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Ecologically Acceptable Flows Phase II

Volume 1: Habitat Time Series Analysis

R&D Technical Report W19

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This report forms part of Environment Agency R&D Project 282 Phase II 'Ecologically Acceptable Flows'. It details work carried out by the Institute of Hydrology to combine the outputs from the habitat modelling procedures undertaken in Phase I of the project, with flow time series data from the National River Flow Archive (NRFA), to develop the techniques for predicting habitat availability on a temporal basis.

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EXECUTIVE SUMMARY

This report forms part of Environment Agency R&D Project 282 Phase II 'Ecologically Acceptable Flows'. It details work carried out by the Institute of Hydrology to combine the outputs from the habitat modelling procedures undertaken in Phase I of the project, with flow time series data from the National River Flow Archive (NRFA), to develop the techniques for predicting habitat availability on a temporal basis. In the Phase I project, the Physical Habitat Simulation (PHABSIM) system, a computer model of instream physical habitat developed in the United States and applied world-wide, was investigated for use in the UK. PHABSIM hydraulic models for nine British rivers were produced. Then, using a habitat model, the hydraulic output was combined with habitat suitability indices for fish (brown trout *Salmo trutta*, roach *Rutilus rutilus* and dace *Leucisus cephalus*), plus suitable invertebrate and macrophyte groups to produce theoretical relationships between physical habitat area (WUA) and river discharge (Q).

It is logical to assume that future population levels in an instream aquatic community will be influenced not only by physical habitat at that future time, but also by the patterns of physical habitat leading up to it. Thus extending the 'traditional' PHABSIM model results (the Weighted Usable Area versus Discharge curve) to temporal predictions of habitat is a crucial step in relating model output to changes in fish and invertebrate populations. In this study, the application of several existing low-flow analysis techniques to the temporal analysis of instream physical habitat have been investigated. Calibrated PHABSIM habitat models were combined with flow time series data from the National River Flow Archive (NRFA), in order to predict habitat availability on a temporal basis. Where possible, comparisons have been made between results from different rivers.

Naturally, the flow regime of a river will be an important factor in determining temporal patterns of habitat. In this study, the greater flow variability in upland catchments (compared to less flashy lowland sites) was reflected in higher habitat variability. However, using currently available habitat suitability indices, the non-linear relationship between habitat and discharge also has profound influence on the form of a habitat time series. This additional source of variation has been shown to be especially important for fish life stages, which generally show optimum habitat at intermediate flows.

A fundamental method for analysis of time series of river flows is to derive a cumulative frequency diagram, this is often known as the flow duration curve. Following this concept, habitat duration curve analysis was undertaken for the nine UK rivers. This report discusses the methods used to create the curves and further analysis that can aid in their interpretation. These methods are of particular use in the analysis of how alternative flow regimes affect habitat available to individual life stages of a species. Techniques for aggregation of daily habitat values to monthly and annual statistics are discussed, as is the use of single - year habitat duration curves.

The study discusses how variations in the flow regime and the habitat - discharge relationship affect the shape of a habitat duration curve. Plotting corresponding flow values on a habitat duration curve can aid in its interpretation, particularly when intermediate habitat values may arise from both high and low flows. For this type of flow - habitat relationship, numbers of flows outside the model calibration, combined with relative habitat values at the model limits,

can have a significant influence on the shape of the habitat duration curve. This emphasises the importance of a robust PHABSIM calibration, using the widest possible flow range.

Application of another low-flow technique, flow-spell analysis is also discussed, as are modifications to aid in habitat time-series interpretation. Habitat-spell analysis characterises the lengths of time the habitat drops below a certain threshold value, and it has been suggested that analysis of these deficit periods could provide further insight into possible critical habitat limitations. Further development of this promising technique is required. This report also briefly reviews options for further research into the sensitivity of habitat time series to variations both in habitat suitability data, and in the transfer of gauged flow time-series to ungauged study sites.

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Abbreviations used

IH	Institute of Hydrology
NBS	US National Biological Service
IFE	Institute of Freshwater Ecology, Wareham
MF	mean flow
NWA	National Water Archive
NRFA	National River Flow Archive
Q	River discharge (measured in cumecs)

Other conventions

Habitat suitability curves developed for invertebrates in Project B2.I Phase I was taken from the RIVPACS database. Species names denote criteria developed from data on occurrence of that species, while generic names (e.g. Leuctridae (A)) refer to curves developed with data on abundance of that genus, as well as occurrence.

Acknowledgements

We would like to thank the staff of the Environment Agency and the Institute of Freshwater Ecology for habitat suitability data and advice. We are also grateful to the staff of the Environment Agency for providing river flow data. We acknowledge the US National Biological Service Instream Flow Group, for the development of PHABSIM and for their assistance in applying the model in the UK. The authors would also like to thank their colleagues at IH for their assistance including Andy Young, Ann Sekulin and Sam Green.

1. INTRODUCTION

1.1 Background

Following concern over low flow conditions arising from recent droughts in the UK, a national low flows assessment by the NRA (1993) identified a priority list of 40 locations perceived as suffering from excessive abstraction. This, coupled with the requirement under 1989 Water Act for the NRA to set Minimum Acceptable Flows when requested by the Secretary of State, has prompted the need to develop operational tools for managing aquatic communities in British rivers on a national scale.

A previous NRA R&D project (Johnson *et al.* 1993a) completed by the Institute of Hydrology, investigated the potential for the use in the UK of PHABSIM, a computer model of instream physical habitat, developed in the United States. This model can be used to predict the reduction in habitat available to various target species resulting from low river flows.

In addition to its routine application in the United States, PHABSIM is the subject of previous studies and ongoing research in several countries world-wide including Canada (Shirvell & Morantz 1983), New Zealand (Scott & Shirvell 1987), Norway (Heggenes 1990) and France (Souchon *et al.* 1989). In the UK, under commissions from MAFF (Johnson *et al*, 1993c, Elliott *et al.* 1995b), PHABSIM has also been used in the environmental assessment of two flood defence schemes in the Thames catchment.

In NRA South Western Region, the Institute of Hydrology has applied PHABSIM to salmonid habitat at two sites on the river Allen (to assess the impact of the historical groundwater abstraction regime which has reduced river flows) (Johnson *et al.* 1995c), the rivers Bray and Barle (Johnson *et al.* 1994b), and the river Piddle (Johnson and Elliott 1995b). An initial investigation into the use of PHABSIM to predict juvenile cyprinid habitat on the Thames, has recently been completed (Elliott *et al.* 1995), and Worcester College of Further Education is currently working on two PHABSIM studies on the rivers Kennett and Tavy, the latter in collaboration with IH.

For this project the Environment Agency has commissioned the Institute of Hydrology to combine the calibrated habitat models from the Phase I R&D project (Johnson *et al.* 1993a) with flow time series data from the National River Flow Archive (NRFA), in order to predict habitat availability on a temporal basis. In particular, the use of the habitat duration curve to predict impacts across the range of flows experienced in a river has been examined. Extending the PHABSIM model to temporal predictions of habitat is a crucial step in relating model output to fish and invertebrate populations.

This report also investigates the application of several other existing low-flow analysis techniques to the temporal analysis of instream physical habitat, and provides suggestions as to how these techniques could be further improved for habitat analysis.

1.2 IFIM and PHABSIM rationale and concepts

The Physical HABitat SIMulation system (PHABSIM) is part of a wider framework, the Instream Flow Incremental Methodology (IFIM), developed at the US Fish and Wildlife Service by an interdisciplinary team of scientists (Stalnaker 1993, Bovee 1995).

IFIM is a framework for analysing spatial and temporal changes in habitat characteristics such as streamflow and channel geometry. Its most commonly-used component is PHABSIM, but it also includes models for water quality, water temperature or indeed any other model which simulates characteristic features which could influence habitat. It also includes mechanisms for analysing the institutional aspects of water resource issues, plus the all-important scoping and planning process, along with techniques for negotiation and resolution.

PHABSIM is a computer model running under the MS-DOS operating system that provides an estimate of physical habitat loss or gain resulting from changes in discharge. It is calibrated by making accurate field survey measurements of channel geometry at transect sites on a river system, along with measurements of water surface level at two or more flows, and stream velocities at one or more flows (Trihey & Wegner 1981, Bovee 1982, Johnson *et al.* 1991). Output from PHABSIM is in the form of a Weighted Usable Area (WUA) versus Discharge (Q) curve, for each species / life stage of interest. This graph shows how habitat (represented by WUA) varies with streamflow. There has been much debate as to the interpretation of these curves (Orth 1987, Mathur *et al.* 1985, Scott & Shirvell 1987, Gore & Nestler 1988), however it is certain that one cannot simply choose an ecologically acceptable minimum by choosing the flow corresponding to maximum available habitat. Further analysis is required. One such approach, as outlined here, is to carry out time series analysis on the predictions of available habitat within a river.

The underlying concepts of PHABSIM are:

- It is habitat-based, with potential usable habitat being simulated for unobserved flow or channel conditions.
- Target species exhibit a quantifiable preference/avoidance behaviour to one or more of the physical microhabitat variables; velocity, depth, cover or substrate.
- Preferred conditions can be represented by a suitability index which has been developed in an unbiased manner.
- Individuals select the most preferred conditions within a stream, but will use less favourable areas with decreasing frequency/preference.
- Species populations respond to changes in environmental conditions that constitute habitat for the species.

