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RIVER FLOW INDEXING USING BENTHIC MACROINVERTEBRATES:

A FRAMEWORK FOR SETTING HYDROECOLOGICAL OBJECTIVES

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Abstract

A method linking qualitative and semi-quantitative change in riverine benthic macro-invertebrate communities to prevailing flow regimes is proposed. The Lotic-invertebrate Index for Flow Evaluation (LIFE) technique is based on data derived from established survey methods, which incorporate sampling strategies considered highly appropriate for assessing the impact of variable flows on benthic populations.

The LIFE technique offers the prospect of objectively utilising macroinvertebrate data to quantify and assess river flows, and hydroecological links have been investigated in a number of English rivers, after correlating LIFE scores obtained over a number of years, with several hundred different flow variables. This process identifies the most significant relationships between flow and LIFE which, in turn, enables those features of flow which are of critical importance in influencing community structure in different rivers to be defined. Summer flow variables are thus highlighted as being most influential in predicting community structure in most chalk and limestone streams, whereas invertebrate communities colonizing rivers draining impermeable catchments are much more influenced by short term hydrological events. Biota present in rivers with regulated or augmented flows tend to be most strongly affected by non-seasonal, inter-annual flow variation.

These responses provide opportunities for analysing and elucidating hydroecological relationships in some detail, and it should ultimately be possible to use these data to set highly relevant, cost effective, hydroecological objectives. An example is presented to show how this might be accomplished.

The LIFE technique is considered to have great potential, and could offer considerable advantages over established methods of setting instream flow objectives, such as PHABSIM. These existing methods can be expensive, and may not adequately account for the dynamic nature of an individual site's flow history, when setting hydrological targets.

Key areas of further work include the need to provide robust procedures for setting hydroecological objectives, investigation of habitat quality and LIFE score relationships in natural and degraded river reaches, and evaluation of potential links with other biological modelling methods such as RIVPACS.

Key words Macroinvertebrates, Flow, Drought, Hydroecology.

Introduction

Changing weather patterns, possibly linked to global climate change, are currently of major concern, not least because alterations in hydrological regime could lead to significant and sustained shifts in riverine ecology (Arnell, 1996). In the United Kingdom, periods of drought are becoming more frequent (Mawdsley *et al.*, 1994) and general declines in precipitation, coupled with unremitting demands on surface and groundwater resources, are resulting in diminished or disappearing river flows.

A number of historic studies have focused on general ecological change associated with drought (eg. Ladle and Bass, 1981) and further work (Extence, 1981; Wright, 1992; Bickerton *et al.*, 1993; Wood and Petts, 1994; Castella *et al.*, 1995) has specifically examined the impact of low flows on lotic macroinvertebrate communities. Many freshwater invertebrates have precise requirements for particular current velocities and flow ranges (Chutter, 1969; Hynes. 1970; Statzner *et al.*, 1988; Brooks, 1990), and certain taxa may, therefore, be ideal indicators of hydrological regime.

As well as qualitative responses to flow changes, site specific studies also show that most taxa associated with low flow tend to increase in abundance as flows decline, whereas most species associated with moderate to rapid flows exhibit the opposite response (Moth Iversen *et al.*, 1978; Extence, 1981; Cowx *et al.*, 1984; Wright and Berrie, 1987; Boulton and Lake, 1992; Wright, 1992; Miller and Golladay, 1996). Alterations in community structure may occur as a direct consequence of varying flow patterns, or indirectly through associated habitat change (Petts and Maddock, 1994; Petts and Bickerton, 1997a).

There have been comparatively few attempts to directly link observed changes in benthic invertebrate communities with permutations in hydrological regime. A number of efforts have historically been made, however, to utilise and adapt techniques designed to meet other needs, for the purpose of flow assessment. Scott Wilson Kirkpatrick (1992), for example, considered that the water quality index, Average Score Per Taxon (Chesters, 1980) could be incorporated into a method to appraise low flow conditions, and a number of initiatives (Armitage *et al.* 1987; Brown *et al.* 1991; Armitage and Petts, 1992) have used RIVPACS methodology (Wright *et al.*, 1984) for assessing the effects of variable flows on macroinvertebrates. Not surprisingly, none of these approaches are currently able to provide a comprehensive and all embracing flow assessment method.

Explicit attempts to connect macroinvertebrate populations with hydrology are less prevalent, although two decades ago Jones and Peters (1977) made some headway in linking flows in unpolluted British rivers to invertebrate community structure. More recently, Armitage (1995) has associated community response with variable current velocities in experimental situations, and Petts and Bickerton (1997a) provide a summary of very detailed investigations into invertebrate/flow relationships in the River Wissey, Norfolk.

Despite these advances, there is still a need for a straightforward and reliable ecological assessment method which is sensitive and responsive to varying flow patterns, and which can be used with existing data. This paper presents results obtained from a number of English rivers, after application of a new indexing technique, based on the known flow preferences of selected benthic invertebrates. Such a technique should enable the effects of low flows, as well as abstraction and augmentation outputs and inputs, to be monitored and assessed. In addition, the method could provide a basis for setting benchmark flows suitable for protecting and maintaining ecological integrity, thus overcoming some of the problems associated with established techniques for setting hydroecological objectives, such as high costs and inadequate ecological input.

The U.K. Environment Agency (EA) has recently made public its environmental strategy for the millenium and beyond (Environment Agency, 1998) and this includes clear commitments to develop new and more effective methods for harmonised environmental management. The strategy also highlights a number of priorities, including the effective management of water resources, improving habitat quality, conserving biodiversity and meeting legal requirements such as the Habitats Directive (EEC, 1992). Several of these topics are linked, and the techniques outlined in this paper provide an opportunity to make substantial progress in a number of these key areas.

Study Sites

In order to critically examine the effectiveness of the proposed flow index, results from five geographically and geologically distinct rivers in England are presented in detail. Data from a number of other rivers are additionally provided in summary form, and in these cases, study site details are more appropriately placed in the results section.

Chalk rivers are now recognised as a key biodiversity habitat in Europe (HMSO, 1995a and 1995b) and most European rivers of this type are found in England, including the Lark and Waithe Beck (Anglian region) and the Kennet (Thames region).

Waithe Beck, rising on the chalk uplands of the Lincolnshire Wolds at 117m, flows 27 km to the North Sea via the Louth Canal at Tetney. Low flows, exacerbated by groundwater abstraction, have characterised this high quality river over the last decade. A number of long-term biological sampling points have been established on Waithe Beck, including Brigsley (TA 253 017) which is located immediately downstream from a permanent flow gauging station.

The River Lark is also a high quality chalk stream. rising at 80m near the town of Bury St. Edmunds, Suffolk, and running in a northwesterly direction, before joining the River Great Ouse near Ely, Cambridgeshire. The river, which has undergone substantial habitat modification in the past (Barham, pers. comm.) has numerous abstractions from the chalk aquifer, and low flows are an increasing problem. Flow data for the Upper Lark originated from the Fornham St. Martin gauging station, located just downstream from Bury St. Edmunds. Family level biological data were available from a nearby monitoring point at Fornham All Saints. (TL 842 678).

With a catchment area of 1156 km^2, the River Kennet is the largest single tributary of the Thames. The river rises south of Swindon, Wiltshire, and runs for 98 km, falling 112m, before joining the Thames at Reading, Berkshire. The Kennet is another high quality chalk stream, summer flow being principally provided from a number of groundwater fed perennial tributaries draining the Marlborough and Berkshire downs. Periods of low winter rainfall have historically led to considerable variation in flow source and volume.

Three large public water supply boreholes are located close to the river at Axford, Speen and Theale, and groundwater abstraction from these sources can total 50 megalitres a day. This demand on the chalk aquifer can intensify low flow impacts on the river, particularly during low rainfall/hot summer periods. Biological data were available from several routine sampling points on the Kennet, including Stitchcombe Mill (SU 227 695), daily flows being gauged 7 km downstream from this point at Knighton.

Distinct from these chalk streams are the Midlands rivers Derwent and Wreake. The River Derwent rises at an altitude of 590m on an area of millstone grit, 8 km south of Holmfirth in

Yorkshire. The river then runs for 97 km before discharging to the Trent at Long Eaton.

Biological data were available for the Upper Derwent from a monitoring site located at Baslow Bridge (SK 252 722) and flow was gauged a short distance downstream at Chatsworth. Upstream from Baslow Bridge are the Howden, Derwent and Ladybower reservoirs, which substantially modify the river's natural flow pattern.

The River Wreake, in contrast, rises at an altitude of 150m near the Leicestershire hamlet of Bescaby. The river then runs through a flood plain of clay and alluvial gravels, before reaching the River Soar just north of Leicester. Biological data were available from the Lower Wreake at Lewin Bridge (SK 622 129), where water quality is generally good, and flows were gauged nearby at Syston. Both of these sites are located close to the confluence with the Soar. .

Materials and Methods

Index Calculation

The proposed Lotic – invertebrate Index for Flow Evaluation (LIFE) method is primarily based on recognised flow associations of different macroinvertebrate species and families. Commonly identified freshwater species were allocated into one of six flow groups set out in Table 1, using information from Macan (1965), Kimmins (1972), Macan (1977), Ellis (1978), Reynoldson (1978), Elliot & Mann (1979), Janus (1982), Hynes (1984), d'Aguilar *et al.* (1985), Fitter and Manuel (1986), Askew (1988), Elliot *et al.* (1988), Friday (1988), Savage (1989), Bratton (1990), Wallace *et al.* (1990), Bratton (1991), Wallace (1991), Wright (1992), Gledhill *et al.* (1993), Edington & Hildrew (1995), Elliot (1996) and Brooks (1997).

Species and their flow group associations are shown in Appendix 1. Selected dipteran taxa, which can be readily associated with specific flow regimes, but which are not easily

Table 1.

Benthic freshwater macroinvertebrate flow groups, ecological associations and mean flow criteria.

Group	Ecological Flow Association	Mean flow criteria
I	Taxa Primarily Associated With Rapid Flows	typically > 100 cm s^{-1}
II	Taxa Primarily Associated With Moderate to Fast Flows	typically 20 - 100 cm s^{-1}
III	Taxa Primarily Associated With Slow or Sluggish Flows	typically < 20 cm s^{-1}
IV	Taxa Primarily Associated With Flowing (Usually Slow) and Standing Waters.	---
V	Taxa Primarily Associated With Standing Waters	---
VI	Taxa Frequently Associated With Drying or Drought Impacted Sites	---

identified to species level, are also included in Appendix 1.

In cases of uncertainty or ambiguity, flow group associations were derived from published information and from the professional experience of freshwater biologists. Mean flow criteria definitions (ie. regimes to which taxa have been assigned) are shown in Table 1, and these are specified using data from Nielsen & Schmitz, outlined in Macan (1963) and Hynes (1970), which state critical mean current velocities for particle movement of given sizes.

Although several taxa may be found colonising a range of habitats, eg. the river limpet, *Ancylus fluviatilis* (Macan, 1977), flow group associations given in Appendix 1 endeavour to define the primary ecological affiliation of all listed species. It is more difficult to provide flow group definitions for taxa commonly found in watercourses which run discontinuously, such as winterbournes. A number of species, such as *Paraleptophlebia werneri*, have life cycles adapted to cope with intermittency (Bratton, 1990) and in these cases, the particular ecological requirement of the aquatic stage is used to define the flow group. *P. werneri* was thus placed into flow group II, because its larvae are generally found in rivers with moderate velocities (Elliot *et al.*, 1988; Bratton, 1990). In effect, the method links group I to V taxa to specific flow regimes rather than to habitat type.

Other taxa which regularly occur on drying out river beds were assigned into group VI to distinguish sites where wetted areas have diminished. Examples of flow group VI species are the drought resistant amphibious gastropod *Lymnaea palustris* (Janus, 1982) and the dytiscid beetle *Agabus biguttatus*. *A. biguttatus* moves underground as surface water disappears (Foster, 1980) and the species is a good indicator of intermittent flow.

