River Wissey Investigations: Linking Hydrology and Ecology

March 1994

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This research was commissioned to investigate the influence of flows on the distribution of fauna in the River Wissey. The report should be used by those seeking to determine preliminary and comprehensive descriptions and classifications and to establish the relationships between biota and river flows.

A further phase is currently being undertaken to demonstrate the transferability of this assessment method to other rivers and further develop the assessment of the sensitivity of species to hydrological stress.

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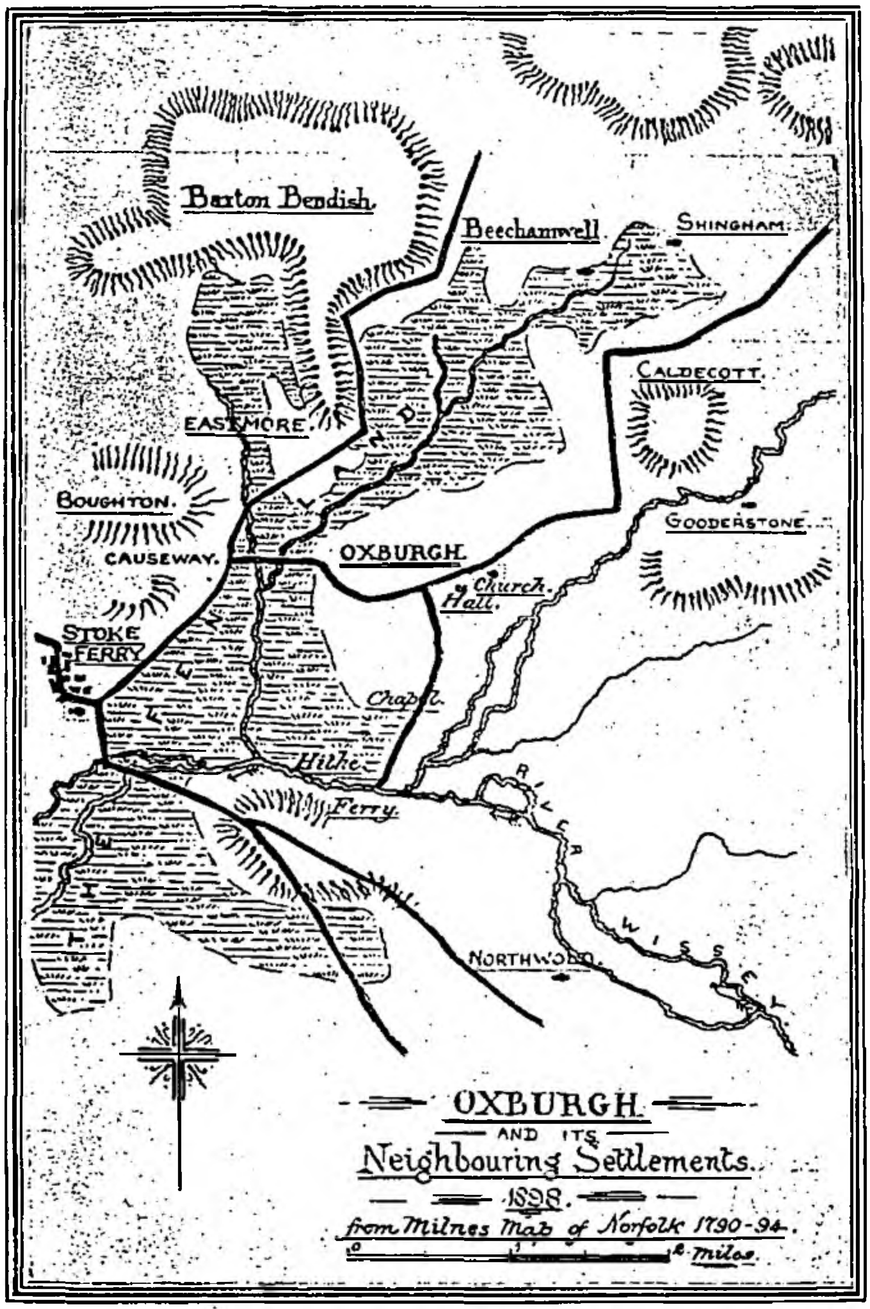

The lower River Wissey, River Gadder and Stringside stream,

from an 1898 reproduction of the Oxborough area of a 1790-94 map of Norfolk.

Edward Beloe, in his account of a visit to Oxborough in 1890, describes the important history of the village which at that time stood on the edge of the great fen (or 'Well'), facing Stoke (Ferry) across "this kind of gulf, over which the road is carried on a dam and bridge with the clear rushing stream (Stringside Stream) in its midst. The causeway is some half a mile long, and on either side of the road it still is little better than a lake full of water. At the head of this gulf lies Beechamwell...forming the 'beach' or shore to the sea-like fen..... Oxborough seems to have been a kind of metropolis, for it had its harbour...still called the Hythe, and up to within the last century there were large warehouses there, and "ships" came backwards and forwards, taking the corn and bringing back merchandise to the district."

Today the "clear rushing stream", flows almost imperceptibly (due to ponding from the gauging station) in a steep sided ditch. The track to the abandoned ferry at Oxborough Hythe still exists, but there is little evidence of the once-busy warehouses, and only the smallest pleasure boats come this far up the Wissey from Stoke Ferry.

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This report summarises the information detailed in the following Annexes, which included full methodological details, data analyses and data tables.

Plate 1. The River Wissey. Top: Bodney Bridge (TL828988), Bottom: Northwold (TL767971), during September 1992. Note the dense stands of *Rorippa* (water cress), the dominant late-summer macrophyte, inportant in maintaining hydraulic diversity at these sites under summer low flows.

Plate 2. The River Wissey at Chalk Hall Farm (TL835981), a typical chalk-stream reach with cobble- and gravel-bed riffles, rich macrophyte and macroinvertebrate diversity and a good Brown Trout population. Top: Summer 1992 (extreme low flow); Bottom: February 1994 (bank-full).

Plate 3. The River Wissey at Langford Hall gravel site (TL830950). Top: Summer 1992, note the fine gravel substrate and growth of *Ranunculus* (water crowfoot); Bottom: February 1994, when the substrate was overlayed with recently-deposited sand.

Plate 4. The River Wissey at Langford Hall sand site (TL830950). This unusual site has shallow, riffle-type characteristics but a substrate of almost 100% sand. Top: Summer 1992 (extreme low flow); Bottom: February 1994 (bank-full).

Plate 5. The River Wissey at Didlington in late summer 1992. Top: The gravel site (TL785957). Note the large beds of *Ranunculus* (water crowfoot) beginning to decay and trap floating debris. This macrophyte is important in maintaining water depths in mid-summer. Bottom: The sand site (TL802945), a deep sand- and silt-bed run typical of this sector of the Wissey.

Plate 7.

Left: The upper River Wissey at Great Cressingham (TF847170). A riffle site, bounded by unimproved pasture which alternates with arable land in this part of the upper catchment. Marginal vegetation is limited by grazing.

Right: The Stringside Stream at Beachamwell (TF743370). This sector has intermittent flow and dried out during the summers of 1991-2, but still supported a good diversity of invertebrate life during winter/spring.

Plate 6. Top: The River Wissey at Whittington (TL708995). The upper navigable limit of the river. This sector is of typical fenland type, with regular channel maintenance exposing bare peat and preventing the development of natural marginal habitat. However, this sector and downstream to the sugar factory at Hilgay is an important coarse fishery.
Bottom: The Watton Brook at Little Cressingham (TF869020). This major tributary of the Wissey has relatively poor water and biological quality, receiving effluent from the water treatment works at Watton. Marginal habitat is also poor with cultivation up to the banks.

INTRODUCTION.

The Wissey is recognised as a Chalk stream of high conservation value, possessing the physical and ecological attributes valued in such rivers, including a rich invertebrate diversity and a natural Brown Trout population. Draining the Chalk Breckland, the river has a naturally regulated flow regime. The river ecology is likely to be adapted to the good year-round flows and concerns have been raised about the sustainability of the Wissey's high biological quality under the pressures of increasing water abstraction.

Little scientific information exists on the crucial link between hydrology and ecology. Studies of the effects of water abstractions on river invertebrates at the national scale (Petts and Armitage, 1991; Armitage and Petts, 1992) have failed conclusively to elucidate links, but have suggested that lowland streams in general, and Chalk streams in particular (Bickerton et al, 1993) might be most severely affected. Furthermore, Wilby (1993) demonstrated that for 17 catchments in England, the hydrology of the Chalk streams of Norfolk (including the Wissey), having low recharge, are likely to be relatively sensitive to groundwater abstraction.

This study evaluates the influence of flows on the distribution of fauna in the River Wissey. Hydrology influences river ecology in two ways: directly, through the flow regime, by determining the hydraulic characteristics within a channel of given form (velocity, depth, shear stress etc.); and indirectly, by affecting water quality and substrate character. There are also important linkages between flow and channel morphology, and flow and macrophyte distribution, and instream hydraulics. Therefore, the approach adopted needed to:

i) closely integrate the ecological investigations with hydrological and geomorphological studies, and

ii) consider the ecological implications of all aspects of the hydrological regime - high flows, low flows, seasonal variations - and their geomorphological manifestations.

The research followed a three-stage process:

1. The *preliminary description* of the river based on both the collation of existing information and field surveys, and *classification* of the river system into sectors and reaches using a range of statistical techniques.

2 The *comprehensive description* of the physical habitat and biota within the main sectors giving special attention to *seasonal variations*.

3. The *experimental assessment* of the relationships between biota and flows, using *representative sites* selected on the basis of the above.

To achieve this, the experimental work was designed as three stages: first, to establish the relationship between the biota and habitat characteristics; secondly, to determine the relationship between habitat characteristics and flows; and thirdly, to integrate the first two stages in quantifying and predicting the responses of biota to flows.

The study also included a review of the range of approaches and methods to elucidate the relationships between flow and biota, and an assessment of the applicability of these to the determination of in-river flow needs - specifically the flows necessary to sustain the "natural" ecological values of a river. The full Terms of Reference are given in Appendix 1.

SECTION 1.
THE RIVER WISSEY: HYDROLOGY. PHYSICAL HABITAT and ECOLOGY.

1.1 The Hydrological Context.

Figure 1.1 shows the River Wissey catchment and location of the main groundwater boreholes. Data were obtained from the National Rivers Authority to describe variations of river flow and groundwater levels.

1.1.1 The water balance.

Rainfall.

Rainfall data for the Thetford gauge are summarized in Figure 1.2. Although located to the south of the catchment and in a drier area, the monthly variability is likely to be similar to that of the rainfall distribution over the Wissey catchment. It is an important gauge with a record from 1961. There is little variation of rainfall between months; monthly rainfalls vary widely from year to year and in all months, except February, rainfall can range from less than 20mm to more than 80mm. Maximum monthly rainfall is just as likely to occur in June and July as it is in the winter months of November, December and January.

Runoff.

Daily flow data for the gauging station at Northwold from 1956 to 1988 have been analysed to establish a 'normal' (i.e. pre-1989-92 drought) flow regime for the river (Figure 1.3). High runoff is seen to occur from December through April, with highest runoff in January. Typically, lowest runoff occurs in September. Comparison of Figures 1.2 and 1.3 clearly illustrates the importance of evapotranspiration in determining the seasonal variation of runoff.

Water balance.

The water balance for the catchment based upon average data for the period 1956-1988 is:

Rainfall (653mm) - Runoff (218mm) = Losses (435mm)

The record includes the 1976 drought. The wettest year on record was 1969. The losses are mainly by evapotranspiration.

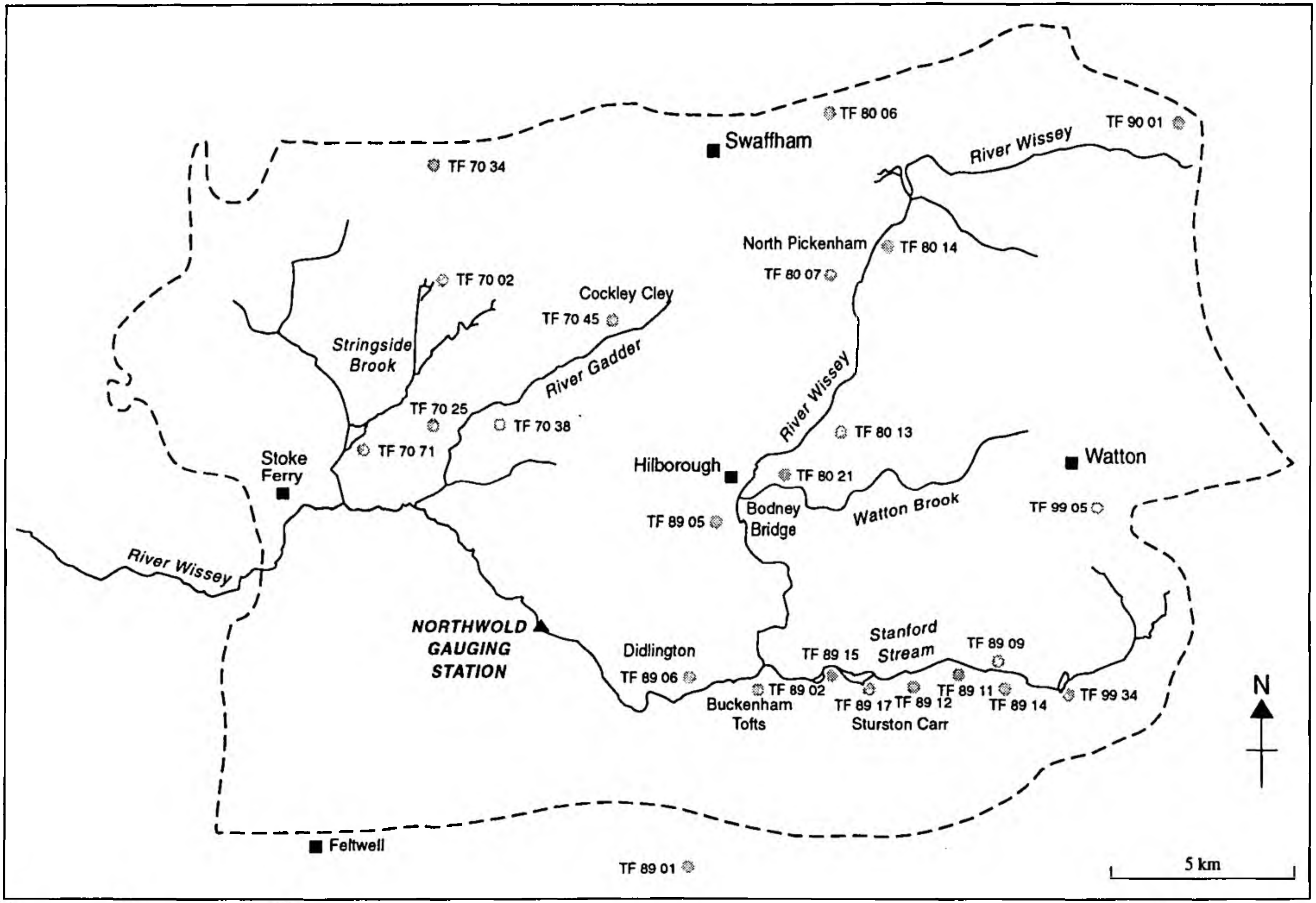


Figure 1.1 The River Wissey catchment, showing the location of groundwater boreholes.

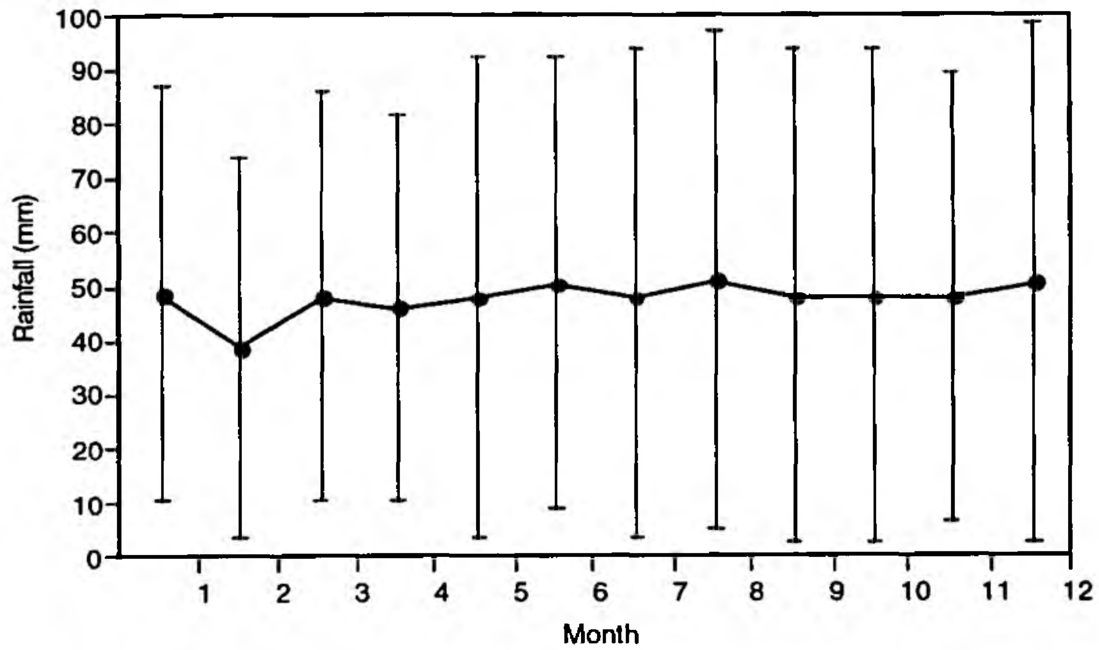


Figure 1.2 Variation in monthly rainfall, Thetford rain gauge, 1961-1988.

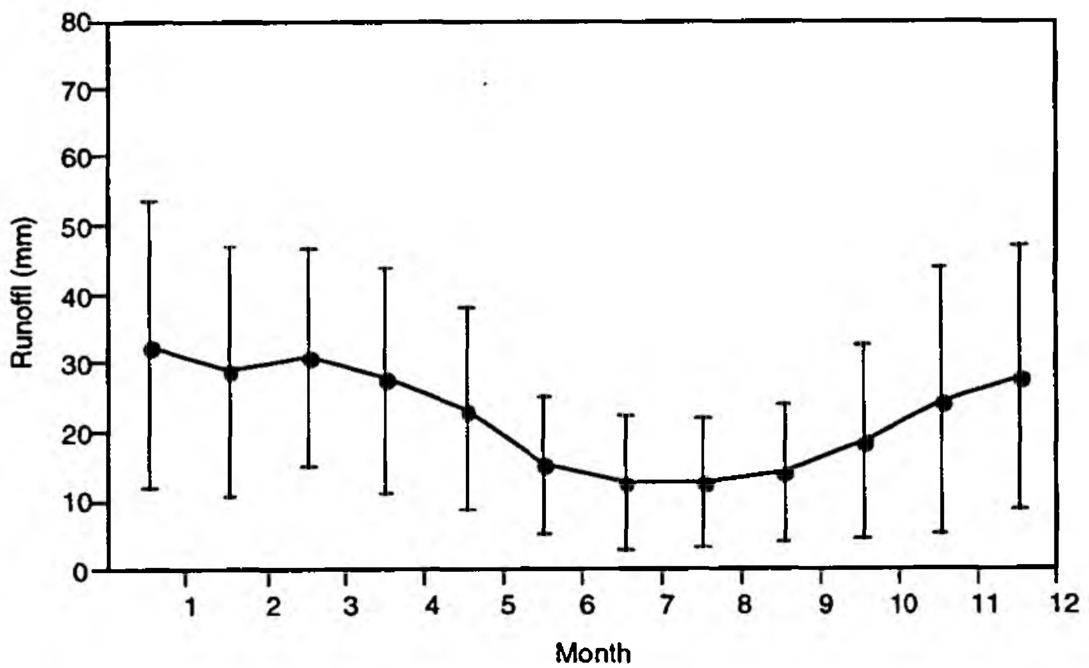


Figure 1.3 Variation in monthly runoff 1956-1988.

1.1.2 Flow regime.

The 1956-88 data for Northwold indicate that the median monthly flow ranges from more than 2 cumecs in December through April, with a maximum of 2.8 cumecs in February, to less than 1.3 cumecs in July through November, with a minimum of about 0.8 cumecs in September. The highest flow on record, 12.86 cumecs occurred in November but high discharges over 9 cumecs have occurred at various times from November through April.

In this study, flows are reported for three standard periods:

i) 1956-85 where summary data are taken from the Hydrometric Register and Statistics (NERC, 1993);
ii) 1956-88, ie. the pre-drought period, for our own analyses;
iii) 1981-88, a short record of about average annual rainfall and one which recognises that pre- and post-1981 gauged flows at Northwold are not entirely consistent because of changes in the vicinity of the gauging station.

1.1.3 Groundwater.

Data were examined for 23 boreholes within the Wissey catchment and one, at Grimes Graves just to the south (see Figure 1.1). The Grimes Graves borehole is important as it provides a relatively long and continuous record.

Catchment perimeter boreholes.

Groundwater data for four boreholes around the catchment perimeter (at Grimes Graves to the south, Wayland Wood to the east, Wolferton to the north by northeast, and Marham to the north) are significantly correlated (Table 1.1). The average groundwater regime for the period 1981-88 for the borehole at Grimes Graves (89-01) is shown in Figure 1.4a. The groundwater regime around the catchment perimeter has minimum levels in November, recharge occuring from December through May followed by groundwater depletion, particularly during July, August and September.

Table 1.1 Correlation coefficients (adjusted r^2) for relationships between monthly groundwater levels (1977-92) at different boreholes (see codes on Figure 1.1) and in relation to MORECS Winter Rainfall (MWR).

Borehole code number	89-01	80-06	70-34	99-05
89-01	1.00	0.75	0.65	0.88
MWR	0.50	0.41	0.78	0.54

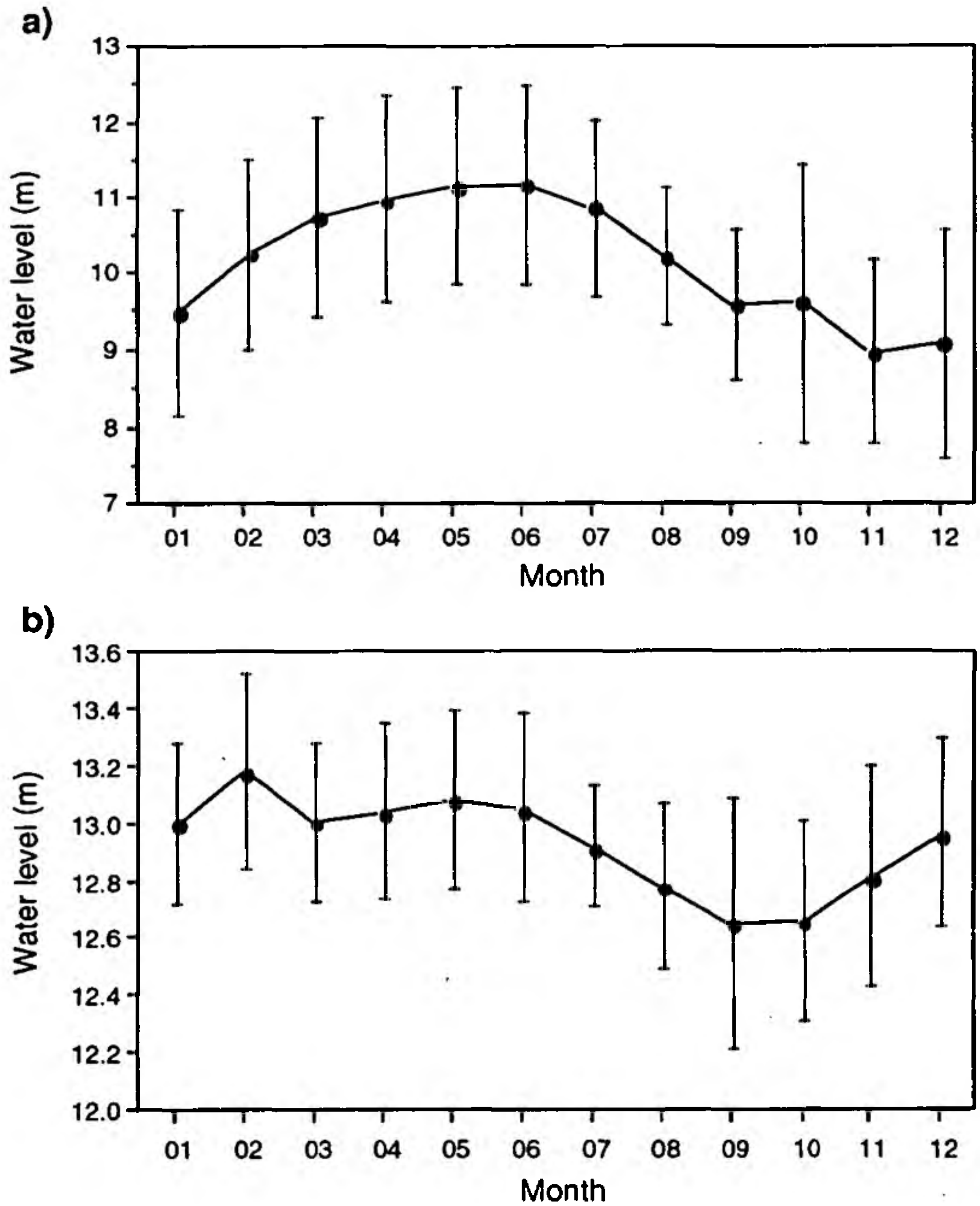


Figure 1.4 Monthly mean groundwater levels with one standard deviation error bars for a) Grimes Graves on the catchment watershed and b) borehole 89-02, in the interior of the catchment.

Annual maximum groundwater levels provide a measure of the degree of recovery of groundwater storage. Recovery levels within a normal range appear to have occurred between 1977 and 1986; an exceptionally high level occurred in 1987 with low levels subsequently. Annual maximum groundwater levels at the four catchment perimeter boreholes over the period 1977-91 are significantly correlated with residual MORECS winter rainfall (Table 1.1).

Interior boreholes.

