring the size of local effects is therefore outside the scope of this catchment-scale project. The importance of artificial influences on flow at local scales can though be inferred. The artificial effects on river discharge or flow velocity which are relevent for the study Rivers are:

Water resource use: abstractions, effluent discharges and effects of water mills.
River engineering: for navigation, water milling, flood alleviation and land drainage.
Catchment land use: farming practices, settlement and roads.

All these influences are, or have in the past, been subject to close management. Only abstractions, effluent discharges and flood alleviation schemes have potential effects on river discharge (termed 'flow'). The other artificial influences listed affect flow velocity and may have no effect at all on total amounts of water in the channel. Generally, it is artificial influences on flow velocity brought about by physical changes to channels which have the greatest ecological significance.

The main part of this Section on causes of variations in hydrology deals with the effect of water abstraction on flow. The results show the net loss of total flows in the study Rivers which has been due to abstraction from their catchments. The results have been gained from computer modelling using a modified version of the Great Ouse Resource Model (GORM). As an aid for resources management, the model has been run to predict the effects on flow of different levels of water abstraction. The method used for flow naturalisation is detailed in Appendix 3.

The Section ends with a discussion of the effects of water milling and other activities which involve river engineering on flow velocity. This work is not quantitative because data on flow velocity are not available. The scale of artificial influences may be very large though. For example, the straightening for navigation of the River Nar below Narborough has undoubtedly had profound effects on the hydraulics and biology of the River. Smaller scale changes in the study Rivers have involved local dredging or removal of small shoals from channels. Where the effect of local changes has been to widen or deepen the channel, then local reductions in flow velocity and settling of suspended sediments probably followed. Reduced flow velocities generally lead to undesirable ecological change in the water environment.

Section 1.1 Management Implications of Natural Variations in Flow.

The seasonal and longer-term variability of weather is beyond the control of resource managers, though if there are long-term trends in regional weather patterns these have implications for management. The implications relate to calculations of groundwater storage and management response to channel narrowing due to shoal formation during prolonged drought flows.

1.1 (i) Implications for groundwater storage.

The main implication of the possibility of long-term variations in climate concerns the calculation of sustainable resource use. Use of annual mean statistics, for example annual mean recharge of groundwater, should be avoided. This is because annual means do not take account of successive years with below average precipitation. Figure 43 shows variation of annual rainfall about the mean at East Dereham for the period 1870-1992. Long periods where rainfall has been substantially below average are evident. These periods occurred during much of the 1940s and, to a lesser extent, the 1970s.

Catchment storage is finite: a long period of above average rainfall cannot sustain flows during similarly long periods of below average rainfall. Even with the existence of extensive groundwater reserves, heavy groundwater abstraction during drought periods could reduce already naturally-depleted flows below ecologically critical levels.

1.1 (ii) Implications for channel maintenance.

Sediments are entrained and transported at times of high-flow. Conversely, sediments are deposited during periods of low-flow and, if deposition occurs within the channel, shoals establish. In extreme cases, channels are colonised by bankside plants which then stabilise the shoals. If major parts of the study Rivers were not embanked to prevent flooding of their former floodplains (which are now cultivated or settled), a proportion of the finest sediments would be deposited on floodplain meadow rather than within channels. The desirability of this where property is not at risk of flooding, forms a reasoned basis for re-creation of floodplains.

Recent experience has shown that following instream incursion of plants and the stabilisation of shoals during the 1989-92 drought, later high-flows have not restored the previous channel cross-section. This has been particularly so in the Wensum (NRA, personal communication). The pattern seems to emphasise those parts of the Rivers which are unnaturally wide. Continued removal of shoals may well be maintaining artificially wide channels and the lower flow velocities that this implies. The NRA has responded recently to a request from a fishing club to remove a newly-formed shoal. Such removal may not be in the best long-term interests of the fishery if the channel has been overwidened in the past or if works involve large-scale bank disturbance.

If the failure of rivers to be largely 'self cleansing' is evidence of unnatural channels reverting to a more natural state, then channel maintenance, to sustain the unnatural, is a permanent obligation. If the preservation of an unnatural channel is considered desirable, then channel maintenance must be undertaken in a way which is sensitive to other aspects of the Rivers' environment.

Section 1.2 Influences of Water Abstraction on Flow.

1.2 (i) Introduction to flow naturalisation.

Chapter 3 has described changes in resource use over time. The effects of net abstractions, at a catchment or large sub-catchment level, on flows between 1971-92 can now be assessed. This involves using different abstraction scenarios and the results can be used to guide future licensing decisions.

Since 1965, the licensing system has controlled the source (ground or surface), location, use-purposes and maximum amounts of water abstracted. Discharge consents set the precise locations, amounts and quality of effluent that may be returned.

Resource management has, since the 1963 Water Resources Act, increasingly balanced the needs of water users with the needs of the water environment. Existing abstraction licences and discharge consents reflect this. Since the 1960s, one notable policy of the licensing authorities has been a moratorium on further surface abstractions.

The assessment of the effects of post-1960s abstraction on surface flows is complicated by the dominance of groundwater abstraction. Not only the size of loss due to abstraction, but timing also, has to be quantified in order to examine any seasonal or annual effects. The dynamics of groundwater movement have to be known and this requires a detailed knowledge of the aquifer and its properties.

Flow modelling to apportion the effect of net abstraction on flow has used rainfall to predict weekly mean-flow by producing baseflow and non-baseflow components with net abstraction and aquifer hydraulic properties as input. This is flow naturalisation and the details of the methods used are given in Appendix 3. By dealing with large sub-catchments, local variations in aquifer properties have been averaged out. This has simplified the complexities of aquifer heterogeneity. This approach is validated by Toynton (1983) who describes the Norfolk Chalk aquifer as having a relatively uniform structure. Toynton has produced catchment-mean values for hydraulic properties of the aquifer.

The concept of catchment averaging has led to the use of a greatly simplified aquifer modelling process which, in calculating net aquifer storage, apportions the effects of groundwater abstractions to predictions of baseflow output. The resultant reduction in data requirement and data handling has allowed the rapid naturalisation (based upon historic net abstraction data) of gauged flows for all the study catchments. Whilst the model has been run for the period 1961-92, the uncertainty with pre-1970 net abstraction data invalidates the naturalisation exercise for the earlier part of the period.

With a view to guiding any future licensing decisions, assessment of the hydrological effects of theoretical change (in licensed quotas) within the post-1963 Act licensing-framework has been made. For example, what would happen to catchment or large sub-catchment flows if (all else being equal) existing spray irrigation licensed quantities were exploited to the full? Alternatively, what would happen if all the spray irrigation licensed quota from surface sources were transferred to groundwater abstraction with full exploitation?

1.2 (ii) Results and discussion of flow naturalisation.

1.2 (ii) a) The effects of actual abstractions, 1971 to 1992.

Table 4.1 summarises the net effect on flows of abstractions and discharges since 1971. Figure 44 shows the full time series of percentage losses to natural flows for each of the study catchments. It must be noted that the higher percentage losses occur when flows are very low. Maximum sustained loss over the period was during 1989-1992 drought, though the maximum loss value of 16.4% for the Bure at Horstead was during 1976 drought.

Table 4.1 The percentage loss to seven-day-mean natural flows in the study catchments due to net abstraction during the period 1971-92. A negative number indicates a percentage gain in flow.

CATCHMENT	MEAN % LOSS	MIN.% LOSS	MAX.% LOSS
Wensum	1.2	-0.6	13.7
Bure	3.0	0.3	16.4
Nar	2.5	-0.1	24.3

Figures 45 to 47 quantify loss in terms of flow units and give perspective to the effects of net abstractions by the inclusion of natural flows on the same axes. Axis scales are logarithmic so that natural flows and losses to flows are shown clearly on the same plot. Figures 45 to 47 and the mean-loss statistics on Table 4.1, suggest that the effects of net abstractions on flow, for the vast majority of the period 1971-92, were very small.

Surface flow characteristics can be described by flow duration plots. Figure 48(a) to 48(c) shows the effects of net abstractions on study River flow characteristics by plotting observed and natural flow duration curves on the same axes. The small scale of the effects of net abstractions is highlighted by the flow duration curves. The difference between the observed and natural flow duration curves for the Wensum shown on Figure 48(a) is barely discernible. Similarly, had the flow duration curves for the other two catchments been plotted with the same vertical axis resolution (Figures 48(b) and 48(c)), the lines would be difficult to distinguish.

The effects of net abstractions during the summer growing seasons (April-September) over the period 1971-92, are shown for the Wensum at Costessey on Figure 49(a). By repeating the analysis for the separate periods 1971-80 (Figure 49(b)) and 1981-92 (Figure 49(c)), the more recent period shows an increased, though still small, effect.

1.2 (ii) b) The effects of hypothetical abstractions, 1971 to 1992.

Figure 50 compares the effect on flows of three different cases for abstraction from the Wensum above Costessey. These cases were:

1) net abstraction as recorded,
2) net abstraction with zero use for spray irrigation, and
3) net abstraction for spray irrigation using full licensed quantity from both ground and surface sources.

The seasonal maximum loss to flow if total licensed quantity for spray irrigation from both surface and ground sources were taken up, has, in recent times, been 0.23 cumecs. This amounts to 17% of the long-term (1960-92) Q95 for Costessey Mill, Table 4.2. However, in drought periods, flow would probably have been lower than the Q95 level and losses to flow much greater than 17%. For example, the 1989-92 drought saw weekly-mean flows below 0.8 cumecs. During the recent drought, the loss to flow if the total licensed quantity for spray irrigation had have been used would have been around 30%.

The highly consumptive nature of spray irrigation is apparent from comparison of losses to flow with and without spray irrigation. The presence of a small but permanent loss to flow in recent years, irrespective of season and in all three cases, is a function of the net abstraction regime. The annual peak loss to flow emphasises the large potential of spray irrigation for depleting summer flows.

Table 4.2 The maximum potential losses to summer low flows (the 1971 to 1992 Q95) and to drought flows (between 1989 and 1992) under two hypothetical abstraction cases of (i) maximum uptake and (ii) tranfer from surface to all ground sources.

	MAXIMUM POTENTIAL LOSS TO FLOW (%)			
CATCHMENT	Full uptake from surface and ground		Full uptake all from ground	
	Q95	89/92 flows	Q95	89/92 flows
Wensum (at Costessey)	17	30		
Bure (at Horstead)	19	29	13	20
Nar (at Marham)	45	66	39	57

Figures 51 and 52 illustrate, for the Bure at Horstead (1974-92) and the Nar at Marham (1971-92), the effects of a different scenario option. This is the removal of the surface component of abstraction for spray irrigation by transferring it to ground sources. Again, the potential effects of spray irrigation are demonstrated by the inclusion of the zero spray irrigation scenario. The three modified abstraction scenarios were;

1 net abstraction with zero use for spray irrigation,
2) net abstraction with irrigation at full licensed quantity from both ground and surface sources,
4) and net abstraction with irrigation at full licensed quantity from groundwater only.

The Bure and Nar sub-catchments show a decrease in maximum reduction in flow, when surface licensed quota are transferred to ground (Table 4.2). Maximum losses would be about 9% less for both Rivers. The same total losses to flow would still be sustained, although more evenly over time.

Conclusions on the Effects of Abstraction on Flow.

1. The average actual losses to seven-day mean flows due to net abstraction for all water uses over the period 1971 to 1992, have been no greater than 3%. The mean, minimum and maximum losses are shown on the table below. Actual losses have been greatest during dry growing seasons, and particularly during the 1989 to 1992 drought. During the recent drought flows in the Nar were the most affected of the study Rivers, with a maximum of 24% loss in the seven-day mean flow. Maximum losses in both the Wensum and Bure were about 15%.

Percentage losses to seven-day-mean natural flows in the study catchments due to net abstraction during the period 1971-92. A negative number indicates a percentage gain in flow.

CATCHMENT	MEAN % LOSS	MIN.% LOSS	MAX.% LOSS
Wensum	1.2	-0.6	13.7
Bure	3.0	0.3	16.4
Nar	2.5	-0.1	24.3

2. Water use for spray irrigation explains the major part of gross and seasonal losses to flow in all three catchments. The Nar sub-catchment has a proportionately higher irrigation requirement than the other two sub-catchments. Modelling of a hypothetical case of full uptake of the quantity of water licensed for spray irrigation in the Nar predicts a maximum of 45% loss to flow during summer low-flow (at the Q95 for 1871-1992) and a 66% loss at the lowest flows recorded during the 1989-1992 drought. This suggests that no further licences for highly consumptive use-purposes should be granted. Further modelling has shown that there would be only a small advantage in exchanging existing surface for ground licenses in the Nar.

3. Potential losses of dry weather flow from the Wensum and Bure with maximum uptake for spray irrigation, particularly if existing surface sources are transferred to ground, would be less than 20%.

4. The effects on flow of abstraction for public water supply, the other major use category in the study area, are mitigated to a large extent by the return of water as discharge from sewage treatment works. There may, however, be local flow depletion if STW discharges are made further downstream than the abstraction. Other types of discharge tend to be made near to the point of abstraction (which is usually from groundwater) and so reduce the net effects of abstraction. Discharge following abstraction from groundwater can enhance surface flow during summer periods.

Section 1.3 Influences of Mains Water Services on Flow.

This Section is concerned with local hydrological effects due to concentration of water use by mains services. The growth of water mains and mains sewage networks, primarily to safeguard public health, marked a decline in numbers of the many, mainly small, abstraction and effluent discharge points. Most properties, except farms, isolated houses and a few industrial users, became connected to mains services. Abstraction and discharge have therefore become concentrated in fewer places. This has potential effects, not on total flow, but upon flow distribution.

The combined effects of water mains and sewerage networks can separate abstraction from discharge points by large distances. This could lead to significant loss of flow in one place, particularly near a large PWS abstraction point, and significant augmentation below the sewage treatment works (STW) discharge point. The net result may be either loss or gain, depending on the relative locations of the abstractions and discharges.

The growth of water and sewage mains networks has been examined in some detail for the period 1944-52 in Chapter 3. The annual reports of the East Suffolk and Norfolk River Board and succeeding river authorities, list sewage schemes, either new or improvements, since their first year of existence which was 1952. The greatest concentration of schemes was during the late 1950s to the early 1970s. For example, schemes for Reepham, Great Witchingham and Fakenham, all on the Wensum, are listed as having been completed during the financial year 1958/9. A scheme for East Dereham, again on the Wensum, was completed in the year 1966/7.

Any change through concentration is impossible to quantify because there are too few early data on abstractions and discharges. Since water and sewage mains transgress parish, district, catchment and other boundaries, a comparison of pre- and post-mains resource use, on anything but a large geographical scale would be meaningless. The implications of concentration can only be inferred. However, qualitative assumptions can be made and these are:

> 1) the larger the abstraction at any point, the greater the localised draw-down of groundwater levels and/or reduction in surface flow downstream.
>
> There are some large PWS abstraction points near the headwaters of the Bure, for example, those at Metton and Matlaske are currently (1992) licensed to abstract 1045 and 800 TCMA respectively. The abstraction points at Beetley, Cawston, and Foulsham (1992 licensed quantities 1100, 310 and 300 TCMA respectively) are on tributaries of the Wensum. It is feasible that there are localised drawdown effects on the hydrology and hydrology-related aspects of the Rivers' environment and these would be compounded by irrigation boreholes.
>
> 2) the net return (wherever made) of resource from PWS use, via STW will be increased by concentration because of lower losses to evaporation. Pre-mains sewage would have seen many septic tank and other discharges to surface soils and minor water courses from which, particularly during summer months, losses to evapo-transpiration would have been high.

The capital economies of scale which relate to the provision of mains services have a great bearing on the siting of abstraction and, more so, discharge installations. Geographical location of high yielding strata, in the case of groundwater, is a primary consideration in the siting of abstraction points.

Conclusions on the Distribution of Abstraction and Discharge Points.

1. In management of the river environment, the relative siting of abstraction and discharge points can be crucial. Optimal management may be complicated by the legacy of Licences of Right which came into being under the Water Resources Act of 1963. With Licences of Right often exploited to the full in recent times, along with the general increase in resource use, there is potential for serious local depletion of flow.

2. There is no evidence of flow depletion on this scale in the study Rivers. Because the investigation has been undertaken at a larger sub-catchment level, it has not, however, been possible to test for any localised effects of groundwater abstraction. There are areas in the headwaters of the Bure and on tributaries of the Wensum where local effects are feasible.

3. From a resource management perspective, the risk of any future localised flow depletion due to abstraction, should be minimised by careful siting of new abstraction points. Existing problems of depleted flows, once identified, may require a review of licensed quotas. If this is not possible, then other flow conservation measures may be required. These could include appropriately sited river support boreholes and the moving upstream of STW discharge points.

Section 1.4 The Influences of Water Milling on Flow.

Working water mills impound and release water. This does not affect total flow. The effect is to vary flow velocity and water depth at fixed locations on a weekly, daily, or even less than daily scale. Flow diversity created by the work of mills in the study Rivers must have mitigated what was probably a reduced natural variation in flow due to the artificial nature of channels. The loss of the effects of mills on flow velocity has simplified biological habitats within the study Rivers. The wider consultation exercise in this project certainly produced anecdotes of biological richness during the milling era and a decline thereafter.

Since impoundment and release undoubtedly favoured biological richness, there are two obvious, and radical, resource management options. The restoration of a more natural channel, alongside the removal of milling control structures and associated artificial channel features, would return greater habitat diversity. Alternatively, the restoration of impoundment and release to mimic the past action of water mills is suggested.

Section 1.5 Influences of River Engineering on Flow.

1.5 (i) Influences of river engineering for navigation.

Canalization to create navigable waterway involves channel deepening and straightening and regulating structures to control depth. Straightening and deepening creates uniform flow conditions and removes natural riffle and pool flow diversity.

The River Bure has been engineered for navigation between Aylsham and Horstead and the Nar between King's Lynn and West Acre. These are substantial parts of both Rivers. The engineering work was carried out in the late 18th century during the 'canal construction era'. Navigation ceased on the Nar in 1884 (Lewis et al., 1970) and on the 'Aylsham Navigation' after flood damage in 1912. Whilst, in most respects, navigation is long forgotten, its legacy of channel works remains on both the Bure and the Nar. The history of intense management of the study Rivers is in common with many other waterways in the United Kingdom (Brooks, 1983).

1.5 (ii) Influences of river engineering for water power.

Engineering for water milling, some of it pre-dating the Norman conquest, has a much longer history than engineering for navigation. To provide the required step in channel gradient for the operation of water wheels and sufficient upstream water storage capacity, rivers were usually diverted away from the valley floor. The construction of artificial embankments, alongside the new channel above mills allowed the creation of sizeable hydraulic heads.

Rose (unpublished), suggests that a major diversion, with associated engineering, was made above Fakenham during the early 18th century to serve a succession of three mills. The removal of channels from the valley floor disrupted natural drainage, a situation greatly exagerated by the nearby creation of artificial hydraulic heads. The result of this was the creation of wetland, particularly in the valley floor area. To counteract this, parallel drainage systems were created, often literally parallel to the new channel and which discharged below the mill structures. The local modifications to hydraulic processes were complex, even without involving temporal changes due to impoundment and release.

The need for adequate hydraulic heads and thus, an upstream channel of high volume capacity, produces a uniform stretch of river with unnatural proportions. Flow velocities, except in spate conditions or rapid release by sluice operation, would be reduced unnaturally with inevitable effects on other flow- related variables. The sediment carrying capacity of the River would, for example, be reduced. Seaman (personal communication) recounts that German prisoners of war removed silt from the Wensum above the sluice gates of Bintree Mill during the First World War.

Below mills, channel and flow characteristics are also dominated by the operation of mill sluices. The very short-term variations of flow would have been enormous with sluice control overriding natural weather-related variability. If the mill were working, sluices would be partially open with the likelihood of artificially enhanced, probably turbulent and oxygenating, flow during summer periods at least. If, again during summer periods, hydraulic heads were being restored, sluices would be closed and flow would comprise discharge from the secondary drainage system. Whenever sluices were fully opened (and this included the operation of bypass channels) to alleviate flood risks or to flush the system, then flows would be high, often artificially so.

The length of channel affected below a mill would have been determined by the distance to the next mill downstream. The Wensum was used extensively for water power, so the spacing between mills was often limited. This produced a highly modified channel with often short stretches of highly unnatural channel between mills.

The succession of artificial river reaches of minimal gradient, elevated water levels and flow restricting mill structures has, to those who favour land drainage and flood alleviation principles, been an absurdity. Jones (1868) wrote [referring to the Wensum and Nar] ..*(It)*.... *"is a standing disgrace that the rivers, the arteries of the county, should be considered, not as water courses, or drains, but simply as means of obtaining power to grind corn. The poor little mills that do all this mischief are generally obliged to use auxiliary steam power, and it would be a matter of easy calculation to estimate how little more power would suffice to enable the rivers to be freed of all their obstructions"*.

Adkin (1933) expressed similar sentiments when he attributed flooding to the actions of millers, with particular mention of those in the County of Norfolk. He looked forward to the impending authority of Catchment Boards, (under the Land Drainage Act of 1930), and their ability to override private water rights in the interests of land drainage. By this time though (1933), a decline in the use of water power for milling was already occurring.

1.5 (iii) Influences of engineering for land drainage and flood control.

The Catchment Boards and succeeding river authorities did indeed begin to improve land drainage. Particularly since the late 1940s, some water rights were purchased, some milling control structures were removed or modified, and some channel reaches deep-dredged and straightened to lower water level. The effect of these was to increase channel capacity and gradient.

In the Study area, the Wensum, having been the River most developed for water power, has seen the greatest amount of effort to improve land drainage. The legacy of the engineered channel remains today and the reversal of previous modifications is not always practicable, nor always desirable. Private interest has not always been overridden by river authorities and drainage schemes have certainly not always been appropriate from a drainage or environmental perspective.

Rose (unpublished) recalls an early 1950s scheme to deep- dredge and remove bends (by dragline) along five miles of the Wensum between Shereford and Sennowe. This is also recalled by Cook (personal communication) who witnessed the induced changes to the river at Sennowe Park. The East Suffolk and Norfolk River Board (1954) refer to the scheme, with particular reference to works upstream of Fakenham. The acquisition of water rights for Mills at Sculthorpe, Hempton, and Bintree was reported in the same year. A Compulsory Purchase Order was necessary in the case of the Mill (Gogg's Mill) at Hempton.

Dredging and straightening operations reduce the diversity of flow conditions in channels and canal type environments are created. It appears that drainage schemes during the 1950s did produce straightened, uniform channels. However, with the exchange of one type of artificial channel for another does not prevent a river (an agent of sediment mobilisation and transport) from reverting to a more natural channel with bends, pools, and riffles and the flow characteristics associated with them.

The reversion process is evident in the Wensum, with previously dredged reaches being re-dredged periodically to remove impediments to flow. Rose notes this above Fakenham, with the restoration of the channel last dredged during 1989.

Where efforts have been made to lower water levels, there have been constraints where fixed control structures could not be lowered or removed permanently. There were problems, for example, if the river authority failed to acquire private water rights and the control structure was downstream of a proposed lowering scheme, or where lowering could have had catastrophic upstream effects. For example, embankments may collapse with loss of stage; and reaches, over-wide for normal flows, may become too shallow with the loss of the control structure. Rose cites the partial retention of a river control structure at Fakenham Mill as an example of a structure (downstream of a water level lowering scheme) which could not be removed entirely for fear of the upstream consequences. In times of high-flow, the control was lowered. During lower-flow conditions, the control was raised to maintain river levels. Mr Schroder, the owner (since 1959) of Taverham Mill on the Wensum, recalls the River Authority (in about 1960) making an offer of £5000 in compensation for the lowering of sills so that water levels could be lowered. The offer was refused and the water rights retained.

Conclusions on the Management Implications of River Engineering.

1. The channels of the study Rivers have been engineered for a variety of purposes. The interests of navigation, water milling, and land drainage/flood relief have, over many centuries, shaped the channels to their present, largely artificial, form.

2. Channel engineering has traditionally been undertaken in a single-minded fashion. When the needs of milling were paramount, land drainage/flood alleviation were secondary considerations. When the needs of land drainage/flood alleviation superseded those of milling, engineering was undertaken to lower water levels and facilitate the passage of high-flows.

3. Overall engineering objectives for land drainage have largely ignored small-scale effects on flow and flow-related aspects of the river environments. Traditional river engineering has reduced the diversity of the flow and thus, flow-related aspects of the river environment. However, it is feasible that certain aspects of the use of water power did, inadvertently, produce sharp diversity in flow conditions which favoured biological richness.

4. More recently, the needs of the whole river environment have modified the previous pursuit of specific objectives. Micro-hydrological and biological issues are now considered and environmentally sensitive engineering options for a variety of objectives are now available to river managers. The prioritising of objectives, including issues of drainage/flood relief, biological features, and aesthetics, should now guide the choice of engineering option.

Section 1.6 The Influences of Land Use on Flow and its Sediment Load.

In common with many other issues that have been discussed, local effects of changes in land use, particularly from grazing to arable agriculture, are possible, although difficult to quantify. Where local effects are evident, changes in flow velocity usually induce changes in sediment removal and transportation capacity.

There is no evidence from the Wensum or Bure that changes in land use since the 1960s have had a significant influence on volumes of runoff from the catchments over the same period. However, the largest increases in the intensity of land drainage probably occurred during the 1950s and so any effect of this on flow remains undetected because most of the change would have occurred before flow records began. There have been very large changes in drainage intensity in the study catchments, with increases of 40% in the Wensum and of 70% in the Bure since 1904. It is therefore possible that changes in the amount and timing of runoff from new drainage arrangements or changes in evaporation and transpiration had their major effect on flows and flow durations before 1960. Changes in land use and land drainage that have occurred since this time have been too small to have any detectable effect on flow volumes.

Urban development has taken place within the study area and flow durations may have been affected on local scales. High and turbulent flow from land with impaired infiltration capacity carries more sediment and if this sediment enters the waterway, water quality and channel dimensions may be affected. Observations made during this Project have shown that roads surfaces, old and new, are important conduits for runoff and suspended sediment, whether or not the runoff has been generated on the road 'catchment' area. Photographs 10(a) and 10(b) show specific instances of how roads can act as open channels to the waterway. Road drains, by design or otherwise, often direct their flow straight into water courses. Larger (usually newer) roads can generate considerable runoff because of their large surface area. The need to keep road surfaces free of water requires efficient drainage systems which quickly concentrate runoff and any materials in it. Even smaller roads can generate considerable runoff as well as receive material from agricultural land. Added to this is soil material from the cutting-away of roadside verges by traffic or the deposits carried by the wheels of agricultural traffic. Soil deposits from agricultural traffic are particularly common during the autumn sugar beet harvest.

Consultation with the Wensum Internal Drainage Board during 1991 revealed a runoff problem on a tributary of the Wensum associated with recent development (including bypass construction) of land near East Dereham. A temporary flow gauge was placed so that flows could be recorded with a view to providing an adequate storage area to alleviate flooding and related problems. The recently (1992) completed Narborough (Nar valley) bypass has runoff storage capacity and silt reservoirs as part of its design. Observations made on site visits do suggest that runoff from roads can contribute large amounts of sediment to the waterway. In almost all cases, such point sources of sediment could be managed effectively and should be if they prove significant compared with other sources.

Sediments eroded from arable land do not enter channels from point sources. Inputs are diffuse are are therefore more difficult to manage than road runoff. Intensification of arable farming as well as conversion of floodplain meadows to arable cultivation has been a national as well as local trend. Increased tillage has a number of effects: more autumn established crops are grown and higher inputs put soils which have low structural stability at an increased risk of erosion by rainfall. Boardman (1985) discusses erosion issues with particular reference to the South Downs in southern England.

In the study area, there are many instances of high intensity arable cropping in areas where features of the soils and geographic location suggest high susceptibility to soil erosion by rainfall. There is strong circumstantial evidence from changes in land use in the study River corridors that soil erosion has increased. This strongly weather-related process has been observed during the wet autumns of 1992 and 1993. Re-establishment of corridors of uncultivated meadow could provide an effective means of trapping sediments which are entering the channel. This could be achieved by active management, and, immediately, by setting aside unploughed strips next to the waterway.

Conclusions on the Management Implications of Land Use Change.

1. Changes in land use and farming practice since 1960 have not had a detectable effect on effective rainfall. It is therefore unlikely that changes in land use since 1960 have had a direct effect on hydrology. Although usually less than 3% of seven-day mean naturalised flow, loss to flow due to spray irrigation is the main effect of land use change on flow. Local effects have not been considered in the analysis and the effects of abstraction are much larger during dry weather and during drought flows.

2. The most probable effect of change in land use involves sediment loading to the study Rivers. Since 1930, 20% of the floodplain meadow alongside the Wensum and 25% alongside the Bure has changed to another land use. Almost all of the change has been to arable cultivation and to woodland. There have also been large increases since 1904 in the intensity of surface drainage in the catchments. The increase has been 75% in the Bure catchment and 40% in the Wensum. Set alongside the susceptibility of many of the catchment soils to erosion, these changes imply increases in the external loading of sediment to the waterway.

3. A dedicated monitoring programme to provide the basis of sediment budgets is needed. This programme should measure sediment loads in runoff from agricultural land, from surface and underdrainage networks and from roads. If the results of the next Chapter show relationships between river biology and the distribution of sediment, measures to detect and, where appropriate, to reduce the entry of sediment to the waterway should be put in place.

CHAPTER 4: Section 2. Causes of Variation in Biology.

The main results from analysis of change in biology were:

> Water plants in the Wensum and Bure did not change significantly during the 1980s though there has been undesirable change in the Nar.
>
> The pattern of change in benthic invertebrates has been similar to the pattern for water plants.
>
> Biological changes cannot be detected reliably in river sediments.
>
> Changes in the biomass of coarse fish have been short-term though undesirable changes in fish distribution have persisted.

Biological change has occurred on two time scales. Undesirable change in the invertebrate and fish communities of the Nar occurred during the 1980s. In contrast to the Nar, there has been no persistent change in the invertebrate communities of monitoring sites in the Bure and Wensum since the beginning of the decade. Invertebrates in these Rivers did respond to the drought flows of 1990, though this was at the end of a period of otherwise little change. During the late 1970s and early 1980s, the richness of water plants of the upper reaches of all three Rivers was low by national standards. This implies that changes occurred before or during the 1970s. However, water plants typical of slower-flowing, more downstream environments, seem always to have been represented well in the study Rivers. Plants of the lower Rivers have thus shown little evidence of past change, though bankside plants have responded to recent drought flows by colonising and stabilising new shoals.

The fish of the three Rivers, particularly the Bure, aggregated at progressively fewer sites over the 1980s. The biomass of pike and eels has increased steadily over the decade. There have been large fluctuations of the biomass of most other fish, though changes have not generally persisted and are therefore most probably related to water temperature.

Observations of biological change therefore suggest that variations in flows over the last ten years have not had a long-term effect on the ecology of the Rivers Wensum and Bure but that earlier features of river and catchment management have caused significant change. Biological change in the Nar does, however, coincide very closely with the effects of water abstraction on already naturally low-flows. In the recent drought, abstraction depleted flows by up to 24%. Biological change has persisted through the decade, which suggests that effects may be significant even in wetter periods. Effects of flow and its recent depletion, may well superimpose upon indirect effects of sewage effluents and earlier influences of channel engineering.

Circumstantial evidence that links recent low-flows and their artificial depletion, with biological change in the Nar is fairly strong. Equally, circumstantial evidence from the Wensum and Bure links biological change with longer-term loss of habitat variation due to the closure of mill-working and the past engineering of channels. The effects of water abstraction from the Wensum and Bure over the last ten years have not had a detectable influence on the overall biology of the two Rivers.

Observations which link water resources management and biology need to be based on numerical analyses. The aim of this Section is to substantiate the links by establishing if relationships between flow, physical habitat structure, sediments and biology exist. The approach is mainly correlative and includes detrended correspondence analysis (DECORANA) of ecological relationships involving invertebrates.

Section 2.1 Changes in the Ecology of River Invertebrates.

2.1 (i) Relationships between invertebrates and rainfall.

Hydrological analyses have shown usually close correspondence between rainfall and flow. If flow is the factor which ultimately limits the ecology of invertebrates, then relationships between their communities and rainfall must exist.

Close relationships between rainfall and invertebrates are more likely in the Wensum and Bure than in the Nar. This is because rainfall makes a significantly higher contribution to riverflow in the Wensum and Bure during prolonged wet periods. Surprisingly, relationships between invertebrates and rainfall in the Nar catchment were the closest of a set of weak trends that applied to all three Rivers. BMWP scores were generally highest in years with most rainfall. Sites in the lower Nar were related to annual rainfall fairly closely, though very weakly, with, for example, correlations of $r=0.56$ ($p<0.20$) at Setchey Bridge and $r=0.72$ ($p<0.15$) at Marham.

In relatively wet years, BMWP scores were generally lowest in upstream sites and highest in sites further downstream. In upstream sites, for example at Billingford Bridge on the Wensum, correlations with rainfall were inverse ($r=-0.51$, $p<0.10$), though were still weak. During the wettest years, invertebrates have presumably been flushed from upstream sites and received further downstream as drift.

In the lower Nar, up to about 50% of the variation in invertebrate BMWP scores has been explained by rainfall. The sensitivity of invertebrates in the largely cannalised lower Nar is most probably because animals are likely to be washed out of structurally simple habitats. Simple habitats are also less likely than more natural meandering channels to retain fish during high-flows and floods. The mills of the Bure and Wensum presumably had a large influence on distributions of animals during high-flows, though in the past they may also have prevented upstream migrations. There was no trend in correlations with rainfall in sites in the middle parts of the Wensum or Bure and this may well be because of the retaining structures that remain at most mill sites. In these sites, site-specific factors are more likely to influence the composition of the communities. The conclusion from this is that physical characteristics of habitats are the major proximate influence on the composition of the invertebrate community.

2.1 (ii) Relationships between invertebrates and flow.

BMWP scores have been correlated with measures of antecedent flow. These measures were total flow over the previous summer and the means of the lowest or highest daily flows in each of the previous four months. The aim of this was to detect any relationships with extremes of flow or with flows which affect earlier parts of invertebrate life cycles.

Relationships between high and low-flow events over the four months before biological sampling, were not detected when all sites from the three Rivers were considered together (n=45) or when they were treated separately. However, when the relationship was examined at individual sites, which had to be those with both a gauging station and a biological monitoring record, trends were evident. Figure 53 shows the correspondence between extreme flow events and BMWP at Horstead Mill on the River Bure. Correlation is not strong, though a trend emerged at this very local scale.

These results on flow follow a pattern similar to rainfall. This is not surprising since flow and rainfall vary together. In the Bure and Wensum, relationships with flow vary from site to site. This means that site-specific factors determine biological response to variations in river discharge. These factors may include plant cover, the meander pattern of the channel, the distribution of mill buildings and the effects that all these have on water velocity and sediments. Of these factors, flow velocity and its effect on sediment composition is likely to be the most important.

In narrow, meandering channels with gradients of coarse and finer sediments, or where flow is constricted by sluice gates or weirs, water velocity is not necessarily related closely to variations in total river discharge. Flow velocity will vary locally according to physical features of the habitat. The relative importance of local variations in velocity for river biology cannot be scaled in numerical terms in this project, though these variations are almost certainly a major and long-term influence.

The distribution of suitable habitat for invertebrates described by BMWP scores, is very likely to be under the influence of variations in flow through effects on river sediments. A plausible explanation for the change in BMWP in the Nar is that, of the three Rivers, sediments in the channel of the Nar are the least likely to be washed downstream during dry periods. Flow analyses have shown that the frequency of high-flows in the Nar has reduced since the early 1980s. This has also been a feature of the Rivers Bure and Wensum, though it has been less marked in them than in the Nar. The flows of the Nar have also been the most depleted by abstractions for spray irrigation during dry weather and drought flows. Observed changes in flows in the Nar are consistent with the correlation between BMWP and rainfall if threshold flows for increases in downstream invertebrate drift are lower than flows needed to entrain sediment. This seems plausible and suggests that accumulation of sediment in the Nar is probable and provides a likely explanation for recent reductions in BMWP scores in the River.

5.2 (iii) Relationships between invertebrates and channel features.

BMWP scores correlated more closely with sediment type than with flow. Relationships with sediment composition are weak, perhaps because of the small number of data points. Unfortunately, information about the distribution of sediments in the Nar is not available; sediments in part of the Bure and in all of the Wensum were described during the 1990 REDS surveys.

In the River Bure, BMWP scores are likely to be highest ($r=0.62$, $p<0.15$) where sediments are composed mostly of silt and clays and lowest where there are high proportions of sands ($r=-0.63$, $p<0.10$) and gravel ($r=-0.53$, $p<0.15$). This parallels observations made by Armitage (1993). The distributions of silt in the Rivers Bure and Wensum are shown in Figure 54. There are two possible explanations for higher BMWP scores where silt is present. The first is that substrata which have a mixture of sediment types, including silt, are likely to support the larger number of taxa. A reason which may apply particularly to the study Rivers, is that sites where sediment is retained are also sites which are likely to retain invertebrates which have drifted downstream.

Invertebrates can be described using measures other than BMWP scores (Fogerty, 1991). The Average Score per Taxon (ASPT) is, for example, more sensitive than BMWP scores to the presence of animals which do not survive small reductions in oxygen availability. Similar analysis using ASPTs rather than BMWP scores showed the opposite response to sediment composition. Correlations were still weak, though the ASPT was generally highest ($r=0.36$, $p<0.10$) in gravel habitats and lowest in fine silts ($r=-0.31$, $p<0.10$). Confidence in these statistics is slightly higher than for the correlations with BMWP scores. The ASPT is the more precise ecological variable and is perhaps more useful because higher average scores represent more fully communities which are desirable in terms of conservation value and value for fisheries.

The conclusion from these weak correlations between ASPTs and BMWPs of individual sites and of all sites together, is that invertebrates are influenced more by the sediment composition of the riverbed than directly by flow volumes.

DECORANA has been applied to raw data on invertebrates to discover if the communities identified by TWINSPAN order along environmental gradients. In this analysis, annual maximum and mean values for ammonium-N were included with measures of flow and information on sediment composition. Neither ammonium nor flow were able to explain patterns of community composition.

DECORANA has shown that Invertebrate Community 1 which was identified by TWINSPAN, occurred only in sites with the lowest proportion of silt. This is consistent with the earlier interpretation of Community 1 as typical of faster-flowing, usually upstream, environments. The relationship with silt was closer in the Bure than in the Wensum.

In their study of the River Glen in Lincolnshire, Petts et al. (1992) concluded that local factors, other than water quality were the main influence on invertebrates. This was based on data from 44 sites which were analysed using CANOCO rather than DECORANA. Conclusions from the River Glen study are therefore similar to conclusions for the Rivers Wensum and Bure, though not the Nar.

Conclusions on Causes of Changes in Invertebrates.

1. Biological changes in the River Nar during the 1980s suggest that flow and its effect on sediment movement are the major cause of reductions in BMWP score. The direction of recent changes suggests that the low frequencies of high-flow and high frequencies of low-flow, which are a recent feature of the Nar, are involved. Extremes of low-flow during the drought have been exaggerated by water abstraction for spray irrigation.

2. Changes in flow in the Nar are likely to have led to increased sedimentation of organic material in the channel. This material may, in part, be from the decomposition of water plants, particularly invasive *Apium nodiflorum* (related to watercress), which has probably responded to recent increases in the load of phosphorus from sewage treatment works.

3. Low flows in the Nar imply that soil particles eroded from the banks or catchment will be retained and have a significant biological effect. The original cause of siltation in the Nar may well be bank erosion as part of a natural process of channel readjustment after channel straightening. The processes involved are probably similar in the other Rivers where the recent loss of mill structures must exaggerate any effect.

4. Relationships between invertebrates, rainfall and flow in the Nar suggest that the uniformity of the lower engineered part of the River, increases the sensitivity of invertebrates to present-day variations in flow.

5. In contrast to the Nar, in the Rivers Bure and Wensum channel characteristics at local scales are a more significant influence on invertebrates than any wider-scale changes, for example in water quality. This implies that management at a local level to increase water velocity and thus remove silt, will have positive biological effect.

Section 2.2 Changes in the Ecology of the Fish Community.

2.2 (i) Relationships with flow.

Relationships between fish density and flow at sites closest to gauging stations have been examined. The sites are Sculthorpe Mill, Ingworth Bridge, Horstead Mill, Fakenham, Swanton Morley, Costessey and Marham.

The mean monthly flow during the month before the sampling day and the total density of fish recorded at the site closest to the gauging station were not related closely. As expected, fish biomass was correlated less closely with flow than fish density. Separate analyses for dace, roach and trout show similar scatter. No trends which link fish density or biomass with antecedent river discharge have emerged. This shows that factors other than, or related to, average discharge are likely to be stronger influences than flow on fish distributions. This parallels conclusions made from analyses of invertebrate data.

Flow velocity is much more relevant to river biology than discharge. Velocity depends upon the shape and size of the channel. Flow velocity has been approximated using estimates of stage and river width taken from a variety of disparate sources. The error here is likely to be $\pm 20\%$ or worse. The results show that total fish density was lowest where the range of flow velocities was greatest during the month before sampling ($r=0.53$, $p<0.05$). This suggests that extremes of flow reduce the likely density of most, though not necessarily of all, species. This effect would presumably be most marked in the simplest reaches with the least habitat diversity. Roach densities did not conform to the pattern and appear to be greatest where flows were the most variable over a four-monthly time scale. In both the Bure and the Nar, roach became restricted to fewer sites over the 1980s. This may well reflect progressive narrowing of the range of flow velocities in the Rivers. In the Nar, this can be associated with the recent effects of water abstraction. In the Bure, the effect is more probably related to a lack of structures which restrict flow and thus vary flow velocity and channel features.

Densities of gudgeon have been correlated with measures of flow to remove the complicating influences of fish stocking. Gudgeon density was not, however, related to river discharge or to estimates of current velocity. This is surprising because gudgeon use faster-flowing riffle habitats. The reliability of analyses which use estimates of flow velocity is not high, though analyses with gauged river discharge are reliable. The results of the project suggest strongly that it is local variations in flow velocity in the Bure and Wensum, and not necessarily total river discharge, that are ecologically significant. Any further work on these relationships should be aimed at local scales in the Bure and Wensum and must involve field measurements of flow velocity.

Conclusion on the Relative Importance of Flow for the Fishery.

1. Direct relationships between river discharge, fish density and calculated estimates of flow velocity have not been detected. Although the size of the data set is small, results do suggest that it is unlikely that recent changes in fish distribution relate directly to changes in flow that have occurred on a catchment scale.

2. No direct measures of flow velocity are available. This means that probably close relationships between local variations in flow velocity and fish behaviour are beyond detection within this project.

2.2 (ii) Relationships with water quality.

The study Rivers have concentrations of ammonium-N which, after pollution events, have exceeded 1mg l^{-1}. In waters of high alkalinity, high concentrations of ammonium are potentially toxic to fish and invertebrates. Between the late 1960s and 1980s, mean and annual maximum concentrations of ammonium in the River Wensum increased significantly, though concentrations have been low during the recent drought. Increases have been most marked in downstream reaches of the Wensum, particularly at Hellesdon Mill. Annual maximum concentrations in the Bure have increased also. Both mean and maximum concentrations have been compared to densities of fish where monitoring sites correspond, and there is no general relationship. A similar conclusion has been reached by a study of the Rivers Gipping and Waveney, where ammonium-rich effluents from livestock units were thought to be affecting the fishery (NRA 1986). This study included the Bure and concluded that contamination by ammonium was not an important long-term influence on fish biomass. This is also the conclusion from this study. Interactions between other variables of water quality and flow are unlikely to have direct significance for the fish community in the study Rivers.

2.2 (iii) Relationships between fish and sediment composition.

Riffles are key biological habitats for both fish and invertebrates. The density of riffle habitats is low in both the Rivers Bure and Wensum, with none in the majority of sites (Figure 55). Riffles are particularly scarce in the middle reaches of the Wensum. This may be legacy of past engineering works which widened and straightened the River channel.

For both the Rivers Bure and Wensum, the distribution of the fish community was related closely and strongly to the distribution of river sediments. Fish density was highest where there were high proportions of gravel ($r=0.78$, $p<0.001$) and of sand ($r=0.45$, $p<0.05$) on the river bed. Fish densities were lowest ($r=-0.72$, $p<0.01$) where the bottom was covered with a large proportion of silt and clays. These are the closest and strongest ecological relationships that have emerged from this study.

There is thus strong circumstantial evidence that patterns of sediment distribution are the most important influence on the distribution of fish in the Rivers Bure and Wensum. Relationships with the carrying capacity of the Rivers are plausible. There is no reason to suppose that similar relationships do not apply to the Nar, for which information on sediments is not available.

Relationships between fish and sediment distribution probably lie ultimately in the structural complexity of habitats. In areas where sediment is most likely to settle, channels are likely to be relatively wide and straight with simple bank profiles. Flow velocity will be reduced and sedimentation of organic silts is likely to occur. These silts, which may provide a rich food resource, do advantage some bottom-feeding fish species. The growth rates of most of the fish in the study Rivers are high by national standards.

The close relationships between fish density and sediment composition probably again relate to habitat structure. Sediments are most likely to settle in uniform habitats. In these, cover from predators normally offered by deeper pools, overhanging banks and plant beds, is limited. Increases in the biomass of pike have occurred since 1980 in all the study Rivers. This will have increased predation pressure on other fish and the predatory success of the animals would have been greatest in the simplest stretches of River. This may apply particularly in the lower part of the River Bure.

The influence of silt accumulation on trout spawning habitat, which is usually riffle, is undoubted. Eggs do not attach to silt and the high BOD of organic sediments competes with the high oxygen demands of developing eggs. Most coarse fish spawn on water plants where egg development is probably advantaged by oxygen evolved by plants during photosynthesis. Concern over the density of wild trout in the upper Nar may be validated if spawning habitat is accumulating silts which are flushed less frequently during drought years. To preserve habitats in the tributaries and upper Rivers as breeding grounds for trout, management effort must ensure that fine sediments do not accumulate on sand or gravel bottomed waterway.

Large accumulations of sediment in tributaries of the upper Bure were noted during site visits made as part of the project during summer 1991. This was particularly so around Scarrow Beck and at Wickmere, Gresham and Bessingham. Headwaters of the Bure in Craymere Beck and of the Wensum around Salle and Cawston all had 100% cover by silt. In the field, the pattern coincided with arable land use close to the waterways. Evidence on land use change has shown that changes toward arable cultivation have been most marked alongside tributaries. During the 1930s, 13% of the tributary corridors in the Bure waterway was under arable. By 1988, 33% of the length of the corridor alongside the same tributaries was under arable cultivation and this compares with 12% alongside the main channel.

Methods for tracing sources of sediment to main channels are available. These methods are needed to distinguish between sediment sources, for example between river banks and from arable fields. The methods include use of radionuclides, clay minerals and the magnetic properties of soils as tracers (Walling et al. 1993). Clay mineralogy involves matching the associations of clays found in river channels to potential source areas in their catchments. This was attempted as a small pilot study within this project to discover its potential for further work in the study catchments. The technique seems to be most useful when there are large differences between source areas and has potential, in combination with other methods, for tracing sources of sediment on a catchment scale. On the more restricted scale of the Wensum above Fakenham (Figure 56), the pattern is probably explained by subtle transformations of the same suite of minerals by weathering.

A history of increased sediment loads from soils prone to erosion, together with recent drought flows in largely artificial channels have allowed colonisation of the previously wet channel by emergent plants. These stands further trap sediment, and, after two or three years of low-flow, may competitively exclude instream water plants. This appears to have occurred in the upper reaches of the River Nar and is probably linked with the low species richness of water plants. The invasion of the channel is undesirable in the upper Nar and is not a natural feature of the River. Channel narrowing has occurred in the middle and lower reaches of the Wensum and Bure, though this is desirable because restoration of more natural channel dimensions will cause local increases in flow velocity. Shoals should not be cleared from reaches which have a history of artificial widening or straightening. The Thames Region of the NRA have recently had considerable success with schemes to artificially narrow parts the Rivers Dun, Coln, Windrush, Chess and Ash. Improvements in both river flora and the fishery have been noted (Driver 1994).

Conclusions on the Effect of Sediment Composition on Fish.

1. The density of fish was related closely and significantly to distributions of sediment. Fish avoided sites with the highest silt cover and congregated in sites with most exposed sand and gravel.

2. Distributions of silt have probably been altered by changes in flow velocity. These have probably been influenced by abstraction in the Nar. Artificial effects on the flow of the Nar during dry weather will tend to lead to retention of any external loads of sediment or sediment that is disturbed on its banks. Longer-term changes in sediment transport and deposition in the Wensum and Bure are more probably related to loss of mill working and a history of local channel engineering and its effect on local flow velocity.

3. Riffle habitats are scarce in the Wensum and this is likely to limit the biological potential of the fishery. During 1990, most of the River channel was underlain by silt.

4. Land use change from meadow toward arable cultivation in the corridors of both the tributaries and main channels of the Wensum and Bure suggests that loads of sediment to the waterway have increased. The most probable explanation for the progressive restriction of fish to fewer sites during the 1980s is increasing silt cover in channels.

Section 2.3 Main Conclusions on Causes of Changes in Biology.

1. In the Rivers Bure and Wensum, physical conditions at a local scale are probably the most significant influence on invertebrates, water plants and fish. Physical conditions include flow velocity, channel depth, sediment composition and the pattern of variation of these factors. The past effect of mill working was to vary these factors over short distances and this must have enhanced, albeit artificially, the biological richness of these Rivers. There is little evidence that variations in water quality or in total flow volumes are important compared to the overall influence of channel structure. Since channel shape determines flow velocity, management at a local level to increase water velocity will have a positive biological effect.

2. Biological changes in the River Nar during the 1980s suggest that low flows over the 1980s have influenced the ecology of the Nar. Recent changes in invertebrates suggest that the low frequencies of high-flow and high frequencies of low-flow, which are a recent feature of the Nar, involve the accumulation of silt in the River. The flows of the Nar have been affected the most of the three Rivers by water abstractions, with the low-flows of the 1989 drought depleted by about 24%.

3. There is evidence to link fish distributions with the distributions of sediment in the Rivers. Fish are more likely to aggregate at sites with the most exposed gravel and sand and to avoid sites with the highest cover of silt. This and interpretations of invertebrate data, suggest that reductions in the cover of silt in channels will increase biological richness.

4. It is not known if the external loading of fine sediments to the main channels of the study Rivers has increased, or if changes in flow behaviour due to the loss of mill working have led to more even cover of silt within the Rivers. About half of the channel of the Wensum was covered in silt during 1990 (25% was sand and 25% gravel) and this has probably had the most significant of all influences on the ecology of the River.

5. More even distribution of silt in the channels than in former times may in part be due to natural readjustment of stretches of channel which have been straightened in the past. Whichever the major cause, management to increase local flow velocities by restricting the width of the channel will displace silt and so enhance the biological status of the Rivers. Silt removal could form part of management to improve the River environments, though it is absolutely essential that coarse sediments are not removed during field operations and that banks are not disturbed.

6. Land use change on the soils of the study area imply that soil erosion from parts of the study catchments has increased since 1960. Where channels have been widened, straightened or deepened by local engineering, new sediments are likely to accumulate. Management to intercept sediments suspended in surface runoff or in underdrainage by recreating wetland corridors before they enter the waterway is appropriate. The prevention of ploughing close to the waterway, which includes tributary streams, should also form part of future river management.

CHAPTER 5: MAIN CONCLUSIONS, RECOMMENDATIONS AND PROJECT APPRAISAL.

CHAPTER 5: Section 1. Main Conclusions of the Project.

1.1 Background to the study Catchments.

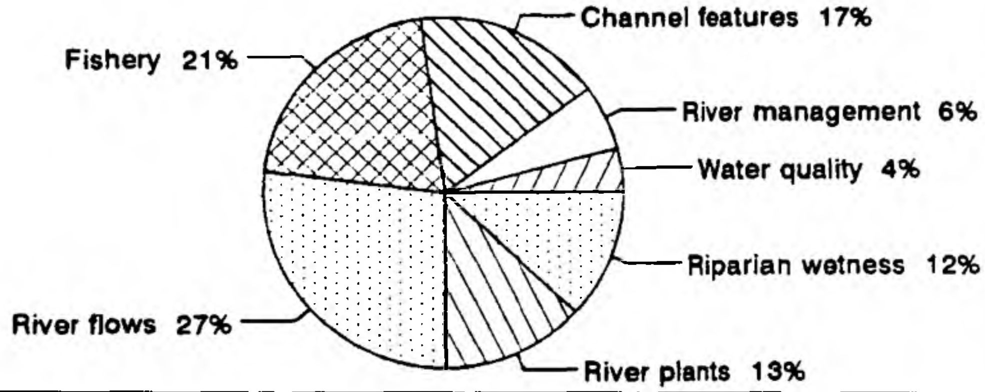
The Rivers Nar, Bure and Wensum in north Norfolk drain lowland, mostly agricultural catchments. The catchments are underlain by a major Chalk aquifer which contributes between 50% and 80% to total river flows. Baseflow is particularly important during summer. The Rivers support coarse fisheries in their lower reaches and small trout-fisheries in their upper springfed waters. During 1990, river quality in most of the waterway was within National Water Council Class 1.

The three Rivers have sustained a long history of water use; water resources in the three catchments have been managed since at least Domesday times. Until the 1950s, water was used to power many mills, particularly on the Wensum and Bure. Channels were engineered to suit milling interests and the working of the mills has had profound effects on channel shape and size, flow behaviour and distributions of sediment. The remains of mill buildings and fixed weirs still affect local flow velocities and the distributions of fish, invertebrates and water plants. The ecology of the Rivers Wensum and the Bure does not, therefore, follow usual changes with distance downstream. The River Nar has been less used for water power, though the lower part of the River was straightened during the late 18th century for navigation.

The major uses of water in the catchments are now for spray irrigation, public water supply, the dilution of effluents from many sewage treatment works, the fishery and for amenity. The use of water for spray irrigation is potentially the most significant for river discharge because this use is entirely consumptive. This means that none of the abstracted water is returned to the waterway; all of the water is transferred to crops or lost by evaporation and transpiration.

The aims of this project have been to document historical changes in the three River environments and then to scale the relative importance of potential causes of any change. Potential causes include physical, chemical and biological aspects of the Rivers and their catchments. The project is focused on water use on a catchment-scale and does not address local issues. The context of the project has been set by public concern about the effects of water use on the Rivers. Some organisations and individuals who have long-standing and informed interests in the study Rivers, believe that by reducing flow, water abstractions have the most significant of many potential influences on the ecology of the Rivers.

At the beginning of the project, over sixty individuals and organisations were asked to comment on their perceptions of change in the study Rivers. Most of these project consultees felt that several aspects of the River environments had changed within their living memories. Very few consultees had documented these changes. Those that have made notes of their observations have provided very valuable written or photographic records which have been used in this project. The diagram on the next page shows how the proportions of comments on different aspects of the Rivers were distributed among the total number of comments made.