Where species data are unavailable, it is possible to work at family level, and family flow group associations are shown in Appendix 2. It will be appreciated that the use of family level data may result in a loss of precision, since a number of families (marked * in Appendix 2) contain species with fairly wide-ranging flow requirements.

Ubiquitous taxa such as Chironomidae and Oligochaeta are not used in this method, since there appears to be no definitive relationship between flow and chironomid/oligochaete abundance at this level of taxonomic resolution (Extence, 1981; Ladle and Bass, 1981; Cowx *et al.*, 1984; Wright, 1992; Miller and Golladay, 1996; unpublished EA records 1980-1998).

Benthic macroinvertebrate samples suitable for assessing the impact of variable flows should be taken following standard EA protocols (Murray-Bligh, 1997) at riffle sites. These techniques require timed 3 minute kick/sweep net sampling of all habitats, and different habitats are sampled in proportion to their occurrence. Environmental change linked to flow, such as siltation and the build up of macrophytes, are thus accounted for, and the methods are of particular value in hydrological assessment.

By adopting existing sampling methodology, current and historical data can be used, and mechanisms are also available (Murray-Bligh, 1997) for incorporating quantitative population change into the LIFE method (abundance estimates of all taxa present must be made following the guidelines set out in Table 2).

The LIFE calculation involves individual flow scores (fs) for each taxon present in a sample being obtained from the matrix shown in Table 3, by using estimated abundancies (Table 2) and defined flow group associations (Appendices 1 and 2). The matrix design in Table 3 is based on the infrastructure of the biotic score system proposed by Chandler (1970) for biologically assessing water quality.

Table 2.
Standard EA macroinvertebrate abundance categories.

Category	Estimated abudance
A	1 - 9
B	10 - 99
C	100 - 999
D	1000 - 9999
E	10000 +

Table 3.
Scores (fs) for different abundance categories of taxa associated with Flow Groups I - VI

		Abundance Categories			
Flow Groups		**A**	**B**	**C**	**D/E**
I	**Rapid**	**9**	10	**11**	12
II	**Moderate/Fast**	**8**	**9**	10	**11**
III	**Slow/Sluggish**	**7**	**7**	**7**	**7**
IV	**Flowing/Standing**	**6**	**5**	**4**	**3**
V	**Standing**	**5**	**4**	**3**	**2**
VI	**Drought Resistant**	**4**	**3**	**2**	**1**

The Index is calculated as follows

$$\text{LIFE} = \frac{\Sigma fs}{n}$$

where Σfs is the sum of individual taxon flow scores for the whole sample, and n is the number of taxa used to calculate Σfs. Higher flows should result in higher LIFE scores.

If taxa have been identified as species, individuals identified with less taxonomic resolution should typically be disregarded for index calculation (Appendix 1 Diptera excepted). In some cases, however, eg. *Rhyacophila*, individuals identified as family or genus can still be used for species level calculation as all species are in the same flow group (I). Similarly, Corixidae nymphs recorded seasonally in a river can still be utilised, since adults concurrently or previously present at the site will provide a reliable indication of the appropriate flow group. Conversely, occasional species records in family level data sets should only be utilised at the family level. Where family level analysis has taken place, the designation LIFE (F) should be used. As well as Chironomidae and Oligochaeta, several other taxa (eg. Ceratopogonidae, Ostracoda and Hydracarina) are not used in calculating this index.

Linking LIFE scores with flows

While the development of a community based flow index may be of considerable value in demonstrating the effect of hydrological variation on riverine invertebrates, it is perhaps more important to validate the model by examining the relationship between index scores and measured flows. Flow can be expressed in a multiplicity of ways, and invertebrate communities colonizing different types of river will respond to multifarious aspects of flow regime (Poff and Ward, 1989). Furthermore, flow dynamics affecting community structure will vary spatially down any given river and temporally at any one site (Armitage *et al.*, 1997). Because of this complexity, it is essential to objectively determine which aspects of flow are of critical importance in influencing the biota at any one site.

To facilitate this evaluation, a computer program was developed to examine the relationship between multiflow parameters and LIFE scores over a number of years. This program enables the determination of those flow parameters which are important in influencing community structure (as measured by the LIFE technique) in different rivers and river types. Significant correlations found during this assessment and screening process may then form the basis for establishing hydroecological objectives.

The following flow measures have been examined for comparison with long term LIFE values for each data set:

i) flow statistics, eg. percentile flow, mean flow, maximum flow, minimum flow, etc. over various time scales, examples of which are given in ii) and iii)

ii) flow duration, eg. 90, 120, 150 days, etc.

iii) flow periodicity, eg. April to September, March to October, etc.

Ecological response has been linked to various combinations of the above using correlation techniques. The correct use of product moment correlation coefficients (Pearson) requires a bivariate normal distribution (Elliot, 1977) and the distribution of data (index and flow variable) were evaluated prior to use. Where possible, Pearson correlation was used with raw data, or following transformation. If asymmetrical data could not be successfully transformed, then Spearman rank-order correlation was employed. Minitab statistical software (Ryan and Joiner, 1994) was utilised for data exploration and the production of correlation coefficients.

This process, in practice, produced several hundred separate scatter-plots linking LIFE scores and flow for each river selected for study, and a few examples of correlations undertaken were LIFE with preceding 120 day five percentile flow, LIFE with preceding 150 day five percentile flow, LIFE with preceding 90 day mean flow, LIFE with preceding 60 day minimum flow and LIFE with preceding 180 day running summer mean (RSM) flow, for a period defined as April to September.

Most of these terms require no further explanation, with the exception of RSM. This term is defined as the average flow for a specified number of days, and for a defined summer period. For example the 180 day RSM (April–September) for a sample taken on September 30 would be calculated from the quotidian flows for the previous 180 days. A sample taken on April 2 would use the flow recorded on April 1, plus the flows recorded on 179 consecutive days up to and including September 30 for the previous year. Samples taken between October and March inclusive would be paired with the previous summers 180 day average ending on September 30.

Results

Waithe Beck

Seasonally consistent abundance data for species were available at Brigsley from 1986 to 1997 (Fig. 1). Fig.2a shows daily flow records between 1985 and 1997 at this site. The trends evident in Fig. 1 should be considered alongside changes in flow occurring concurrently (Fig. 2a) and it is clear from these data that quantitative changes linked to flow need to be accounted for in any comprehensive method of hydroecological assessment.

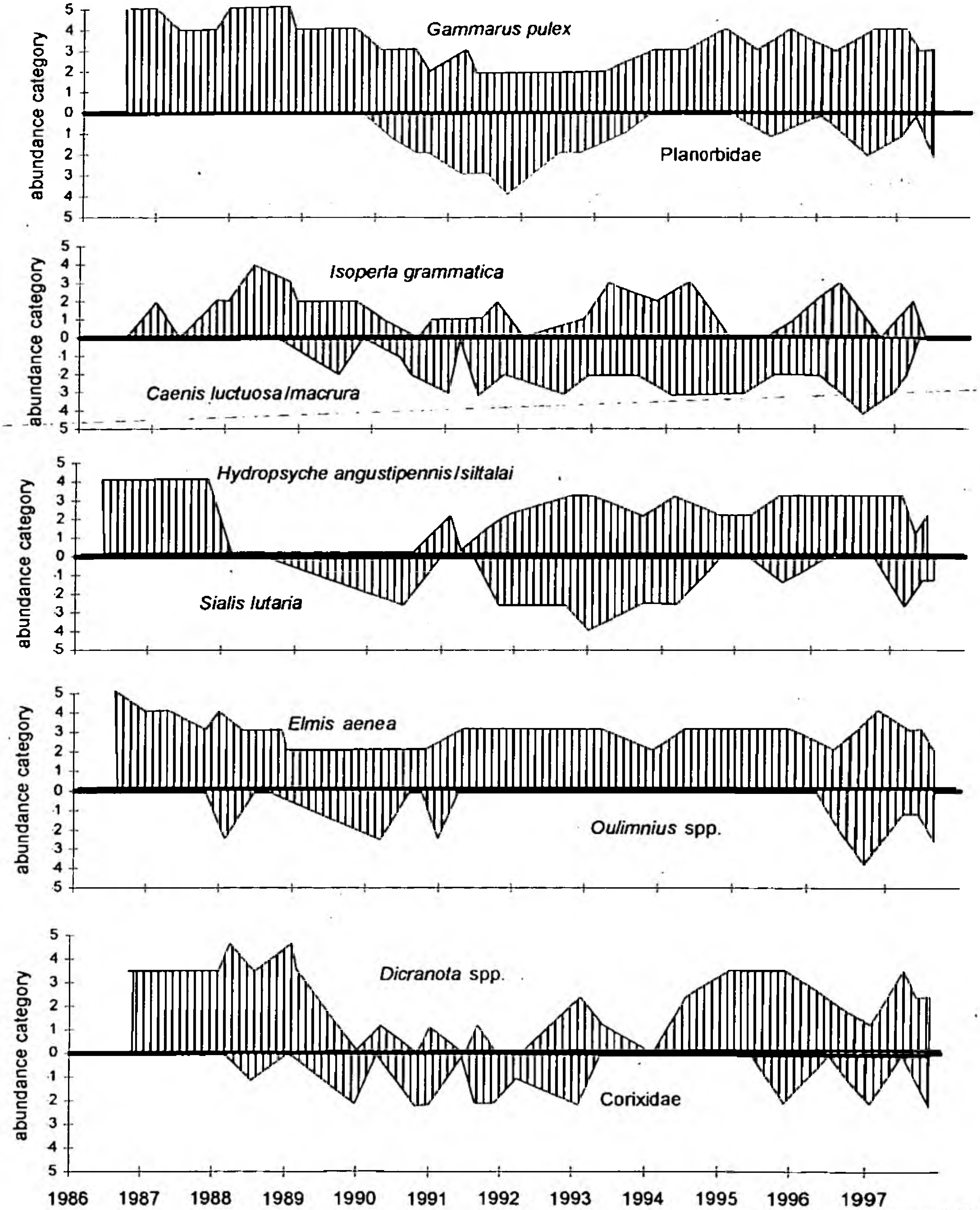


Figure 1. Selected invertebrate taxa and abundances recorded from the Waithe Beck at Brigsley, 1986-97. For each pairing, taxa associated with high flows are shown in the upper sector, and taxa associated with low flows are shown in the lower sector. In this case abundance categories are defined as the following numbers of individuals, 1 = 1, 2 = 2–10, 3 = 11–100, 4 = 101- 1000 and 5 = >1001.