In contrast to the catchment perimeter boreholes, those within the centre of the catchment show a rather different groundwater regime (Figure 1.4b). Typically, minimum levels are reached earlier, in September; recharge begins in October, and maximum levels are achieved in February. The strength of relationships between interior and perimeter borehole data, and between interior borehole levels and residual MORECS winter rainfall, declines with distance from the watershed. The groundwater regime along the main valley closely matches the flow regime of the river.

1.1.4 The 1988-92 drought.

Rainfall in 1989, 1990 and 1991 was, respectively, 85%, 81% and 78% of the pre-1988 annual average rainfall. Monthly runoff was exceptionally low throughout the period, especially during September, October and November when runoff was well below the minimum levels recorded during the 1956-88 period and about one third of the long-term average values for these months. From February through April the monthly runoff during 1989-91 was about two-thirds of the long-term average. Median (50th percentile) monthly flows at Northwold for the period 1956-88 are shown in Figure 1.5 together with the median monthly flows for the 1989-91 drought to illustrate the severity of the low flows during this period.

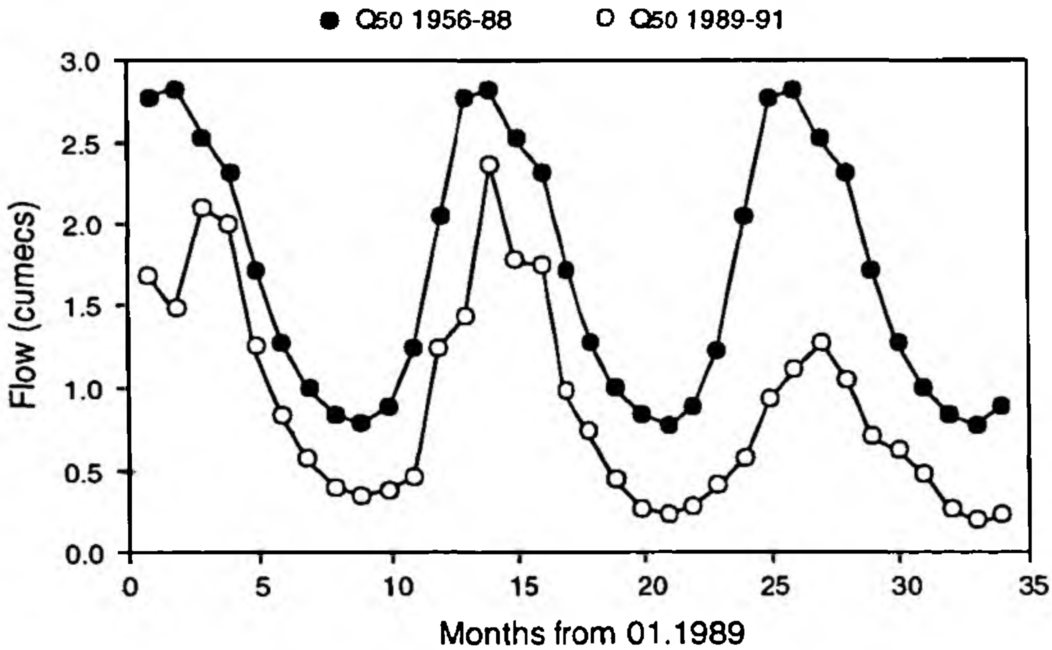


Figure 1.5 Median monthly flows (Q_{50}) during the 1989-91 drought in comparison to the long-term flows at Northwold gauging station.

In Chalk catchments, such as the Wissey, summer flows relate particularly to the effectiveness of aquifer recharge during the previous winter. Most rainfall in summer does little to replenish groundwater levels and is lost through evapotranspiration. The most important months for aquifer recharge in the Wissey catchment are November through May.

Winter rainfall throughout the Anglian Region was particularly low from October 1988 to March 1989, about 74% of the long-term average. Summer rainfalls in 1989 were also low, at 81% of the long-term average. Although the following winter had about average rainfall, summer 1990 was very dry with only 58% of the long-term average. The six months from October 1990 to March 1991 again experienced below-average rainfalls as did the subsequent summer. The cumulative rainfall deficit that had begun in 1988, was further exacerbated by exceptionally dry conditions in the autumn of 1991; the rainfall for October, November and December being only 62% of the long-term average.

Monthly groundwater levels for Grimes Graves and Wolferton (80-06) for the period 1977-1992 are presented in Figure 1.6. The plots clearly show the recovery of groundwater levels after the 1975-76 drought. The wet years of 1987-88 were followed by a marked decline of groundwater levels during the period of this study. Examination of annual maximum levels highlights the failure of winter recharge during 1990.

1.1.5 Valley profile in relation to interior borehole levels.

Data describing groundwater levels along the upper Wissey and Thompson stream valleys have been compared with estimates of channel elevation taken from Ordnance Survey 1:25000 maps (Figure 1.7). The information suggests that the original springhead of the Wissey was at Manor Farm, Shipdham, and mean groundwater levels at Leys farm (90-01) are at about the same elevation as the Fish Ponds at Manor farm. Downstream, between North Pickenham and Hilborough, there appears to be a positive hydraulic gradient between groundwater levels and the channel, suggesting that for most of the year the river gains flow through this reach. This was confirmed by stream gauging data (see Table 2.1).

Along the Stanford Stream, the original springhead is likely to have been at Thompson College although mean groundwater levels at Wayland Wood (99-05) suggest a higher elevation. A positive hydraulic gradient appears to exist through Sturston Carr and downstream to Buckenham Tofts.

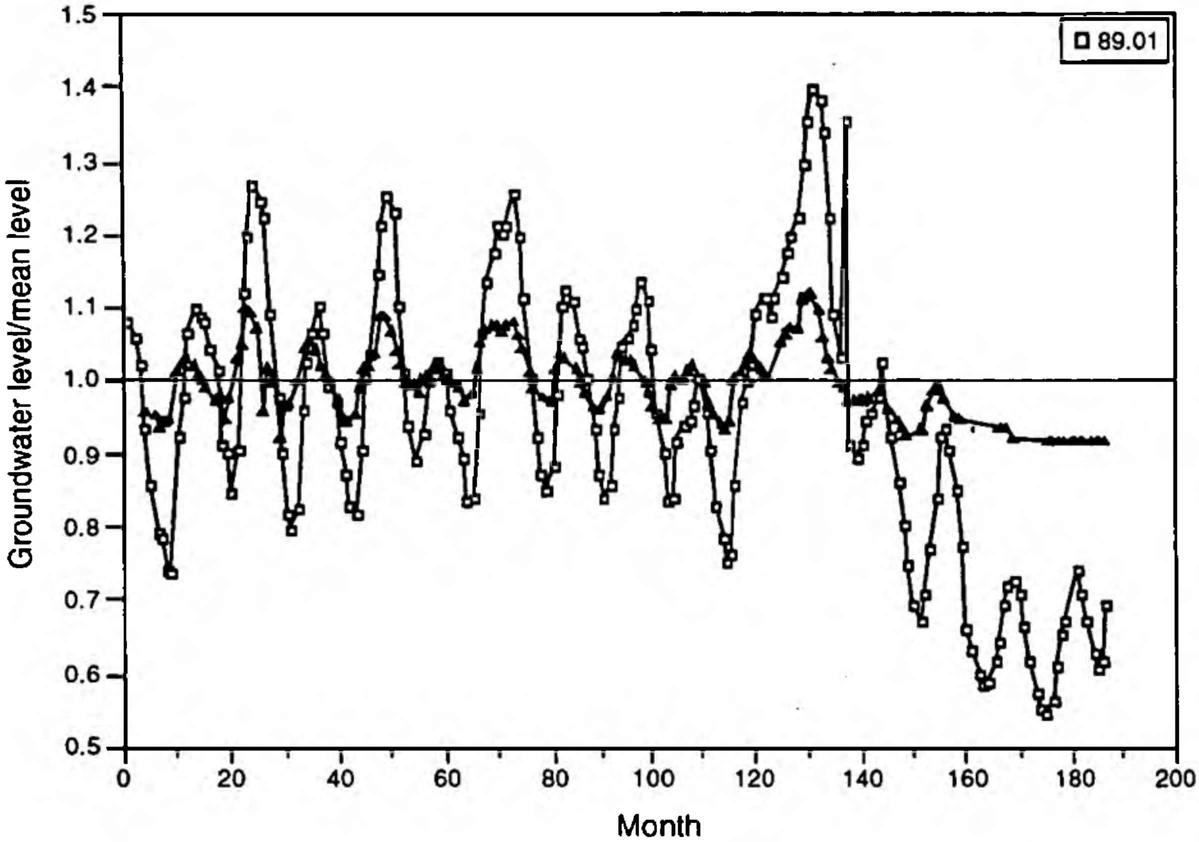


Figure 1.6 Monthly groundwater levels for Grimes Graves (89-01) from 01.1977 to 1992. Levels are normalised values (actual divided by mean for record).

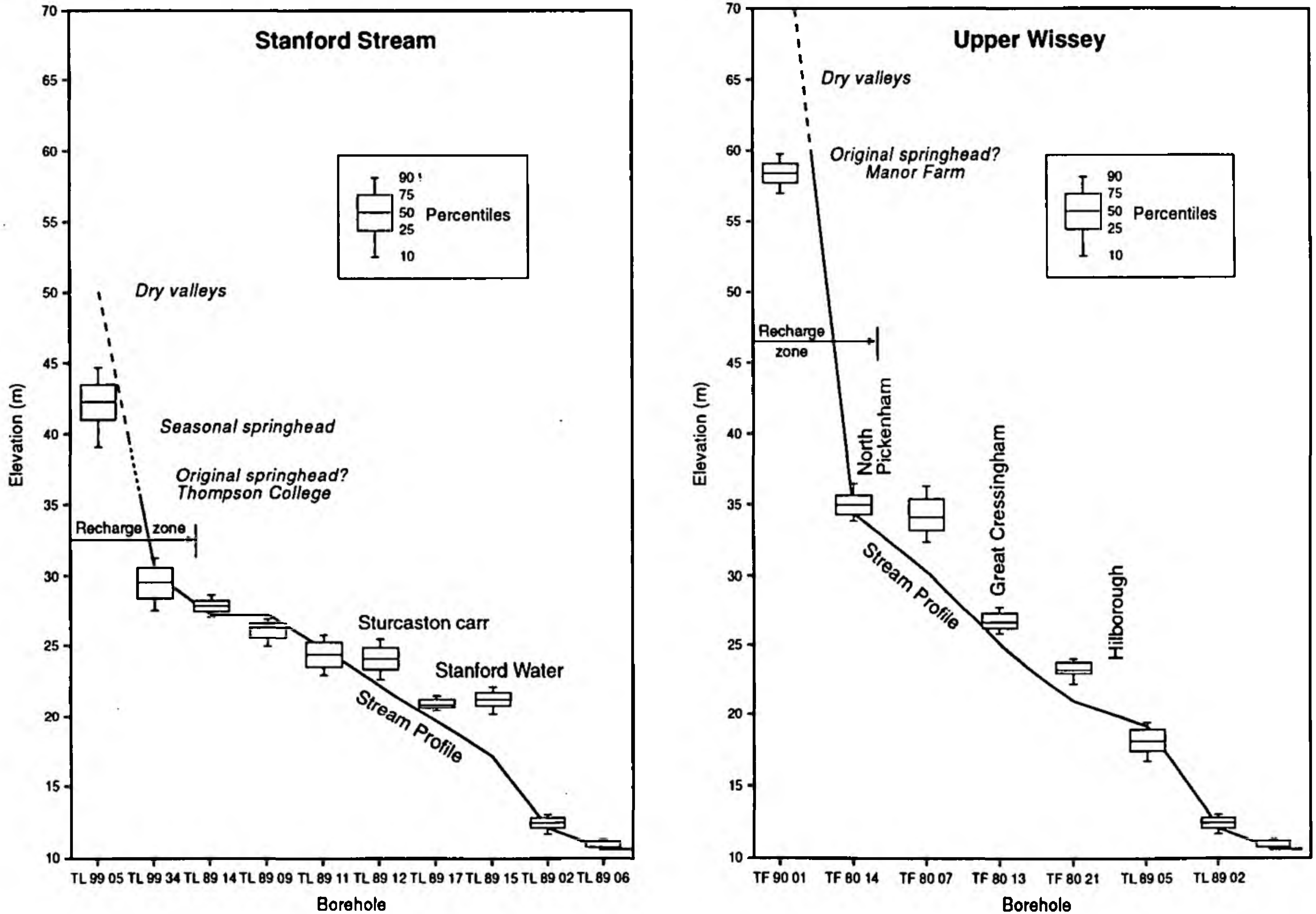


Figure 1.7 Stream profiles in relation to groundwater levels along the Stanford Stream and Upper Wissey.

Below the Stanford Stream and Wissey confluence the river appears to be in equilibrium with the local groundwater. Certainly there is no evidence that the river is perched, at least downstream to Ickborough (89-06). However, in 1992, groundwater levels at Bodney (89-05) fell to below 16 m a.O.D. and from cartographic evidence the elevation of the valley floor appears to be about 19m, suggesting that transmission losses through the channel bed may have occurred within this reach.

1.1.6 Summary and regional context.

i) The Wissey has a naturally regulated flow regime and the ratio of the highest (February) and lowest (September) median monthly flows is only 3.5 (compared with a value of over 8 for catchments with rapid storm runoff and little groundwater storage).

ii) Annual maximum groundwater levels around the catchment perimeter are significantly correlated with rainfall during the winter recharge period.

iii) Groundwater seepage to the main river appears to be especially important through the overdeepened valley between North Pickenham and Hilborough and on the Stanford Stream between Sturston Carr and Buckenham Tofts.

iv) Annual runoff during 1989, 1990 and 1991 was less than 60% of the long-term average. This reflected the rainfall deficit that accumulated from October 1988 to December 1991; as a proportion of annual rainfall, runoff fell from an average of 33% to less than 25%.

v) Throughout north Norfolk, 1991 established new records for the lowest annual and monthly runoff, and daily mean flows. Together with the Wissey and its tributary the Stringside Brook, record low flows were also experienced on the Nar, Cam, Heacham, Little Ouse, Bedford Ouse, Yare, Bure,Wensum and Waveney (NERC, 1992).

vi) The return period of the drought in Anglian Region has been estimated as rarer than once in every 200 years (NERC, 1992).

1.2 The Ecological Context.

Information on the fish population, instream flora and invertebrates was obtained from the National Rivers Authority and other sources to provide the ecological context for the study.

1.2.1 Fisheries.

Data were obtained from four NRA electrofishing surveys of the main River Wissey in 1983, 1986, 1990 and 1993 and from three surveys on the tributaries in 1986, 1990 and 1993. Table 1.2 and Figure 1.8 show the changes in fish biomass recorded over the four surveys.

Table 1.2 Total fish biomass (gm^{-2}) from the 1983-1993 NRA electrofishing surveys.

Location/Year	1983	1986	1990	1993
River Wissey	13.1	16.84	12.61	5.04
River Gadder	-	6.73	4.15	2.93
Stringside & Old Carr	-	6.94	4.60	14.3
Watton Brook	-	4.18	4.07	3.88

The River Wissey.

The Wissey is primarily managed as a Trout fishery, with the removal of coarse fish between Bodney Bridge and Northwold, and artificial stocking with Brown Trout. The dominant species is Eel, with Brown Trout and Dace sub-dominant in the upper river, and Dace, Pike and Chub sub-dominant in the lower river. Total biomass was at a maximum in 1986, with a decline through 1990 and 1993. The 1983 survey followed a pollution incident in the upper river which lowered the total catch and was believed to still be affecting Brown Trout recruitment in 1986. Low biomass in 1990/93 (down by 60% in the latter survey) is attributed to extreme low flows.

The River Gadder, Old Carr & Stringside Streams.

Eel again dominate these tributaries, with Brown Trout, Dace and Pike sub-dominant in the Gadder, and Dace and Pike in the other streams. The latter two species occur mainly near the confluences with the main river Wissey. The upper sites on the three streams all experienced a decrease in biomass in 1990 and 1993 due to drought (several sites becoming dry), with Brown Trout absent from all sites in 1993.

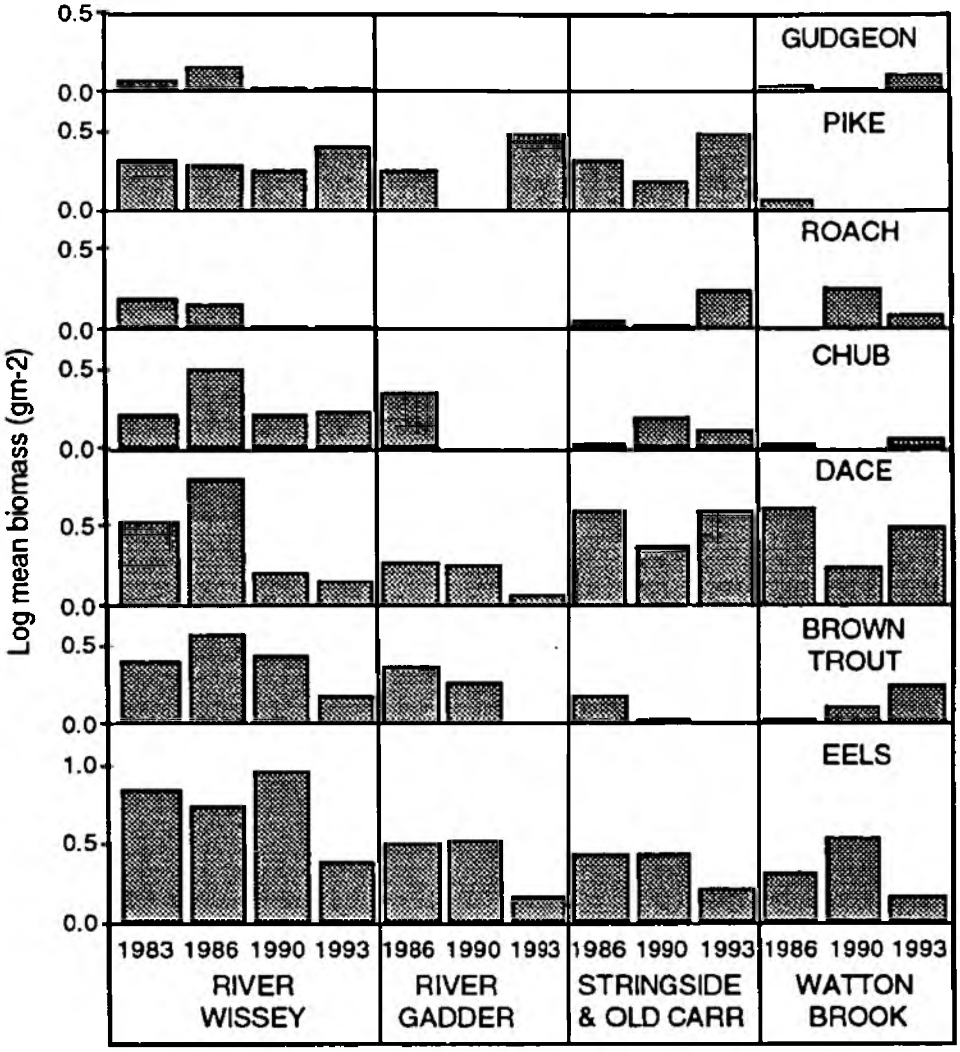


Figure 1.8 Fish biomass (gm^{-2}) from the 1983-1993 NRA electrofishing surveys.

The Watton Brook.

The Watton Brook differed from the other surveyed sections in showing very little decrease in biomass in 1990/93, suggesting that drought has impacted this tributary to a much lesser extent. Indeed, the numbers of Brown Trout increased at the lowest site - possibly due to fish taking refuge from the drought-affected upper River Wissey. However, chemical water quality is a problem on this tributary and probably accounts for the lack of Brown Trout recorded at, or above, Watton. Eel, Dace and occasionally Roach are the dominant species throughout Watton Brook.

1.2.2 Instream flora.

Data for the River Wissey (Table 1.3) were obtained from the survey of British rivers which resulted in a national classification based upon riverine flora (Holmes, 1983). It is evident that the Wissey exhibits a wide diversity of both natural and disturbed vegetation types. In the reach between Hilborough and Didlington, the Wissey was cited as possessing one of the most characteristic examples of the rich flora associated with fast-flowing, calcareous rivers.

Table 1.3 Vegetation classification of River Wissey sites (NCC British rivers survey).

Site	code	class description	comments
Bradenham (TF 913087)	A4iii	Spring fed streams in clay catchments.	Flora associated with steep, high sided ditched streams. Disturbance tolerant species.
N. Pickenham (TF 865067)	A1iii	Highly managed, unstable, sand rivers.	Species poor.
Hilborough (TF 833009) Langford Hall (TL 839964) Didlington (TL 771967)	A1vi	Fast-flowing, calcareous small rivers on mixed substrates.	The Wissey is described as one of the most characteristic rivers for this community type. Species rich due to diversity of sediment types.
Oxborough (TL 732995) Hilgay (TL 621 988)	A1ii	Canalised fenland reaches on clay and sand.	A combination of species typical of fenland and clay rivers.
Wissington (TL 664 977)	A1i	Artificial channels in tidal reaches.	The Wissey is not tidal at this point, but supports an impoverished flora typical of this group.

1.2.3 Invertebrates.

Records were obtained from the NRA for 432 samples taken from 49 sites on the River Wissey and its tributaries over the period 1964-1991. The data were used to determine long term temporal and spatial differences in aquatic macroinvertebrate communities within the Wissey catchment and to examine variations of the Biological Monitoring Working Party (BMWP) score, an index of organic pollution.

Classification of sample communities.

Two-Way Indicator Species Analysis (TWINSPAN) was used to classify the sample data and investigate between-site community relationships. Figure 1.9 summarises the classification, showing four major site groupings, the associated taxa, and inferred habitat characteristics for each group.

1	2	3	4
WSKF WFMH WHLG SWTB	**WLGF WGCR WHLB WHBH WBYB WIKB WNTW WFBF BHLB GOXB FFCM LNTW**	**WSFM WSPK GCKY GGDN FSTW BSAT BLCR DSTW**	**WBME WBMF WBMW WHHL WENF WEFH WNPK BTXT**
Lymnaeidae Copepoda Cladocera Unionidae Notonectidae Neritidae Coenagriidae Molannidae Porifera	Rhyacophilidae Hydropsychidae Sericostomatidae Leuctridae Ephemeridae Simuliidae Nemouridae Tipulidae	Ostracoda Ephemeridae Physidae Sialidae Planorbidae Hydropsychidae Hydrobiidae Sphaeriidae	Veliidae Leptophlebiidae
lowland sites with specialist taxa	upland sites with specialist taxa	degraded sites	small, naturally habitat poor sites
Leptoceridae Polycentropodidae Valvatidae Hydrobiidae Ephemerellidae Ephemeridae Physidae Caenidae Sialidae Planorbidae Ceratopogonidae Hydroptilidae	Ancylidae Ostracoda Piscicolidae Dendrocoelidae Goeridae Sericostomatidae Gyrinidae Rhyacophilidae Leuctridae Cladocera Notonectidae		
main river and lower tributary sites with diverse faunas		upper main river sites, tributary sites and degraded sites with impoverished faunas	

Figure 1.9 Summary of TWINSPAN classification of NRA macroinvertebrate routine monitoring data, showing main end-groups, sites represented in each end-group, preferential taxa and interpretation of site types. Numbers indicate TWINSPAN divisions, site codes are given in Table 1.3.

The classification reveals:-

i) natural community differences related to longitudinal habitat changes from upland, headwater streams through to lowland rivers and fenland drains - associated taxa reflect mainly differences in substrate and riparian macrophytes;

ii) a group of sites (group 3) with impoverished faunas which have been subject to pollution and habitat degradation.

Water quality.

Numbers of taxa collected, Biological Monitoring Working Party (BMWP) score and Average Score Per Taxon (ASPT) were used to examine the extent of organic pollution and other impacts on the invertebrate fauna. Figure 1.10 displays the scores for a number of sites in relation to the catchment mean scores. It is apparent that while both the upper Wissey, lower Wissey and Watton Brook sites have reduced BMWP scores, this is more a function of ASPT in the latter two sections than the former. This suggests that organic pollution is more likely to be the dominant impact in the Watton Brook and Wissey downstream of Stoke Ferry, and other factors (probably associated with low flows) in the upper Wissey.

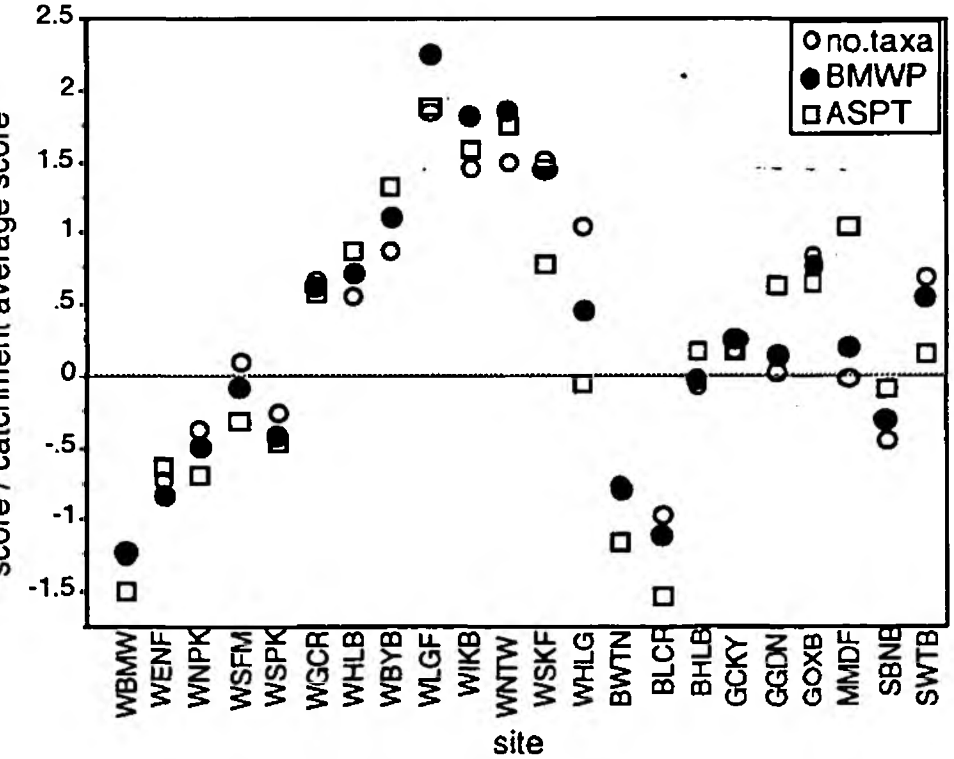


Figure 1.10 Numbers of taxa, BMWP and ASPT scores for sites on the River Wissey and tributaries (mean score for all samples), showing site scores in relation to the catchment mean. Site codes are listed in Table 1.7.