The distribution of comments on aspects of change in the study Rivers.

1.2 Main Conclusions on Changes in the Rivers.

1.2 (i) Rainfall.

1. Since 1931, there has been no change in either the thirty-year mean gross rainfall over the study catchments or in the seasonal distribution of rainfall. This means that if there have been any long-term changes in the total flow in the channels, such changes are likely to have an artificial cause.

1.2 (ii) Land Use in the River corridors.

1. Land use change in the corridors of the Rivers Wensum and Bure has important implications for the Rivers. The direction of change has been from uncultivated floodplain meadow toward arable farming and has been most marked alongside tributaries. A summary of the changes is given in the table below.

Proportions of different land uses within 50-100m of the waterway of the Rivers Bure and Wensum. Land use alongside tributaries is included.

	Percentage of total river corridor area				
	The Bure Catchment			The Wensum Catchment	
Land use	1930	1960	1988	1930	1988
Arable	16	21	31	22	29
Meadow	71	65	44	71	53
Woodland	9	11	23	5	16
Housing	4	2	2	2	2

2. The possible consequences for the Rivers of these changes in land use are:

- Changes in evaporative demands in the catchments and therefore changes in effective rainfall which could then have an effect on flow volumes;
- Increased sediment loads to the waterway from cultivated land;
- Increased loading of soluble agricultural effluents from arable land;
- Increased land drainage in the catchment with potential effect on flow durations and loading of particulate material to the waterway.

3. The risk of erosion from soils under arable cultivation in the study area is large. The risk is large enough to suppose that substantial external contributions of sediment are made to parts of the main channels, and particularly the tributaries.

4. Land use change in the Bure valley has been accompanied by a 75% increase in the intensity of the surface drainage network in the catchment since 1904. There has been a 40% increase in the Wensum. The difference between the two catchments reflects differences in soil types.

5. The combination of soil texture, change in land use, susceptibility to soil erosion and increase in land drainage close to the Rivers Bure and Wensum and particularly their tributaries, makes increases in external loading of sediment to the waterway highly probable.

1.2 (iii) Flow.

1. Despite changes in land use since 1960, the proportion of gross rainfall that eventually becomes streamflow has not changed. This implies that since the early 1960s, any changes in evaporation from the catchment that have occurred have not altered streamflow significantly. Significant changes may have occurred before this time, though any such changes are undetectable because flows were not recorded before 1960.

2. Modelling of the relationship between gross rainfall and river flow has shown that for the period 1964 to 1992, the relationship between rainfall and flow has remained the same. The conclusion from this is that changes in catchment land use and land drainage since 1964 have not had a significant influence on flow volumes. This does not imply that changes did not occur before the 1960s.

3. Since 1960, there has been no evidence of a reduction in the baseflow component of flows. This indicates that, over this time-scale, the amount of groundwater recharge has not changed.

4. Similarly, there have been no changes since 1960 in the amounts of the non-baseflow components of flow in either the longer-term or in terms of their seasonal distributions. Flow volumes have thus followed variations in rainfall closely. The timing and volumes of all components of flow in relation to rainfall have not, therefore, changed since the beginning of the flow record in the early 1960s.

1.2 (iv) Water use.

1. This century, the greatest change in water use in the Rivers Wensum and Bure has been the ending of water milling. Although the work of mills had no effect on the amount of flow in the Rivers, regular impoundment and release of water had profound influences on flow velocities and channel dimensions. These influences shaped the physical conditions in the Rivers over many centuries.

2. Since 1960, increase in use of water for spray irrigation has been the next most significant change in water use. Demands for irrigation water associate closely with changes in land use in the catchments. Spray irrigation implies loss to flow volumes because, unlike use for public water supply, none of the water used is returned to the waterway. Over the whole study area, the increase in the total licensed quantity from 2319 TCMA (thousands of cubic metres per annum) in 1961 to 5692 TCMA in 1981 was 44%. This compares with an increase of 86% from 1981 to 10,612 TCMA by 1991. During 1990, uptake of the total licensed quantity was 64% and during 1991, 54%. By 1992, uptake was 25% of the total licensed quantity.

3. The average actual losses to seven-day mean flows due to net abstraction for all water uses between 1971 and 1992 have been no greater than 3%. The mean, minimum and maximum losses are shown in the table below.

Percentage losses to seven-day-mean natural flows in the study catchments due to net abstraction during the period 1971-92. A negative number indicates a percentage gain in flow.

CATCHMENT	MEAN % LOSS	MIN.% LOSS	MAX.% LOSS
Wensum (above Costessey)	1.2	-0.6	13.7
Bure (above Horstead)	3.0	0.3	16.4
Nar (above Marham)	2.5	-0.1	24.3

Actual losses have been greatest during dry growing seasons, and particularly during the 1989 to 1992 drought. Flows in the Nar have been the most affected by abstractions for spray irrigation, with a maximum loss of 24% in the series of seven-day mean flows during the recent drought. Maximum losses in both the Wensum and Bure were about 15%.

4. Water use for spray irrigation explains the major part of gross and seasonal losses to flow in all three catchments. The Nar sub-catchment has a proportionately higher irrigation requirement than the other two sub-catchments. Modelling of a hypothetical case of full uptake of the quantity of water licensed for spray irrigation in the Nar predicts a maximum of 45% loss to flow during summer low-flow (of the Q95, which are the flows which occur for 5% of the time or less, for 1971-1992) and a 66% loss at the lowest flows recorded during the 1989-1992 drought. This suggests that no further licences for highly consumptive water use should be granted. Further modelling has shown that there would be only a gain of 6% to dry weather flows by exchanging existing surface for ground licences in the Nar.

5. Potential losses of dry weather flow from the Bure with maximum uptake for spray irrigation, particularly if existing surface sources were transferred to ground, would be about 13%. If the drought flows of 1989-1992 were repeated, the loss to flows would increase to about 20%. Predictions of the size and local ecological importance of these potential effects on flow would need to be made from local environmental impact assessments. On a wider scale, increased abstraction of water for spray irrigation from the upper Bure may have implications for flows in the lower tidal part of the River. The significance of changes in flow from the upper catchment for the flushing of the Broads of the lower Bure should be considered.

6. The effects on flow of abstraction for public water supply, the other major use category in the study area, are mitigated to a large extent by the return of water as discharges from sewage treatment works. There may, however, be local flow depletion if STW discharges are made further downstream than the abstraction. The relative siting of abstraction and discharge points can be crucial. The risk of any future local flow depletion due to abstraction, should be minimised by careful siting of new abstraction points. Existing problems of depleted flows, once identified, may require a review of licensed quotas. If this is not possible, then other flow conservation measures may be required. These could include appropriately sited support boreholes and the moving upstream of STW discharge points.

1.2 (v) Water quality.

1. Since records began in 1975, concentrations of dissolved phosphorus have increased markedly in all but the upper monitoring station on the River Wensum. The increases are due to the influence of sewage effluent. Measurements for the Nar began in 1989 and only seasonal variation can be detected over this time-scale. Changes in the Bure been much less marked than in the Wensum because of control measures at sewage treatment works. The phosphorus contribution from the catchment of part of the upper Bure has been estimated. During the low rainfall year of 1990, the reduction in the phosphorus load compared with wetter years has suggested that the catchment contributed as much as one third of the total phosphorus in the River. Total phosphorus includes particulate material which may enter the River in surface runoff or from under-drainage pipes. The calculated contribution is large compared with published estimates, though it compares fairly well with an estimate that has since been made in another study. Diffuse sources, other than from cultivated agricultural land, may be from disturbed river banks, runoff from roads or overflow from septic tanks.

2. Although increases in ammonium in both the Rivers Wensum and Bure have been large, present-day concentrations are not generally high enough to have a significant effect on the coarse fishery. The frequency of contamination of the Rivers has not changed since 1966, though occasional contamination of both Rivers has been sufficient to affect trout fisheries. Sub-lethal effects on the coarse fishery are plausible.

3. Records of water temperature in the study Rivers are consistent with the results of hydrological analyses which show no change in the baseflow component of flow in the Rivers Bure and Wensum. Temperatures in upper reaches are typically between 10°C and 15°C, with the lower Rivers reaching annual maxima of around 18°C to 20°C. Temperature changes during the 1989 drought were consistent with low contributions of surface runoff in the lower Rivers. The changes in water temperature over the drought were the largest in the River Nar.

4. Variations in biological oxygen demand (BOD) have been short-term and unlikely to have had any longer-term significant effects on fish or invertebrates. Pollution events have caused local increases in BOD although their frequency has not changed over time. BOD was generally low during the drought; this reflects a combination of reduced input of suspended organic material and more rapid settling of materials in suspension.

5. Annual maximum concentrations of suspended material in the Rivers Bure and Wensum have increased threefold since recording began in 1977. Increases in sampling frequency in 1987 suggest that earlier concentrations were underestimated and may have been as high as $100 mgl^{-1}$ during the 1980s. Sediment loads may have originated from external sources, such as arable fields, or they may be from material eroded from banks. The study Rivers have a long history of channel engineering with much opportunity for large-scale physical disturbance.

1.2 (vi) Channel dimensions.

1. By comparison with past engineering to create the gradients needed for water milling and to create navigable waterway, the scale of channel engineering for land drainage and flood alleviation has been small. The interests of water milling, navigation, land drainage and flood relief have, over many centuries, shaped the channels to their present form which is largely artificial.

2. Water milling, which was particularly intense during the 18th century, increased river widths above mill sluices. Old photographs show particularly good evidence of this. However, today the bankfull width of much of the Wensum is similar to estimates of its

width made from 13th century maps. This suggests that since the end of the working regime of mills, natural processes of accretion have tended to restore earlier, though still not necessarily natural, channel dimensions.

3. In part of the upper Wensum, channel narrowing is more likely to be an indirect result of engineering for land drainage which was carried out during the 1950s by the old River Boards. Where channels were deepened or widened, water velocity must have decreased and depositional environments created. Such areas may well accumulate sediments. Where straightening of the channel occurred, natural processes of bank erosion as well as accretion will tend to return the channel to its former shape. Erosion implies that sediments from banks will continue to enter the channels.

4. Predictions of equilibrium channel widths made from the shape of unengineered meanders, show that in particular, the middle reaches of the Wensum are still wider than expected. This implies that removal of sediment will be a continuing commitment in this part of the River if present widths are to be maintained. Former channels could be allowed to reshape naturally, or they could be re-engineered according to known principles which link flow and channel geometry.

6. River engineering for navigation has straightened channels and so reduced variations in flow velocity which are a feature of natural river meanders. Natural patterns of erosion and deposition do not occur in straightened channels. However, the artificial flow regimes associated with water milling did cause large local variations in flow velocities. These flow conditions and variations in other physical aspects of the channels, such as depth and width, must have enhanced biological richness.

4. More recently, consideration the needs of the whole river environment have challenged the previous pursuit of single objectives. Local-scale ecological issues are now considered seriously and environmentally sensitive engineering options for a variety of objectives are now available to river managers. Former channels could be allowed to reshape naturally, or, for example, they could be re-engineered according to known principles of hydraulics and channel geometry.

1.2 (vii) Biology.

Water plants.

1. Since the early 1980s, there have been local gains and losses of water plant species in the study Rivers. This is not surprising. For the Bure, the pattern does not relate to any overall change in ecology over the decade. In the Wensum, changes in plants between 1976 and 1990 suggest an improvement in water quality. Changes in the lower Nar indicate deterioration of habitat variety since 1980 and the pattern is consistent with accumulation of organic sediments in the channel.

2. The time scales of biological change in the study Rivers are different. The Nar has shown change during the 1980s; in the other Rivers changes in plant communities of the upper reaches probably occurred before the early 1980s.

3. All three Rivers have areas where bankside plants have recently colonised the main channel. This change occurred during recent drought flows and there is anecdotal evidence that it occurred in the drought of 1976 also. The effect of channel encroachment is local increase in flow velocity. This change is desirable in all stretches of the study Rivers which have a history of artificial channel widening. However, channel encroachment is not desirable in the natural channel dimensions of the upper 12km of the Nar. Here, channel encroachment by tall plants would reduce conservation value.

4. Water plants do not receive serious attention in NRA monitoring programmes. Very few data have been collected in the past. Since water plants are involved in nutrient cycles and also provide cover and essential spawning habitat for fish species which are important in the study Rivers, their distribution should be described routinely.

Invertebrates.

5. The composition of invertebrate communities in the Bure and Wensum did not change during the 1980s, although there were changes in most sites on the Nar. Since the late 1970s, the invertebrates of the Nar have become more typical of slow-flowing and silty environments. Patterns are generally consistent with observations on water plants.

6. Features of the invertebrates of the Wensum and Bure correspond with local variations in habitats. Variations over the last decade have probably been due to short-term changes in flow velocity and patterns of sediment deposition, rather than to any progressive change through the decade.

7. The invertebrates of the three study Rivers divided into two groups which are broadly typical of either faster-flowing or slower-flowing and more silty environments. The overall biological similarity between the Rivers is surprising and does not generally follow differences in their natural features.

8. Artificial influences have shaped many of the Region's rivers similarly. The results of this project suggest that it should be no surprise if natural biological differences between such rivers become progressively less over time.

The Fisheries.

9. The natural influences of water temperature are reflected in fish distributions and in other annual changes in the fisheries of the study Rivers. Links were weakest in the Nar, where undesirable changes in the fishery have been consistent with changes in both plants and invertebrates.

10. During the 1980s, fish generally became less evenly distributed, particularly in the Bure and Nar. This has probably been due to increasing restriction of physical variety in habitats, rather than to restrictions in food supply. This is consistent with observations on invertebrates and the generally high individual growth rates of fish. Fish with the most flexible habitat requirements have invariably maintained their biomass and equitable pattern of downstream distribution.

11. Fish distributions still reflect the distribution of mills and any other artificial structures which provide cover and vary flow velocity and water depth. The work of mills undoubtedly enhanced the fishery, invertebrate and plant communities of the study Rivers. Re-instatement of the effects of mill working on sediment distributions, flow velocity and water depth would enhance the biology of the Rivers greatly.

Section 1.3 The Causes of Biological Change and their implications for management.

1. Biological changes in the Rivers Wensum and Bure occurred before large demands for spray irrigation and, on a catchment-scale and in the longer-term, are not related closely to artificial effects on flow volumes. Variations in biology in these Rivers have been more consistent with progressive narrowing of physical variation between habitats.

2. In contrast to the Wensum and Bure, the scale of water abstraction for spray irrigation in the Nar catchment is likely to have had a significant effect on the River's ecology. Biological changes since the early 1980s have been consistent with lower-flows, increased sedimentation of fine sediments and less dilution of treated sewage effluents.

3. Of all the potential influences on biology for which at least some data are available, the distributions of silt and gravel have associated most closely with biological features. Gravel cover is desirable, although variations in sediment type typical of natural riffle and pool habitats are likely to support the highest species richness. In 1990, about 50% of the channel of the Wensum was covered by silt: this is undesirable. It is very likely that more of the waterway has become covered with silt since the end of water milling and the cultivation and drainage of floodplain meadows. The effects of these changes will have been exaggerated during recent drought flows when silt has been more likely to be deposited and retained on gravel. In the catchment of the upper Bure, soils are particularly susceptible to erosion when cultivated. Sediment loading from arable land and its drainage network is very likely to have increased since the 1960s. A case study of historical river engineering for water mills and land drainage in the Wensum has shown that natural river processes acting to return the channel to a narrower equilibrium width, may also be a significant cause of siltation. This may well apply to the cannalised part of the River Nar.

4. The implication for river management is that silt should be removed from the channels, though only if bank material and gravel are not disturbed. Monitoring effort by the NRA could usefully include estimation of the proportions of silt in channels.

5. Since sediment loads from cultivated fields are significant for the Rivers and their tributaries, land should not be ploughed close to the waterway. Perennial grasses should be planted next to waterways to intercept materials likely to be received from cultivated fields. Engineering solutions may be needed to trap sediment from roads and other developments. The importance of sediment contributions from under-drainage systems is unknown though may be large. A monitoring programme to provide the basis of sediment budgets is needed. This programme should measure sediment loads in runoff from agricultural land, from surface and underdrainage networks and from roads. If any of these are significant sources, new management techniques may need to be developed.

6. The influence of water quality on biology is not significant compared to the overall influences of habitat structure. Contributions of treated sewage effluent to the upper Nar should be diverted or the quality of effluent improved. This is because drought flows depleted by abstraction will not dilute effluent to standards which will maintain the high conservation status of the River.

7. The overall conclusions for river management are that management to enhance the biological community should be focused at local levels in the Wensum and Bure, and at a catchment level in the Nar. Further use of the Nar's water resources for spray irrigation will further deteriorate the biological community of the River.

8. Local relationships between use of water resources and biology should be detected within future research effort by the NRA. Flow in the upper reaches of the Rivers should be gauged on a permanent basis.

9. Local effects of abstractions also merit further study. This should be with a view to formulating rules for the location and operation of future groundwater abstractions and for the location of water discharge points.

CHAPTER 5: Section 2. Assessment of the Desk Approach.

This has been an unusual study for several reasons. The first reason is that, despite its wide scope, the work has been financed entirely from the budget of the NRA's Water Resources section. The project brief has brought together the interests of managers of biology, river engineering, water quality, fisheries and hydrology. In order to accomplish the aims of the work, an interdisciplinary research team has been essential.

The second reason is that the analysis has involved features of the whole catchment in explanations of changes in biology and hydrology. This is an important and relatively recent approach, and now forms part of the NRA's programme of catchment management planning. Because of its emphasis on the whole catchment, the project has taken account of all reasonable influences on the River environment. The work programme has therefore been complicated. The major disadvantage of the approach is that it neglects the local effects of water resource management on flow.

The time scale for analysis has been unusually long. The disadvantage of this is that results may not be reliable because few data exist from the past. Where past information has existed for the study Rivers, it has often been difficult to find and lengthy searches have been involved. Old records are often in unusual units, sites may not be defined precisely or sites do not correspond at all with those for which more recent information is available. The only approach possible is qualitative assessment, which, with a restricted data set, may not be at all reliable. The great advantage of the historical approach however, and perhaps one of the features of most interest in this project, is that influences the Rivers have been set in the context of changing demands on the Rivers. It is only through this approach that the relative significance of any single influence can be put in perspective. An example of the usefulness of the approach has been the assessment of changes in channel dimensions. It may not be valid to assume that sediment loads from the agricultural catchment have increased significantly; natural processes of channel readjustment, after historic engineering, may explain the major part of the change in distributions of sediment in parts of the main channels.

One disadvantage of the project approach is the result of having so large a number of questions to answer. Analysis therefore relied upon existing data, rather than new information collected to answer specific questions. If the role of the project has been primarily to focus on the most relevant questions, then the approach has proved very well fitted to its aim. Where useful data do exist, the interpretative approach has tended to be rather correlative and has relied upon regression analyses. At best this will link effects to their likely causes. At worst, the factor to which all variables relate may be missed because too few, or no, data are available for its inclusion in the analysis. One of the most relevant uncertainties in this project has been the relationship between flow and sediment transport. This should be described in further work.

The alternative to a wide approach is to use existing best judgments or experience from previous research, to exclude certain factors from analysis and instead to allocate effort to a programme dedicated to the collection of relevant field data. This can carry a large risk that more significant and long-term influences will not be researched.

Precise questions are best answered using focused programmes of field work which should, in part, adopt a large-scale experimental approach. This means that likely causes of change are imposed and the actual effects monitored. This is the approach used in pump testing of boreholes to discover if groundwater abstraction will affect nearby surface flows. A similar experimental approach in biological work might involve the testing of the effects of river enhancement schemes. This might be the reinstatement of traditional operation of one of the mills on the study Rivers. This work tends to be rather long-term and monitoring of such schemes tends to be neglected. Part of this work lends itself to research, rather than monitoring effort.

3.1 Work on the local effects of abstraction

The local effects of water abstraction should be monitored by the NRA where local effects on flow are likely. This involves the installation of at least one permanent flow gauge in the upper reaches of the most vulnerable rivers. Detailed work on the topic lends itself better to research than monitoring effort. The questions that need to be answered are:

(i) How and where are local flows affected by nearby abstractions?

This should involve case studies of tributaries in Norfolk and Suffolk.

(ii) Where should boreholes be best located to minimise effects on local flows ?

This is detailed hydrogeological work which would aim to establish rules for the location and operation of both boreholes and water discharge points. The work would require coupled surface and groundwater modelling to assess the relationship between the size and distance of an abstraction point from a river and the loss to flow in that river. Such modelling would require information and understanding of local aquifer properties, variation in the quantity of aquifer recharge and the effect of interference from nearby abstraction points. We again recommend that this work should involve case studies in the Anglian region.

3.2 Work on sediment

Flows, sediment loads and sediment loading from the upper parts of the catchments, should be monitored so these can be related to biological data. A temporary gauge could be installed in King's Beck, or one of the other Bure tributaries. Flow velocities need to be measured and biological monitoring must be carried out at the same site: this should include invertebrates, plant cover and plant species richness during April, July and September. Sediment loads in the flow could be monitored as part of a co-ordinated monitoring and research effort. We recommend that the research effort answers the following questions:

(i) Has internal sediment loading increased due to channel readjustments in the Rivers Wensum and Bure ?

The Nar is already the subject of NRA research programmes which should include work on sediment which will be useful for management of the River.

(ii) How large are today's external and internal sediment loadings ?

This involves field programmes of sediment trapping and flow gauging. A project could be completed in a three-year research programme.

(iii) How would it be best to intercept external sediment loads and how best to displace or remove silt from rivers ?

This is experimental work which involves the design and testing of different management schemes. This approach is suitable for a research student.

The existing monitoring programmes of the NRA could collect further useful information. For example, fisheries surveys at the beginning of the 1980s included notes on plant cover and other observations of habitats. Since fisheries surveys give the most complete geographical cover of all NRA monitoring programmes, they are useful opportunities for recording other information. The most important information is the percentage cover of different sediment types in the sampling sites and the frequency of riffles. Reference points should be established for the longer-term monitoring of the bankfull width of channels.

(ii) Have sediment exports from the upper River increased and what are the implications for the lower tidal part of the system ?

Very preliminary calculations have been made from the work of Garrad (1984) who analysed sediments in Wroxham Broad, about 10km below Horstead Mill in the tidal reaches of the Bure. Using clay mineralogy, Garrad found that about 25% of the material in the lake came from above Horstead Mill. Preliminary back calculations from his work, which have involved many assumptions, suggest that in 1840, 20 tonnes of sediment per year were received from above Horstead, about 200 tonnes per year in the 1960s and over 600 tonnes in 1984. Further work would improve confidence in these estimates which are given here to illustrate that the approach is feasible.

3.3 Work involving the effects of mills

The assumed effects of the past operation of mills and their remains on the study Rivers, have been brought to bear in most, if not all, of the interpretations we have made. The use and disuse of mills have both complicated and shaped the Rivers Bure and Wensum. The reinstatement of a working mill regime in either one of the study Rivers, or elsewhere, would provide a very interesting opportunity to measure both local hydrological and biological effects. Amenity value of this would extend to the interests of other organisations and the wider public. For the NRA it would provide an interesting opportunity to test the effects of flow regime on plant, invertebrate and fish communities. We recommend that such an opportunity be used experimentally to develop fully a description and understanding of the relationships between flow and sediment transport.

3.4 Water resources management in other catchments

The general approach used to answer the questions in this project could be applied to other catchments in the Anglian Region or elsewhere.

The experience gained from this project shows that interpretations were limited by lack of data on: flow velocity; flow in headwaters; plant data; past sediment distributions (and present distributions in the Nar); suspended solids; total phosphorus and imprecise site referencing in special reports of biological status. Routine water quality monitoring programmes should always record both water and air temperature and the time of day of the recording. Changes in the relationship between the two temperatures can be interpreted as variations in the contributions of baseflow to surface runoff. The accommodation of these measures in future monitoring effort would greatly assist any further studies which might parallel this one in north Norfolk.

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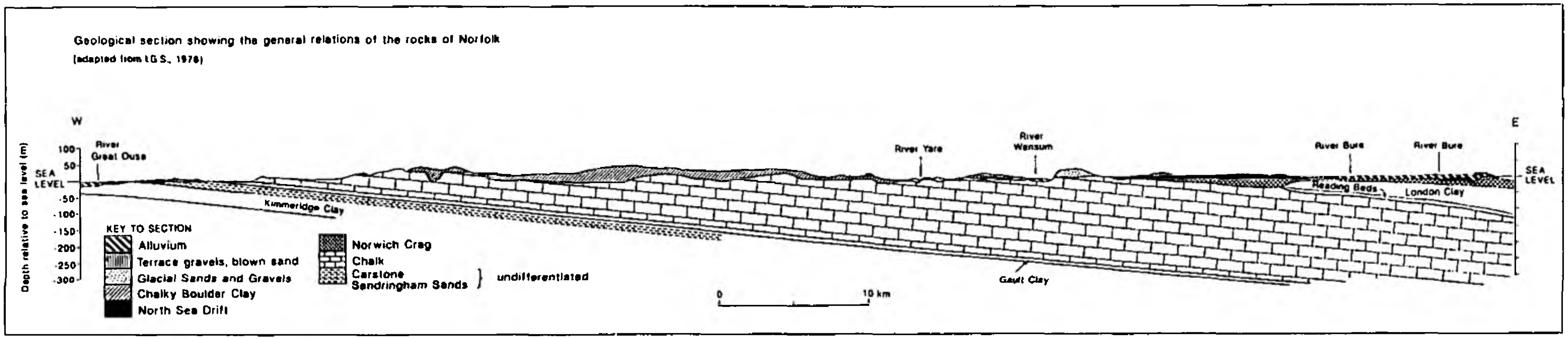


Figure 1 Geological cross section of north Norfolk which shows the Chalk aquifer and major Norfolk Rivers. Maps are adapted from the Institute of Geological Sciences, 1976.

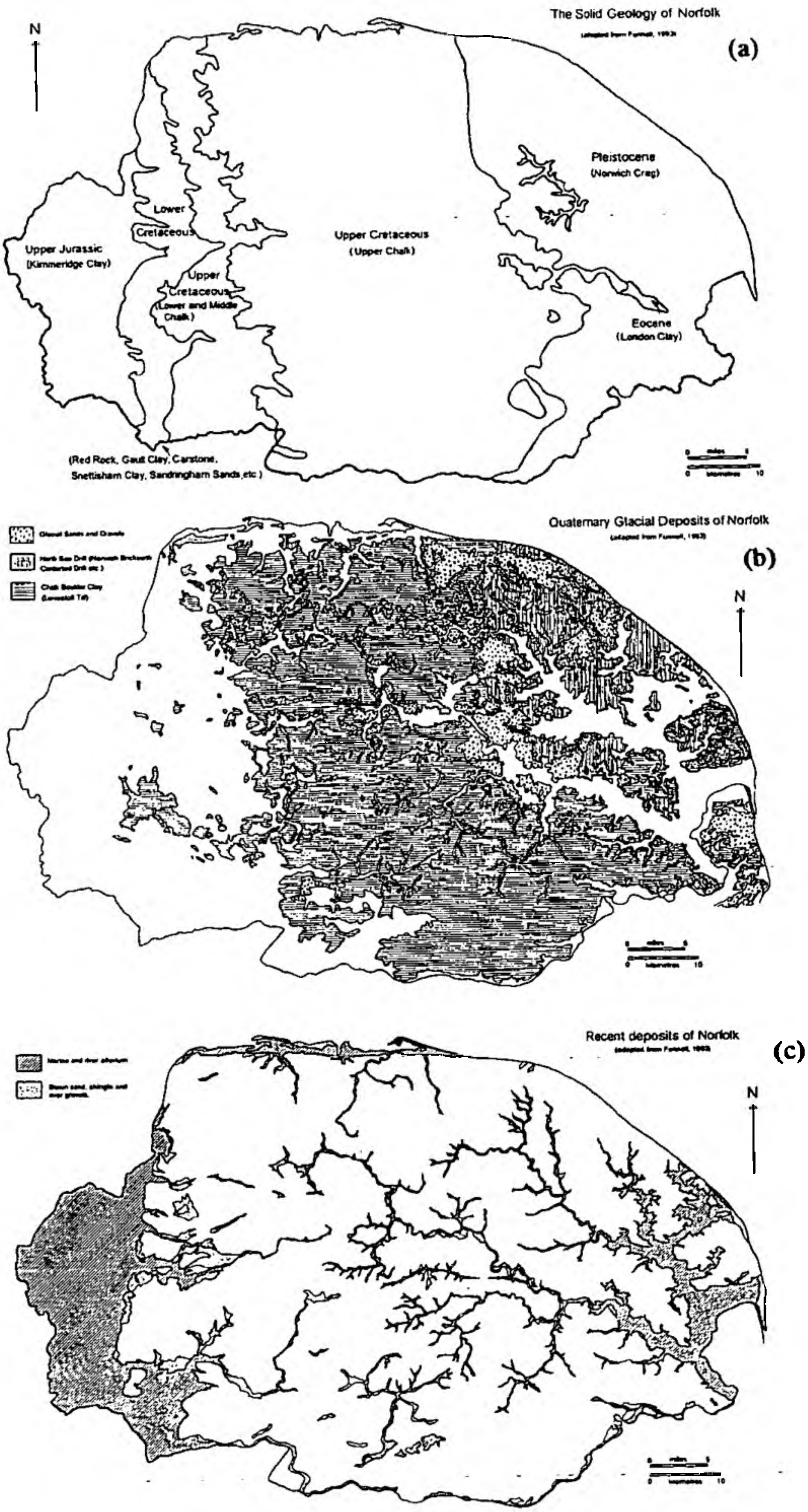


Figure 2 Solid and drift geology of north Norfolk showing (a) solid geology (b) Quaternary glacial deposits and (c) Recent deposits. Maps are adapted from Funnell, 1993.

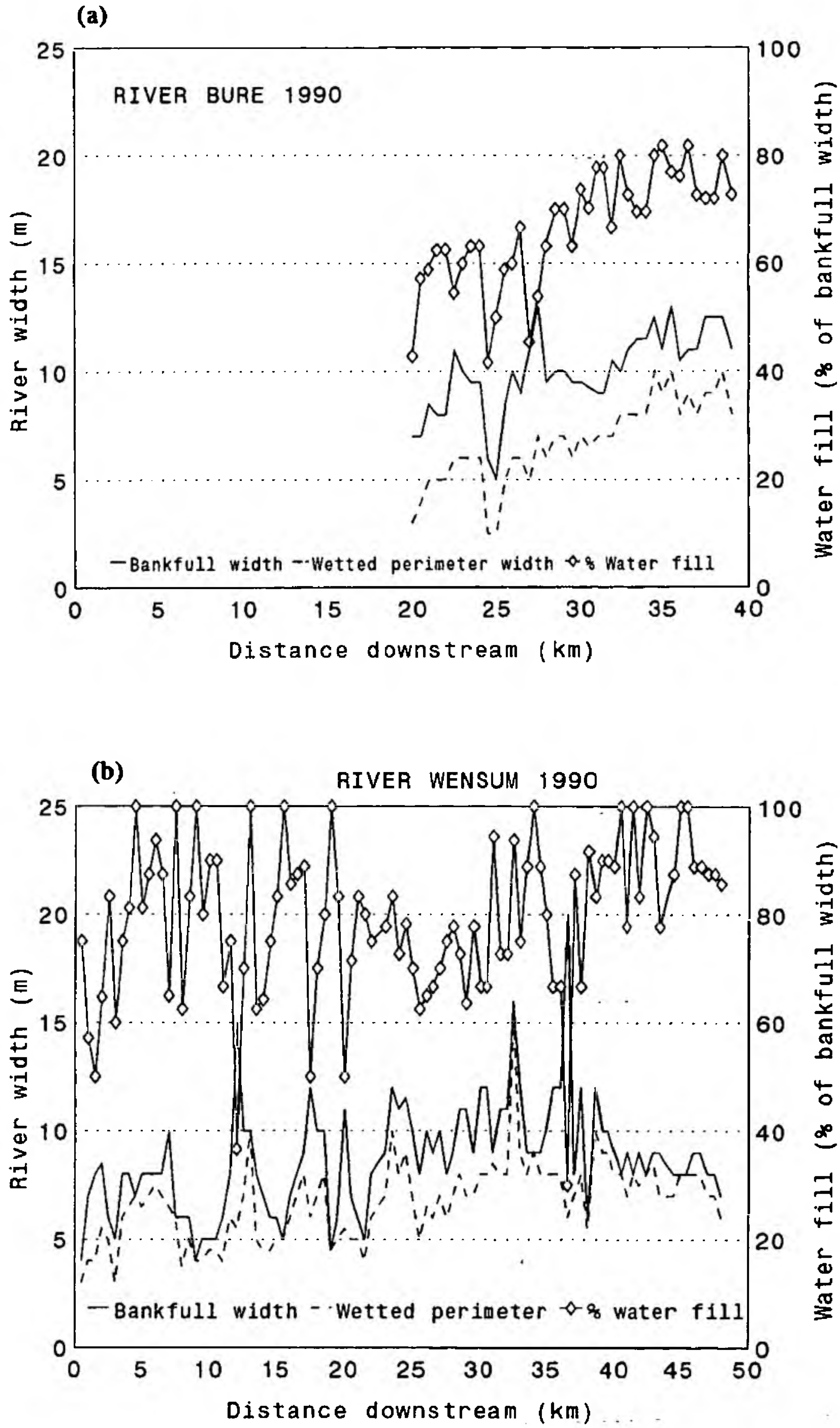


Figure 4 Bankfull channel widths and the proportions of the channel widths filled with water during 1990 in (a) the River Bure and (b) the River Wensum.

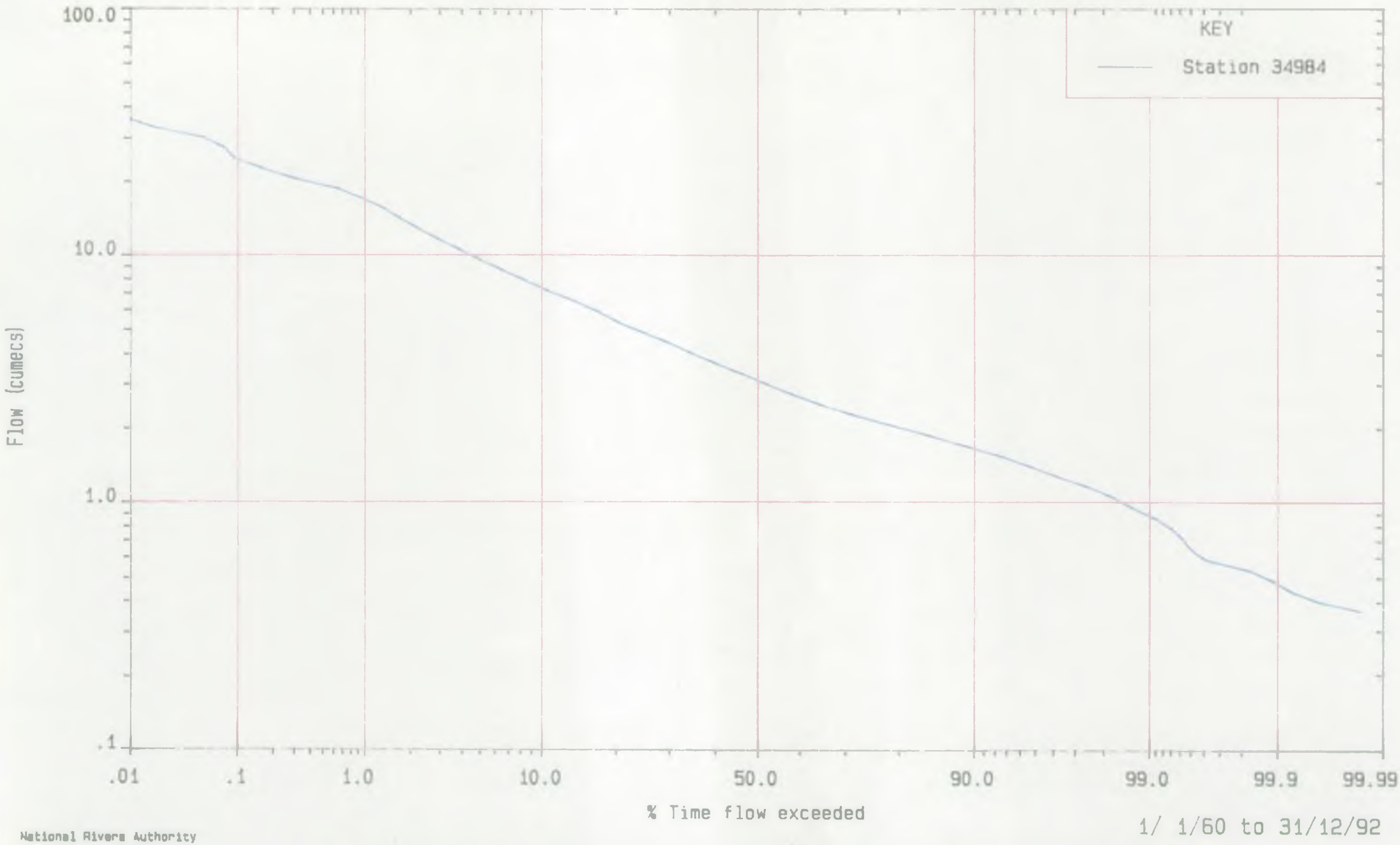
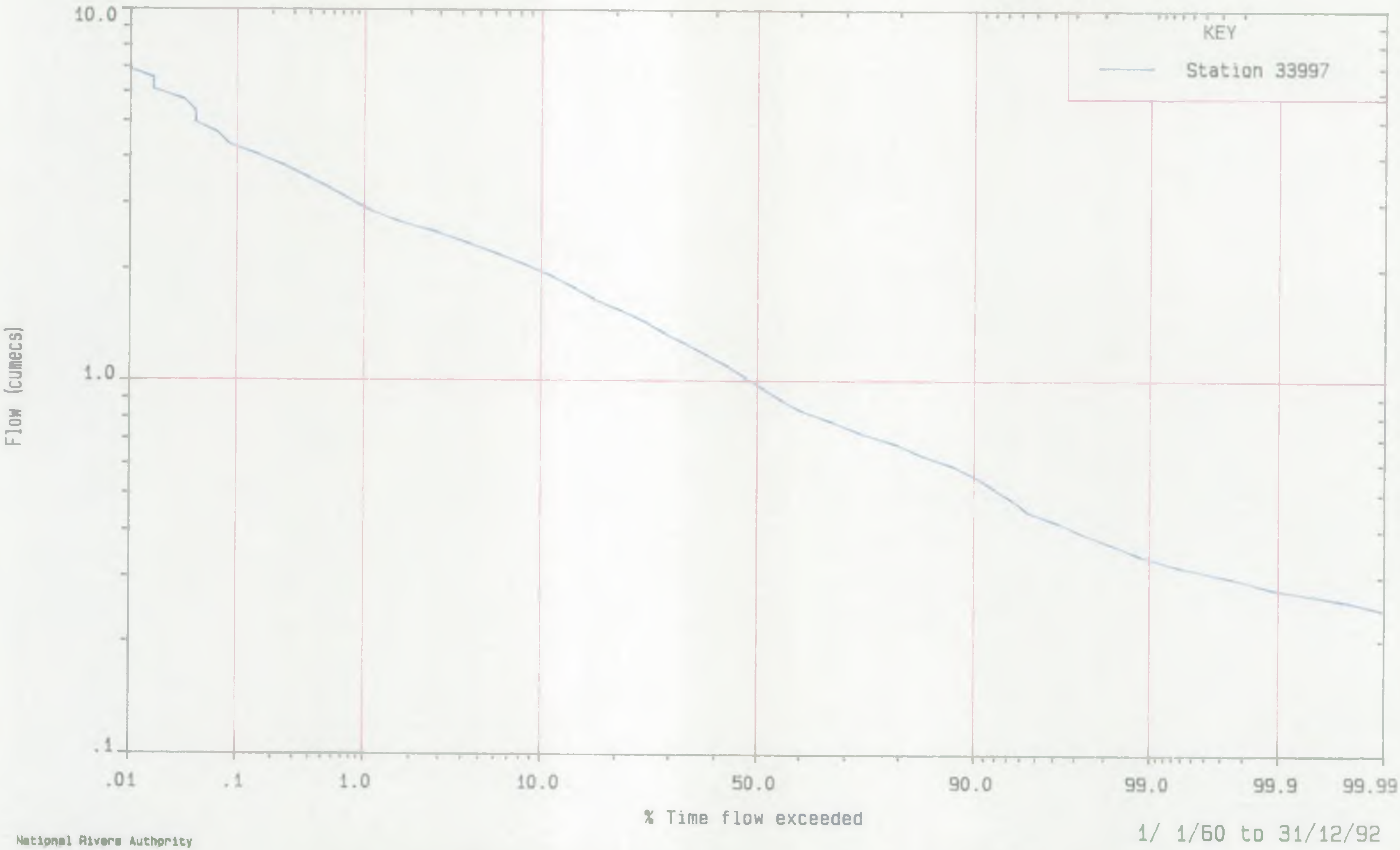


Figure 3(a) Flow duration curve for the River Wensum at Costessey. Surface abstractions (above Costessey) for public water supply have been taken into account.



National Rivers Authority

Figure 3(b) Flow duration curve for the River Nar at Marham. Surface abstractions for public water supply have been taken into account.

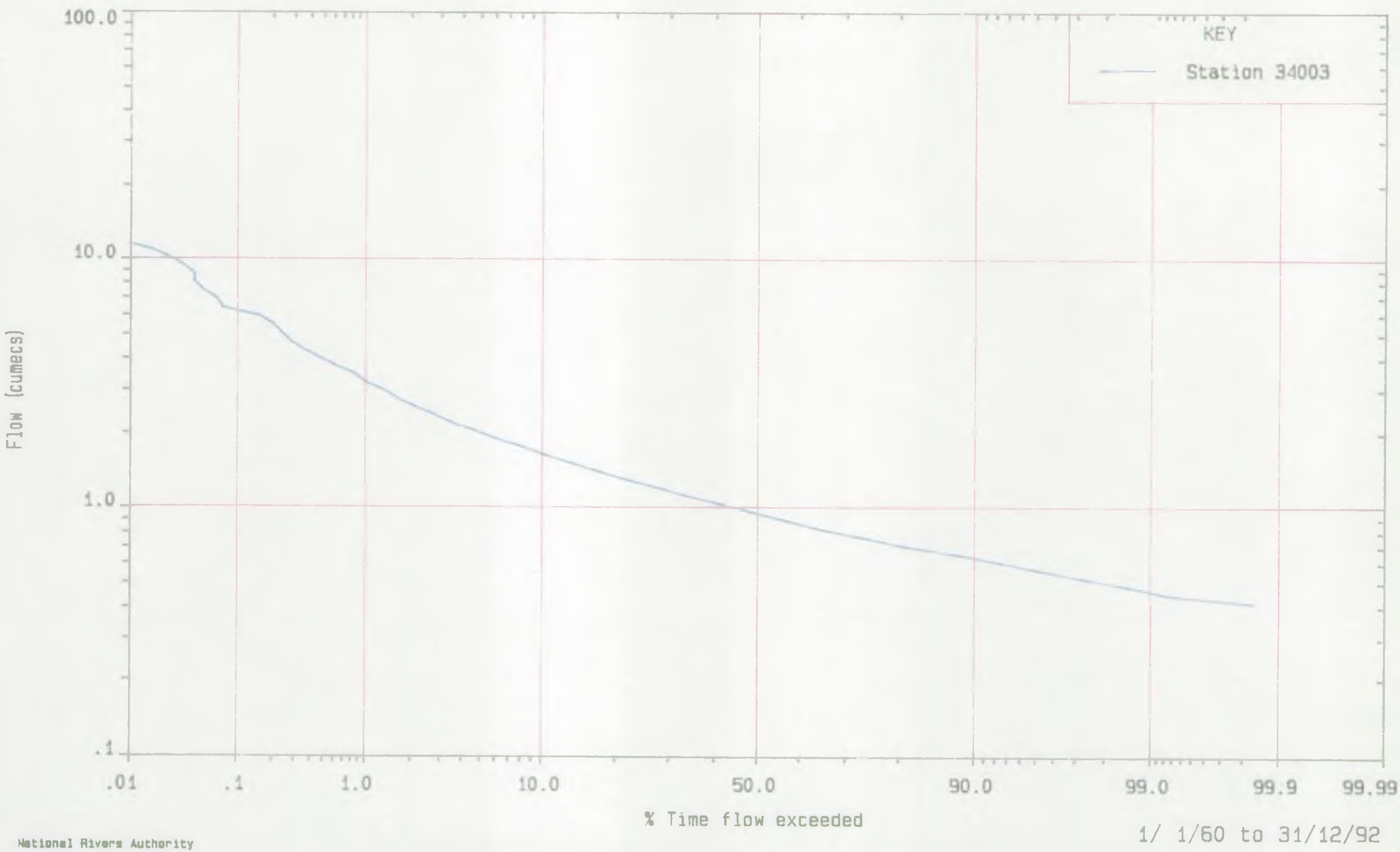


Figure 3(c) Flow duration curve for the River Bure at Ingworth. Surface abstractions above Ingworth are not significant.

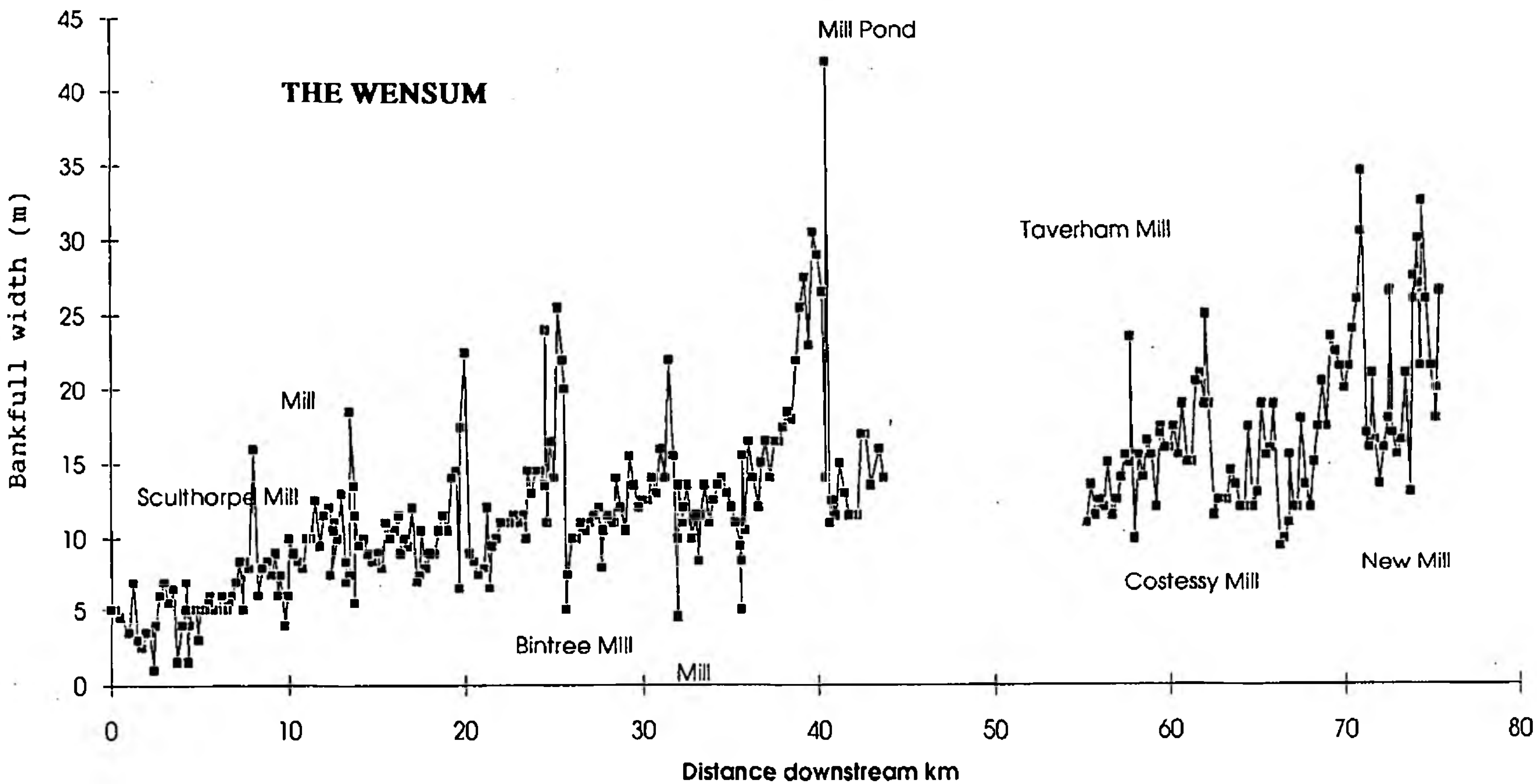


Figure 5 Long profile of bankfull widths of the River Wensum during 1993. Information from a survey commissioned by the NRA.

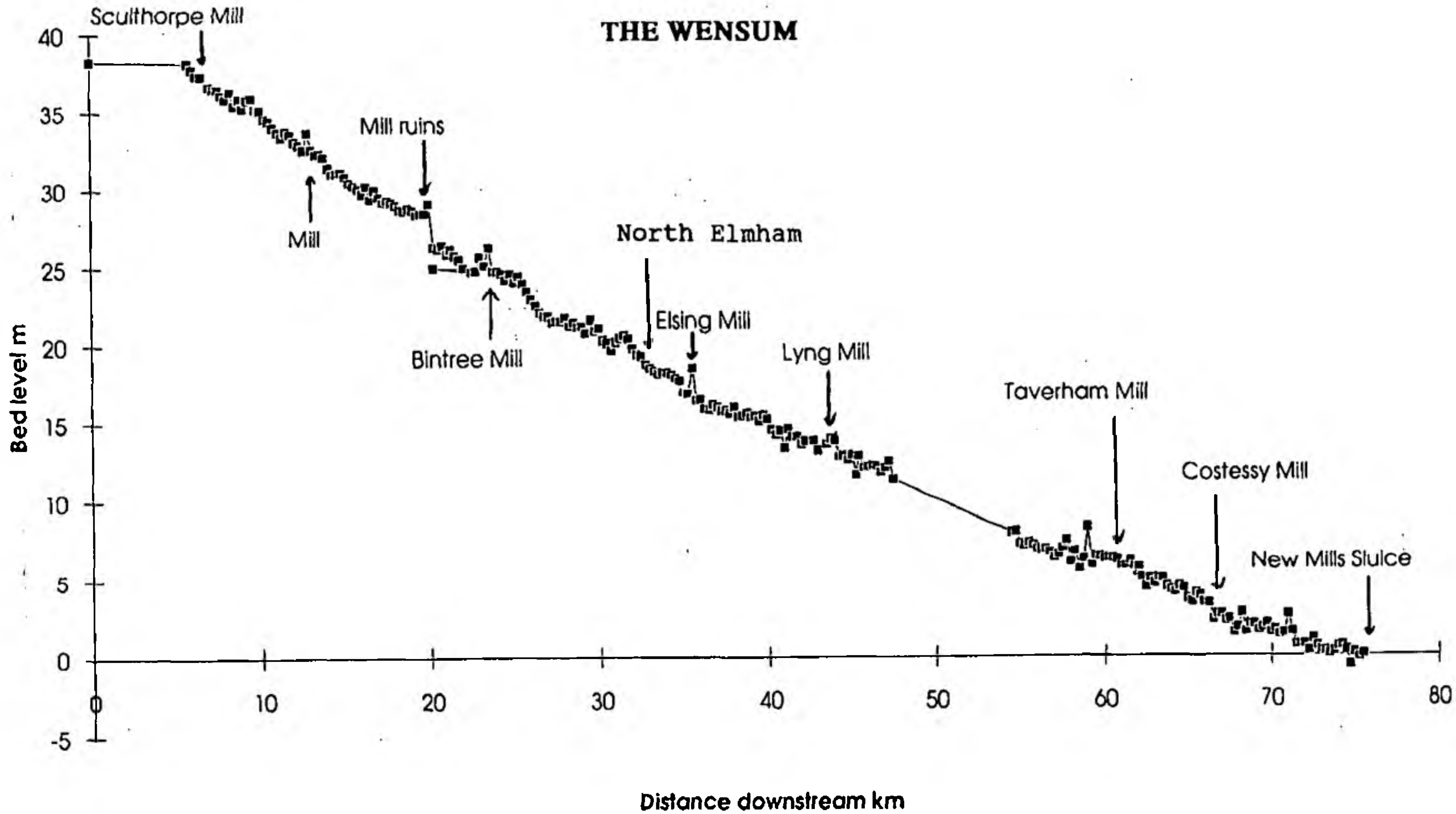


Figure 6 Long profile of channel depths in the River Wensum during 1993. All the Mills, except at North Elmham, retain structures which have some influence on river hydraulics.