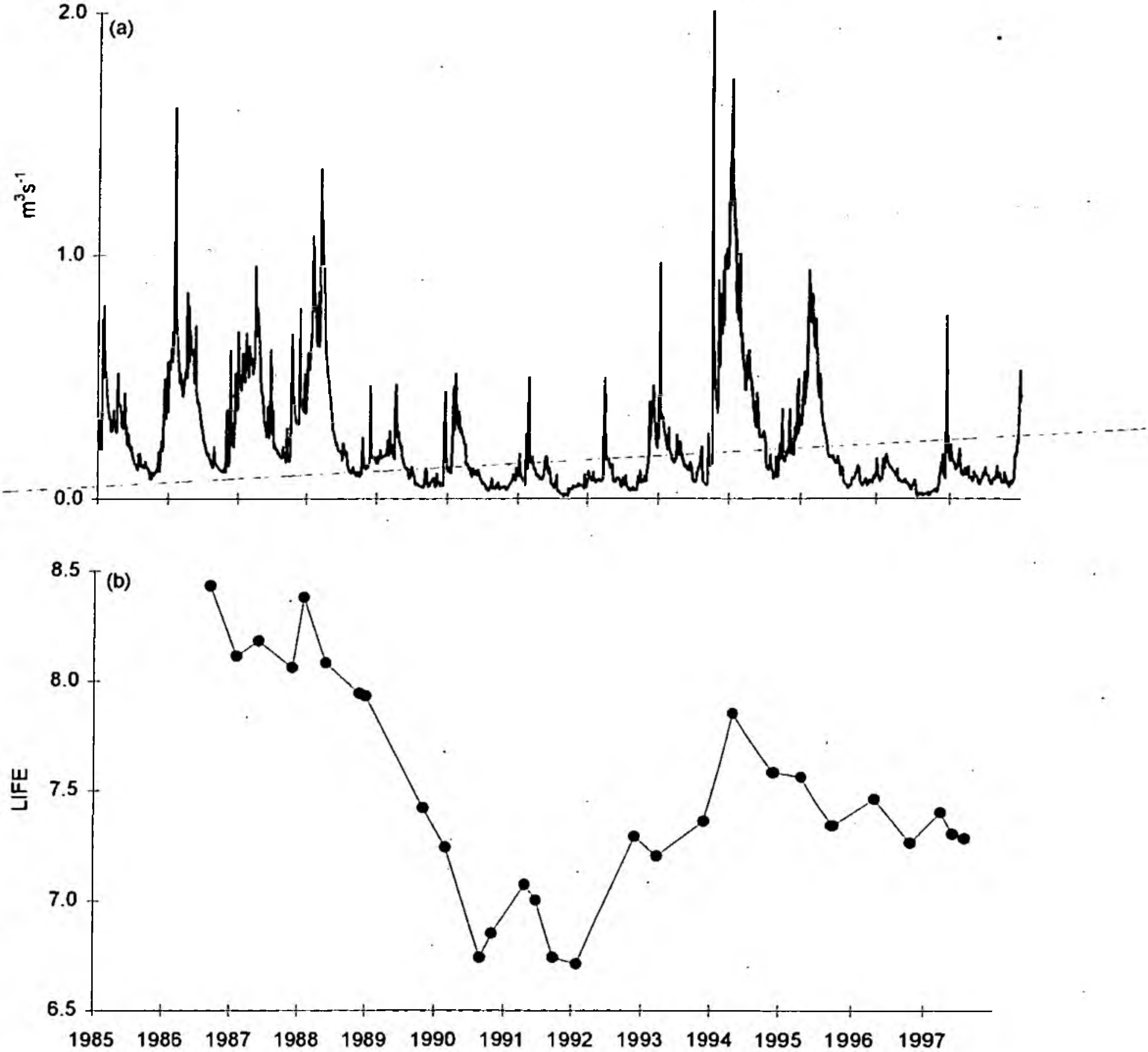


Figure 2. Waithe Beck at Brigsley. (a) Hydrograph. (b) LIFE scores.

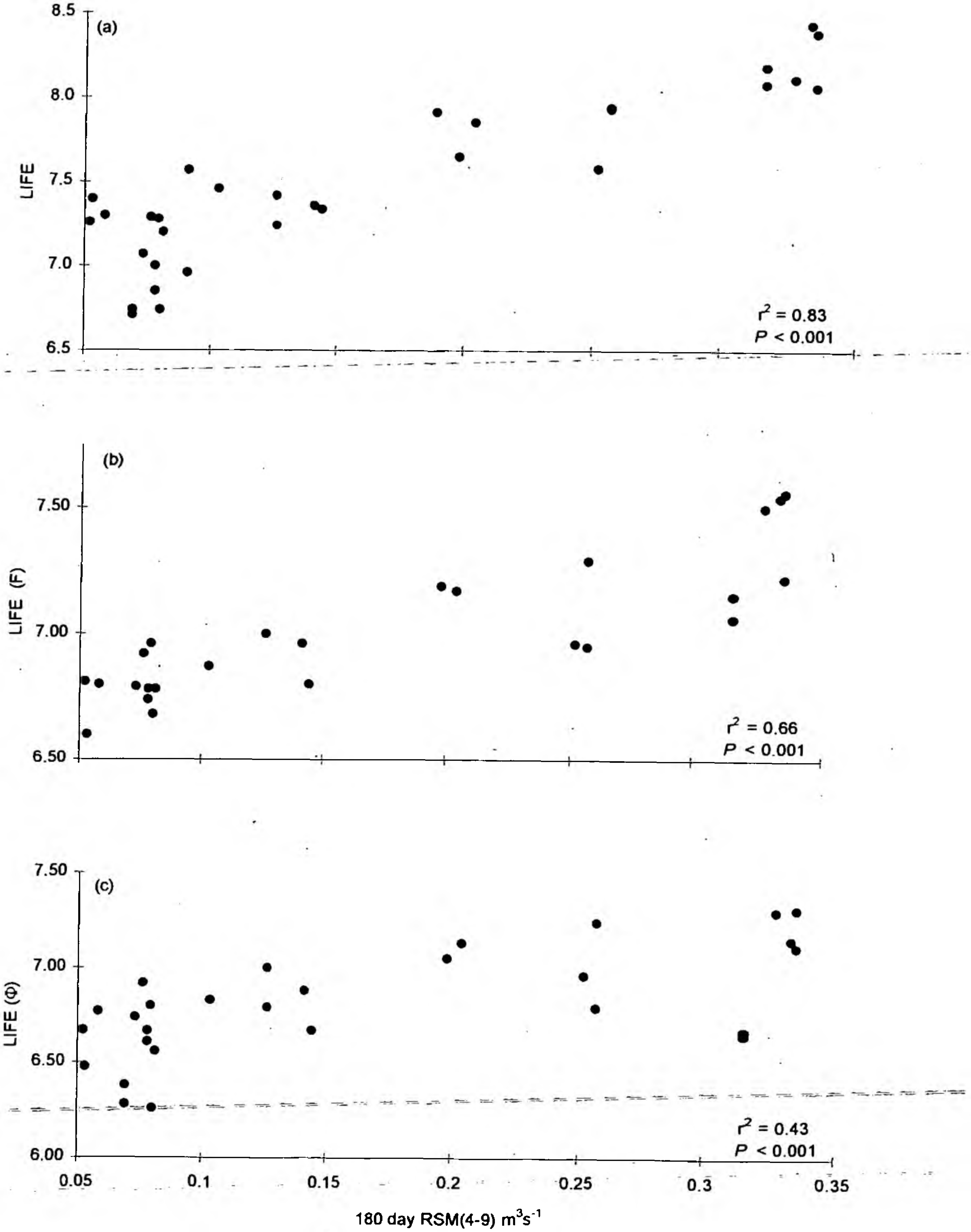


Figure 3. Waithe Beck at Brigsley. Scatterplots of LIFE scores against flow using, (a) Semi-quantitative species data, (b) semi-quantitative family data and (c) qualitative family data, LIFE (Φ). Flow is expressed as a 180 day running ... (RSM) April to September inclusive.

Fig. 2b shows the LIFE response to varying flow patterns in Waithe Beck, and scores ranged from 6.7 - 7.1, obtained in the low flow years of the early 1990's, to 8.0 –8.4 calculated from samples taken between 1986 and 1988, following periods of relatively high flow.

Scrutinisation of the scatter-plots produced after running the multiple flow/LIFE computer program, indicates that summer flow is of cardinal importance in influencing LIFE scores in Waithe Beck. The strongest relationship occurs between LIFE values and the 180 RSM for summer periods defined as April to September (Fig. 3a). Where family data were used for LIFE score calculation (LIFE F) the resulting correlation was less strong (Fig. 3b) and lower still if family level data were utilised without regard to relative abundance (LIFE Φ - all families present assigned into abundance category C) – Fig. 3c.

River Lark

Flow data for the Upper Lark are shown in Fig. 4a and LIFE scores derived from family level data are shown in Fig. 4b. Protracted low flows recorded between 1990 and 1993, and from 1995 onwards, caused a marked decline in LIFE (F). The strongest correlation found was LIFE (F) with 300 day RSM for a summer period defined as April to September (Fig. 4c). Baseline LIFE (F) scores recorded at Fornham, between 1989 and 1997 were very low, and only ranged from 5.2-6.0.

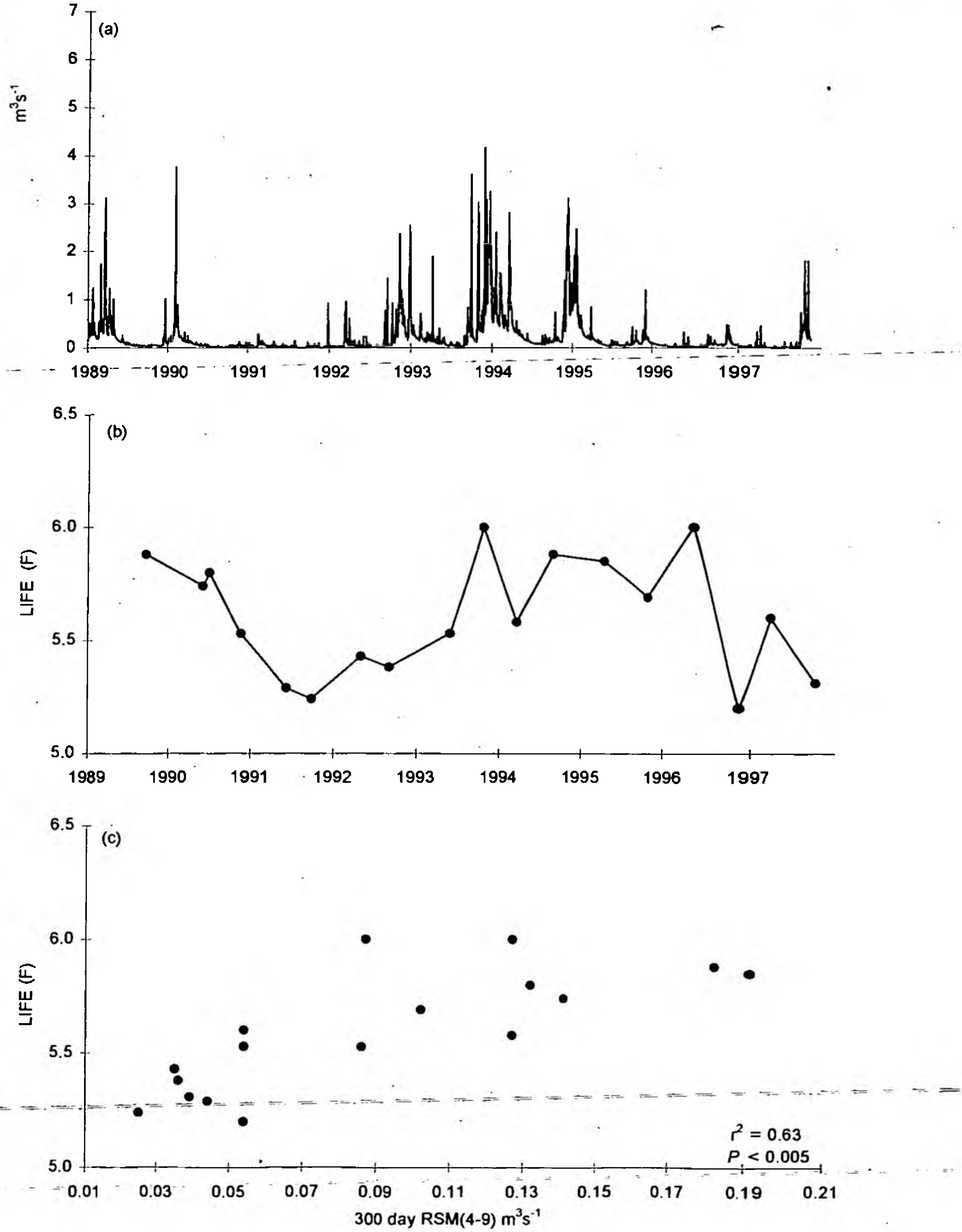


Figure 4. River Lark. (a) Hydrograph from Fornham St. Martin. (b) LIFE time plot from Fornham All Saints. (c) Scatter-plot of LIFE scores against flow. Flow is expressed as a 300 day running summer mean (RSM), April to September, inclusive.