The purpose of the PHABSIM system is the simulation of the relationship between streamflow and available physical habitat where physical habitat is defined by the microhabitat variables depth, velocity and substrate/cover. The two basic components of

PHABSIM are the hydraulic and habitat simulations within a stream reach using defined hydraulic parameters and habitat suitability criteria, as displayed in Figure 1.1 below.

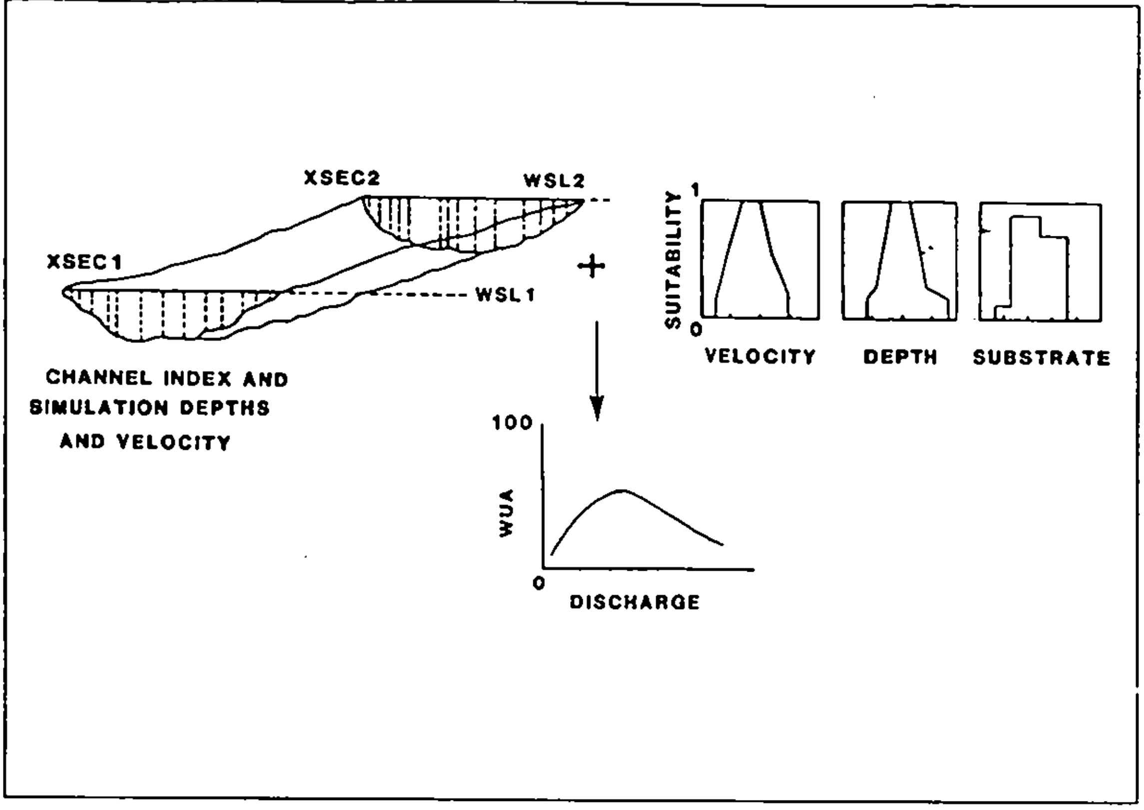


Figure 1.1 PHABSIM

The PHABSIM **hydraulic simulation model** is calibrated with field survey data and is able to model depths and velocities (along with substrate and / or cover as unchanging parameters), at calibration and non-calibration flows. The PHABSIM **habitat model** then receives these data and combines them with habitat suitability indices for target species / life stages. For each target life stage, it produces a single index, the Weighted Usable Area (WUA) at each modelled flow.

It is clear that in conducting a PHABSIM study, an ideal goal would be to relate changes in aquatic populations to change in the flow regime. Although some studies have successfully demonstrated that PHABSIM may be capable of achieving this goal, it must be appreciated that PHABSIM alone is not capable of this task since it predicts change in a weighted measure of physical habitat area (WUA) available to aquatic species and does not predict change in biomass. In some instances a linear relationship between biomass and WUA has been demonstrated (Milhous, 1988, Jowett, 1992) but it is clear that over a period of years, this will not be the case in most rivers since for some of the time, **factors other than physical habitat may be limiting to populations**. However in the analysis of the impacts of low flows, lack of physical habitat will clearly be a key factor.

In the absence of equivalent population models, one accepts the limitation of using WUA as the key variable and attempts to take into account, as rigorously as possible, factors which are likely to influence the relationship between WUA and populations. Gore and Nestler (1988) make the following statement with regard to this issue:

"PHABSIM is a vehicle for presenting biological information in a format suitable for entry into the water resources planning process. It is not, nor was it ever intended to be, a replacement for population studies, a replacement for basic research into the subtleties of fish or benthic ecology, nor a replacement for biological innovation or common sense. As such, PHABSIM has been found to be a defensible technique for adjudicating flow reservations".

1.3 Analysis of flow and habitat time series

1.3.1. Habitat time series

A time series is a sequence of events, arranged in order of occurrence. In this study, historical time series of flows taken from gauging station data held either by the National River Flow Archive (NRFA) at the Institute of Hydrology, or regional EA offices, were combined with PHABSIM habitat model output to predict the temporal patterns of habitat that would have occurred during the period of record.

The major premise of habitat time series analysis is that habitat is a function of streamflow:

$$\text{Habitat}(t) = f(Q(t))$$

where t=time

Time series of available habitat (as represented by WUA) may be used to analyse the impacts on river biota of alternate flow regimes; this is a major advantage of PHABSIM over multi-variate statistical models. It provides the first stage in linking the 'traditional' PHABSIM output - the WUA v Discharge curve, with the recognition that single and multiple critical events can limit physical habitat, and thus have major impacts on river biota. A more complete assessment of the effects of a hydrological regime requires consideration of all life stages, and where required, targeting the analysis to crucial time periods. For example, for fish species, critical flows during spawning or fry development will affect recruitment and thus have a knock-on effect on the adult population, even if adult habitat is good in following years.

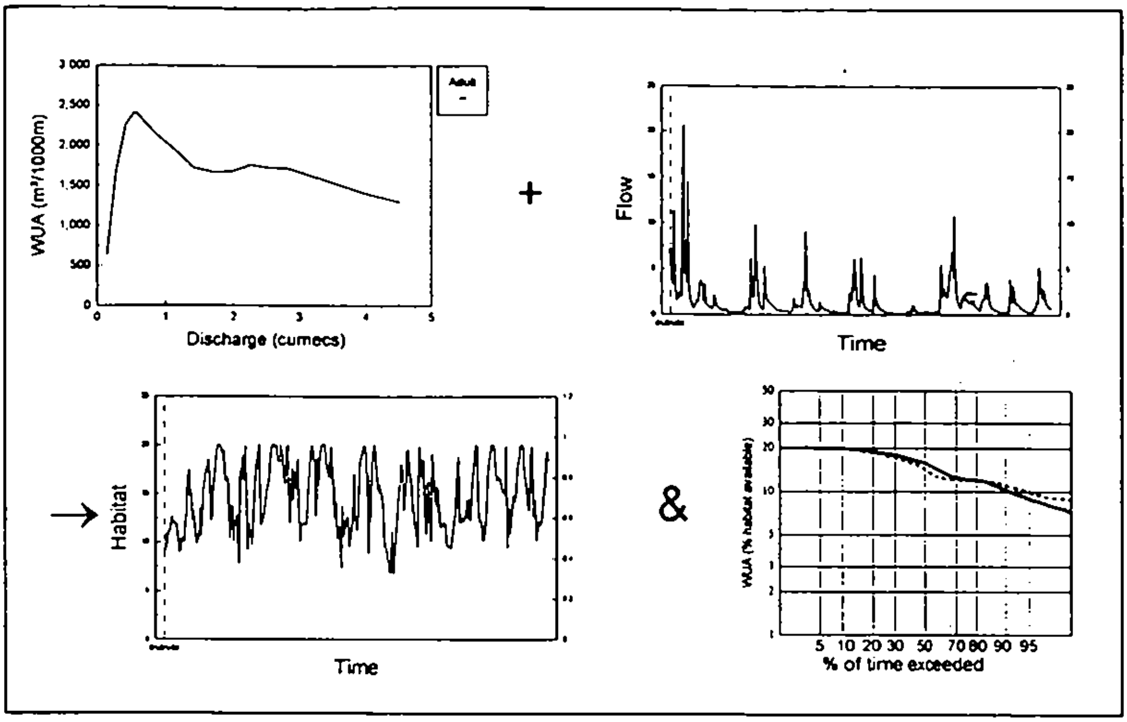


Figure 1.2. Development of a habitat time series

1.3.2. Summary habitat statistics

Once a daily habitat time series has been calculated, the user may wish to aggregate daily values to monthly or even yearly, in order to examine habitat changes on a long-term basis. Commonly-used summary statistics include (Milhous 1990b):

- Mean habitat
- Median habitat
- Index-A: mean of all the habitats between 50% and 90% exceedance, i.e. the majority of the low flow events
- Index-B: mean of all habitats between 10% and 90%
- Minimum habitat : not recommended in most cases
- Maximum / optimum habitat
- An exceedance statistic e.g. 90, 95 percentile habitat (see section 4.12 for example)
- Number of days below threshold, or total threshold deficit (see section 4.13 for example)

1.3.3. Habitat duration curves

Habitat time series may be subjected to further analysis using the techniques developed for river flow analysis. The first example of this is the **habitat** duration curve (Milhous 1986, Gordon McMahon and Finlayson 1992, Vogel and Fennessey 1995). A duration curve, whether for flow, habitat or another instream variable, displays the relationship between the variable and the percentage of time it is exceeded.