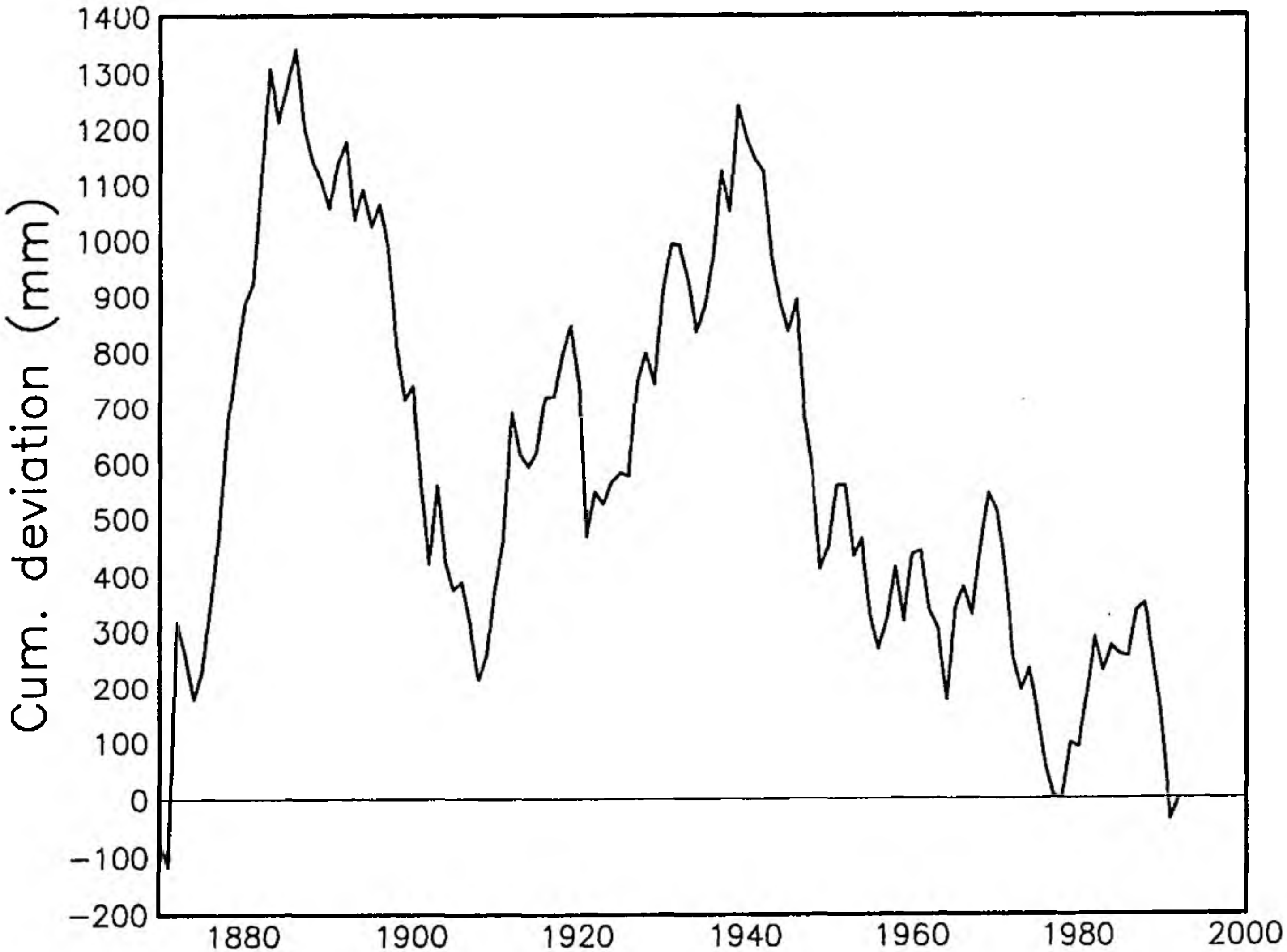


Figure 7 The cumulative deviation of mean annual rainfall about mean rainfall over the period 1870 to 1992 at East Dereham, Norfolk.

Figure 8

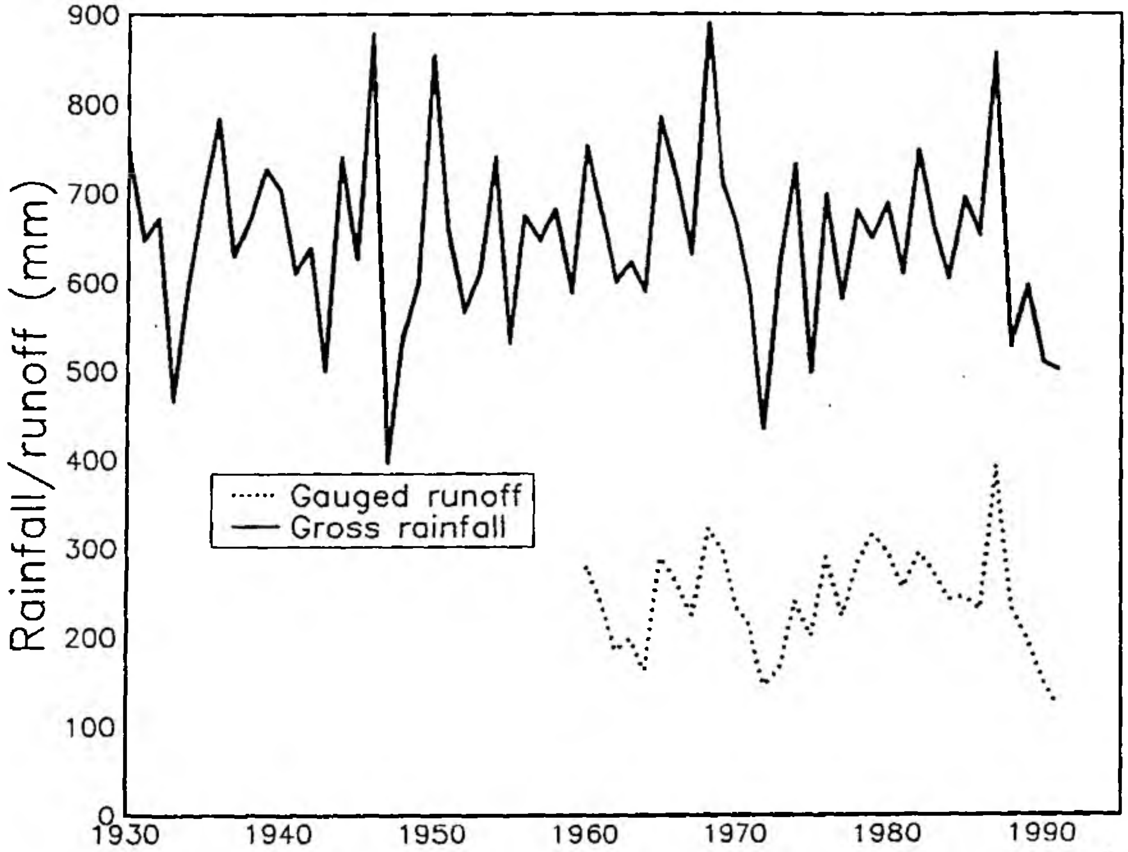


Figure 9

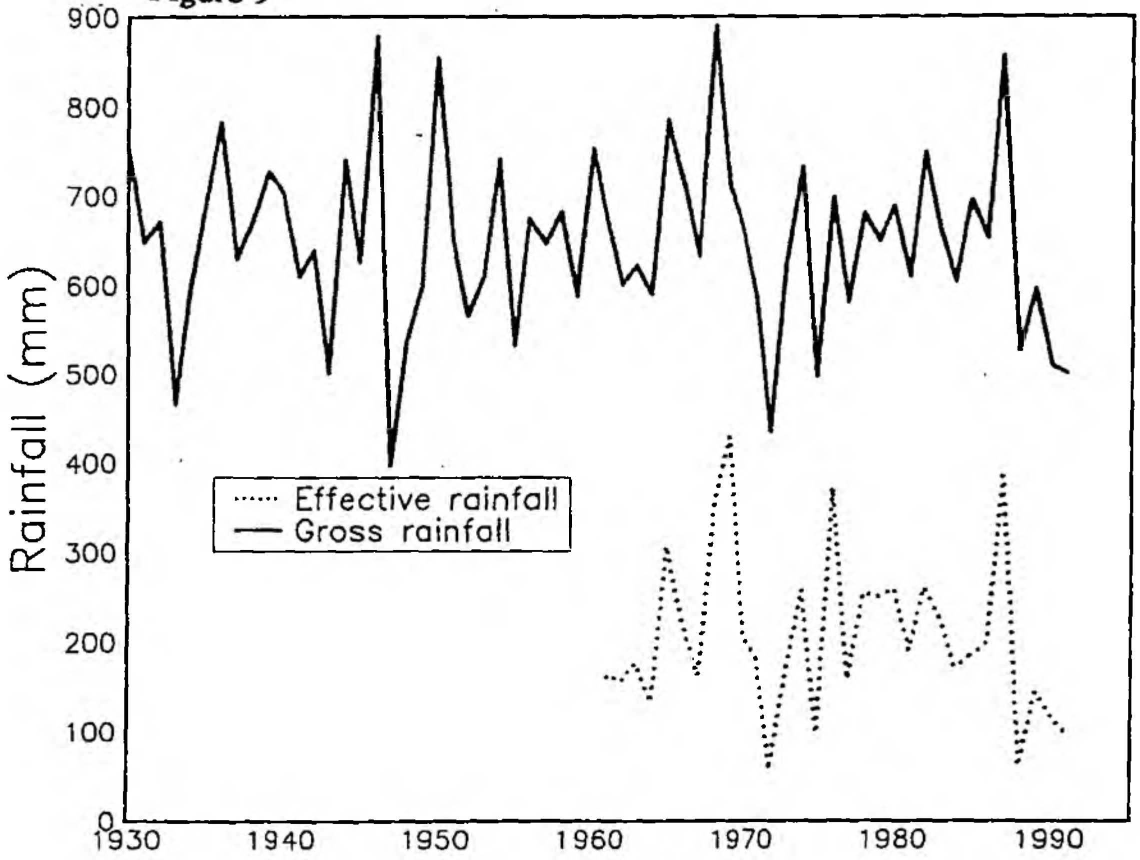


Figure 8 Gross annual rainfall and runoff at Costessey on the Wensum, 1930-1991.

Figure 9 Gross and effective annual rainfall for the study area, 1961 to 1992.

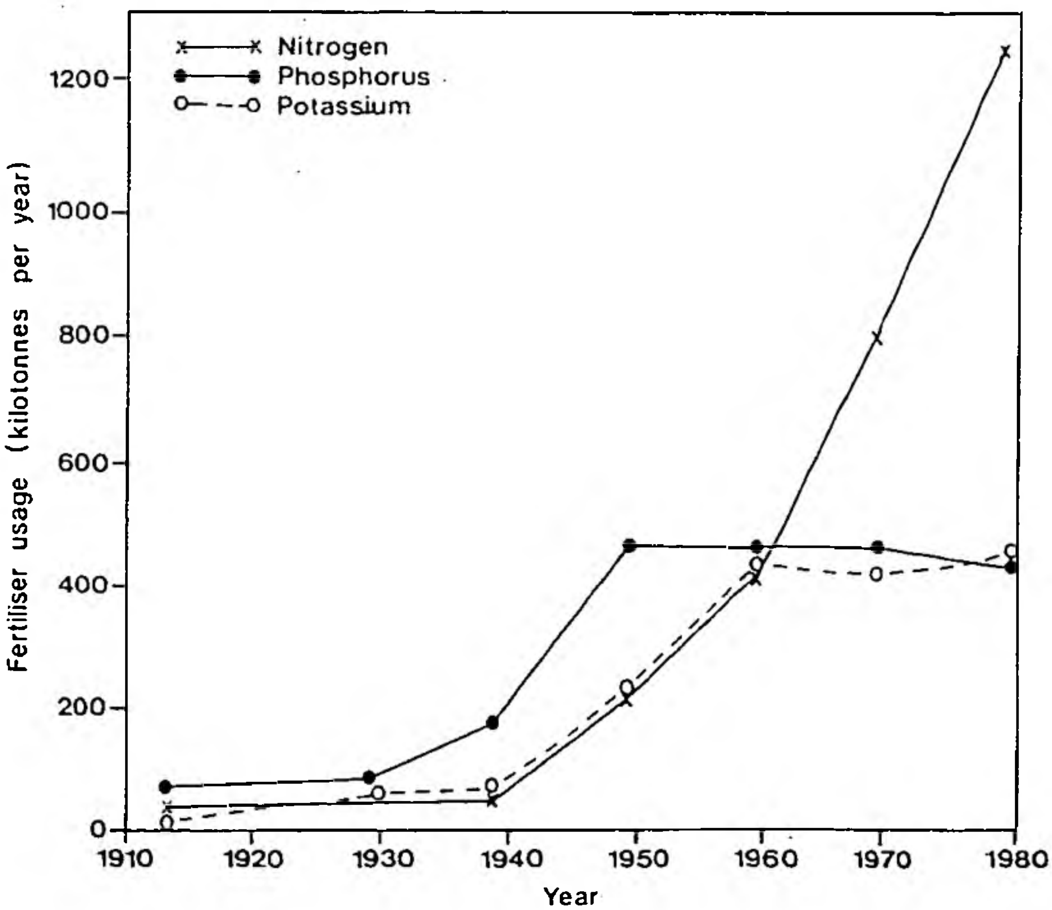


Figure 10 Changes in fertiliser use in the United Kingdom since 1913. From Briggs and Courtney (1989).

Figure 11

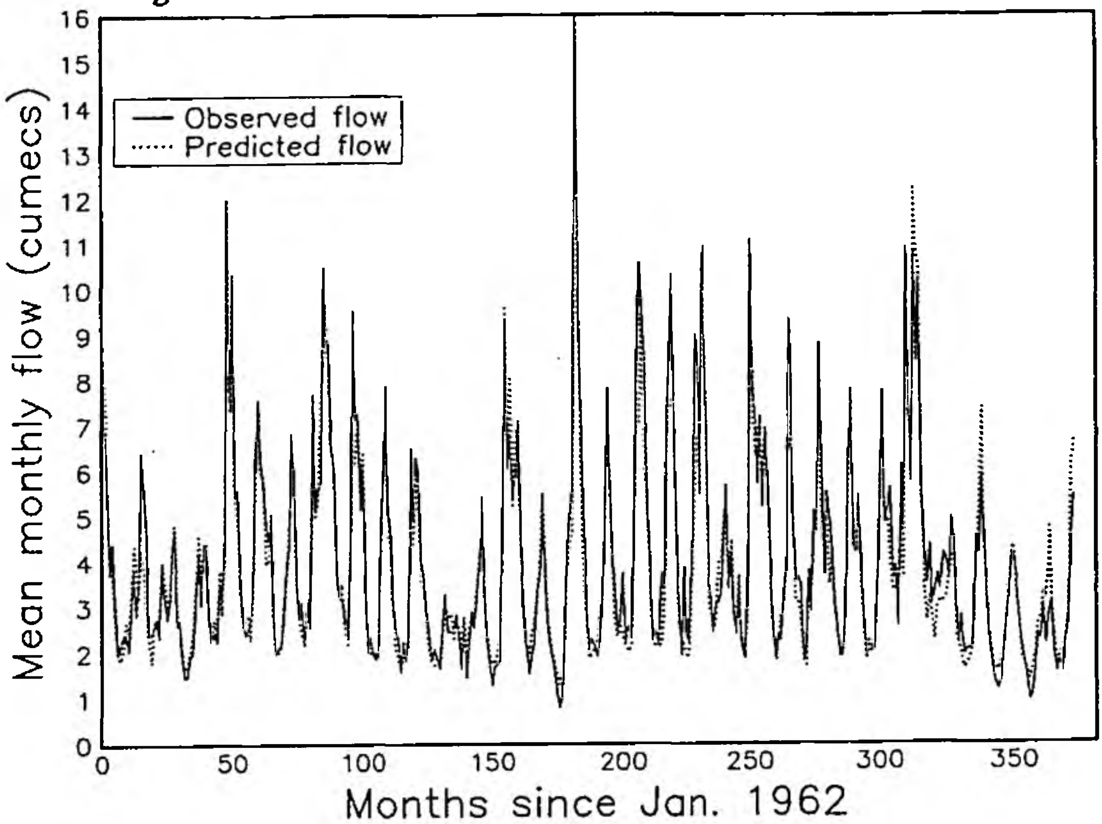


Figure 12

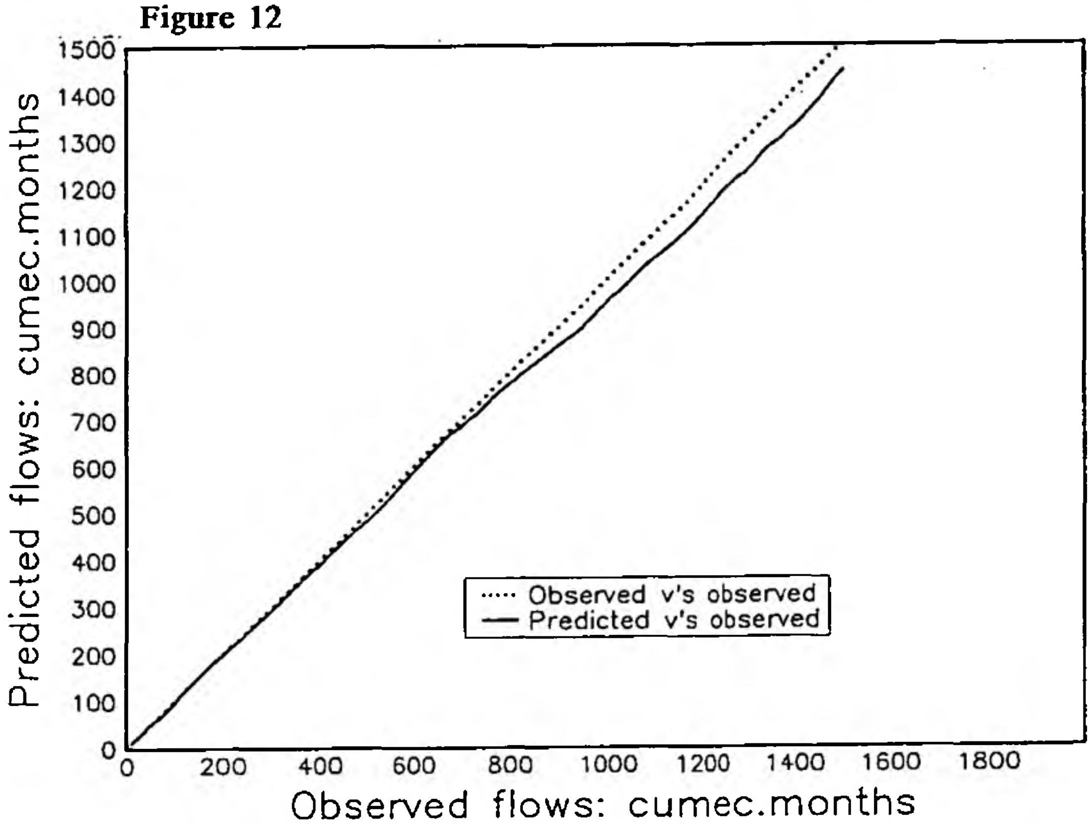


Figure 11 Observed flows at Costessey between 1962 and 1992 and the flows predicted from gross rainfall over the period.

Figure 12 Predicted and observed cumulative monthly flows at Costessey, 1962 to 1992.

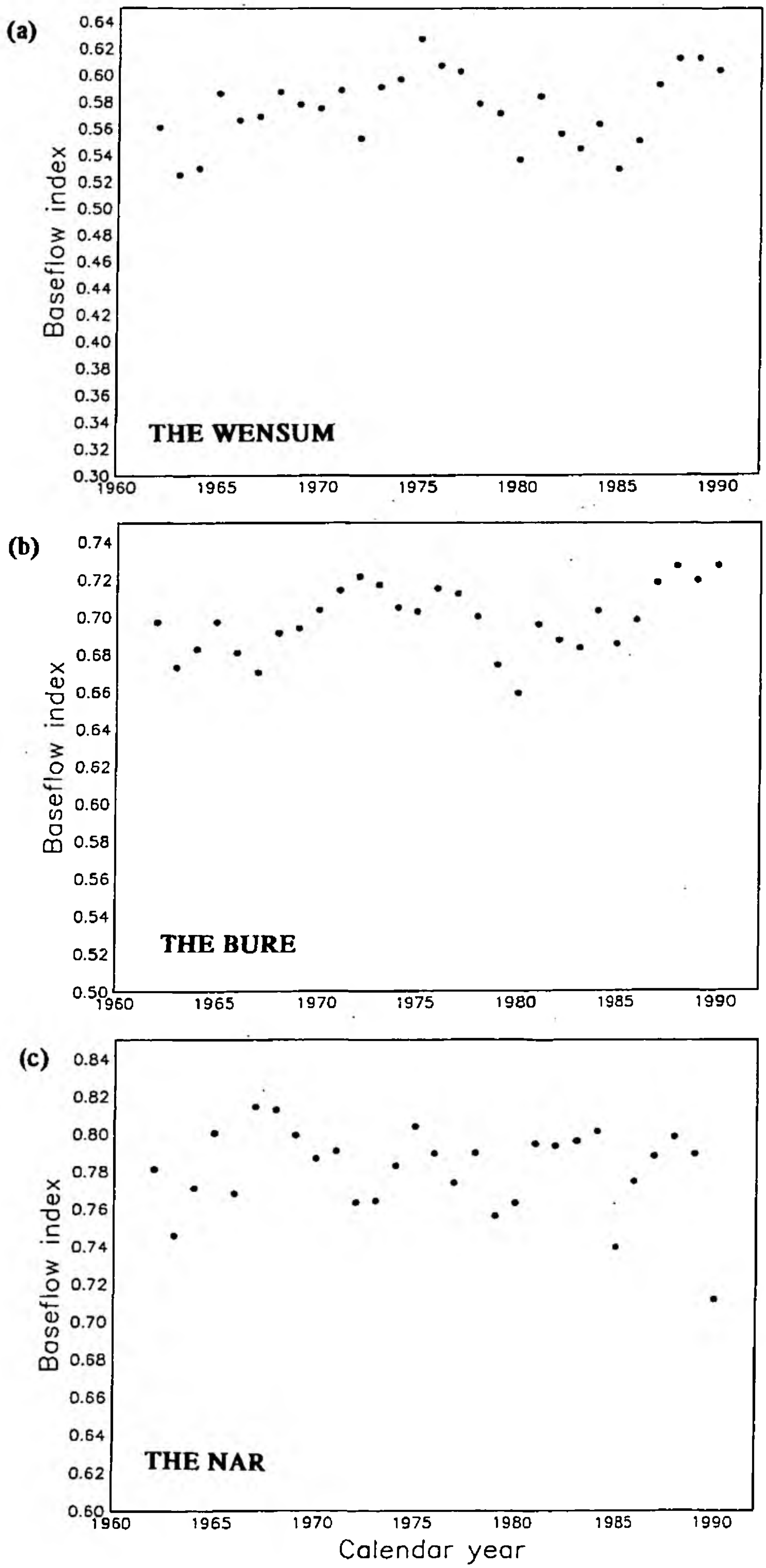


Figure 13 Variations in 5-year running-mean baseflow index between 1961 and 1992 in (a) the Wensum at Costessey (b) the Bure at Ingworth and (c) the Nar at Marham.

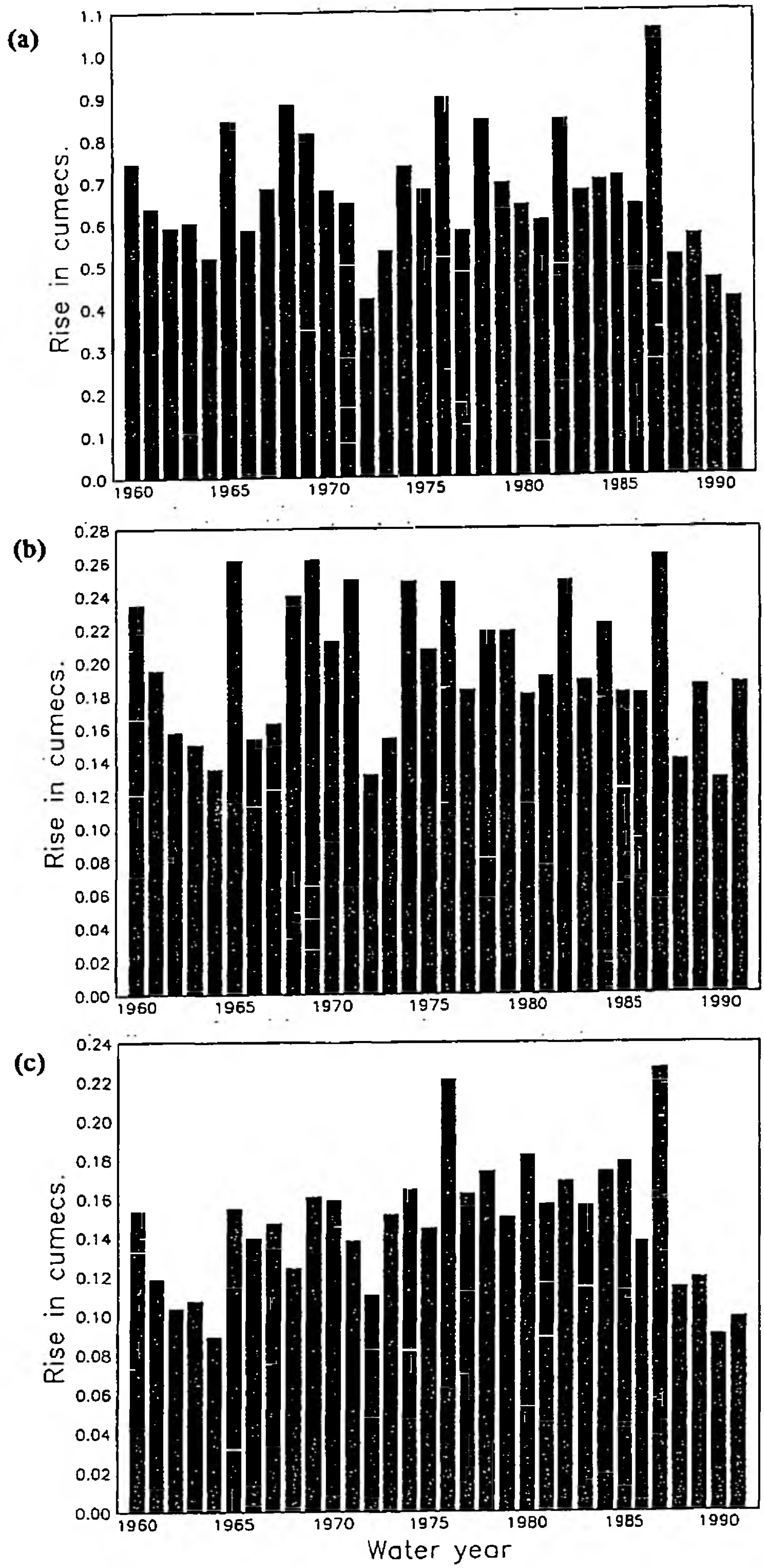


Figure 14 Mean daily hydrograph rise between 1960 and 1992 in (a) the Wensum at Costessey (b) the Bure at Ingworth and (c) the Nar at Marham.

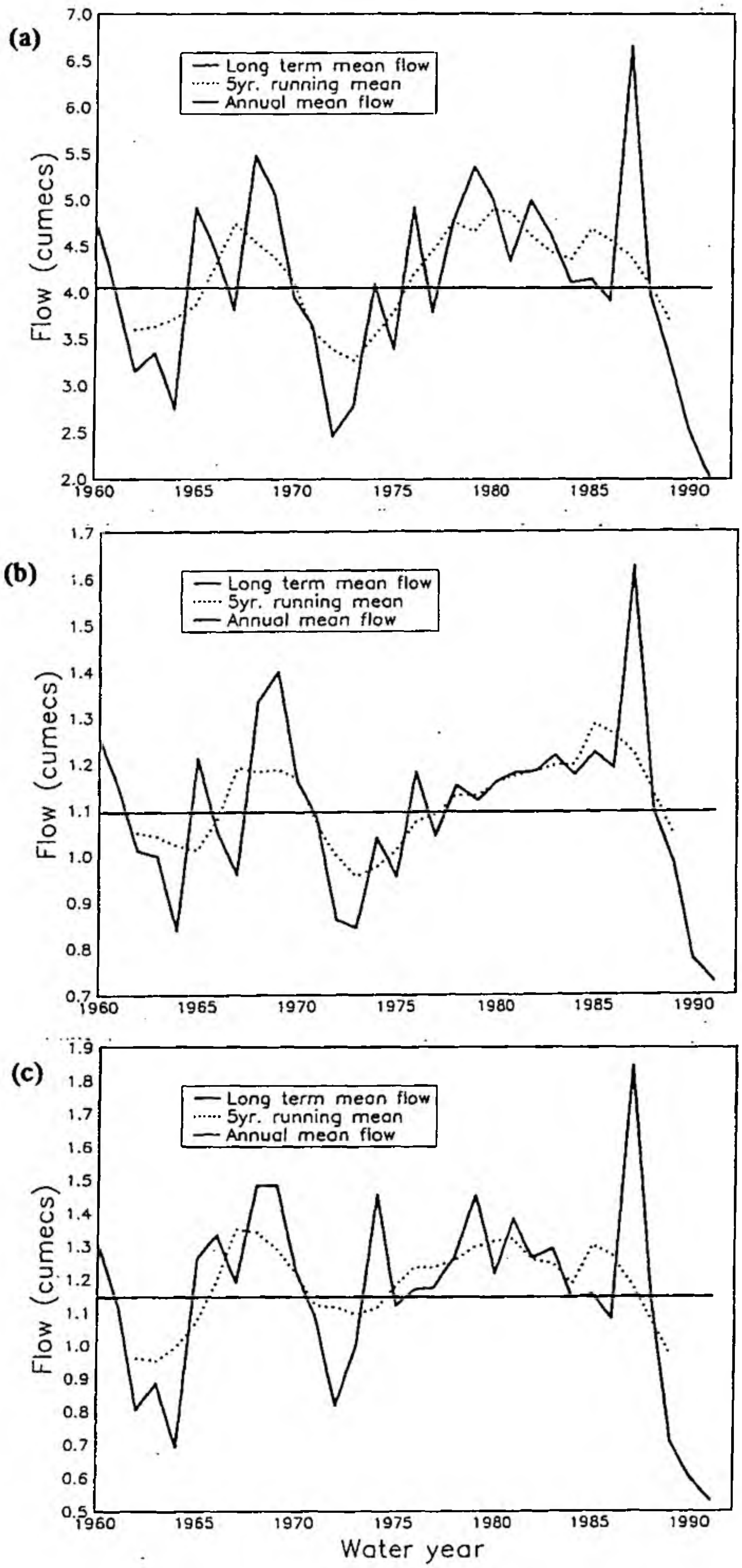


Figure 15 Long-term (1969 to 1992) mean daily flow, annual and 5-year mean daily flows in (a) the Wensum at Costessey (b) the Bure at Ingworth and (c) the Nar at Marham.

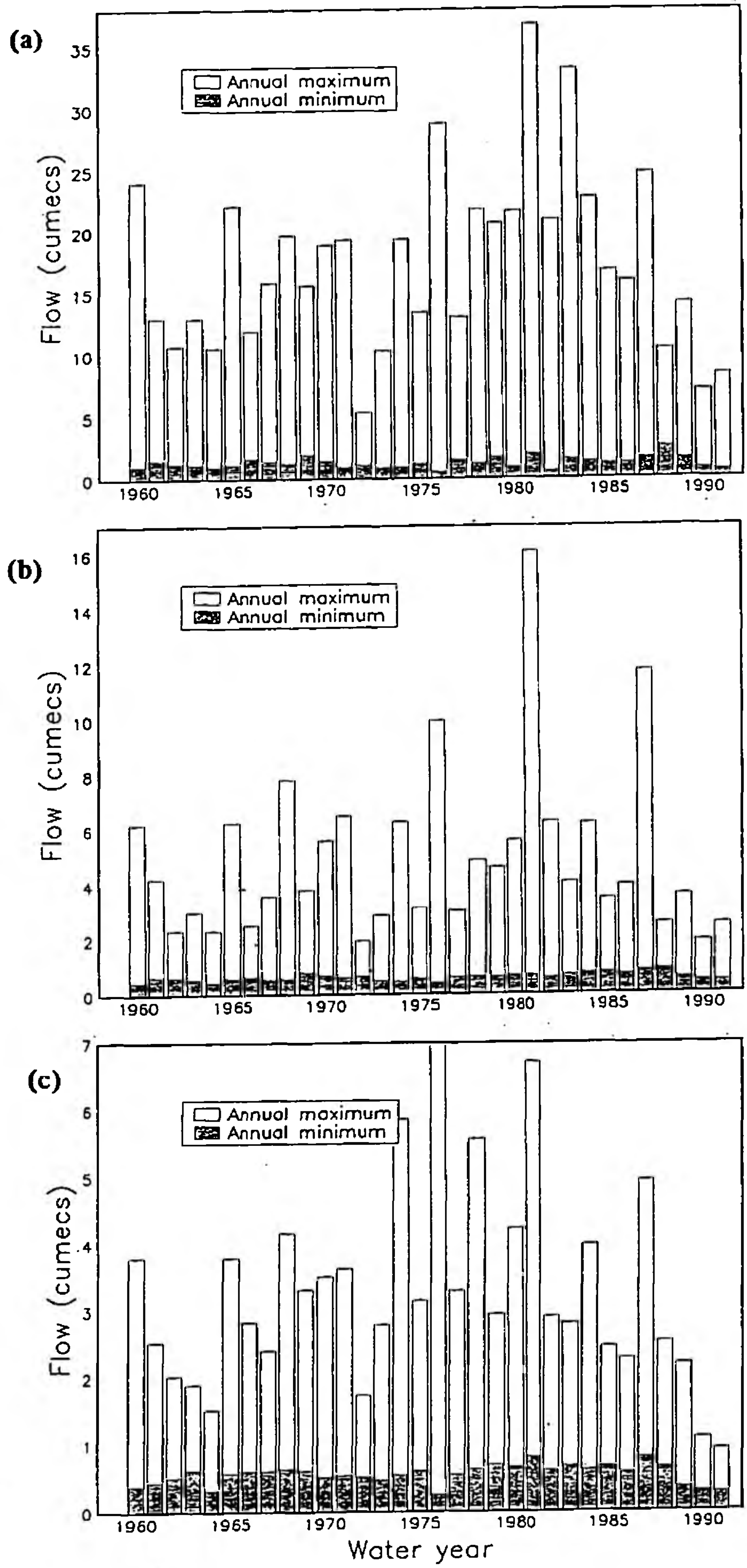


Figure 16 Annual extremes of mean-daily-flow between 1960 and 1992 in (a) the Wensum at Costessey (b) the Bure at Ingworth and (c) the Nar at Marham.

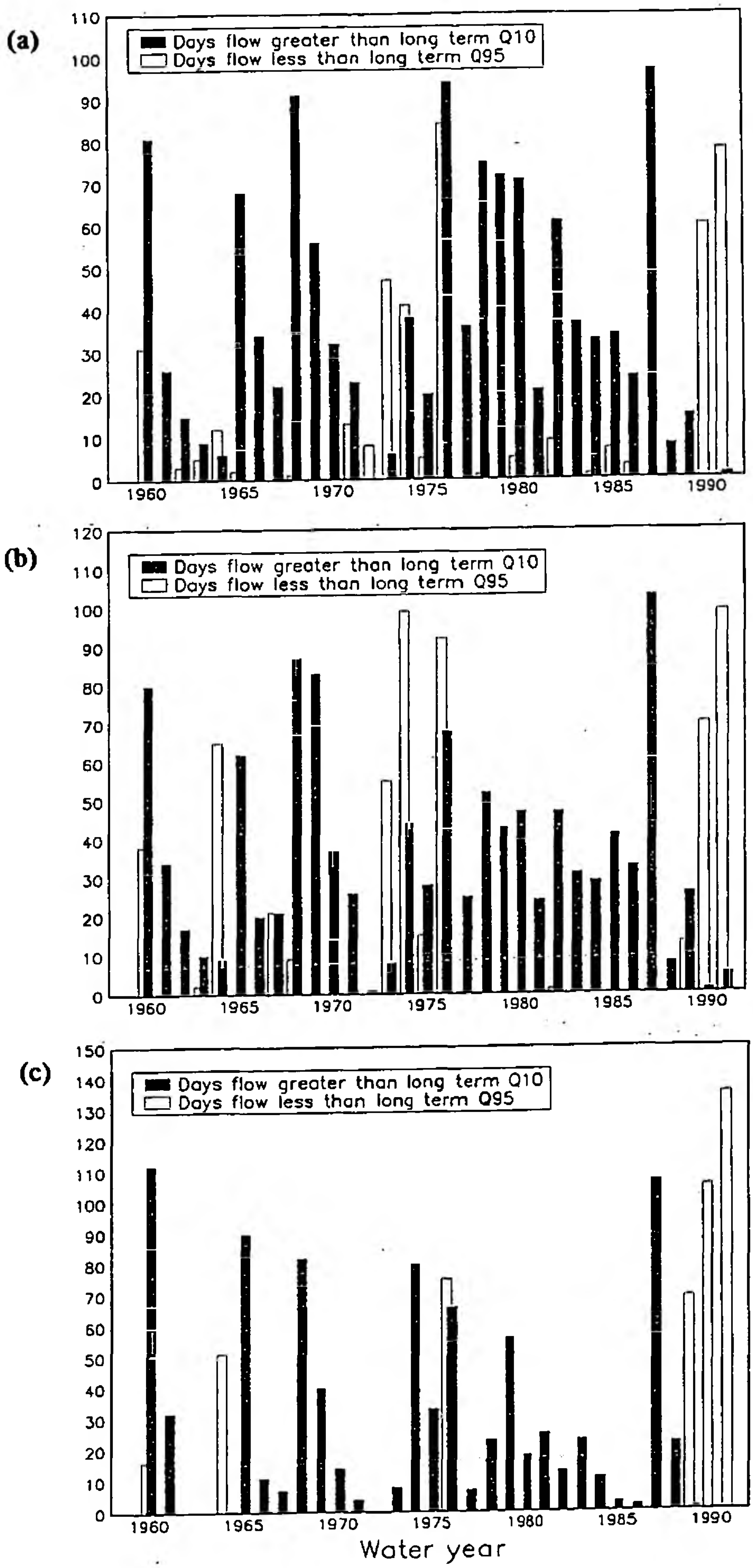


Figure 17 Annual frequencies of high and low daily flows between 1960 and 1992 in (a) the Wensum at Costessey (b) the Bure at Ingworth and (c) the Nar at Marham.

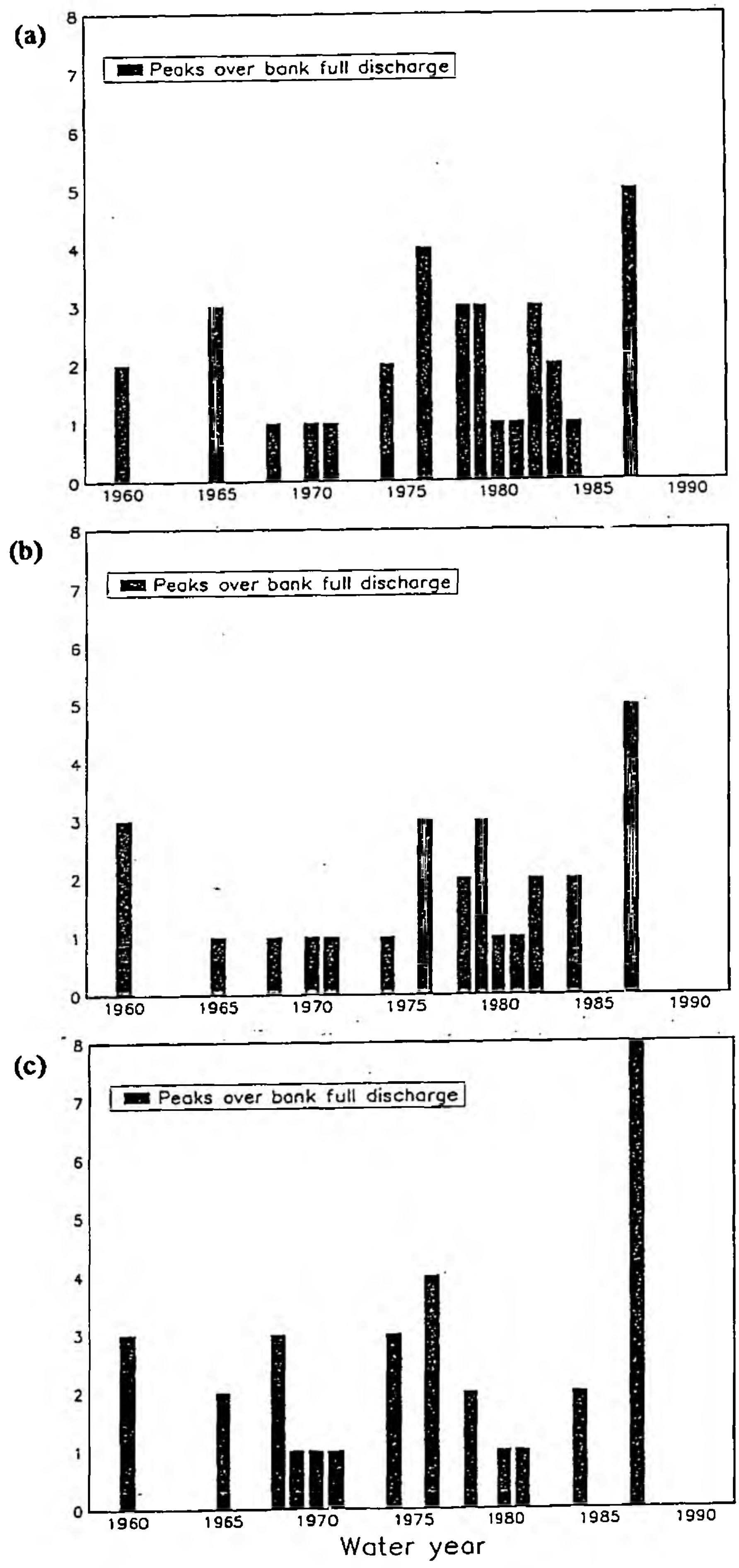


Figure 18 Annual frequency of peak-over-threshold flows between 1960 and 1992 in (a) the Wensum at Costessey (b) the Bure at Ingworth and (c) the Nar at Marham.

Figure 19

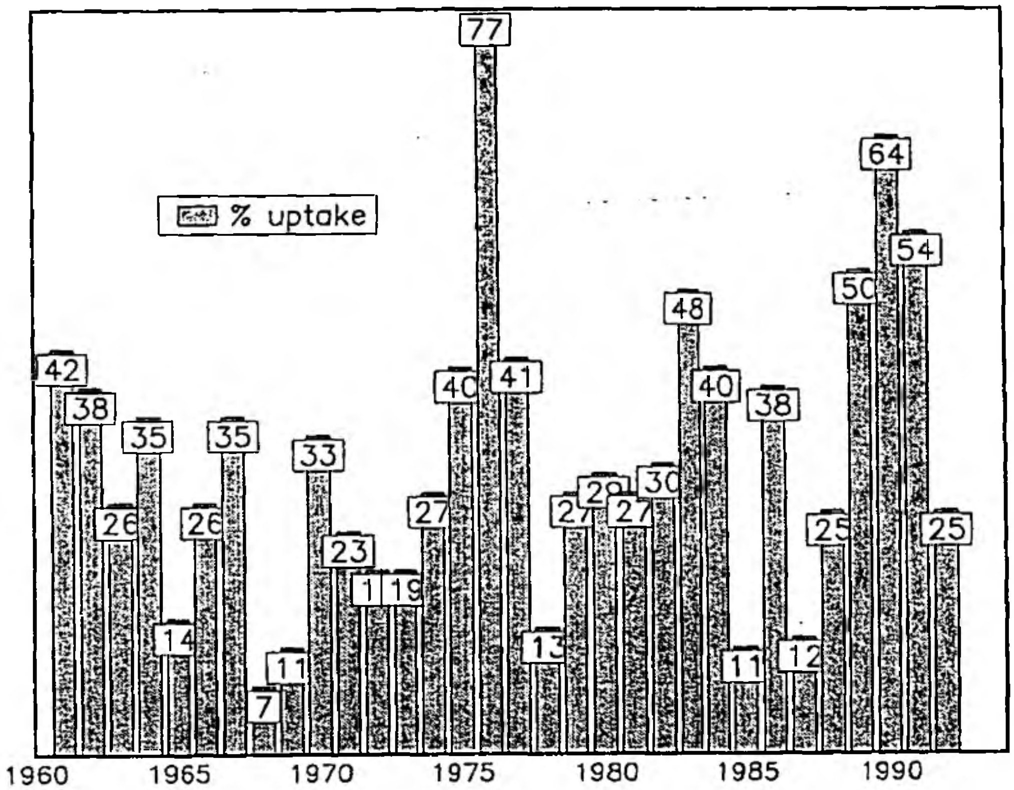


Figure 20

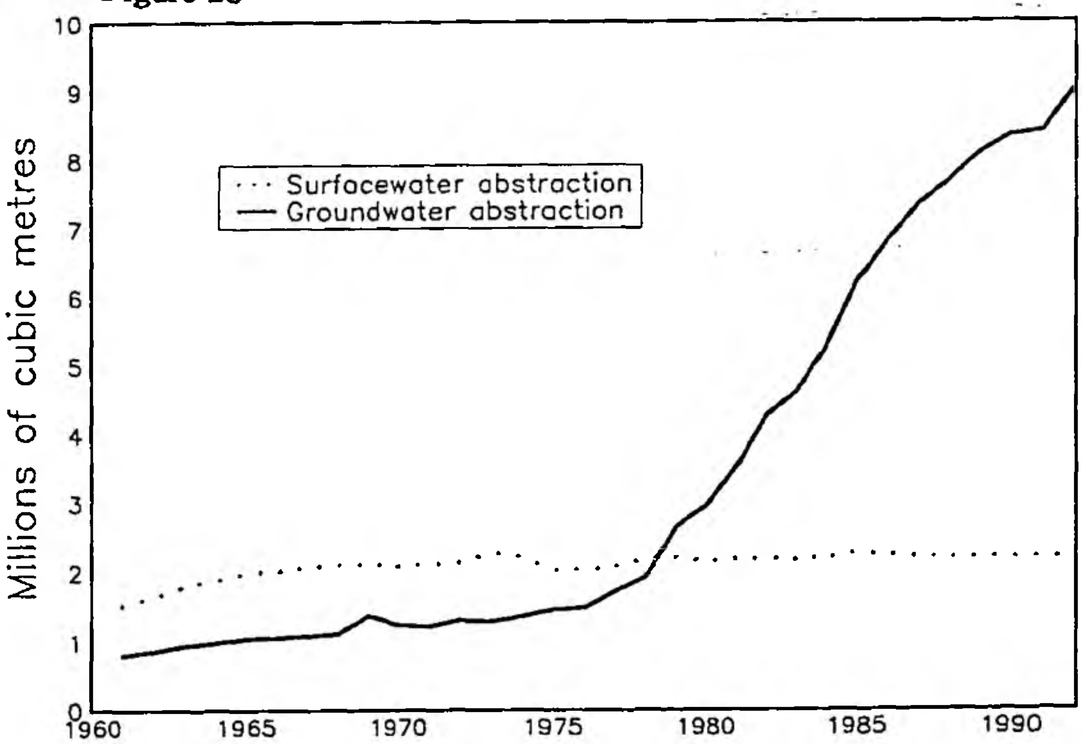


Figure 19 Uptake of licensed spray irrigation in the study area between 1961 and 1992.

Figure 20 Annual licensed totals for spray irrigation in the study area between 1961 and 1992.

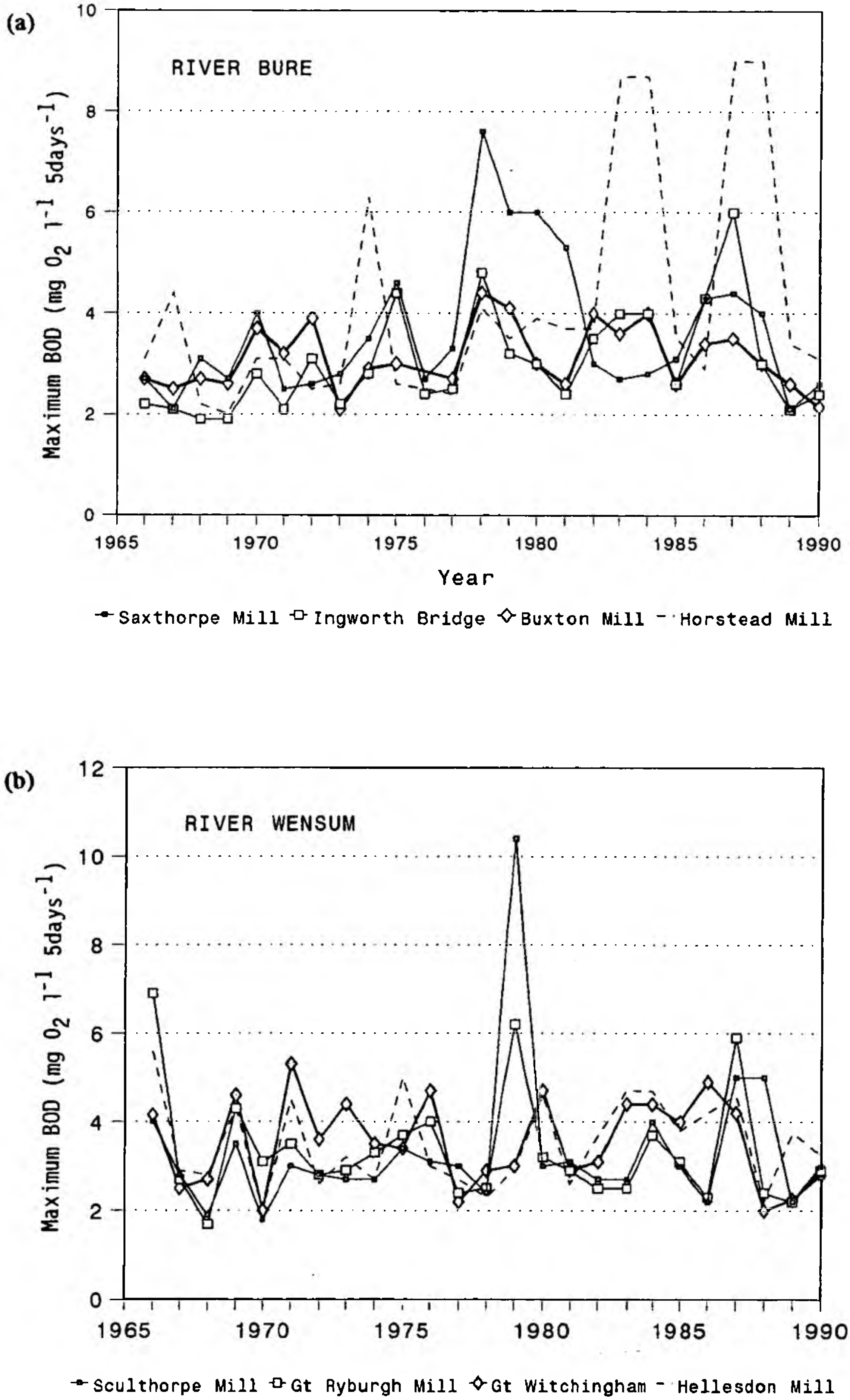


Figure 21 Annual maximum biological oxygen demand in (a) the Bure and (b) the Wensum between 1966 and 1990.

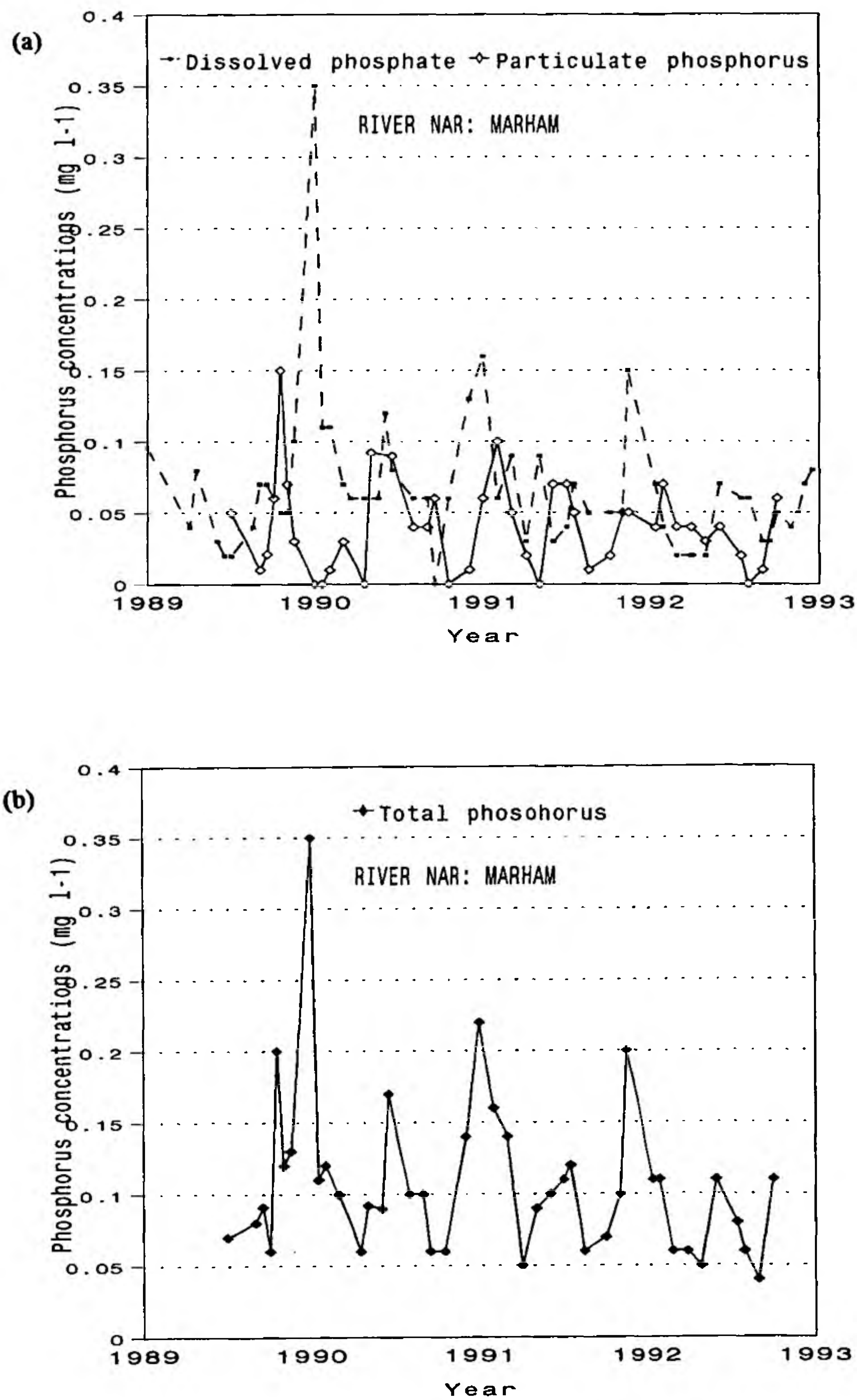


Figure 23 Concentrations of (a) dissolved and particulate forms of phosphorus and (b) total and particulate forms in the River Nar at Marham.