River Kennet

Daily flows at Knighton are shown in Fig. 5a and LIFE (F) scores calculated at Stitchcombe Mill are shown in Fig. 5b. The strongest hydroecological relationship found was LIFE (F) with 210 day RSM for a period defined as April to September (Fig. 5c). As in previous chalk stream examples, summer flows were again identified as being of greatest importance in influencing community structure in the Kennet, and similarities in flow parameters providing the best prediction of ecological state, clearly exist at this and the Waithe Beck site.

River Derwent

LIFE scores derived from Baslow Bridge samples indicate that communities here are typically exposed to substantial discharges of fast flowing water (Figs. 6a and 6b). Significant correlations at this site were obtained over the study period with flow maxima, flow minima, and full year mean and percentile flows. The most significant relationship was LIFE with 210 day five percentile flow (Fig. 6c). No significant correlations were found here with April to September summer flow variables, presumably because the maintenance of regulated compensation flow from the three upstream reservoirs provides little inter-annual variation during these months. If the defined summer period is lengthened, however, then relationships become increasingly significant, as flows from spring and autumn months are progressively incorporated and used in the analytical process.

River Wreake

Flow data and LIFE values recorded at Syston and Lewin Bridge are shown in Figures 7a and 7b respectively. Flows in the Lower Wreake rapidly rise and fall over short periods of time, years of low discharge being characterised by a reduced frequency of high flows and/or the loss of summer spate flows. Fig. 7c shows the strongest relationship enumerated at Lewin Bridge (LIFE with 60 day minimum flow) and given the downstream location of this site, and

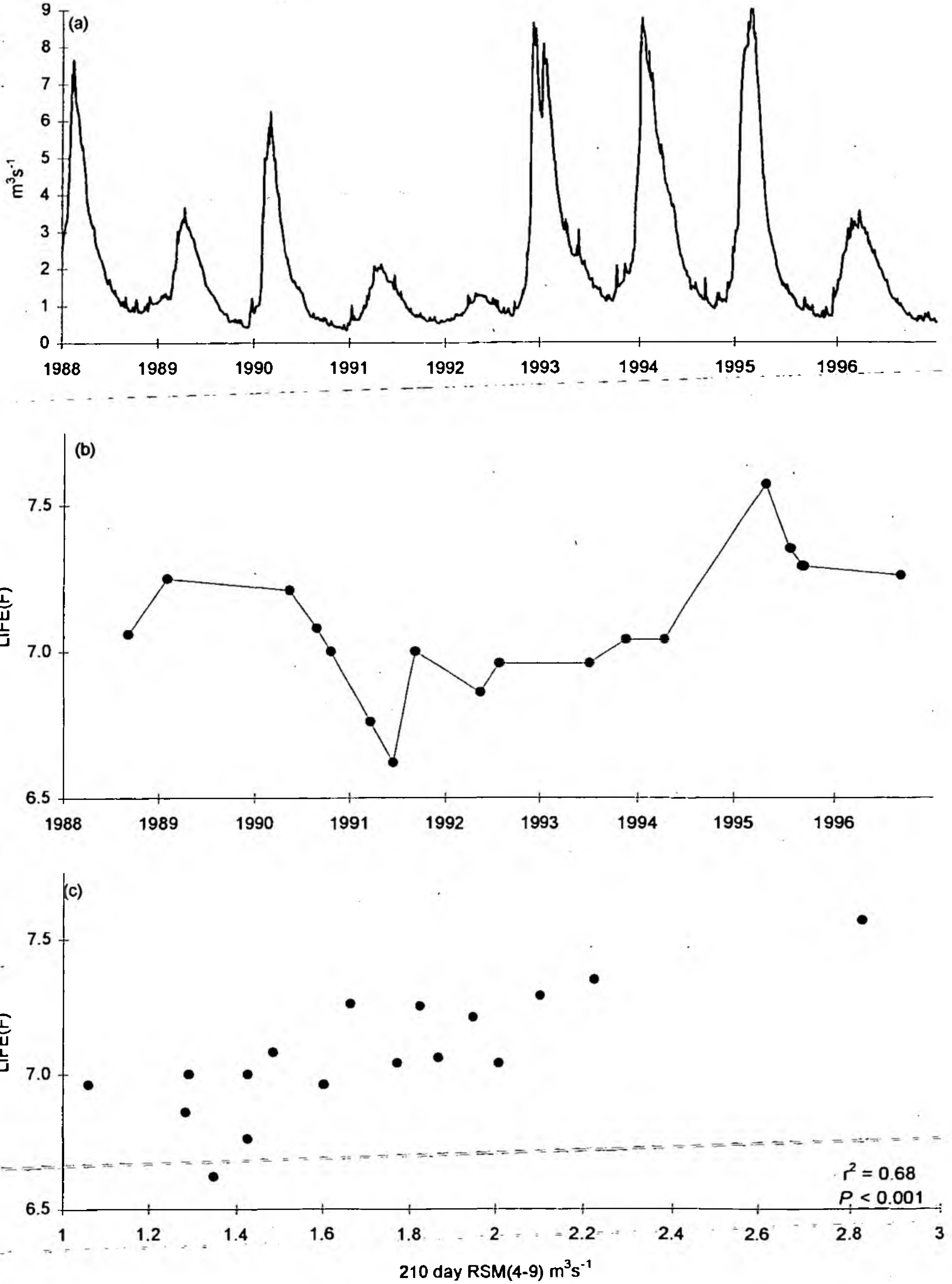


Figure 5. River Kennet. (a) Hydrograph from Knighton. (b) LIFE time plot from Stitchcombe Mill. (c) Scatter-plot of LIFE scores against flow. Flow is expressed as a 210 day running summer mean (RSM), April to September, inclusive.

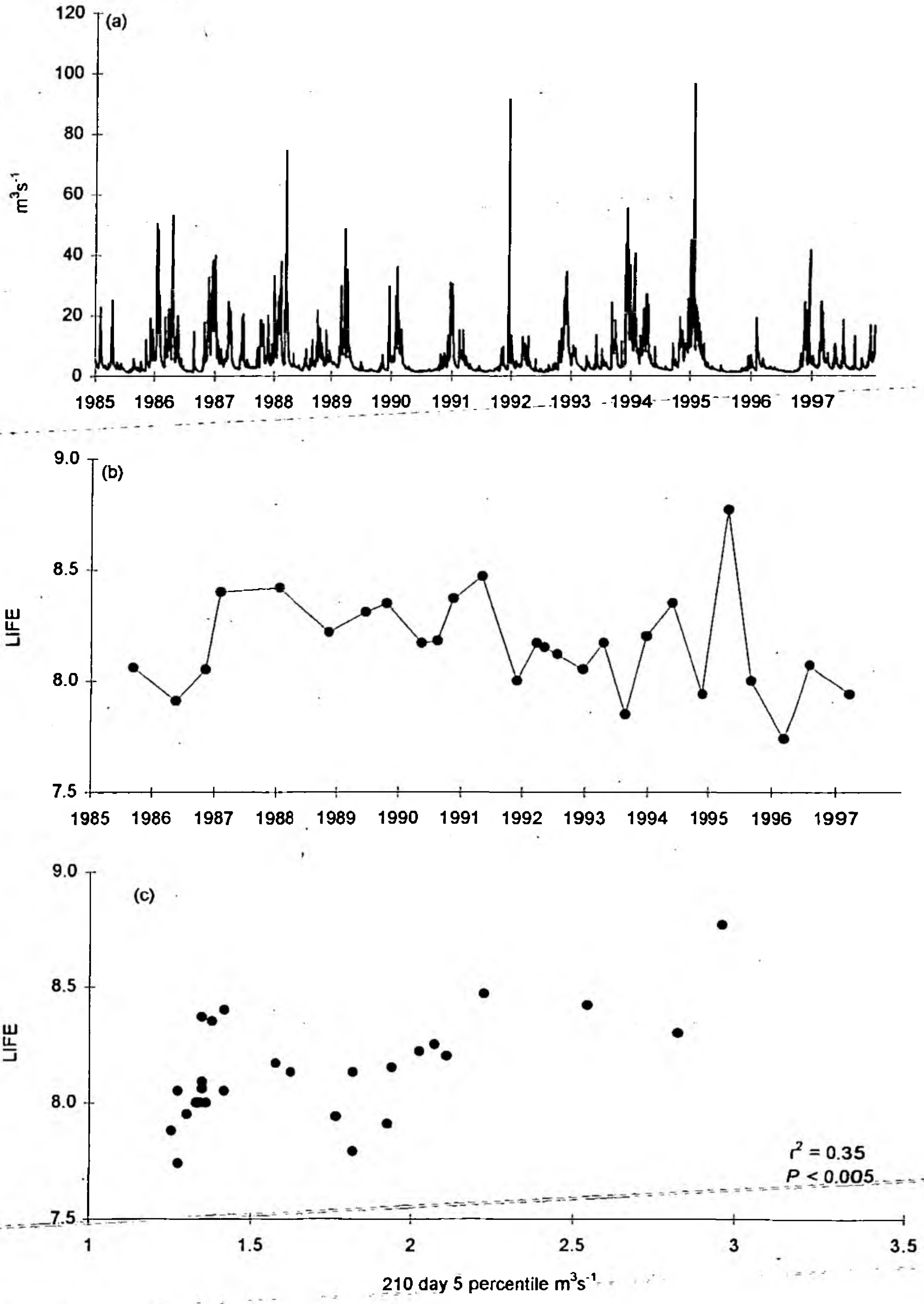


Figure 6. River Derwent. (a) Hydrograph from Chatsworth. (b) LIFE time plot from Baslow Bridge. (c) Scatter-plot of LIFE scores against flow. Flow is expressed as a 210 day five percentile.

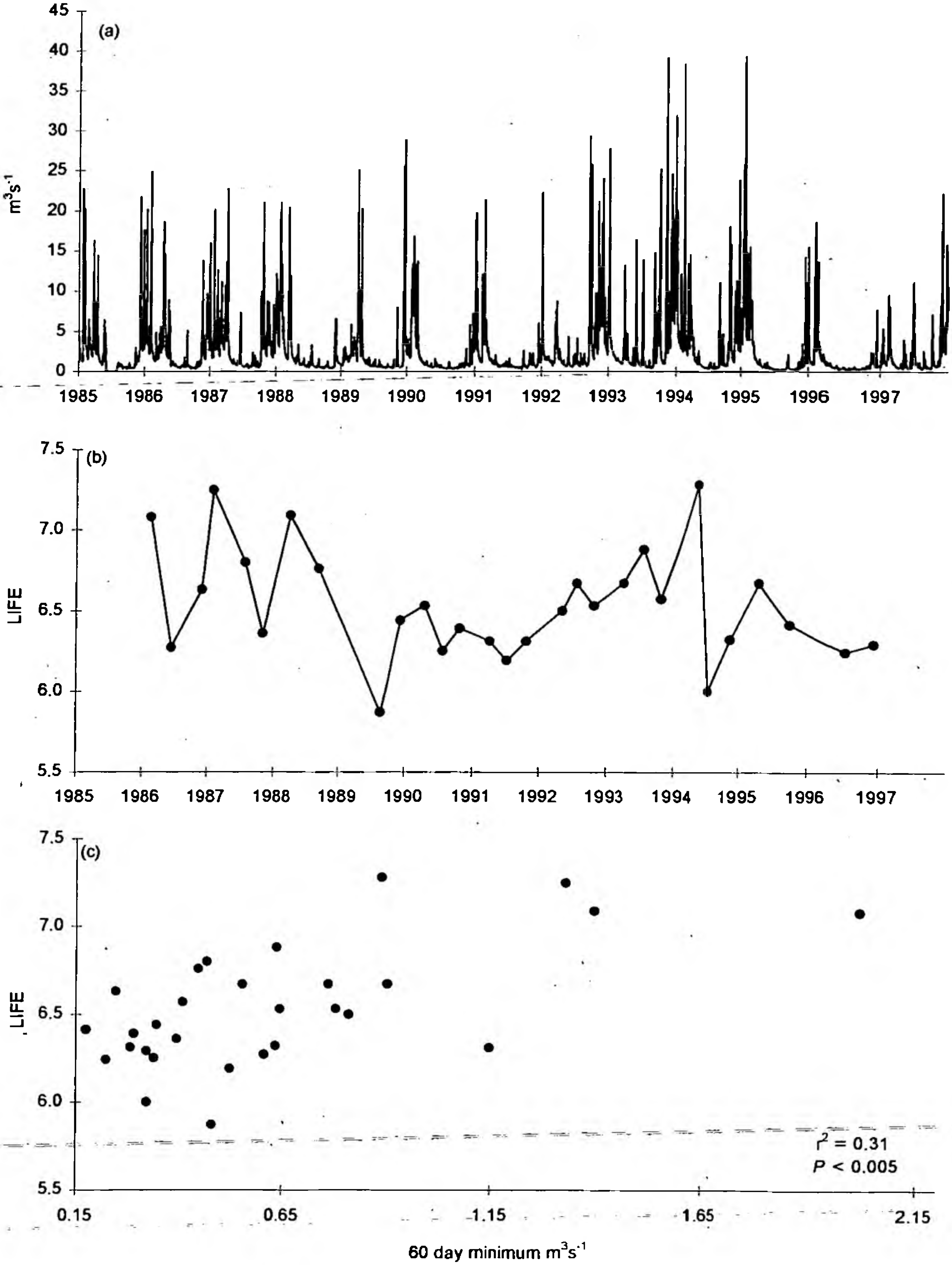


Figure 7. River Wreake. (a) Hydrograph from Syston. (b) LIFE time plot from Lewin Bridge. (c) Scatter-plot of LIFE scores against Flow. Flow is expressed as a 60 day minimum.