Duration curves are constructed by sorting the data (time series of flows or habitat values) from highest to lowest, and expressing each data point as a percentage of the total number of values.

When a flow-duration curve from UK catchments are plotted with a normal probability (x) axis and logarithmic flow (y) axis, the curve approximates to a straight line indicating that the logarithm of discharge follows a normal distribution. However this is less often the case for habitat duration curves.

Duration curves are particularly useful for assessing the impacts of alternative flow regimes. Johnson *et al.* (1993b, 1994b, 1995b) demonstrated their use on several rivers in the EA South Western region.

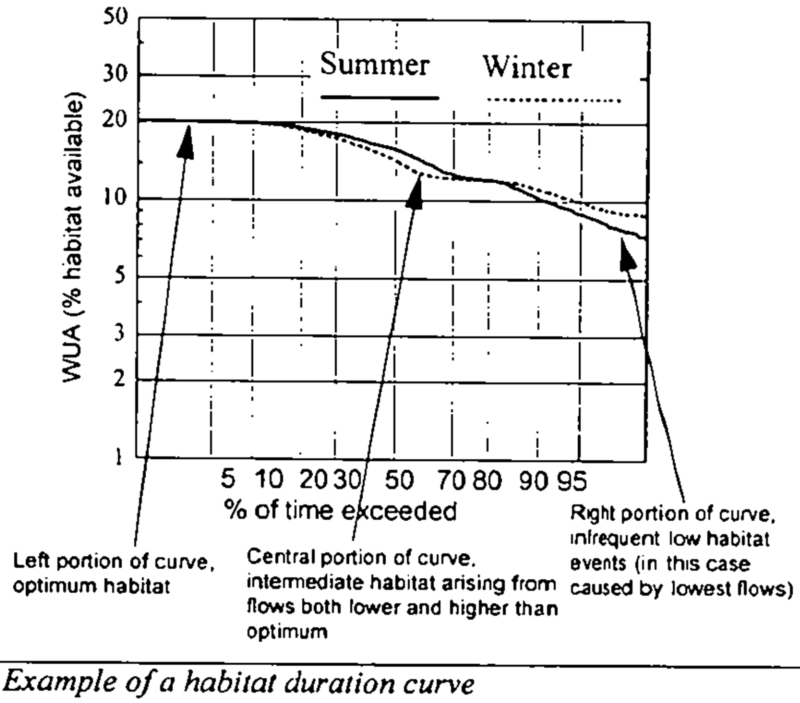


Figure 1.3. Example of a habitat duration curve

1.3.4. Points to note in duration curve analysis of habitat data

It is important to note that a habitat duration curve shows exceedance percentiles for values of habitat, ranked from highest to lowest. It does not simply show flow exceedance percentiles mapped to their corresponding habitat values. It is also important to note that especially for fish life stages, there is not generally a continuous increasing relationship between habitat and flow. Instead, habitat often increases with flow up to a certain flow, and then decreases. There are many examples of this in the results of R&D project B2.I. The results of this phenomenon are that some central portion of the habitat duration curve will be made up of habitat arising from both high and low flows. This is unlike a flow duration curve, where high flows are always on the left and low on the right. Instead, 'optimum habitat' arising from intermediate flows forms the left hand side of the curve (see Figure 1.3), combinations of intermediate habitat arising from either higher or lower than optimum flows comprise the central portion, and depending on the range of the calibrated model and range of flows in the time series, the right hand portion will comprise of low habitat figures arising from either the highest or lowest flows.

While not detracting from the use of habitat duration curves in the evaluation of the impacts of alternate flow regimes, caution should be exercised in their interpretation. It is possible to plot values of flow on a habitat duration-curve-to aid in interpretation, this procedure is further discussed in section 4.6 below.

In this study, habitat-discharge curves for invertebrates and macrophytes exhibit either continuous increasing or continuous decreasing behaviour. This one-to-one mapping of flow and habitat makes interpretation of their habitat duration curves more straightforward.

Duration curves also do not give information about the temporal distribution of low flow or habitat events, i.e. whether they occur together or separately. Other techniques such as flow & habitat spell analysis have been developed for this purpose.

1.3.5. Flow and habitat spell analysis

This technique, described in the Low Flow Studies Report (IH, 1980) characterises periods of flow below a certain threshold value. Its advantage over the flow duration curve is that it considers the temporal distribution of low flow events. This technique has been applied to simulated habitat (Capra, Breil and Souchon, 1995). The methodology is discussed in Section 3 below.

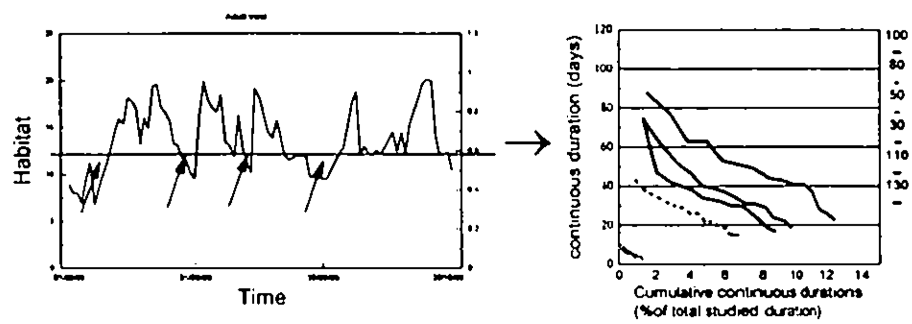


Figure 1.4. Flow/habitat spell analysis.

2. REVIEW OF PHABSIM OUTPUT FROM PHASE I OF THE ECOLOGICALLY ACCEPTABLE FLOWS PROJECT

2.1. Background

During NRA R&D Project EAF Phase I, calibration data were collected from ten sites, each representing one ecological group defined using data from the RIVPACS database (Wright *et al.* 1988, Johnson *et al.* 1993a). It was not possible to calibrate the PHABSIM model for the Great Ouse / Lees Brook, so this site is not considered further in this report.

The following table indicates the calibration flows (C1, C2, C3) for the remaining study sites along with the lower and upper limits of the model (MLow and MHigh). It also lists the out-of-range flows for summer and winter separately, when the time series of daily mean flows was run through the model. The time series were 16 years (5844 days) except where stated.

Table 2.1. *Table of calibration flows, model ranges and out-of-range flows for EAF Phase I sites*

Site	C1 (m^3/s)	C2	C3	MLow	MHigh	no. flows below lower limit		no. flows above upper limit		no. flows missing	
						S	W	S	W	S	W
Exe at Warren Farm (Using time series transferred from Barle at Brushford)	0.87	0.21	0.12	0.057	1.70	359	3	0	13	0	0
Wye at Pant Mawr	0.55	1.87	2.63	0.14	4.53	203	23	128	352	0	33
Hodder at Hodder Bank	2.24	2.83	5.27	0.42	12.74						
Blithe at Hamstall Ridware	0.46	0.59	0.48	0.142	2.83	0	0	63	301	344	247
Itchen u/s of Highbridge	3.41	5.1		0.42	7.64	0	0	111	560	0	0
Lymington at Balmer Lawn	0.38	0.09	0.59	0.057	2.69	203	0	102	459	42	0
Millstream at IFE East Stoke	0.52	1.77	2.01	0.11	4.53	189	60	0	0	0	0
Lambourn at Hunt's Green	0.55	0.68	0.78?	0.42	5.66	121	41	0	0	0	0
Gwash at Belmesthorpe	0.37	1.17	1.35	0.14	1.70	0	0	132	385	0	0

s=summer, w=winter

2.2. Influence of missing values and out of range flows on time series and duration curves

Of particular note are the numbers of flows above the model range for almost all sites (all except the Lambourn and Millstream). Given the time that would be required to re-calibrate the models to obtain more complete calibrations, and as this report is mostly concerned with the analysis of low flow events, this was not considered a major problem.

Currently, the IH PHABSIM time series analysis software simply ignores missing values. In contrast, the flow-spell analysis software developed for IH (1980) and Gustard, Bullock and Dixon (1992) interpolates between the known values that bound a region of missing data. The influence of the missing data on the form of habitat duration curves is investigated below.