Within-site community changes.

Most sites displayed a consistent pattern of change, with generally increased taxa richness in the mid-1980's, and a recent decline in 1989-91. Figure 1.11 shows a summary of the analysis for Northwold, which is typical of the majority of sites. Seventy-three families were recorded from 25 samples. Classification of the data defines three main groups. Three sets of factors are probably responsible for this classification: long-term, seasonal and recording factors. The 1987/88 samples (group III) are separated first on the basis of a few taxa which suggest possible recording changes/errors. Samples from 1981-1985 (group II) are grouped because of the occurrence of a number of taxa requiring excellent instream and marginal habitat conditions (eg. three Plecopteran families, three Hemipteran families). The separation of this group probably reflects an improvement of habitat quality in the relatively wet early-mid 1980's. The division of group I into two sub-sets probably relates to seasonal factors - IA being mainly winter/spring samples and group IB summer samples - either due to life-cycle characteristics or dependence on seasonal macrophytes.

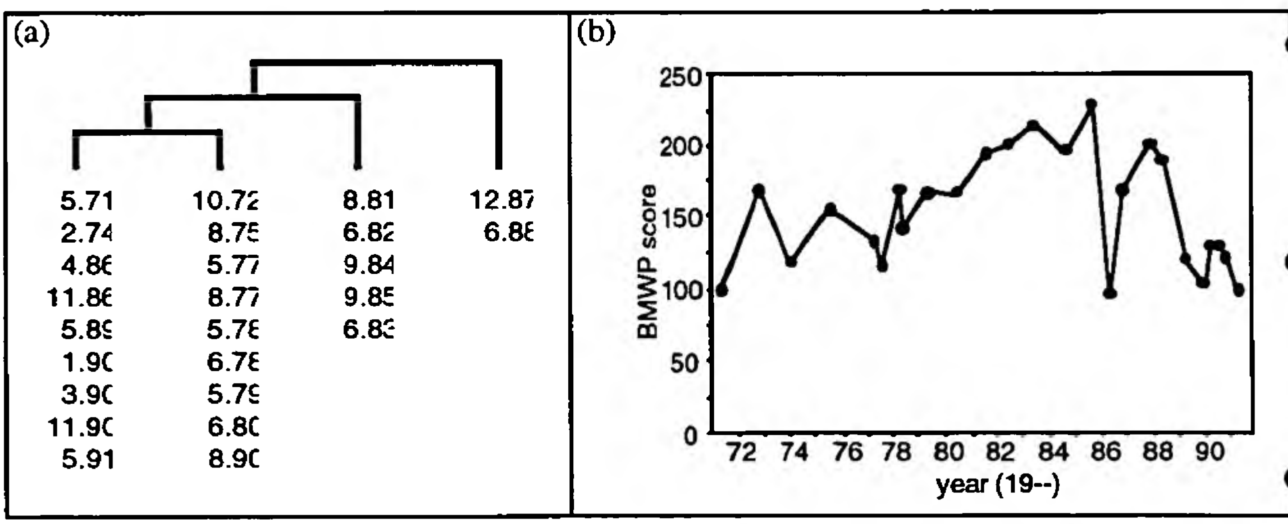


Figure 1.11 Changes of invertebrate community composition and BMWP scores at Northwold 1971-1991. a) classification of samples by sample date (month.year) using TWINSPAN; b) long-term variations in BMWP score.

Changes in BMWP scores illustrate the typical change in biological quality with increasing values through the 1970's and 80's and reduced values since 1988. The former change may result from either improvement in actual habitat quality, which could be explained as recovery from the drought years of the 1970's, or in sample identification and recording procedures. The latter change is probably an accurate reflection of drought impacts. Low values were recorded in the main river sites in 1986, from Holm Hale (where large numbers of dead *Gammarus* were noted) to Ickborough, possibly resulting from a single pollution incident in December/January with effects persisting through to April.

1.2.4 Recent trends - summary.

i) The river through Hilborough to Didlington contains a classic Chalk-stream flora and a diverse invertebrate fauna. Downstream the river becomes a fenland drain but the invertebrate fauna remains diverse. Small streams throughout the catchment have naturally-poor headwater faunas which has often been degraded by ditching and pollution, factors that are also reflected by the poor flora.

ii) The fish population is dominated by eel, with dace in the upper river, dace and trout in the middle river, and dace and chub in the lower river. However, the population is artificial because of trout stocking and selective removal of coarse fish. Through biological interactions, the artificial structure of the fish population is likely to have an effect on the way the 'ecosystem' functions.

iii) A reduction in trout biomass (from more than 1.8 gm^{-2} to 0.55 gm^{-2} in 1990 and 1993, respectively) appears to correlate with the decline in flows.

iv) A recent decline in invertebrate richness may also relate to the decline in flows, although this link may be indirect, reflecting a decline in water quality in the lower Wissey below Stoke Ferry and along Watton Brook, and a degradation of physical habitat elsewhere.

1.3 Environmental survey of the river corridor.

To supplement the information obtained from secondary sources, field surveys were undertaken of the riparian vegetation, important wetland sites, and channel morphology.

1.3.1 Riparian vegetation.

Expert assessment of the riparian vegetation along the River Wissey, River Gadder and Stringside Brook was undertaken during July 1991. The aim of the survey was to evaluate the naturalness and ecological value of respective sections of the river system. In addition, tentative predictions on the influence of any decrease in groundwater levels on riparian wetland vegetation were made. Detailed descriptions of the locations of surveyed sections and botanical information are given in Annex A.

Eight sections were defined which were mainly distinguished by distinct differences in riparian land-use. Table 1.4 summarises the flora of these sections.

The core area of the River Wissey is identified as exceptionally valuable, both regionally and nationally, and requires careful management directed at promoting conservation-sensitive forestry and farming practices. Reintroduction of native tree species would significantly enhance the conservation value of the large areas of alluvial woodland presently managed as plantation. The reintroduction of wet meadow / pasture as a buffer zone where at present arable cultivation is practised up to the bank would also be advantageous.

If the groundwater levels in the riparian and floodplain zones were to decrease, the most threatened habitats are the wet alluvial woodlands where nettle, *Urtica dioica* , would be predicted to expand, outcompeting other species. The same species would possibly also spread into the lower riparian zone, partly outcompeting or pushing down the other species. Other communities would not be expected to change dramatically. Remarkably, no invasive riparian weeds were found in the area surveyed. This is exceptional in the present, intensively used, landscape and any disturbance of the river margin could result in the appearance of invasive species.

Table 1.4 Vegetation characteristics of surveyed sections of the River Wissey, River Gadder and Stringside stream.

Section	in-stream	riparian	adjacent land
WISSEY			
1 - Bodney. (NGR TL 828988- TL 833980)	Low macrophyte cover.	Moderate diversity, typical and common species.	Some interesting alluvial woodland. Pasture.
2 - Heathland, Chalk Hall Fm. (NGR TL 833980-TL 840966)	Low-moderate cover.	"	Important grasslands on sandy soils typical of the region, particularly valuable wet meadow between upper dry grassland and riparian strip.
3 - Langford Farm. (NGR TL 840966-TL 832963)	Moderate cover, mainly *Ranunculus fluitans.*	Relatively diverse.	Poplar plantation but with alder and willow. Some relatively undisturbed and interesting pasture.
4 - Stanford stream confl.- Buckenham Tofts. (NGR TL 832963- TL 832953)	Relatively poor except at the confl. with Stanford stream, a very rich area including *Nuphar lutea* and *Sagittaria sagittifolia* .	"	The best example of wet alluvial alder carr, in relatively natural state. In places this has been disturbed by planting of Poplar.
5 - Buckenham Tofts - Ickborough. (NGR TL832953-TL822948)	Very poor.	Poor.	Poor, mainly plantation of Poplar, Scotch pine and Norway spruce. Large areas are disturbed by gravel workings, with ruderal species dominating.
6 - Ickborough-Mundford. (NGR TL 822948- TL 809944)	"	Moderate.	Mainly Poplar but some Alder, poor ground layer flora. Valuable for it's proximity to the village, and has potential for improvement.
GADDER			
7 - Gooderstone. (NGR TL 778034-TL 759023)	Poor.	Moderate diversity.	Mainly drier alluvial woodland, with some wetter alder carrs near village. Extremely valuable wet grassland. Very species rich, with many orchid(*Dactylorhiza fuchsii)* and other species typical of such sites.
STRINGSIDE			
8 - Oxborough. (NGR TL 738040- TL 721018)	Poor, due to shading.	Poor, due to shading.	Pasture and plantation. Fen wood is a dry-ish alluvial woodland, has been disturbed in the past but has potential to regenerate and would be improved with the reintroduction of more native tree species.

1.3.2 Diptera associated with wetland areas.

In addition to the vegetation survey of riparian areas, the Dipteran fauna of two potentially interesting wetland sites was surveyed in particular to assess the functional role of wetland areas dependent on river and groundwater levels, and to support the aquatic macroinvertebrate surveys in aiming to assess the conservation value of the River Wissey for invertebrates.

Two sites were surveyed:
1. River Gadder, Rookery Farm (OS Grid Ref. TF7502)
2. "Mill Covert Fen," Cockley Cley (OS Grid Ref. TF7703)

Collections were made with a hand net, and the following families were recorded: Tipulidae; Ptychopteridae; Bibionidae; Mycetophilidae; Stratiomyidae; Rhagionidae; Syrphidae; Sciomyzidae; and Scatophagidae. Full details of collecting methods and species lists are given in Annex A. Diptera of note, being either rare or specifically dependent on wetland habitats are given in Table 1.5.

Table 1.5 Species of Diptera that are either rare or highly adapted to wetland habitats found during the Wissey survey.

Odontomyia argentata (Fabricius). (Soldier fly).	A nationally vulnerable species (Red Data Book 2). An early species but non-the-less rare. A species of spring-fed fens. Only 6 known post-1960 sites.
Chrysopilus cristatus (Snipe fly).	Not rare but restricted to damp meadows and marshes, etc..
Neoascia tenur (Harris). (Hoverfly).	Common at richer types of 'boggy' ground.
Orthonevra brevicornis (Loew). (Hoverfly).	A nationally rare species (RDB3). Very local but widespread. Marshes and fens with seepages and streamlets are typical sites.
O. geniculata (Meigen).	A nationally rare species (RDB3). Mainly northern and western, although recorded from East Anglia. As with the last species the larvae are said to occur in organically rich mud.
Pelidnoptera nigripennis (Fabricius). (Snail fly).	A nationally rare species (RDB3). Mainly a Scottish species, although also recorded from East Anglia. A species of shaded woodlands.
Cordilura albipes (Dungfly).	The larvae mine in Liliaceae leaves.

From a national perspective, the expert opinion was that both are extremely valuable sites. The outstanding site is the damp woodland and grazed fen north of Mill Covert near Gooderstone, which is not presently a SSSI or known to the County Conservation Trust. It is considered most important that this site be protected from changes in management or water regime.

1.3.3 Physical habitat survey.

At the outset of the project in January/February 1991 the channel network of the River Wissey was walked to make a general assessment of the river. The survey included the River Wissey from west Bradenham to Whittington, the Stringside stream from Beachamwell to the River Wissey, and the River Gadder from Cockley Cley to the River Wissey. Seven parameters, determined at approximately 50 m intervals, were used to describe catchment size (contributing area indexed by distance from source and Shreve Index, a measure of the drainage density), channel size (bank-to-bank width and wetted width), energy environment (flow velocity), channel type (riffle, pool, run) and substrate (gravel, sand, silt).

The morphology of the river varies downstream as the catchment area increases. Using the Shreve Index as a measure of contributing area - which is particularly difficult to define in groundwater dominated systems - channel width increases from 2 m to about 10m at a Shreve Index of 450, downstream of which width is maintained at about 10m to a Shreve Index of more than 750. The relationships with channel width for 822 measurements are:-

$$\log \text{Channel Width} = -2.726 + \log \text{Distance Downstream } 0.818$$

the correlation coefficient (adjusted r^2) is 0.79.

$$\log \text{Channel Width} = -0.648 + \log \text{Shreve Index } 0.614$$

the correlation coefficient (adjusted r^2) is 0.82

However, the downstream change of instream habitat (riffle/run/pool etc) was not progressive. Gravel-bed, riffle-pool reaches contrast with ponded, sand-bed reaches; macrophyte-rich reaches contrast with heavily shaded macrophyte-poor reaches. In most cases the contrasts between reaches reflect recent or historic management practices, especially the affects of dredging and mill weirs. A detailed physical description of the river is given below.

1.4 Delineation of channel sectors.

On the basis of the physical habitat survey and background information summarized in previous sections, the river network was divided into 5 sectors comprising 13 reaches (see Figures 1.12 and 1.13). The characteristics of the sectors are summarized below.

1.4.1 The River Wissey.

Figure 1.12 illustrates physical characteristics of the five sectors: The upper part of the Figure displays the change in Shreve Index with distance from source. Change related to stream order defines the first four sectors. In sector 1 there is rapid increase in Shreve Index typical of headwater regions. Below this the increase is more gradual (sector 2) except at the confluence with the Watton Brook, which marks the divide between sectors 2 and 3, and the confluence with the Stanford stream above Buckenham Tofts, which marks the divide between sectors 3 and 4. The change from sectors 4 to 5 is related to management and the change from shallow peat and sand on chalk to deep peat - ie. the beginning of the fenland area.

The middle part of Figure 1.12 illustrates changing channel width with distance from source. Overall there is the expected downstream increase, but superimposed on this are local differences related to channel management. In sector 1 channel width is relatively narrow and heavily managed. In sector 2 the channel is more natural with pasture the dominant land use, and this is reflected in greater and more variable channel widths. The increase in widths at the junction of sectors 2 and 3 follows the confluence with Watton Brook. The lower part of sector 3 and upper sector 4 are characterised by high and variable widths in this semi-natural, wooded section, before the river enters the intensively managed fenland reaches. Finally the width increases after the confluence with the Gadder and Stringside stream, below which the river width is probably maintained to allow navigation.

The lower part of Figure 1.12 summarises the proportions of riffle/pool habitat, flows and substrate types. The trends in these variables indicate the change from the gravel-riffle headwater section (sector 1), through the more variable, semi-natural middle river (sectors 2,3,4) to the slow flowing, silty fenland drain (sector 5). Details of each sector are summarized in Table 1.6

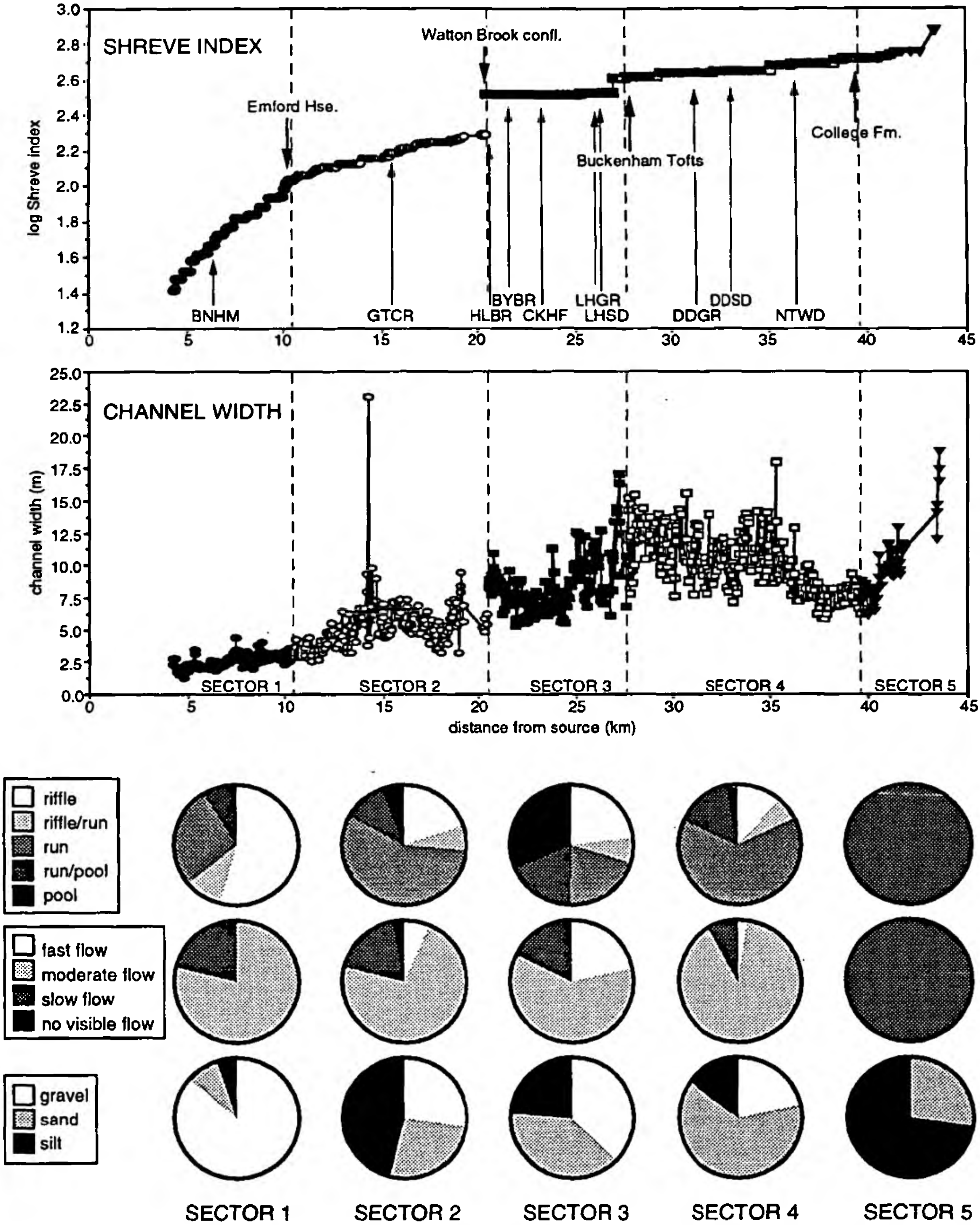


Figure 1.12 Sector characteristics for the main River Wissey. Top: Shreve index and channel width, with site locations marked; Bottom: proportional distribution of riffle/pool habitat, flow velocity and dominant substrates.

Table 1.6 Summary characteristics of the River Wissey sectors

Sector 1. Headwater section from Bradenham to Ernford house. The river is heavily managed for land drainage, rapidly increasing in size by the addition of small tributaries which appear as deeply-ditched field drains. There is virtually no riparian strip and no floodplain, the adjacent land use being nearly all arable and the channel being dredged to well below the surrounding fields. Despite heavy management, there is a well defined series of riffles and shallow pools, the former of medium sized gravel, the latter mainly gravel with sand and silt. Macrophyte cover is minimal due to dredging except in inaccessible areas.

Sector 2. Small river section from Ernford House to the confluence with Watton Brook. This sector is more diverse, has still been managed through ditching and straightening, though less recently and frequently so than in sector 1. Adjacent land use is mixed with a high proportion of pasture. The gradient of the river appears lower than in sector 1, with long stretches of silty runs which appear to flood occasionally onto the adjacent wet meadow land. Grazing has reduced the riparian vegetation in some sections, although the instream flora is richer in unshaded areas due to lower banks.

Sector 3. Watton Brook confluence to Buckenham Tofts. This sector contains the most natural sections of the River Wissey, notably the Breckland- and woodland-bordered section through the army training area. Large gravel riffles alternate with sandy runs where the river is not ponded by Langford and Buckenham sluices. *Ranunculus* is the dominant instream macrophyte, with extensive marginal beds of the emergent *Glyceria*. The latter marks the noticeable present division between sectors 3 and 4, although before the building of the sluice the confluence with the stream draining Stanford Water would form the natural sector divide.

Sector 4. Buckenham Tofts to College Farm. This sector is similar to sector 3. The river is larger (manifest in greater depths rather than channel widths), with a higher proportion of sandy runs which have periodically been deepened for flood defence purposes. The end of the sector, where the river enters the true fenland section, is difficult to define, but has been taken as the point where the flow velocity reduces to continuous slow flow and the substrate becomes dominated by silt overlying peat.

Sector 5. College Farm to Whittington. In this sector the river is heavily managed as a fenland drain. Channel form is uniform; flow slow and bed silted. *Ranunculus* is still the dominant macrophyte down to the point where the river is navigable, below which instream vegetation is reduced through smothering with continuously disturbed silt. Riparian vegetation is poor due to frequent dredging and cultivation up to the river margin.

1.4.2 The River Gadder.

Despite the diversity of habitat found within the River Gadder, it has been classed as a single sector as the habitat diversity results from very localised management differences.

The river rises in woodland above Cockley Cley Hall lake. From here it flows through the village of Cockley Cley, beyond which it is impounded to form a large but shallow lake. Below the lake the river flows through open meadow and is then augmented by several springs rising in wet woodland. Flow through the whole of this upper section has been intermittent in recent years. The river and lakes have dried out in 1990, 1991 and 1992. Physically the river is a small stream in this section, with a sand and gravel bed in shaded areas, and silt accumulating around dense stands of emergent vegetation in the open section below the lower lake.

Below the springs the river flows through more open meadow with patches of riparian scrub, until it enters a Willow "swamp" area above Gooderstone. Below this and Gooderstone Water Gardens, the river meanders through pasture at the back of Gooderstone village. After a small weir the river again becomes more natural in character, with good fine-gravel riffles in the shaded sections.

The ponding from the sluice at Oxborough Hall causes the formation upstream of a long, silted run. The appearance of the bed suggests that this section also dries out periodically. Below the Hall and until it enters arable land adjacent to the River Wissey, the Gadder runs through meadow and pasture in a fairly natural course. Small weirs locally pond the river.

The last section of the river is through arable land where the channel has been deepened and straightened and is peat-bedded.

1.4.3 The Stringside stream.

The Stringside stream has two main headwater tributaries which were both surveyed. Two sectors were defined: an upper, headwater sector and a lower; fenland sector.

<u>Sector 1.</u> The Stringside stream from Beachamwell to the confluence with the Barton Bendish tributary, and the main tributary which joins the Stringside stream at Beachamwell. This sector is characterised by its more upland, headwater nature. The channel is small, flow is temporary in dry years, and substrates are of fine gravel, sand and silt, heavily influenced by vegetation growth and management. In the uppermost sections the surrounding land use is arable; lower down the stream is bounded mainly by woodland and pasture. Dredging has revealed bare chalk at the section between Eastmoor and Oxborough wood. At the time of survey the Beachamwell section was dry.

<u>Sector 2.</u> Stringside stream from the confluence with the Barton Bendish tributary to confluence with the main river Wissey. This sector is heavily managed as a fenland drain. Dredging takes place every year, maintaining a clear steep sided channel well below surrounding land level. Substrate is bare peat with some accumulated sand and silt; lower down dredging exposes bare chalk. Macrophyte growth is limited by annual cutting. The upper half of this sector is ponded by the gauging station. Below this the channel is mainly intensively managed and ponded from the main river Wissey.

1.5 Site selection.

The preliminary assessment of the past and present characteristics of the Wissey was undertaken to establish the hydrological and ecological context for the study and has highlighted both the variety of channel types, defined using both geomorphological and ecological information, and changes over the past decade, especially since 1988.

Classification of the river into sectors and reaches was used to assess the diversity of riverine habitats in the river catchment, to identify areas of valuable, unusual or potentially flow-sensitive habitat, and to identify sites for subsequent research that are representative of the range of habitats found. This information was used to select 21 survey sites. These comprise:-

- seven primary sites being located in the most ecologically interesting sectors 3 and 4 (Watton brook confluence to Northwold gauging station).
- fourteen secondary and tertiary sites, chosen to cover as wide a range of habitat types as possible.

Locations of the sampling sites are shown in Figure 1.13, and codes and locations of the sites listed in Table 1.7.

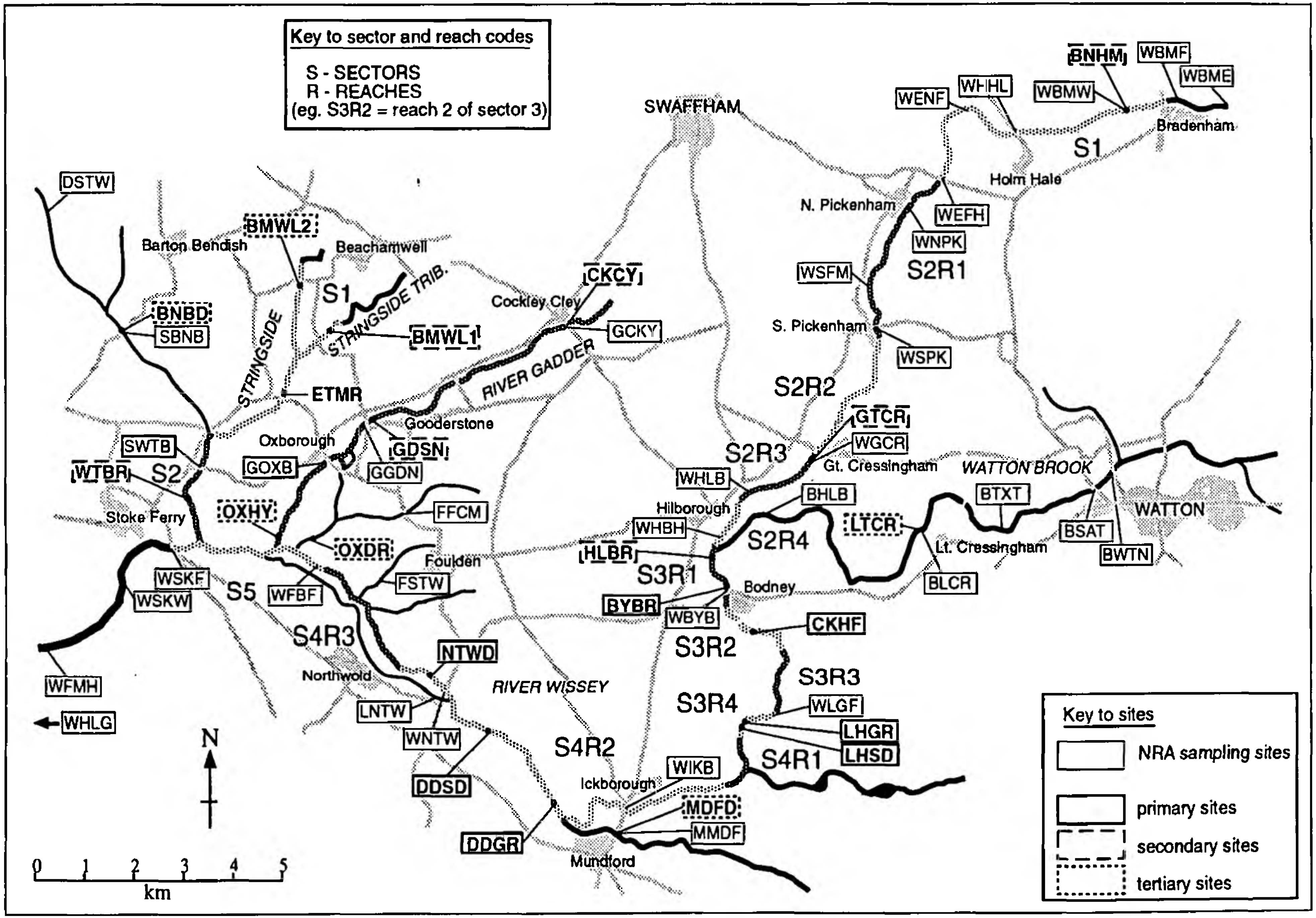


Figure 1.13 The River Wissey and tributaries: sectors, reaches, NRA and Loughborough sampling sites. Site codes are explained in Table 1.7.