the geology of the catchment, it is perhaps not surprising that invertebrate communities respond primarily to short term flow events here. These community responses support the established view of the Wreake as a very "flashy" river.

Other Examples

Relationships between flow parameters and LIFE values have been analysed for a variety of additional rivers in England. It is not intended to examine these data in detail, but some examples of further results obtained are summarised in Table 4. Flow variables shown in this table are those providing the best prediction of LIFE score.

Confirmation of the importance of summer flows in influencing chalk stream ecology is again provided by these results, although considerable variation in response time was once more apparent (presumably due to dissimilar aquifer characteristics, discharge regimes and habitat structure in the rivers in question). Contrasting results were found for the River Wye, draining a chalk catchment in Buckinghamshire, where long-term minimum flows produced the best correlation with LIFE. Upstream effluents maintain flow at relatively high levels throughout the year at Hedsor, however, accounting for this apparent anomoly.

Summer flows were also important in determining community structure in the sandstone River Teme, and in a number of rivers draining limestone areas in both northern and southern England. These disparate rivers again displayed considerable variation in flow parameters providing best fits with LIFE score.

Minimum flows produced the optimum correlation at Rushton on the River Ise, draining a clay catchment in Northamptonshire.

Table 4.

Examples of 'best fit' flow variables and correlation coefficients for various English rivers.

Region	River	Location	NGR	Geology	Type	Length	Duration	Statistic	n	r^2	*p*
Anglian	Bain	Biscathorpe	TF 231 850	Chalk	Species	330 Days	Full Year	Minimum	21	0.55	<0.001
Anglian	Bain	Thornton Bridge	TF 260 680	Chalk	Species	150 Days	Mar - Sep	Mean	23	0.74	<0.001
Anglian	Cam	Gt. Chesterford	TL 503 427	Chalk	Family	480 Days	Mar - Oct	Mean	27	0.52	<0.001
Anglian	Granta	Linton	TL 571 463	Chalk	Family	300 Days	Apr - Sep	5 percentile	21	0.66	<0.001
Anglian	Ise	Rushton	SP 840 826	Clay	Species	180 Days	Full Year	Minimum	25	0.37	<0.005
Midlands	Teme	Tenbury	SO 595 687	Sandstone	Species	120 Days	Mar - Oct	Mean	24	0.26	<0.02
North East	Ure	Wensley	SE 092 894	Limestone	Family	240 Days	Apr - Sep	5 percentile	23	0.37	<0.005
North East	Wharfe	Addingham	SE 092 494	Limestone	Family	210 Days	Mar - Oct	Mean	26	0.46	<0.001
North East	Wharfe	Boston Spa	SE 432 458	Limestone	Family	300 Days	Mar - Sep	5 percentile	28	0.26	<0.01
Southern	Dour	Pencester Gardens	TR 320 416	Chalk	Family	150 Days	Arp - Oct	Mean	19	0.60	<0.001
Southern	Rother	Hardham	TQ 034 179	Chalk/ Greensand	Family	120 Days	Mar - Sep	Mean	17	0.50	<0.001
Thames	Chess	Chesham	SU 982 996	Chalk	Family	120 Days	Apr - Sep	Mean	19	0.45	<0.005
Thames	Evenlode	Chadlington	SP 333 207	Limestone	Family	420 Days	Apr - Sep	Mean	16	0.77	<0.001
Thames	Lambourn	Bagnor	SU 453 691	Chalk	Family	120 Days	Apr - Oct	Mean	18	0.48	<0.005
Thames	Windrush	Swinbrook	SP 282 118	Limestone	Family	330 Days	Apr - Sep	Mean	18	0.71	<0.001
Thames	Wye	Hedsor	SU 896 866	Chalk	Family	390 Days	Full Year	Minimum	22	0.46	<0.001

Discussion

The advantages and use of benthic macroinvertebrates in environmental assessment are long established (Cairns and Pratt, 1993) and the proposed LIFE technique offers new opportunities to utilise key taxa in highly topical hydroecological work. Results presented here show LIFE to be exceptionally robust (working at variable levels of resolution – Figs. 3a, 3b and 3c) and very effective in encapsulating ecological response to changing flow patterns in a range of river types. The method can thus be effectively used to summarise the multiple effects of flow on invertebrate populations, much as biotic indices have historically been used to integrate water quality effects. This positive response occurs despite the fact that the flow data used in the LIFE method may not necessarily be the flows to which benthic macroinvertebrates are normally exposed, because of the complex interactions that exist between river hydraulics, habitat morphology and habitat composition (Gore, 1996).

It is clear that baseline LIFE values are inextricably linked with the physical locations of biological sampling sites, for example, the upland situation of the River Derwent provides much higher species based LIFE scores (Fig. 6b) than the lower altitude Waithe Beck (Fig. 2b) or Wreake sites (Fig. 7b). Analysis has, moreover, shown that on rivers like the Lincolnshire Bain, where a number of biological sampling sites are established, LIFE scores show a progressive downstream decline as current velocities diminish.

The physical size of a watercourse may also be important in determining raw LIFE scores. At similar discharge, for example, a narrow confined channel may have adequate flows over the whole bed, whereas at wider points, areas of low flow with potential dewatering will be more likely.

LIFE values enumerated at individual sites will be further influenced by the quantity and quality of instream habitat available for invertebrate colonization. In this context, it is of interest to note that, even during periods of relatively high flow, LIFE (F) scores at Fornham on the channelised River Lark (Fig. 4c) were poor compared to family derived scores obtained at all times from other chalk stream sites on the Kennet (Fig. 5c) and Waithe Beck (Fig. 3b). This variability can be explained by a number of factors, including geological and structural differences between disparate rivers, the latter being strongly influenced by past and present engineering practices and policies.

A number of authors have recently made efforts to quantify the hydroecological link, including Bickerton (1995), who demonstrated that mean flows in April, and low flows prior to sample collection on the River Glen, Lincolnshire, could be linked to the summer invertebrate fauna, at both the community and the individual taxon level. An alternative approach has been described by Clausen and Biggs (1997) who have examined the relationship between a number of biotic measures, including invertebrate density and diversity, and 34 hydrological variables in New Zealand streams. This work has several features in common with the present study, including the production of a range of hydroecological correlation coefficients, and the subsequent determination of ecologically relevant flow variables. The LIFE methodology, however, offers substantial progress in this area, most notably in enabling the performance of an extended range of flow measures to be assessed against an index specifically designed to respond to flow variation, and not simply to general measures of community structure, such as species richness or diversity.

The LIFE software currently produces 200 to 300 different scatter-plots, and this procedure can be shortened or expanded as appropriate. The output from this process provides a wealth of salient data, permitting the in-depth evaluation of hydroecological relationships. At

Brigsley on the Waithe Beck, for example, there are 177 separate correlation coefficients significant at $p < 0.001$, 13 at $p < 0.005$, 6 at $p < 0.01$, 10 at $p < 0.05$ and 8 correlations which are non-significant, for the period 1986-1997. From this surfeit of usable statistics, those flow variables showing the best relationships with the invertebrate fauna are proposed as being of primary importance in determining community structure in particular river systems.

In most cases considered so far, single flow variables account very effectively for much of the ecological variation exhibited at individual river sites. Where data are normally distributed, or can be transformed to approximate normality, flow variables can be combined using multiple regression, to produce a more comprehensive description of the flow factors influencing the invertebrate community. For example, LIFE scores obtained from the Lincolnshire Bain at Hemingby (TF 235 743) correlate separately with 180 day RSM (April-September) and 30 day minimum (both $p < 0.005$). These variables can be combined to increase the level of significance to $p < 0.001$ (based on adjusted r^2 values).

The facility to enhance the general ecopredictive power of the various flow components may be worth exploiting at selected river sites, and this approach could ultimately help define multiple flow objectives in appropriate cases. An alternative way forward involves exploration of the interrelationships between correlation coefficients derived from single flow variables. This process can provide added insight, for example, the recognition of the importance of spring and autumn flow periods in determining community structure in the River Derwent

Producing an extended range of correlations between LIFE and hydrological parameters identifies different key flow variables in contrasting types of river. Summer flows are thus pinpointed as being of paramount importance in chalk and limestone streams, as are short term episodic flow events in rivers like the Wreake, draining impermeable catchments.

Provided significant relationships exist between hydrological and ecological variables, these distinct responses provide the opportunity to set flow objectives that are ecologically relevant.

This process is far from straightforward (see future work) but detailed evaluation of results should enable provisional targets to be set for most sites. On several rivers, for example, the relationship between key flow parameters and LIFE deteriorates during periods of prolonged drought and this is well illustrated at Brigsley on the Waithe Beck (Fig. 3a) where such conditions result in LIFE scores becoming independent of flows. In this case, examination of the residuals produced during regression analysis identifies several outliers that correspond to periods of extreme drought. These points can be justifiably removed from the main data set and used to define flow and ecological thresholds, below which significant "damage" occurs. Flow thresholds identified in this way must be evaluated against long term hydrological records, before being incorporated into any targetting procedure.

The use of twinned targets is advocated because failure to meet the hydrological objective may not necessarily result in an equivalent failure to attain the ecological standard (ecological response will lag behind hydrological change, and allowance must also be made for the influence of healthy antecedal flows at a site). Active water resource management procedures, such as providing river support or prohibiting surface water abstraction, would only be needed in cases where concomitant failures to reach hydrological and ecological objectives occurred. In practice, employing integrated objectives in this way maximises the judicious use of water resources, while simultaneously minimising inconvenience and disruption to abstractors and water managers.

The issue of setting practical and utilitarian flow targets for lotic waters has been the focus of much worldwide attention and research over the last decade. Approaches to setting river flow objectives have recently been reviewed by Dunbar *et al.* (1998) and a more specific appraisal of the use of ecological information in the management of low flows has latterly been provided by Armitage *et al.* (1997).

The most commonly applied techniques currently employed for setting benchmark flows involve the use of "look up" tables, wherein hydrological targets are set after examining a river's natural flow pattern (eg. Tennant, 1976). These methods make no direct reference to ecology, although more complex analyses of flow data, such as that provided by the Range of Variability Approach. (Richter *et al.*, 1997) can provide a highly relevant hydrological framework for setting ecological objectives.