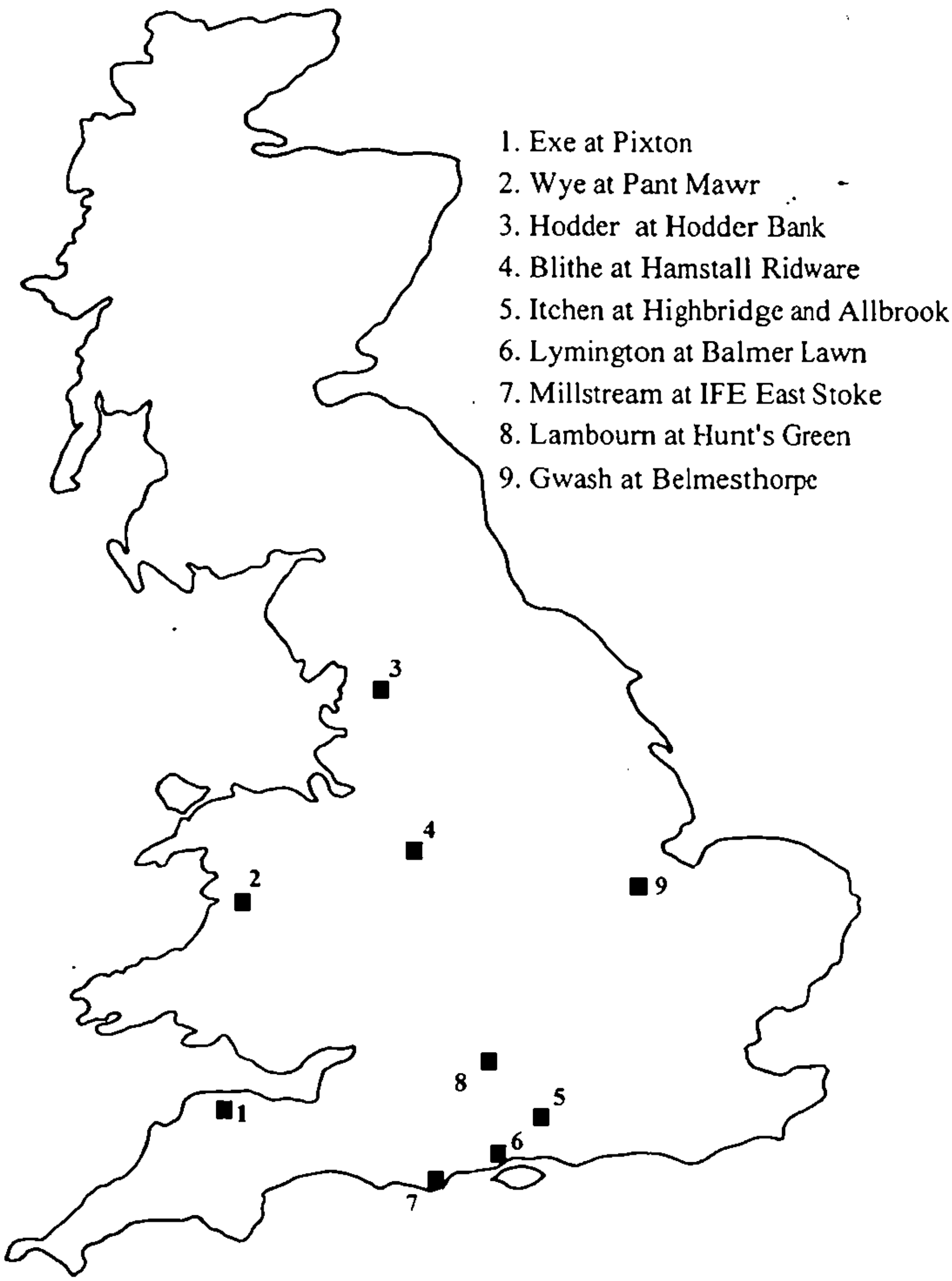


Figure 2.1 Location of study sites

3. METHODOLOGY

3.1. Time series analysis

Unlike the wealth of literature on procedures for other parts of the PHABSIM process (e.g. collection of suitability data, hydraulic modelling), information on time-series procedures is limited, whether in published papers (Capra *et al.* 1995), the US-specific 'how-to' manual (Milhous 1990b), or UK applied studies from IH (Johnson *et al.* 1993b, 1994b, 1995b).

In Project B2.I, a computer data file containing the relationship between WUA and Q for each species/life stage was produced for each study site by running hydraulic simulation output through the habitat simulation software. The IH PHABSIM software suite includes a program, WUAQT, which combines a flow time series with the WUA v Q file (known as a ZHAQFM file), to produce a time series of flow, habitat for all life stages of a species, and total habitat. The latter is effectively a measure of total river area per 1000m length of river. The software can currently analyse daily and monthly mean flow data. WUAQT performs an interpolation on the data in the ZHAQFM file in order to match any flow within the model range to a habitat value.

The bulk of the analysis was performed on datasets of daily mean flows for each study site of 16 years duration (1966-1981 inclusive). This period was chosen as the longest available that covered all required gauging stations, although later changes to procedures for the Exe and Hodder required use of different time periods for those two sites. Study sites for NRA R&D EAF Phase I were chosen to be close to NRFA stations, and six of the nine sites (Wye at Pant Mawr, Blithe at Hamstall Ridware, Itchen U/S of Highbridge, Lymington U/S of Balmer Lawn, Frome at I.F.E. East Stoke (the Millstream), and Gwash at Belmesthorpe) were within 1.5km of the station. The others were situated as follows:

Site	Distance from station
R. Exe at Warren Farm	15 km
R. Hodder at Hodder Bank	12 km
R. Lambourn at Hunt's Green	4 km

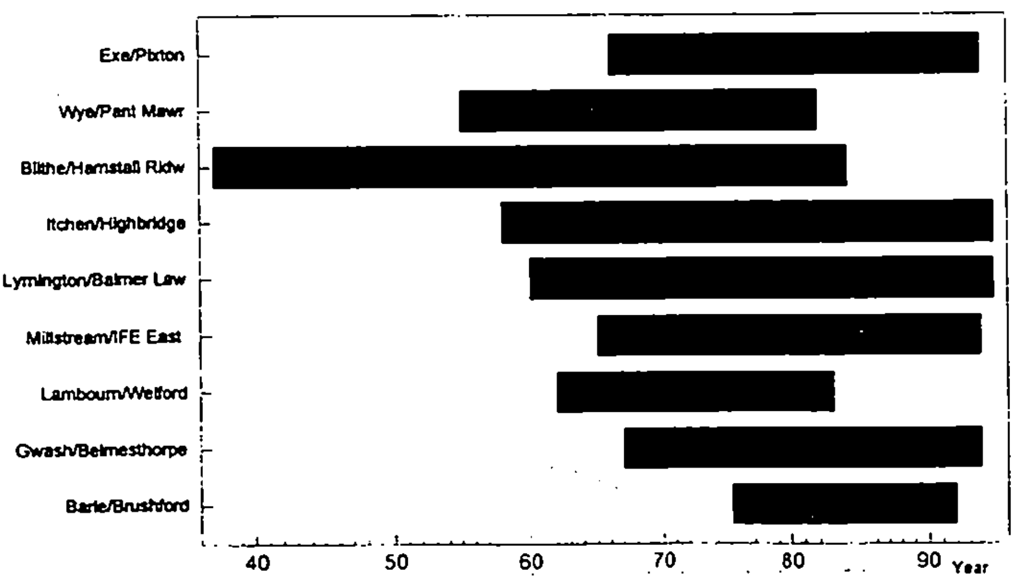


Figure 3.1 Summary of data availability for each gauging station

The Micro Low Flows software package (Young, 1992) was used to estimate time series at these sites by correcting the gauged flows by a factor representing the difference in catchment characteristics, i.e. (estimated mean flow at site)/(estimated flow at gauging station).

Table 3.1 Summary of gauging stations close to the PHABSIM sites.

River	Catchment	Station	Data type	Mean flow	Q10	Q50	Q95	Notes
Exe	Upland impervious sandstone	45009	BC	4.42	11.0	2.52	0.579	15km from site. Wimbleball reservoir a major influence
Wye	Upland, peat over slates / shales	55010	AA	1.65	3.94	0.86	0.166	<1km from site. Natural
Hodder	Peat moorland over millstone grit and carboniferous limestone							
Blithe	Sandstone and clay	28002	BC	1.23	2.81	0.586	0.320	At site. Both gauge and site influenced by Blithefield reservoir
Itchen	Chalk, very permeable	42010	AA	5.26	7.68	4.80	2.92	At site. Currently minor artificial influences
Lymington	Impervious, clay, sand and gravel	42003	AA	0.99	2.55	0.431	0.049	1.5km d/s of site
Millstream	Chalk, some sand / gravel / clay		EA station only, data obtained from Blandford Forum office					
Lambourn	Chalk downland	39031	BA	1.02	1.68	0.882	0.409	4km u/s of site
		39019	AB	1.69	2.76	1.49	0.749	4km d/s of site below confluence
Gwash	Clay / limestone	31006	AA	0.79	1.45	0.632	0.289	1.5km d/s of site

Source: National River Flows Archive and IH Report 108

Output was calculated as follows:

Flow:	**daily flow expressed as a percentage of the mean flow of the dataset**
Total habitat:	**daily values expressed as m^2/1000m of river.** This is effectively the area of river which would be available to a species that had no restrictions in its preference. It is measure of total river area per 1000m of river, regardless of habitat quality.
Habitat for species / life stage	**daily values expressed as percentage of total habitat at that flow.** This procedure is analogous to the standardisation of flows above.

By expressing habitat for each species / life stage in this way, one is able not only to compare relative areas of habitat in rivers of different sizes, but also retain the ability to compare areas of habitat between different species / life stages in the same river.