Table 1.7 Survey sites and codes.

KEY TO SURVEYS	
1 - NRA macroinvertebrate sampling sites.	4 - Temperature recording sites.
2 - Loughborough macroinvertebrate and water chemistry sampling sites (p=primary, s=secondary, t=tertiary).	5 - Sediment survey sites.
3 - PHABSIM survey sites.	6 - Diatom survey sites.
	7 - Loughborough macrophyte mapping sites.

SITE LOCATION	NGR	CODES	surveys
RIVER WISSEY			
East Bradenham	TF931088	WBME	1
Bradenham Ford	TF921089	WBMF	1
West Bradenham	TF912087	WBMW / BRHM	1,2s
Holm Hale - Necton Rd.	TF887082	WHHL	1
Erne Fm., Necton	TF872082	WENF	1
Ernford Hse.	TF872072	WEFH	1
North Pickenham	TF866067	WNPK	1
d/s Swaffham STW	TF858047	WSFM	1
South Pickenham B1077 rd.br.	TF858043	WSPK	1
Great Cressingham	TF847170	WGCR / GTCR	1,2s,6
Linghills Fm., Hilborough	TF834009	WHLB	1
Hilborough Hall, d/s mill	TL826998	WHBH	1
Hilborough, d/s Watton Brook confl.	TL825996	HLBR	2s
Bodney Bridge	TL828988	WBYB / BYBR	1,2p,3,5,6
Chalk Hall Farm	TL835981	CKHF	2p,3,4,5,6,7
Langford battle area	TL839963	WLGF	1
Langford Hall (gravel)	TL830950	LHGR	2p,3,4,5,7
Langford Hall (sand)	TL830950	LHSD	2p,3,4,5
Ickborough	TL808944	WIKB	1,5
Didlington (sand)	TL802945	DDSD	2p,3,5
Didlington (gravel)	TL785957	DDGR	2p,3,5,7
Northwold	TL767971	WNTW / NTWD	1,2p,3,5,6
Foulden, Borough Fen	TL747990	WFBF	1
old A134 rd.br. Stoke Ferry	TL708995	WSKF	1
Five Mile House	TL663978	WFMH	1
A10 Hilgay	TL620987	WHLG	1
WATTON BROOK			
Watton, A1075	TF919019	BWTN	1
Saham Toney, B1077	TF904011	BSAT	1
Threxton	TF885002	BTXT	1
Little Cressingham	TF869020	BLCR / LTCR	1,2t,6
Linghills Fm., Hilborough	TF837004	BHLB	1
RIVER GADDER			
Cockley Cley br.	TF794420	GCKY / CKCY	1,2s
Gooderstone	TF753190	GGDN / GDSN	1,2s,4,6
Oxborough br.	TF744014	GOXB	1
Oxborough Hythe	TL736996	OXHY	2t
STRINGSIDE STREAM			
Beachamwell 1	TF743370	BMWL1	2s
Beachamwell 2	TF738490	BMWL2	2t
Eastmoor	TF736270	ETMR	2s
Whitebridge rd.br.	TF719011	SWTB	1
Whitebridge, d/s G.S.	TF717050	WTBR	2s,4
LODE DYKE			
Wereham, d/s Fincham STW	TF688051	DSTW	1
Barton Bendish	TF704400	SBNB / BNBD	1,2t
WEST TOFTS MERE STREAM			
Mundford	TL807940	MMDF / MDFD	1,2t
FOULDEN COMMON STREAMS			
trib., d/s Foulden STW	TL755988	FSTW	1
Foulden Common	TF761002	FFCM	1
Oxborough Drain	TL741997	OXDR	2t
LITTLE RIVER			
Northwold	TL770965	LNTW	1

SECTION 2
VARIATIONS OF INSTREAM CHARACTERISTICS 1991-92.

2.1 Introduction.

The establishment of functional relationships between hydrology and ecology is a goal of current scientific research. It requires detailed knowledge not only of biological preferences, adaptations and behavioural strategies to changing habitat conditions, developed in Section 3, but also of the complex interactions between flow and the physical attributes that define habitat patches. Thus, the core of this project involved detailed investigations of the habitats at the selected sites chosen as representative of the range of channel characteristics within the main river (Section 1.5). These investigations included measurements of flow and water-quality (using chemical and biological methods); studies of the influence of vegetation growth on instream hydraulics and substrate; and studies of hydraulic variations with changing discharge within channels of different size and shape. Field surveys were undertaken between May 1991 and October 1992.

2.2 Hydrology.

2.2.1 Discharge.

Throughout the survey period, daily flows at Northwold gauging station were well below normal, as defined by the 1956-88 record (Figure 2.1) and for most of the period they were below the monthly 95th percentile flow, especially from August 1991 to March 1992. The mean daily flow during the period of field survey (0.479 cumecs) was only about 25% of the long-term mean daily flow (1.9 cumecs).

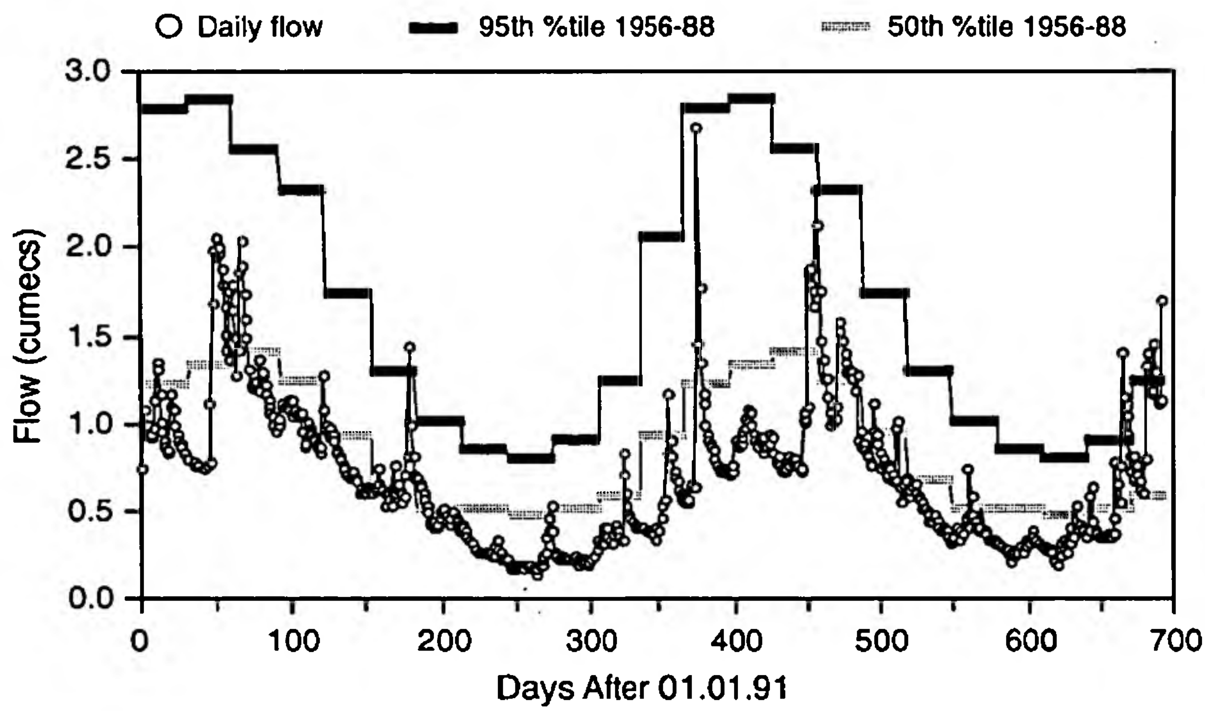


Figure 2.1 River Wissey flows 1991-92 at Northwold gauging station.

2.2.2 Streamflow Characteristics 1991-92.

Stream gauging was undertaken at 16 sites at monthly intervals (Table 2.1). Along the main river, flow was intermittent at Bradenham but increased downstream to Northwold gauging station. There was no evidence of losses through the channel bed. Notable, however, is the considerable gain in flow between Great Cressingham and Hilborough, a reach of only about 2.5km, and this reflects the high groundwater gradient through this sector (see Section 1.1.6). Many of the small tributaries were dry for some months during the survey period.

Table 2.1 Summary of monthly flow gauging data, May 1991-October 1992. Site codes are listed in Table 1.7.

Site	Average discharge (m^3s^{-1})	Maximum discharge (m^3s^{-1})	Dry months
BRHM	0.021	0.119	5
GTCR	0.091	0.309	0
LTCR	0.078	0.235	0
GTCR+ LTCR	*0.190*	*0.663*	
HLBR	0.260	0.755	0
BYBR	0.271	0.641	0
CKHF	0.280	0.637	0
LHSD	0.307	0.624	0
DDSD	0.480	0.868	0
NTWD Gs	**0.479**	**1.114**	**0**
1956-85	**1.900**	**12.860**	**0**
CKCY	0.008	0.029	9
BNBD	0.014	0.054	6
BMWL	0.019	0.066	4
OXHY	0.025	0.072	4
ETMR	0.029	0.084	4
GDSN	0.039	0.073	1
OXDR	0.056	0.115	2
WTBR	0.129	0.278	0

Significant relationships exist between the flow at sites along the river and the gauged flow at Northwold, at least over the range experienced. The regression coefficients are given in Table 2.2.

Table 2.2 Regression coefficients describing relationships between flows along the Wissey and gauged flows at Northwold (site codes are given in Table 1.7 and locations on Figure 1.13).

Site	Intercept	Slope	Correlation with Northwold gauge (R^2)
BRHM	-0.01	0.071	0.23
GTCR	-0.04	0.274	0.77
LTCR	-0.023	0.202	0.72
HLBR	-0.061	0.637	0.75
BYBR	0.001	0.564	0.85
CKHF	-0.037	0.663	0.90
LHSD	0.004	0.634	0.91
DDSD	0.064	0.869	0.83
BNBD	-0.009	0.053	0.82
WTBR	0.007	0.254	0.69

2.3 Water quality.

The assessment of water quality involved two separate studies: data from chemical analyses on samples collected during the study period (1991-2) and comparison of these data with NRA records for previous years and the assessment of data derived from biological monitoring, using diatoms. The impact of low flows on stream temperatures and on temperatures within the biologically-important zone of the channel bed are considered in the next sub-section.

2.3.1 Chemical water quality.

Monthly water samples were collected from the 21 surveyed sites and analysed at the NRA laboratories at Kingfisher House for the following determinands:

pH	ammonia *	
electrical conductivity	chloride *	
total oxidised nitrogen	nitrite *	
orthophosphate	total phosphorus *	
	silica *	
	sodium *	* to coincide with diatom samples only

Table 2.3 gives a summary of the data for the main river and tributary sites.

Table 2.3 Selected summary data for chemical determinands for January-October, 1992. Site locations are given in Table 1.7 and Figure 1.13.

determinand:	Conductivity µS/cm		Orthophosphate Mg/l		pH		T.O.N Mg/l	
period:	Jan- Oct		Jan- Oct		Jan- Oct		Jan- Oct	
site	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev
BRHM	815	101	0.03	0.02	8.16	0.10	10.40	6.24
GTCR	852	105	1.26	0.72	8.25	0.21	12.05	5.86
HLBR	794	131	0.83	0.30	8.07	0.10	10.20	3.79
BYBR	801	104	0.93	0.35	8.21	0.17	9.57	3.41
CKHF	828	118	0.95	0.42	8.27	0.18	9.40	3.25
LHGR	746	98	0.74	0.38	8.18	0.23	8.72	2.98
DDGR	630	89	0.37	0.14	8.17	0.23	6.04	2.75
DDSD	637	85	0.37	0.14	8.35	0.20	6.10	2.83
NTWD	635	102	0.35	0.13	8.31	0.20	5.99	3.19
LTCR	1087	42	1.90	1.22	8.04	0.11	11.26	3.46
MDFD	805	108	0.04	0.03	7.62	0.27	2.22	1.34
CKCY	603	102	0.77	1.22	7.99	0.16	5.71	2.53
GDSN	527	33	0.02	0.00	8.13	0.08	4.88	0.80
OXHY	541	46	0.23	0.12	8.15	0.16	4.92	1.32
OXDR	690	19	0.02	0.00	7.86	0.08	8.59	0.53
BMWL2	712	39	0.02	0.00	7.89	0.09	13.61	1.41
BMWL1	681	15	0.02	0.00	7.84	0.15	15.03	1.41
ETMR	758	41	0.02	0.00	7.99	0.10	12.72	1.02
BNBD	929	112	0.84	1.09	8.17	0.24	12.02	5.45
WTBR	771	85	0.03	0.02	7.94	0.09	10.46	2.94

River Wissey

As expected for a Chalk stream, mean concentrations of most determinands and electrical conductivity were relatively high (Table 2.3). Chemical analyses of water samples from the River Wissey demonstrated a downstream improvement in water quality from NWC Class 1B between the source and Ickborough to NWC Class 1A subsequently. This is the same picture as that given by the past data (Section 1.2). Although the Wissey is situated in a rural catchment, most of the population is concentrated in the upstream areas at Swaffham & Watton where the river's dilution capacity is lowest.

The high levels of TON and other nutrients at Great Cressingham were almost certainly due to being downstream of the main Swaffham sewage outfall. Further downstream at Hilborough, dissolved nutrients declined because of dilution by spring water influx (confirmed by discharge comparisons, see 2.2.2).

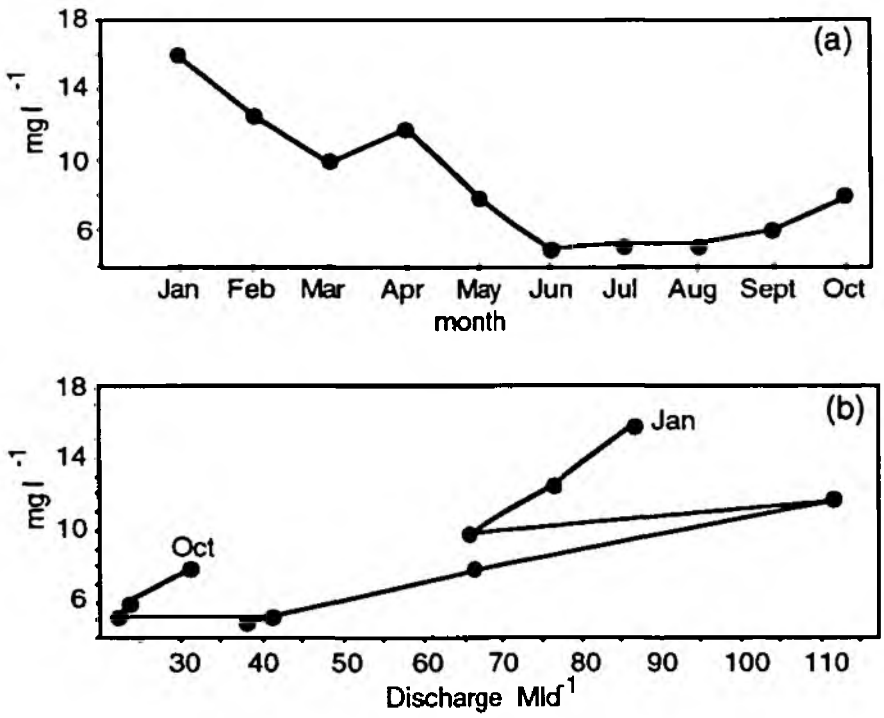


Figure 2.2 Changes in Total Oxidised Nitrogen in River Wissey water samples. a) seasonal pattern (mean for all sites); b) relationship with discharge.

Seasonal conductivity changes corresponded well with Total Oxidized Nitrogen (Figure 2.2a), displaying a distinctive annual cycle related to solute accumulation and leaching and uptake by aquatic macrophytes. Orthophosphate concentrations showed a contrasting seasonal pattern with low levels in January (< 0.5 mg l^{-1}) reaching near maximum levels in October. Distinct patterns of hysteresis with discharge were observed with TON (Figure 2.2b) and other nutrients.

Tributaries

All the tributaries except Watton Brook were relatively uncontaminated. Watton Brook was classed as NWC Class 1A (NRA 1990) in the upper reaches declining to NWC Class 2 below Watton Village after receiving sewage effluent.

The Watton Brook generally displayed highest solute concentrations, receiving effluent from Watton STW. The exception to this was TON, which was observed to be highest in the Old Carr (Barton Bendish) and Stringside streams (10-15 mgl^{-1}), probably attributable in the former case to fertiliser runoff, and in the latter to nitrate flush where the site was dry for most of the preceding summer months.

2.3.2 Biological water quality: Diatoms.

Diatoms are potentially excellent indicators of water quality, as unlike consumer organisms (fish, macroinvertebrates) most algae receive nutrients directly from the water and the effects of chemical pollutants will most immediately be felt by these primary producers before being cycled to higher trophic levels. Also, as diatoms are one of the most truly cosmopolitan groups of organisms, it is possible to apply indices developed for one region to any other given similar habitat conditions. The most quantitative study of diatom communities as indicators of pollution in rivers is from Japan (Watanabe *et al.* 1988, 1990). Round (1991a) has highlighted the potential for diatom water quality monitoring in the UK.

Methodology.

A survey of the diatom flora of the River Wissey and its tributaries was made based on six sites: Gooderstone, Little Cressingham, Great Cressingham, Bodney Bridge, Chalk Hall farm and Northwold (see Table 1.7 and Figure 1.13). An extensive sampling programme was undertaken in May 1992, samples being collected from a range of substrates and the water column and fixed using 10% formalin. In addition, at each site (with the exception of Gooderstone) an artificial substrate collecting technique using glass microscope slides suspended in the water column was utilised. On monthly visits between June and October 1992 slides were collected, replaced and additional suspended and epilithic diatom samples taken.

Species diversity and diatom abundance.

A total of 144 diatom taxa were identified to species or sub-species level. Most were rare (less than 5% of the sample) and species diversity was accordingly low. A diversity index (Shannon-Weiner) produced values between 0.64 and 3.30. Diversity varied most between the types of substrate sampled (highest in the water column and on living and dead plant material; lowest on the artificial substrate) rather than between sites. The environments studied in the Wissey were neither pristine nor highly polluted and no clear relationship was found between species diversity and water quality.

Diatom abundance was measured at four sites from the colonization of the artificial substrates. Broadly similar abundance values of <1000 cells.mm^{-2}.$month^{-1}$ were found for Bodney

Bridge, Chalk Hall farm and Little Cressingham, whereas Great Cressingham had abundance values >3000 cells.mm^{-2}.month^{-1}. This suggests a longitudinal gradient from highly productive headwaters to lower productivity levels downstream. Chemical inhibition at the lower sites, or differences in shading might also be possible explanations.

Classification of diatom communities.

Classification of the diatom communities using TWINSPAN (Hill 1979) revealed differences in sample species assemblages between methods of sample collection, between-sites and between months. Notable groupings include:-

i) The artificial substrate and water (planktonic) samples - the colonisation of the glass slides from drifting diatoms probably accounts for their similarity.

ii) The Gooderstone samples which possessed a unique flora in the context of this survey.

iii) The August samples, characterised by a bloom of a single species.

iv) The Watton Brook samples followed by the the other main river sites, suggesting a longitudinal trend, with true planktonic diatoms appearing only at Northwold.

Diatom communities and water quality.

The Diatom Index of Pollution (DAIpo) developed for Japanese rivers was used to assess the water quality of the Wissey. This scores species from 1-100, where values <30 are pollution tolerant (saprophilous), and species scoring >70 are indicative of clean water conditions (saprophobic). Over 70% of the diatom values in each sample from the Wissey were found within the Japanese index. DAIpo values for Wissey sites ranged from 47-55.

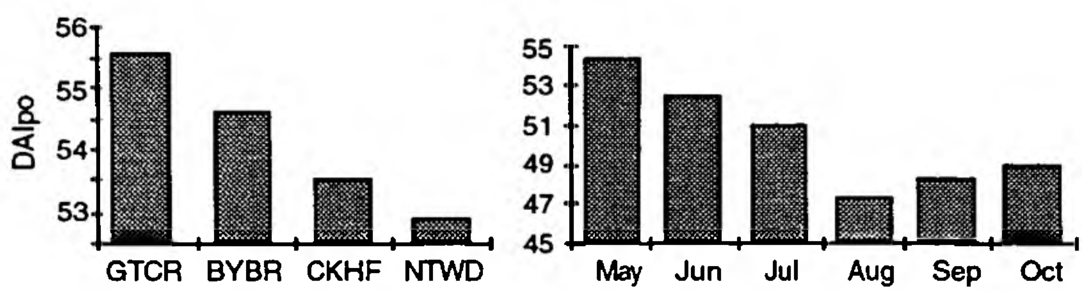


Figure 2.3 Mean DAIpo index scores for River Wissey sites, showing longitudinal (left) and temporal (right) trends.

A longitudinal decline was found (based on the major May survey) from Great Cressingham to Northwold (Figure 2.3), due to an increase in the proportion of saprophilous taxa downstream while saprophobic taxa remained relatively constant.

A seasonal decline (based on the monthly artificial and natural substrate samples) was noted from May to August, with a recovery in September and October. The range of DAIpo scores was greatest at the uppermost site (Great Cressingham), and least at the lowermost (Northwold), suggesting that the smaller, headwater sites are more vulnerable to pollution under low flows.

Of the tributaries, Gooderstone on the River Gadder showed few pollution-tolerant but several pollution-intolerant species. In contrast, the Watton Brook site had the highest proportion of pollution-tolerant species (as might be expected from it's known chemical water quality status) although, paradoxically, a relatively high proportion of pollution intolerant species also.

Chemical gradients.

The diatom communities were related to measured water chemistry using Canonical Correspondence Analysis (CCA, ter Braak 1987). Conductivity, pH, ammonia, orthophosphate, total phosphorous, dissolved silica, and total organic nitrogen (TON) were introduced as environmental variables (the last two were later omitted due to problems of collinearity). The first three ordination axes explained nearly 80% of the variance in diatom sample communities.

High orthophosphate and to a lesser extent ammonia were related to the saprophilic species characterising the Watton Brook site, while total phosphorus correlated more closely with those at Northwold. The Gooderstone samples possessed a distinct diatom community but failed to correlate with any of the measured variables. The unusual substrate at this site (a calcareous concretion) may be implicated. Conductivity and pH were not found to correlate significantly with the diatom assemblages.

2.3.3 Conclusions.

During 1991-2 water-quality was poor throughout the stream network. Using chemical data, the diatom assay and information provided by recent invertebrate surveys (Section 1.2.3) four water-quality types have been defined characterised by decreasing concentrations of orthophosphate and total oxidized nitrogen along a general downstream gradient:

i) Watton Brook being moderately polluted (NWC Class 2);
ii) the upper Wissey sectors 1 and 2 (NWC Class 1B);
iii) River Wissey sectors 3 and 4 (NWC Class 1B); and
iv) the lower middle river, sector 5 (NWC Class 1A).

The last type also includes the Gadder but the Stringside Stream, whilst having low concentrations of orthophosphate, has very high nitrate levels. The biological indicators suggest that small streams such as the Stringside and upper Wissey may be particularly sensitive to water-quality problems during periods of low runoff. The strong influence of orthophosphate concentrations on the biological quality of the river was demonstrated by analyses of the diatom data.

2.4 The channel bed environment.

The channel bed provides important habitat for benthic invertebrates and some important fishes, notably for Trout spawning and egg incubation. With reference to the channel bed, 'habitat quality' is defined by the sediment composition and the temperature profile. Water temperature is a primary environmental factor influencing the distribution of aquatic communities, affecting the embryonic development, growth, life cycle, physiology and distribution of fish and aquatic invertebrates. Temperatures within the channel bed - at the interface between surface water and groundwater - are dependent on both river flows and groundwater levels.

2.4.1 Surface sediments.

Assessments of the percentage composition of surface sediments were made during each of the monthly surveys of the 21 sites (see Section 1.5). Between- and within-site variability is high, ranging from cobbles through gravels and sands to silts. Of the main sites Bodney Bridge, Chalk Hall Farm, Langford hall, and Didlington gravel are characterised by cobbles and gravels. High proportions of sand (>30%) dominate at Langford Hall sand, Didlington sand and Northwold. Sites with high proportions of sand are characterised by low maximum velocities. Of the minor sites, Cockley Cley and Beachamwell are characterised by gravels and cobbles whereas Gooderstone, Eastmoor and Whitebridge are dominated by sand. Silt was a particularly important component of the substrate at Great Cressingham, Cockley Cley and Whitebridge.

2.4.2 Freeze-core survey of surface and subsurface sediments.

Quantitative data on the particle-size distributions of the channel-bed sediments were obtained for 8 sites on the River Wissey (see Table 1.7 and Figure 1.13). Sediment samples were obtained using a freeze-coring method to obtain representative samples. Each sample was a composite of 5 cores with a combined weight in excess of 20kg.