Other initiatives that have been developed to help set flow standards involve holistic and professional judgement methods. These techniques generally attempt to use cross-functional ecological and hydrological expertise to propose flow objectives for rivers, and include procedures like the Expert Panel Assessment Method of Swales and Harris (1995).

Alternative approaches to setting benchmark flows have focused on biological response modelling (BRM) and the methodology outlined in this paper fits unequivocally into the array of BRM techniques which have gradually developed over the last thirty years or so. This evolutionary process has culminated in a group of techniques generally referred to as IFIM, or Instream Flow Incremental Methodology (Stalnaker 1994; Bovee 1995). One important component of IFIM is the Physical HABitat SImulation Model, or PHABSIM (Milhous, 1990) and the use of this model enables the impact of changing flow regimes on physical instream habitat to be assessed for specified target species. The technique has been applied to a number of British rivers since 1989 (Dunbar *et al.*, 1998), including the River Wissey, Norfolk (Petts and Bickerton, 1997b and 1997c), where its application, alongside new methodologies, has enabled acceptable end of summer minimum target flows to be defined.

It is our view that the LIFE method is suitable for use, within, alongside or in lieu of many of these techniques, and indeed, the LIFE approach may offer some considerable advantages. PHABSIM, for example, is not specifically designed for measuring low flow effects, and the methodology is therefore unable to easily provide information regarding drought and abstraction impacts on freshwater biota (Armitage *et al.*, 1997). Nor does the PHABSIM procedure take into account the dynamic nature of a site's flow history, and the impact of this variation on the structure of the resident invertebrate community at any one point in time. LIFE can potentially accomplish all this. PHABSIM additionally requires considerable financial and technical resources, and this is likely to restrict its use to high priority sites. Finally it has been shown that while IFIM/PHABSIM methodologies can produce invertebrate derived flow objectives for single river systems, derived biotic/hydraulic relationships cannot be readily transferred from one river to another, even if these rivers are of similar type (Petts and Bickerton, 1997a). In contrast, the LIFE approach offers the possibility of evaluating hydroecological relationships at many more river sites than has hitherto been possible, providing suitable long term flow and ecological records are available. Ideally, accurate daily flow records and bi or triannual species level data should co-exist, although the method appears robust enough to provide very usable results when these standards are not met. The continuation or upgrading of current biological sampling programmes for localities with long term results available, should improve the fit between hydrological and ecological components as databases continue to expand. For areas where this information is lacking or insufficient, the instigation of regular invertebrate sampling programmes at priority sites will enable hydroecological relationships to be determined in the future, as well as providing valuable additional information on water quality. This process may be relatively straightforward for much of Britain, with its long history of catchment-based river management, and a substantial database of hydraulic and biological information. Other parts of the world may not have such detailed data available, but the LIFE approach could be readily adapted and used for future hydroecological analysis.

There is an urgent and incontrovertible need, both nationally and internationally, for methods to facilitate the sustainable use and development of water resources. The conceptual ideas and detailed methodologies elaborated in this paper, may provide a timely opportunity for additional cost effective input into these very important areas.

Future work

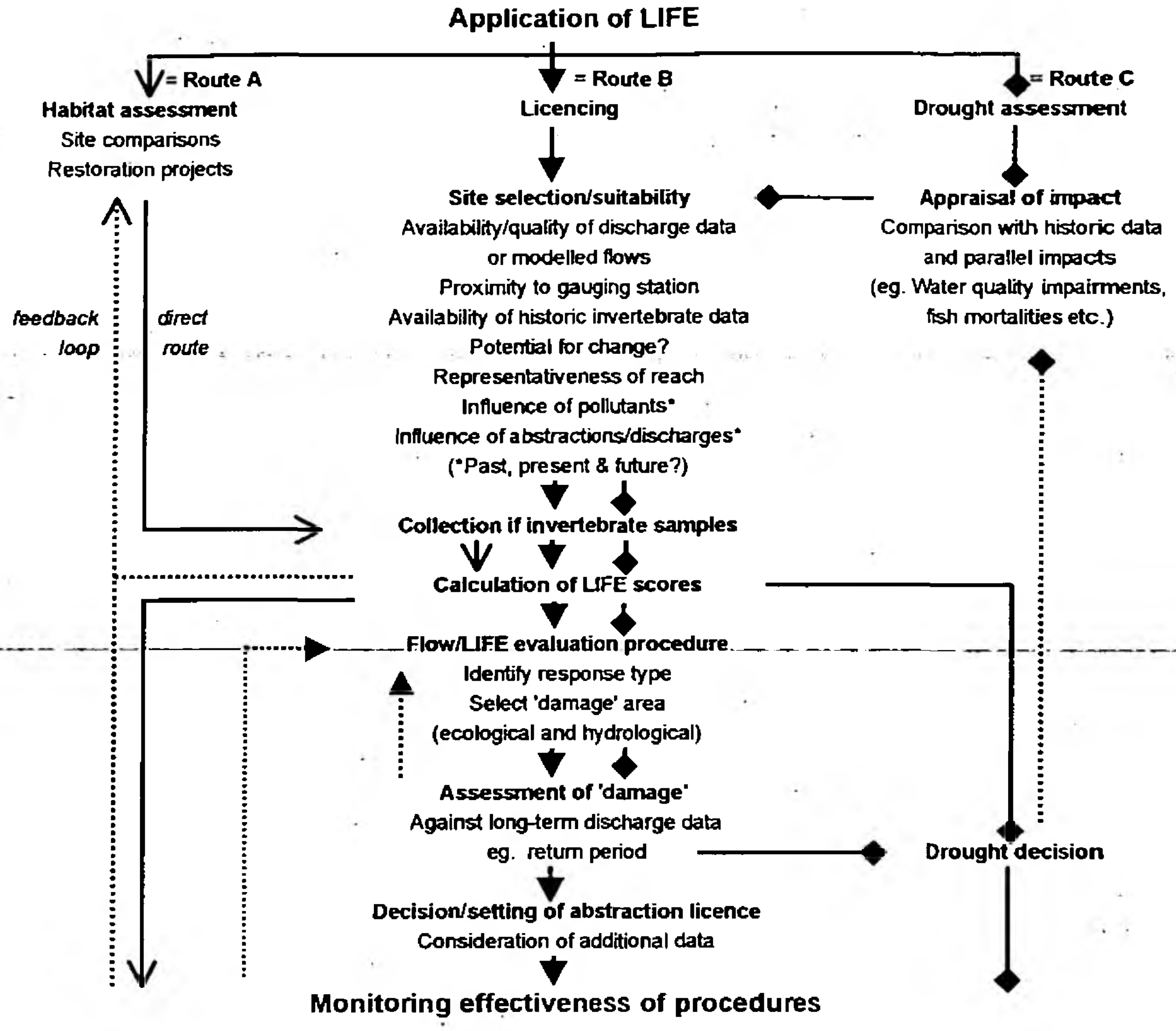
There is considerable scope for further work arising from the present studies. Index scores should, for example, be examined in watercourses which periodically dry up, and the hydroecological relationship needs elucidating in small streams where flows are discontinuously recorded rather than permanently gauged. There are also opportunities to appraise ecological response to modelled flows, either in situations where hydrological data are missing, or in cases where biological sampling sites are considered to be too remote from permanent flow gauging stations for results to be reliable. Ultimately, it may prove possible to define general responses for specific river types, which could then be transferred from river to river.

Additional research is also needed to establish the connection between LIFE scores and habitat characteristics. A link exists between poor habitat quality and depressed LIFE scores, and results derived from rivers like the Lark aptly demonstrate this. In this situation, it may be helpful to identify typical LIFE ranges for natural rivers with common physical and chemical attributes. Shortfalls in LIFE scores, particularly during high flow periods, would indicate the need for more detailed habitat assessment to be made. Poor habitat subsequently identified would suggest that some measure of habitat restoration might be necessary as an adjunct to the introduction of active flow management procedures. Good river habitat identified would imply that flow inadequancies were primarily responsible for poor LIFE scores.

A variety of techniques are available for assessing instream habitat, including the River Habitat Survey methods currently being used by the EA (Environment Agency, 1997) and other methods could be equally useful in this context, including the Functional Habitat Approach summarised by Harper *et al.* (1995) and the Riparian Channel and Environmental Inventory method of Petersen (1992). This latter technique generates a numerical habitat score, which can then be used to compare the physical and biological condition of different streams within a region or catchment. The use of a habitat-based grading system like this is an interesting prospect, since results obtained could be considered alongside measured LIFE scores, enabling remediation measures involving habitat restoration and/or water resource schemes to be prioritised.

Another potentially productive area of future work involves establishing the relationship between RIVPACS (Wright *et al.*, 1984) and LIFE methodologies. LIFE may, for example, provide a sensible explanation for situations where shortfalls in the predicted fauna cannot be accounted for by water quality impairment.

For individual rivers, it should eventually be possible to provide information on threshold LIFE scores necessary to preserve invertebrate diversity, although rules to facilitate this will be needed before any new water resource licensing strategy can be proposed. These potential applications of LIFE are summarised in Figure 8, which, with its accompanying notes,



Route A
At its most simple, habitat assessment, the method could comprise a comparison of achieved LIFE scores with those expected, for a particular river type. Additionally, the success of river restoration projects could be readily quantified.

Route B
The inclusion of the LIFE methodology into ground and surface water licencing procedure is likely to be a complex process, as presently the ecological requirements of river invertebrates are rarely considered. Here, the initial emphasis is on site selection and suitability, which is of fundamental importance to the method's success. The necessity for good quality discharge data is probably more important than a sample site's proximity to a gauging station. It is also preferable to choose a site that has potential for change, since it is this process which is exploited in the LIFE methodology.

Identification of 'flow response type' is the next critical stage of the process. Rivers with a short response (< 90 days, full year data) are normally flashy with little or no 'base flow' component. In systems which are principally ground-water fed, LIFE scores will usually correlate most significantly with longer-term changes in discharge (>100 days, over summer periods). Once a response has been established and areas of damage have been identified, proposed flow thresholds must be evaluated against the long-term actual and naturalised flow data, and expressed as return periods. At this stage management decisions need to be made about the impact of current/future licencing policy. For example, if 'damage' naturally occurs at a frequency of 1:20 and a proposed abstraction is likely to increase this to 1:18, will this be acceptable?

Route C
The drought impact route in practice is very similar to the licencing route. Results must be put into historical context in order to assess the current situation. If drought is resulting in serious environmental damage then 'route B' could be taken to set the impact into its long-term perspective, and licencing policy could be reviewed if appropriate.

Figure 8. Future or potential applications for LIFE.

illustrates some of the key points that should be considered, along with proposed decision routes and feedback loops. The implementation of procedures like this could ultimately offer an unprecedented degree of protection to freshwater biota.