Note that this procedure does not make any judgements about biomass of various life stages, or that the biomass of 1 unit of WUA for one life stage at carrying capacity is equivalent to the biomass of one unit of WUA for another. Bovee (1982) discusses methods that may be used to deduce this relationship, and thus assess how critical levels of habitat for each life stage may influence population levels on an ongoing basis.

In order to provide a visual image of how habitat is distributed in space and time, time series of daily mean flows, along with total habitat and habitat for all fish and invertebrate species / life stages are presented in Appendix C. Although 16 years of time series data were used in the analysis, either eleven or three years of data are presented for illustrative purposes in Appendix C. The number of years displayed was reduced from eleven to three for the flashier catchments to maintain legibility.

3.2. Duration curve analysis

Time series of habitat were then analysed to indicate the proportions of time each habitat value was exceeded (duration curve analysis). This was performed using the HABDC program, an IH addition to the US PHABSIM software. During the project, the HABDC software was altered to make it more user-friendly. It now accepts a list of habitat time-series files (usually one per species) from the WUAQT program and also enables duration curves for summer (April-September), winter (October to March), or any user-definable period, to be calculated from an annual time series. Output from HABDC is in the form of a data file indicating habitat and percentage exceedance, and plots which appear on-screen and may be printed.

Clearly it is advisable that analysis of habitat time series of certain life stages be restricted to the months in which these life stages actually occur. The following time periods were selected as a compromise between a realistic portrayal of the conditions that would be experience by the life stage and the desire to keep to the simplest possible analysis.

Brown trout (*Salmo trutta*)	
Adult & Juvenile	Summer and winter
Fry / Juvenile (Wessex curves)	Summer and winter
Fry	Summer only
Spawning	November-December
Dace (*Leucisus cephalus*)	
Adult & Juvenile	Summer and winter
Fry	Summer only
Spawning	March-April
Roach (*Rutilus rutilus*)	
Adult & Juvenile	Summer and winter
Fry	Summer only
Spawning	April-June
All invertebrates	Summer and winter
All macrophytes	Summer only

Duration curves all species / life stages are presented in Appendix C, along with curves for flow and total habitat. Also presented in Appendix A are 5%, 50% and 95% exceedance percentiles for summer and winter habitat for all fish life stages, and as a measure of habitat variability, the ratio (5th percentile)/(95th percentile) habitat.

3.3. Combination of flow data with habitat duration curves

As mentioned above, the nature of some WUA v Q relationships - i.e. rising to a peak WUA then falling, can make interpretation of duration curves difficult. An example is given in Appendix D (figures D1-D3) of some habitat duration curves from the river Lymington where flow is also plotted on a habitat duration curve. The IH duration curve software currently does not allow this, instead a habitat duration curve was constructed from first principles in a spreadsheet, using methods from Low Flow Studies (IH, 1980). Corresponding flows for each sorted habitat value were retained as in the following table:

Table 3.2 Output for combined habitat / flow duration curve

Percentile	habitat	corresponding flow
0.50	31.77	28.007
0.70	31.75	27.808
0.89	31.75	27.808
1.08	31.75	27.808
1.47	31.75	27.808
2.01	31.7	28.801
2.52	31.7	27.312
2.94	31.66	27.014
3.52	31.63	26.716
3.91	31.58	29.794
4.45	31.57	29.894
5.00	31.52	25.723
5.50	31.47	30.788
6.00	31.47	25.325
6.47	31.46	30.887
7.01	31.42	24.829
..	..	..

3.4. Single year duration curves

Habitat duration curves for single years may also be calculated using the IH PHABSIM software, by extracting individual years of data to separate files and passing each individually to the HABDC program. Results for two life stages for brown trout on the Wye and Lambourn are presented in Appendix D (figures D6-D12).

3.5. Flow and habitat spell analysis

Software to perform flow/habitat spell analysis is not provided with the standard IH or US releases of PHABSIM. IH has in-house software for low-flows analysis running under the Unix operating system on Sun workstations. For this project, individual time series of habitat for life stages of brown trout in the Wye and Lambourn were treated as 'flow' data and transferred in the correct format to the IH Unix system. When data are input from a file (as opposed to the NRFA or FRIEND river flow archives), only one dataset (i.e. one file) may be analysed per program run. The program is able to interpolate missing values if required, alternatively it can ignore years where there are more than a certain number of missing values. For this project the threshold was set to a whole year, to ensure that years were never discarded and interpolation of missing values always occurred. Thresholds are specified as percentages of the mean 'flow'. Although this method works well for flows, it may not be the best way to specify habitat thresholds, indeed Capra *et al.* (1995) specified percentages of optimum habitat. Nevertheless, for this analysis, percentages were selected as 100, 80, 50, 30 and 10% of mean flow or habitat as appropriate.

Output is in the form:

```
Gauge xx MF  23.538 from 1966 to 1981 minimum duration  1 yield (%MF)100.0
      SPELL        FROM          TO
      (days)
       455.   17 11 1975   13  2 1977
       226.   28  6 1973    8  2 1974
       199.   18  8 1978    4  3 1979
       178.   29  7 1970   22  1 1971
       143.   19  9 1969    8  2 1970
       ..      .  .  .      .  .  .

Gauge xx MF  23.538 from 1966 to 1981 minimum duration  1 yield (%MF) 80.0
      SPELL        FROM          TO
      (days)
       420.    5 12 1975   27  1 1977
        90.    7 10 1973    4  1 1974
        20.   20 11 1978    9 12 1978
```

The software only outputs the longest period below the threshold in each year, so does not compare directly with the method proposed by Capra *et al.* (1995).

The spell values are plotted as spell (continuous duration under threshold) on the y-axis and cumulative continuous duration (% of total studied duration) on the x-axis. The theory behind this, explained in Capra *et al.* (1995) is that a highly-impacted river will have a long curve that has a shallow slope, i.e. a high proportion of long periods below the threshold. A curve with fewer days below threshold will be shorter, while a lower or steeper curve of the same length along the x-axis indicates an equivalent number of days impacted, but that there are more periods of a shorter duration. Results are presented in Appendix D.

4. RESULTS

This section refers to statistics presented in Appendix A, Weighted Usable Area v Discharge curves in Appendix B, time series and duration curves in Appendix C and further example charts (flows plotted on habitat duration curves, effects of missing values and flow/habitat-spell analysis) in Appendix D.
Habitat model output was taken directly from Project B2.I, which used suitability data developed by IFE Wareham. The only exception was for brown trout on the rivers Itchen and Lambourn, where the habitat model was re-run using suitability data collected by the then Wessex NRA, as outlined below.

4.1. River Exe at Warren Farm

Three gauging stations were considered for transfer to the study site: Exe at Pixton, Bray at Leehamford and Barle at Brushford. Although it has a larger catchment, the latter was considered to be the only station with a natural regime comparable to the study site, so was chosen. A complete time series for the Brushford station from 1982-1992 was available from a previous study (Johnson *et al.* 1994b), so was used for this analysis.

The habitat model for the Exe was re-run and with the hydraulic model calibrated to half the low-flow limit used in the B2.I study, was still within US National Biological Service (NBS) guidelines of 0.2x the lowest calibration flow. As the time series is a best estimate, rather than direct from a close gauging station, there is perhaps a higher potential error in the results of the time series analysis for this site. However the methods used to obtain the best estimate are current state of the art, and errors in this element are likely to be comparable or lower than those introduced in other parts of the modelling process.

The most important aspect of this analysis is that the majority of flows are at the lower end of the calibration, (Figure 4.1 illustrates flow frequencies plotted on the WUA v Q curve for adult brown trout). For adult and juvenile brown trout (fig C1.4), this results in duration curves which are flat to the left of the 10-20% area point, becoming steeper towards the right, and for the summer curve, flattening slightly around the 95 percentile mark (both summer 95 percentile of 1.6%). The left flat area is caused by flows corresponding to the peak of the WUA v Q curve, while the slightly higher WUA value for adults is a direct consequence of the higher peak of the WUA v Q curve.

On the other hand, fry brown trout produce a generally flatter curve with summer habitats above the 10% area level being greater than equivalent winter percentiles. This is due to the model indicating that this life stage has a preference for low discharges.

Spawning trout habitat drops to 0 between 0.4 and 0.5 cumecs, which leads to the rapid tail off of spawning habitat to the right of the 30 percentile level.