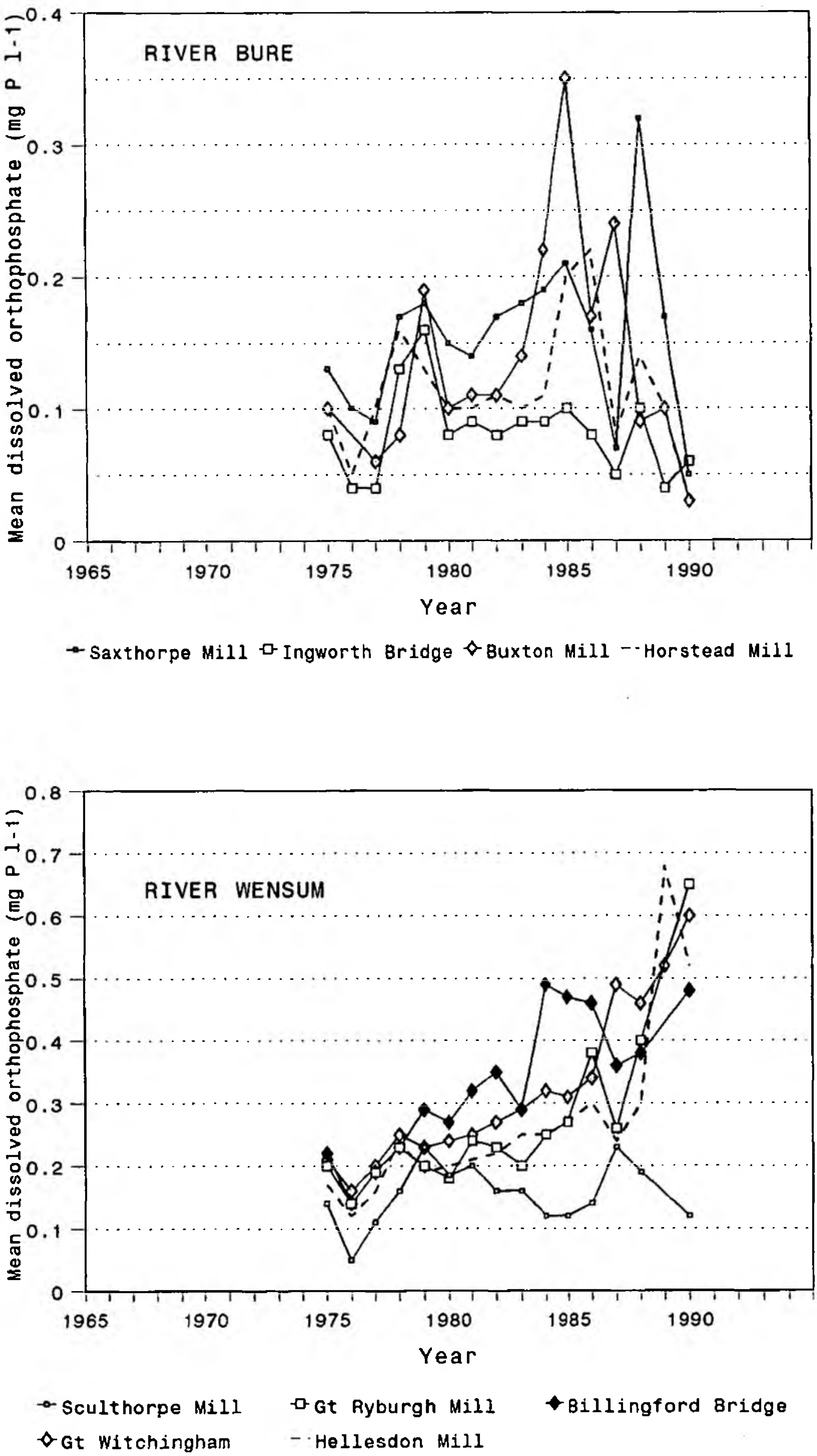


Figure 24 Annual mean concentration of dissolved phosphorus in (a) four sites on the Bure and (b) five sites on the Wensum between 1975 and 1990.

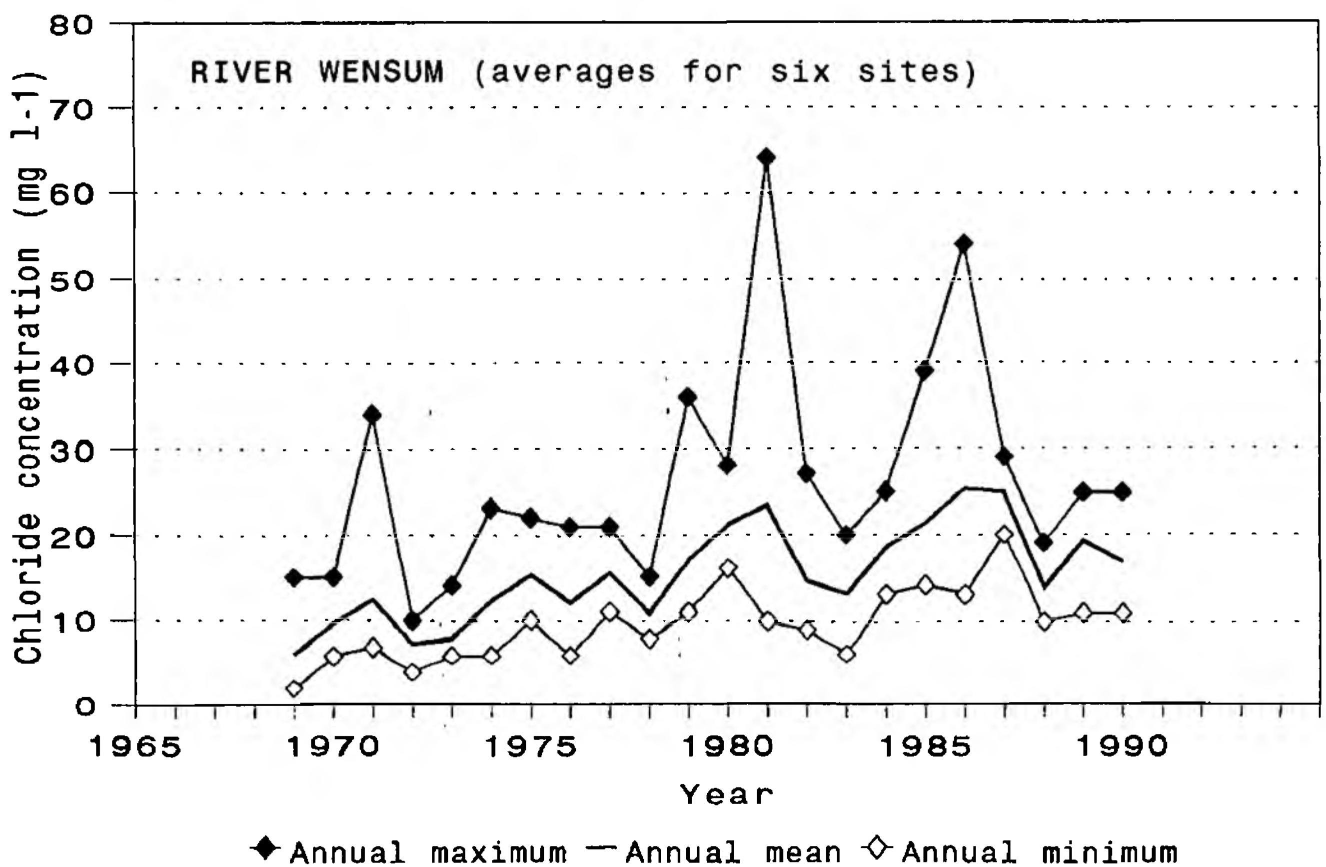


Figure 25 Annual mean, minimum and maximum concentrations of chloride between 1969 and 1990 averaged for six sites on the River Wensum.

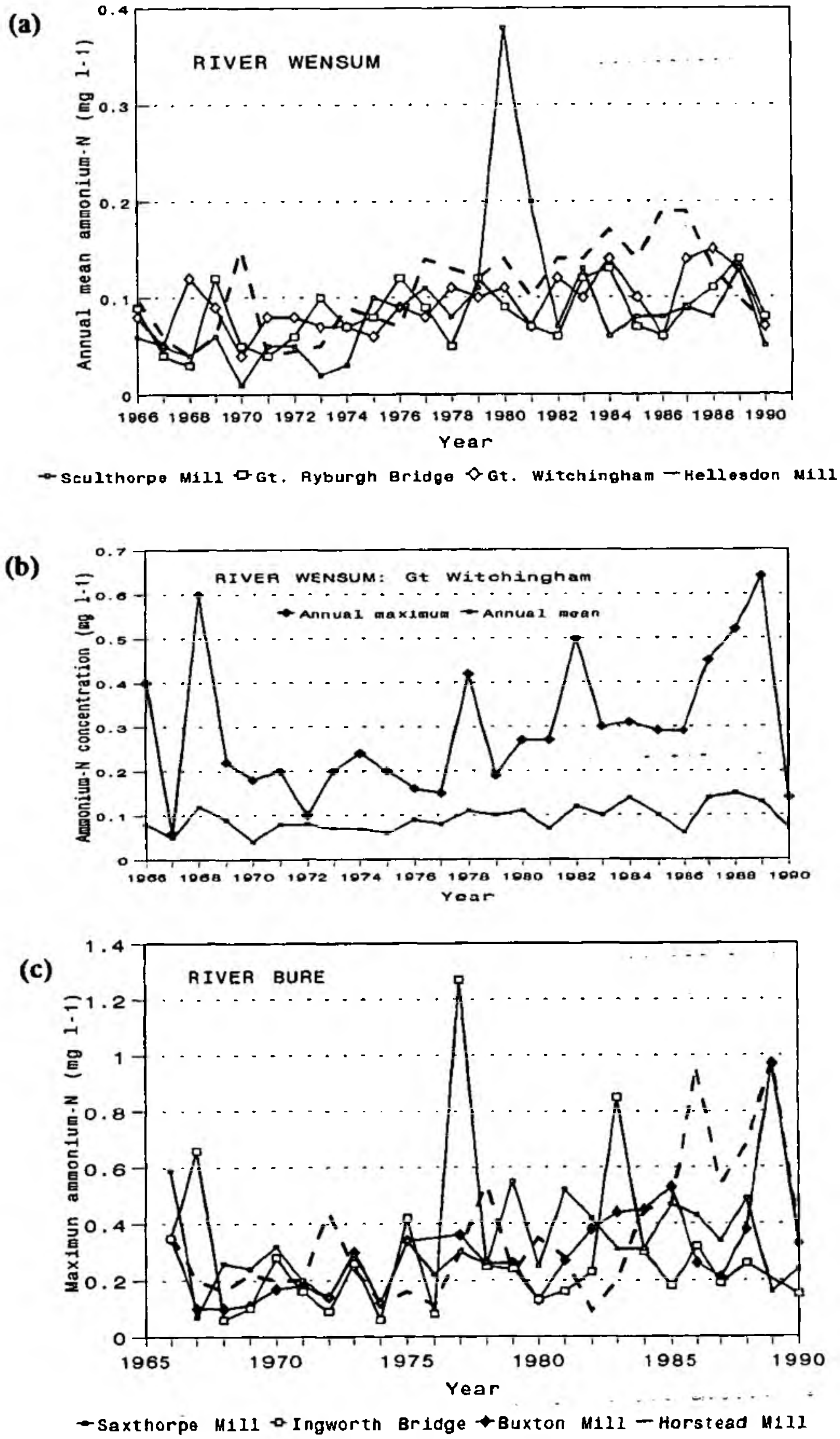


Figure 26 Measures of ammonium concentrations in (a) four sites on the Wensum (b) at Great Witchingham on the Wensum and (c) four sites on the Bure.

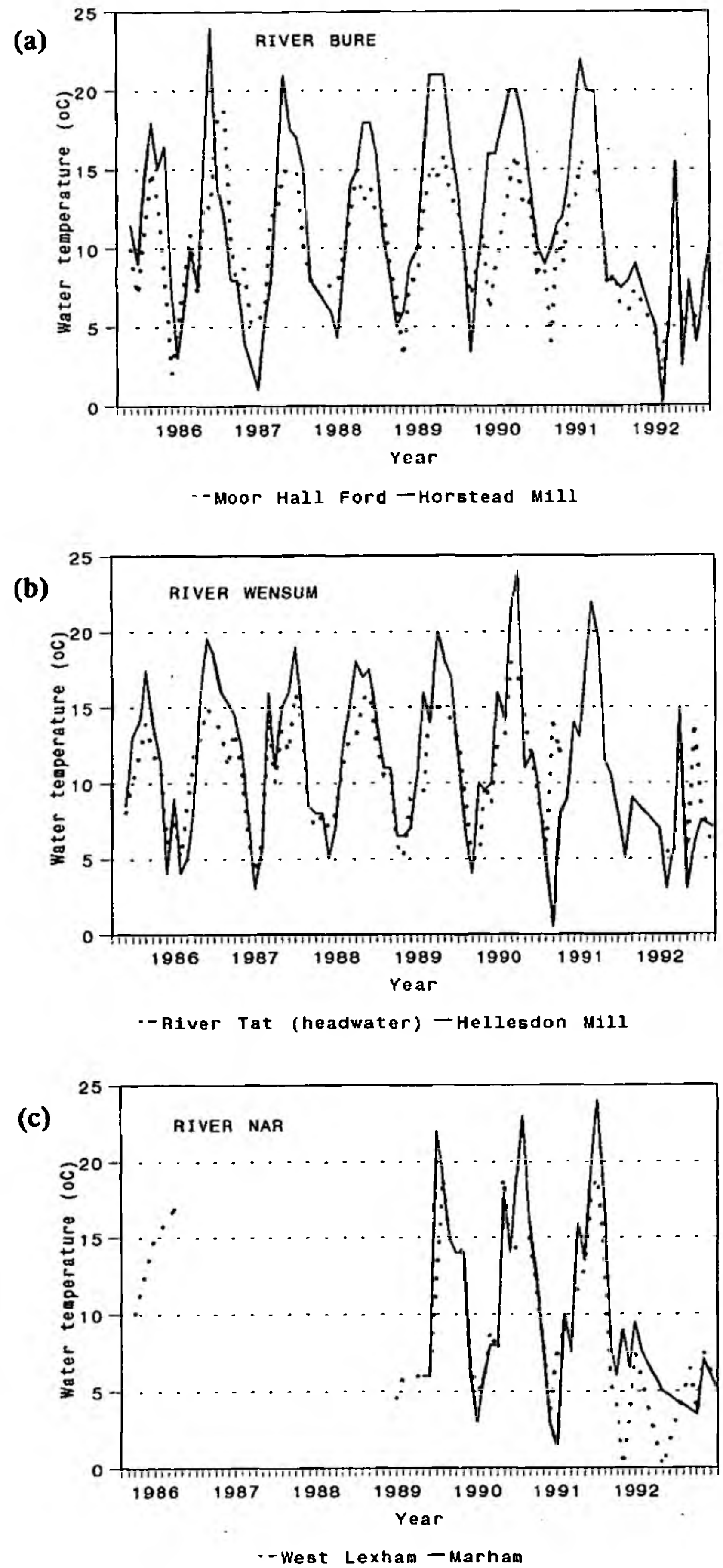


Figure 27 Comparisons of water temperature in upstream and downstream sites on (a) the Bure (b) the Wensum and (c) the Nar.

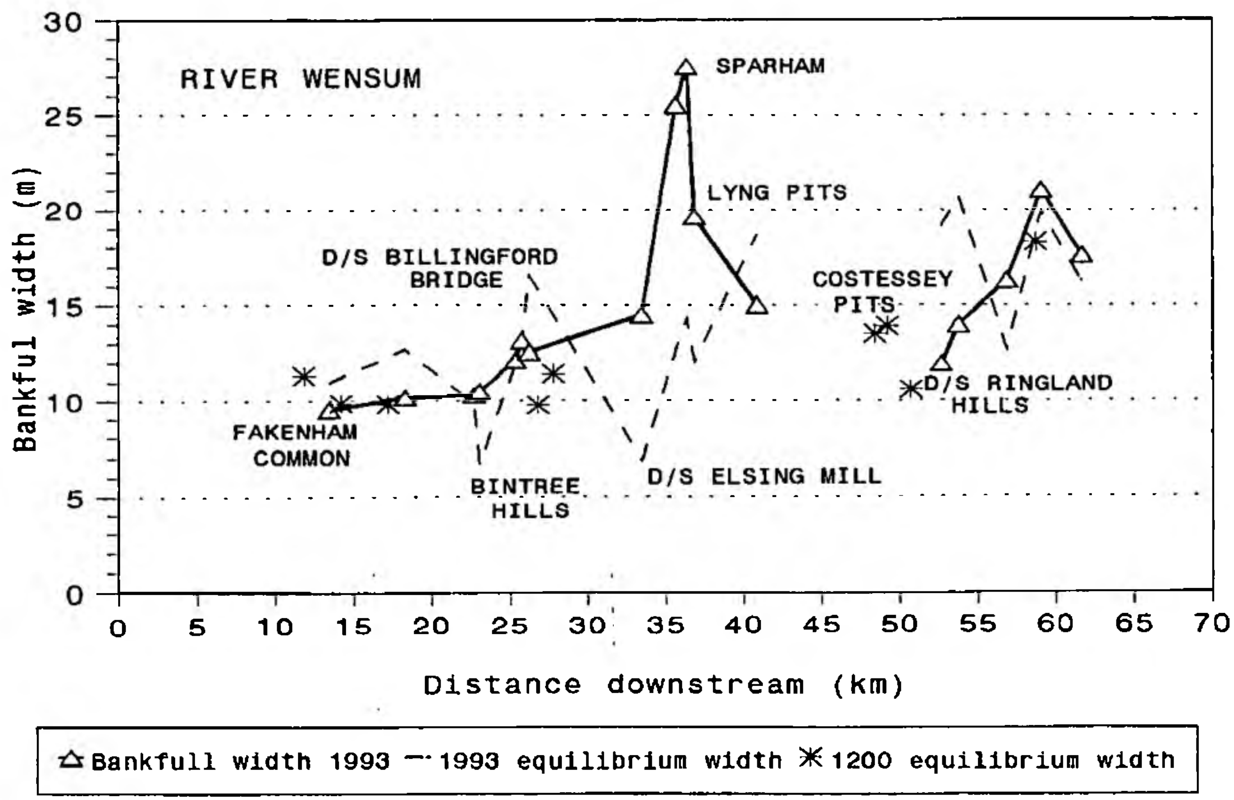
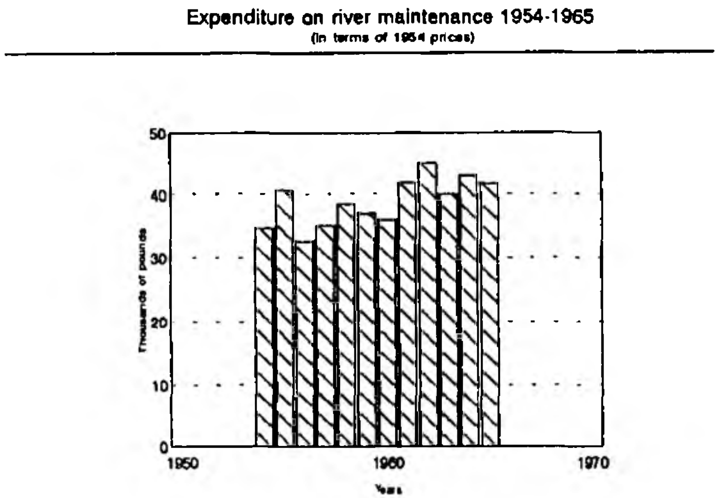
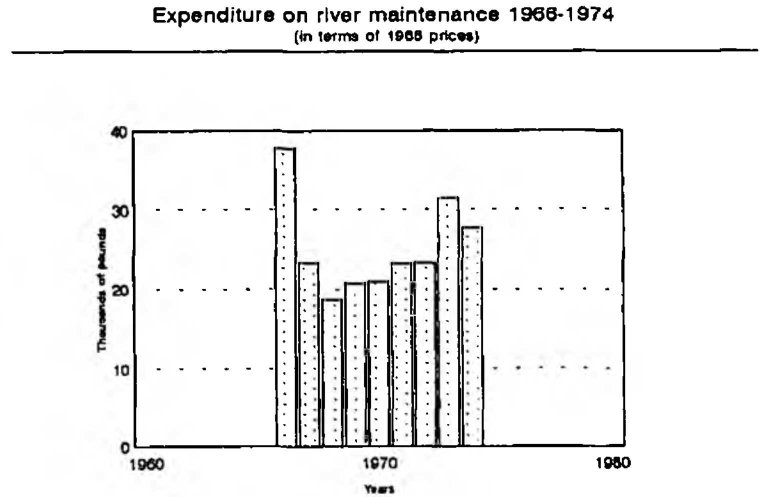


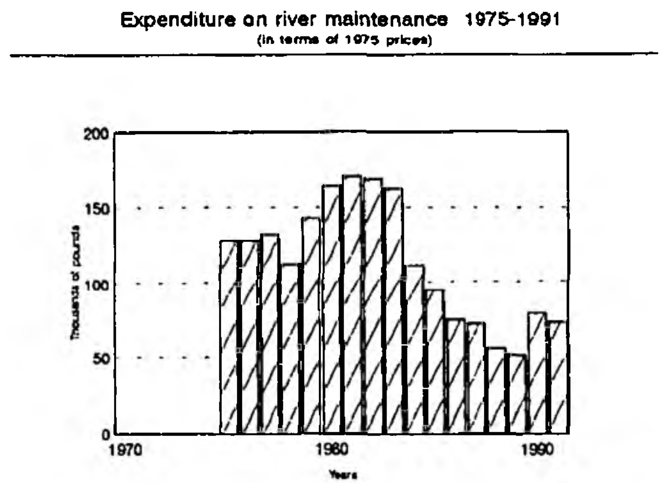
Figure 28 Bankfull widths in the River Wensum in 1993 compared with calculated equilibrium widths for 1993 and for 13th century meander patterns. Calculations have been made only from meanders which appeared unengineered



(a) *Data for all waterways*



(b) Data for upland rivers only



(c) Data on dredging and weedcutting for tidal and non-tidal waterways

Figure 29 Spending on maintenance of Rivers in Norfolk and Suffolk, 1954 to 1991.

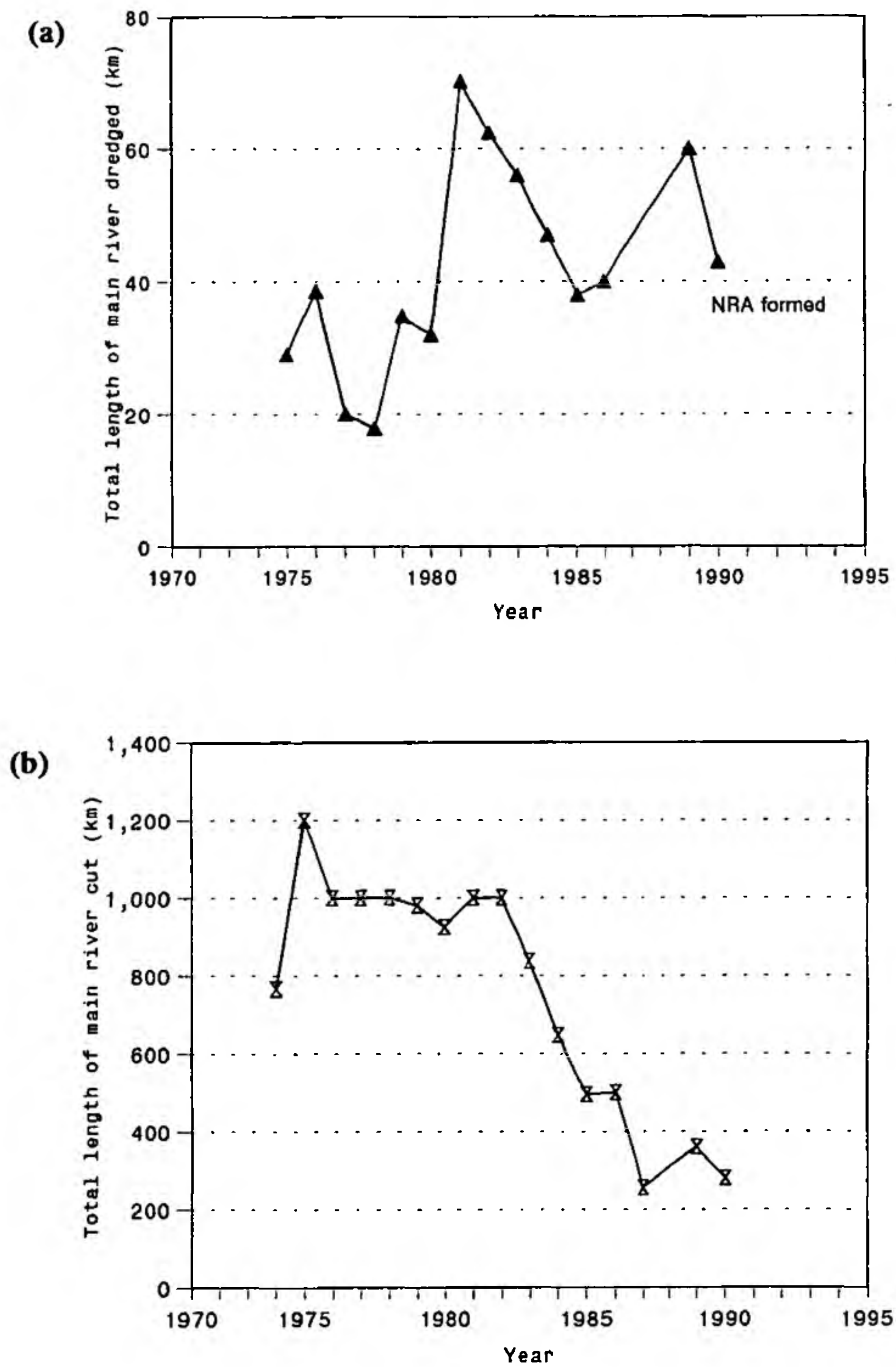


Figure 30 Changes in (a) dredging and (b) weed cutting in Norfolk and Suffolk rivers.

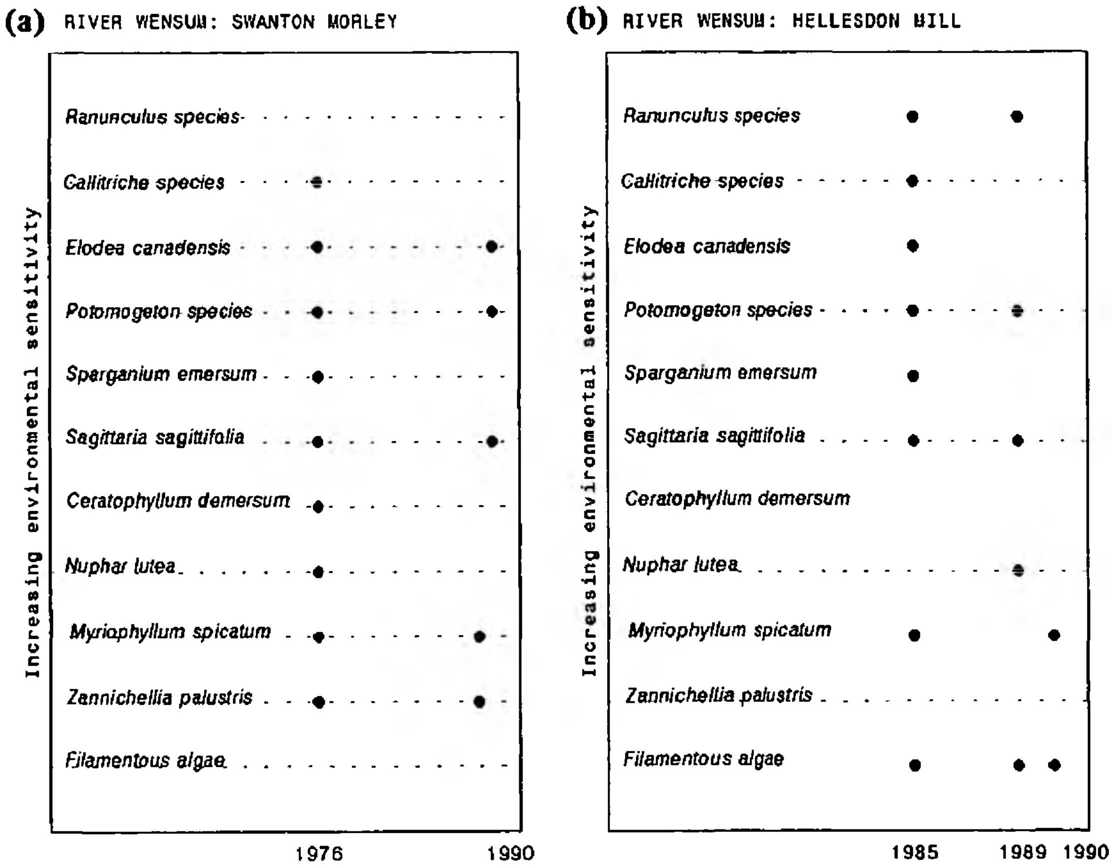


Figure 31 Water plants recorded in surveys of the Wensum during 1976, 1989 and 1990 at (a) Swanton Morley and (b) Hellesdon Mill.

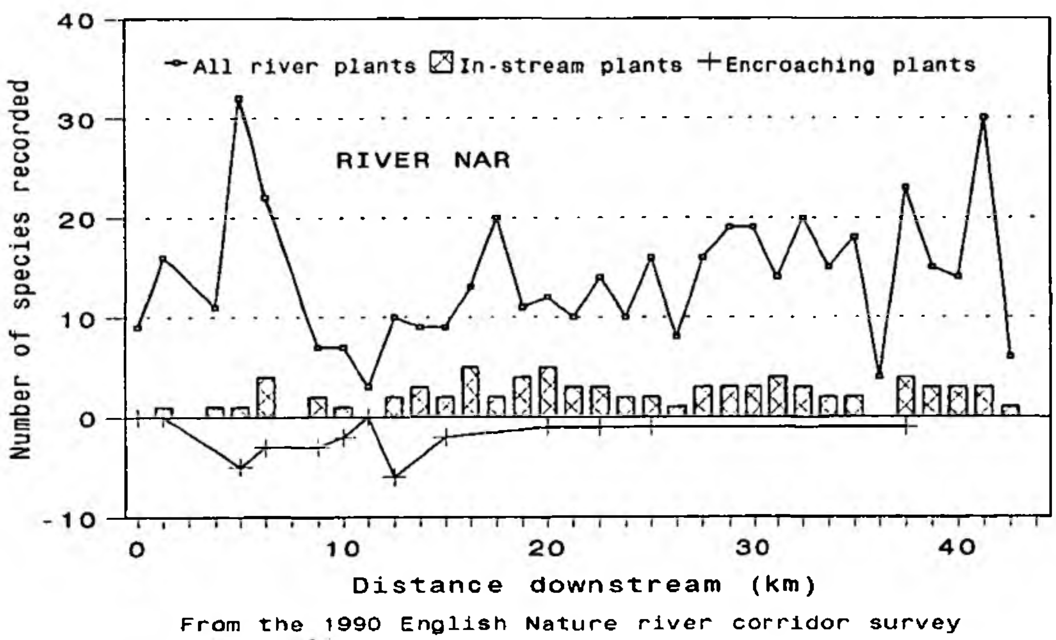


Figure 32 Species richness of water and of bankside plants in the River Nar during 1990.

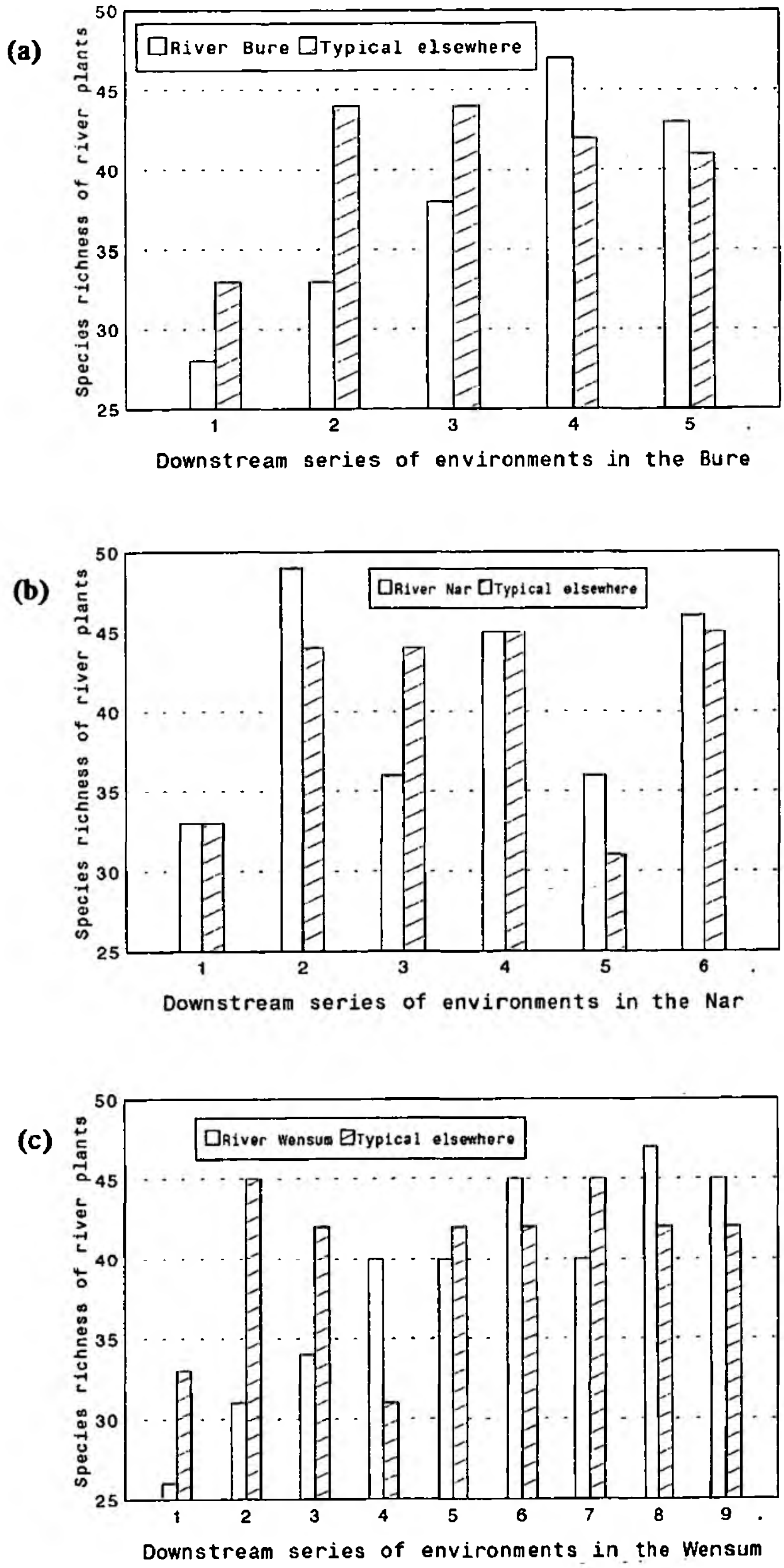


Figure 33 Comparisons between the species richness of water plants in the study Rivers with the richness of water plants in similar river environments.

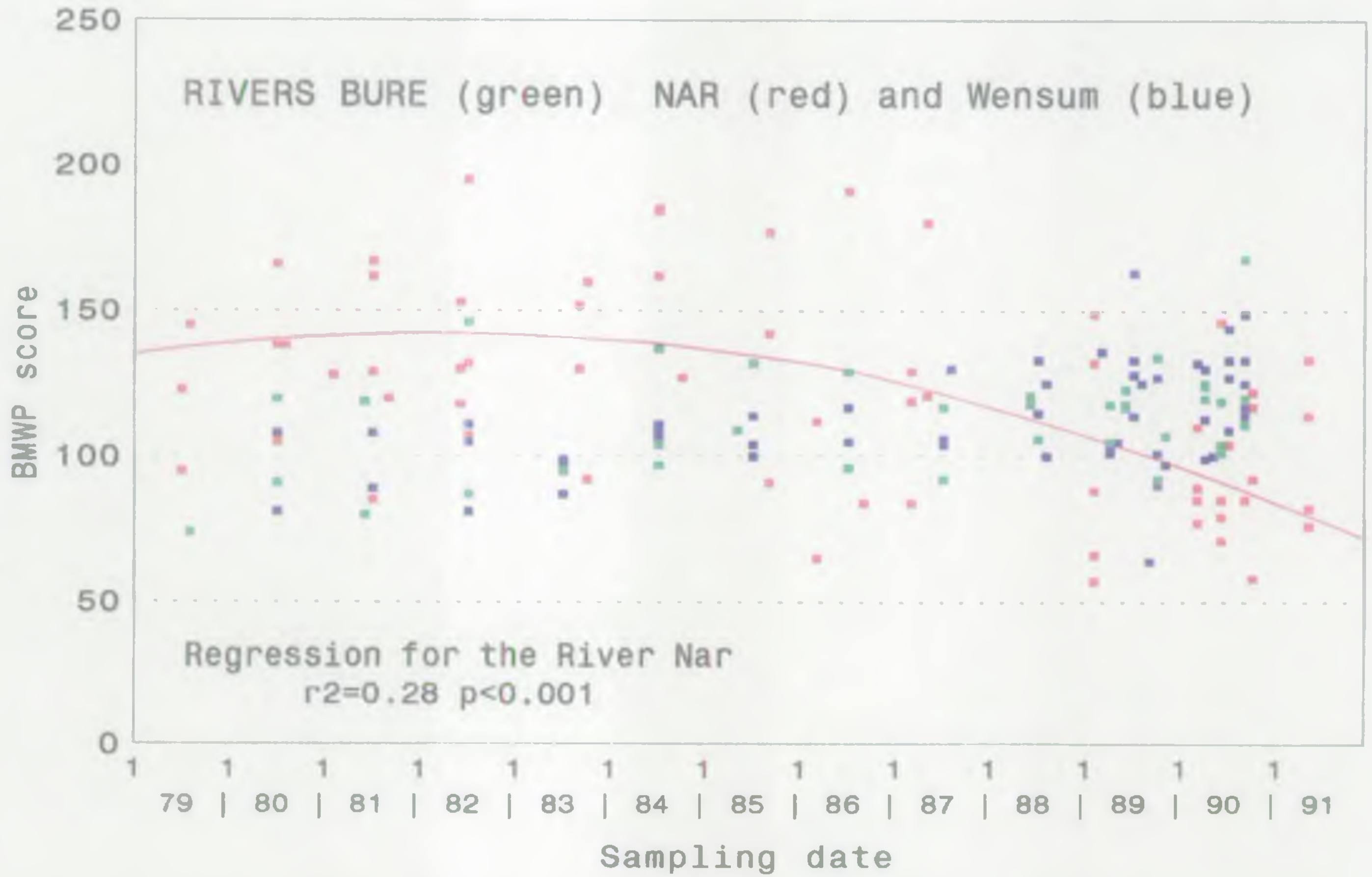


Figure 34 The BMWP scores of invertebrate communities from of all of the biological monitoring sites sampled in the study Rivers.

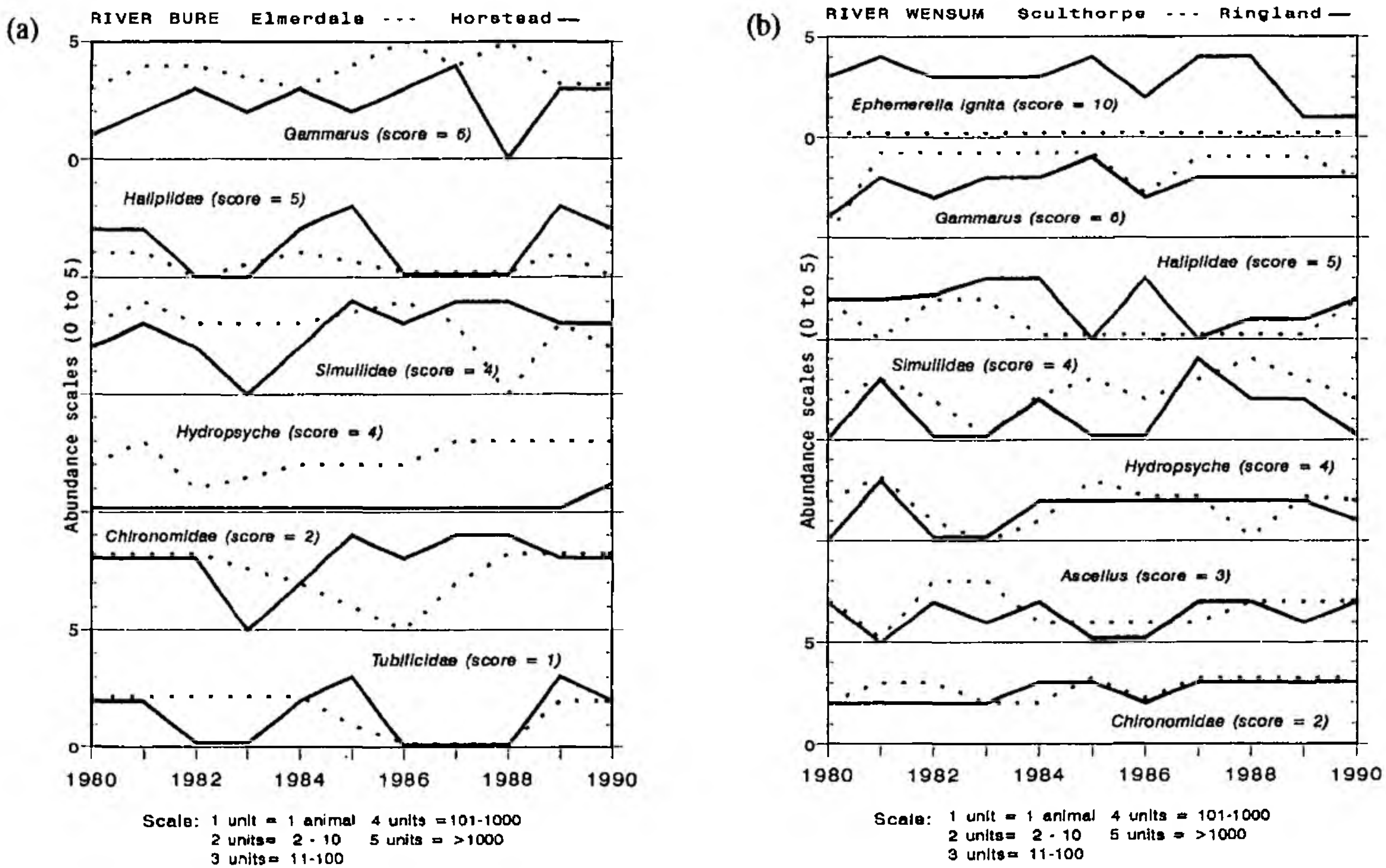


Figure 35 The abundance (on a logarithmic scale) of invertebrates sampled from upstream (Elmerdale and Sculthorpe) and downstream (Horstead and Ringland) sites on (a) the Bure and (b) the Wensum.

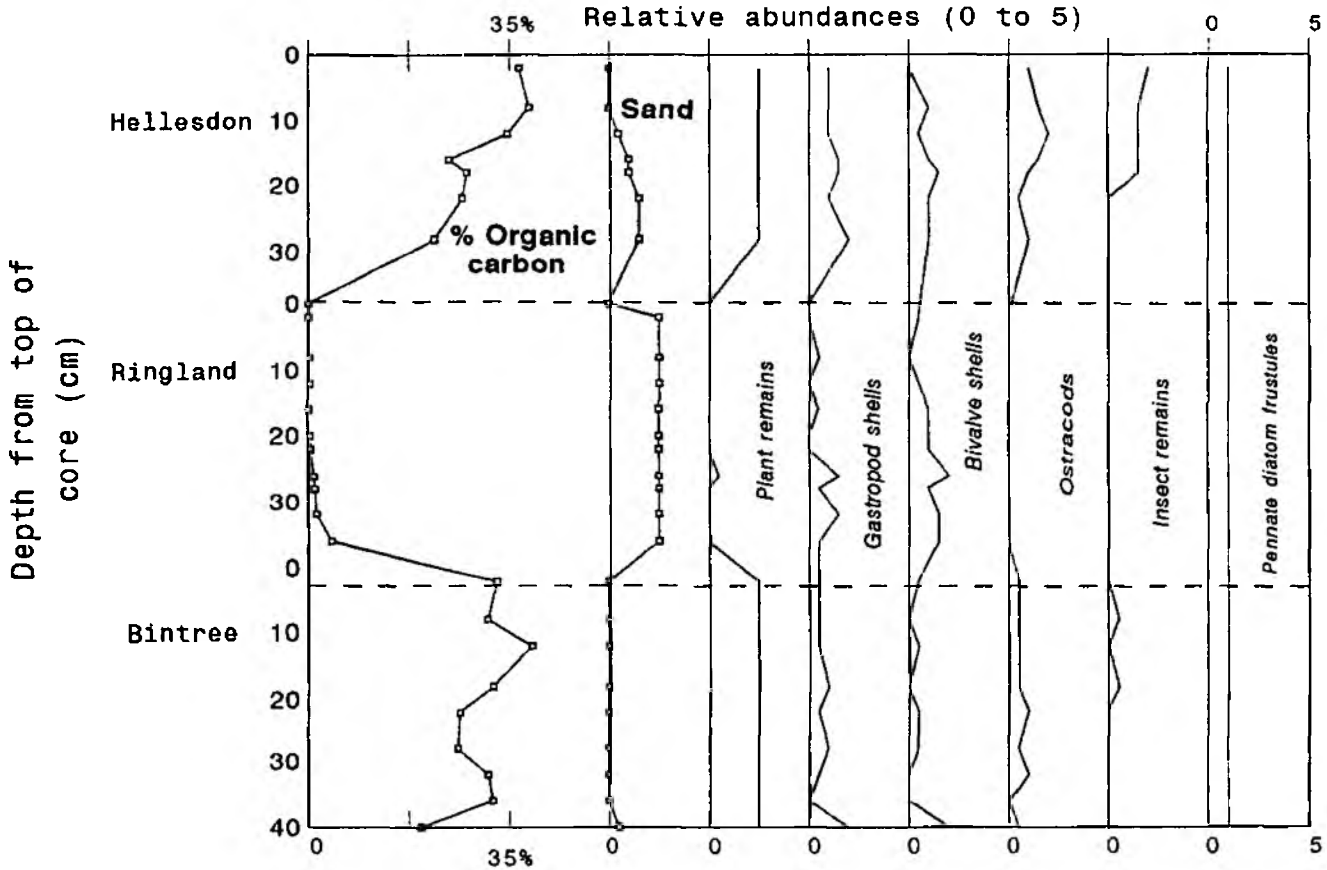


Figure 36 The organic content, relative proportions of sand and of biological remains in sediment cores taken from the middle of the channel of the River Wensum.

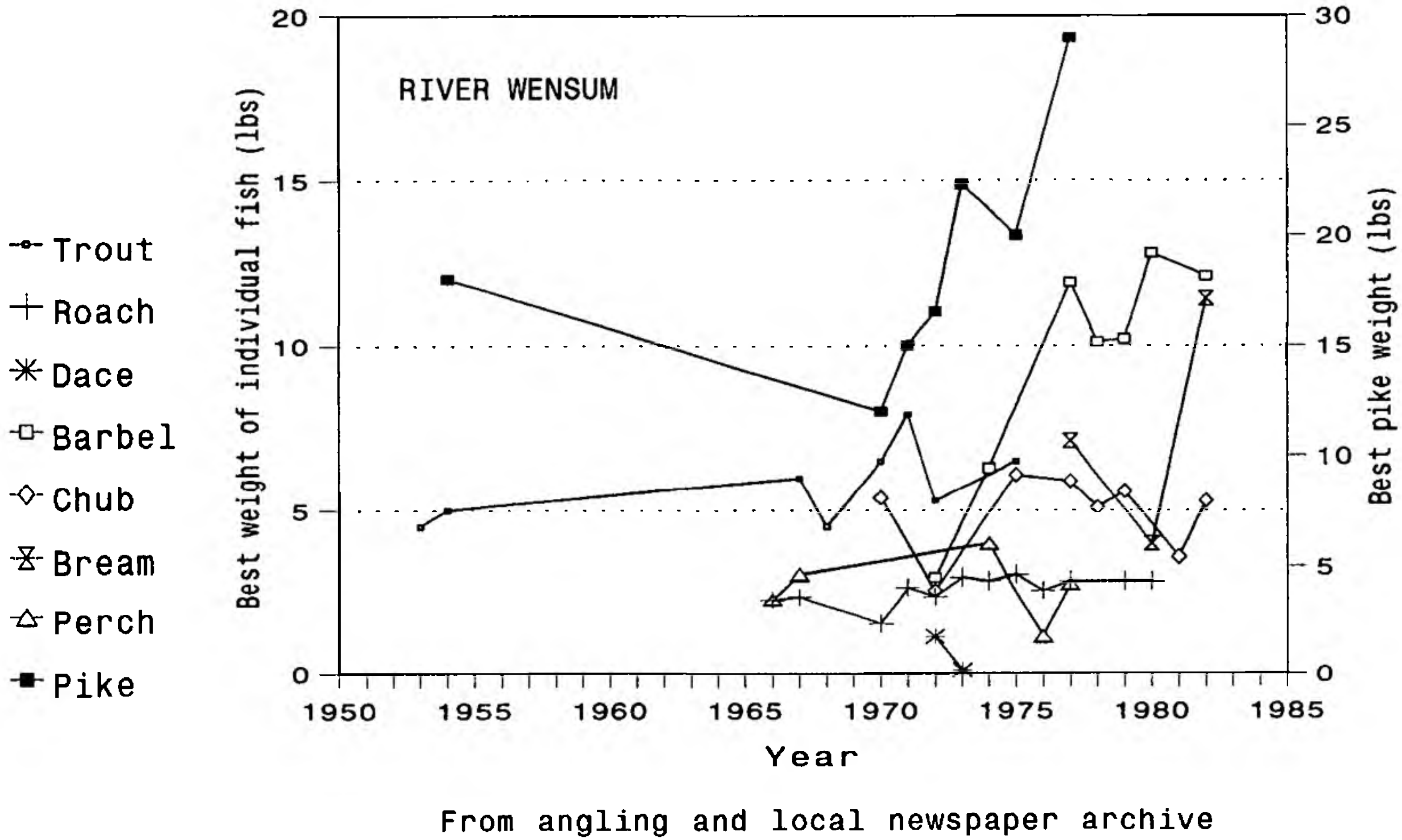
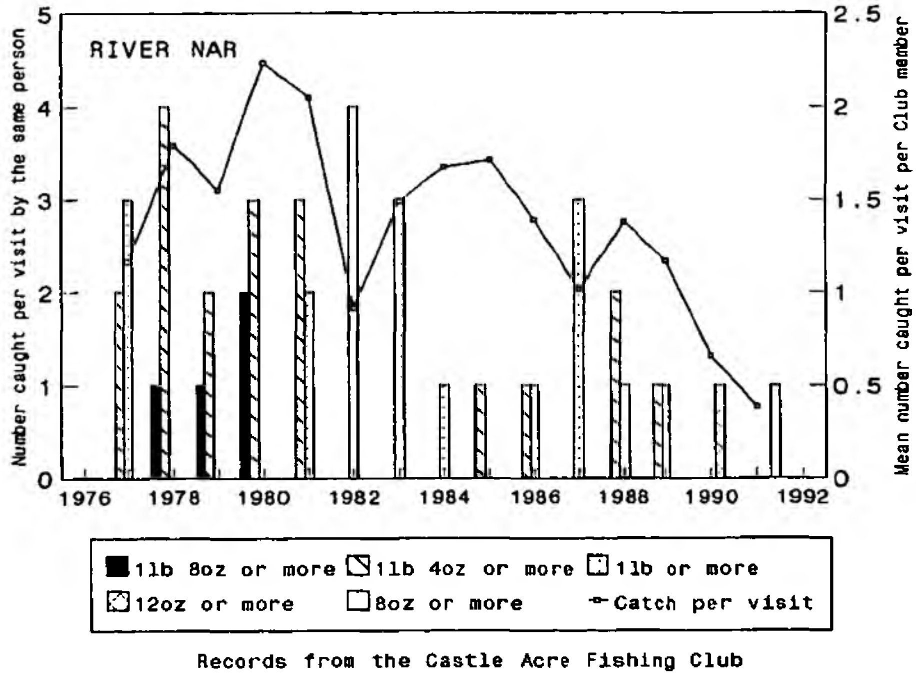


Figure 37 The best weights per year of individual fish caught in the River Wensum and reported in angling and local newspapers.

(a)



(b)

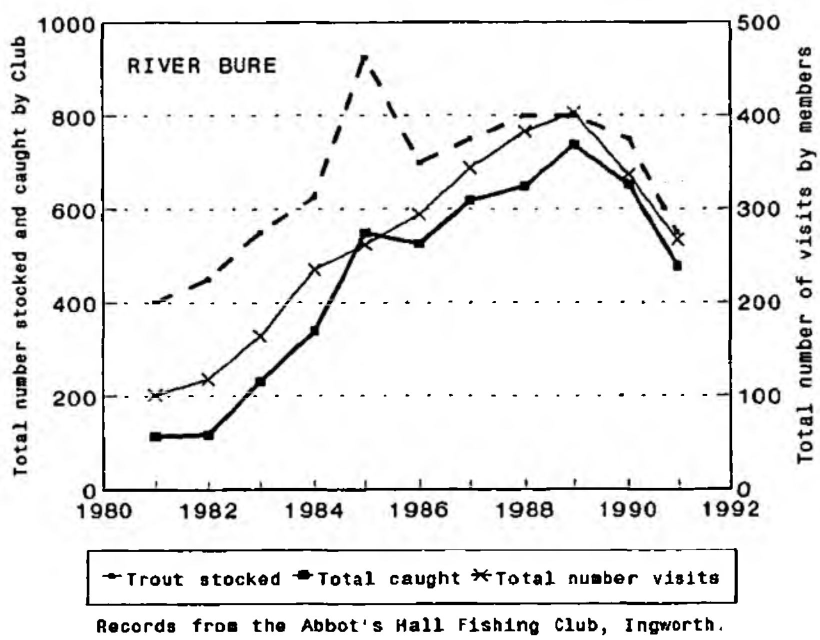


Figure 38 (a) The weight class distribution of wild trout caught in the River Nar since 1976 and (b) the relationship between the number of trout stocked and the number caught at Ingworth on the River Bure.