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Appendix 1

Species Flow Group Associations
(Associations are at family or generic level for Diptera)

TRICLADIDA		
Planaria	*torva*	IV
Polycelis	*nigra*	IV
	tenuis	IV
	felina	II
Dugesia	*lugubris*	IV
	tigrina	III
	polychroa	IV
Phagocata	*vitta*	II
Crenobia	*alpina*	II
Dendrocoelum	*lacteum*	IV
Bdellocephala	*punctata*	V
GASTROPODA		
Theodoxus	*fluviatilis*	II
Viviparus	*viviparus*	III
	fasciatus	III
Valvata	*cristata*	IV
	macrostoma	V
	piscinalis	IV
Potamopyrgus	*jenkinsi*	III
Bithynia	*tentaculata*	IV
	leachi	IV
Lymnaea	*truncatula*	VI
	glabra	VI
	palustris	VI
	catascopium	V
	stagnalis	IV
	auricularia	IV
	peregra	IV
Myxas	*glutinosa*	IV
Aplexa	*hypnorum*	VI
Physa	*fontinalis*	III
Planorbarius	*corneus*	IV
Menetus	*dilatatus*	V
Planorbis	*carinatus*	IV
	planorbis	IV
	vorticulus	VI
	vortex	IV
	leucostoma	VI
	laevis	V
	albus	IV
	acronicus	IV
	crista	IV
	contortus	IV
Segmentina	*complanata*	V
	nitida	V
Acroloxus	*lacustris*	IV
Ancylus	*fluviatilis*	II

BIVALVIA		
Margaritifera	*margaritifera*	II
Unio	*pictorum*	IV
	tumidus	III
Anodonta	*cygnaea*	IV
	anatina	III
	complanata	III
Sphaerium	*rivicola*	III
	corneum	IV
	transversum	IV
	lacustre	V
	solidum	III
Pisidium	*amnicum*	III
	casertanum	IV
	conventus	V
	personatum	V
	obtusale	IV
	milium	III
	pseudosphaerium	IV
	subtruncatum	IV
	supinum	III
	henslowanum	III
	lilljeborgii	V
	hibernicum	IV
	nitidum	IV
	pulchellum	IV
	moitessierianum	IV
	tenuilineatum	IV
Dreissena	*polymorpha*	IV
HIRUDINEA		
Piscicola	*geometra*	II
Theromyzon	*tessulatum*	IV
Hemiclepsis	*marginata*	IV
Glossiphonia	*heteroclita*	IV
	complanata	IV
Boreobdella	*verrucata*	IV
Haementeria	*costata*	IV
Batracobdella	*paludosa*	IV
Helobdella	*stagnalis*	IV
Haemopsis	*sanguisuga*	IV
Hirudo	*medicinalis*	IV
Erpobdella	*testacea*	V
	octoculata	IV
Dina	*lineata*	IV
Trocheta	*subviridis*	IV
	bykowskii	II
ARANEAE		
Argyroneta	*aquatica*	V
ANOSTRACA		
Artemia	*salina*	VI
Chirocephalus	*diaphanus*	VI

NOTOSTRACA		
Triops	*cancriformis*	VI
MALACOSTRACA		
Mysis	*relicta*	V
Asellus	*aquaticus*	IV
	communis	V
	meridianus	IV
Corophium	*curvispinum*	III
Crangonyx	*pseudogracilis*	IV
Gammarus	*duebeni*	III
	lacustris	V
	pulex	II
	tigrinus	III
Orchestia	*cavimana*	VI
Austropotamobius	*pallipes*	II
EPHEMEROPTERA		
Siphlonurus	*armatus*	IV
	lacustris	IV
	linnaeanus	IV
Ameletus	*inopinatus*	I
Baetis	*fuscatus*	II
	scambus	II
	vernus	II
	buceratus	II
	rhodani	II
	atrebatinus	II
	muticus	II
	niger	II
	digitatus	II
Centroptilum	*luteolum*	III
	pennulatum	III
Cloeon	*dipterum*	IV
	simile	IV
Procloeon	*pseudorufulum*	III
Rhithrogena	*semicolorata*	I
	haarupi	I
Heptagenia	*sulphurea*	I
	longicauda	I
	fuscogrisea	IV
	lateralis	I
Arthroplea	*congener*	III
Ecdyonurus	*venosus*	I
	torrentis	I
	dispar	I
	insignis	I
Leptophlebia	*marginata*	IV
	vespertina	IV
Paraleptophlebia	*submarginata*	II
	cincta	II
	werneri	II
Habrophlebia	*fusca*	III
Ephemerella	*ignita*	II
	notata	II
Potamanthus	*luteus*	III
Ephemera	*vulgata*	III

	danica	II
	lineata	III
Brachycercus	*harrisella*	III
Caenis	*macrura*	III
	luctuosa	IV
	robusta	IV
	horaria	IV
	rivulorum	II
	pusilla	II
	pseudorivulorum	II
	beskidensis	II
PLECOPTERA		
Taeniopteryx	*nebulosa*	II
Rhabdiopteryx	*acuminata*	I
Brachyptera	*putata*	III
	risi	I
Protonemura	*praecox*	I
	montana	I
	meyeri	I
Amphinemura	*standfussi*	II
	sulcicollis	II
Nemurella	*picteti*	IV
Nemoura	*cinerea*	IV
	dubitans	II
	avicularis	IV
	cambrica	II
	erratica	II
Leuctra	*geniculata*	II
	inermis	I
	hippopus	I
	nigra	II
	fusca	II
	moselyi	I
Capnia	*bifrons*	I
	atra	V
	vidua	I
Isogenus	*nubecula*	I
Perlodes	*microcephala*	I
Diura	*bicaudata*	I
Isoperla	*grammatica*	I
	obscura	III
Dinocras	*cephalotes*	I
Perla	*bipunctata*	I
Chloroperla	*torrentium*	I
	tripunctata	I
	apicalis	II
ODONATA		
Platycnemis	*pennipes*	IV
Pyrrhosoma	*nymphula*	IV
Ischnura	*elegans*	IV
	pumilio	V
Enallagma	*cyathigerum*	IV
Coenagrion	*armatum*	V
	hastulatum	IV

	mercuriale	III
Coenagrion	*puella*	IV
	pulchellum	IV
	scitulum	V
Ceriagrion	*tenellum*	IV
Erythromma	*najas*	IV
Lestes	*dryas*	V
	sponsa	IV
Calopteryx	*splendens*	III
	virgo	II
Gomphus	*vulgatissimus*	III
Cordulegaster	*boltonii*	II
Brachytron	*pratense*	IV
Aeshna	*caerulea*	V
	cyanea	IV
	grandis	V
	isosceles	V
	juncea	V
	mixta	IV
Anax	*imperator*	V
Cordulia	*aenea*	V
Somatochlora	*arctica*	V
	metallica	IV
Oxygastra	*curtisii*	III
Orthetrum	*cancellatum*	V
	coerulescens	IV
Libellula	*depressa*	V
	fulva	III
	quadrimaculata	IV
Sympetrum	*flaveolum*	V
	fonscolombei	V
	nigrescens	V
	sanguineum	V
	scoticum	V
	striolatum	IV
	vulgatum	IV
Leucorrhinia	*dubia*	V
HEMIPTERA		
Mesovelia	*furcata*	V
Hebrus	*pusillus*	V
	ruficeps	IV
Hydrometra	*gracilenta*	V
	stagnorum	IV
Velia	*caprai*	III
	saulii	IV
Microvelia	*pygmaea*	IV
	reticulata	IV
	buenoi-umbricola	IV
Gerris	*costai*	V
	lateralis	V
	thoracicus	IV
	gibbifer	V
	argentatus	V
	lacustris	IV
	odontogaster	V

	najas	IV
	paludum	V
Limnoporus	*rufoscutellatus*	IV
Nepa	*cinerea*	V
Ranatra	*linearis*	V
Ilyocoris	*cimicoides*	IV
Aphelocheirus	*aestivalis*	II
Notonecta	*glauca*	IV
	marmorea-viridis	IV
	obliqua	V
	maculata	IV
Plea	*leachi*	IV
Micronecta	*scholtzi*	IV
	minutissima	IV
	poweri	IV
Cymatia	*bonsdorffi*	IV
	coleoptrata	IV
Glaenocorisa	*propinqua*	IV
Callicorixa	*praeusta*	VI
	wollastoni	V
Corixa	*dentipes*	IV
	punctata	IV
	affinis	IV
	panzeri	IV
Hesperocorixa	*linnei*	V
	sahlbergi	IV
	castanea	V
	moesta	V
Arctocorisa	*carinata*	IV
	germari	IV
Sigara	*dorsalis*	IV
	striata	IV
	distincta	IV
	falleni	IV
	fallenoidea	V
	fossarum	IV
	scotti	V
	lateralis	V
	nigrolineata	IV
	concinna	IV
	limitata	V
	semistriata	IV
	venusta	IV
	selecta	V
	stagnalis	V

COLEOPTERA

Brychius	*elevatus*	II
Peltodytes	*caesus*	V
Haliplus	*apicalis*	IV
	confinis	IV
	flavicollis	IV
	fluviatilis	IV
	fulvus	V
	furcatus	V
	heydeni	V

	immaculatus	V
	laminatus	IV
	lineatocollis	III
	lineolatus	IV
	mucronatus	V
	obliquus	IV
	ruficollis	V
	variegatus	V
	varius	V
	wehnckei	IV
Hygrobia	*hermanni*	V
Noterus	*clavicornis*	IV
	crassicornis	V
Laccophilus	*hyalinus*	III
	minutus	IV
	obsoletus	V
Hydrovatus	*clypealis*	V
Hyphydrus	*ovatus*	IV
Hydroglyphus	*geminus*	V
Bidessus	*minutissimus*	IV
	unistriatus	V
Hygrotus	*decoratus*	V
	inaequalis	IV
	quinquelineatus	V
	versicolor	IV
Coelambus	*confluens*	V
	impressopunctatus	V
	novemlineatus	V
	parallelogrammus	V
Hydroporus	*angustatus*	V
	discretus	II
	elongatulus	V
	erythrocephalus	V
	ferrugineus	IV
	glabriusculus	V
	gyllenhalii	IV
	incognitus	IV
	longicornis	V
	longulus	II
	marginatus	VI
	melanarius	V
	memnonius	V
	morio	V
	neglectus	IV
	nigrita	V
	obscurus	V
	obsoletus	II
	palustris	IV
	planus	V
	pubescens	IV
	rufifrons	V
	scalesianus	V
	striola	V
	tessellatus	IV
	tristis	V
	umbrosus	V

Suphrodytes	*dorsalis*	V
Stictonectes	*lepidus*	IV
Graptodytes	*bilineatus*	V
	flavipes	V
	granularis	V
	pictus	IV
Porhydrus	*lineatus*	V
Deronectes	*latus*	II
Potamonectes	*assimilis*	V
	depressus depressus	IV
	depressus elegans	III
	griseostriatus	V
Stictotarsus	*duodecimpustulatus*	II
Oreodytes	*davisii*	I
	sanmarkii	II
	septentrionalis	II
Scarodytes	*halensis*	IV
Laccornis	*oblongus*	V
Platambus	*maculatus*	II
Copelatus	*haemorrhoidalis*	V
Agabus	*affinis*	V
	arcticus	V
	biguttatus	VI
	bipustulatus	IV
	chalconatus	IV
	congener	V
	conspersus	V
	didymus	III
	guttatus	II
	labiatus	V
	melanarius	V
	melanocornis	IV
	nebulosus	V
	paludosus	II
	striolatus	V
	sturmii	IV
	uliginosus	V
	undulatus	V
	unguicularis	V
Ilybius	*aenescens*	V
	ater	V
	fenestratus	IV
	fuliginosus	IV
	guttiger	V
	quadriguttatus	V
	subaeneus	V
Rhantus	*bistriatus*	V
	exsoletus	V
	frontalis	V
	grapii	V
	suturalis	V
Colymbetes	*fuscus*	V
Hydaticus	*seminiger*	V
	transversalis	V
Acilius	*canaliculatus*	V
	sulcatus	V