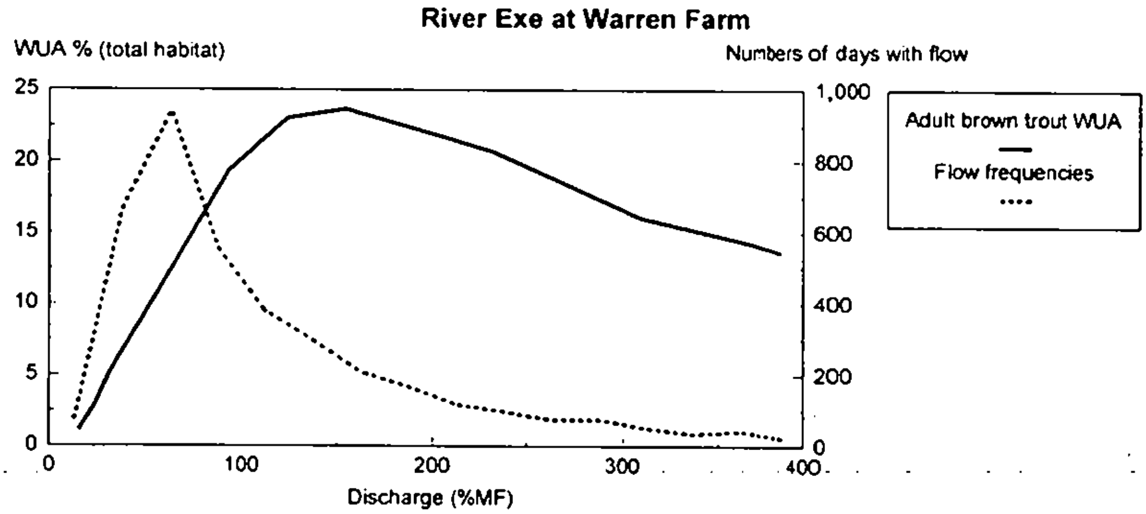
4.2. River Wye at Pant Mawr (including comparison with the Exe)

Adult and juvenile brown trout show a similar level of optimum habitat to that on the Exe (20%), but less steep curves (summer 95 percentile of 9.0% area and 7.0% area respectively). A possible reason for this is that for the Wye, the mean flow is much higher than the optimum habitat level, while for the Exe it is lower (see Figure 4.1 and B2). The results suggest that abstraction above the Exe site would have more serious consequences than abstraction above the Wye.

The 95 percentile fry habitat is also much higher on the Wye, perhaps reflecting the flatter WUA Vs Q curve (i.e. less variable habitat).

Duration curves for invertebrates show some similarity between the Wye and the Exe, but the maximum available habitat is higher on the Wye. This is perhaps a reflection of the more simple nature of the WUA v Q curves for these species (compared to trout). However the results are insensitive to the fact that on the Wye, the mean flow is close to the peak of the curves, while for the Exe, it is well to the left - on the steep portion of the curve.

The duration curve for *Ranunculus* again shows a maximum habitat of around 50% of total river area, and compared to Leuctridae (A), the central portion of the curve is shifted to the right.



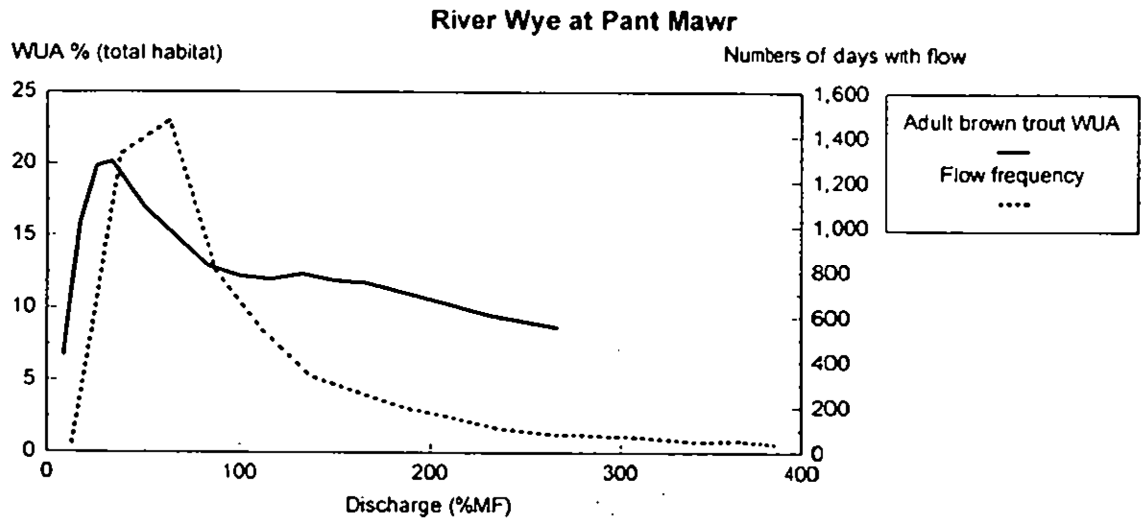


Figure 4.1. Rivers Exe and Wye: comparison of flow frequencies and habitat. Note: the flow frequencies are grouped into 25% class intervals, so 12.5 represents flows between 0-25% etc.

4.3. River Hodder at Hodder Bank

As with the Exe, the closest gauging station to the site (71002, just below Stocks Reservoir), is a significant distance (~ 15km) from the site. In this case it is above the site, with several tributaries joining the river system in-between. A record for a more suitable station, Hodder at Hodder Bridge (71008), is currently being investigated for transfer to this site, assisted by the methods outlined in IH Report 108.

4.4. River Blithe at Hamstall Ridware

The river has a relatively constant base flow, with some very high but short peak discharges which greatly exceed the mean flow. The flows are 'un-natural', being downstream of Blithefield reservoir, but with the gauging station close to the study site, using the gauged flows will provide an accurate assessment of the conditions experienced at the study site. Unfortunately, there is a high number of missing flows (591, 10% of the dataset), and (364 flows above the range of the model, a further 6% of the dataset).

The model shows high levels of adult and juvenile roach habitat for all percentiles, and high levels of roach fry habitat for all but the most infrequent events. From the WUA v Q curve for fry, it can be seen that the high model limit corresponds to a lower WUA than the low model limit. This indicates that the drop off of habitat above 90% is due to high flows. The spawning habitat duration curve is influenced primarily by the distribution of flows in the spawning months, as the WUA v Q curve increases gradually with flow.

Time series analysis suggests that adult dace habitat is extremely limited, particularly in the summer months, suggesting that combinations of adequate velocity and depth are unavailable. Juvenile dace tolerate lower depths and velocities than the adults, so the corresponding curves show rather more habitat at intermediate percentiles, however the drop off at low flows is still significant. Increasing the model simulation limits in the high flow range would show increasing levels of adult habitat, however the magnitude of this change is not known. Fry dace are shown to tolerate lower velocities well, and still exhibit available habitat at the 95 percentile suggesting that higher flows perhaps make marginal habitats available at the edges.

Invertebrates show generally high levels of habitat, reflecting the high levels of habitat throughout the modelled range.

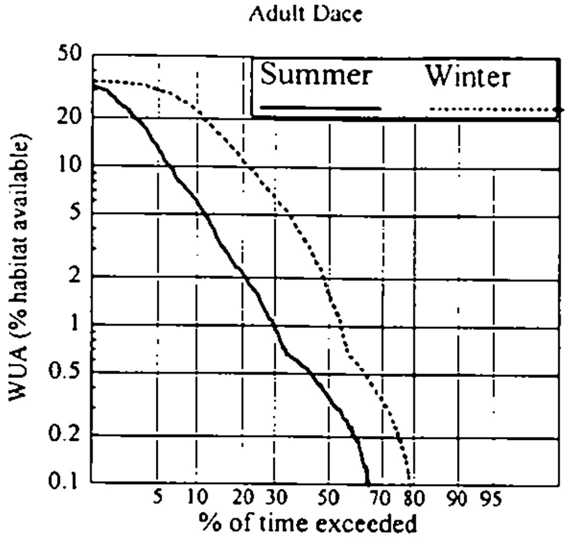


Figure 4.2. River Blithe: adult dace habitat.

4.5. River Itchen u/s of Highbridge

For brown trout, time series analysis was first performed using the suitability data gathered by IFE for R&D Project B2.I. However as can be seen from the WUA v discharge relationship plot (Figure B4, 'IFE B2.I curves'), this results in there being virtually zero habitat at mean flow and above. It was suggested that this situation was not realistic, and in particular, the habitat suitability curve for depth was suggesting that large areas of the river were 'unsuitable'.

Instead, the habitat model was re-run using brown trout suitability data collected by the then NRA Wessex Region for applied studies on chalk streams in south-west England (Johnson *et al.* 1993b, 1994b, 1995b). This produced habitat-flow relationships which were likely to be more realistic; these relationships were then used for subsequent time series analysis.

The 'Wessex' curves suggest that the river provides suitable habitat for adult brown trout at all flows. Absolute levels of fry/juvenile habitat are similar, but slightly lower. Spawning habitat is high at the optimum spawning flow (15% of area), but suffers a progressive reduction beyond the 10th percentile, reaching 1.4% area at the 95 percentile level. An examination of the WUA v Q relationship and the suitability data suggests that lower habitat levels are caused by higher flows, and particularly deeper water (see section 4.8.2 for discussion).

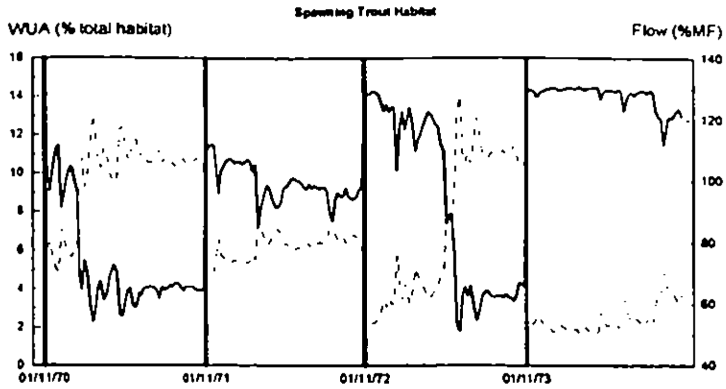


Figure 4.3. *River Itchen: time series of habitat for spawning brown trout, November and December 1970-73.*

The invertebrates each have high levels of habitat at all flows (50 percentile > 50% area), as does *Ranunculus* (50 percentile 30% area). *Nasturtium* has lower maximum habitat (9%), which decreases to <3% at the 95 percentile, probably due to lower suitability in deep water.