Gravel-bed sites are typical of trout streams and the bed surface comprises an armour layer of coarse and medium gravel (6-10cm). However, in comparison to spawning grounds of typical upland trout rivers, the substrate comprises finer gravel (5-28mm) and higher levels of material in the sand size range (0.125-1.0mm), rendering many of the sites 'matrix-supported'. Only at Chalk Hall Farm did the gravel substrate contain more than 40% coarser than 28mm with less than 25% finer than 2mm, but here the gravel had a depth of only 22cm Gravels are found to greater depths at Langford but these contain about 35% of fine sediment within the surface 15cm layer. At all sites the deeper substrate comprises sand or gravelly-sand. The large amount of fines at many of the sites suggests that they would provide a poor intragravel environment for developing salmonid embryos.

2.4.3 Surface and hyporheic water temperature.

This study investigated surface and hyporheic temperatures at five sites on the Wissey and tributaries - Chalk Hall Farm, Langford Hall (gravel and sand), Gooderstone and Whitebridge, over the period February - October 1992. The method used a chemical technique involving the hydrolysis of potassium ethyl xanthate, KEtX, (After Ashworth,1980; Ashworth & Crépin, 1990.). Surface flows were also recorded using a continuous monitoring temperature probe sited near Langford Hall.

Surface water temperatures ranged from mean monthly values of 17.3°C+/-0.7°C to 7.1°C+/-0.5°C. The temperature probe recorded an instantaneous maximum of 21.8°C (July) and a minimum of 1.0°C (December, 1991). All of the sites demonstrated large ranges (2<4°C) between temperatures experienced in the free flowing water of the river and those found at a depth of 65cm within the substratum (Table 2.4)

Table 2.4 Maximum and minimum mean monthly temperatures in profiles through the channel bed at five sites on the River Wissey (for codes see Table 1.7 and Figure 1.13).

Site\Depth	0 (max.)	0 (min.)	-25cm (max)	-25cm (min.)	-65cm (max)	-65cm (min.)
CKHF	17.8	6.9	17.2	7.1	15.7	7.5
LHGR	17.6	7.1	16.5	7.2	15.2	7.5
LHSD	17.5	7.3	15.8	7.3	13.7	7.6
GDSN	17.9	7.5	16.9	7.7	15.6	8.1
WTBR	16.6	6.6	15.6	6.9	14.0	7.1

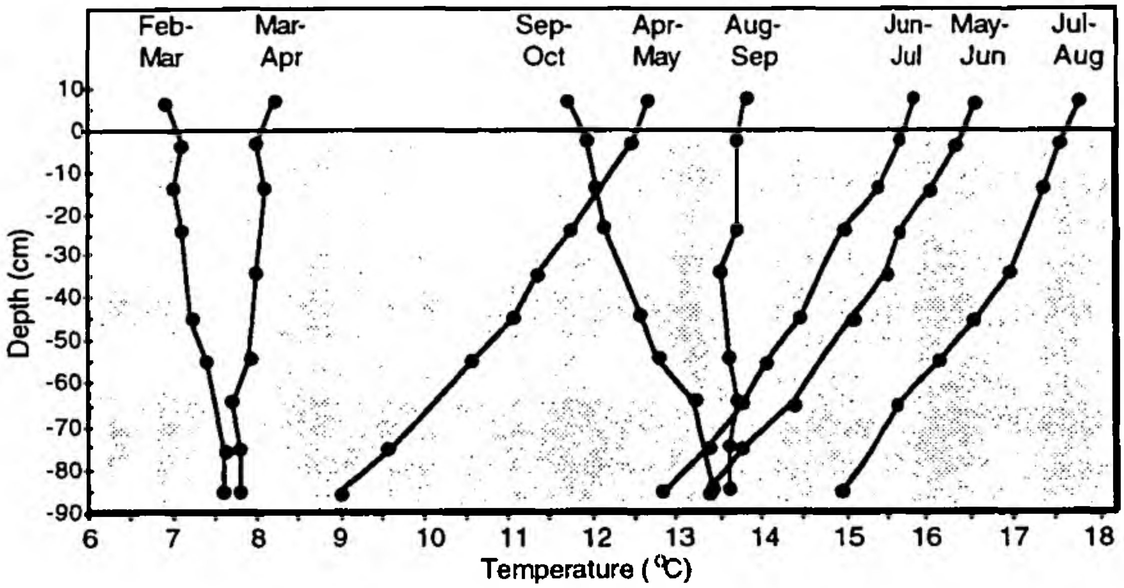


Figure 2.4 Thermal profiles for Chalk Hall Farm, February - October 1992.

Lowest summer temperatures at depth were observed at the sand-bed site and at Whitebridge where the channel bed was weathered Chalk. Thermal processes at the surface appear less important here that at the other, gravel bed, sites or upwelling groundwater may have a greater influence. The higher permeability of the gravel-bed sites may allow greater throughflow of surface water and it is at these sites that temperature profiles within the substratum may be most sensitive to flow changes.

Published information on the responses of trout to surface water temperature (Crisp 1989, Elliot 1981) suggest that high summer maxima could stress Trout with decreasing feeding and growth rates due to rising water temperatures. Macroinvertebrates do not appear to become stressed until much higher temperatures, although the effects on their growth rates are not well known. The data on hyporheic temperature patterns in the Wissey during the survey period suggest that differences of the temperature within the substratum between sites might influence the timing of invertebrate life stages.

2.5 Macrophytes.

During the survey period, most of the main sites were characterised by high macrophyte growth. With the exception of Bodney Bridge and Langford Hall sand site, *Ranunculus* had an average cover of 10-20%. Cress (mainly *Rorippa*) was patchy, but important at all sites except the two sand-bed sites. Algae was particularly abundant at Bodney Bridge. Of the minor sites, Whitebridge was especially affected by macrophyte growth with both *Ranunculus* and Cress being important at different times of the year (Figure 2.5). The seasonal development of macrophytes was shown to play a major role in maintaining a diversity of habitat patches within a site during low-flow periods, patches defined especially by flow velocity and substrate type.

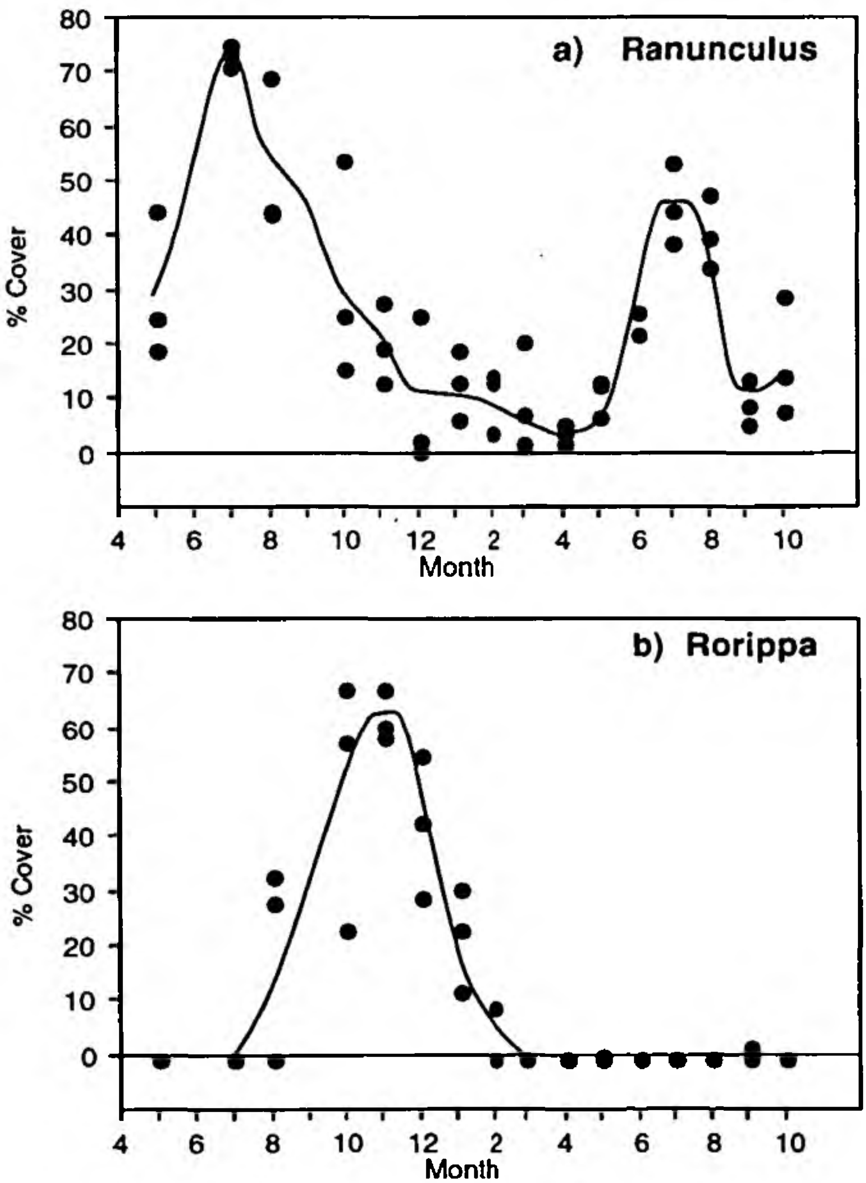


Figure 2.5 Seasonal changes in macrophyte cover at Whitebridge, May 1991-October 1992.

2.5.1 Detailed mapping of spatial and temporal changes.

Three sites were chosen for detailed mapping of aquatic macrophyte distributions over three seasons. Data on seasonal growth and recession patterns, sediment distribution and hydraulic variables were used to assess the interrelationships of aquatic vegetation and flows. Sites were: Langford Hall (gravel),, Didlington (gravel), and Northwold. Surveys took place in January, May and October 1992.

The mapping method used was adapted from that described by Wright et al (1981). Permanent pegs marked a 10m reach centred around the middle invertebrate survey transect. On each survey occasion strings and measuring tapes were used to divide the reach into 0.5x0.25m cells. Dominant macrophyte species and substrate type were recorded for each cell, later used to construct detailed site maps. Comparisons were made between macrophyte and substrate distributions, between sites and between seasons using Chi-squared analyses, and qualitatively with longitudinal depth distribution.

Figure 2.6 illustrates the seasonal changes and between-site differences in dominant macrophytes and sediment types. The two major species recorded, *Ranunculus fluvitans* and *Rorippa nasturtium-aquaticum,* show contrasting seasonal growth patterns, with the former dominant in the summer months and the latter developing later and persisting through to spring. Both species have been shown to influence hydraulics (Gregg and Rose 1982), by exerting flow-resistance, resulting in lower stream-bed velocities within the stands and higher velocities around them. By comparing macrophyte and depth distributions in the Wissey, *Ranunculus* , in particular, was shown to be a major factor in elevating depths in October.

Silt accumulation was closely associated with macrophyte development. Increased proportions of silt corresponded particularly closely with *Ranunculus* distribution in October. However, by maintaining hydraulic diversity, areas of high flow velocity around macrophyte stands are scoured free from silt, thus the overall effect is of increasing substrate heterogeneity, particularly in late summer under low flows.

The survey demonstrated the differing seasonal behaviour of the various species but was unable to fully account for between-site differences. The greater water depths and flow velocities, and consequent substrate stability, in winter at Didlington is postulated as the reason for earlier *Ranunculus* development at this site, underlining the reciprocal nature of the macrophyte - hydraulics relationship.

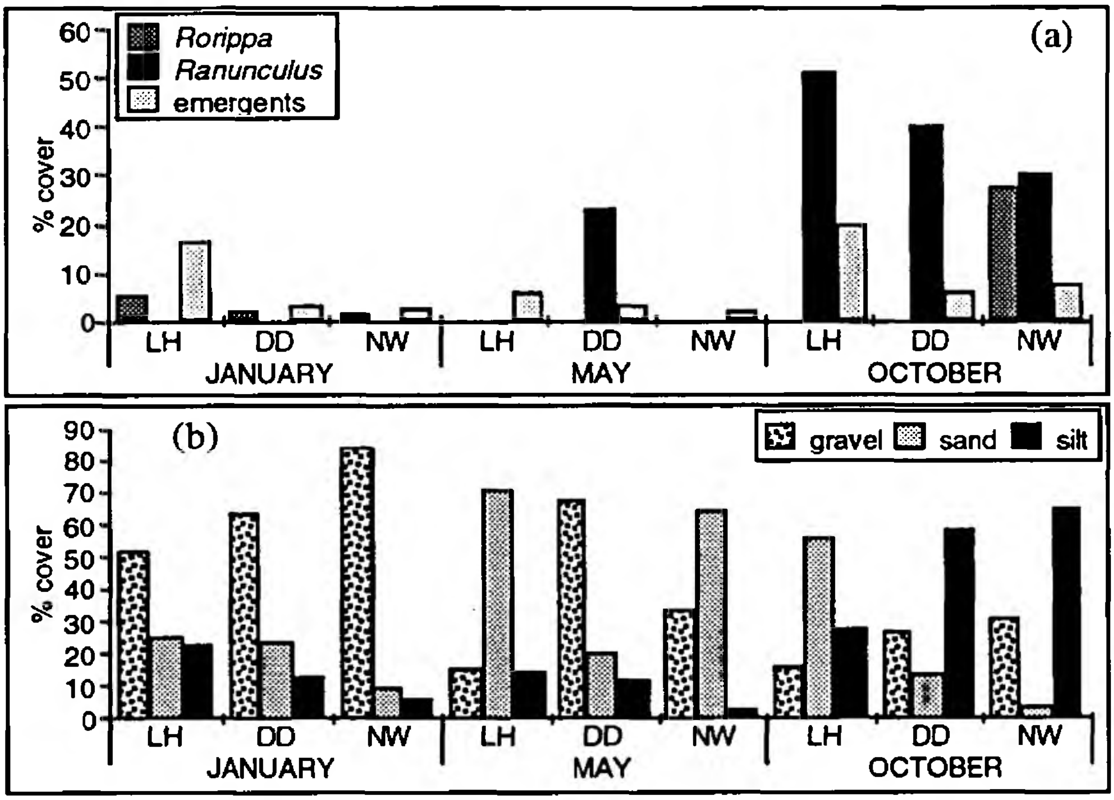


Figure 2.6 Seasonal changes in percentage cover of: a) Dominant macrophyte types at Langford Hall (LH), Didlington (DD) and Northwold (NW); b) Dominant substrate classes.

2.6 Hydraulic characteristics.

Velocity and water depth are the primary variables determining instream habitats, although some researchers have shown that complex combinations of these variables, such as the Froude Number or boundary shear stress, may yield stronger correlations with species distributions. At each of the seven main sites, riffles or runs, 20 point measurements of velocity and depth along each of three transects were made during each monthly survey to provide the primary database for subsequent analysis.

2.6.1 Instream hydraulics.

Despite the low flow conditions during the survey period, the variation of hydraulic conditions between sites was considerable. The three extremes are high depth (greater than 0.5m) and low velocity (less than $0.05ms^{-1}$) sites; low depth (less than 0.1m) and low velocity (less than 0.1 ms^{-1}) sites; and sites with high velocity (greater than $0.6ms^{-1}$) and low depth (less than 0.2m). These types may be termed deep run, shallow run and riffle, respectively.

In addition to monitoring depth and velocity, an index of bed shear stress was determined using calibrated hemispheres. The mean maximum hemisphere value for the main sites ranges from 0.2 at Langford Hall sand to 4.5 at Chalk Hall Farm. Both maximum hemisphere and mean hemisphere values at a site were significantly related to both maximum and mean velocities.

Major contrasts exist between the gravel-bed sites and the two predominantly sand-bed sites at Langford Hall and Didlington. However, the Didlington sand site, with a mean depth of 0.6m was exceptionally deep, all other sites being shallower than 0.2m. Between the main sites, located between Bodney and Northwold, mean velocity varies little, ranging from $0.14ms^{-1}$ at Langford Hall sand to $0.28ms^{-1}$ at Chalk Hall Farm. Greatest differences exist between sites in terms of maximum velocity (Figure 2.7): the sand-bed sites at Langford Hall and Didlington having the lowest values.

At-a-station hydraulic changes.

Summary relationships between flow depth and velocity with discharge are usually expressed as hydraulic geometry relationships (Table 2.5). At most sites, velocity increases most rapidly in relation to discharge and the rate of change of velocity tends to increase along the river, being highest at the downstream sites. The main exception to the general trend is the Langford Hall sand-bed site where depth is the dominant variable. Changes of instream hydraulics with discharge are least sensitive at the Didlington sand-bed site, reflecting the importance here of macrophytes (mainly *Ranunculus* see Section 2.5). Maximum and mean velocities are strongly related to discharge, but depth variations are determined by macrophyte growth, especially during the low-flow period (Figure 2.8).

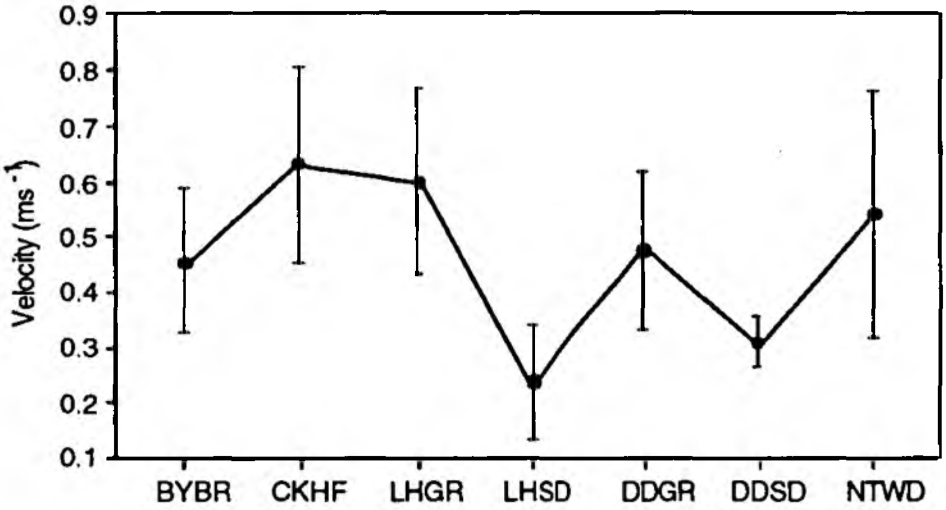


Figure 2.7 Variation of maximum velocity within and between sites. Mean and one standard deviation error bars for each of three transects at each site (n = 16).

Table 2.5 Hydraulic geometry relationships (log v=k+logQm, log d=c+logQf) and correlation coefficients (r^2) for selected sites on the River Wissey and tributaries. Site codes and locations are given in Table 1.7 and Figure 1.13).

	m	r^2	f	r^2
BRHM	0.456	0.94	0.443	0.97
GTCR	0.510	0.91	0.343	0.89
HLBR	0.588	0.85	0.427	0.88
BYBR	0.823	0.80	0.325	0.37
CKHF	0.644	0.44	0.400	0.40
LHGR	0.618	0.42	0.342	NS
LHSD	0.249	NS	0.645	0.77
DDGR	0.914	0.52	0.054	NS
DDSD	0.458	0.24	-0.049	NS
NTWD	1.084	0.74	-0.159	NS
CKCY	0.196	NS	0.482	0.54
BMWL	0.620	0.89	0.341	0.81
GDSN	0.557	0.88	0.354	0.81
BNBD	0.710	0.84	0.186	0.47
OXHY	0.147	NS	0.070	NS
OXDR	-0.240	NS	-0.066	NS
ETMR	0.540	0.84	0.307	0.73
LTCR	0.625	0.82	0.449	0.76
WTBR	0.518	0.65	0.372	0.59

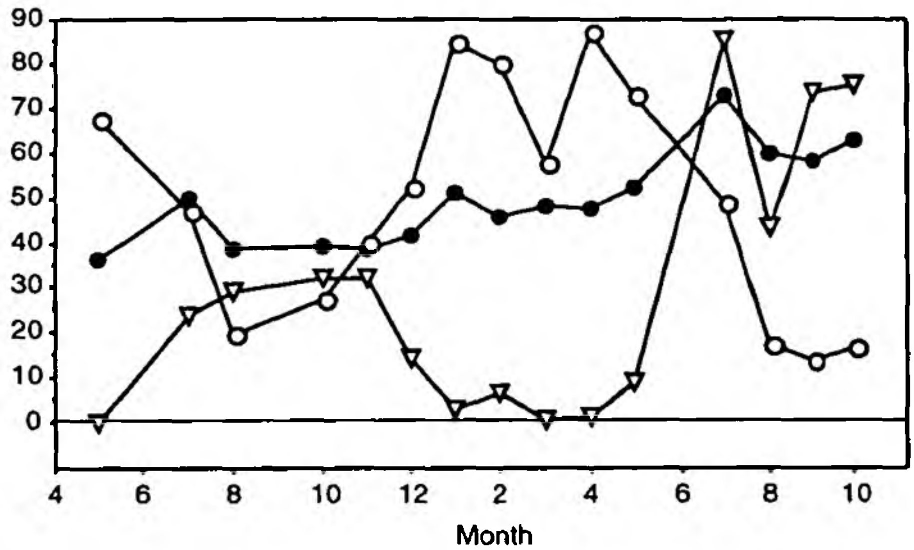


Figure 2.8 Variation of mean depth (●, cm) with discharge (o, m^3s^{-1} x 100) and changing macrophyte cover (▽, %) at Didlington Sand from 10/91 to 10/92.

2.6.2 Hydraulic refuges.

Natural channels have a form that produces a diversity of habitats. Under the range of normal flows, the range of habitats - defined by velocity, depth and substrate - is sustained during declining discharges although the relative area of each changes. For example, the reach through Chalk Hall Farm is a classic Chalk stream with a sinuous course creating an asymmetric distribution of velocities and depths across the channel; and a gravel-cobble bed with a well-developed pool-riffle sequence. Over the period of survey, depths and velocities over the riffle ranged up to 0.4m and $0.9ms^{-1}$ respectively. The spatial variability of hydraulic conditions was reflected by the bed sediments with patches of sand and silt in the low-velocity areas. The site was also characterised by growths of macrophytes, and the total cover of macrophytes ranged from 15% to 75%; maximum development occurred during the summer, increasing flow depth and causing flow convergence between the macrophyte beds, maintaining high-energy habitats during the low-flow conditions.

During the decline in flow, as gauged at Northwold, from $0.88m^3s^{-1}$ in February, to $0.76m^3s^{-1}$ in May and to $0.36m^3s^{-1}$ in October, patches with mean velocities greater than $0.5ms^{-1}$ - a flow threshold of significance for a number of invertebrate taxa such as Simuliidae - were maintained, although the "usable" area declined from about 40%, to 20% and to 7% respectively. Patches characterised by velocities less than 0.2 ms^{-1} were present even during the highest flow, and their area increased with declining flows from 35%, to 48% and to 50% respectively.

The maintenance of hydraulic patches within a site is well demonstrated by the distribution of Froude Numbers - a hydraulic index that combines velocity and depth (Figure 2.9a). The major difference between the hydraulic conditions in May and October, when flow declined by more than 50%, was the increase in the proportion of the channel with still water, rather than the elimination of higher energy habitats.

In contrast, the sand-bed reach at Langford presents a relatively uniform habitat; more than 50% of the reach is deeper than 20 cm over the range of flows experienced, compared with 10 cm at Chalk Hall Farm, yet maximum depths are similar (over 40cm). However, velocities during the survey were always below 0.4 ms^{-1}; between 30% and 60% of the reach had velocities below 0.15ms^{-1} over the range of flows experienced. Maximum velocity within the reach shows no significant change with discharge. The channel substrate is dominated by sand but the surface of the channel bed became progressively coated by silt during the 18 month period of survey. At the end of the survey in October 1992, 40% of the bed was coated with silt. Variation of hydraulic patches, as indicated by the Froude Number (Figure 2.9b) again shows that even under extreme low flow 40% of the reach has a value of greater than 0.15, which is associated with velocities of greater than 0.2ms^{-1}.

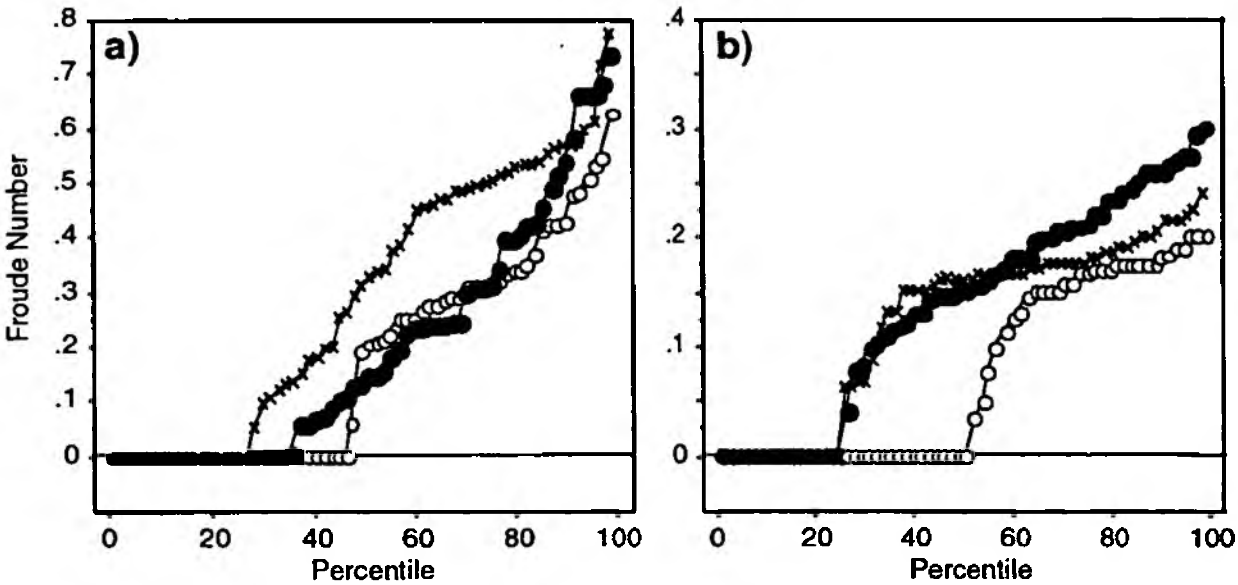


Figure 2.9 Variation of the range of habitats, described by the Froude Number at three flows (O - 0.36 m^3s^{-1}; ● - 0.76 m^3s^{-1}; × - 0.88 m^3s^{-1}) for a) a typical gravel-bed, riffle-pool reach and b) a sand-bed reach.