Graphoderus	*bilineatus*	V
	cinereus	V
	zonatus	V
Dytiscus	*circumcinctus*	V
	circumflexus	V
	dimidiatus	V
	lapponicus	V
	marginalis	IV
	semisulcatus	V
Gyrinus	*aeratus*	IV
	caspius	IV
	distinctus	V
	marinus	V
	minutus	V
	paykulli	V
	substriatus	IV
	suffriani	V
	urinator	III
Orectochilus	*villosus*	II
Georissus	*crenulatus*	VI
Spercheus	*emarginatus*	V
Hydrochus	*angustatus*	V
	brevis	V
	carinatus	V
	elongatus	V
	ignicollis	V
	megaphallus	V
	nitidicollis	IV
Helophorus	*aequalis*	V
	alternans	V
	arvernicus	III
	brevipalpis	IV
	dorsalis	V
	flavipes	V
	fulgidicollis	V
	grandis	IV
	granularis	V
	griseus	V
	longitarsis	V
	minutus	V
	nanus	V
	nubilus	V
	obscurus	V
	strigifrons	VI
	tuberculatus	V
Coelostoma	*orbiculare*	VI
Cercyon	*bifenestratus*	VI
	convexiusculus	VI
	depressus	VI
	granarius	VI
	impressus	VI
	lateralis	VI
	littoralis	VI
	lugubris	VI
	marinus	VI
	melanocephalus	VI

	sternalis	VI
	tristis	VI
	ustulatus	VI
Paracymus	*scutellaris*	IV
Hydrobius	*fuscipes*	V
Limnoxenus	*niger*	V
Anacaena	*bipustulata*	IV
	globulus	IV
	limbata	IV
	lutescens	IV
Laccobius	*atratus*	V
	atrocephalus	VI
	biguttatus	IV
	bipunctatus	VI
	minutus	V
	sinuatus	IV
	striatulus	III
Helochares	*lividus*	V
	obscurus	V
	punctatus	V
Enochrus	*affinis*	V
	bicolor	V
	coarctatus	V
	fuscipennis	V
	halophilus	V
	isotae	V
	melanocephalus	V
	ochropterus	V
	quadripunctatus	IV
	testaceus	IV
Cymbiodyta	*marginella*	V
Chaetarthria	*seminulum*	VI
Hydrochara	*caraboides*	V
Hydrophilus	*piceus*	V
Berosus	*affinis*	V
	luridus	V
	signaticollis	V
	spinosus	V
Ochthebius	*auriculatus*	VI
	bicolon	VI
	dilatatus	V
	exsculptus	II
	marinus	V
	minimus	V
	nanus	V
	poweri	VI
	punctatus	V
	pusillus	V
	subinteger lejolisii	V
	viridis	V
Hydraena	*britteni*	IV
	gracilis	II
	minutissima	IV
	nigrita	II
	palustris	V
	pulchella	III

	pygmaea	II
	riparia	IV
	rufipes	II
	testacea	IV
Limnebius	*aluta*	V
	nitidus	IV
	papposus	V
	truncatellus	II
Elmis	*aenea*	II
Esolus	*parallelepipedus*	II
Limnius	*volckmarii*	II
Macronychus	*quadrituberculatus*	III
Normandia	*nitens*	II
Oulimnius	*major*	IV
	rivularis	IV
	troglodytes	IV
	tuberculatus	IV
Riolus	*cupreus*	II
	subviolaceus	II
Stenelmis	*canaliculatus*	III
Helichus	*substriatus*	IV
MEGALOPTERA		
Sialis	*lutaria*	IV
	fuliginosa	II
	nigripes	IV
NEUROPTERA		
Osmylus	*fulvicephalus*	II
Sisyra	*fuscata*	IV
	dalii	I
	terminalis	III
TRICHOPTERA		
Rhyacophila	*dorsalis*	I
	septentrionis	I
	obliterata	I
	munda	I
Glossosoma	*conformis*	II
	boltoni	II
	intermedium	II
Agapetus	*fuscipes*	II
	ochripes	II
	delicatulus	II
Philopotamus	*montanus*	I
Wormaldia	*occipitalis*	I
	mediana	I
	subnigra	I
Chimarra	*marginata*	I
Neureclipsis	*bimaculata*	III
Plectrocnemia	*conspersa*	II
	geniculata	I
	brevis	II
Polycentropus	*flavomaculatus*	II
	irroratus	II
	kingi	II

Holocentropus	*dubius*	V
	picicornis	V
	stagnalis	V
Cyrnus	*trimaculatus*	IV
	insolutus	V
	flavidus	IV
Ecnomus	*tenellus*	III
Tinodes	*waeneri*	III
	maclachlani	II
	assimilis	II
	pallidulus	II
	maculicornis	II
	unicolor	II
	rostocki	II
	dives	I
Lype	*phaeopa*	II
	reducta	II
Metalype	*fragilis*	II
Psychomyia	*pusilla*	II
Hydropsyche	*pellucidula*	II
	angustipennis	II
	siltalai	II
	saxonica	I
	contubernalis	II
	bulgaromanorum	III
	instabilis	II
	fulvipes	II
	exocellata	II
Cheumatopsyche	*lepida*	II
Diplectrona	*felix*	II
Agraylea	*multipunctata*	IV
	sexmaculata	IV
Allotrichia	*pallicornis*	I
Hydroptila	*sparsa*	II
	simulans	II
	cornuta	II
	lotensis	II
	angulata	II
	sylvestris	I
	martini	III
	occulta	I
	tineoides	IV
	pulchricornis	IV
	forcipata	II
	vectis	II
	tigurina	II
	valesiaca	II
Ithytrichia	*lamellaris*	II
	clavata	II
Orthotrichia	*angustella*	IV
	tragetti	V
	costalis	IV
Oxyethira	*flavicornis*	V
	tristella	IV
	simplex	IV
	falcata	IV

	frici	II
	distinctella	V
	sagittifera	V
	mirabilis	III
Tricholeiochiton	*fagesii*	V
Hagenella	*clathrata*	III
Phryganea	*grandis*	IV
	bipunctata	IV
Oligotricha	*striata*	V
Agrypnia	*varia*	V
	obsoleta	V
	picta	V
	pagetana	V
	crassicornis	V
Trichostegia	*minor*	VI
Ironoquia	*dubia*	II
Apatania	*wallengreni*	V
	auricula	V
	muliebris	II
Drusus	*annulatus*	II
Ecclisopteryx	*guttulata*	I
Limnephilus	*rhombicus*	IV
	flavicornis	V
	subcentralis	V
	borealis	V
	marmoratus	V
	politus	IV
	tauricus	V
	pati	V
	stigma	V
	binotatus	V
	decipiens	IV
	lunatus	IV
	luridus	VI
	ignavus	III
	fuscinervis	V
	elegans	V
	griseus	V
	bipunctatus	VI
	affinis	IV
	incisus	V
	hirsutus	II
	centralis	IV
	sparsus	VI
	auricula	V
	vittatus	V
	nigriceps	V
	extricatus	III
	fuscicornis	II
	coenosus	V
Grammotaulius	*nitidus*	V
	nigropunctatus	V
Glyphotaelius	*pellucidus*	IV
Nemotaulius	*punctatolineatus*	V
Anabolia	*nervosa*	IV
Phacopteryx	*brevipennis*	IV

Rhadicoleptus	*alpestris*	V
Potamophylax	*latipennis*	II
	cingulatus	II
	rotundipennis	II
Halesus	*radiatus*	II
	digitatus	II
Melampophylax	*mucoreus*	II
Stenophylax	*permistus*	III
	vibex	II
Micropterna	*lateralis*	II
	sequax	II
Mesophylax	*impunctatus*	V
	aspersus	II
Allogamus	*auricollis*	I
Hydatophylax	*infumatus*	II
Chaetopteryx	*villosa*	II
Molanna	*angustata*	IV
	albicans	V
Beraea	*pullata*	III
	maurus	II
Ernodes	*articularis*	II
Beraeodes	*minutus*	II
Odontocerum	*albicorne*	I
Ceraclea	*nigronervosa*	IV
	fulva	IV
	senilis	IV
	annulicornis	II
	dissimilis	IV
Athripsodes	*aterrimus*	IV
	cinereus	II
	albifrons	II
	bilineatus	II
	commutatus	I
Mystacides	*nigra*	IV
	azurea	IV
	longicornis	IV
Triaenodes	*bicolor*	IV
Ylodes	*conspersus*	II
	simulans	II
	reuteri	III
Erotesis	*baltica*	V
Adicella	*reducta*	III
	filicornis	II
Oecetis	*ochracea*	IV
	furva	V
	lacustris	IV
	notata	II
	testacea	IV
Leptocerus	*tineiformis*	V
	lusitanicus	III
	interruptus	III
Setodes	*punctatus*	II
	argentipunctellus	V
Goera	*pilosa*	I
Silo	*pallipes*	I
	nigricornis	I

Crunoecia	*irrorata*	II
Lepidostoma	*hirtum*	II
Lasiocephala	*basalis*	II
Brachycentrus	*subnubilus*	II
Sericostoma	*personatum*	II
Notidobia	*ciliaris*	III

DIPTERA

Dicranota sp.		II
Pedicia sp.		II
Ptychoptera sp.		II
Eristalis sp.		V
Simuliidae		II
Chaoboridae		V
Culicidae		V

Appendix 2
Family flow group associations

TRICLADIDA					
[Planariidae**	IV*	Dugesiidae**	IV]	Dendrocoelidae	IV
GASTROPODA					
Neritidae	II	Viviparidae	III	Valvatidae	IV
[Hydrobiidae**	IV*	Bithyniidae**	IV]	Lymnaeidae	IV*
Physidae	IV*	Planorbidae	IV	[Ancylidae**	II
Acroloxidae**	IV]				
BIVALVIA					
Margaritiferidae	II	Unionidae	IV*	Sphaeriidae	IV*
Dreissenidae	IV				
HIRUDINEA					
Piscicolidae	II	Glossiphoniidae	IV	Hirudidae	IV
Erpobdellidae	IV				
ARANEAE					
Agelinidae	V				
ANOSTRACA					
Chirocephalidae	VI				
NOTOSTRACA					
Triopsidae	VI				
MALACOSTRACA					
Mysidae	V	Asellidae	IV	Corophidae	III
[Gammaridae**	II	Crangonycitidae**	IV]	Talitridae	VI
Astacidae	II				
EPHEMEROPTERA					
Siphlonuridae	IV*	Baetidae	II*	Heptageniidae	I*
Leptophlebiidae	II*	Ephemerellidae	II	Potamanthidae	III
Ephemeridae	II*	Caenidae	IV*		
PLECOPTERA					
Taeniopterigidae	II*	Nemouridae	IV*	Leuctridae	II*
Capniidae	I*	Perlodidae	I	Perlidae	I
Chloroperlidae	I				
ODONATA					
Platycnemididae	IV	Coenagriidae	IV	Lestidae	IV
Agriidae	III*	Gomphidae	II	Cordulegasteridae	II
Aeshnidae	IV	Corduliidae	IV*	Libellulidae	IV*

HEMIPTERA					
Mesovelidae	V	Hebridae	IV*	Hydrometridae	IV
Veliidae	IV*	Gerridae	IV	Nepidae	V
Naucoridae	IV	Aphelocheiridae	II	Notonectidae	IV
Pleidae	IV	Corixidae	IV		
COLEOPTERA					
Haliplidae	IV*	Hygrobiidae	V	Noteridae	IV*
Dytiscidae	IV*	Gyrinidae	IV*	Hydrophilidae	IV*
Hydraenidae	IV*	Scirtidae	IV*	Elmidae	II*
MEGALOPTERA					
Sialidae	IV*				
NEUROPTERA					
Osmylidae	II	Sisyridae	IV*		
TRICHOPTERA					
[Rhyacophilidae**	I	Glossosomatidae**	II*]	Philopotamidae	I
Polycentropodidae	IV*	[Psychomyiidae**	II*	Ecnomidae**	III]
Hydropsychidae	II	Hydroptilidae	IV*	Phryganeidae	IV
Limnephilidae	IV*	Molannidae	IV	Beraeidae	II
Odontoceridae	I	Leptoceridae	IV*	Goeridae	I
Lepidostomatidae	II	Brachycentridae	II	Sericostomatidae	II
DIPTERA					
Tipulidae	IV*	Ptychopteridae	II	Chaoboridae	V
Culicidae	V	Simuliidae	II	Syrphidae	V

* -Families containing species/genera with variable flow requirements
** -Historical data may include combination of both families, or separate families (use first family of pair in cases where both family names used, *eg.* Gammaridae/Crangonycitidae = II)

MANAGEMENT AND CONTACTS:

The Environment Agency delivers a service to its customers, with the emphasis on authority and accountability at the most local level possible. It aims to be cost-effective and efficient and to offer the best service and value for money.

Head Office is responsible for overall policy and relationships with national bodies including government.

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The 24-hour emergency hotline number for reporting all environmental incidents relating to air, land and water

ENVIRONMENT AGENCY EMERGENCY HOTLINE
0800 80 70 60

ENVIRONMENT AGENCY

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