4.6. River Lymington at Balmer Lawn

For adult brown trout, optimum habitat (10% area) occurs for 10% of the time. For the rest of the time, habitat drops to a low of 0.42% area at the 95 percentile. Juveniles follow a similar pattern, only with an optimum of 4% area. Fry levels seem to be very high, with optimum conditions occurring for 75% of the time. Beyond this, the reduction in habitat is caused by high flows. Spawning habitat is optimal (5% area) for 10% of the time, and drops to a 95 percentile level of 0.2% area.

For invertebrates, Gammaridae (A) summer habitat levels are above 10% area for 95% of the time. On the other hand, Leuctridae suffer a significant fall off on habitat, dropping to less than 1% area at the 95 percentile. A glance at the WUA v Q curve suggests that this drop is due to low habitat levels at low flows. *Nasturtium* and *Ranunculus* show similar duration curves, despite having very different WUA v Q relationships (see section 4.10 for discussion).

4.7. Millstream at I.F.E East Stoke

Adult dace show a marked decline in habitat from a high optimum (40%) above the 5th percentile in summer and 30th percentile in winter, with habitat dropping below 1% of total habitat at 75% (summer) and 92% (winter). As on the river Blithe, this is probably due to the adult's preference for water above 40 cm depth and 30 cm/s velocity. Juveniles show a similar tail-off, but from a lower optimum (15% of total habitat). The summer and winter curves are more similar than for adults. For fry, as with dace and other species on other rivers, summer habitat is maintained at a more consistent level, even at low flows. Spawning habitat is consistently high, except at low flows, reflecting its wide preference curves.

Adult, juvenile and fry roach again show relatively high levels of habitat at low flows, and greater summer habitat at medium percentiles. This reflects their tolerance of lower flows, specifically lower velocity. Lower fry habitat at the 95 percentile may represent lower tolerance of high flows. Low base levels of spawning habitat may be influenced by the narrow substrate preference curves, along with water shallower than 50cm. As levels of vegetation are not specifically modelled, results should be treated with caution.

The invertebrates show very shallow curves, demonstrating relatively insensitive response to flow, except at very low flows. High levels of *Ranunculus* habitat reflect the distribution of the WUA v Q curve optimum around the mean flow.

4.8. River Lambourn at Hunt's Green

As with the Itchen, the 'Wessex NRA' suitability data for brown trout in chalk streams was used in the time series analysis. Compared to output using the IFE B2.I curves, use of these curves indicates greater habitat availability at high flows, and slightly less habitat at the lowest modelled flows.

The high base flow on the Lambourn produces 95 percentile habitat levels that are a relatively high proportion of the optimum, for all brown trout life stages. Similar results are obtained for invertebrates and macrophytes.

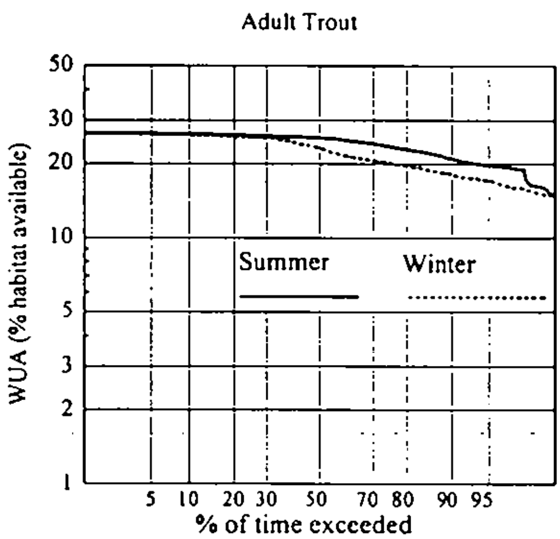


Figure 4.4. River Lambourn: habitat duration curve for adult brown trout

Comparison of Lambourn and Itchen

A combination of a high base flow, coupled with the nature of the 'Wessex NRA' brown trout suitability curves, leads to quite flat habitat duration curves for adult, and fry/juvenile life stages. In contrast, spawning habitat at high percentiles (e.g. 95) is still high on the Lambourn, but declines on the Itchen. Possible reasons for this include either that it is not appropriate to apply the 'Wessex' brown trout curves to rivers the size of the Itchen, or that there was indeed little suitable spawning area at the study site.

4.9. River Gwash at Belmesthorpe

For both adult and juvenile brown trout, optimum habitat levels are present for 30% of the time in summer and 20% in winter. As with other rivers, the magnitude of optimum habitat area for adults is greater than for juveniles. Examining the WUA v Q curve for fry trout shows a dramatic decrease in habitat area with increasing flow, with an optimum of 10% of total area at 25% MF, declining to 1% area at 100% MF. This is reflected in the duration curve, which shows a 95% summer percentile of just 0.2% area available. Drop off for spawning habitat is even more dramatic, with a dramatic and rapid reduction in habitat available above the 50th percentile.

Invertebrate and macrophyte habitat levels are maintained well, and at the 95th percentile show a relatively small drop from the optimum.

4.10. River Lymington: habitat duration curves combined with flow data

(See figures D1-D3)
The duration curves for *Ranunculus, Nasturitum* and brown trout fry on the Lymington illustrate the care that must be taken in using duration curves to interpret habitat time series.
Plotted on the duration curve is not only habitat, but the flows corresponding to each habitat percentile (note that this is not the same as flow exceedance percentiles). The relationship for *Nasturtium* is relatively simple, with high flows producing low habitat and vice-versa. A similarly shaped curve is produced for *Ranunculus*, yet in this case, high habitat levels come from intermediate flows, intermediate habitat levels from a combination of high and low flows, and the lowest habitat from low flows. Likewise the brown trout fry curve produces similar high habitat from intermediate flows, but in this case the lowest habitat is caused by high flows.

4.11. River Gwash: plotting missing values on time series and duration curves

(See figures D4&5).
The IH duration curve suite of software considers habitat values arising from flows out of range of the model (i.e. at the low and high flow ends) to be 'undefined'. The significance of periodic very low and high flow events for PHABSIM analysis has never been thoroughly analysed. There has been some suggestion (Milhous 1990b), that the biota would not respond to events shorter than a month, but with no clear supporting evidence; this was then used to justify the choice on a monthly time period for time series analysis. Alternatively, one could suggest that acute low flow periods of only a few days could also have an effect on a stream population. Clearly the use of monthly mean flows, if appropriate would be a way of drastically reducing the number of out of range flows. What is certain is that ignoring out-of-range flows is not a very satisfactory solution. Other possible solutions include:

- Ensuring a widest possible range of calibration flows, resulting in fewest possible out-of-range flows.
- Ensuring the most accurate possible calibration, from accurate field measurements and care in the calibration itself. Aside from giving better results over the range of calibration flows, a good calibration will be more forgiving when extrapolated outside the calibration flows.
- In the absence of the above, the potential for simply setting out-of range flows to the limits of the model is examined here.

The rationale behind setting out-of range flows to model limits is simply that when constructing a duration curve of habitat, inclusion of habitat at high exceedance percentiles (set to model limit) will result in a more accurate duration curve for the range of flows within the model. For example on the river Gwash, there are 132 summer flows and 385 winter flows outside model range, a total of 8.8% of the data. Considering adult brown trout, as habitat at high flows is at a low percentage of the optimum, ignoring this data must have an impact. The impact on the duration curve will be in two forms, incorrect percentiles at the extreme right of the duration curve and inaccurate percentiles for ALL OTHER HABITAT VALUES.

As the WUA at the high limit of the model is lower than the WUA at the lower limit, one can be sure that all these flows will correspond to the right hand limit of the duration curve chart. Figure D5 illustrates duration curves for adult brown trout with and without the out-of range flows set to the model limit.

From Table 2.1, it can be seen that 132/5844 = 2% of summer flows and 7% of winter flows are beyond the high limit of the Gwash habitat model. Figure D5.2 illustrates the effect of their inclusion, set to the habitat value at the high limit. The flat portions on the right of the summer and winter curves reflects these values which are estimates, but still incorrect. However due to the inclusion of all flows, values to the left of the 98 percentile for the summer graph, and 93 percentile for the winter graph, are at their correct percentiles. This is not true for the duration curve in fig D5.1.

Comparing the two graphs, one can now see for example that when the missing data is included, 80 percentile summer habitat is reduced from 4% area to 2% area.