2.7 Summary.

i) Flows during the period of survey were exceptionally low. It is likely that the biota were stressed both by the low flows and by siltation caused by the lack of flushing flows, the highest flow during the period of survey being less than 10% of the long-term maximum flow.

ii) Flow gaugings confirmed that about 30% of the flow at Bodney Bridge is from springs and groundwater seepage between Great Cressingham and Hilborough.

iii) Flows at sites along the main river can be predicted from the Northwold gauge record and the similarity in hydrological variability allows the Northwold gauge to be used as the control point for flow management.

iv) High nutrient levels characterize the whole river, especially the headwaters and concentrations tend to decline downstream. Levels were particularly high throughout 1991-2, possibly because of the low flows.

v) Water temperatures during the period peaked at 21.8°C during July. Mean temperatures declined markedly with depth within the substrate, especially in the sand-bed and chalk-bed sites reflecting the influence of substratum permeability.

vi) The channel bed has high sand concentrations and gravels suitable for trout spawning are often shallow.

vii) Macrophyte growth showed strong seasonality with *Rorippa* dominating in late summer and autumn, and *Ranunculus* dominating in early-mid summer.

viii) Hydraulic variations with discharge reflected channel form, variations of discharge were associated mainly with changes of depth at the sand-bed sites and of velocity at the gravel-bed sites.

ix) Hydraulic refuges and a patchwork of different habitats are shown to be sustained during declining flows by both a diverse channel form and by macrophyte growth

SECTION 3
LINKING HYDROLOGY AND ECOLOGY.

3.1 Introduction.

Section 1 of this report described the hydrology, physical habitat and ecology of the River Wissey and it's catchment, paying special attention to the role of surface- and groundwaters in maintaining habitat character. Section 2 summarized the procedures undertaken to quantify the dynamic characteristics of the range of habitats found along the river. The final step was to establish approaches to link hydrology and ecology so that responses of biota to changing flows can be assessed.

Linking hydrology and ecology is a complex science because of the many ways in which discharge influences biota (by determining habitat suitability for each life stage) and biotic interactions (predation, competition etc). The influence between flow and biota is often indirect, relating to combinations of hydraulic conditions, which are dependent upon the channel bed form, and influenced by substrate and macrophyte growth. These interrelationships were elucidated in Section 2.

Three approaches were used:

i) Hydrological approaches recommended in the literature were considered. These are easy to determine but make important assumptions about the biological significance of flows.

ii) An established simulation model (PHABSIM) was used to integrate hydraulic data and published information on the habitat preferences of target species. This approach assumes that the habitat preferences for the target species are not river specific.

iii) A new approach was developed based upon data on macroinvertebrate distributions in relation to habitat within the River Wissey. The approach can be justified on three grounds. First, in comparison to fish, invertebrates have lower trophic positions, are generally less mobile and may have narrower tolerances to habitat changes. Secondly, their rapid colonisation of habitats and short life cycles allows the development not only of river-specific habitat preferences for both species and communities, but also season-specific habitat preferences giving due regard to the different life stages. Thirdly, invertebrate data are collected routinely by the National Rivers Authority, so potentially, an invertebrate-based method might allow routine instream-flow assessment.

3.2 Hydrological Approaches.

Traditionally, minimum flows for rivers have been set using discharge-based methods. The justification for the hydrological approach is that over the long term, stream flora and fauna have evolved to survive periodic adversities without major population changes.

A minimum flow is expressed as a hydrological statistic: commonly either as a flow duration statistic (such as the 95th percentile) or as a fixed percentage of the average daily flow (ADF). Orth and Leonard (1990) demonstrated that for streams in Virginia, USA:

- i) 10% ADF correctly defined degraded or poor habitat conditions;
- ii) 20% ADF provided an appropriate criterion for protecting aquatic habitats; and
- iii) 30% ADF defined near optimum habitat in small streams

The Northeast Region of the US Fish and Wildlife Service have established an Aquatic Baseflow (ABF) which defines the minimum acceptable flow as the median flow in the month during which low flow conditions typically result in the most metabolic stress to aquatic organisms (Kulik, 1990). Stress was recognised as being exerted by high water temperature and diminished living space, dissolved oxygen and food supply.

The average daily flow for the River Wissey at Northwold for the period 1956-85 is 1.9 cumecs, a value which is reduced only marginally, to 1.86 cumecs, if the record up to and including 1990 is used. Applying the above criteria suggests the following flow recommendations for the Wissey at Northwold:

absolute minimum flow to prevent marked habitat degradation	= 0.19 cumecs
minimum flow to protect fish habitat	= 0.38 cumecs
optimum flow for fish	= 0.57 cumecs
September median flow	= 0.79 cumecs

The above values compare with the 95th Percentile (1956-85) of 0.58 cumecs. The biological significance of the various hydrological criteria has not been evaluated for any type of stream in the UK. This may be particularly significant for Chalk streams, characterised by very low flow-variability. Comparison of the criteria with biological response information developed in subsequent sub-sections will allow an evaluation to be made at least for the Wissey, and one which may provide a guide for baseflow streams within the Anglian region.

3.3 PHABSIM habitat assessment.

The Physical Habitat Simulation (PHABSIM) System is the cornerstone of the Instream Flow Incremental Methodology, which is widely used throughout USA for defining impacts of changing instream flows. PHABSIM is a set of computer models that are used to relate changes in discharge or channel structure to changes in physical habitat availability for a selected species.

3.3.1 Methods.

Site Selection.

Reaches used for PHABSIM incorporated the main sites (Figure 1.13, Table 1.7). Each reach consisted of a riffle - pool - riffle - pool - riffle sequence or, in sand-bed reaches, were 10 times channel width in length. Seven transects were established along each reach in order to sample the microhabitat variability present at each site. Mean velocities were measured at 0.6 times the depth. Substrate type was also recorded for each point. Each reach was visited under three different flows i.e. low, medium and high calibration flows. On each occasion, water surface elevations and velocities were recorded whereas substrate is assumed to be constant and was therefore only recorded on one of the visits. Both the reach length and number of transects was smaller than that normally used for PHABSIM, but when used with a sector-reach classification system has been found to yield comparable results (Petts et al., 1993).

Ecological data.

Microhabitat suitability curves utilised in this study were originally developed by Armitage and Ladle (1989) and Mountford and Gomes (1989). The curves themselves were developed based on experience and local knowledge of UK conditions. Curves have been used for:-

- seven species of fish (Brown trout, Dace, Chub, Roach, Bream, Pike and Perch),
- four life stages for each fish species (i.e. spawning, fry, juvenile and adult),
- four species of aquatic invertebrates (i.e. one stonefly (*Leuctra fusca*), two caseless caddis (*Rhyacophila dorsalis* and *Polycentropus flavomaculatus*) and one pea mussel (*Sphaerium corneum*)).

Habitat preferences are expressed in each case as functions of depth, velocity and substrate.

3.3.2 PHABSIM simulation and results.

The model was calibrated for each site to three flows ranging from 0.23 cumecs to 2.3 cumecs. Simulated flows range from 0.4 times the lowest calibration flow to 2.5 times the highest calibration flow.

Habitat versus discharge relationships.

Output from the PHABSIM simulations were used to determine the habitat versus discharge relationships for the selected life stages and species. An example of these relationships is shown in Figure 3.1 which highlights the results for Brown Trout at Northwold. Habitat is expressed as the percentage of a reach that is usable habitat for the chosen species/life stage and discharge is expressed in m^3s^{-1}.

Such plots allow the definition of:-

i) the flow that provides the maximum area of usable habitat;
ii) the critical flow below which the habitat availability rapidly declines, which may the be same as (i);
iii) the critical flow below which no habitat is available;

The species and life stages for which a reach is most suitable can be identified by comparison of usable habitat - discharge plots. From this example it is evident that the Northwold reach is most suitable for the juvenile life stage of Brown Trout but habitat availability rapidly declines below flows of 0.45 m^3s^{-1}. Also, the reach is characterised by no suitable habitat for the adult life stage when flows are below 0.19 m^3s^{-1}.

From the full analysis presented in Annex C, four different responses of biota to declining flows are defined. Certain taxa are shown to be more susceptible to reductions in flow below average levels than others and adult Brown Trout are shown to be particularly sensitive to low flows.

Differences between sites reflect channel form, substrate and macrophyte growth. Over half (10 of the 19) of the species considered were shown to have the largest proportion of habitat available at Didlington Sand - a deep reach with moderate flow velocities (maintained during low flows by patchy macrophyte growth).

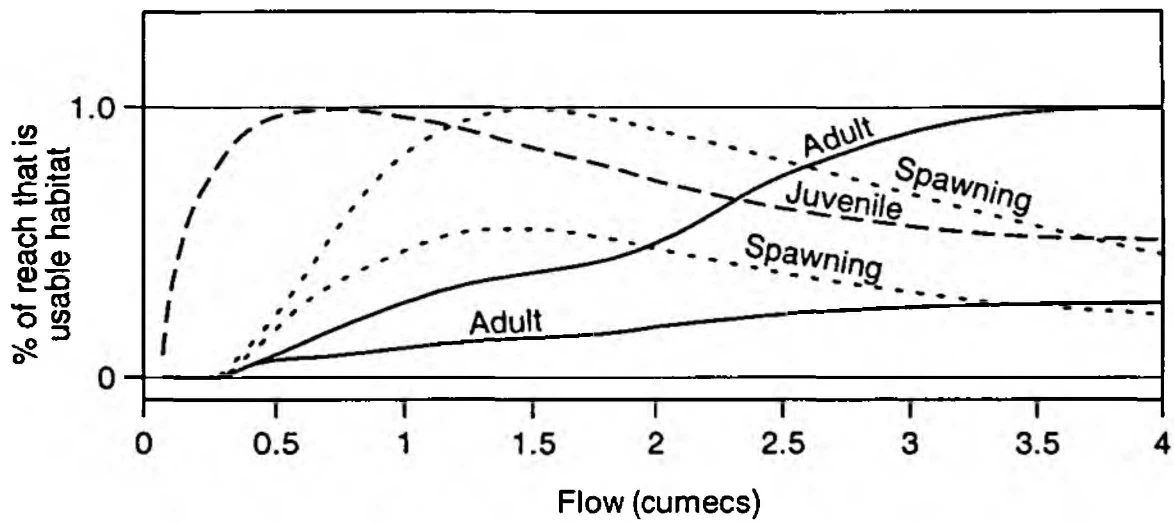


Figure 3.1 Habitat-discharge relationships for Brown trout at Northwold

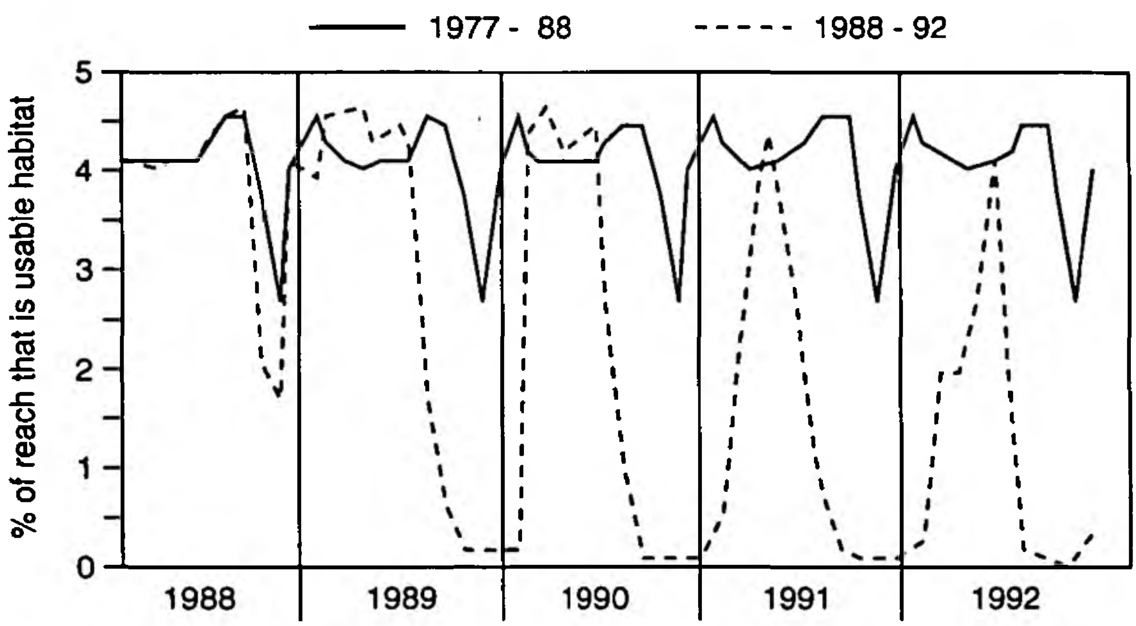


Figure 3.2 Habitat usable area time series for Brown trout at Northwold

Habitat area-time series.

The results of the discharge versus per centage usable area relationships have been combined with the actual discharges experienced during the drought to show the effect that reduced flows had on habitat area available for each life stage of Brown Trout at the Northwold site. Figure 3.2 shows the habitat area-time series for thc 1988-92 drought compared with a habitat area plot based upon average monthly flows (1977-87) for adult Brown Trout.

3.3.3 Summary.

Classification of channel sectors and reaches enabled the selection of sites that represent the range of habitats that characterize the main river. Table 3.1 summarizes the flow criteria determined for adult and juvenile trout at the seven main sites. The key points are:-

i) the minimum flow to maintain some habitat for adult trout at <u>all</u> sites is 0.80 cumecs.

ii) the minimum flow below which adult trout habitat will be eliminated throughout the river is 0.19 cumecs.

iii) a flow of 0.35 cumecs will sustain habitat for adult trout in 'good trout habitat' in both sectors.

iv) optimum habitat within the main river for juvenile trout is available at a flow of 0.85 cumecs.

<u>Table 3.1</u> Flows (cumecs at Northwold gauge) predicted to provide the limit of usable habitat and the maximum area of usable habitat for adult and juvenile life stages of Brown Trout at the main sites (codes given in Table 1.7 and locations in Figure 1.13). [1] minimum habitat is defined arbitrarily as 0.2% of the reach.

	Sector 3				Sector 4		
Site code	BYBR	CKHF	LHGR	LHSD	DDGR	DDSD	NTWD
Bed material	Gravel	Gravel	Sandy-gravel	Sand	Gravel	Sand	Sandy-gravel
Bed form	Channel-ized	Riffle-pool	Riffle-pool	Run	Run	Run	Deep-riffle-pool
Vegetation	Marginal	Marginal	Shaded	Shaded	Submerged	Submerged	Submerged
Adult:							
zero habitat	0.57	0.25	0.35	0.33	0.35	0.80	0.19
minimum[1] habitat	0.60	0.27	0.43	0.43	0.40	0.90	0.43
max. habitat	2.83+	2.96+	1.98	3.39+	2.83+	3.96+	1.42
Juvenile:							
zero habitat	<0.06	<0.06	<0.09	<0.06	<0.14	<0.11	<0.14
max. habitat	0.85	0.85	0.71	1.41	0.85	2.54	0.85

From the full results of the simulations:-

- spawning areas were available but in reduced amounts during November/December 1990 and 1991,
- under average conditions the river provides good habitat for juvenile trout;
- under the drought conditions usable habitat for juveniles varied around average conditions except during summer 1990 and 1991 but nevertheless did not fall below 11% of the total reach.
- maximum habitat is available for adult trout during late winter/spring,
- suitable habitat for adult trout was virtually eliminated during the late summer periods of 1989-1992.

PHABSIM results demonstrate that a decline in the flows below 0.80 m^3s^{-1} at Northwold gauging station will be associated with a progressive loss of adult trout habitat. A discharge of 0.20 m^3s^{-1} at Northwold may be considered as an absolute minimum flow, below which a total loss of suitable habitat would be experienced throughout the main river.

3.4 Macroinvertebrates.

Investigations of biological responses to flow variations focused upon the spatial and temporal distribution of aquatic macroinvertebrates. The aims of this investigation were to:

1. Describe the macroinvertebrate fauna of the Wissey and tributaries, identifying sites of unusually high or low diversity or rarity.

2. Quantify spatial and temporal differences in macroinvertebrate distributions and relate these to hydraulic and other habitat variables.

3. Predict the effects of different flows on the macroinvertebrate fauna.

4. Recommend minimum flows and other habitat management procedures to optimise habitat conditions for macroinvertebrates.

3.4.1 Methodology.

Twenty-one sites were selected for macroinvertebrate sampling and monthly habitat assessment (Table 1.7, Figure 1.13). Sites are classified as primary, secondary and tertiary:

Primary sites:	Selected for most detailed study. 12 macroinvertebrate samples collected at each survey;
Secondary sites:	3 samples per survey;
Tertiary sites:	Generally small tributary sites of lesser importance. 1 sample per survey.

Sampling from the 21 sites was carried out on five occasions: May and October 1991, and February, May and October 1992.

Twelve two-minute kick/sweep samples were collected from the primary sites, four located along each of three transects (Figure 3.3). Transects were located at the centre, top and bottom of a riffle where possible. Cell width was determined by dividing the channel width by four, and remained constant at each survey. Cell length varied depending on channel width such that approximately the same area was sampled at each cell. At secondary sites three samples were taken, one centred along each of the three transects, and at tertiary sites a single sample was taken along the single transect. The transects were also used for hydraulic measurements (see section 2.6).

Samples were preserved in the field in 4% formaldehyde. In the laboratory, samples were washed, sorted into 70% alcohol, and animals identified and counted. Identification was mainly to species level, with a higher taxonomic level used for some difficult groups. Abundance data for each sample was recorded.

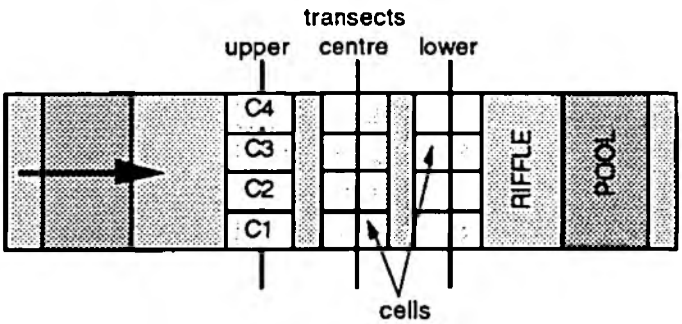


Figure 3.3 Sampling design for the primary sites. Position of the transects was marked by permanent pegs.

3.4.2 Spatial and seasonal variability in macroinvertebrate communities.

The number of macroinvertebrate samples collected from the 21 sites totalled nearly 570 and contained over 120 taxa. Species richness and abundance varied enormously between sites; abundances ranged from less than 10 to more than 1,500 per sample. No nationally rare taxa were recorded, most sites exhibited more or less rich assemblages typical of Chalk streams. An exception was Beachamwell, an intermittent tributary site, which at some sampling seasons supported a number of Plecopteran taxa unusual for the area.

Classification and ordination analyses were used to examine spatial and temporal differences between and within sites and seasons, and identify the main habitat variables in relation to which the invertebrate communities are structured.

Classification of site data.

TWINSPAN (Hill, 1979) was used to classify the sample data, using cell data, transect mean data, and site mean data. Figure 3.4 summarises the latter analysis, showing the main site and month groupings. As predicted, the smaller tributary sites displayed very different faunas from the larger main river sites. Typical of the temporary sites which formed the majority of the former group were species such as *Lymnaea palustris* and *Limnephilus lunatus* which are tolerant of drought conditions. Also in this group were sites such as Oxborough Drain, permanently flowing but having sand/peat substrates and macrophyte-rich margins which formed the major habitat area. Taxa associated with these sites were, again, molluscs and Trichoptera. Overall these sites were species-poor compared to the large, main-river group, having unusual habitats but of limited diversity.

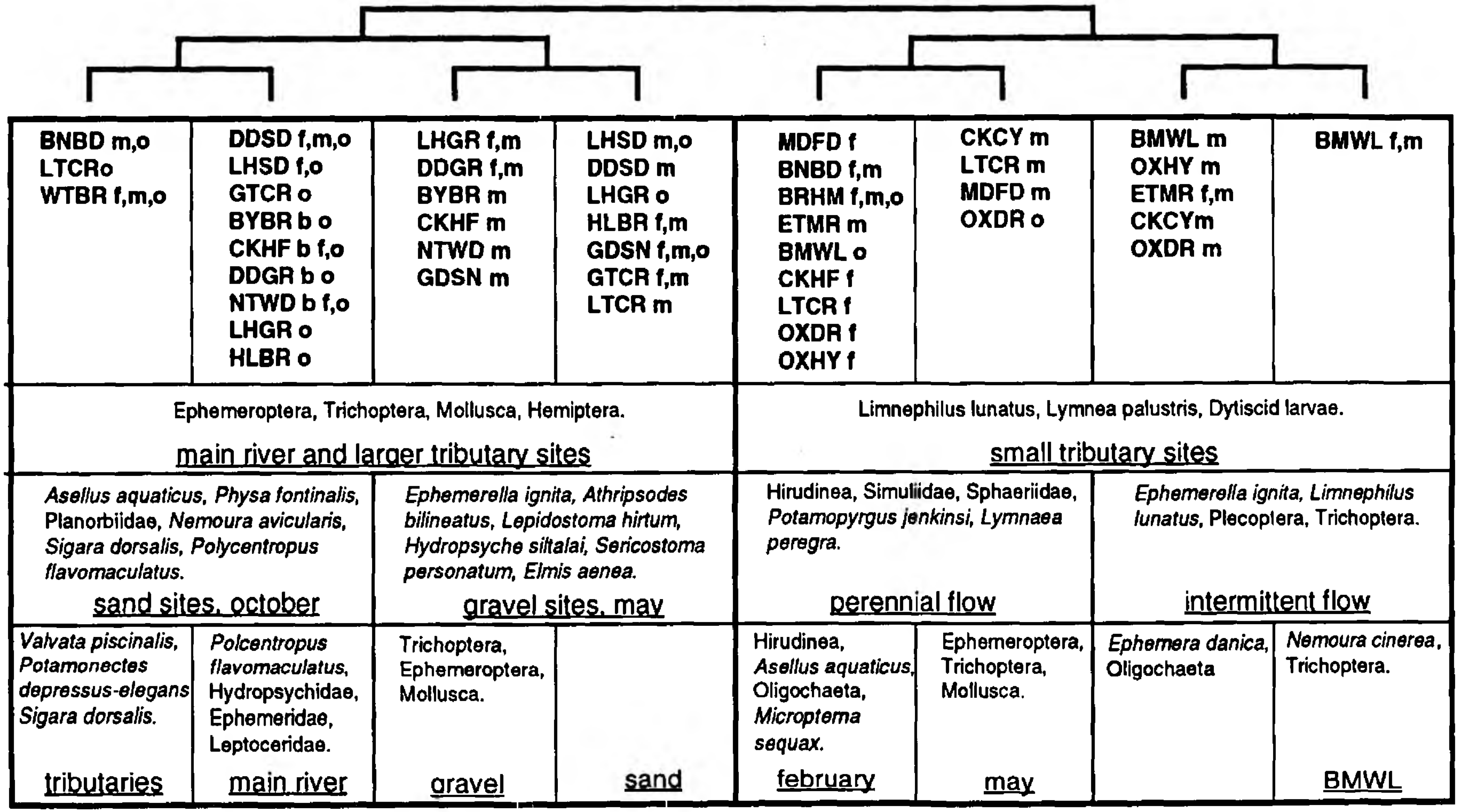


Figure 3.4 Summary of the TWINSPAN analysis of site data for the 21 macroinvertebrate sampling sites. Site codes are given in Table 1.7. f=February; m=May; o=October. Preferential species and an interpretation of the sample groupings are shown.

Within the main river sites, substrate and seasonal differences were noted, with the gravel-bed sites separating from the sand- and chalk-bed sites. Within the former group, the May samples were differentiated because of a number of taxa (notably *Ephemerella ignita*) with limited seasonal distributions due to life history traits. The sites identified from the NRA invertebrate data analysis (Section 1.2.3) as organically polluted - Great Cressingham on the Wissey and Little Cressingham on the Watton Brook - did not show particularly similar faunas, grouping instead with sites with which they shared general habitat characteristics: Great Cressingham with the other main river gravel-bed sites; Little Cressingham with the more heavily managed Whitebridge site.

Habitat variables controlling macroinvertebrate community distributions.

Ordination analyses were used in conjunction with the classification analyses to confirm site and sample groupings and relate habitat data to community distributions. Habitat data for all samples (hydraulic variables, substrate and macrophyte data) were analysed using principle components analysis (PCA) to examine the interrelationships of the variables alone. Detrended correspondence analysis (DCA) was used to ordinate the macroinvertebrate communities. The environmental data was subsequently correlated with the axis scores derived from the ordination in order to determine the dominant variables influencing the invertebrate distributions. Figure 3.5 shows the results for the three months in diagrammatic form.

The PCA of the habitat data illustrates the polarised distribution of samples between sites with high flow velocity and coarse substrate, and those with low velocity and fine substrate. High water depth and *Ranunculus* distributions are related, because of the occurrence of this macrophyte in the deeper main river sites (see section 2.5.). Very little seasonal difference is shown between the relative distributions of velocity, depth and fine substrate. A clear seasonal shift in total cover is apparent due to the change from *Ranunculus* to *Rorippa* as the dominant macrophyte in October.

The DCA results show definite seasonal shifts in the relative importance of the environmental variables for the invertebrate communities. Flow velocity appears to be an important variable in all months and is closely linked with the distribution of gravel, reflecting the fact that a large group of taxa show a preference for high flow velocity, gravel-bed conditions. Sand and silt are separately related to different communities, with the latter also associated with total cover and detritus.