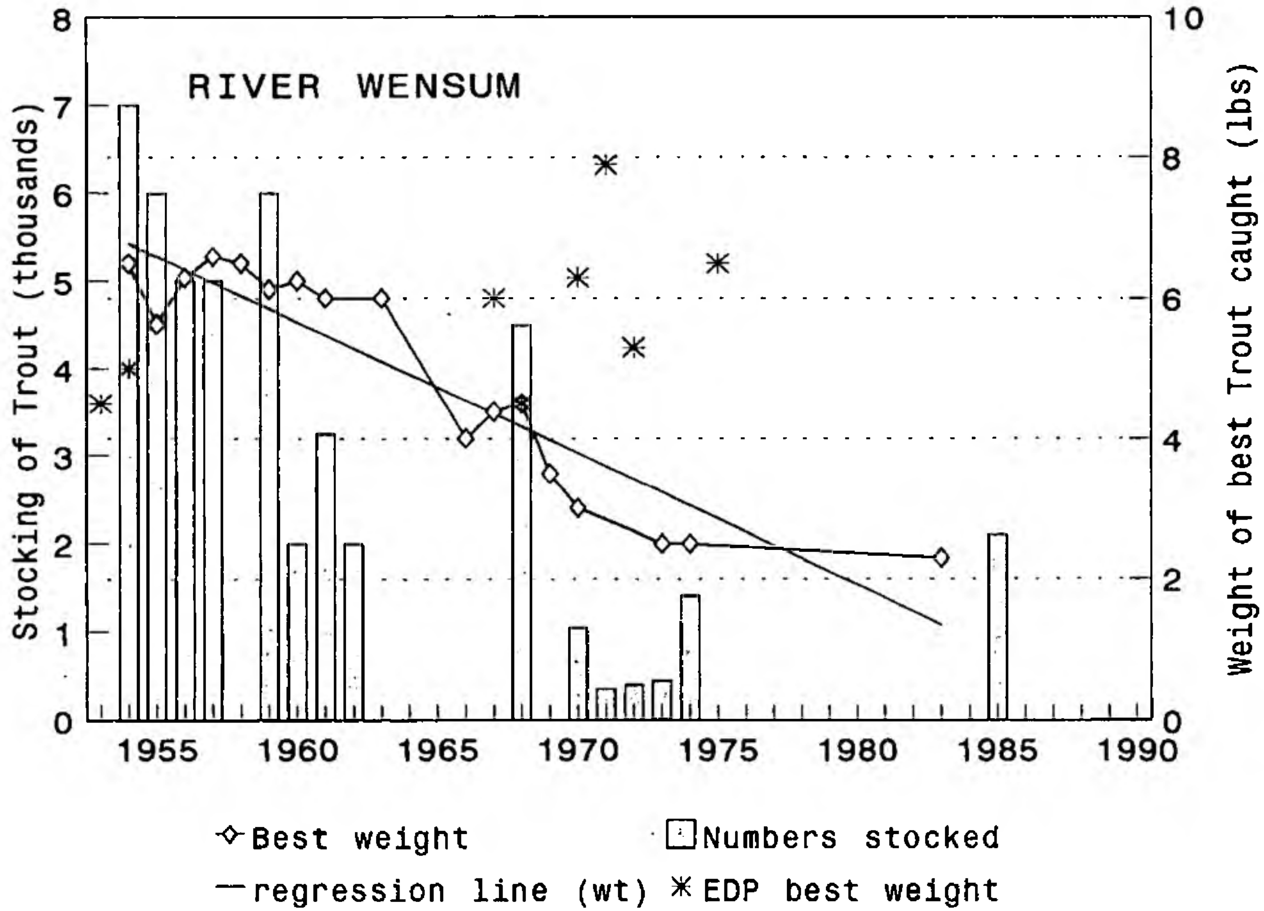


Figure 39 The numbers of brown trout added to the Wensum and the best weights of the trout caught. Best weights are from River Board and Authority Reports and from reports given in the Eastern Daily Press (EDP).

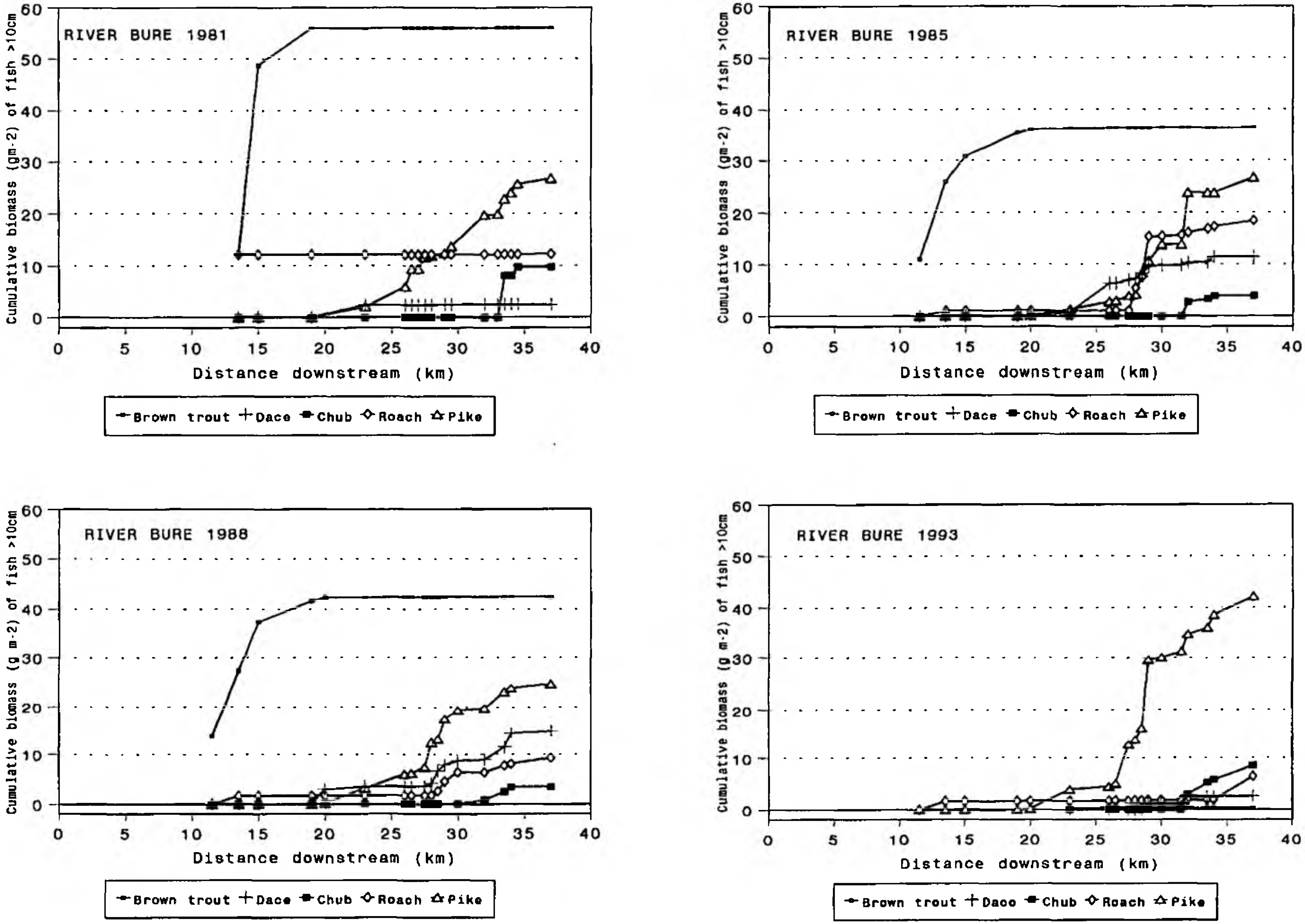


Figure 40 (a) Cumulative biomass (gm^{-2}) in different years of fish caught in the River Bure. Data are from Water Authority and NRA electro-fishing surveys.

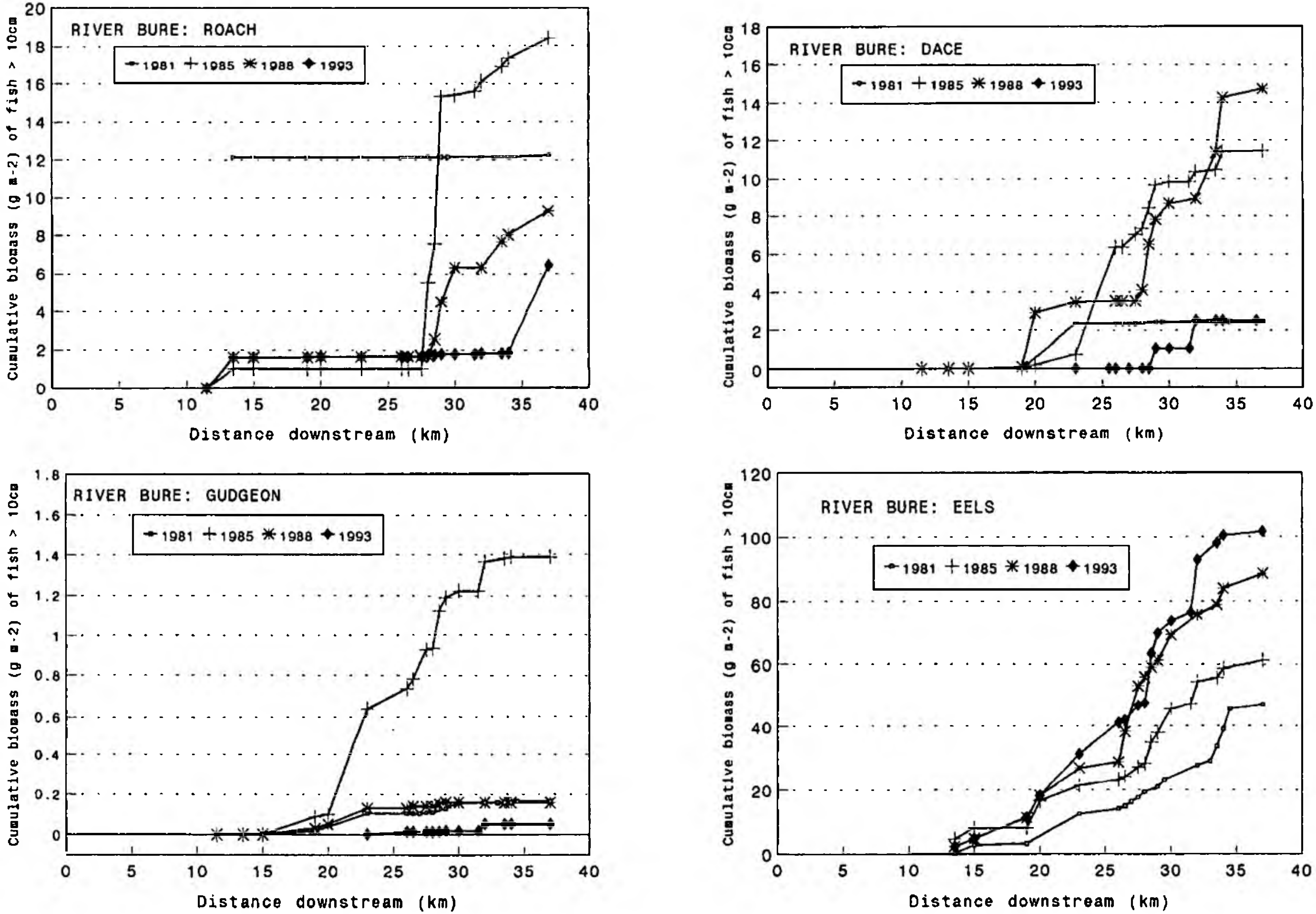


Figure 40 (b) Cumulative biomass (gm^{-2}) of the most abundant fish caught in the River Bure. Data are from Water Authority and NRA electro-fishing surveys.

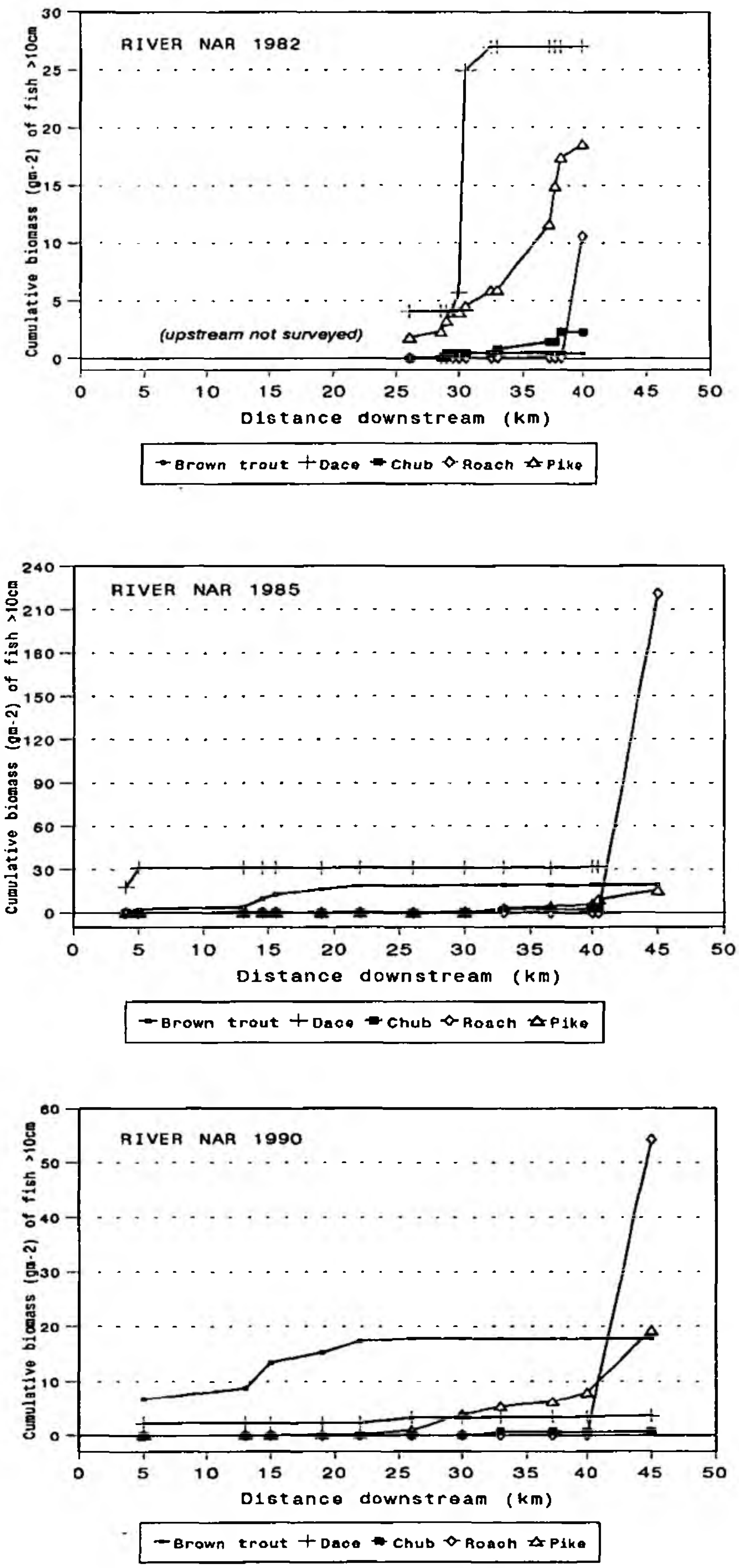
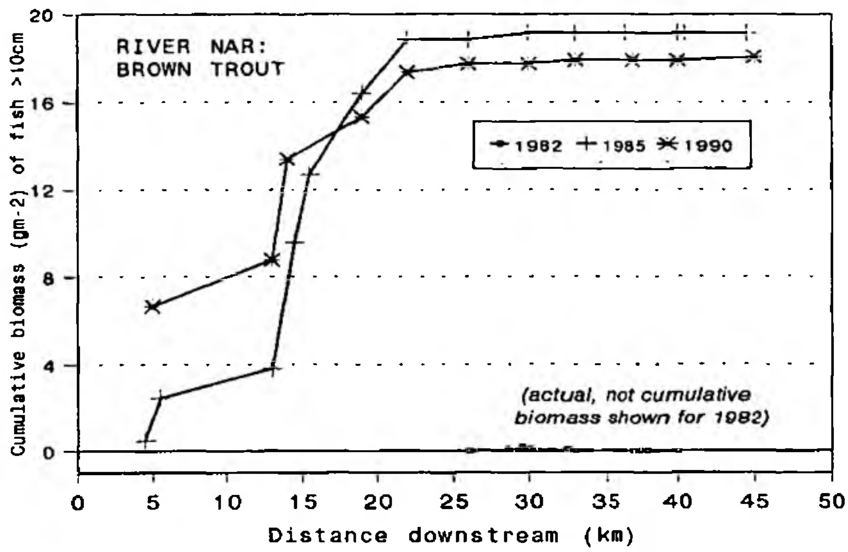
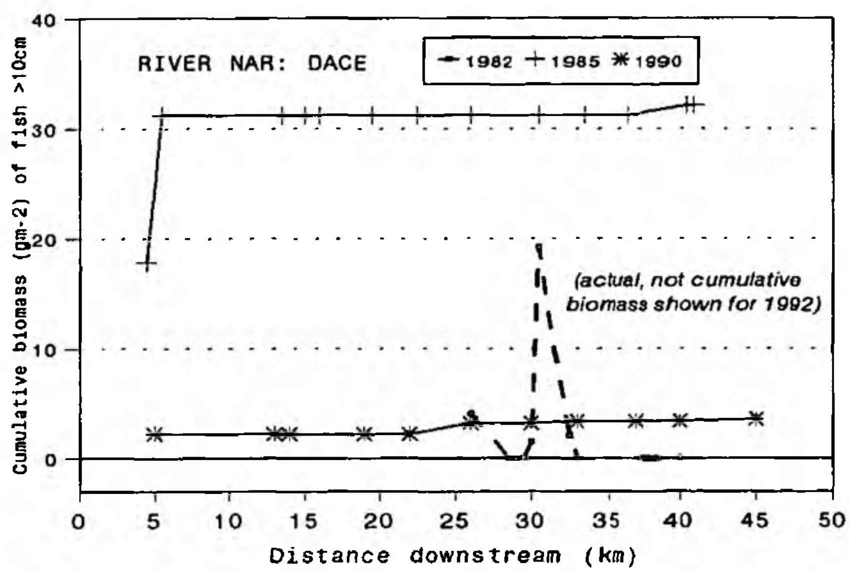


Figure 41 (a) Cumulative biomass (gm^{-2}) in different years of fish caught in the River Nar. Data are from Water Authority and NRA electro-fishing surveys.





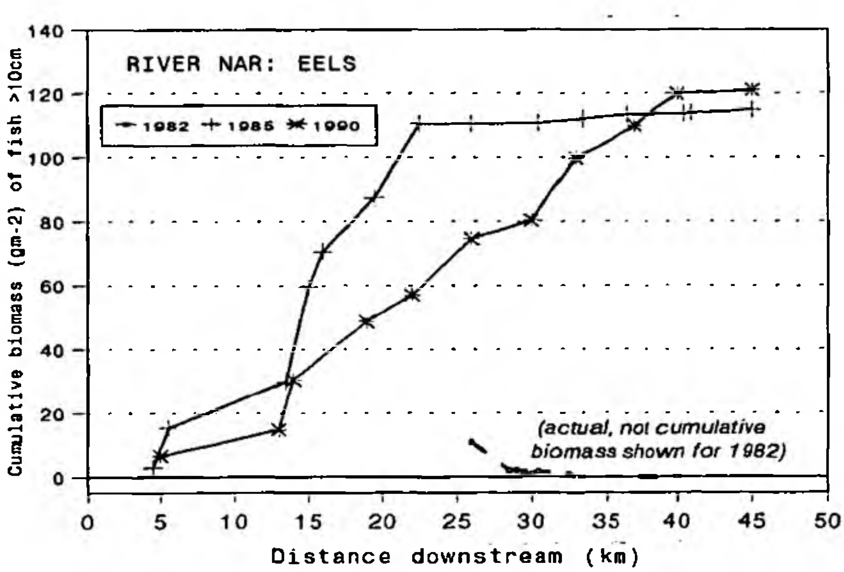


Figure 41 (b) Cumulative biomass (gm^{-2}) of the most abundant fish caught in the River Nar. Data are from Water Authority and NRA electro-fishing surveys.

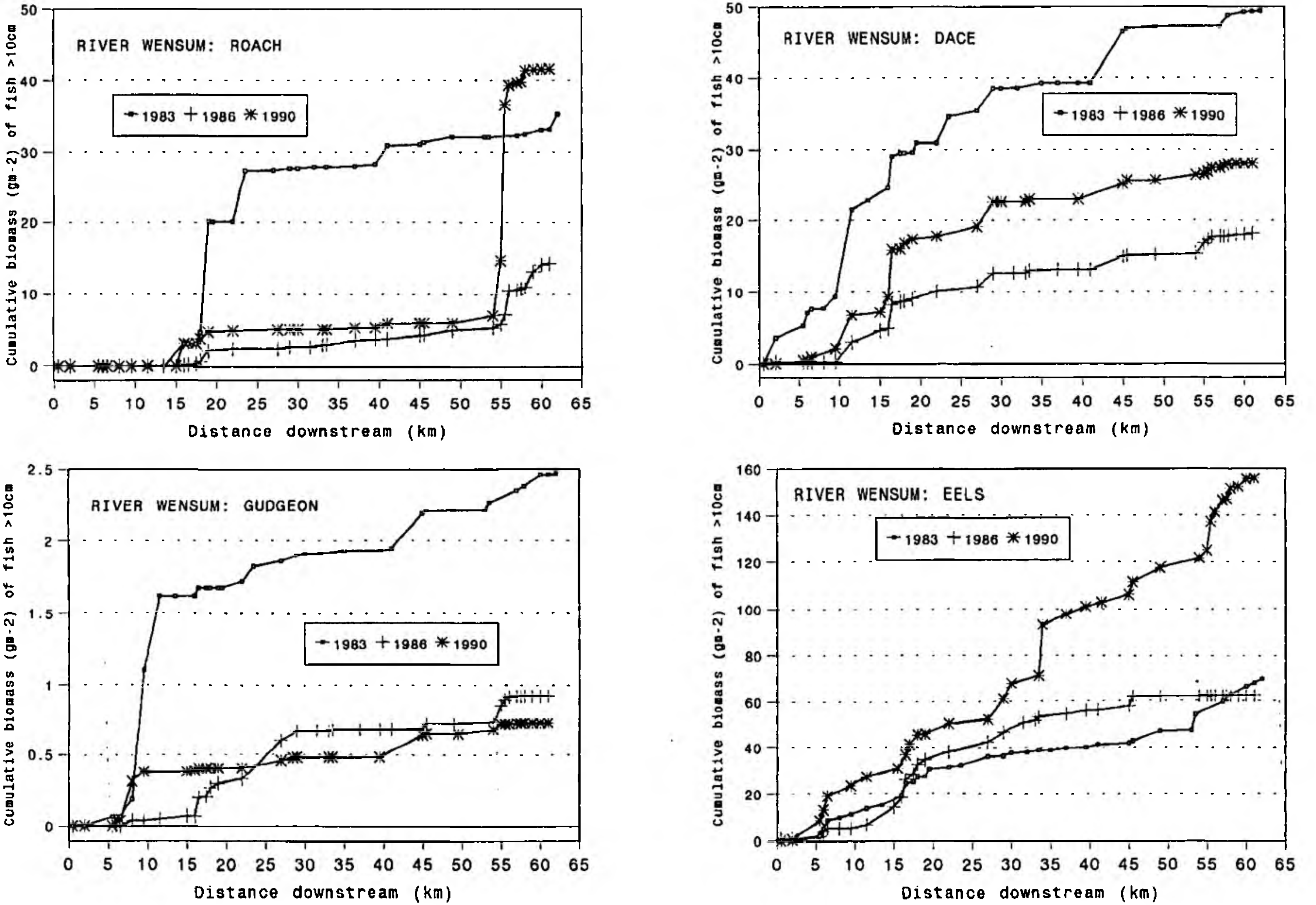


Figure 42 (a) Cumulative biomass (gm^{-2}) in different years of fish caught in the Wensum. Data are from Water Authority and NRA electro-fishing surveys.

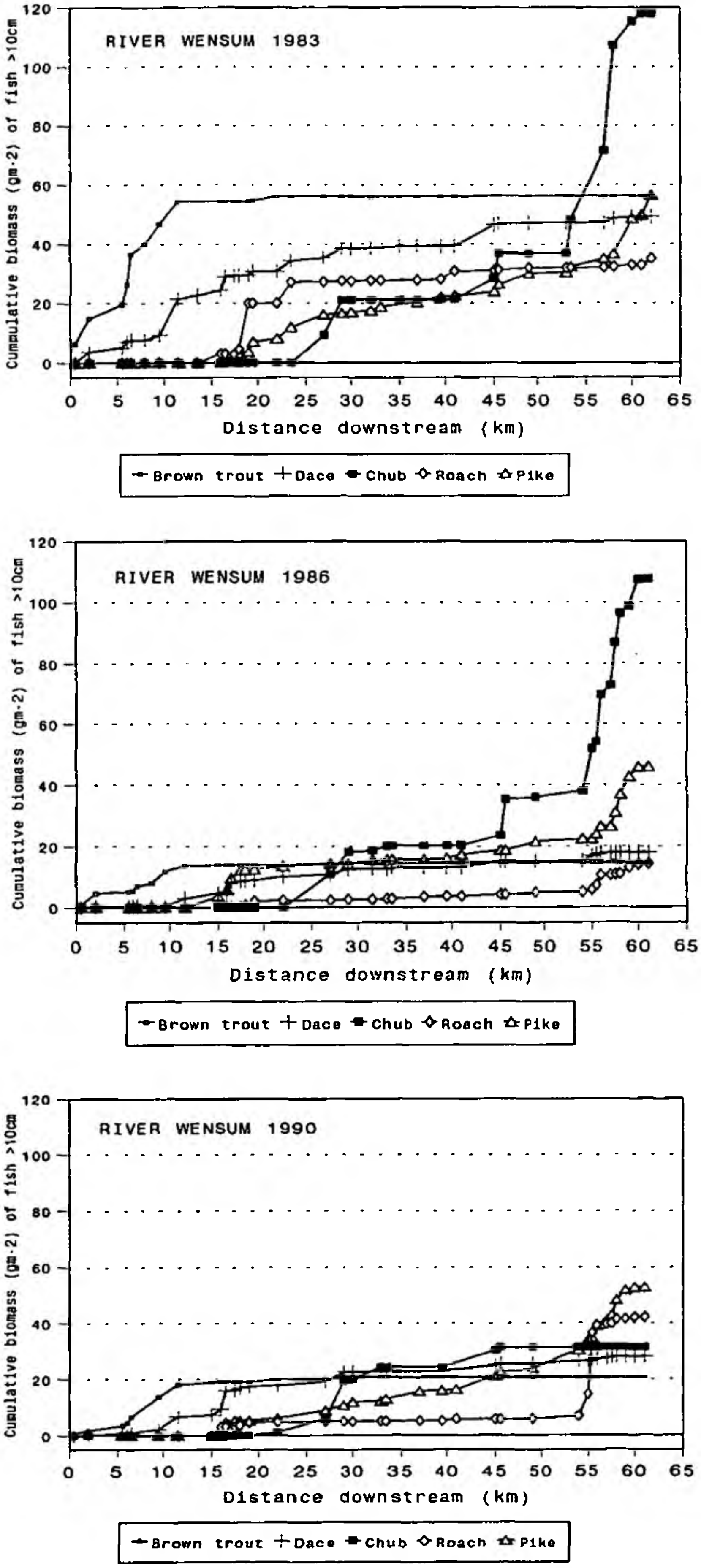


Figure 42 (b) Cumulative biomass (gm^{-2}) of the most abundant fish caught in the Wensum. Data are from Water Authority and NRA electro-fishing surveys.

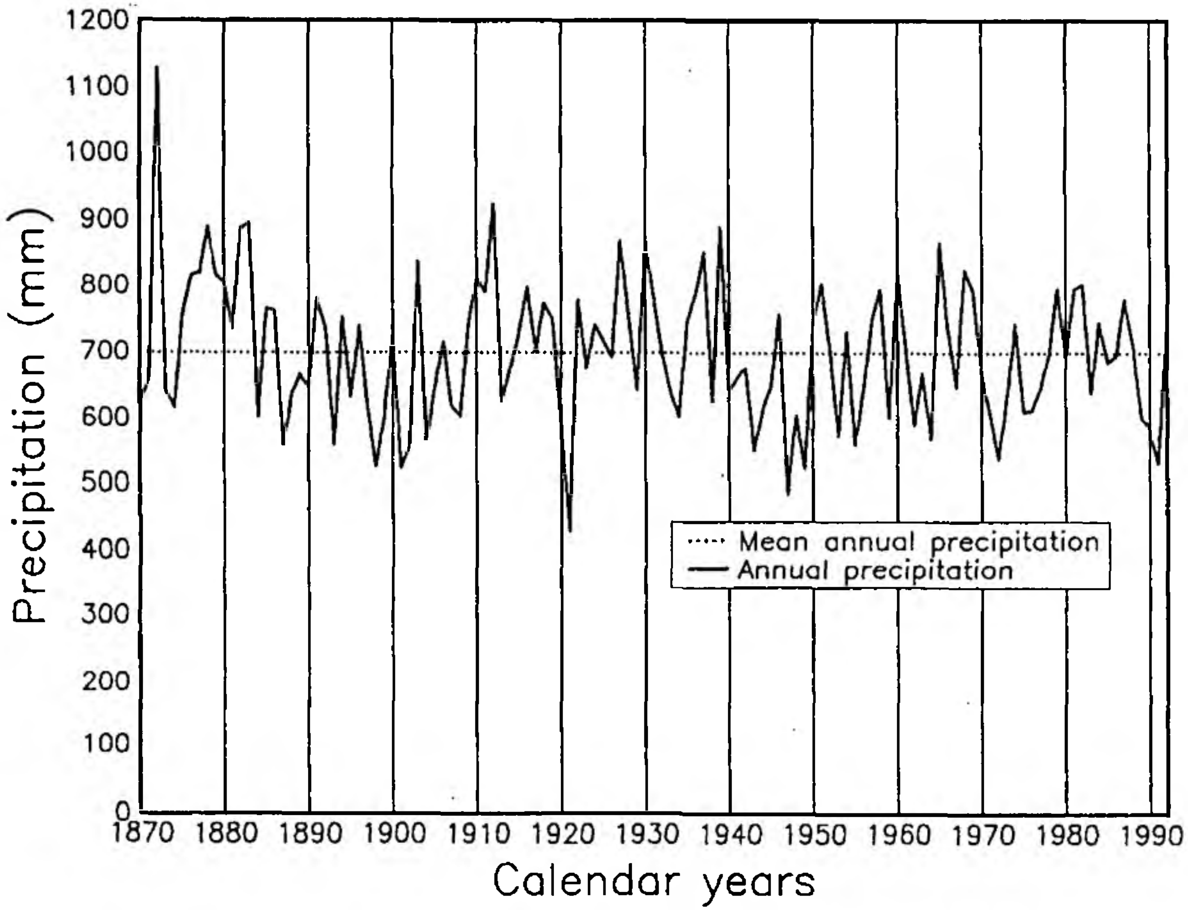


Figure 43 Total annual precipitation between 1870 and 1992 at East Dereham, Norfolk.

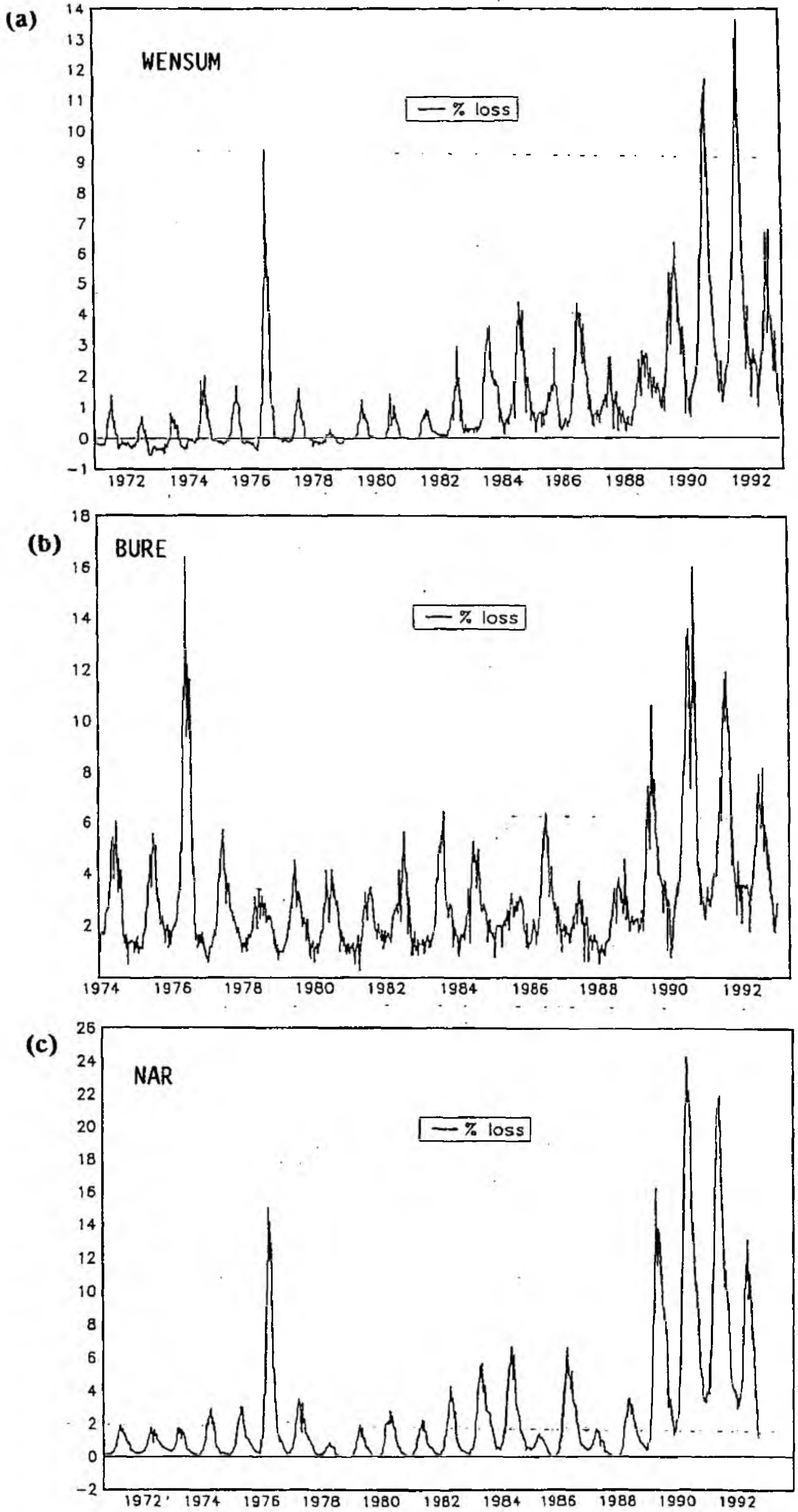


Figure 44 The percentages of seven-day mean flow lost due to the net effect of abstractions and discharges in (a) the River Wensum above Costessey (b) the River Bure above Horstead and (c) the River Nar above Marham.

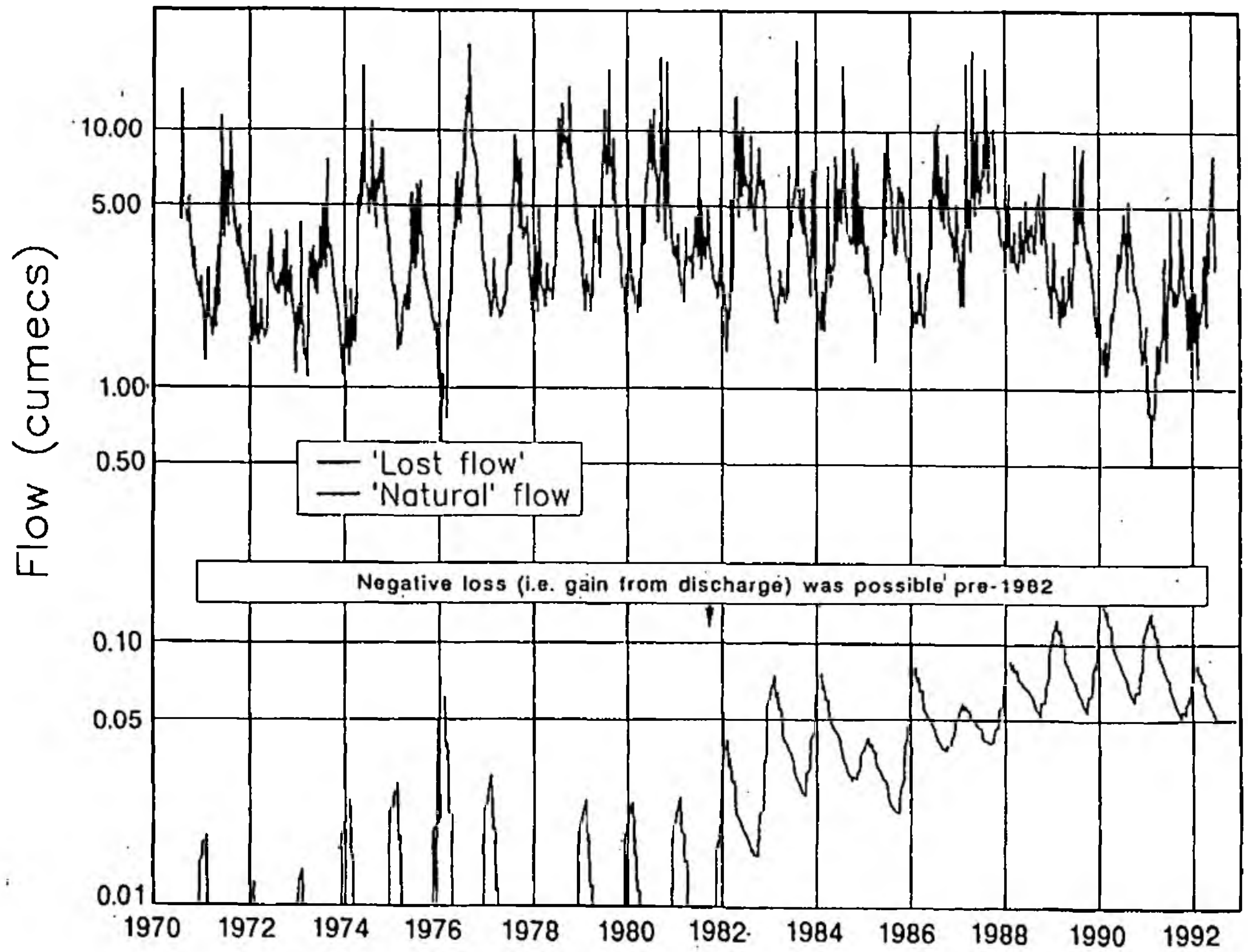


Figure 45 Naturalised 7-day mean flows at Costessey Mill on the Wensum generated by GORM modelling (the upper trace) and the losses to flow (the lower trace) due to net abstraction over the same period. Flow is plotted on a logarithmic scale.

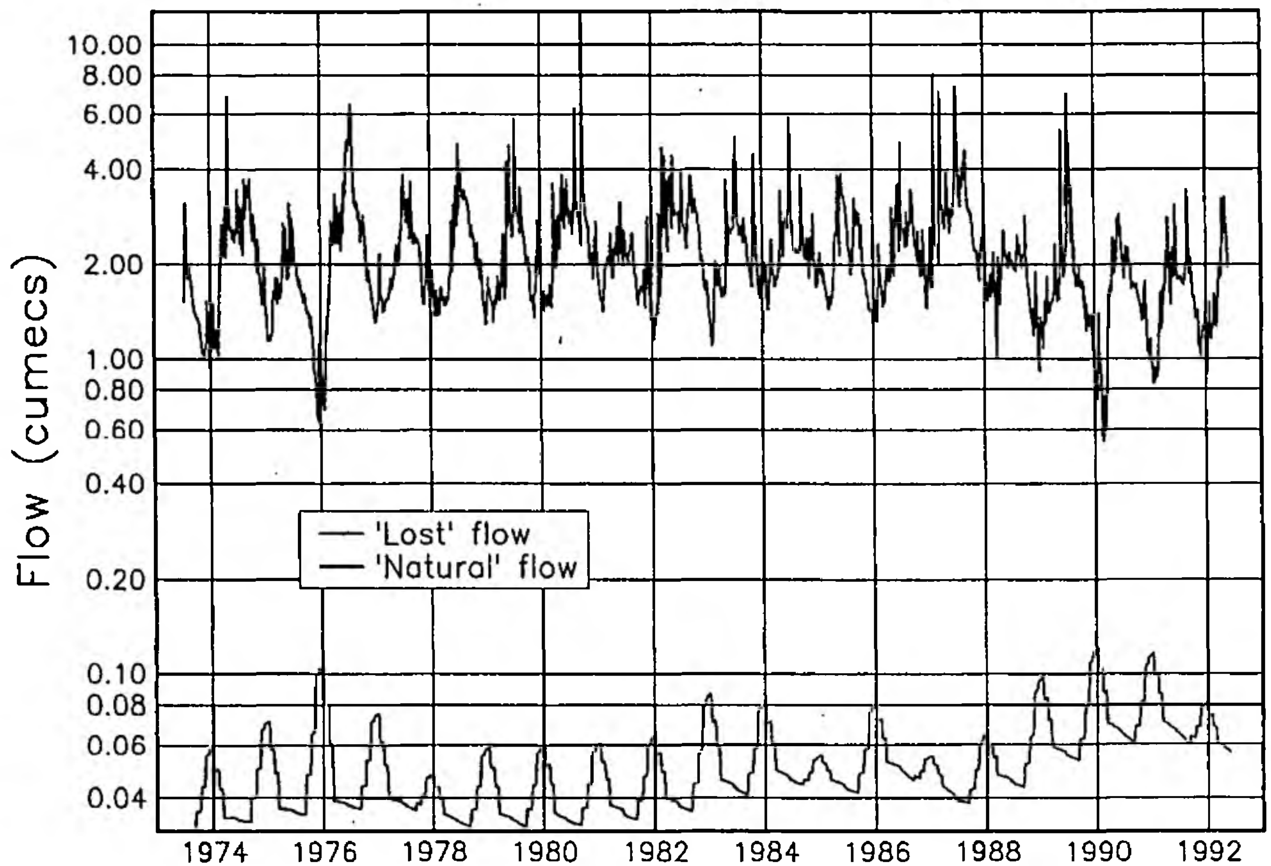


Figure 46 Naturalised 7-day mean flows at Horstead Mill on the Bure generated by GORM modelling (the upper trace) and the losses to flow (the lower trace) due to net abstraction over the same period. Flow is plotted on a logarithmic scale.

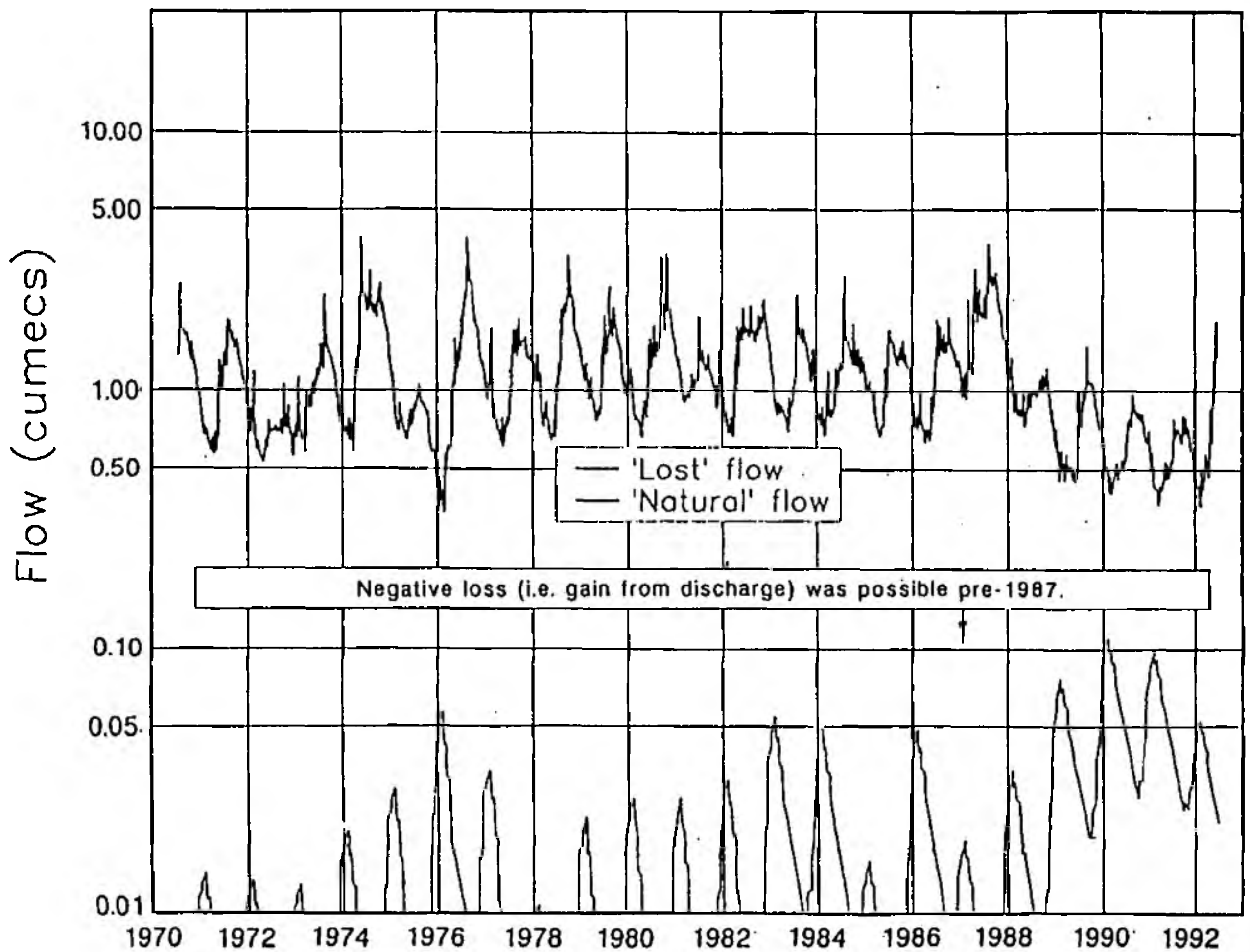


Figure 47 Naturalised 7-day mean flows at Marham on the Nar generated by GORM modelling (the upper trace) and the losses to flow (the lower trace) due to net abstraction over the same period. Flow is plotted on a logarithmic scale.

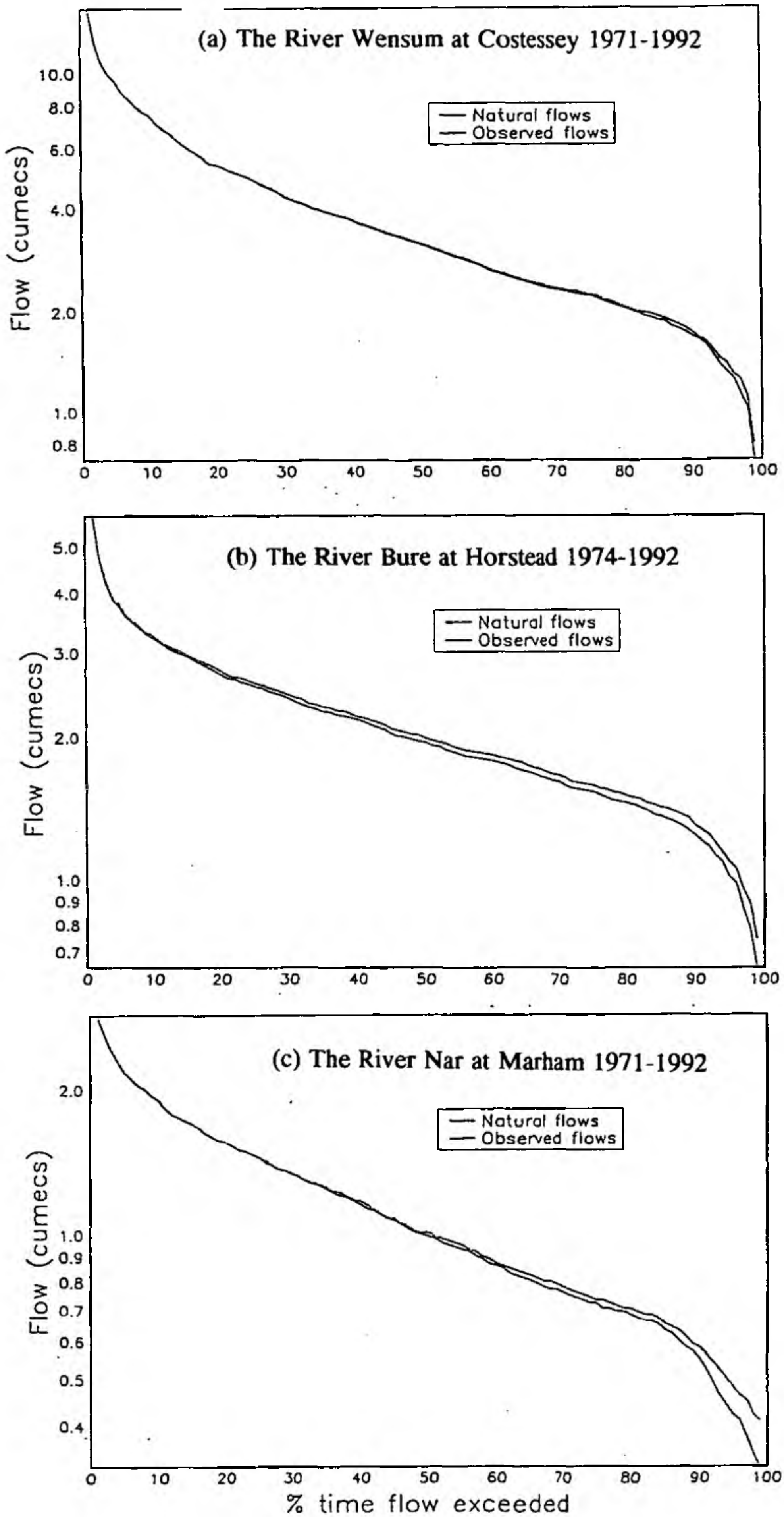


Figure 48 (a) to (c) 7-day flow duration curves showing both naturalised flows (the upper trace) generated by GORM modelling and the flows observed in the study Rivers.

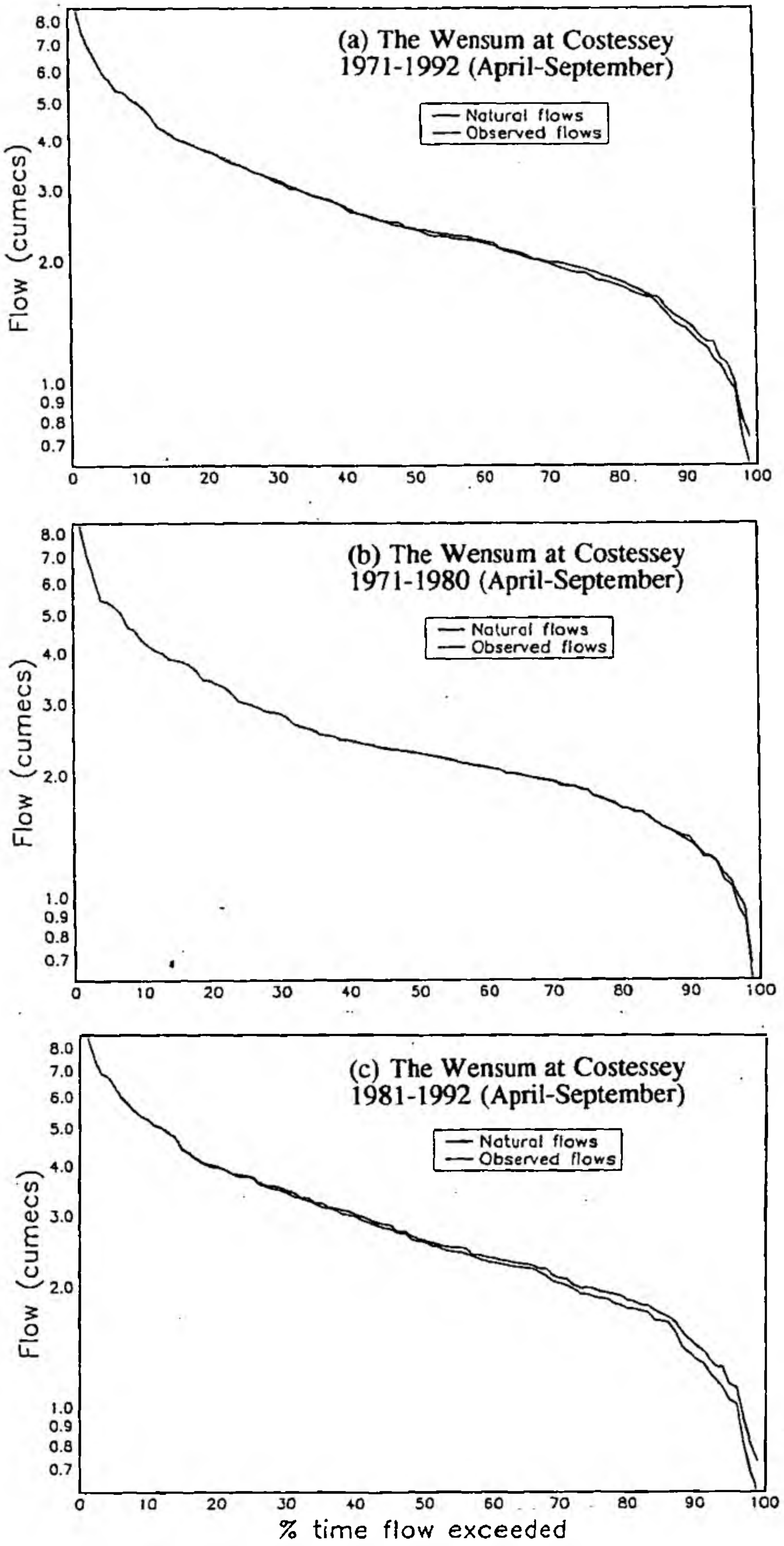


Figure 49 (a) to (c) 7-day flow duration curves for summer flows (April to September) showing both naturalised flows (the upper trace) generated by GORM modelling and the flows observed in the study Rivers.

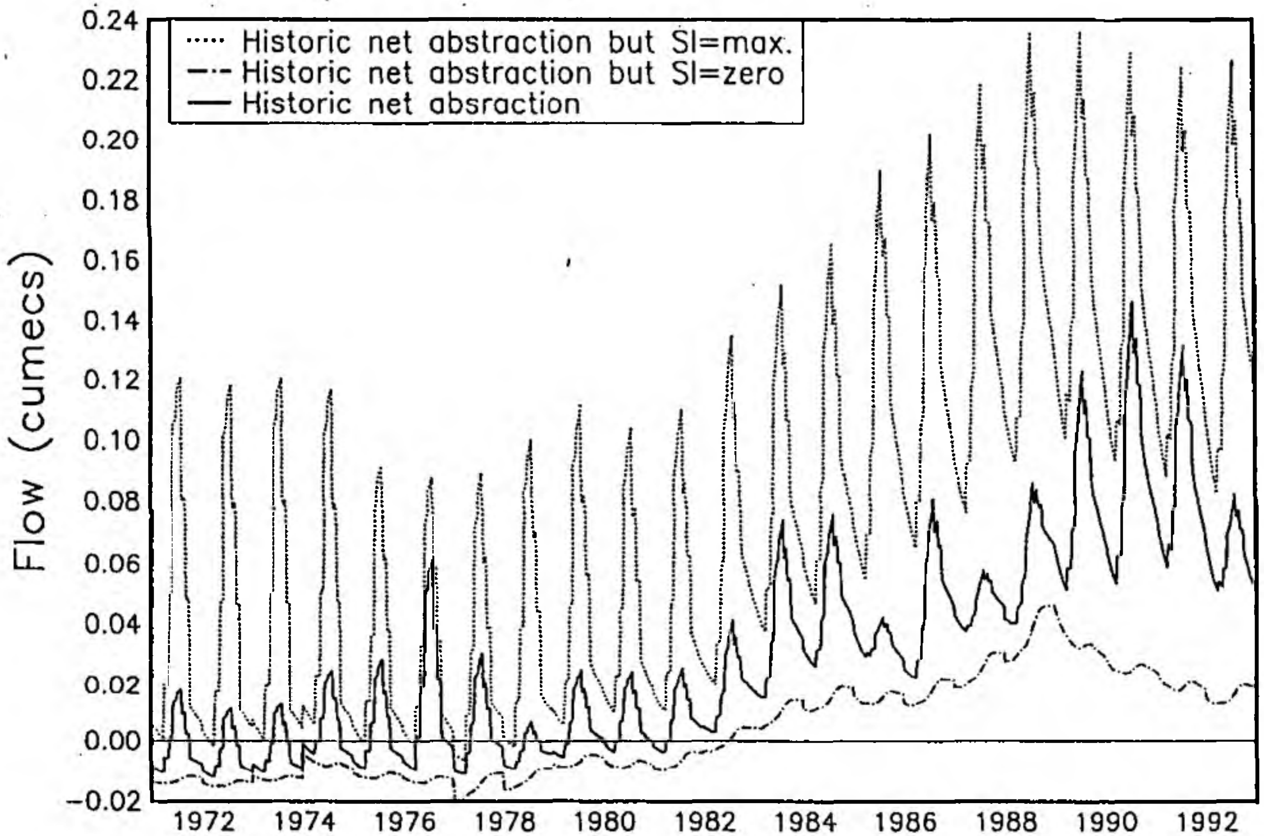


Figure 50 Predicted losses to flow in the Wensum with maximum uptake of licensed quantity for spray irrigation (upper trace), with zero uptake (lowest trace) and with the record of actual uptake (middle trace).

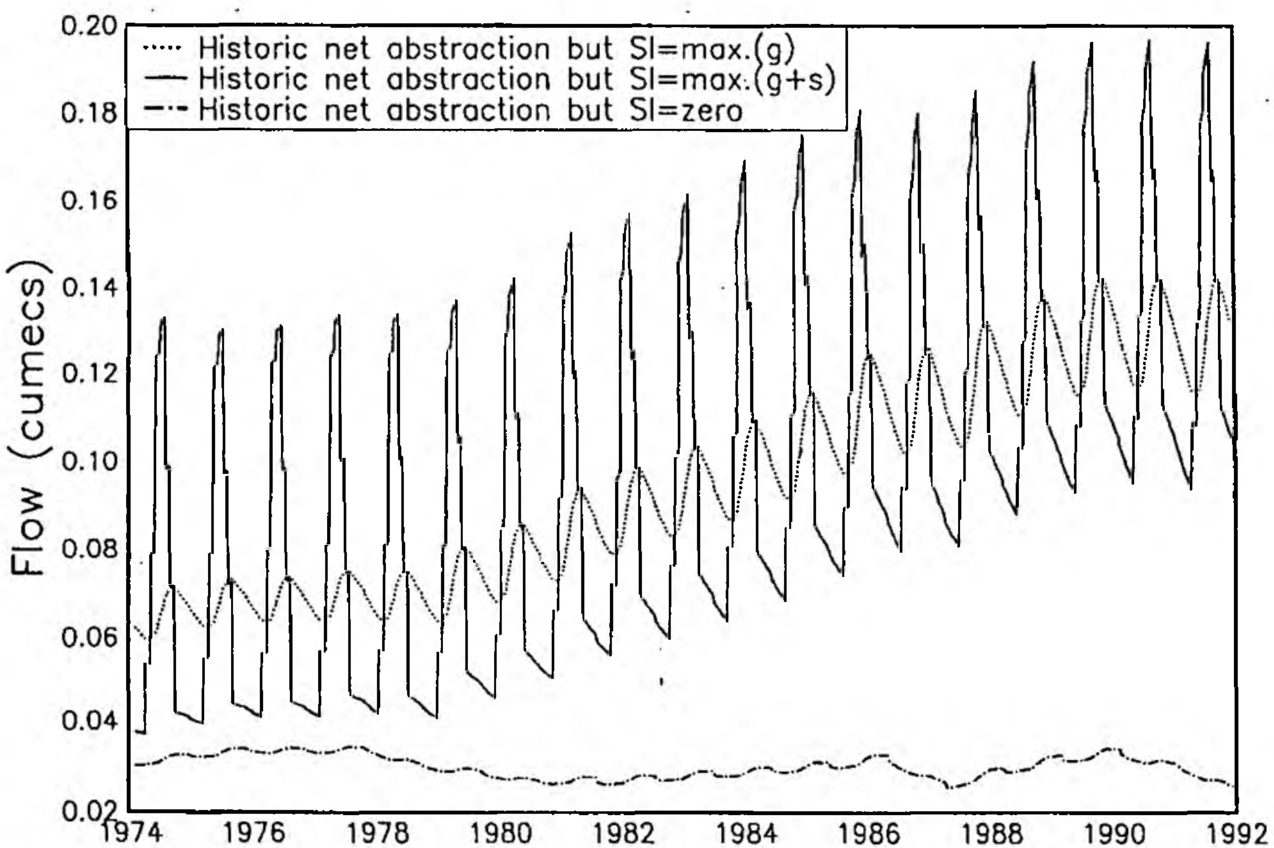


Figure 51 Predicted losses to flow in the Bure with maximum uptake of licensed quantity (from surface and groundwater) for spray irrigation from groundwater alone (middle trace), with maximum uptake from surface and groundwater licences (upper trace) and with zero uptake (lowest trace).

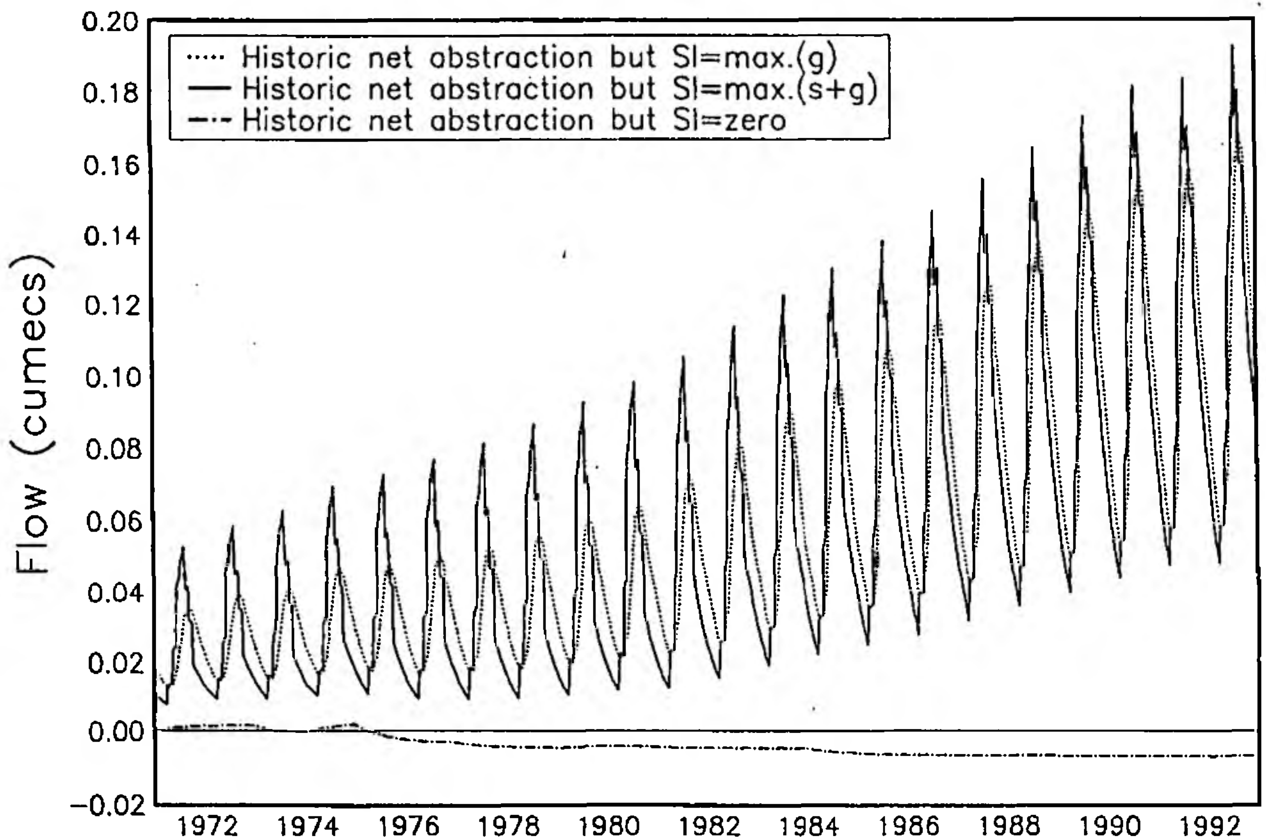


Figure 52 Predicted losses to flow in the Nar with maximum uptake of licensed quantity (from surface and groundwater) for spray irrigation from groundwater alone (middle trace), with maximum uptake from surface and groundwater licences (upper trace) and with zero uptake (lowest trace).

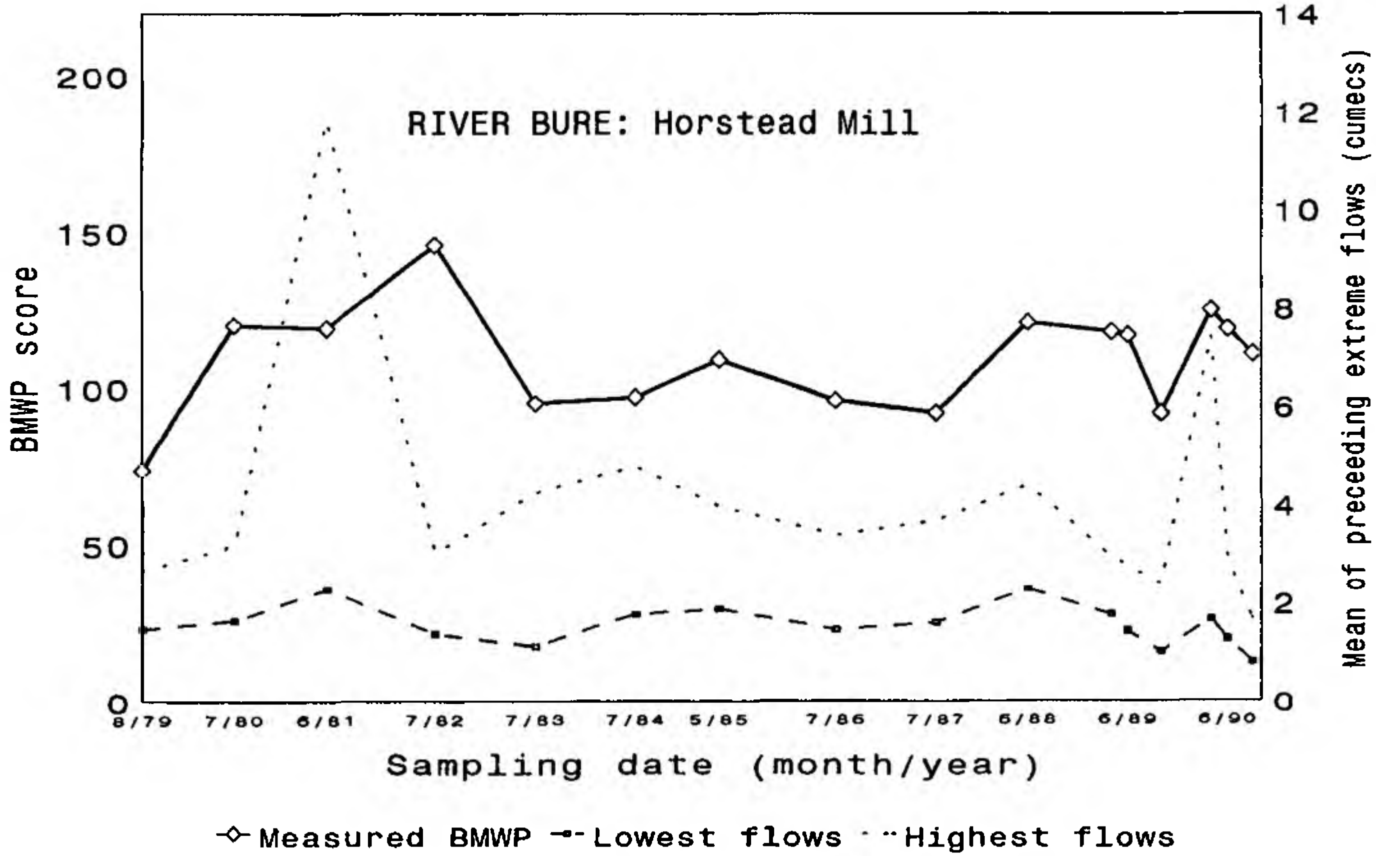


Figure 53 BMWP scores for the invertebrates sampled at Horstead Mill on the River Bure and the mean of the four highest and lowest mean daily flows of the four months before sampling.

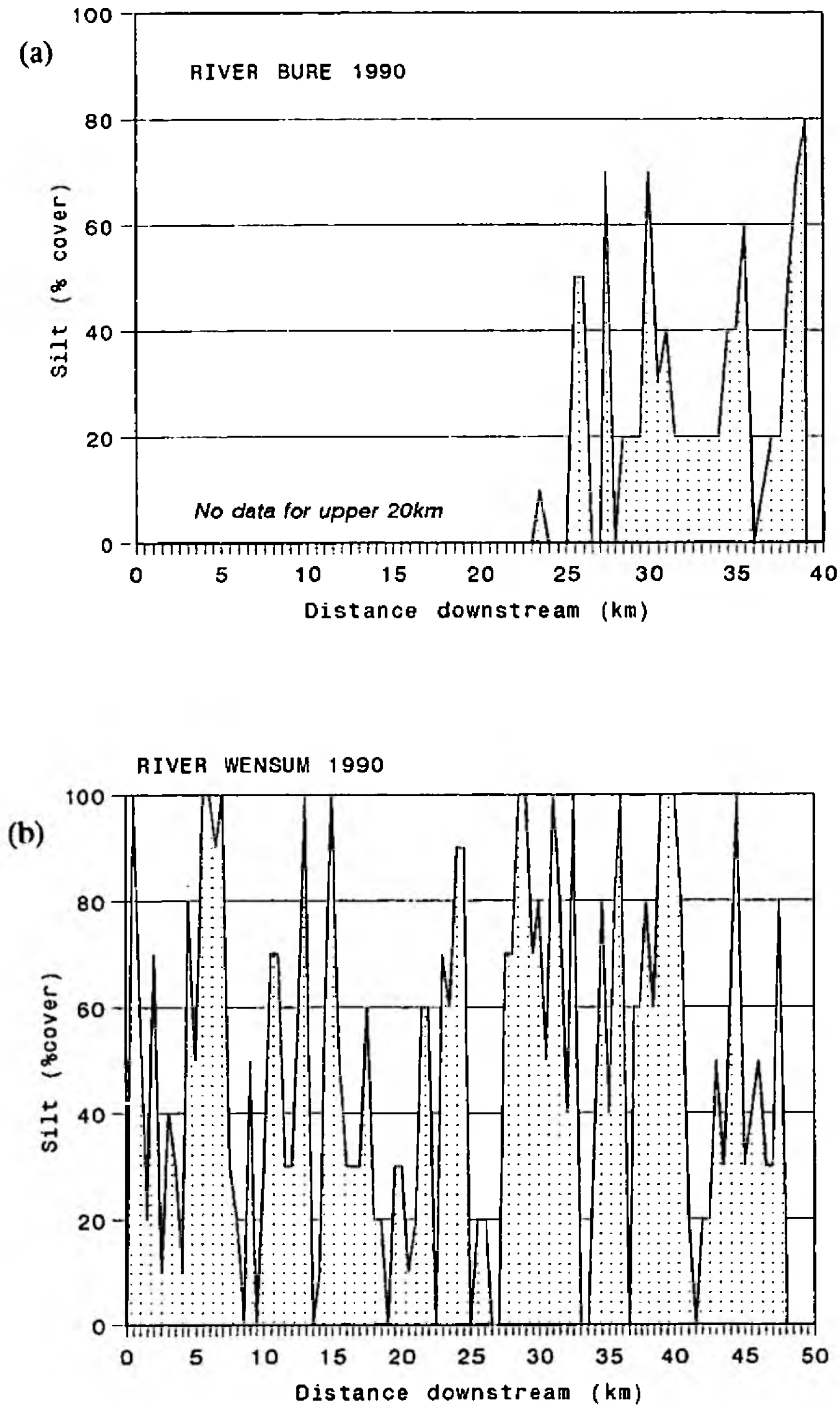
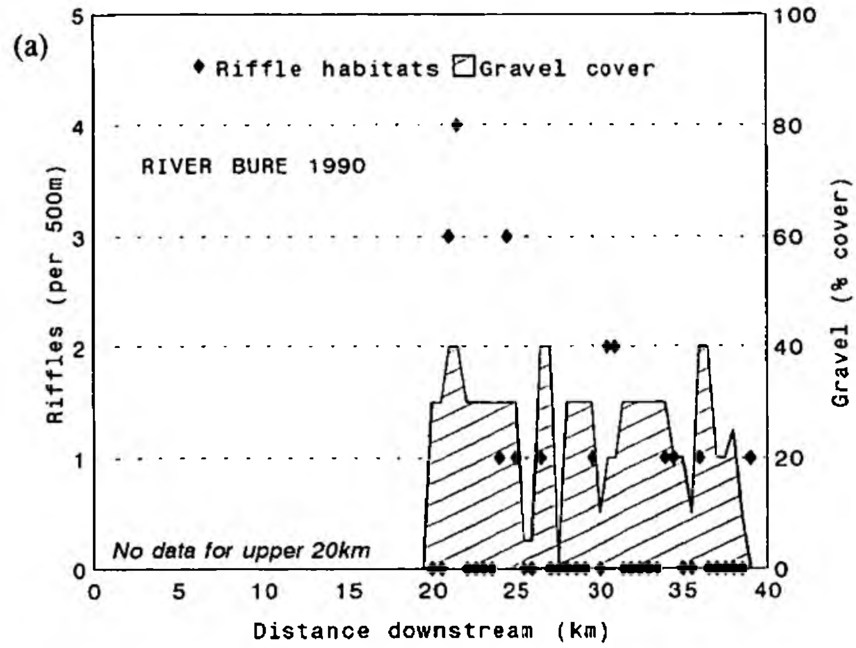


Figure 54 The percentage of the channel of (a) the River Bure and (b) the River Wensum covered by silt. Information is from the 1990 REDS survey.



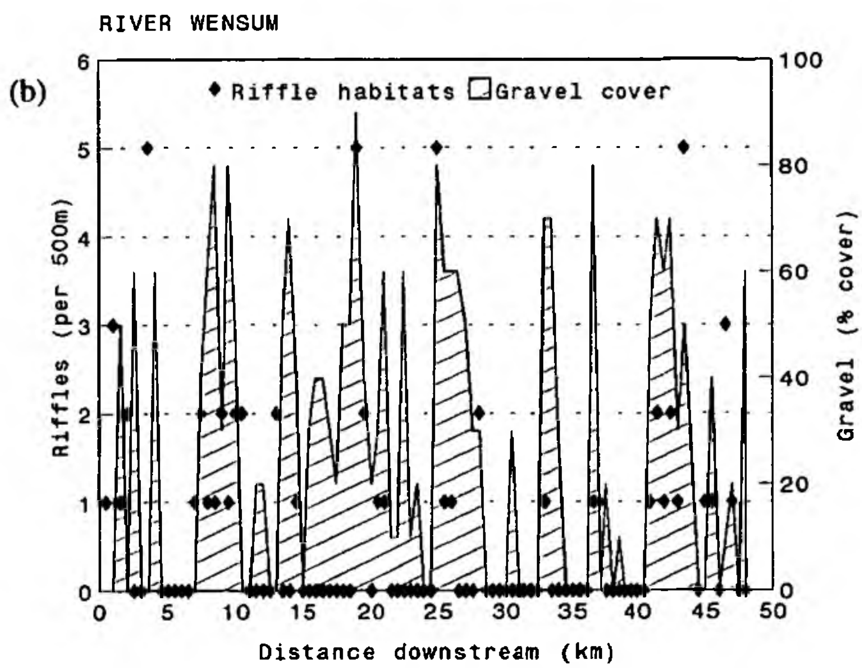
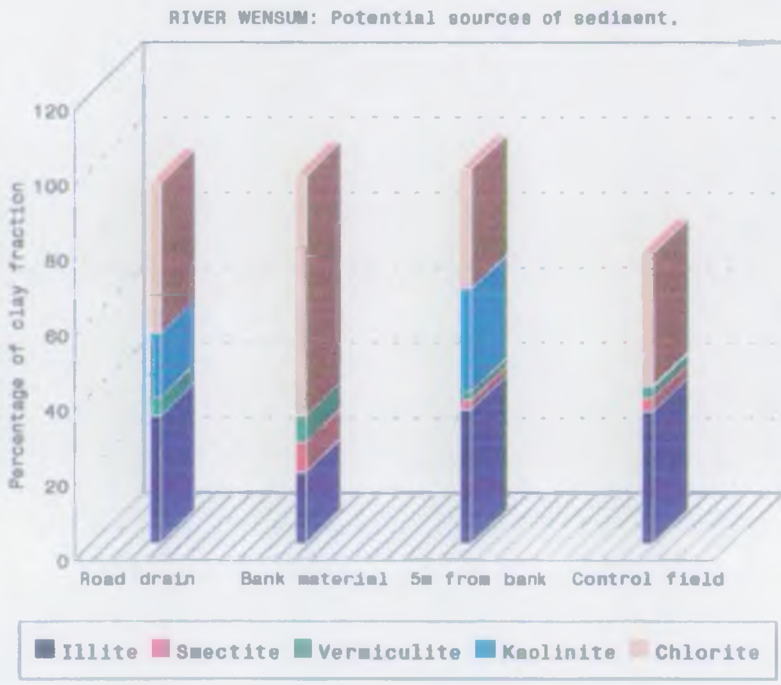


Figure 55 The number of riffles per 500m stretch of River and the percentage of the channel covered by gravel in (a) the River Bure and (b) the River Wensum during 1990. Information is from the 1990 REDS survey.

(a)



(b)

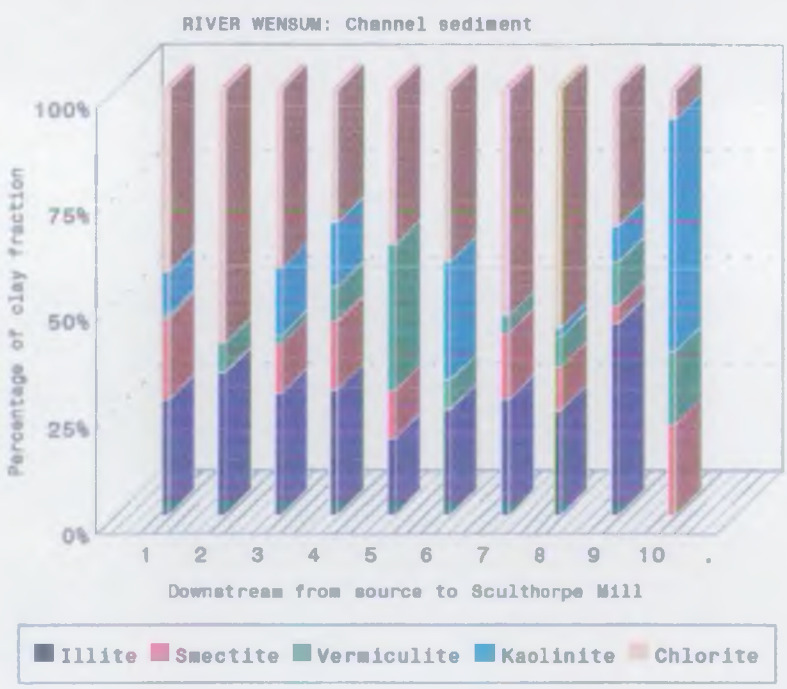
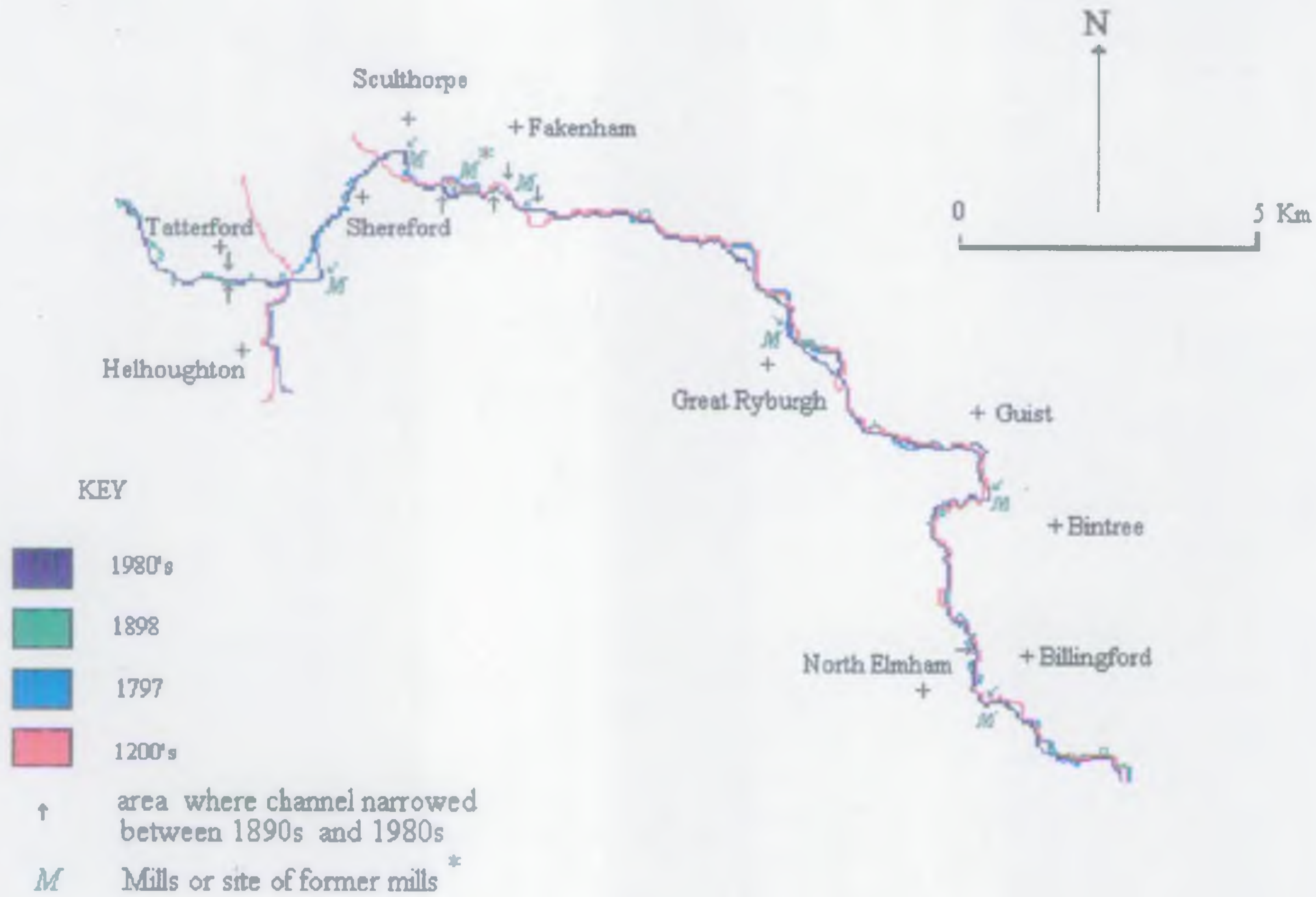
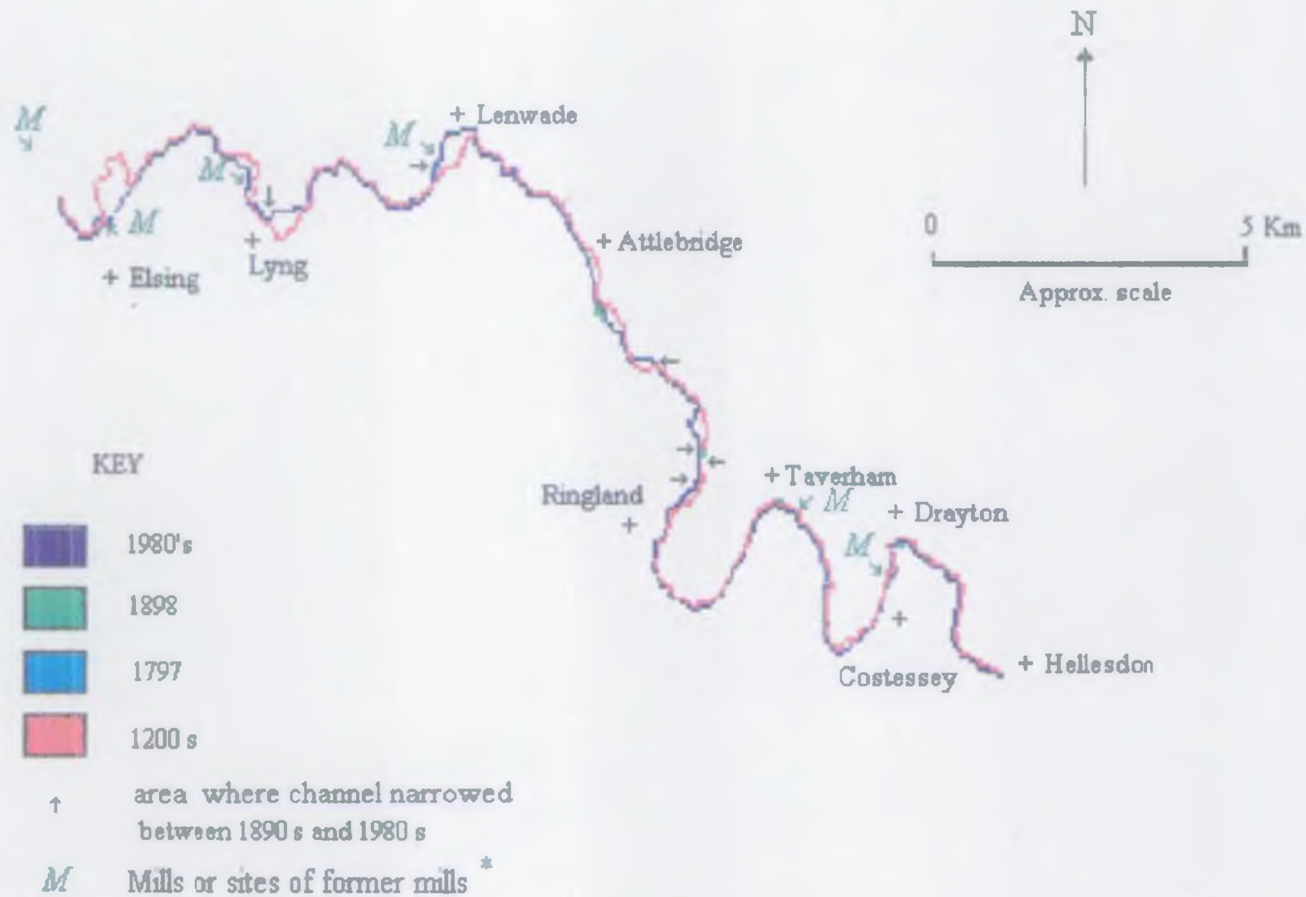


Figure 56 Clay minerals in (a) potential sources of sediment from the immediate catchment of the upper River Wensum and (b) the suite of minerals found in sediments from ten sites in the River channel from source to Sculthorpe Mill.

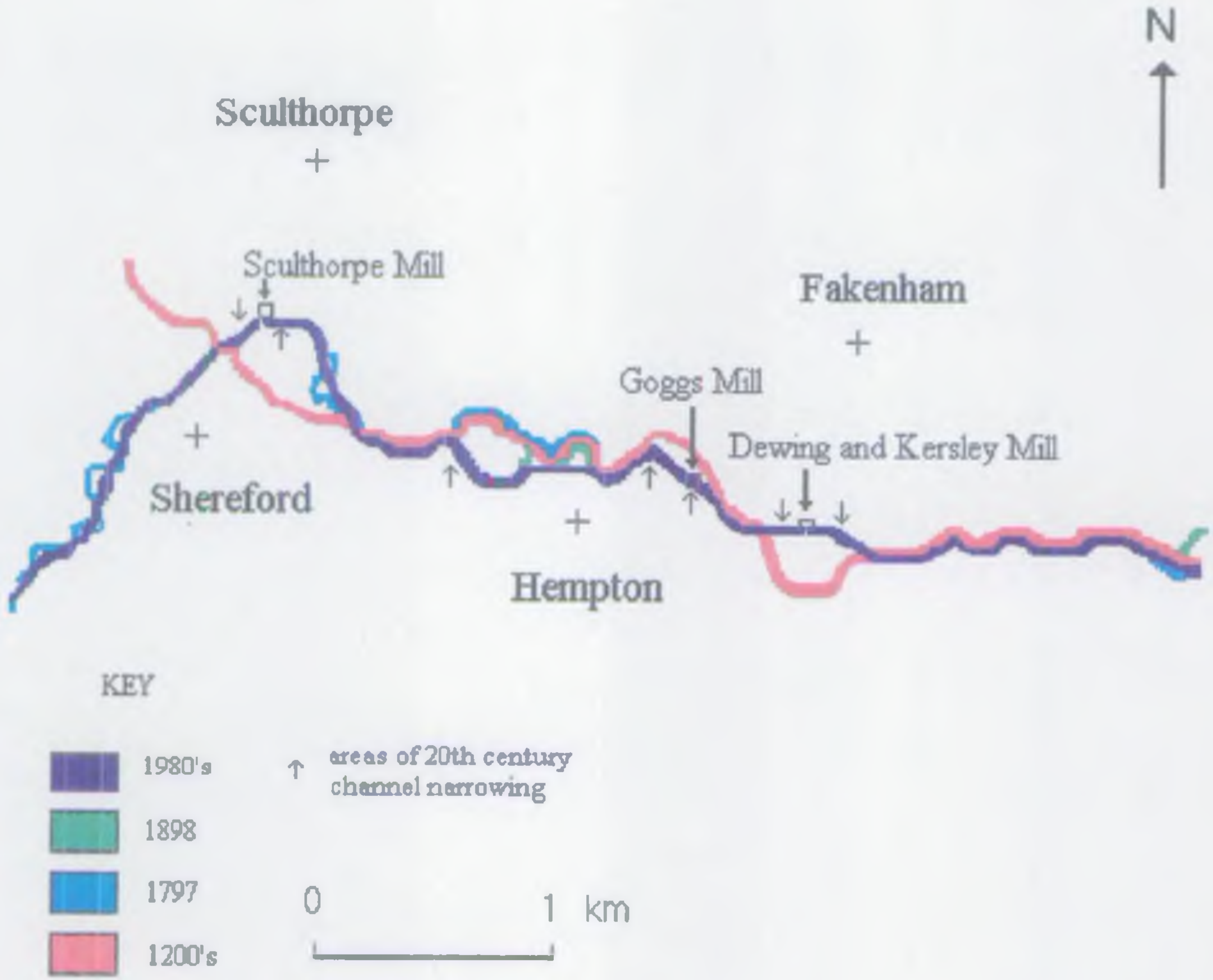
Colour Map 1 **Location of watermills, past and present, on the main channel of the river Wensum**



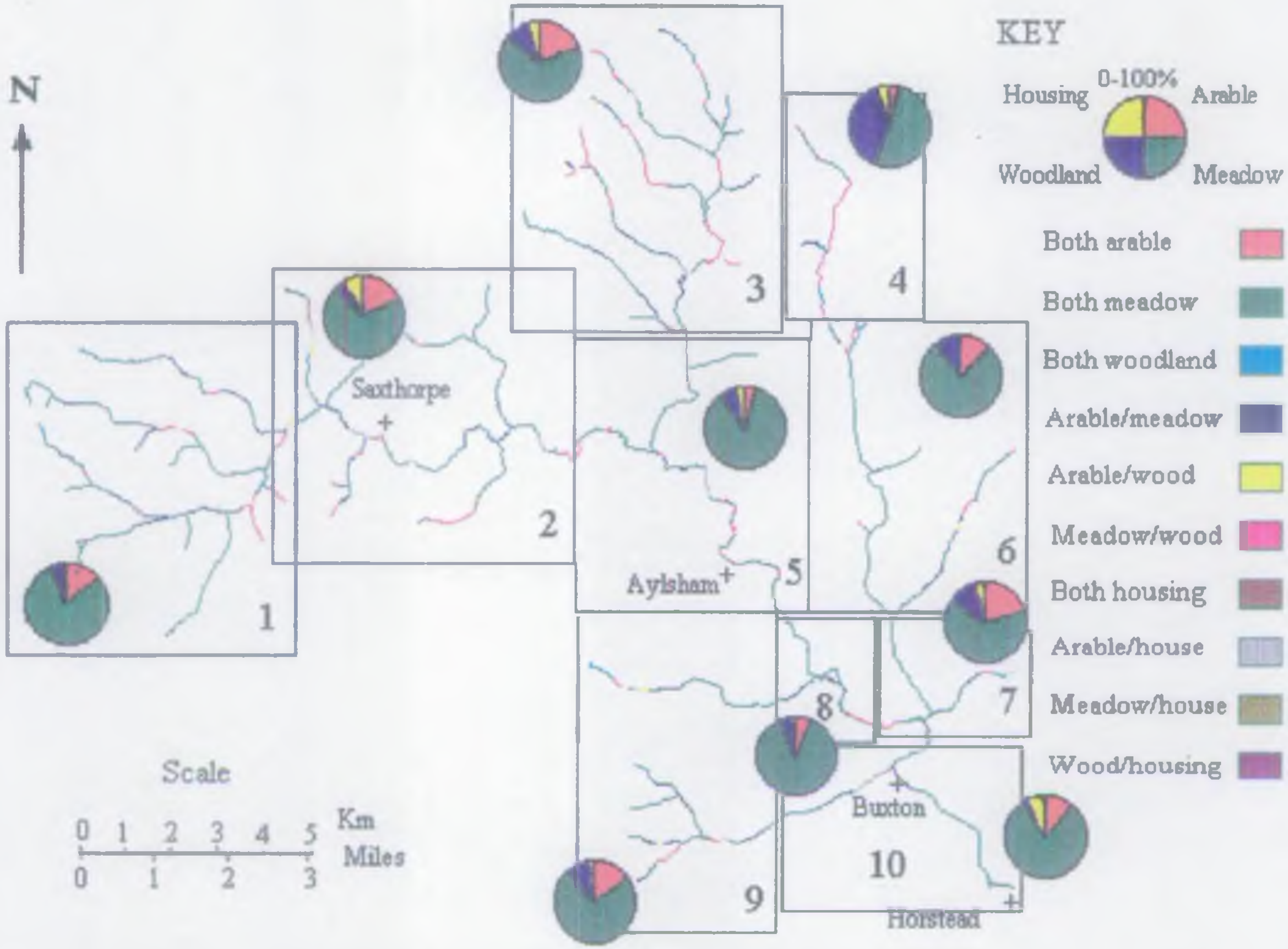
Colour Map 2 (a) **Changes in the position of the main channel in the upper course of the Wensum between the 1200s and 1980s**



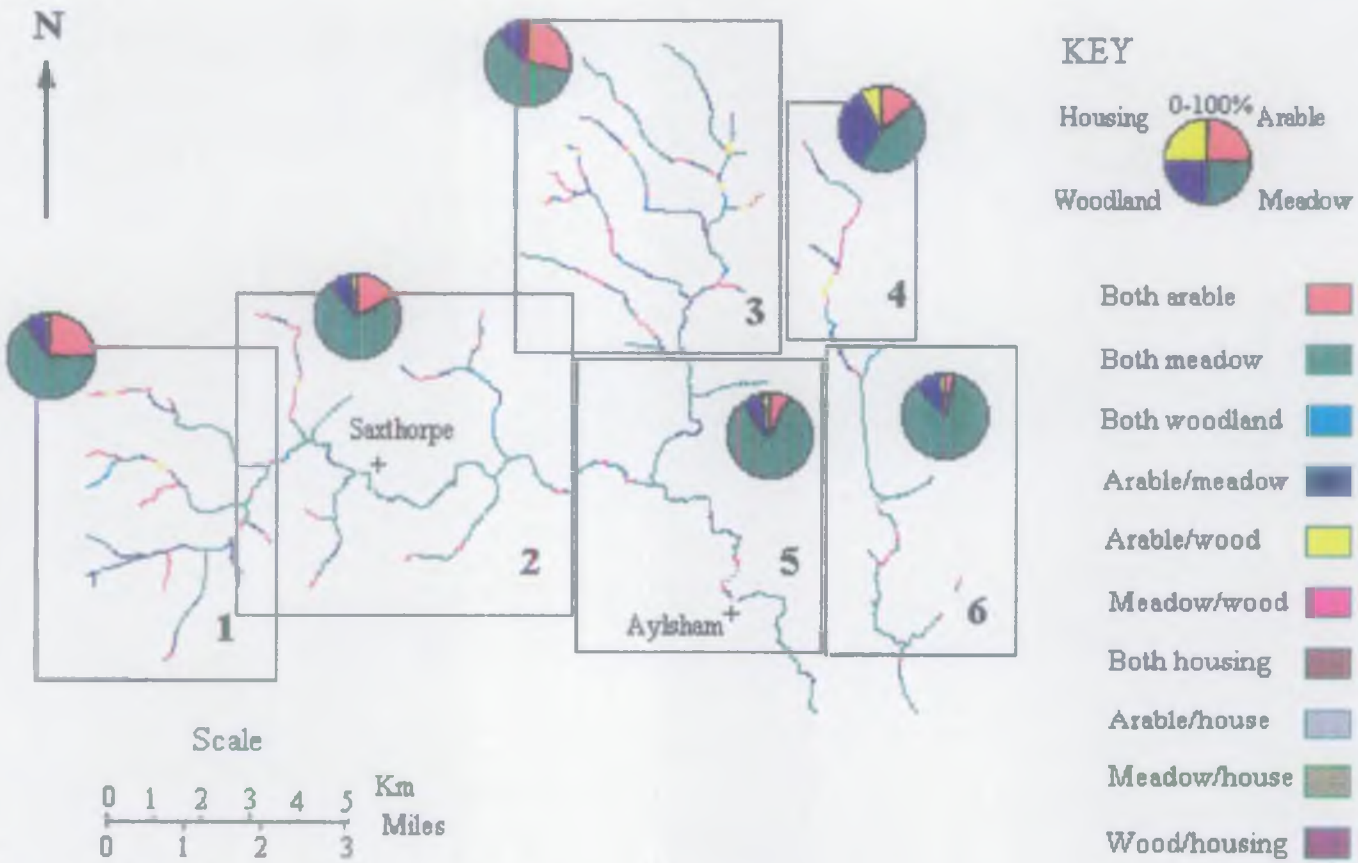
Colour Map 2 (b) **Changes in the position of the main channel in the lower course of the lower Wensum between the 1200s and the 1980s**



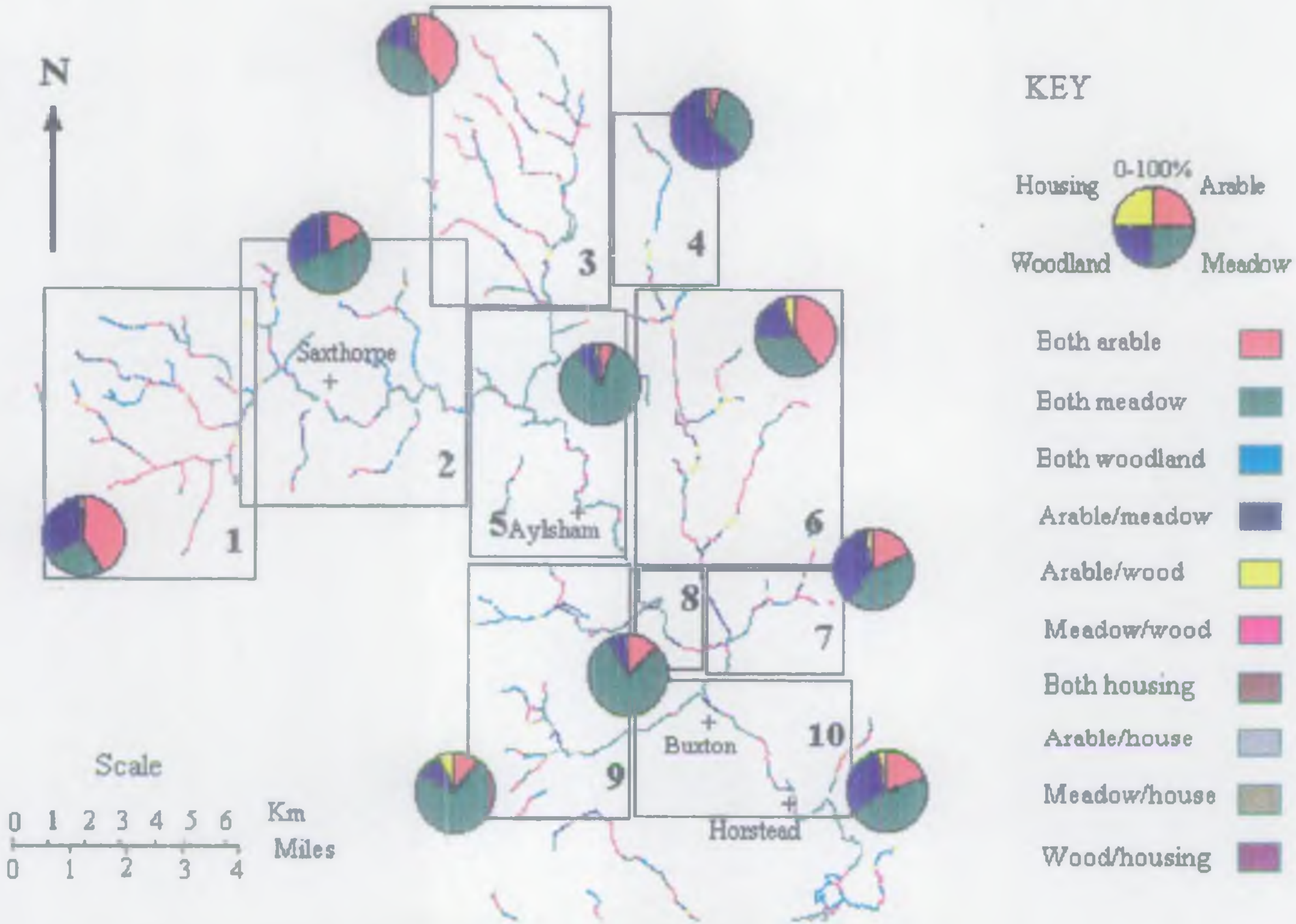
Colour Map 3 Changes in channel position in the Fakenham area



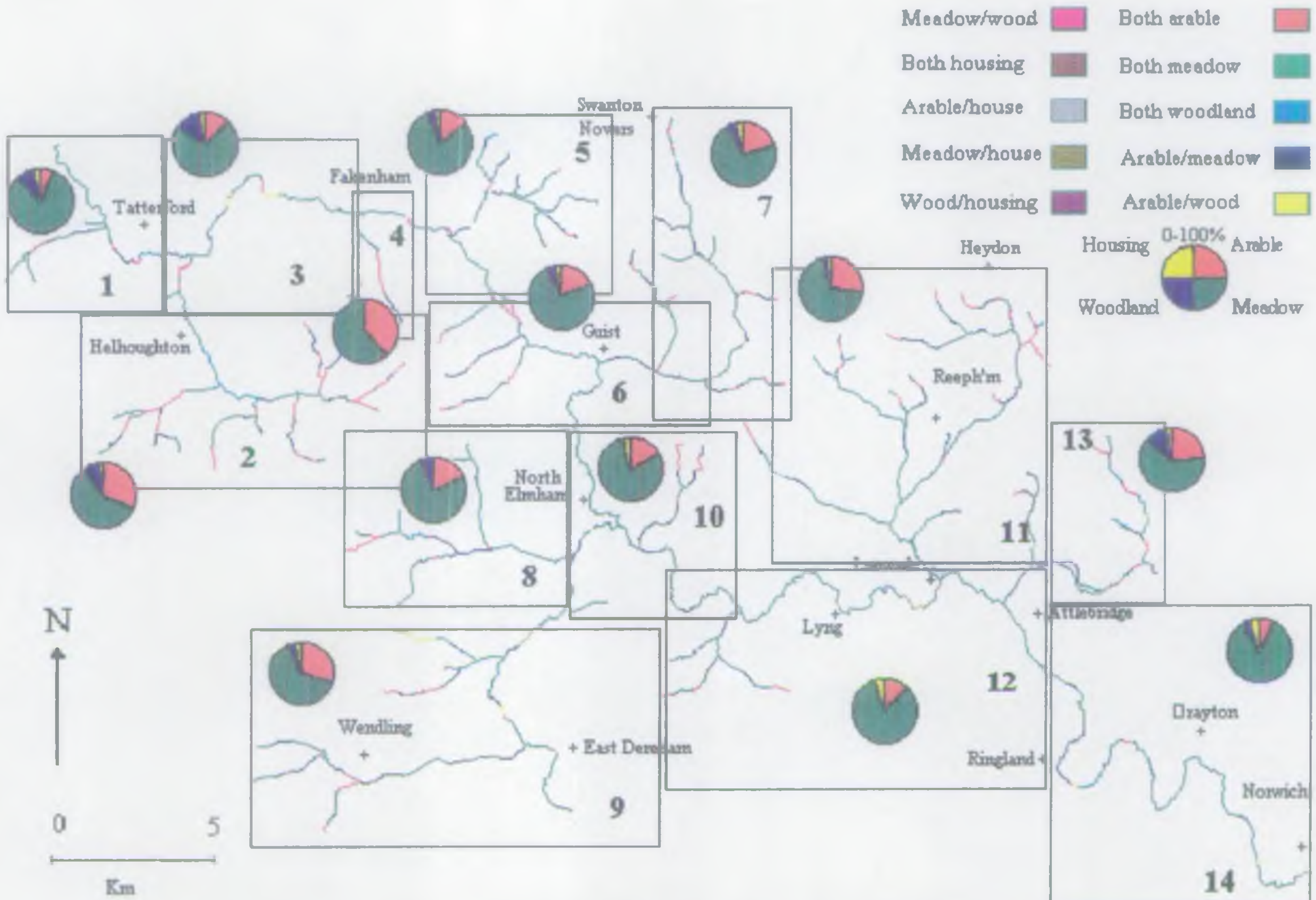
Colour Map 4 **Land use in the Bure valley (1930s)**



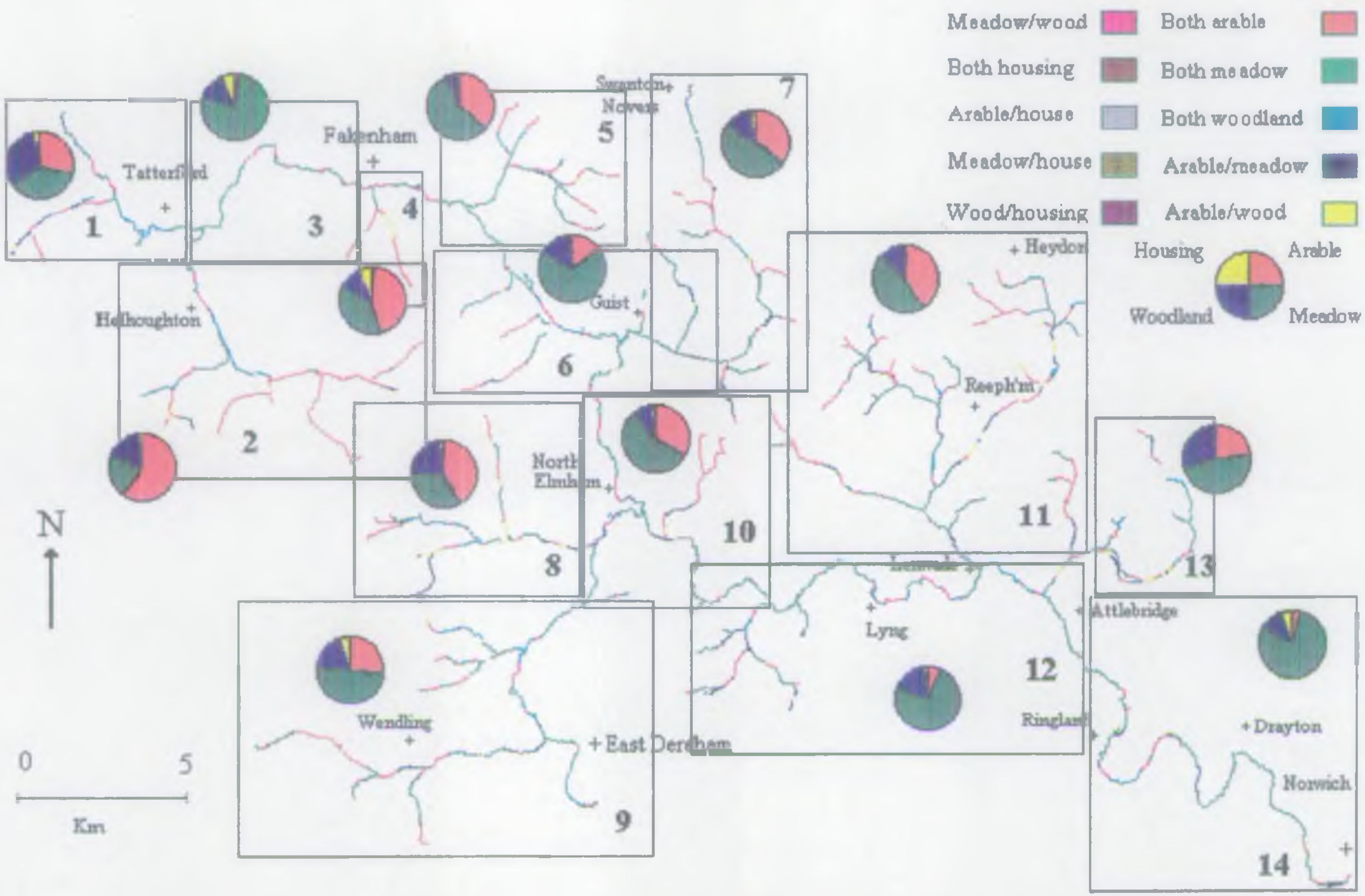
Colour Map 5 **Land use in the Bure Valley (1960s)**



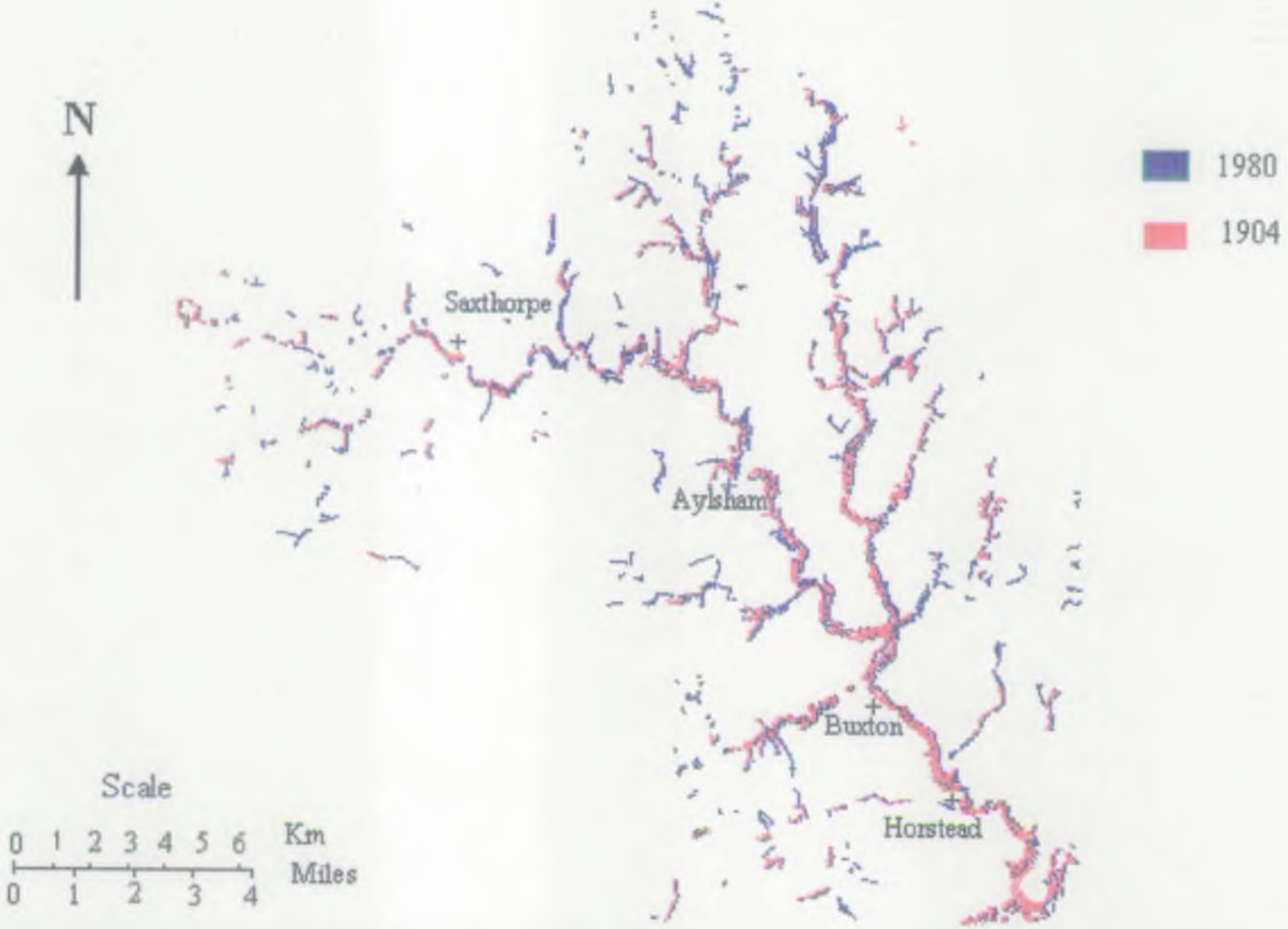
Colour Map 6 **Land use in the Bure valley (1988)**



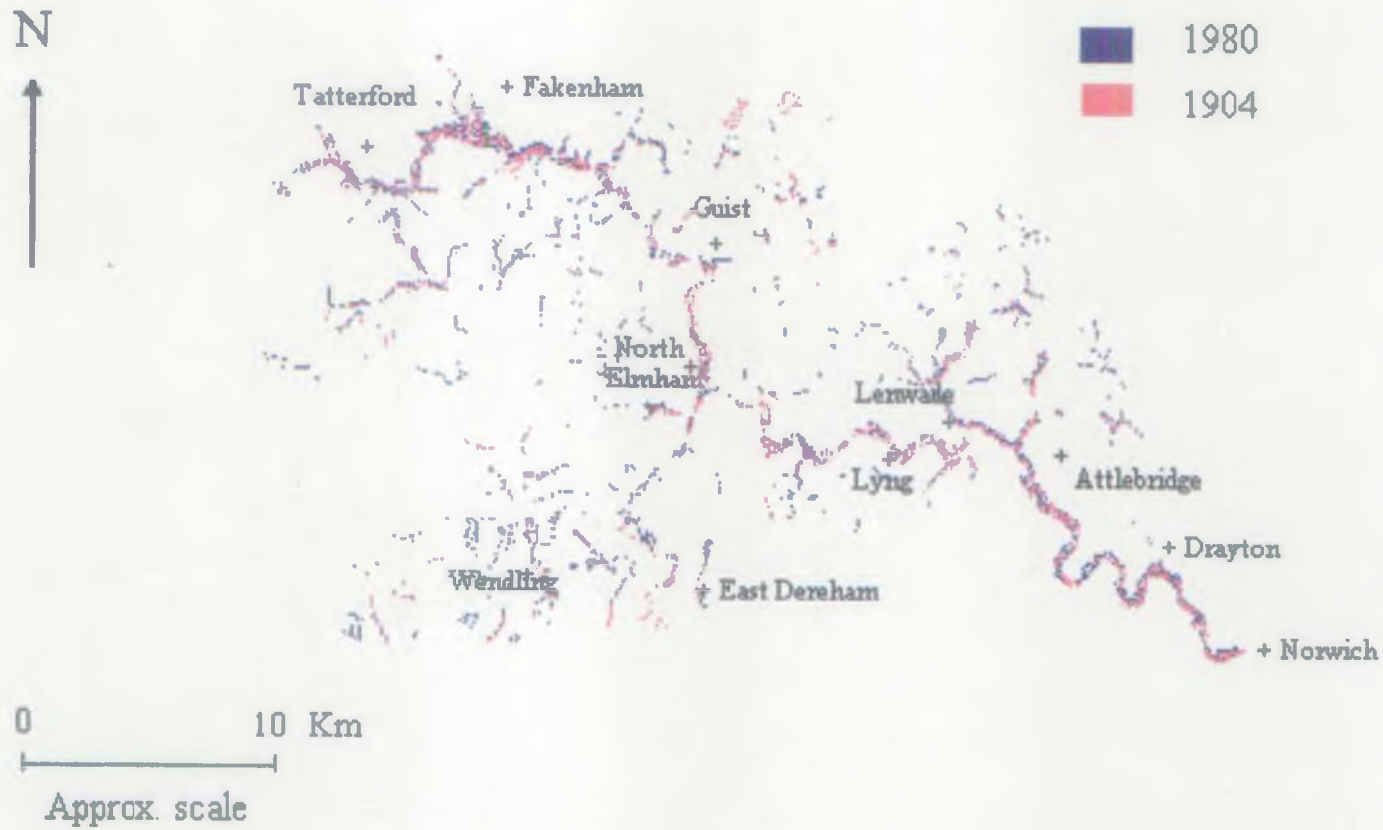
Colour Map 7 **Land use in the Wensum valley (1930s)**



Colour Map 8 **Land use in the Wensum valley (1988)**



Colour Map 9 Change in the drainage ditch network in the non-tidal Bure catchment between 1904 and the 1980s



Colour Map 10 **Change in the drainage ditch network in the Wensum catchment between 1904 and the 1980s**

Photograph 1 Hempton Fen in the upper Wensum photographed during the 1950s.