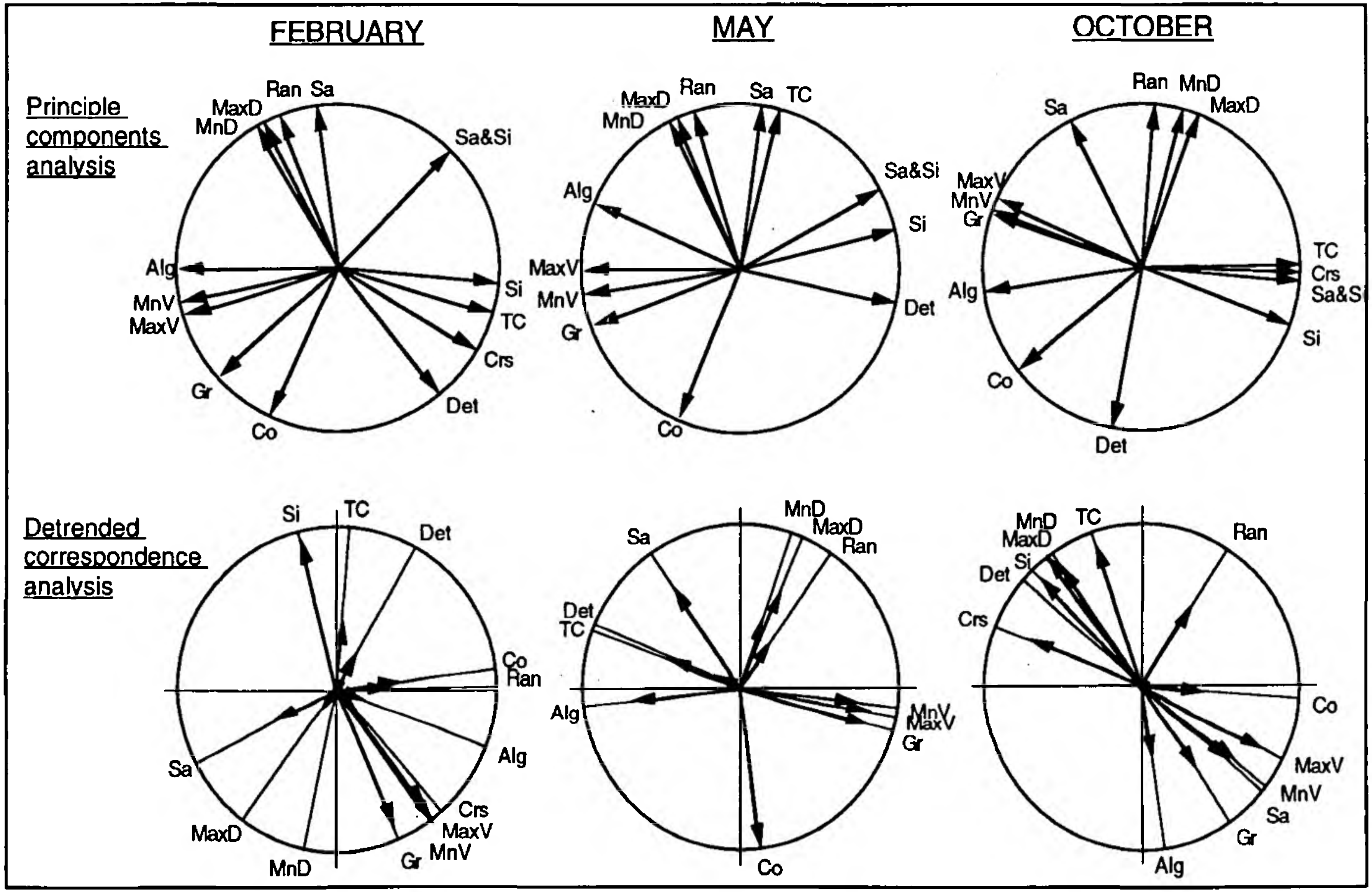


Figure 3.5 Principle components analysis of sample environmental data (top) and detrended correspondence analysis of sample macroinvertebrate abundance data with correlated evnironmental variables (bottom) for February, May and October.

There is a polarisation of communities in October between two groups of taxa:-

i) those preferring high velocities, gravel and sand (including taxa such as Elmid beetles, Leptocerid caddis and Hydrobiid molluscs), and
ii) those preferring (or tolerant of) high water depth and silt (eg Polycentropus, Lymnaeid molluscs and a number of Hemiptera associated with marginal macrophytes).

Under extreme low flows, the taxa in the first group are likely to be the most stressed as this habitat declines in availability.

3.3.3 Macroinvertebrate habitat preferences.

Investigation of the distribution of macroinvertebrates on the River Wissey identified the most influential habitat variables and highlighted the importance of seasonal changes. In order to establish quantitative relationships between the fauna and specific variables, habitat preference curves must be constructed for individual taxa.

Numerous methods exist for preference curve construction. Originally developed for fish, some attempts have been made to test these methods for use in expressing invertebrate habitat preferences. In this study, the River Wissey primary-site data set was used to construct taxa preference curves and then to predict site habitat suitability under varying discharge for individual and communities of macroinvertebrates.

Comparison of preference curve construction methods.

Three established methods of preference curve construction have been evaluated using the River Wissey data set:

1. Incremental Method (Gore and Judy, 1981).
For each taxon, average abundances (ln-transformed) are calculated for equal increments of a chosen habitat variable and plotted as a cumulative frequency curve. This curve is then described by a statistical relationship.

2. Independent Regression Method (Orth and Maughan, 1983).
A curve is fitted to a plot of the ln-transformed sample data against a chosen variable.

3. Multiple Regression Method (Gore and Judy, 1981).
This method attempts to overcome the problems of interrelatedness of variables. A statistical equation is derived for the relationship of abundance data against velocity (v), depth (d), v^2, d^2 and v x d.

In each case the derived curves are rescaled by dividing all values by the optimum to give suitability values of 0 - 1. In the first two methods, composite habitat suitability can be calculated for a number of variables (in this case velocity and depth) by multiplying the individually calculated suitabilities.

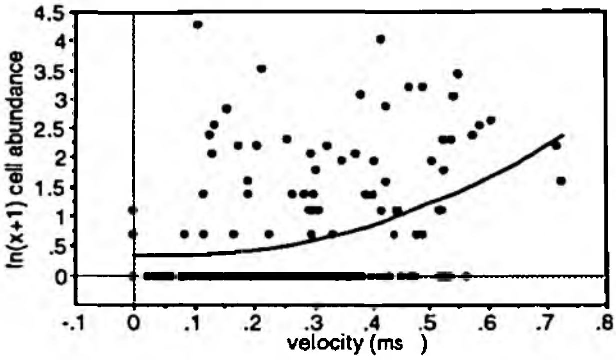
The relative effectiveness of the three methods in predicting the observed relationships between taxa abundance and velocity and depth was tested by relating the observed abundances against predicted sample habitat suitability. It was found that the multiple regression method gave the best predictions for velocity, but the poorest for depth. The independent regression method gave the best predictions for depth and composite suitability, and was thus chosen as the best method for further analyses. It is also the easiest method to use, which is a major advantage when dealing with large numbers of taxa and variables. Figure 3.6 illustrates the steps in producing habitat suitability curves using the independent regression method, using *Hydropsyche siltalai* as an example.

Macroinvertebrate habitat suitability curves.

Suitability curves for the key hydraulic variables: flow velocity and depth, were produced for all taxa occuring in more than 20% of the cells. Separate curves were defined for May, October (combining data for the two years) and February. In addition, curves were produced for the habitat variables: % cobble, % sand and silt, and % total cover for selected taxa. Figure 3.7 shows a selection of the suitability curves for some of the common taxa. Note the similarity of habitat preferences in February and May, but the markedly different preferences expressed by some taxa in October; clearly these animals show an adaptation to seasonal habitat availability.

3.3.4 Macroinvertebrate habitat suitability and discharge relationships.

The relationships between discharge (as gauged at Northwold) and velocity and depth were determined for the primary sites using the monthly field data. Composite suitabilities for all taxa occurring in >0.5 of cells at each site were calculated. The Shannon-Weiner diversity index (H) was used to produce a measure of predicted community diversity: Figure 3.8 shows the change in community diversity of suitabilities with discharge for Chalk Hall Farm, Langford Hall (sand), Didlington (sand) and Didlington (gravel) for February, May and October.

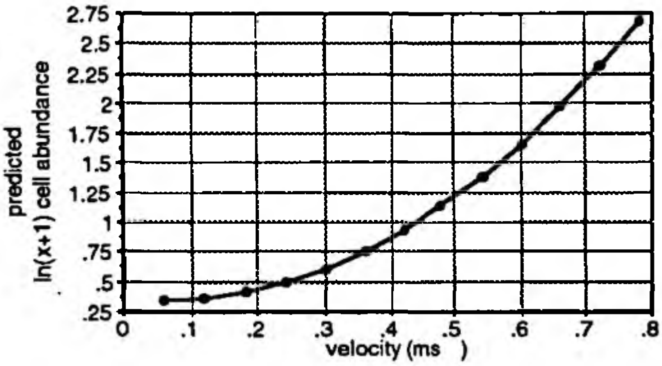


1. A second order polynomial curve is fitted to a plot of the log-tranformed cell abundance data against velocity:

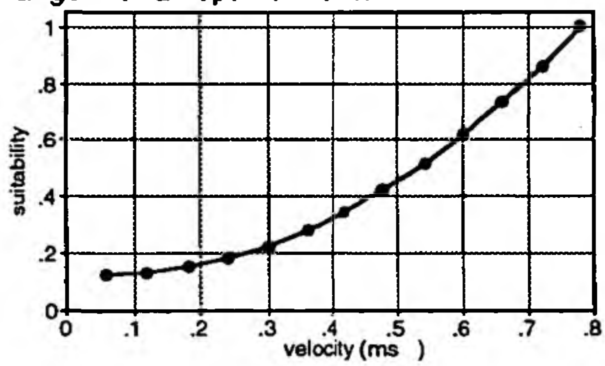
$$\ln(x+1)\ \text{abundance} = a + b(\text{velocity}) + c(\text{velocity}^2)$$

where a, b and c are constants (in this example: a = 0.134, b = -0.20, c = 1.679)

2. Predicted values of abundance for standard increments of velocity are generated using the constants generated from this equation:



3. Predicted log-transformed abundances are converted to "suitabilites" by dividing by the optimum value, to give a range with an optimum of 1:



4. The relationship between predicted suitability and observed abundance is tested by plotting the log-transformed observed abundances against the suitability predicted from the velocity for each cell. The strength of the relationship is measured by the r value of a regression line fitted to the distribution:

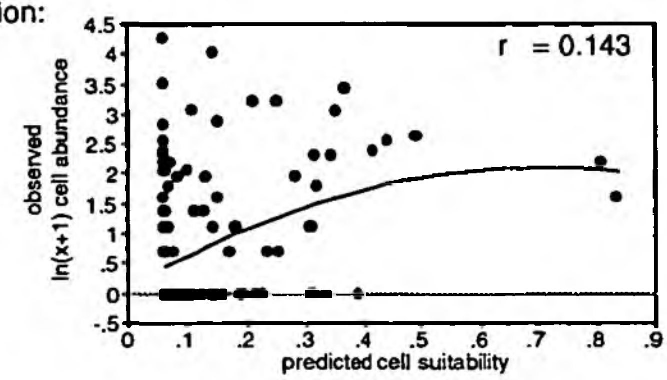


Figure 3.6 The independent regression method of suitability curve production, and prediction testing, using Hydropsych siltalai (May data) as an example.

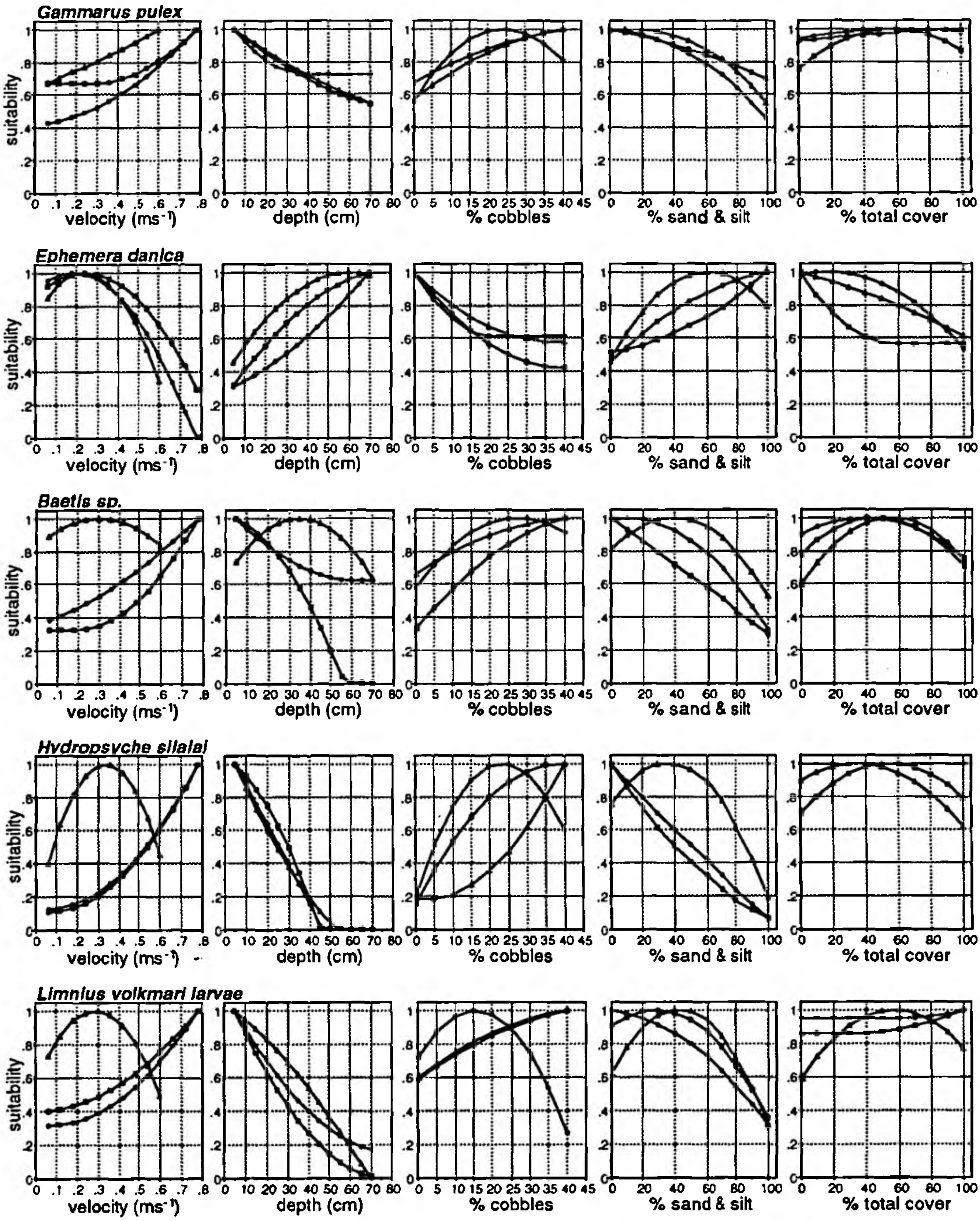
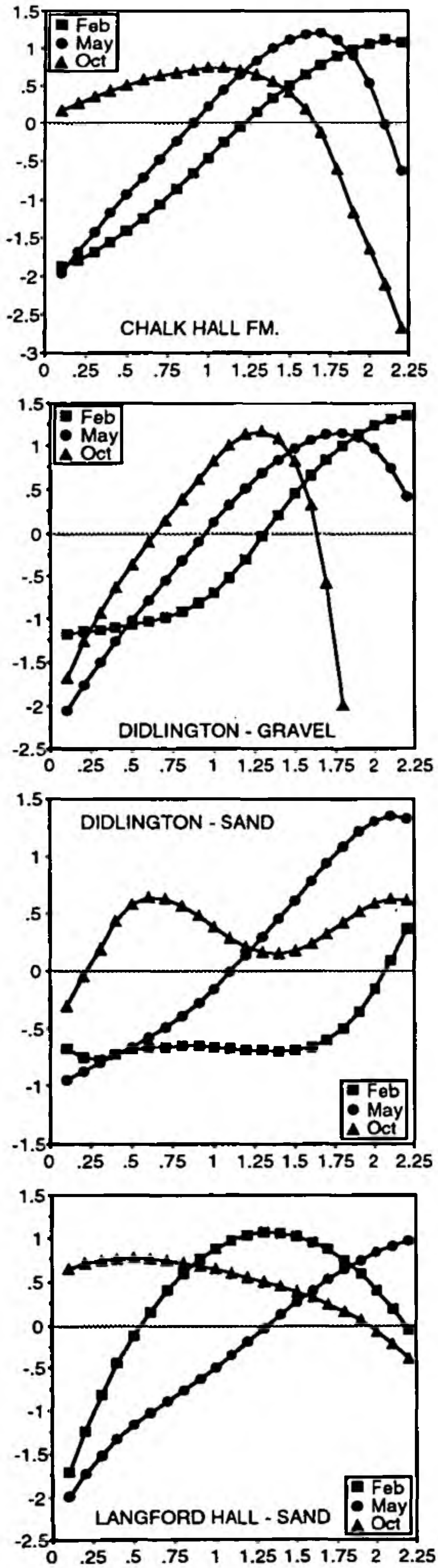
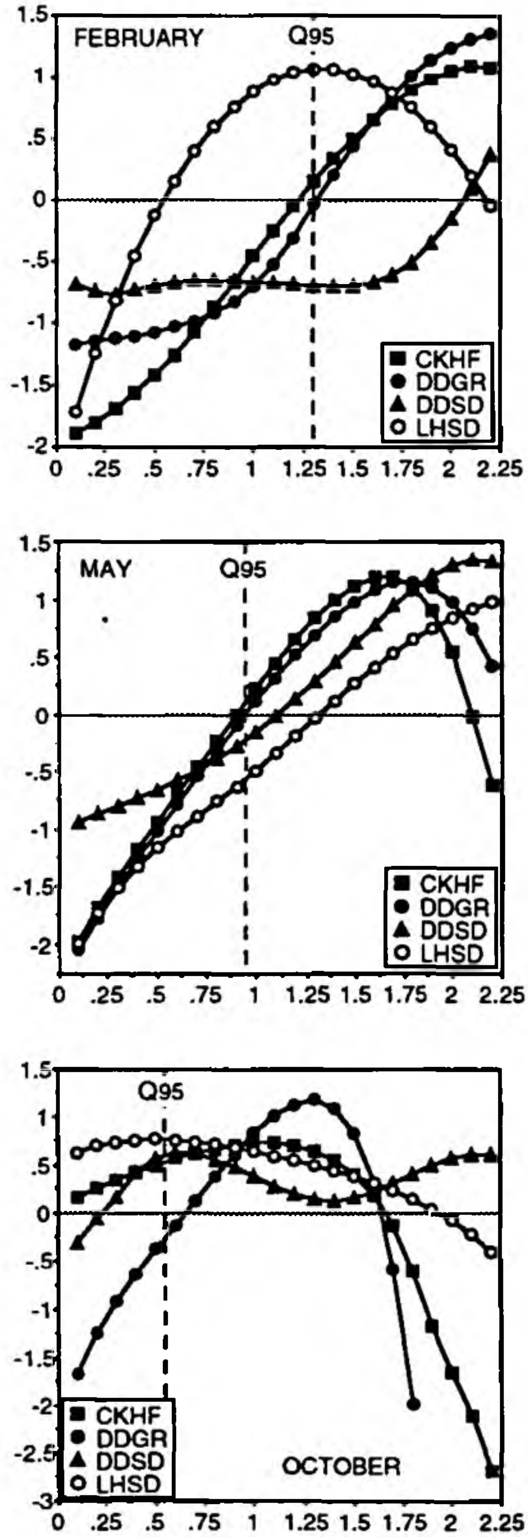


Figure 3.7. Habitat suitability curves for five taxa in relation to flow velocity, depth and substrate variables: % cobbles, % sand and silt and % total cover, for February (■), May (●) and October (▲).

Figure 3.8
Change in diversity of taxa habitat suitabilities with discharge.

Diversities ($H = -\sum (\ln p_i \times p_i)$) are based on all taxa occuring at the site with a cell frequency of >0.5. Taxa showing no significant preference for velocity or depth are given a nominal suitability of 1 for all variable values.





The monthly optima reflect the natural flow regime - declining from February to October - suggesting adaptation of the fauna to seasonal flows. The exception to this is at Langford (sand) where an unusually high discharge is optimal in May. This is probably related to the need to maintain acceptable current velocities: at the other sites, summer macrophyte growth maintains areas of high velocity even under low flows.

From these relationships, optimum discharges (cumecs) - defined as those flows that are associated with maximum species diversity - can be determined for any site and any month (eg Table 3.4). Lower flows are associated with lower diversities, and the shape of the curve (Figure 3.8) describes the rate of reduction in diversity with declining flow.

Table 3.4 Discharges (cumecs) for optimum invertebrate community diversity.

Site	February	May	October
Chalk Hall Farm	2.20	1.75	1.10
Langford Hall (sand)	1.30	2.25	0.60+
Didlington (gravel)	2.25	1.90	1.30
Didlington (sand)	2.25+	2.20	0.60

SECTION 4.
DISCUSSION AND RECOMMENDATIONS.

4.1 Flow-biota relationships.

The detailed assessment of the ways that flow influences biota, presented in the Annexes to this report, and summarized in this volume, demonstrates five important factors relevant to decisions concerning the setting of minimum flows:-

i) Optimum conditions for biota are provided by long-term average flow conditions, that is they are adapted to the 'normal' environmental regime.

ii) The habitat ranges of biota are limited by both high flows and low flows at the extremes of the long-term average range.

iii) Most taxa do not have clearly defined thresholds in their tolerance of environmental conditions, rather they display a more or less progressive decline in their preferences as environmental conditions change away from the 'norm' (see Figure 4.1).

iv) In natural channels, when exposed to extreme environmental conditions, species become dependent upon refuge habitats; species are more sensitive to flow extremes in reaches of uniform channel morphology, lacking the necessary structural diversity to maintain these refuges.

v) Classification of a river as sectors and reaches, and then determination of in-river flow needs for each reach type, provides a useful approach for the objective assessment of in-river flow requirements in relation to other users.

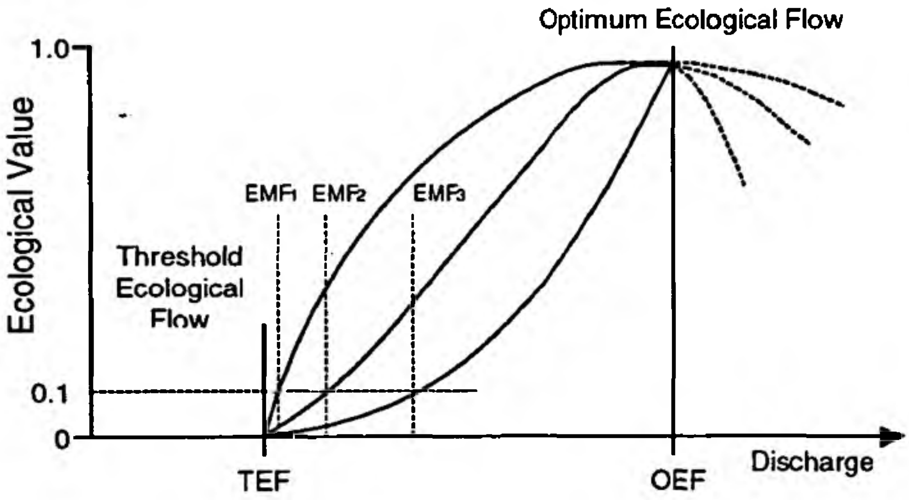


Figure 4.1 Typical flow-biota preference curves illustrating the definition of limiting flow criteria.

4.2 Flow criteria.

Recommendations for defining flow criteria for river management are presented as the outcome of: i) investigations of the ways in which biota respond to changing flows and ii) detailed analyses of habitat and biotic data from sites representative of the range of channel types found along the Wissey. These provide guidelines *based upon environmental considerations* to be used in determining a Minimum Acceptable Flow for individual rivers, a process that should give due regard to the needs of all water users within the context of a catchment management plan.

4.2.1 Guidelines for defining flow criteria.

For any flow recommendations to be made it is important that *a river should be classified into sectors,* as proposed herein, *and the range of habitat types (reaches) evaluated within each sector.* This approach could be developed further by integration with the current investigation on 'functional' habitats (NRA Project 346 *Physical Habitat for Invertebrate Communities* undertaken by C.D. Smith and D. Harper).

Natural rivers show clear downstream patterns of environmental conditions, and these patterns relate to a continuum of ecological characteristics that change from headwaters to mouth. This longitudinal continuum is reflected by a sequence of indicator taxa: for example, trout - grayling - chub - bream. For any minimum flow recommendations 'sector(s) of concern' should be defined according to the desired biological community which could be determined by reference to:-

- (i) the 'natural' biological community;
- (ii) the established biological community; and
- (iii) the potential biological community that could develop given specified instream- and/or riparian physical-habitat enhancement.

Four flow criteria are proposed (Table 4.1), equating, respectively, with the flow below which a river will become severely degraded; the flow necessary to sustain target biota in some reach types along a river, although in many cases at low abundance; the flow necessary to sustain target biota within all reach types; and the flow necessary to maintain optimum conditions for target biota.

Table 4.1 Flow criteria for meeting environmental objectives.

i) The **Threshold Ecological Flow** (TEF) is the absolute minimum flow necessary to sustain refuges for biota associated with relatively high-velocity, clean substrate, riffle and run habitats; below this threshold there is no suitable habitat for target species.

ii) The **Ecological Minimum Flow** (EMF) may be defined as the flow which provides at least a minimum area of suitable habitat for a target species or life stage in at least one reach type within each sector of concern along a river;

iii) The **Desirable Ecological Flow** (DEF) may be defined as the flow which provides at least a minimum area of suitable habitat for a target species or life stage in every reach type within each sector of concern along a river;

iv) The **Optimum Ecological Flow** (OEF) may be defined as the flow providing either the maximum area of suitable habitat for a target species within a river or the maximum community diversity, or which provides the optimum combination.