Photograph 2 The bluff in the middle of the photograph is the bank of the former channel of the Wensum at Hempton Fen. The photograph was taken in 1992.

(a)

(b)

Photographs 3(a) and 3(b) The River Wensum above Gogg's Mill at Fakenham (a) around 1900 and (b) photographed from the same viewpoint during 1993.

(a)

(b)

Photographs 4(a) and 4(b) Gogg's Mill at Fakenham (a) in 1914 and (b) in 1993.

(a)

(b)

Photographs 5(a) and 5(b) The Mill pond at Dewing and Kersley's Mill on the Wensum below Fakenham photographed during (a) 1905 and (b) 1993.

(a)

(b)

Photographs 6(a) and 6(b) The upper Wensum in Sculthorpe Woods during 1992 photographed from the same viewpoint showing (a) the upstream reach which was last dredged during the 1950s and (b) the downstream reach which dredged again in 1989.

(a)

(b)

Photograph 7(a) and 7(b) Examples of channel encroachment of the Bure during 1992 showing (a) *Apium nodiflorum* at Briston and (b) *Phalaris arundinacea* at Blickling.

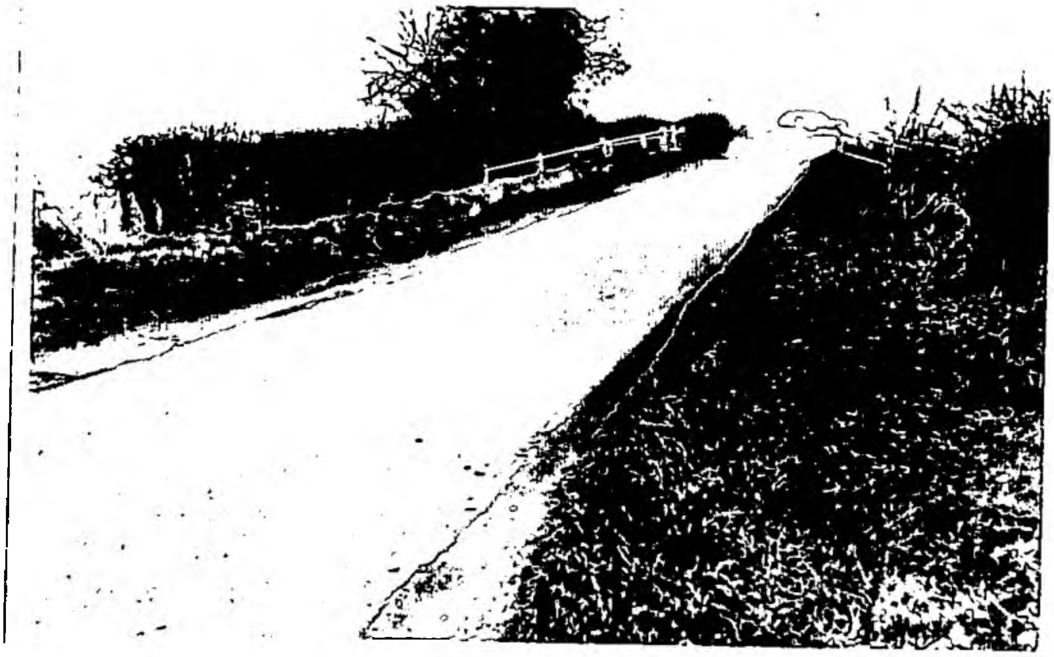
Photograph 8 Gully erosion at Sparham in 1992 with close-up views of the same gully.

(a)

(b)

Photographs 9(a) and 9(b) Examples of soil erosion from cultivated fields in the upper Wensum catchment showing (a) surface runoff next to a Wensum headwater at Pear Tree Corner and (b) erosion from a maize field next to the River at West Raynham.

(a)



(b)

Photographs 10 (a) and 10(b) An example of sediment loading showing (a) sediment-laden road runoff and (b) the drain which takes the road runoff directly into the upper Wensum.

ACKNOWLEDGEMENTS

The National Rivers Authority funded this project and provided most of the data. We also acknowledge contributions of numerical data from Anglian Water Services, the Biological Data Bank of the Norwich Castle Museum, English Nature, Abbotts Hall Fishery, the Castle Acre Fishing Club and the Climatic Research Unit at the University of East Anglia. Project consultees made important contributions of their time for both interviews and for field visits. Project consultees included representatives and members of angling and fly-fishing clubs, local historical societies, the Norfolk Naturalists Trust, the Wensum Valley Project and many individuals who have a long-standing interest in the study Rivers. Members of the School of Environmental Sciences or of the Climatic Research Unit who have contributed to this project are: Richard Hey; Phil Jones; Steve Anthony; David Brown; Bill Corbett; Tim Atkinson; Andrew Lovett and Tim O'Riordan. The research associates who have worked on the project are: Alastair Pitty; Peter Doktor; Jane Harris and Frances MacGuire. Proof reading was undertaken by Cathy Hiscock.

We thank the Fakenham Local History Society, in particular Mr J.Baldwin, and also Mr Aldis and Jonathan Guy for providing photographs.

APPENDIX 1. SOILS OF THE STUDY AREA

Based upon information from:
Soils and their use in Eastern England
by C.A.H.Hodge, W.M.Burton, W.M.Corbett, R.Evans and R.S.Searle. Soil Survey of England and Wales, Bulletin Number 13, 450pp, Harpenden, 1984.

Soil Associations in the Upper Bure Valley

Along the floodplain of most of the upper Bure the most common soil association is the **Hanworth Association** (map no. 871c). It is found on the flat valley floor in narrow strips, often less than 1km wide. The soils are formed in stoneless aeolian drift and peat and overly coarser glacio-fluvial sediments which are covered by a coarse loam. These soils are considered excellent for arable farming being water retentive and easy to work. Unfortunately, they occur in lowlands with high groundwater where natural drainage is poor. Soils are therefore waterlogged for periods of the year. However, in areas such as Scarrow Beck where there is sufficient fall in gradient, farmers risk the periodic flooding of the soils and crop as in nearby higher ground.

Other soil associations which are associated closely with the floodplain of the upper Bure and its tributaries are more limited in their distribution, for example the **Isleham 2 Association** (861b). These are sandy and peaty soils on low lying ground which are therefore affected by groundwater. This association is found in the floodplain of Camping Beck and the headwaters of the Bure around Briston and Hindolveston. The soils are permeable and drainage therefore depends on the ability to reduce high groundwater levels. In some areas of the Fens, these soils are drained using pumps but in other areas the drainage of such soils depends upon efficiency of ditches. The soils of this association are as easily worked for agricultural purposes. However, the hummocky micro-relief often associated with this soil, together with variable organic content and vulnerability to wind erosion makes this a less than attractive agricultural soil type. Despite this, in some areas it is cropped for cereals and sugar beet but in the river valleys (Camping Beck and the headwaters of Bure) it is usually under grass with scrub.

In the headwater catchment of the Bure in the area of Melton Constable and Hindolveston, at some distance from the floodplain are the soils of the **Burlingham 1** Association (572n). These soils are found on gently sloping ground and are formed in clayey or fine loamy chalky till covering glacio-fluvial sands and gravels. They tend to have only slowly permeable subsoils and are prone to seasonal waterlogging. Such soils may be well structured locally and better drained on slopes overlying glacio-fluvial sands and gravels. The association is composed of several soil series with differing agricultural qualities most of which are prone to winter waterlogging. After drainage, these soils tend to be slightly dry for some crops and almost all soils require regular liming. Most of the land is arable, mainly under autumn and spring barley, wheat and sugar beet.

Above Ingworth and in the upper part of Scarrow and King's Beck, the catchment is dominated by soil association **Wick 3** (541t). The soils are commonly developed in aeolian drift lying upon glacio-fluvial deposits. They generally have a high silt content, are slightly flinty and the subsoil is generally sandy. The soils are permeable, unaffected by groundwater and are therefore usually well drained. However, they are prone to gully erosion in heavy rain and require irrigation to produce good crop yields. The main crops grown on these soils are barley (autumn and spring sown) and sugarbeet. The direct drilling of crops is not considered advisable due to the low organic content and sandy texture of the soils.

The remainder of the upper Bure catchment is dominated by the **Wick** 2 (541s) soil association. This is a coarse loamy soil and covers an area of gently undulating landscape being developed in aeolian drift with a subsoil commonly in till. Some of the soils are permeable and unaffected by groundwater and remain well drained, but others, despite having permeable subsoils, are waterlogged during the winter due to the high water table. However, if the water table is lowered, the soils become well drained and are suitable for the growth of autumn sown cereals, sugar beet and potatoes. The soils are worked easily and are water retentive for crops and produce some of the best agricultural land in Norfolk.

Soil Associations in the Wensum Valley

Along the floodplain of the River Wensum and most of its tributaries from its headwaters to approximately Alderford, the **Isleham 2 Association** (861b) is the dominant soil type. As in the Bure valley, these are sandy and peaty soils on low lying ground which is affected by groundwater. When drained, these soils result in agricultural land of varying quality.

The floodplain between Alderford and Norwich is characterised by soils of the **Adventurers' 2** association (1024b). These are amorphous and semi-fibrous peat soils, often with underlying sandy subsoils. Where the peat has wasted, soils of the Isleham series are produced. These soils are permeable and can often be drained by ditches alone, but in some less well drained areas, the land cannot be used for anything but grassland. When drained, the soils are used to grow mainly cereals and some beet, potatoes and other field vegetables. There are some disadvantages to agricultural development on these soils since they sometimes result in poor finishing of cereals and low sugar content in sugar beet. They are also subject to wind erosion and potential fires in the peaty subsoil.

In the headwater catchment of the Wensum (South Raynham, Syderstone and Harpley) the soils are of the **Barrow** (581f) association. This is a deep well drained coarse loamy soil developed over clayey soils. It has developed mainly in areas where aeolian sands have been incorporated into the upper layers of a chalky till. It is permeable, easily worked and absorbs winter rainfall easily. The main crops are barley (mostly autumn sown), sugar beet, winter wheat and winter root vegetables. The fields are usually large and in an open landscape.

Within the upper reaches of the catchment, around Tattersett, East Rudham, Roughton, West Lexham and south of Fakenham, there are also small patches of **Newport** 4 (551g) which is also found more extensively further downstream between Reepham and Norwich. This is a deep, well drained stoney/sandy acid soil, occurring mainly on glacio-fluvial deposits on low river terraces or gently sloping hilltops. They are permeable soils and absorb winter rain but have a low moisture retention, making such areas poor for summer crops and susceptible to wind erosion. Therefore, crop yields tend to be low unless irrigated. Barley (autumn and spring sown) is the most common cereal, with large areas of sugar beet. Heath and Forestry Commission woodland are not uncommon in these areas.

The majority of the rest of the catchment is composed of two relatively impermeable soils. The first, being more common within a kilometre or so of the River and its tributaries, is the **Burlingham 1**(572n) association. (see Bure valley). This is a soil which tends to have slowly permeable subsoils and is prone to seasonal waterlogging. The land is used for general arable farming with more crops being sown in the autumn than spring and little being used for grassland.

The other impermeable soil is the **Beccles** 1 (711r) 33 association which is somewhat removed from the main river channels, at least in the upper catchment. In areas further removed from the river and its tributaries the 711r Beccles 1 association occurs.

Soil Associations of the Nar valley

The soil Associations along the floodplain of the upper reaches of the Nar are those of the Isleham 2 Association (861b). In the lowlying lands of the lower part of the catchment (downstream of West Acre) the sand/peat soils of the Isleham 2 series cover a large area of land away from the river channel itself. As the River approaches the Wash, it occupies a flood-plain and catchment of a mosaic of different soil associations. The transition from Isleham 2 to the mosaic of other soils such as: Adventurers2, Midenley and Blacktoft occurs near Blackborough. The channel itself is embanked in the lower reaches of its course and reflects the highly enginered drainage of the lower part of the Nar. Many of the soils in this area are fine grained sand and peat soils some with marine clay influences and all would tend to be naturally waterlogged due to the high water table but the presence of pumped dykes ensures that these naturally fertile soils are available for agricultural use for most of the year. Many of these soils are highly fertile and are used for large scale vegetable growing. In some areas the soils are suceptible to wind erosion especially due to the exposed nature of the landscape.

In the upper part of the Nar catchment (above Mileham) the soils are similar to those of the upper part of the Wensum. Such soils are relatively poor for agriculture many having an impermeable clay subsoil (Beccles 2) or being so permeable they are suceptible to erosion and poor for summer crops (Newport 4). However, other soils associations which are moderately suited for arable use (Burlingham 1) are found to the south of the catchment near Litcham. Such soils are used for general arable farming.

Between West Lexham and West Acre the Nar catchment occupies an area dominated by Newmarket 1 and 2 soil associations which are sandy loamy calcarous soils often overlying chalky rubble. Such soils are highly permeable and in some areas too dry for grass. The chief crop on these soils is barley although winter wheat and sugar beet is also grown, however nutrients are readily leached from the soils and top dresssings of nitrogen are often applied in Feburary and March togethger with boon and sodium for sugar beet. In some areas the sandier soils are suceptible to wind erosion.

In summary the soils of the Nar catchment fall into three main groupings;

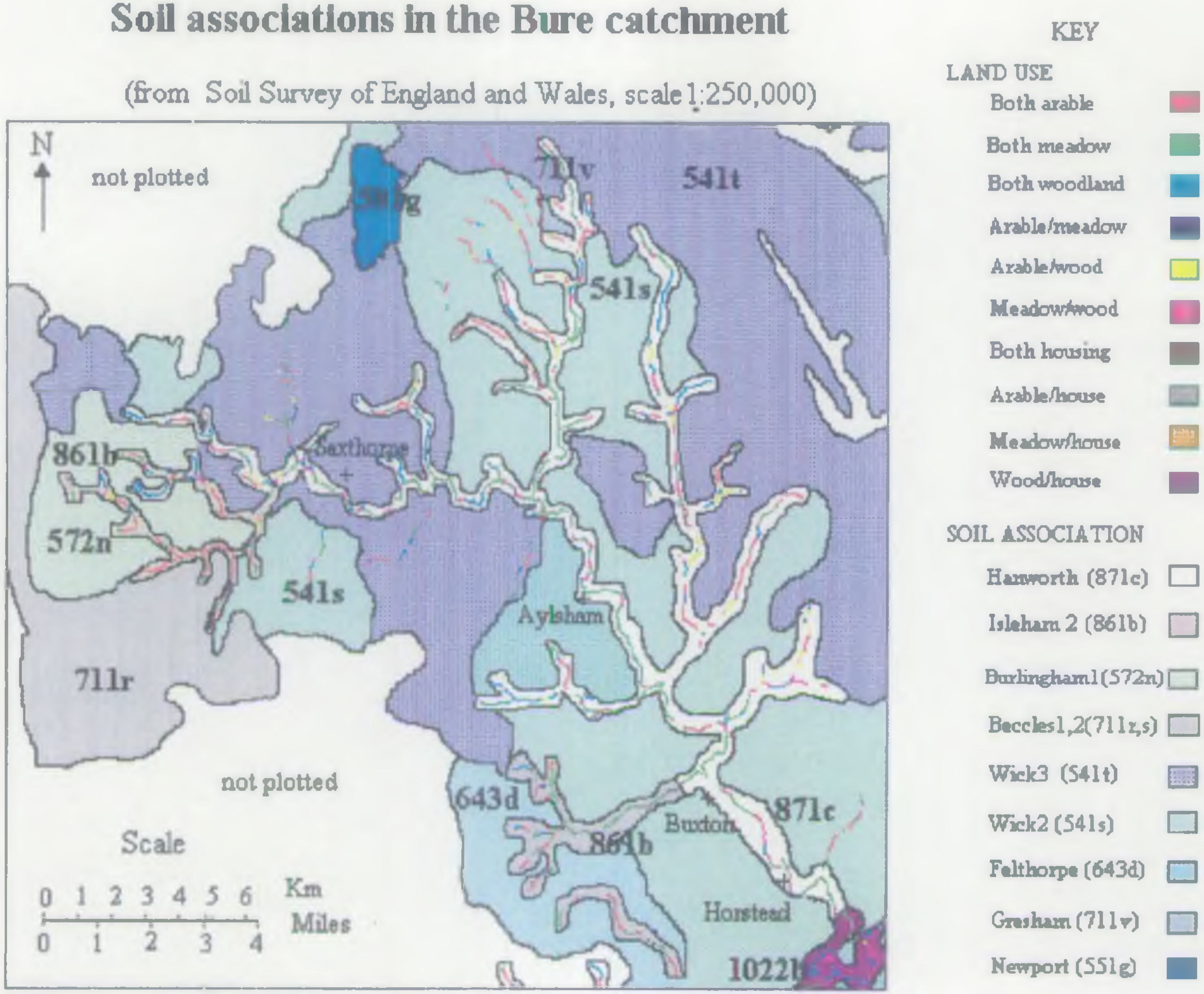
1. The relatively impermeable clayey soils of the upper part of the catchment, especially above Mileham.

2. Sandy, permeable soils to the north of the main channel between Mileham and East Lexham and to the north and south of the catchment between East Lexham and West Acre.

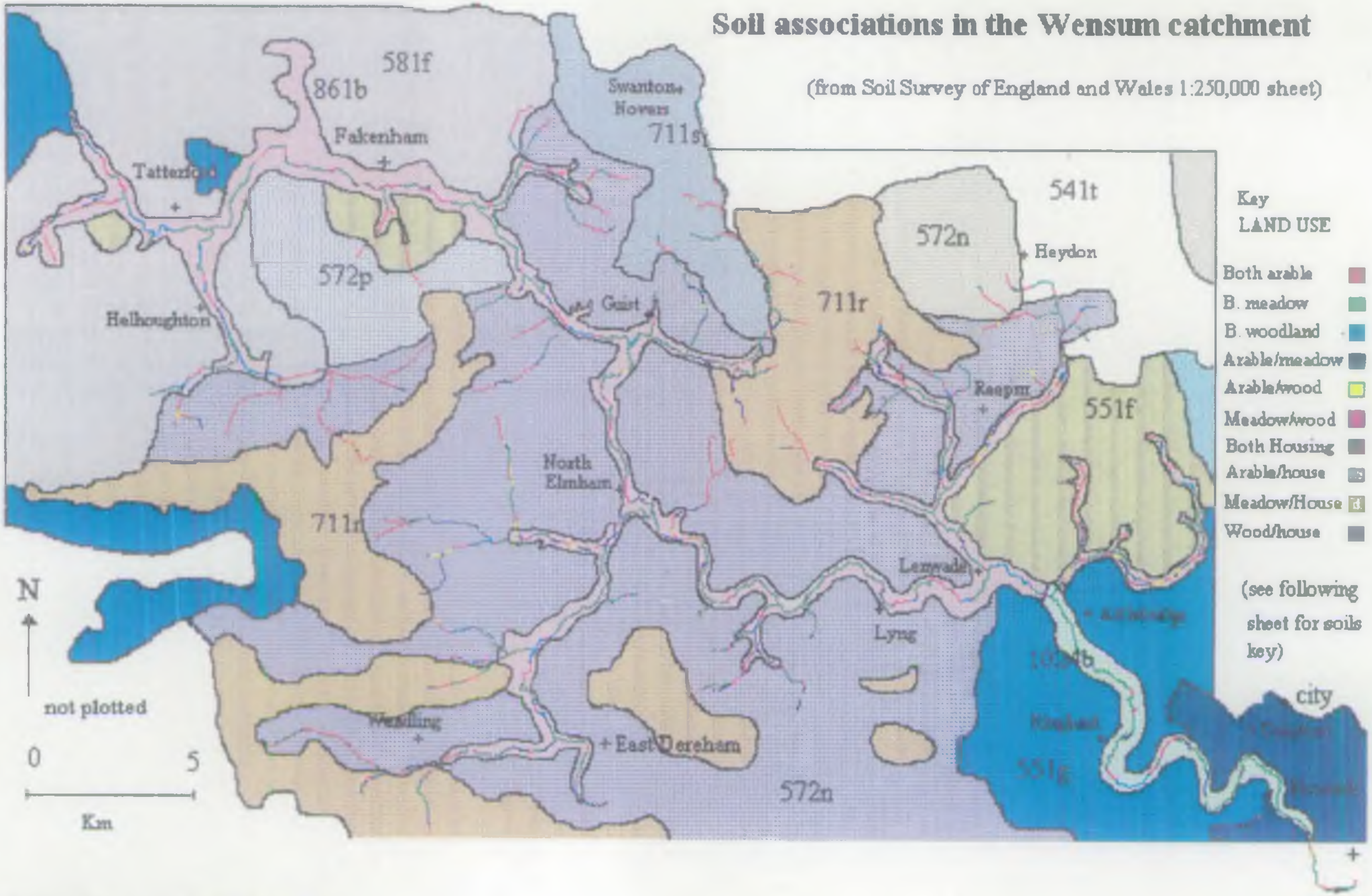
3. The fine grained sandy/peaty naturally waterlogged soils of the lower part of the catchment between West Acre and King Lynn.

Soil associations in the Bure catchment

(from Soil Survey of England and Wales, scale 1:250,000)



Appendix 1. Colour Map 1



Appendix 1. Colour Map 2

KEY (soil associations in the Wensum catchment)

Isleham 2 (861b)

Adventurers 2 (1024b)

Wick 2 (541s)

Wick 3 (541t)

Newport 3 (551f)

Newport 4 (551g)

Burlingham 1 (572n)

Burlingham 3 (572p)

Barrow (581f)

Beccles 1 (711r)

Beccles2 (711s)

APPENDIX 2. AREAL RAINFALL ANALYSIS, 1930 to 1992.

Introduction

The potential for both temporal and spatial variation of rainfall, even over short distances and over relatively uniform terrain, dictates minimum rain gauge network requirements (Bleasdale, 1965). However, the calculation of meaningful long term areal-rainfall statistics relies on the continuity of site-specific component gauge records. This invariably leads to a compromise situation in which less than the ideal number of records are used, particularly as the time scale of the inquiry increases. Even then, the long run gauge records may not be complete and have to be patched using nearby gauge data. In many cases, gauge records have to be combined both spatially and temporally to form composite records. Once produced, areal rainfall series are the background to any retrospective investigation into the terrestrial hydrological cycle.

1. Method

By looking back to 1930, the choice of gauge record has been severely limited by the need for continuity and the use of some composite records has been necessary. The minimum requirement for both numbers and locations of gauges has suffered as a result. Any areal or locational bias thus introduced, can be minimised by the use of appropriate weighting factors which are applied to the chosen gauge records as follows:

Locational or geographical bias can be minimised if long-term areal, and specific-gauge average rainfall values are already known. These data are usually available, having been calculated by the United Kingdom Meteorological Office (UKMO) (Jones, 1984). The chosen-gauge records are first modified by the factor AAGR/AAR, where:

AAGR = average annual catchment rainfall (1941-70)
AAR = average annual rainfall for that gauge (1941-70)

The modified gauge records can then be re-modified to minimise areal bias using the factor of: the (areal) percentage of the catchment which is nearest to that gauge, this being determined using the Thiessen polygon method which is explained by Linsley et al, 1975. The sum of the re-modified component-gauge data then gives the areal rainfall which, in this case, was expressed on an annual basis.

Ideally, any gauge record should be subjected to quality control tests before inclusion in the above process. Continuity of record is not proof that observer practice has always been consistent. Similarly, precise gauge location may have been changed or vegetation may have overgrown the site, thus affecting the catch.

Again, these considerations are particularly relevant when dealing with long records. Since 1961, stricter quality control has been employed by UKMO (Jones, 1984) thus Met Office data post-1961 should be reliable.

Since the main objective of the assessment of catchment areal- rainfall statistics has been towards the investigation of the fluctuation of river flows with time, rather than the production of precise areal-totals, pre-1961 quality control checks have not been employed. However, the vast majority of data used has been taken from official sources, namely UKMO/British Rainfall publications, Table 1.

Table 1. Principal rain gauge records used

UKMO ref.	AAR(41-70) (mm)	Location	Grid reference
204583	637	Browick Hall	TG130015 (complete)
207616	663	Cawston	TG136238 (composite)
203876	631	Cromer	TG208422 (patched)
207040	676	E. Dereham	TF994132 (composite)
199778	613	Gayton	TF733206 (patched)
208400	643	Norwich	TG212086 (composite)
201056	709	Sandringham	TF697289 (complete)
213598	660	Woodgate Ho.	TG181260 (patched)

Before the production of specific catchment areal-rainfall statistics was attempted, the three gauge records which were the most complete throughout the period 1930-92 were averaged without the use of any weighting factors. The locations of these three gauges, namely Browick Hall, Sandringham and Cromer roughly mark out the areal extremities of the Study area. Their average value produces a useful guide to the fluctuation of annual rainfall with time, at a point in the centre of the Study region. It also acts as a check for the catchment areal statistics which, by necessity, rely more on composite and, so possibly, less reliable gauge data.

The composite gauge records are essentially those used by Jones (1984) who compiled them for the purposes of riverflow reconstruction using methods outlined by Craddock (1977). They have been extended, where necessary, using the records of adjacent gauges. To be suitable for this purpose, the adjacent gauge record has to overlap, by several years, the record which is being extended. The ratio of substitute/original for the overlapping period provides a suitable modification factor which removes any locational bias from the substitute record. The main substitute gauge records that were used are listed in Table 2.

Table 2. Rain gauges used to extend composite records

UKMO gauge reference	Location	Grid ref.(composite record)
207568	Heydon	TG107266 (Cawston)
206950	Wendling	TF927128 (E. Dereham)
208389	Norwich	TG211095 (Norwich)

2. Results

2.1. Annual (January-December) rainfall.

For the preliminary exercise, that of averaging the non weighted annual rainfall series for Cromer, Browick Hall, and Sandringham, the 30-year mean rainfall statistics are listed in Table 3. Statistics for individual gauges are in Table 4.

Table 3. Thirty-year-means produced from non-weighted peripheral, but virtually unbroken gauge records

PERIOD	RAINFALL (mm)
1931-60	648
1941-70	659
1951-80	652
1961-90	652

Table 4. Thirty-year-mean statistics for individual gauges used in the non-weighted series

PERIOD	RAINFALL (mm)		
	Cromer	Browick Hall	Sandringham
1931-60	619	635	690
1941-70	631	637	709
1951-80	637	627	693
1961-90	631	640	684

For the production of individual catchment-areal statistics, the boundaries used were the topographical divides as drawn from principal river gauging stations. For reasons outlined above, the availability of appropriate rain gauge records was limited to those listed in Table 5.

Table 5. Rain gauge records used for the production of catchment areal-rainfall series

RIVER/CATCHMENT	RAIN GAUGE RECORDS USED
Wensum to Costessey	Gayton Cawston Norwich E.Dereham
Bure to Horstead	Woodgate House Cawston Cromer
Nar to Marham	Gayton E.Dereham

The amalgamation of these records (using the method outlined above) for the three catchments, produced thirty-year mean statistics as in Table 6.

Table 6. Thirty-year-mean areal rainfall for the catchments.

PERIOD	RAINFALL (mm)		
	Wensum	Bure	Nar
1931-60	677	677	678
1941-70	673	677	681
1951-80	678	668	694
1961-90	683	669	704

2.2. Seasonal rainfall (April-September and October-March).

It was necessary to check that annual rainfall analysis was not masking any seasonal rainfall trends. Precipitation losses to transpiration and evaporation have to be taken into account when looking at riverflow. Summer loss is usually high, thus winter precipitation is the main producer of riverflow.

Summer and winter gross rainfalls were calculated from the mean monthly gauge data for the Cromer, Browick Hall and Sandringham stations, these being the only gauges for which monthly data, for the whole period, were available. Thirty-year-mean values were again calculated, Table 7.

Table 7. Thirty-year-mean winter and summer rainfall statistics.

PERIOD	RAINFALL (mm)	
	Winter	Summer
1931-60	335	312
1941-70	332	325
1951-80	335	315
1961-90	333	317

3. Discussion and conclusions

3.1. Annual rainfall, thirty-year-means.

There is no evidence of a particular overall trend in the thirty year mean-annual-rainfall statistics produced. The individual catchments display marginal but contradictory trends and this is corroborated by the statistics produced by the averaging of the three non-weighted records, two of which are not used in the catchment average statistics and therefore give independent measures.

The comparison of UKMO statistics for the periods 1941-70, and 1961-90, for individual gauge records, impresses the contradictory nature of local trends for the period 1941 onwards, as Table 8 shows.

Table 8. The comparison of 1941-70 and 1961-90 mean annual rainfall values for individual gauges. (Data from Water Data Unit and NRA).

GAUGE	1941-70 Average	1961-90 Average
Browick Hall	637 (mm)	641 (mm)
Cawston	663	---
Cromer	631	634
East Dereham	676	---
Gayton	613	635
Norwich (208389)	---	609
Sandringham	709	683
Woodgate house	660	649

Clearly however, individual gauge records can have a disproportionately large bearing on catchment average statistics. This is particularly so where suitable records are few and one particular record, due to skewed areal gauge distribution, dominates the areal averaging process. For example, if the Sandringham gauge had been used for the Nar-to-Marham areal averaging process (see Table 6), the areal statistics may have shown a slight decrease, not the small increase in thirty-year-mean rainfall which derives primarily from the Gayton gauge recorded trend.

3.2. Annual rainfall, shorter term trends.

Annual mean rainfall is frequently expressed in terms of thirty-year-mean values to avoid undue influence from possible shorter term cyclical fluctuations of weather pattern. Shorter term fluctuations or trends which may be within the natural variability of an unchanged climatic regime can however, last for several years.

Figure A1 shows the annual and the five-year-running mean rainfall for the Wensum catchment for the period 1930-92. The five-year running mean plot suggests that the shorter term fluctuations in rainfall pattern have been pronounced since about 1965. The extent and duration of the drier periods in the early to mid 1970s was more than matched by the wetter spell that spanned the decade from 1977 to 1987. Annual rainfall declined dramatically between 1988 and 1991 and the 1970s dry period looks set to be surpassed in extremity and duration.

3.3. Seasonal rainfall.

Table 7 shows that, taken over a thirty year period, seasonal rainfall for the project area is essentially unchanged. Figure A2 shows the variation in annual rainfall for the Study area (based on the three peripheral gauge records, see Table 3) for the period 1930-92. Also plotted since 1961 (data began in 1961) are the annual effective precipitation totals for the same area, as supplied by the Meteorological Office Rainfall and Evaporation Calculation System, 'MORECS' (Meteorological Office, 1982). The close correlation between the two plots since 1961 shows that, since 1961 at least, effective and gross rainfall have fluctuated more of less together. This also indicates that there has not been any significant seasonal trend through time with respect to summer or winter rainfall patterns. In effect, summer and winter rainfall fluctuations do not diverge significantly from the annual trend.

3.4 Conclusion

There is no evidence of longer term change in gross rainfall distribution, on an annual or seasonal basis, for the Study area. The seasonal analysis suggests that effective rainfall, that which eventually becomes flow, is unchanged in the longer term. However, this assumes that the effects of catchment management and the inter-seasonal distribution of rainfall events and their intensity is unchanged. (For a full discussion, see Chapter 3). Unfortunately, comprehensive data relating to event distribution and intensity have not been available.

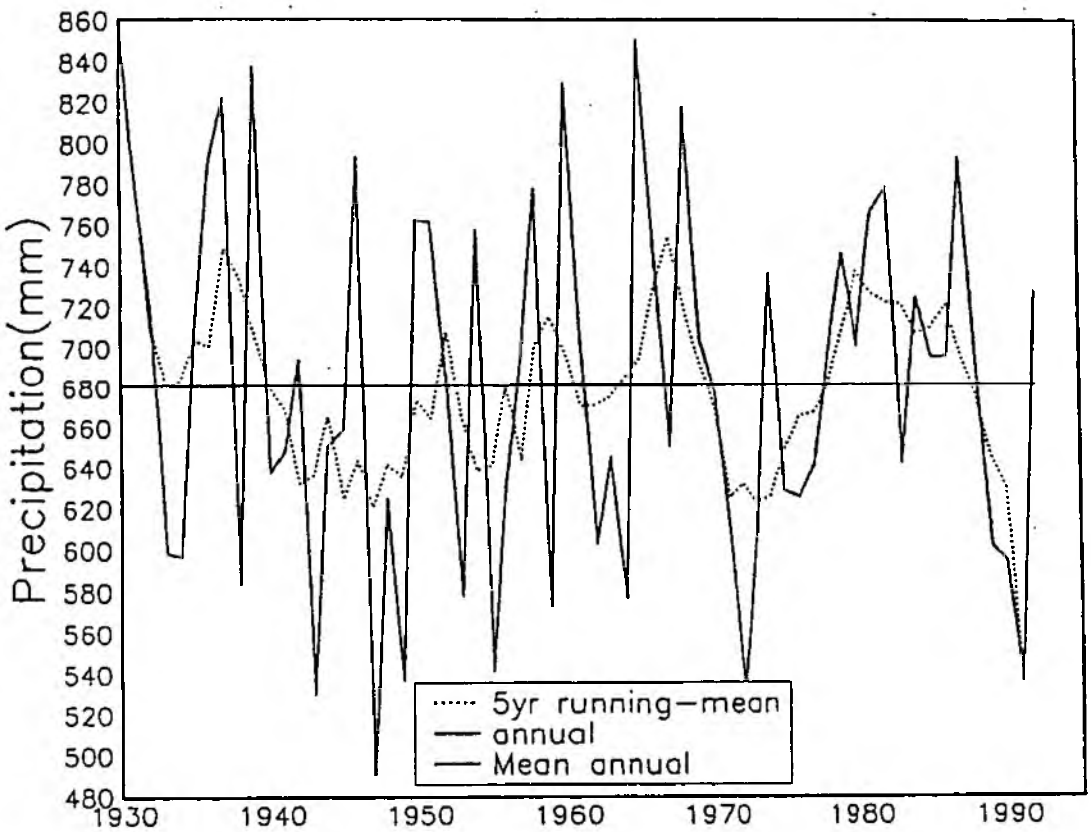


Figure A1 Annual rainfall analysis for the River Wensum above Costessey Mill, 1930 to 1992.

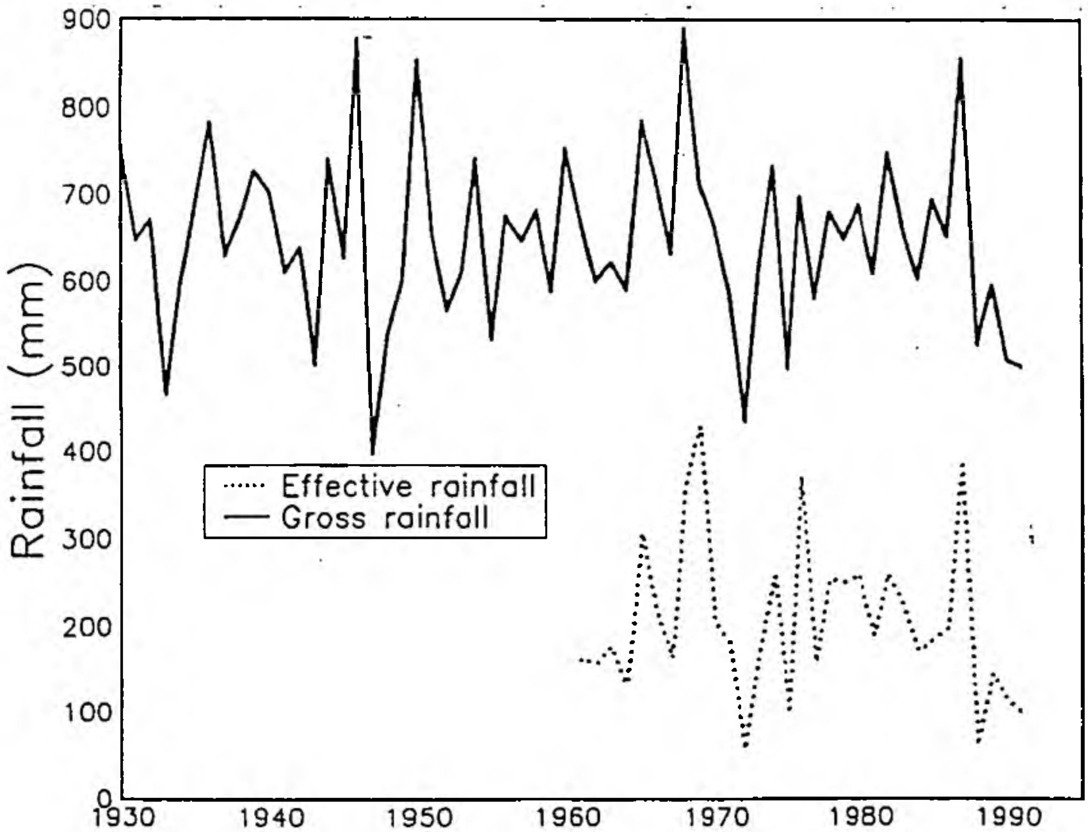


Figure A2 Gross and effective rainfall (water years) in the study area, 1961/2 to 1991/2.

APPENDIX 3. FLOW NATURALISATION USING GORM

1. Apportioning the effects of net abstractions

Introduction

Study area abstraction is from ground and surface sources, with the emphasis on ground. Discharges are made to surface and ground waters, with the emphasis on surface. Interference with either source affects surface flows, but with groundwater intervention the effects are less direct. The assessment of the effects of net abstraction on surface flow is, therefore, a complex process - one which invites the use of computerised modelling.

The choice of particular modelling approach for apportioning the effects of abstraction and discharge needs to be explained. The modelling process used, GORM (Great Ouse Resource Model), has required the production of detailed data sets relating to abstraction and discharge with time. Their methods of production have involved considerable research and require description.

The Great Ouse Resource Model (GORM), as developed by WRC and NRA (NRA, 1990), simulates river flows from their basic components of baseflow (aquifer discharge) and non-baseflow (overland flow plus through flow). Using simple conceptualised mechanisms for the calculation of these component net values, GORM has few input requirements and thus keeps work to a minimum. It is potentially an ideal tool, capable of apportioning the effects of historic abstractions and discharges if their values are known with reasonable accuracy.

Effective rainfall input of MORECS data is routed by GORM to surface flows via soil and aquifer conduit systems, having regard for aquifer storage states and net ground and surface water abstractions. Output is in the form of weekly mean flows. So long as actual soil and aquifer mechanisms are reasonably approximated, the model should apportion the effects of abstractions and discharges with reasonable accuracy.

A full naturalisation of gauged flows back to 1961 was sought, in line with the availability of MORECS and licensed abstraction data. The importance of the possible effects of abstraction on summer low flows gives the simulation of summer (baseflow dependent) flows the highest priority. The very high level of simplification used in the generation of the non baseflow component of flows by GORM, in catchments where baseflow dominates flow levels for much of the time, suggests that greater simulation error would be expected and indeed could be acceptable at higher flow levels.

Extensive model calibration exercises for all the Study catchments have been necessary to ensure that simulated historic flows have followed those observed - particularly during summer seasons. Whilst the apportioning of the effects of abstraction and discharge relies merely on the difference in flow output-series between natural (zero abstraction and discharge) and non-natural (actual abstractions and discharge) model runs (see 2.1, below), it is only meaningful if in-catchment processes are being simulated. Of particular importance here, as stated above, is the adequate simulation of the baseflow component of flow.

Methods

1.1 Input requirements and calibration of GORM

The primary data input files to GORM are those which determine for each reach:

- effective rainfall
- contributing area
- length of reach
- average split of rain input between base/non-base flow
- nature of soil cover and its hydraulic properties
- nature of the aquifer and its hydraulic properties
- net abstraction from ground water
- net abstraction from surface water

One of the stated reasons for using GORM was to minimise the work required to apportion the effects of abstractions and discharges. Whilst it is possible with GORM to split river systems down to short reaches, with the advantages from higher resolution, an attempt has been made to treat the Study catchments as single 'reach' entities. The provision of whole catchment-mean aquifer hydraulic properties by Toynton (1983) invited attempts to do this.

1.1.1 Effective rainfall input

With effective rainfall data referring to mean values as calculated for 40km * 40km grid squares in MORECS, variation due to areal rainfall, soil and geological differences within grid squares is to be expected. Effective rainfall has therefore been modified so that GORM has generated the correct mean flows for each catchment for the period 1971-1992.

Since MORECS data are only available back to 1961, this becomes a limitation to this means of historic enquiry. The model generates flows from 1961, but due to internal model workings, output is only produced from 1971. The fact that uncertainty with abstraction and discharge quantities increases rapidly back in time beyond the late 1960s, means that it would be pointless trying to go further back in time, even if effective rainfall data were available.

1.1.2 Contributing area and length of reach

The runoff contributing areas have been fixed to those of the catchment topographical divides. Since the whole catchments have been treated as having single aquifer units, the areal extent of aquifer units is similarly defined. The length of channel in a reach should reflect the length of main channel and tributaries which are in hydraulic contact with the aquifer. This is not known exactly and has therefore been subject to a degree of alteration during calibration.

Baseflow varies with: $1/L$
where L is the length between the river and aquifer/catchment boundary (see 1.1.5, below).

Length of reach is therefore an important factor in determining aquifer discharge since it determines the dimensions of the conceptualised aquifer units used in GORM and thus L.

1.1.3 Groundwater/non-groundwater split for effective rainfall

Here, a catchment average value related to the hydraulic infiltration routing of effective rainfall that reaches the aquifer and so becomes baseflow, has been used. Governed chiefly by the nature of soil cover, and type of land use, the proportion of effective rainfall that reaches the aquifer has great bearing on surface flow hydrology throughout the year. The determination of the catchment average value is therefore a crucial part of the calibration process.

During this part of calibration, guidance to the approximate values for the proportion of effective rainfall entering the aquifer system was obtained from Baseflow Index (BFI) (Institute of Hydrology, 1980) data.

1.1.4 The nature of catchment geography and its effects on overland flow and interflow

Again, catchment mean values have been used which evaluate the time lags for that part of effective precipitation which becomes runoff without entering the aquifer. That is, the component of effective rainfall which becomes surface runoff via overland and interflow routing.

Governed chiefly by the nature of soil cover, physical relief, and type of land use, mean catchment values were less easily quantified. However, values universally employed by WRC and NRA during GORM calibration work for the Great Ouse (NRA, 1990) have been used. GORM, in its simplified treatment of the hydraulic mechanisms involved, allows up to five weeks for this component of surface flow to reach the river channel.

1.1.5 Aquifer hydraulic properties

Having simplified river and associated groundwater systems down to single reach, single homogeneous aquifer units, one for each catchment, the use of GORM further simplifies aquifer mechanisms. By approximating to a rectangular shape, having area equivalent to the runoff contributing area of the reach, the discharge of aquifer units is given by (Oakes and Wilkinson, 1972):

discharge (baseflow) = 3.2 * Ta * storage

where Ta = T/(S * L2)

T=the transmissivity
S=the storage coefficient
L=the aquifer length from river to catchment boundary.

The value of T/S is thus the remaining 'unknown quantity', L being already defined by the reach length and contributing area dimensions.

The mean catchment values for T/S, as derived from values given by Toynton (1983), were used as starting values during GORM calibration work.

1.1.6 Net abstraction input files

These were compiled directly from abstraction and discharge data and produced in the form required by GORM. Net groundwater abstractions are derived as total catchment/sub-catchment abstraction less groundwater discharges. Similarly, net surface abstractions are derived as total surface abstraction less total surface discharges. In the latter case, net abstractions are frequently negative, discharges being greater than abstractions.

The methods used in the preparation of abstraction and discharge series, the basics of net-abstraction input files, require some description (see next section).

1.2 The production of abstraction and discharge data series

The use of GORM requires that both net surface and groundwater abstraction series list monthly values from 1961. (Although predicted flows are not programmed to appear as output before 1971, the aquifer storage has to be approximated in advance to produce a realistic baseflow component of flow from 1971). Licensing under the 1963 Act (see Chapter 3:2.) did not take full effect until around 1968. This means that, with the exception of abstraction data given for a limited number of uses (essentially non-agricultural) by the Ministry of Housing and Local Government surveys published in 1960 and 1963, assessments have been necessary for agricultural use purposes for 1961-68.

The assessment has to be done, initially, on an annual basis. (This can then be apportioned seasonally where appropriate, see below). The method used for spray irrigation use was based on 1968 licence data and information as to the local uptake of spray irrigation practice since 1960. This information was from the East Suffolk and Norfolk River Authority annual report of 1971. For general agricultural use, the 1968 licensed totals have been carried back in time. For the other use purposes, that is those quantified by the Ministry surveys, linear interpolation between 1961 and 1968 abstraction values has been used to complete the annual abstraction series.

A substantial proportion of abstractions show at least some degree of seasonal fluctuation. Also, GORM requires the production of net monthly abstraction series. The availability of appropriate monthly abstraction data or the means to assess them is therefore required (see below).

In the case of discharges, the degree of uncertainty with their estimation on an annual basis permits no more than their equal distribution between all months of the year. Annual abstraction values for use-categories which do not display seasonal fluctuation can also be distributed equally between all months of the year. Net abstraction series are comprised of monthly abstractions less monthly discharges for ground and surface sources.

1.3 Abstraction for use categories having seasonal trends

1.3.1 Spray irrigation

Whilst abstractors are obliged to provide monthly breakdowns of annual quantities used, the extensive, often incomplete and sometimes confusing nature of the information given, makes the production of long time series a difficult task. However, considerable river authority annual-summary data, relating to resource use within hydrometric area 34, have been located (NRA unpublished data). These data are the basis of a viable means to produce monthly abstraction series data.

Annual uptake of licensed total has, since 1968, been calculated by the River Authorities for hydrometric area 34. Uptake (total abstracted quantity)/(total licensed quantity), expressed in percentage terms, is a useful statistic for the provision of specific catchment annual use. Thus, assuming relatively uniform seasonal irrigation requirement across the Study area for any one year, knowledge of catchment annual-licensed total and the areal uptake value for the same year becomes the basis of the production of catchment specific annual abstraction series.

Growing season (April to September) monthly use factors based on a study of monthly abstraction data, which were summarised for eleven years by the River Authority, have been produced. These factors which apportion the annual uptake on a fixed monthly percentage basis for the growing season, have allowed the production of monthly abstraction data for each catchment for the period of inquiry. This has been done for surface and groundwater abstraction for spray irrigation.

The inaccuracies introduced with the use of common monthly factors by the assumption that, in all years, growing season monthly demand is a fixed proportion of the whole seasonal demand, appear not to be large. When seen against the potential fluctuation in whole seasonal irrigation requirement, there is a much greater need for accuracy with this aspect of the production of monthly abstraction series.

1.3.2 Public water supply

As with spray irrigation, statistics relating to monthly use in hydrometric area 34 have been located for a period of several years (NRA unpublished data). These were the basis for the production of monthly use factors which apportion total annual abstraction in percentage terms, between the months of the year. In the case of PWS, where abstractors are few, it has been possible to sum licensed abstraction return data to produce accurate annual abstraction totals for each catchment.

The subsequent production of monthly abstraction series for the period of enquiry has been relatively straightforward. In ranging between 7% and 10% of annual total, the monthly factors do not vary greatly. Any error through the use of common monthly factors for all years will therefore be small.

1.4 Abstraction for use-categories not showing seasonal trends

The main use categories involved here are those for: industry; sand and gravel working; and general agriculture. Annual summary statistics for hydrometric area 34 have been closely examined before the extraction of annual abstraction data. (In the case of most general-agricultural licences, no abstraction returns have been required by the river authorities. Annual licensed quantities are assumed to be half utilised in all years with ninety percent return, half to groundwater and half to surface waters).

The annual total abstraction data were divided equally between all months of the year, towards the production of monthly abstraction series for each use category for each catchment. None of these non-seasonal use categories is significant in the Nar catchment to Marham. The paucity of abstraction returns data for hydrometric area 33 did not therefore, pose any real obstacle to the production of credible monthly abstraction series for all Study catchments.

1.5 Discharges

1.5.1 PWS discharges

Discharges which enter surface waters via sewage treatment networks are notoriously difficult to quantify in the absence of measured discharge flow data. The method of producing monthly time series for STW discharges has relied on the use of some recent flow data from Anglian Water, discharge consent DWF data from the NRA and parish population census data relating to the catchments of STWs from Anglian Water and Norfolk County Council.

Ideally, STW discharge flow data for 'dry periods' are required, particularly for the larger 'town' sized STWs, for the period of enquiry. Urban sewage works tend to carry storm discharges from storm drainage networks. These can be substantial but are not related to any abstraction, and therefore form part of the non-baseflow component of river flows.

Daily discharge flow data from the larger STWs have been obtained for early 1990s summer periods having high soil moisture deficits. These data should represent PWS abstraction related discharges and thus be the basis of annual estimates. For the smaller, more rural sewage networks which tend not to carry storm discharges, discharge in recent times, has been taken to be equal to DWF consents. These values are based substantially upon their catchment population numbers and average per-capita consumption/discharge data. The sum of catchment discharges, gauged and/or estimated, forms the end point for discharge data series production.

The starting point for the catchment discharge series was taken as the (catchment) sum of STW discharges as reported for 1961 in the Ministry of Housing and Local Government reports of 1960 and 1963. Intermediate points, for the discharge series, representing 1971 and 1981 (to coincide with available population census data) were based on population change and per-capita consumption/discharge estimates with time. In effect, discharge at 1971 and 1981 was taken to be:

(recent gauged value)*(% population change)*R/100

where R = (population discharge estimate 1971 or 1981)/(discharge estimate 1991)

The per-capita consumption/discharge estimates used for discharge series are given in Table 1.

Table 1 Estimated per-capita discharge data, 1971, 1981, and 1991 in the Study area.

PER-CAPITA CONSUMPTION (litres/day)	YEAR
128	1971
139	1981
156	1991

(Data from NRA, 1993).

Catchment discharge series were completed by linear interpolation between the estimated values for 1961, 1971, 1981, and 1991. To obtain monthly series, annual series were divided equally between months.

1.5.2 Non-PWS discharges

For most other abstraction use which has produced significant discharge within the Study area, records of approximate amounts and the consumptive loss have been located. Study area annual totals for discharge, calculated from areal-mean consumptive loss and annual abstraction totals were then divided equally between months in the year. The only exception here was that of abstraction for general agricultural use. Here, it is assumed that half of the discharge produced (uptake being fifty percent of licensed quantity, return being ninety percent of abstraction) is returned to groundwater, half to surface waters.

In the knowledge that surface abstraction (with the exception of that for PWS) use-categories which produce discharges are small, it has been assumed that a near-by, virtually equivalent discharge will be made which has negligible net effect on flow.

1.6 The production and testing of GORM calibration output

Calibration parameters have been varied systematically in order to produce the best fit between predicted and observed flows for all Study catchments. For reasons discussed earlier, the simulation of summer baseflow-dependent flows takes priority.

Measured values (for example, T/S as given by Toynton) or suggested values (for example, BFI values for the proportion of effective rainfall becoming baseflow) were first used in GORM calibration runs. Systematic variation of parameters was then undertaken until the 'best fit' was achieved.

Analysis to determine 'best fit' can be done in different ways, ideally it emphasises the fit between predicted and observed summer flows. The testing for fit has taken the following forms:

- Sum of squares of (predicted-observed) all flows
- Sum of squares of (pred.-obs.) flows < obs. mean flow
- Percentage of time pred. flow=obs. flow +/- 20%
- Average difference between pred. and obs. flows as % of mean flow
- % difference between pred. & obs. Q95 & Q50 flows

Table 2 summarises the testing for fit for all the Study catchments.

Table 2 The statistics of 'fit' for the best GORM calibration run for each catchment

	WENSUM	BURE (#)	NAR
Catchment area (km^2)	536	313	153
Mean flow observed (cumecs)	3.99	2.15	1.13
Mean flow predicted (cumecs)	3.99	2.15	1.13
% of time that predicted = observed flow ± 20%	50	62	69
Average difference between predicted and observed flow as % of mean flow (*)	37	32	21
% difference between and observed -- Q95	+1.5	+3.0	-9.5
-- Q50	-1.0	-11.0	+3.0

notes for Table 2:

(#) observed flows only available since Feb. 1974. Comparison between observed and predicted therefore relates to a slightly different period to that for the other catchments.

(*) calculated as the square root of: sum of squares of (obs.-pred. flows) divided by the number of observations.

2. GORM modelling of historic flows

Results

Reference to Figures A3 to A5, the time series plots of observed and predicted seven-day-mean flows for the Study catchments, shows reasonable simulation by GORM. As may have been expected, the larger the catchment area, the greater the predictive errors brought about by the simplification down to single reach, single aquifer units (see Table 2).

The quite close relationship between observed and predicted flows during summer periods, as shown by Figures A3 to A5, is corroborated by reference to the Q95 flow duration statistics in Table 2. This permits the use of GORM to naturalise historic flows and in doing so, to apportion the effects of abstractions and discharges.

2.1 Naturalisation of flow

Having obtained optimum calibration parameter settings for each catchment, it is a straight forward operation to re-run GORM with all net abstractions at zero. The arithmetic difference between GORM flow output series for historic-net- abstraction, and historic-'nil-abstraction-and-discharge' conditions becomes the series of the net effects of abstractions and discharges.

The net effects can then be added to the series of historic observed flows and thus produce a series of 'natural' flows. The possible errors due to model short-comings (derived from inaccurate flow prediction) are greatly reduced by this technique as predictive output is only being used indirectly to apportion the magnitude and timing of the effects of net abstractions.

Net effects can be described by various methods and these include:

- Summary statistics to express effect on flow
- Time series plots showing effects in percentage terms
- Time series plots showing effects in actual terms
- Flow duration plots which compare observed and natural flows

The results and conclusions of the historic naturalisation exercise for each Study catchment, using the above listed means of illustration, can be found in Chapter 4:1. This has been taken one step further by the addition of different theoretical uptake and abstraction-source scenarios so as to guide future resource use.

Note:

Since 1987, the large surface abstraction for PWS upstream of Costessey Mill has been capable of removing about 0.6 to 0.7 cumecs from above the gauge. If these post-1987 values had been fed through GORM, there would have been a very large increase since 1987 in 'loss to flow' and related statistics. This effect, whilst real, would have shown alarming increases in losses to flow because returns are made below Norwich at Whittlingham STW and thus outside the study area. The effect of the abstraction is only for a short length of the River (from Costessey to Heigham works) and is only since 1987. To be consistent with the period before 1987 and thus give fair comparison over the whole period, observed flows were adjusted as if the abstraction were downstream of the gauge. Similarly, the PWS abstraction just upstream of Marham gauge, which has been *in situ* for many years, has been treated in the same way. Abstracted amounts are however, intermittent and at 0.05 cumecs, very small.

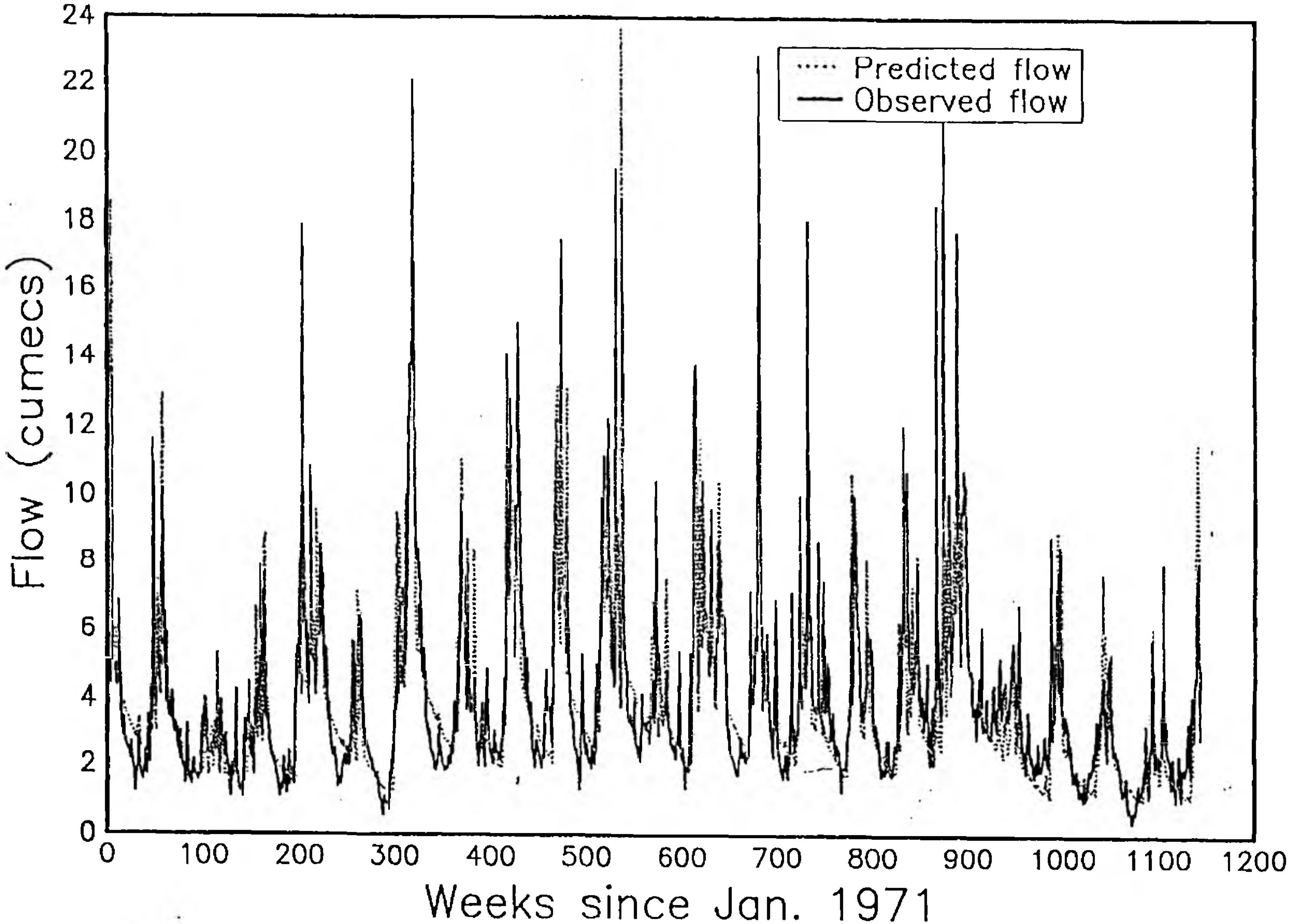


Figure A3 Predicted and observed 7-day-mean flows of the Wensum above Costessey between 1971 and 1992.

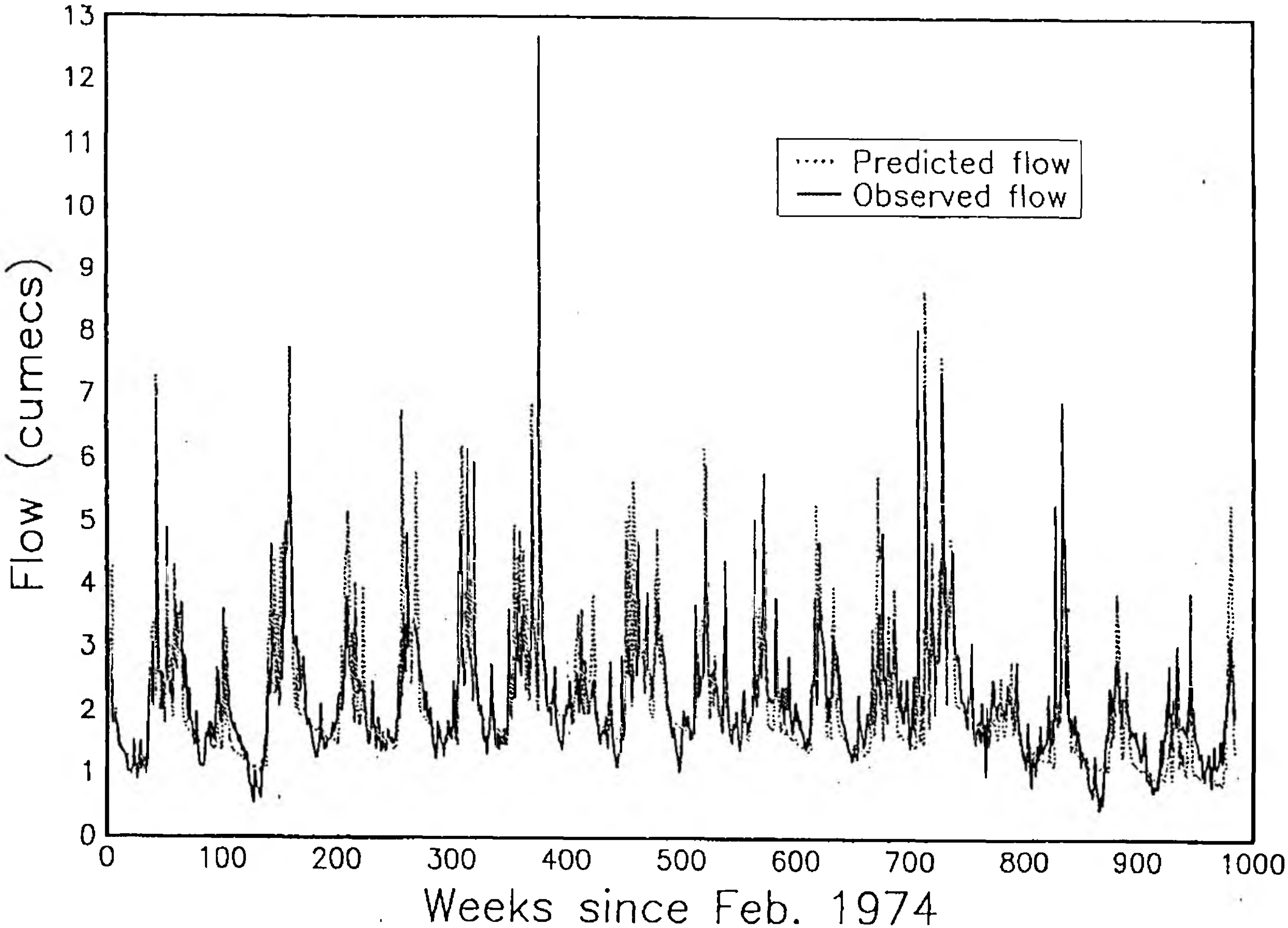


Figure A4 Predicted and observed 7-day-mean flows of the Bure above Horstead between 1974 and 1992.

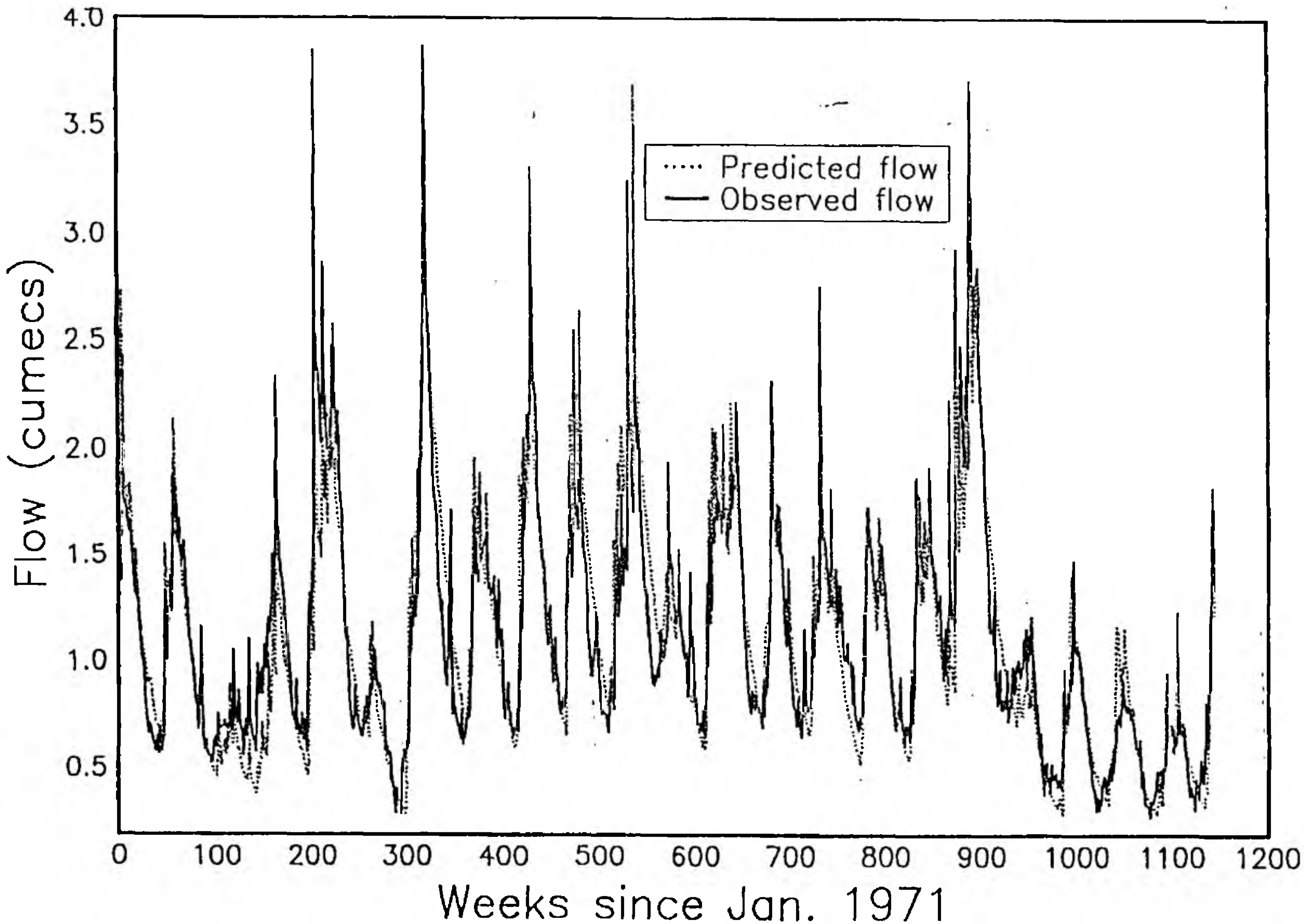


Figure A5 Predicted and observed 7-day-mean flows of the Nar above Marham between 1971 and 1992.

APPENDIX 4. EXPLANATION OF TERMS REFERRED TO IN FOOTNOTES

Page 13. National Water Council river classes.

Criteria set by the National Water Council and used to classify river quality. Based upon Table 5.5 in *Ecology of Fresh Waters* by B.Moss, Blackwells, 1988.

NWC Class	Dissolved oxygen (mgl-1)	Biological oxygen demand (mgl-1)	Ammonia (mgl-1)	Observations:
1A	⩾80	⩽3	⩽0.4	Trout fishery, high amenity value.
1B	⩾60	⩽5	⩽0.9	Trout or coarse fishery and moderate flow.
2	⩾40	⩽9		Coarse fishery, slow flow, probably silty.
3	⩾10	⩽17		Fish may be absent, water polluted.
4	may be anaerobic			Highly polluted water.

Page 18. Fisheries status.

Working definitions of fishery status.

	Average biomass including all fish species present
Class A	> 20 gm-2
Class B	11 - 20 gm-2
Class C	5 - 10 gm-2
Class D	< 5 gm-2

Page 19 and Figure 28. Latin names of water plants.

Common names of water plants. Taken from *the Collins Guide to Freshwater Life* by R.Fitter and R.Manuel, Collins, 1986.

Latin name	a common name
Ranunculus species	belong to the Water crowfoot family
Callitriche species	are from the Water starwort family
Elodea canadensis	Canadian waterweed
Fontinalis antipyretica	Willow moss
Potomogeton on species	from the pondweed family
Nuphar lutea	Yellow water-lily
Myriophyllum spicatum	Water milfoil
Lemna species	from the Duckweed family
Hippuris vulgaris	Marestail
Zannichellia palustris	Horned pondweed
Enteromorpha	a genus of filamentous green algae

Plants are listed in approximate order of increasing tolerance to slow-flowing and silty habitats although there is much variation within the Pondweeds and, to some extent, within some of the other groups.

Page 65 and Figure 32.
Notes on the ecology of invertebrates used as habitat indicators.

Simuliidae (the larvae of blackfly) are especially characteristic of faster flowing waters where they attach to stones or sometimes plants anchored when moving by a silk thread. They are a food much-favoured by fish. Simulids are contrasted with the abundance of **Chironomids** (the larvae are called 'bloodworms'), which are a large group gnats and midges typical of oxygen-depleted organic sediments.

Members of the family **Gammaridae** (freshwater shrimps) are typical of clean flowing waters, plants and stony or sandy substrata. **Ascellus** (water slaters) are also crustaceans, though with woodlouse-like bodies. Ascellus are more likely than Gammarus to occur in slower-flowing water with an accumulation of plant debris.

Hydropsyche (net-spinning caddis flies, an important prey for fish) are usually found in fast-flowing water whereas **Haliplidae** larvae (beetles) are often found in slack flow amongst filamentous algae.

Ephemerella ignita (a mayfly, the blue-winged olive) scores very highly on the BMWP scale and is usually found in fast-flowing water. Members of the family **Coenagrionidae** (damselflies) occur in still or slow-flowing water.

Tubificids (sludge worms) are often numerous in very organic sediments, particularly where contaminated by sewage. Tubificids have the lowest score of 1 out of 10 on the BMWP scale.

Page 64 in Table 3.10 which shows the results of TWINSPAN analysis

Common names of families of invertebrates. Taken from *the Collins Guide to Freshwater Life* by R.Fitter and R.Manuel, Collins, 1986.

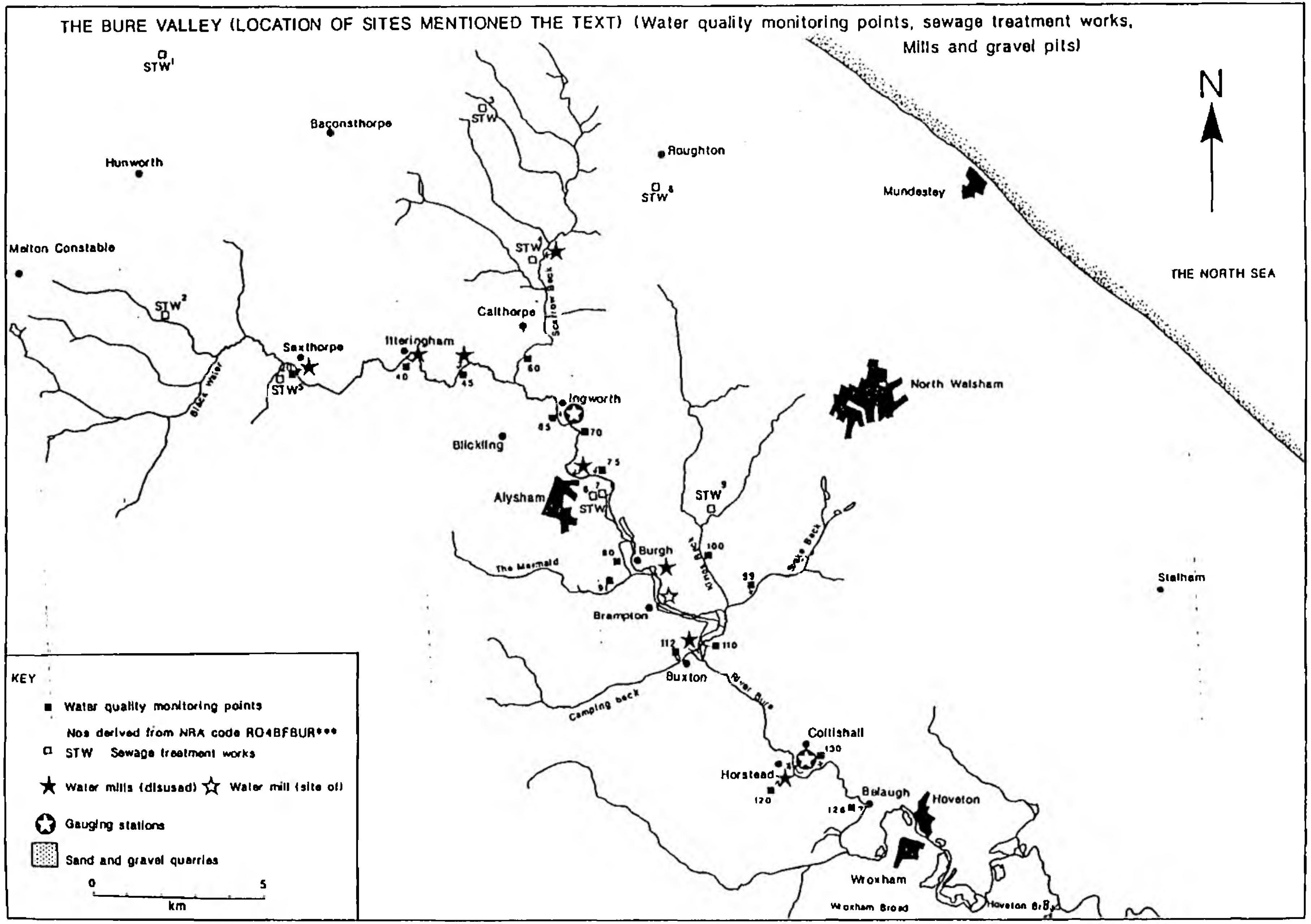
Community 1: animals are most likely to use fast-flowing, silt-free habitats

Hydropsychidae (5)	A family of net-spinning caddisflies
Rhyacophilae (7)	Caddis fly larvae which attach a silk case to gravel
Ecdyonuridae (7)	Mayflies with nymphs which cling to stones
Ancylidae (6)	River limpets which attach to gravel
Tipulidae (5)	Daddy-long-legs, a family of two-winged flies
Simuliidae (5)	Black fly larvae, the adult females bite
Leuctridae (10)	Willowflies which have two 'tails', a type of stonefly
Polycentropidae (7)	Caddis fly larvae with cases made from local debris
Leptoceridae (10)	a family of caddisflies

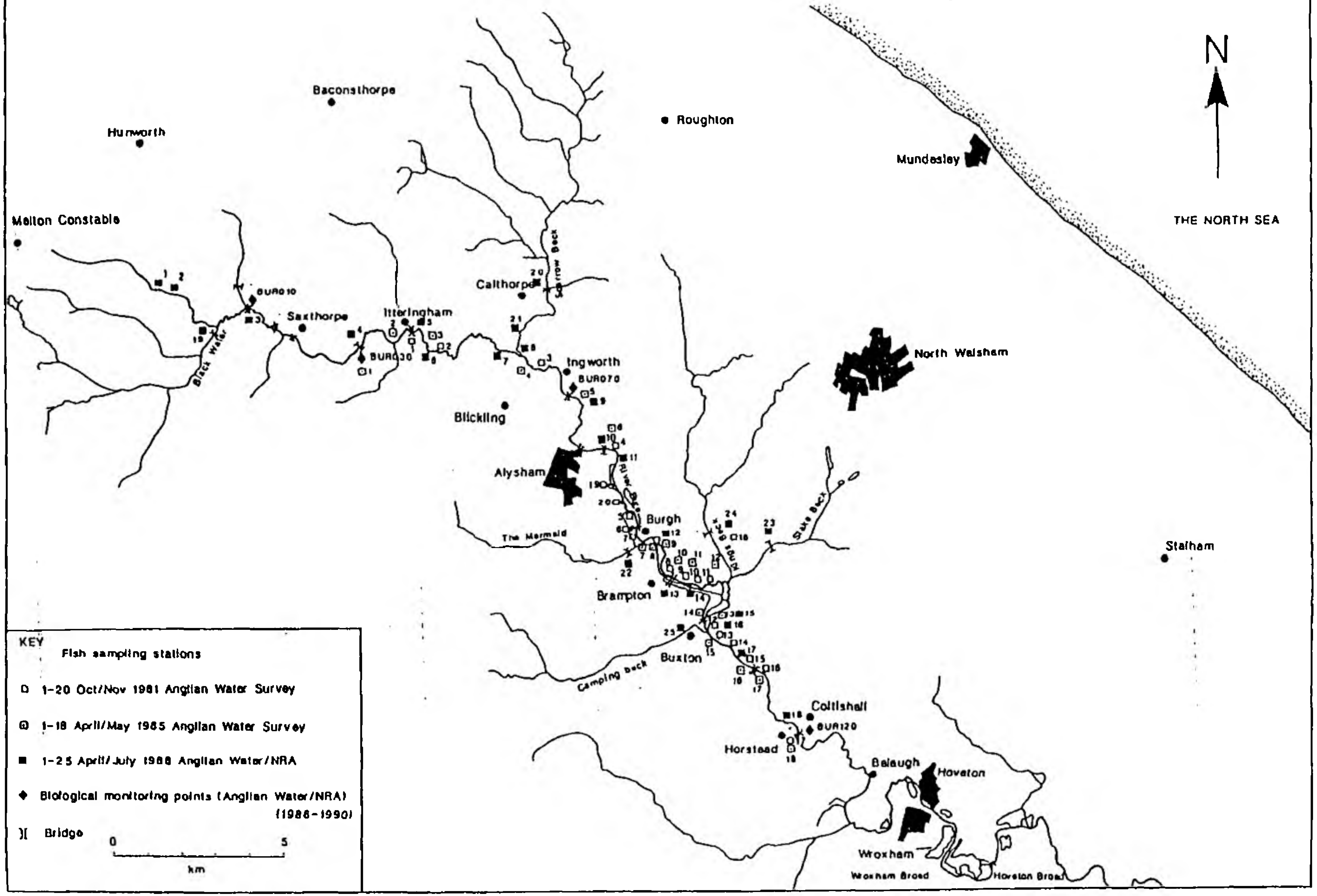
Community 2. animals more typical of slower-flowing and silty habitats

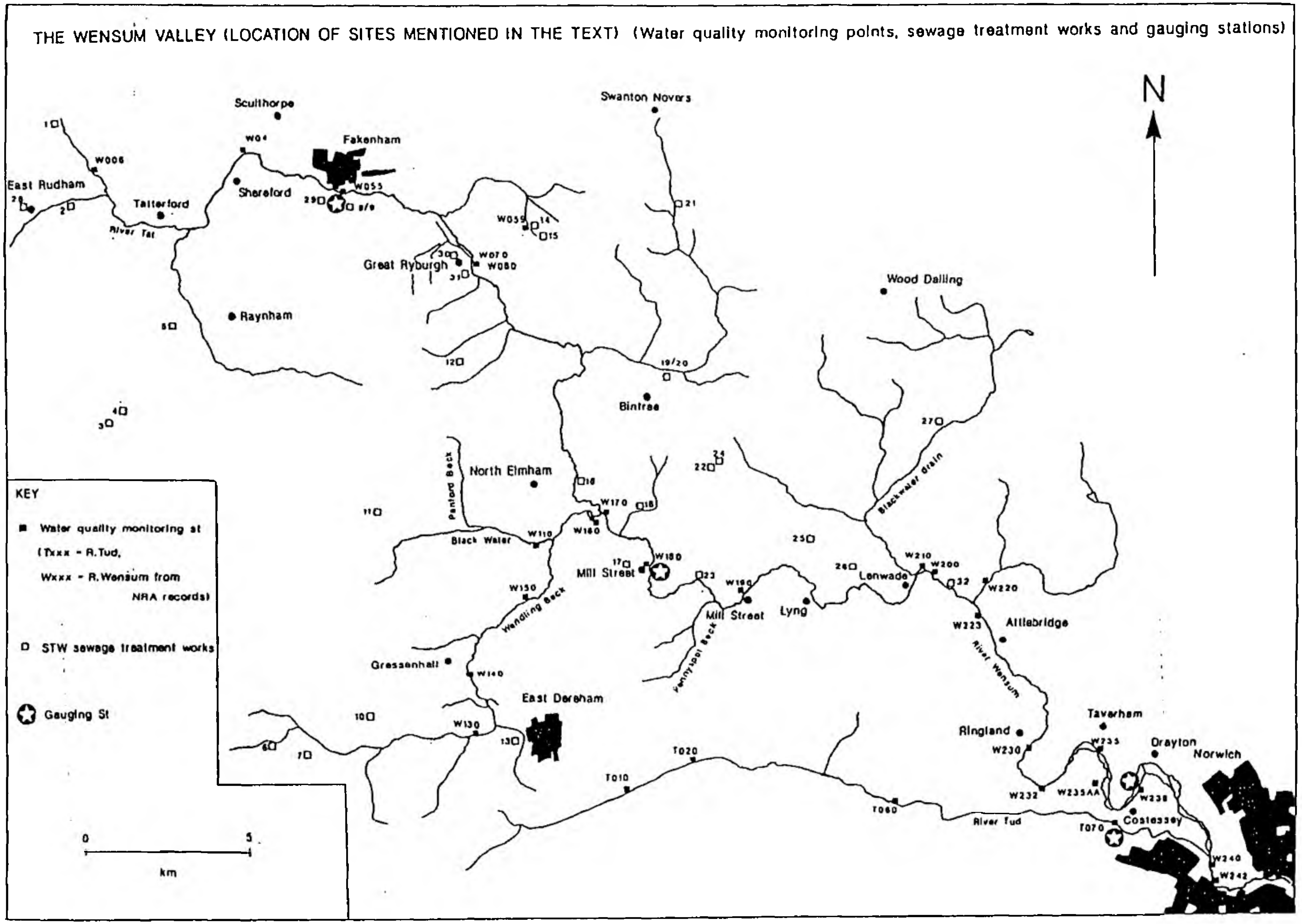
Coenagriidae (6)	A family of damselflies
Lymnaeidae (3)	Pond snails which usually have fairly thick shells
Neritidae (6)	another family of usually small snails
Physidae (3)	Small delicate 'bladder snails'
Valvatidae (3)	Small snails with flat shells
Ascellidae (3)	Water slaters, these are related to woodlice
Planaridae (5)	Flatworms, usually less than 5mm long and carnivorous

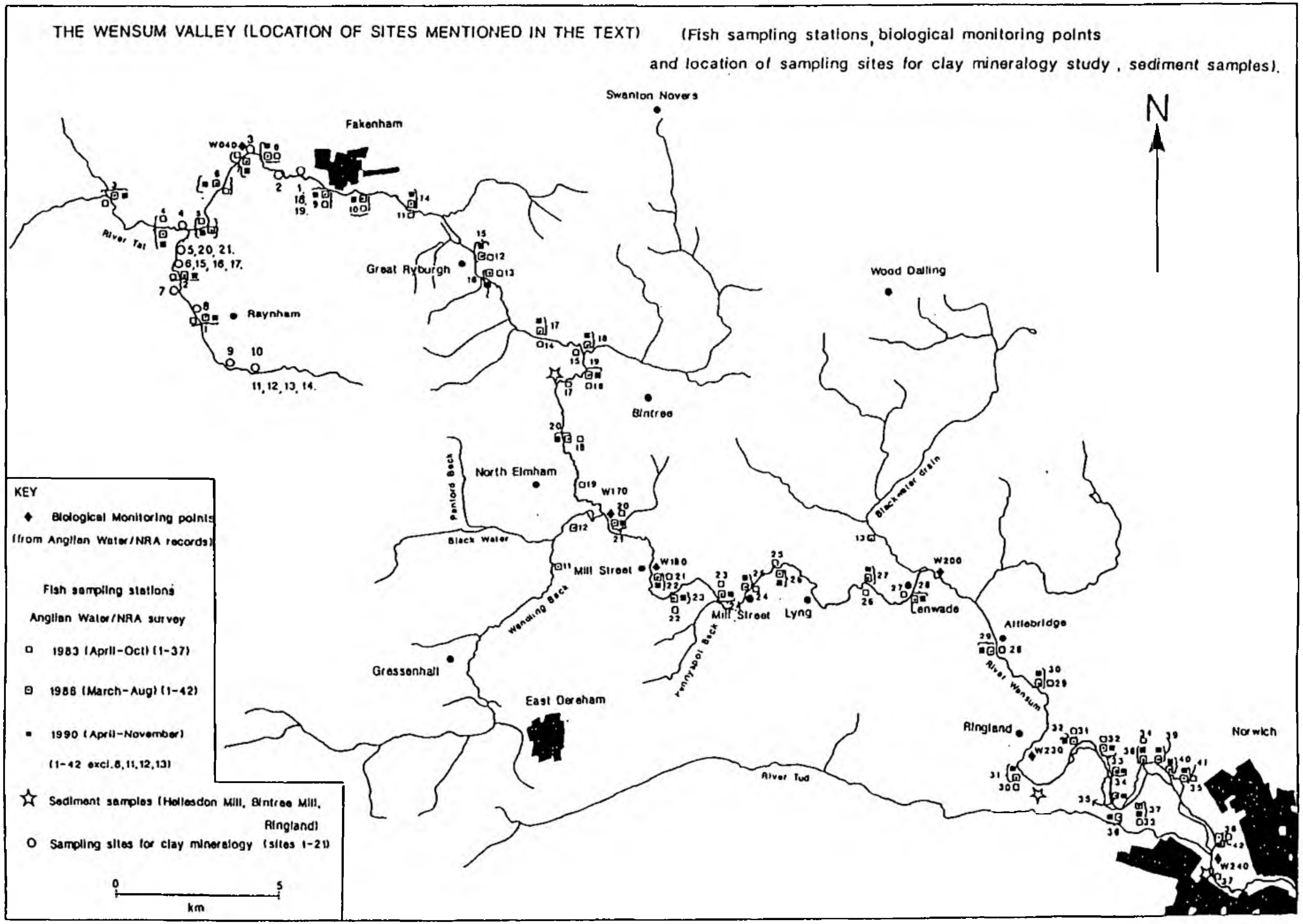
BMWP scores on the scale of 1-10 are shown in brackets.

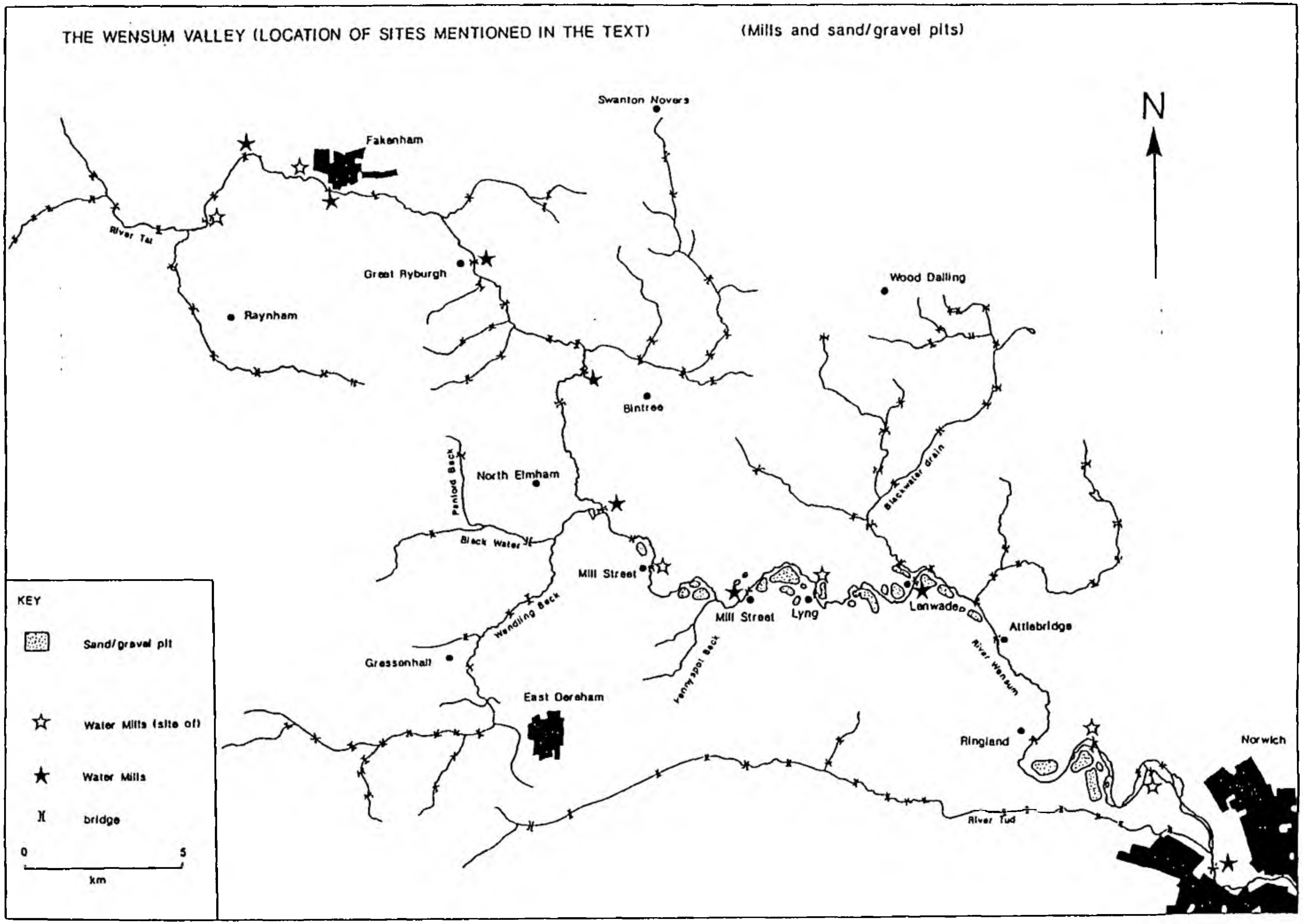

THE BURE VALLEY (LOCATION OF SITES MENTIONED THE TEXT) (Water quality monitoring points, sewage treatment works, Mills and gravel pits)
N
THE NORTH SEA
STW
Baconsthorpe
Hunworth
Roughton
Mundesley
Melton Constable
Calthorpe
Saxthorpe
Itteringham
Ingworth
North Walsham
Blickling
Alysham
Burgh
The Mermaid
Brampton
Stalham
Buxton
Camping beck
River Bure
Coltishall
Horstead
Belaugh
Hoveton
Wroxham
Wroxham Broad
Hoveton Gt B
Scarrow Beck
Blick Water
Kings Beck
Spike Beck
KEY
Water quality monitoring points
Nos derived from NRA code RO4BFBUR***
STW Sewage treatment works
Water mills (disused)
Water mill (site of)
Gauging stations
Sand and gravel quarries
0
5
km

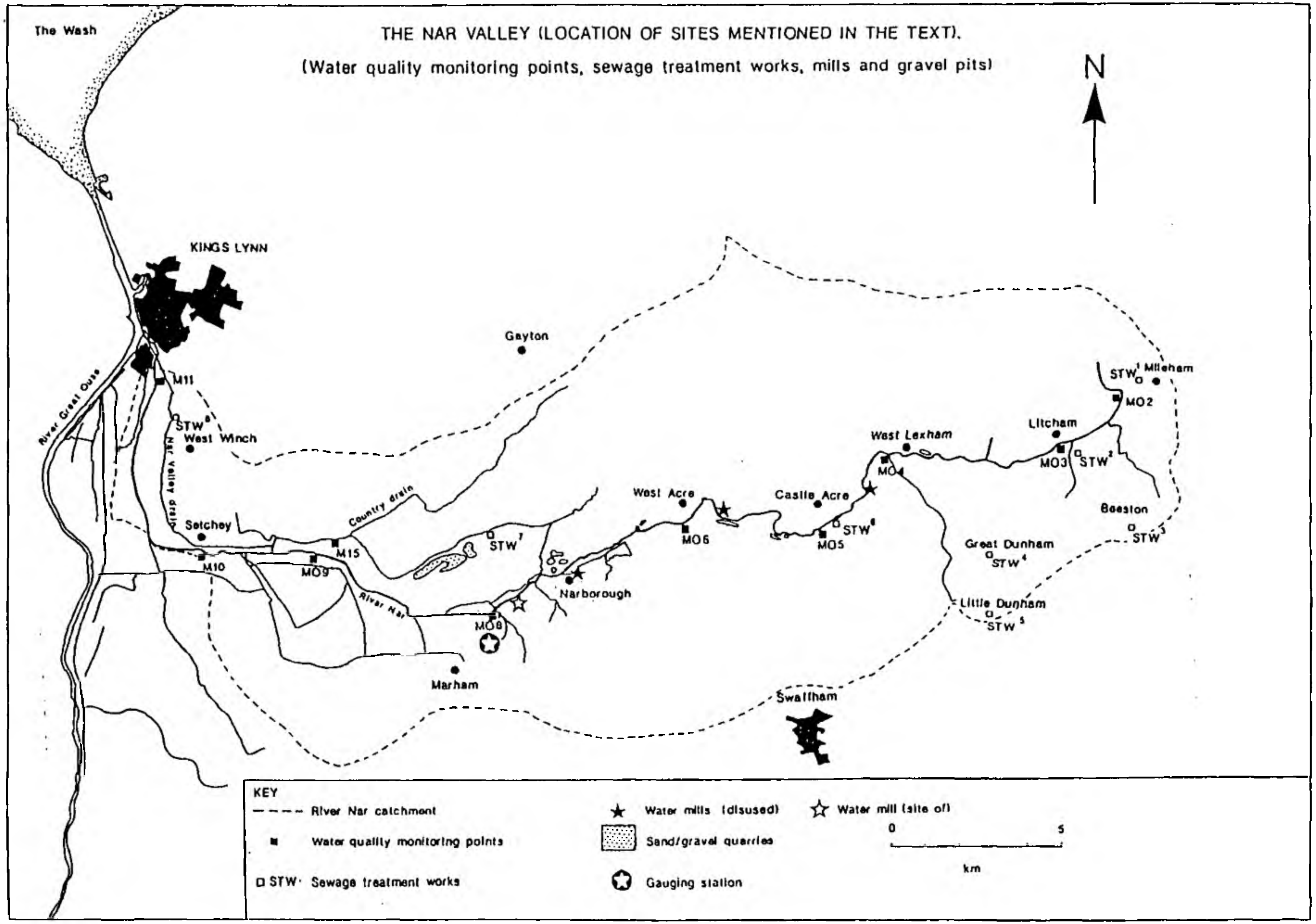
THE BURE VALLEY (LOCATION OF SITES MENTIONED IN THE TEXT) (Fish sampling stations, biological monitoring points).

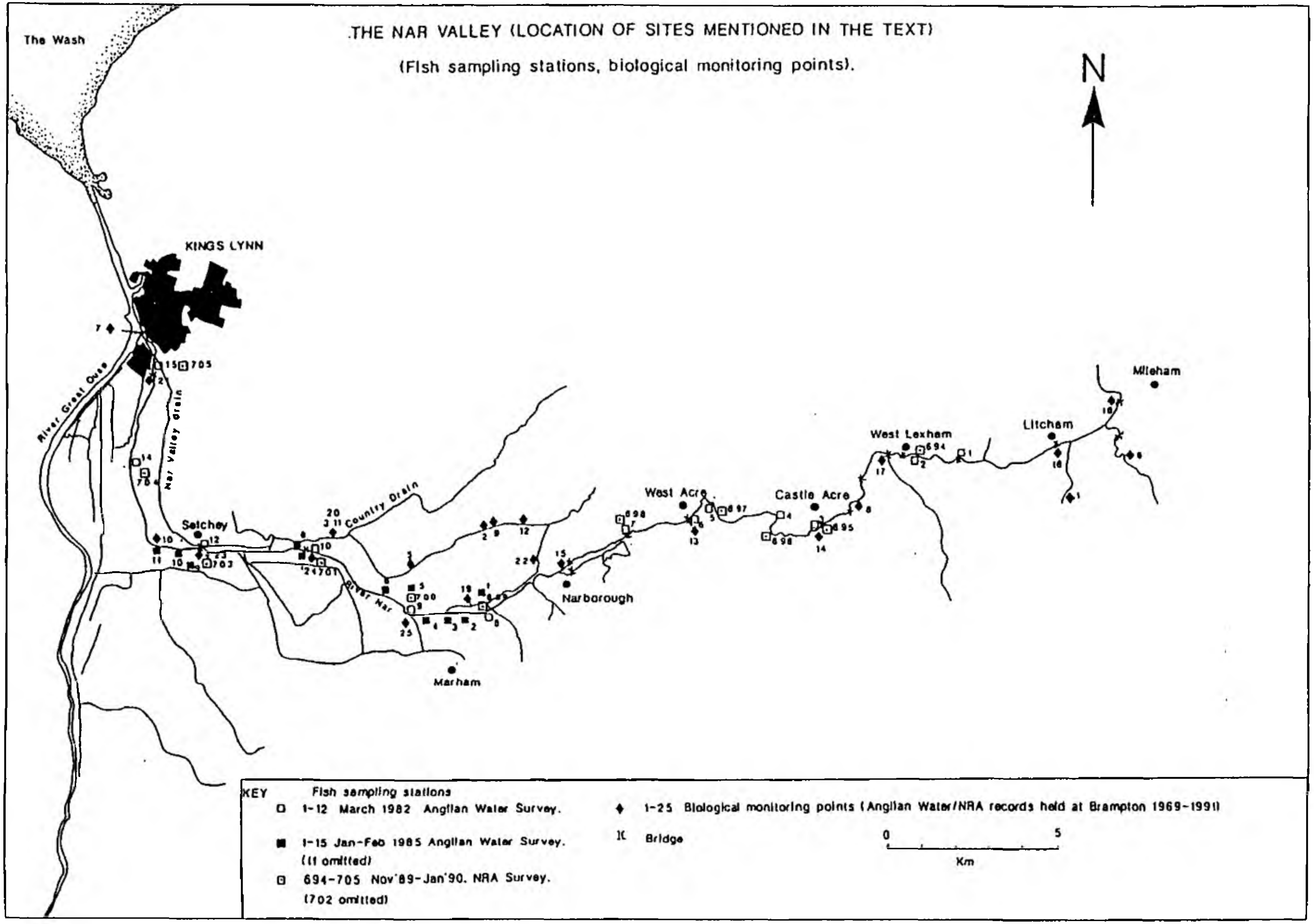



THE WENSUM VALLEY (LOCATION OF SITES MENTIONED IN THE TEXT) (Water quality monitoring points, sewage treatment works and gauging stations)
N
KEY
Water quality monitoring st
(Txxx - R.Tud,
Wxxx - R.Wensum from
NRA records)
STW sewage treatment works
Gauging St
0
5
km
Sculthorpe
Fakenham
Swanton Novers
East Rudham
Tatterford
Shereford
River Tat
Great Ryburgh
Raynham
Wood Dalling
Bintree
North Elmham
Pentford Beck
Black Water
Mill Street
Wendling Beck
Gressenhall
East Dereham
Blackwater drain
Lenwade
Lyng
Attlebridge
River Wensum
Ringland
Taverham
Drayton
Norwich
Costessey
River Tud
Penny Spot Beck


THE WENSUM VALLEY (LOCATION OF SITES MENTIONED IN THE TEXT)
(Fish sampling stations, biological monitoring points
and location of sampling sites for clay mineralogy study, sediment samples).
N
Swanton Novers
Fakenham
Great Ryburgh
Raynham
River Tat
Wood Dalling
Bintree
North Elmham
Pensford Beck
Black Water
Blackwater drain
Mill Street
Wendling Beck
Lyng
Lenwade
Attlebridge
Gressenhall
East Dereham
River Wensum
Ringland
River Tud
Norwich
W040
W170
W180
W200
W230
W240
KEY
Biological Monitoring points (from Anglian Water/NRA records)
Fish sampling stations
Anglian Water/NRA survey
1983 (April-Oct) (1-37)
1988 (March-Aug) (1-42)
1990 (April-November) (1-42 excl.8,11,12,13)
Sediment samples (Hellesdon Mill, Bintree Mill, Ringland)
Sampling sites for clay mineralogy (sites 1-21)
0
5
km


THE WENSUM VALLEY (LOCATION OF SITES MENTIONED IN THE TEXT)
(Mills and sand/gravel pits)
N
Swanton Novers
Fakenham
River Tat
Great Ryburgh
Raynham
Wood Dalling
Bintree
North Elmham
Penford Beck
Black Water
Blackwater drain
Mill Street
Mill Street
Lyng
Lenwade
Attlebridge
Wendling Beck
Gressenhall
East Dereham
River Wensum
Ringland
Norwich
River Tud
KEY
Sand/gravel pit
Water Mills (site of)
Water Mills
bridge
0
5
km


THE NAR VALLEY (LOCATION OF SITES MENTIONED IN THE TEXT).
(Water quality monitoring points, sewage treatment works, mills and gravel pits)
N
The Wash
KINGS LYNN
Gayton
River Great Ouse
M11
STW8
West Winch
Nar Valley drain
Setchey
M10
Country drain
M15
MO9
River Nar
STW7
MO8
Marham
Narborough
West Acre
MO6
Castle Acre
MO5
STW6
West Lexham
MO4
Litcham
MO3
STW2
STW1
Mileham
MO2
Beeston
STW3
Great Dunham
STW4
Little Dunham
STW5
Swaffham
KEY
River Nar catchment
Water quality monitoring points
STW Sewage treatment works
Water mills (disused)
Sand/gravel quarries
Gauging station
Water mill (site of)
0
5
km


THE NAR VALLEY (LOCATION OF SITES MENTIONED IN THE TEXT)
(Fish sampling stations, biological monitoring points).
N
The Wash
KINGS LYNN
River Great Ouse
Nar Valley Drain
Setchey
Country Drain
River Nar
Marham
Narborough
West Acre
Castle Acre
West Lexham
Litcham
Mileham
KEY
Fish sampling stations
1-12 March 1982 Anglian Water Survey.
1-15 Jan-Feb 1985 Anglian Water Survey. (11 omitted)
694-705 Nov'89-Jan'90. NRA Survey. (702 omitted)
1-25 Biological monitoring points (Anglian Water/NRA records held at Brampton 1969-1991)
Bridge
0
5
Km