Table 4.2 Guidelines for using minimum flow criteria to meet environmental objectives.

i) Any reduction in flow below the OEF will be associated with a reduction in ecological quality of the river. Under natural conditions, biological populations have variable demographic characteristics reflecting environmental fluctuations and the dynamic influence of biological interactions (competition, predation etc.). *The OEF is a relatively unusual condition*; for most of the time natural biological communities occur in some reduced state.

ii) Any minimum flow recommendation should be assessed in relation to opportunities for channel rehabilitation works. Natural channels, with numerous hydraulic refuges (see Figure 2.9), recover quickly following summer low flows; channelized or polluted systems, or systems subjected to long periods of extreme low flows, will recover less quickly and may show a long-term decline in ecological quality. Flow reduction below the TEF will lead to a loss of refuge habitats and to a severe reduction in recovery potential. However, *a reduction in the magnitude of the TEF, EMF and DEF may be achieved by physical habitat enhancement works in channelized or heavily maintained reaches* (see 4.3.1).

iii) The choice of an acceptable ecological flow below the OEF and above the TEF will be arbitrary and based upon judgement concerning trade-offs between water-resource needs and the relative decline in ecological quality. *Together the OEF and TEF describe the sensitivity of biota to changes in flows.* Consideration of biological response curves (e.g. Figure 4.1) would enable an estimate to be made of the loss of suitable habitat for specified ecological targets under different flow scenarios.

iv) The EMF and TEF proposed herein provide objective guidelines for setting minimum flows. The EMF should be applied to one-year droughts but in Chalk streams particularly, droughts often persist for more than one year. In such cases, the TEF should be applied in the second and subsequent years. On rivers with special ecological value (such as SSSI status), for the purpose of abstraction licensing one-years drought minimum flows might be set with reference to the DEF.

4.3 Minimum flows for the River Wissey.

The main river between the Watton Brook confluence and Stoke Ferry can be divided into two sectors, above and below Langford Hall weir. For each reach type within these sectors, the TEF has been defined as the flow that maintains usable habitat within 0.2 % of the reach, an arbitrary figure but one that can be defined with more confidence than absolute zero because of the asymptotic nature of the biological response curves.

Table 4.3 includes a wide range of flow recommendations based upon the different approaches reviewed in this report. It should be noted that the PHABSIM approach used here employed generic habitat suitability curves. The study of invertebrates within the Wissey suggests that river-specific and season-specific habitat preference curves ideally should be established. A range of taxa were shown to demonstrate marked changes of habitat preference during the year. The conclusions from the analyses are:-

- the recommended **TEF is 0.30 cumecs**, below this threshold there will be a complete loss of habitat suitable for adult trout and a loss of high-velocity refuges; this may be seen as the absolute minimum flow necessary to protect the river's ability to recover from low-flow stress.

- the recommended **MEF is 0.40 cumecs** (the '99th %ile flow; 1956-88); which should maintain some (limited) habitat for adult trout within the Chalk Hall Farm (sector 3) and Didlington (sector 4) reaches, a slight increase to 0.43 cumecs should provide usable habitat in all reaches except at Didlington Sand and Bodney Bridge (i.e. in 5 of the 7 reach types; see Table 3.1). Furthermore, this flow would sustain reasonable habitat for juvenile trout, and a fair invertebrate diversity.

- the **DEF is 0.9 cumecs**, below this threshold deep, sand-bed reaches become unsuitable for adult trout within both sectors 3 and 4; the flow would maintain excellent habitat for juvenile trout, and a good invertebrate diversity. However, relatively deep, sand-bed reaches are not typical trout habitat. A requirement to sustain some trout habitat in all gravel-bed reach types, including channelized and maintained reaches, would allow the reduction of the DEF to 0.6 cumecs

- the **OEF is 1.25 cumecs**; this flow is associated with high invertebrate diversity at all sites, good habitat for adult trout throughout the river and excellent habitat for juveniles.

Table 4.3 Data relating to the definition of minimum acceptable flows at Northwold gauging station. Hydrological statistics based upon the 1956-85 record.

River target and flow-duration percentile (1956-88)	Method (sector : reach)	Flow (m^3s^{-1})	Sector target
TEF : 99.8	PHABSIM (3 : CKHF)	0.30	Trout, adult; TEF
EMF : 99.2	PHABSIM (4 : DDGR)	0.40	Trout, adult; TEF
	Invertebrate diversity	0.55	EMF
	PHABSIM (3)	0.60	Trout, adult; DEF
DEF : 79.0	PHABSIM (4)	0.90	Trout, adult; DEF
	PHABSIM (3 : CKHF)	0.85	Trout, juveniles; OEF
	PHABSIM (4 : DDGR)	0.85	Trout, juveniles; OEF
OEF : 63.0	Invertebrate diversity	1.25	OEF
	PHABSIM (4)	1.42	Trout, adult; OEF
	PHABSIM (3)	1.98	Trout, adult; OEF
	10% ADF	0.19	Absolute minimum; TEF
	20% ADF	0.38	Fish habitat minimum; EMF
	30% ADF	0.57	Fish habitat optimum; DEF
	Q95	0.58	EMF
	Aquatic Baseflow Index	0.79	September median flow; DEF

4.3.1 The biological basis of minimum flow recommendations.

Table 4.3 also compares flows defined by hydrological criteria with those derived from analyses of biological responses. This indicates that:-

- the Threshold Ecological Flow approximates to 15% ADF
- the recommended EMF approximates to 20% ADF

Review of the results suggests that the Aquatic Baseflow Index (ABF), yielding a minimum flow of $0.79m^3s^{-1}$ in September, has biological foundation, maintaining good adult Trout and invertebrate habitat within six of the seven reach types defined along the main river above Northwold. At the other extreme, 10% of the mean daily flow - an index of flow below which severe degradation would occur - equates here to the flow below which Trout habitat would be eliminated. For the Wissey, the 95th Percentile flow (Q95) closely approximates to 30% ADF and would sustain some adult Trout habitat in five of the seven reach types. However, this flow is significantly higher than the recommended Ecological Minimum Flow and approximates to the Desired Ecological Flow. The highly regulated nature of Chalk streams - the Wissey has a ratio of Q_{10}:Q_{95} of only 6.0 and a median flow equal to 84% of the mean flow - may influence the relationship between Q_{95} and ADF.

During this study, flows were below the historic "normal" flows (Table 4.4); flows were below the monthly median flows for 66% of the time in 1991 and 58% of the time in 1992. The above recommendations, therefore, were derived during a period of sustained ecological stress under exceptional low flows and the minimum recommended flows are likely to be a true reflection of the sensitivity of the aquatic ecosystem.

Table 4.4 Comparison of historic and recent flows at Northwold (cumecs).

	1 October 1956 to 30 September 1988	1 October 1988 to 30 September 1992
Average daily flow	1.922	0.926
95 percentile	0.576	0.236
75 percentile	0.974	0.389
50 percentile	1.588	0.736
5 percentile	4.332	2.189
0.1 percentile	9.957	6.114

4.3.2 Habitat enhancement and flow management.

It is important to emphasise the influence of channel morphology in the determination of flow criteria. This is well illustrated by comparing the reaches within sector 3 at Chalk Hall Farm (CKHF), Langford Hall Gravel (LHGR) and Bodney Bridge (BYBR). The minimum TEF was derived for the Chalk Hall Farm reach which had excellent habitat with clean gravel riffles, good pools and an asymmetric flow pattern providing a wide range of hydraulic conditions. The TEF of 0.30 cumecs contrasts with that derived for the regularly dredged/cleaned reach at Bodney Bridge, which had relatively poor habitat with a less diverse hydraulic structure and a TEF of 0.60 cumecs. At Langford Hall, a reach of intermediate physical habitat in comparison with the other two reaches, the derived TEF was 0.43 cumecs.

The above indicates that in channelized or heavily maintained reaches, more environmentally-sensitive river engineering and channel maintenance should significantly reduce the rate of habitat degradation with declining flows, and channel rehabilitation works could reduce the flow requirements to sustain in-river needs.

4.3.3 Flushing and channel maintenance flows.

To sustain the ecological value of a river requires high flows as well as the prevention of exceptionally low flows. Channel maintenance flows are those discharges that induce sediment transport, flushing fine sediment accumulations formed during low flows, cleaning pools, rejuvenating cut banks and gravel deposits, disturbing weed beds, and maintaining the overall form of the channel and river margin.. Recommended flows for the Wissey are given in Table 4.5. Over the 1956-88 record, flows of greater than 3.5 m^3s^{-1} occurred more than 10% of the time.

Table 4.5 Data relating to the definition of flushing and channel maintenance flows at Northwold gauging station. q is the mean annual flow, Q10 is the 10th percentile exceedence flow and Q2.33 is the flood which occurs every 2.33 years on average.

	1956-85 (m^3s^{-1})	
200% q	3.80	Flushing flow
Q10	3.50	Flushing flow
Q2.33	8.60	Channel/riparian flow

Whilst high flows can be provided along regulated rivers below major storage reservoirs, such hydrological control is not possible on rivers like the Wissey. However, during a series of dry years (without flows above the 3.5 m^3s^{-1} threshold) additional instream maintenance may be required to reduce the accumulation of sand and silt at gravel-bed sites and to clean pools. Such high flows are also required to saturate riparian areas and marginal wetlands. Important sites may require irrigation during drought periods to maintain local water levels.

4.4 Seasonal flow regimes.

Three seasonal flow regimes have been defined, based upon the DEF, EMF and TEF. The biological-response analyses, especially the investigations of invertebrate distributions, suggest that using the DEF as the annual minimum flow and the median flow for each month, based upon the long-term record (1956-88), a Desired Ecological Flow regime may be defined (Table 4.6). The minimum flow would be 0.90 m^3s^{-1} in September (see Table 4.3). The median flows for February, May and October approximate to the optimum flow for invertebrates. This regime also provides good spawning habitat for trout, dace and chub.

Demonstration that the Desired Ecological Flow regime is closely associated with near optimum biological functions is important, providing evidence to support the assumption that biota are adapted to the normal flows experienced. It also indicates that any variation from this 'norm', *associated with natural climatic variations or artificial influences*, will cause a decline in the suitability of the available habitats for biota.

Table 4.6 The Desired Ecological Flow regime for the River Wissey, based on flows at Northwold gauging station.

1956-88	Flow (m^3s^{-1})	Spawning habitat(1)	Adult Trout habitat(1)	Juvenile Trout habitat(1)	Invertebrate optima (m^3s^{-1})
January	**2.79**	70 (Trout)	98	54	
February	**2.83**		98	56	2.2
March	**2.55**	67 (Dace)	90	61	
April	**2.32**	71 (Dace)	80	66	
May	**1.74**	94 (Chub)	53	80	2.2
June	**1.30**	93 (Chub)	28	92	
July	**1.01**		20	98	
August	**0.90**		16	99	
September	**0.90**		14	99	
October	**0.90**		16	97	1.25
November	**1.25**	95 (Trout)	27	92	
December	**2.07**	86 (Trout)	67	71	

(1) proportion (%) of the maximum available habitat predicted by PHABSIM for target species.

Table 4.7 presents the recommended minimum flow regimes and summarizes the link between these regimes and habitat. Key months are considered to be February (DEF), July (EMFm), September (EMFn) and November (EMF). The EMFm maintains habitat for adult trout in all reach types within sector 3 and in two of the three reach types within sector 4 and the EMFn continues to sustain habitat in two reach types in sector 4 and maintains habitat in two reach types of sector 2. Flows are allowed to decline from April through to November, following a normal flow recession.

It is important to note that during drought years on Chalk streams, flow recovery may not begin until January (compared with October in other areas and in normal years). Hence the EMF, which also maintains some spawning habitat (up to 18% of that potentially available) in three reach types in sector 3 and two reach types in sector 4 - has been applied to November, December and January. *It is recommended that river support should be used to maintain the EMF regime during one-year droughts.* The EMF regime would benefit the river in 1:4 < 1:6 years.

Severe droughts in Chalk catchments extend over two or more consecutive summers. During such rare events, that naturally occur perhaps once in every 10 years or more, groundwater storage can be severely reduced and a second regime is proposed to protect the river against severe degradation. *It is recommended that the Threshold Ecological Flow regime in the second and subsequent years of a prolonged drought.*

Table 4.7 The Ecological Minimum Flow regime and Threshold Ecological Flow regime for the River Wissey, based on flows at Northwold gauging station.

Month	Ecological Minimum Flow Regime		Threshold Ecological Flow Regime	
	Monthly EMF (m^3s^{-1})	Ecological rationale	Monthly TEF (m^3s^{-1})	Ecological rationale
January	0.6	EMFm	0.6	EMFm
February	0.9	DEF	0.6	
March	0.9		0.6	
April	0.9		0.6	
May	0.8		0.5	
June	0.7		0.4	
July	0.6	EMFm	0.3	TEF
August	0.5		0.3	
September	0.45	EMFn	0.3	
October	0.45		0.3	
November	0.4	EMF	0.3	
December	0.4		0.3	

4.5 Management implications.

The application of a range of hydrological, habitat-based, and biological-response approaches has enabled determination of minimum flow criteria:-

i) to sustain refuges for biota associated with relatively high-velocity, clean substrate, riffle and run habitats (TEF);

ii) to provide at least a minimum area of suitable habitat for adult Trout in one reach type within each of the two sectors along the middle river (EMF);

iii) to provide at least a minimum area of suitable habitat for a target species or life stage in every reach type within both sectors of concern (DEF);

iv) to provide either the maximum area of suitable habitat for a target species within a river or the maximum community diversity, or which provides the optimum combination (OEF).

The OEF (iv above) is rare in natural systems, on the Wissey this high flow has an average duration (1956-88) of less than 20% of the time, and typically occurs during December through April. Similarly, the DEF approximates the median flow for July-October inclusive, and the natural river has experienced flows below this level on many occasions.

The following management rules are recommended:-

(i) the EMF flow regime rules become operational, requiring river support, when the flow has fallen below an EMF target flow on 14 consecutive days.

(ii) the TEF flow regime rules become operational in the year following one in which the EMF target flows were inceeded on 28 days or more, irrespective of whether the EMF or TEF rules were operated in that year. River support will be required immediately flow falls below target.

(iii) TEF rules should continue to be operated until a year passes when EMF target flows were NOT inceeded for more than 28 days; at this point EMF rules should be reapplied (see i above)..

Application of the these rules to the flow record for 1956-1993 indicates that river support would have been required on 547 days (less than 4 % of the time) with a frequency of 1:4 years. TEF rules would have been applied in 12 of the 38 years but river support would have been required in only 3 years: 1990, 1991 and 1992. River support lasting for more than 70 days in a year would have been required in 1976, 1989, 1990 and 1991.

From a management perspective, the recommended flows must be considered in terms of both duration (number of days in each month) and frequency, in terms of the recurrence interval of the event. Low flows are difficult to analyse in these statistical terms because a single 'event' can last several years (the 1988-92 drought was a good example!). These aspects are currently being investigated as part of another investigation for the Anglian Region of the National Rivers Authority ('The River Babingley: a study of in-river needs'). It is recommended that the above findings should be reviewed following publication of the results of this other study.

4.6 Other recommendations.

In addition to the flow recommendations detailed above, the study has provided a catchment perspective on the Wissey. The conservation value, potential for enhancement and recommendations for management of the the Wissey and its tributaries are summarized in Table 4.9. Specific attention should be given to:-

- creating buffer zones along most of the headwater streams to reduce nutrient and fine sediment inputs from agricultural land; to control instream macrophyte growth by shading, reducing maintenance costs and ecologically-damaging dredging activities; and improving the conservation value of the river corridor.
- from Hilborough to the Buckenham Tofts sluice ensure that no works are undertaken to degrade the channel form and riparian areas.
- from Buckenham Tofts sluice downstream, habitat diversity should be improved along the channel margins by creating eddies, backwaters, and marginal cover; the careful location of dead trees would be advantageous, and gravel accumulation and limited bank erosion should not be revented.
- during dry summers, management of macrophytes should be limited to the maintenance of a few, fast-flowing runs.
- monitoring of water quality and flows should be undertaken at Hilborough, below the Watton Brook confluence, an important control point in the stream network, in order to monitor long-term trends and short-term incidences.
- monitoring of groundwater levels surveyed into river levels is recommended between North Pickenham and Hilborough, an important reach for groundwater discharge maintaining flows during dry periods.

Table 4.9 Conservation value, potential for enhancement and recommended management for the River Wissey and tributaries.

Sector/reach.	Character	Present conservation value.	Potential for enhancement.	Recommendations.
Wissey. Sector 1. Bradenham to Emford Hse.	Heavily managed, ditched section through arable surroundings. Good gravel substrate and moderate flow velocities. Upper reach is intermittent.	Low. Some organic pollution and high-nutrient arable runoff problems.	Good. A relatively natural, attractive stream could be acheived with moderate investment in management.	Introduce buffer zones / reduce frequency of dredging to allow emergents/riparian flora to develop. Any additonal measures to improve channel diversity.
Wissey. Sector 2. Emford Hse. to Watton Brook confl.	Moderate to low intensity of managment, mainly pasture/wet meadow. Silty runs with few gravel riffles.	Mixed. Some excellent wet meadows of very high value. Instream habitat moderate-poor. organic pollution problems.	Good. Riparian habitat already quite good, instream habitat could be improved.	Preserve and extend wet meadow areas. Reduce access for stock to riparian margins to limit grazing and poaching. Control organic pollution problem - at source or through root exclusion zones / ponds.
Wissey. Sector 3. Watton Brook confl. to Buckenham Tofts.	Semi-natural, typical Chalk stream. Good pool-riffle structure but some ponding from sluices.	Exellent. Instream habitat good, especially around Chalk Hall Fm. with diverse substrate, flora and invertebrate and fish fauna. Riparian woodland of moderate value.	Moderate. Instream habitat requires preservation rather than enhancement. Riparian alluvial woodland could be significantly improved.	Preserve instream habitat. Replace riparian plantation trees with native species and let understory develop naturally.
Wissey. Sector 4. Buckenham Tofts to College Fm..	Semi-natural, with deep run habitat predominating in-stream. Mainly plantation surrounding.	Moderate. Instream habitat of only moderate quality for invertebrates and flora due to predominance of deep runs. Good adult trout habitat.	Good. Instream habitat fulfills function as adult trout habitat; fry habitat and riparian flora could be greatly improved.	Improve marginal habitat for fry / invertebrates by increasing diversity. Develop backwater areas. Replace riparian plantation trees with native species.
Wissey. Sector 5. College Fm. to Whittington.	Heavily managed, fenland section.	Moderate. Habitat typical for this type of section, with good coarse fishery. Riparian zone is poor.	Moderate. Natural character and drainage function will limit potential for instream improvements.	Introduce buffer zones. Create adjacent fish fry habitats - backwaters areas. Any measures to increase habitat diversity.
River Gadder. Cockley Cley to Gooderstone.	Intermittent in upper section with artificial lakes; perennial in lower section with wet woodland / meadow.	Good. Natural, if recently more frequent, drying out severely limits instream habitat above spring-head, but seasonally wet meadows at Mill Covert were identified as extremely valuable invertebrate habitat.	Moderate. Intermittency of upper reach limits instream improvements. However, wet meadow areas could be extended.	Preserve and extend wet meadow areas around the springs. Wildfowl lakes are being created above Gooderstone Water Gardens - removal of willows and extension of wetlands around these lakes would be an improvement.

Table 4.9 (continued) Conservation value, potential for enhancement and recommended management for the River Wissey and tributaries.

River Gadder. Gooderstone to Wissey confl.	Run-type instream habitat through pasture and arable land in the lower part. Dense emergent vegetation in places controlled by cutting.	Moderate-low. Grazing and arable cultivation limit riparian vegetation in most parts. A Brown Trout population existed prior to 1990.	Moderate. Riparian flora could be improved.	Limit stock grazing of banks in pasture areas to allow regeneration of riparian zone. Develop buffer zone in lower reach and improve channel management for fish fry habitat.
Stringside Stream. Upstream of Barton Bendish and Beachamwell tributaries.	Intermittent headwaters through arable land.	Low. Heavily dredged.	Good. These tributaries are more frequently dry than the upper main river, limiting potential for instream improvements. However, in these intensive arable areas small streams/ditches provide valuable damp refugia for a variety of invertebrates and even birds and mammals, and provide landscape interest.	Anything to improve riparian zone - both in extent and diversity. Plant buffer zones, aim to reduce dredging/cutting in the medium-term.
Stringside Stream. Beachamwell to confluence with Barton Bendish stream (Lode Dyke).	Intermittent, wooded stream u/s Oxborough Wood; perennial, spring-fed stream through woodland/arable land d/s Eastmoor.	Mixed. In the Beachamwell section there is an interesting aquatic invertebrate fauna associated with the intermittent flows. Lower section of lesser interest.	Moderate. The perennial section could be improved by measures to improve riparian and instream flora.	Oxborough Woods are already under management to improve the conservation value of the woodland. Instream flora through the Woods may be improved by selectively reducing shading.
Stringside Stream. Confluence with Barton Bendish stream to confluence with main Wissey.	Ponded by G.S. in upper section and from main river in lower. Heavily dredged except immediately d/s G.S..	Poor, except for a small section immediately d/s the G.S. the flow is faster and riparian trees limit access for dredging equipment. Coarse fish proliferate in the lower section, which is probably a good refuge from the main river during high flows.	Poor. Ponding and necessary drainage work limit possibilites for enhancment.	Extension of buffer zone above and below G.S.
Watton Brook	Gravel bed, naturally riffle-pool stream but dredged and cultivated up to banks. Organic pollution problems.	Poor. Very little interest.	Good. Instream habitat could drastically improve if water quality was raised. Potential also for improving riparian flora.	Buffer zones. Improve / reduce effluent entering stream. Reduce cutting and manage channel to increase instream and riparian macrophytes which will also improve water quality.

4.7 Research needs.

This project has, for the first time in the UK, achieved a detailed knowledge of the links between hydrology and ecology within a single river. The approach developed has considerable potential for wide application to river protection and enhancement. There are three priorities:-

- because the approach was developed from data obtained under conditions of record low flows, predictions of biological responses to higher flows within the 'normal' range have been extrapolated; a resurvey of key sites should be undertaken in February, May and October, including a fish survey in the last, to assess the recovery of the river following drought and to validate the model under 'normal' flow conditions.

- the approach should be applied to other streams to assess its validity for application to (i) Chalk streams, (ii) other lowland streams in Anglian Region, (iii) other lowland streams throughout England, and (iv) to assess its potential for calibration to upland rivers.

Other aspects of the overall approach would benefit from further development:

- the diatom index (DAIpo) as developed for Japanese rivers was found to be a valuable means for monitoring changes in British rivers, responding in particular to changes in orthophosphate concentration. The pollution tolerance of the diatom species, and the longer term responses of the diatom community to a more extensive range of chemical parameters, needs further research if the method is to realize its potential for general application.

- important information is unavailable on the effects of the duration and frequency of low flows on biota. Provision of data on the latter requires long-term monitoring but knowledge on the former may be realized by experimental research. This research should address the recovery of biota following low-flow stress and should assess the opportunities for management to enhance the recovery mechanisms. It is recommended that the necessary monitoring and research programmes should be established as a matter of priority.

- with regard to fish stocks, a fish survey should be undertaken in October 1994 to assess the post-drought recovery. This survey should be repeated annually and should be supported by detailed records on stocking and selective fishing. The level to which the river is managed as a put-and-take fishery should be carefully evaluated.

Finally, with regard to the hydrology of the catchment:

- this project has suggested that important links exist between the groundwater and main river between North Pickenham and Hilborough. It is recommended that research should be commissioned to investigate this relationship with a view to improved control on any abstractions that may affect the important contributions made by groundwater discharges to river flows within this reach.

GLOSSARY.

armour layer (substrate)
A layer of gravel- and cobble-sized sediment on the surface of the channel bed.

Average Score Per Taxon (ASPT)
A measure of the average organic pollution-sensitivity of a macroinvertebrate sample community (high scores = high sensitivity). Calculated by dividing the BMWP score by the number of scoring taxa.

Biological Monitoring Working Party (BMWP) score
A measure of the "biological quality" of a macroinvertebrate sample community. Calculated by summing the individual organic pollution-sensitivity scores of the collected taxa (scores range from 1 - highly tolerant, to 10 - highly sensitive), BMWP is thus a combined measure of taxa-richness and sensitivity to organic pollution.

Correspondence Analysis (CA)
An multivariate statistical method of ordination suitable for non-linear variables (eg species abundances) which arranges samples according to the species which they contain and, reciprocally, species according to the samples in which they occur. Samples and species are given axis scores which describe their similarity. Environmental variables can be correlated with the axis scores - the strength of the correlations suggest which variables are determining the species/sample distributions. **Detrended Correspondence Analysis (DCA)** is a variant containing a correction for mathematical errors inherent in CA. In **Canonical Correspondence Analysis (CCA)** the axes are constrained to be linear combinations of the given environmental variables.

Diatoms
Diatoms are single celled algae. **Benthic** diatoms are bottom-living; true **planktonic** diatoms live in the water column. Benthic diatoms may be washed into the water column and be collected in plankton samples. **Epilithic** benthic diatoms live on the surface of stones, **epiphytic** types on other plants. **Saprophilic** diatoms prefer high-nutrient conditions; **saprophobic** diatoms prefer low-nutrient conditions.

Diptera
Are the True Flies, and as highly habitat-specific invertebrates are useful in measuring a range of terrestrial, semi-aquatic and aquatic habitat conditions.

Froude Number (F)
An index of the energy environment:

$$F = v \div \sqrt{(gd)}$$

where v = velocity(ms^{-1}), d = depth (m), and g = gravity (c. $9.81ms^{-2}$).

hemispheres
Hemispheres are a relatively new tool in measuring shear stress conditions on the channel bed. A series of plastic hemispheres of different densities are placed on a (relatively) frictionless metal plate levelled on the stream bed. The hemisphere of maximum density to be just moved by the current is the measure of shear stress.

hyporheic
The region below the surface of the stream bed.

matrix supported (substrates)
having >30% substrate particles of <2mm size.

Principal Components Analysis (PCA)
A multivariate statistical method, PCA is an ordination method suitable for linear variables.

Shannon Wiener diversity (H)
A measure of species diversity, incorporating both species richness and abundance:

$$H = \Sigma (p_i \times \ln p_i)$$

where p_i = proportion of the i^{th} species. In Section 2.4.4 species suitabilities were substituted for proportions in the calculation of diversity of community suitabilities.

Shreve Index
An index of drainage network magnitude: the sum of the number of first order streams, measured on 1:25000 O.S. maps.

Two-Way Indicator Species Analysis (TWINSPAN)
TWINSPAN is a method of hierarchical, dichotomous classification: Sample data are first ordinated (arranged along a gradient according to their species composition) and divided into two groups. Species significantly more frequent in one group than the other are identified (preferential species). The process is then repeated on the two groups separately to produce the next division (resulting in four groups), and so on.

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