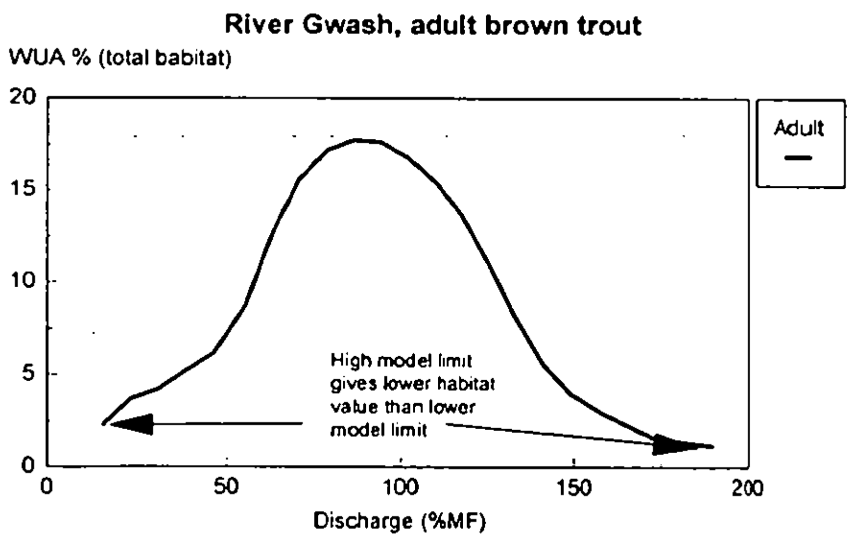


Figure 4.5. River Gwash: WUA v Q curve for adult brown trout

It should be noted that this process as outlined above was only valid when the habitat value of the limit beyond which the out-of range flows are incorporated is lower than the habitat value for the other limit of the graph. Otherwise, a series of 'incorrect' values will be incorporated into some central portion of the duration curve, which is of little use.

To conclude, to avoid bias in the construction of duration curves, it is necessary to ensure the widest possible model calibration. In the absence of the widest possible calibration limits, a well-calibrated model could be extended beyond the limits currently advised in order to minimise bias in the duration curve.

4.12. Lambourn and Wye: comparison of single - year duration curves

(See figures D6-D11)

In order to try to overcome the loss of temporal precision that comes from producing a duration curve from a long time series, yearly duration curves of flow, adult and juvenile brown trout habitat were plotted for the Lambourn (lowland site, high base flow) and Wye (upland site, flashy catchment). The time period was 1966-1977. The Wye shows a remarkably stable yearly habitat regime, while the habitat on the Lambourn seems to be clearly impacted during 1976, and to a lesser extent 1977. In both cases, 95 percentile habitat shows less variation than 95 percentile flow.

Table 4.1. Lambourn and Wye: Variation in 95 percentile flow and habitat

Wye	**min.**	**max.**
flow (% MF)	4.8 (1976)	23 (1967)
adult (WUA)	9.0 (1974)	10 (1963)
fry (WUA)	6.7 (1974)	9.4 (1976)
Lambourn		
flow (% MF)	22 (1976)	80 (1968)
adult (WUA)	14 (1976)	24 (1968)
fry / juv(WUA)	10 (1976)	23 (1968)

4.13. Lambourn and Wye: flow and habitat spell analysis

(See figures D12&D13)

The graphs show that the narrower range of habitat data (compared to flow data) means that it is especially important to choose the correct thresholds. Thresholds within 10% of each other may give widely differing results.

The Lambourn is dominated by a few years in which habitat drops below the thresholds for long periods. For adult trout, the curve for the 100% mean habitat threshold is high (up to 550 days) and long (up to nearly 50% of total duration). The fry/juvenile trout curve is shorter and lower, suggesting that the adult trout may be most impacted by low flows.

On the Wye however, for adult trout the cumulative duration of flows below 100% mean habitat is shorter (8% of time period) and the longest time period is also shorter (75 days).

Comparing flow and habitat deficit periods, it appears that habitat deficits seem to be shorter but more frequent.

Modification of the IH flow-spell software to considering all periods below threshold in each separate year, plus the ability to specify percentages of optimum habitat would form a useful part of future PHABSIM development work.

5. CONCLUSIONS AND RECOMMENDATIONS

Analysis of time series is a major step towards an understanding of how physical habitat may limit or alter river wildlife, as the biota will be influenced not only by current physical habitat, but also past physical habitat events. Unlike the wealth of literature on procedures for other parts of the PHABSIM process (e.g. collection of suitability data, hydraulic modelling), information on time-series procedures is limited. This report provides a methodology for application of physical habitat time series in UK rivers.

The additional programs WUAQT and HABDC written at IH and provided on the EA release of the PHABSIM software provide the basis for time series analysis of habitat data. WUAQT produces a time series of habitat from a time series of flow, while HABDC produces duration curves, of habitat for a species / life stage, flow and total habitat.

This initial study has concentrated on the temporal relationships between daily physical habitat and daily mean flow for nine quite different UK rivers. In order to aid comparison between rivers, habitat has always been expressed as a percentage of total habitat area in the river in question, and flow as percentage of the mean flow. Due to the nature of the data collection program, only broad comparisons between river types was possible. Comparisons between sites has been restricted by the different species present, and in the case of brown trout, the lack of UK-specific suitability curves transferable to all sites.

To some extent, a river's habitat time series will reflect the flow regime. For example in this report, the flashier upland streams show steeper habitat duration curves than do chalk streams. However, habitat for a life-stage is also fundamentally linked to the shape of the WUA v Q curve. Depending on the shape of the curve (combined with characteristics of the flow regime), on some rivers, small changes in flow may produce large changes in available habitat, in contrast on other rivers, large changes in flow may produce small changes in habitat. Figure 5.1 illustrates the properties of a WUA v Q curve that may particularly influence habitat time series. A fundamental property of PHABSIM is that there will be a flow corresponding to an 'optimum' habitat, this leads to significant differences in the shape of a habitat time series compared to the flow time series for a river.

Habitat duration curves are a valuable analysis tool, particularly in the assessment of alternative flow regimes. However their limitations, particularly the influence of missing / out of range data, and the potential relationship between one habitat value and two or more flows must be recognised. When applying PHABSIM, all possible attempts should be made to ensure the widest and best model calibration to minimise the number of out-of range flows.

Depending on the combination of flow regime and WUA v Q relationship, seasonal habitat duration curves may be similar to or different from whole-year habitat curves.

In this study, habitat was highest for the invertebrate groups, with optima reaching over 50% area for Leuctridae and *Polycentropus flavomaculatus* on the river Wye, and for Ephemeridae and *Gammarus pulex* on the river Itchen. Although invertebrate habitat in this study was generally high, even at high (95+) exceedance percentiles, this is partly a reflection of the broadly-based nature of the suitability curves. It would not preclude the possibility of greater habitat reduction for other specific invertebrate species in the study rivers. Habitat for macrophyte species was also consistently high.

Habitat calculated for fish species was much more variable, with optima varying between 40% area (adult dace in Millstream) and 1.6% area (spawning trout on Gwash). Variability in habitat, calculated as (5 percentile habitat)/(95 percentile habitat) varied between 1.3 (adult trout on Lambourn) to 1300 (adult dace on Blithe and Millstream). On the cyprinid streams, dace habitat showed a consistent, severe reduction in habitat at low flows, while roach habitat levels were maintained at low flows. For brown trout, dace and roach, spawning habitat levels were difficult to interpret, and widely differing WUA v Q relationships produced comparable spawning habitat duration curves. This suggests that significant information was being lost in the construction of the duration curves.

Differences between life stages on the same river showed some consistency, often where adult habitat was highest, juvenile habitat was lower and fry habitat lowest, and vice-versa, although there were some exceptions. For brown trout on the Exe, Wye, Lymington, roach on the Blithe and Millstream and dace on the Blithe, fry habitat levels at high exceedance percentiles were greater than corresponding percentiles for adults, consistent with a greater preference for fry for low flows. Fry dace on the Millstream and brown trout on the Gwash showed the opposite tendency.

Differences in the known territory requirements of different life stages would provide a useful comparison, especially regarding the areas required for spawning.

This report has highlighted the requirement for greater information on transfer of habitat suitability curves between different rivers (both within and between ecological groups).

Recommendations for software enhancement

Certain additional features in the HABDC software would be highly desirable, in particular the ability to produce separate duration curves for each year in a time series. It will also be possible to enhance the IH flow spell analysis software to produce data on all periods below threshold in each year of a time series. This could be combined with the transfer of the software to the PC platform, in preparation for its incorporation into a future UK version of PHABSIM.

Recommendations for further data analysis

More information is required on how habitat varies in rivers of the same ecological group, and to compare rivers of different ecological groups. This could be combined with an investigation of 'regional' suitability curves.

Another useful line of work would be a sensitivity analysis of the effects of altering preference curves on both WUA v Q relationships in different rivers, and time series methods such as duration curves. One way of achieving this could be with a set of 'parameterised' suitability curves, specified by mean and standard deviation.

Sensitivity analysis of the influence of systematic errors in the flow time-series on habitat duration curves (and low habitat spells) would also be useful, especially given the requirement to sometimes transfer a flow time-series from a gauged to ungauged site. Topics in forthcoming IH research on low flow estimation such as flow time series synthesis and seasonal duration curve estimation are highly relevant to this work (NRA R&D Note 330, Gustard *et al.* 1995).

Better ways must be sought to display information such as habitat duration and spell curves. There is certainly scope for further modification and adaptation of existing 'low flow' analysis methods as applied to quantitative habitat analysis.

Although not attempted in this report, there may be some merit in applying regional habitat suitability data to a river model even where species are not found (or rarely found), for example brown trout in the Millstream. This would indicate whether physical habitat, or some other factor such as water quality or inter-species competition was limiting.

This report has only touched on the influence of critical periods of habitat. The use of 'effective habitat' analysis (Bovee 1982) should be investigated in the UK as a precursor to linking WUA more closely with biomass estimates from fish surveys.

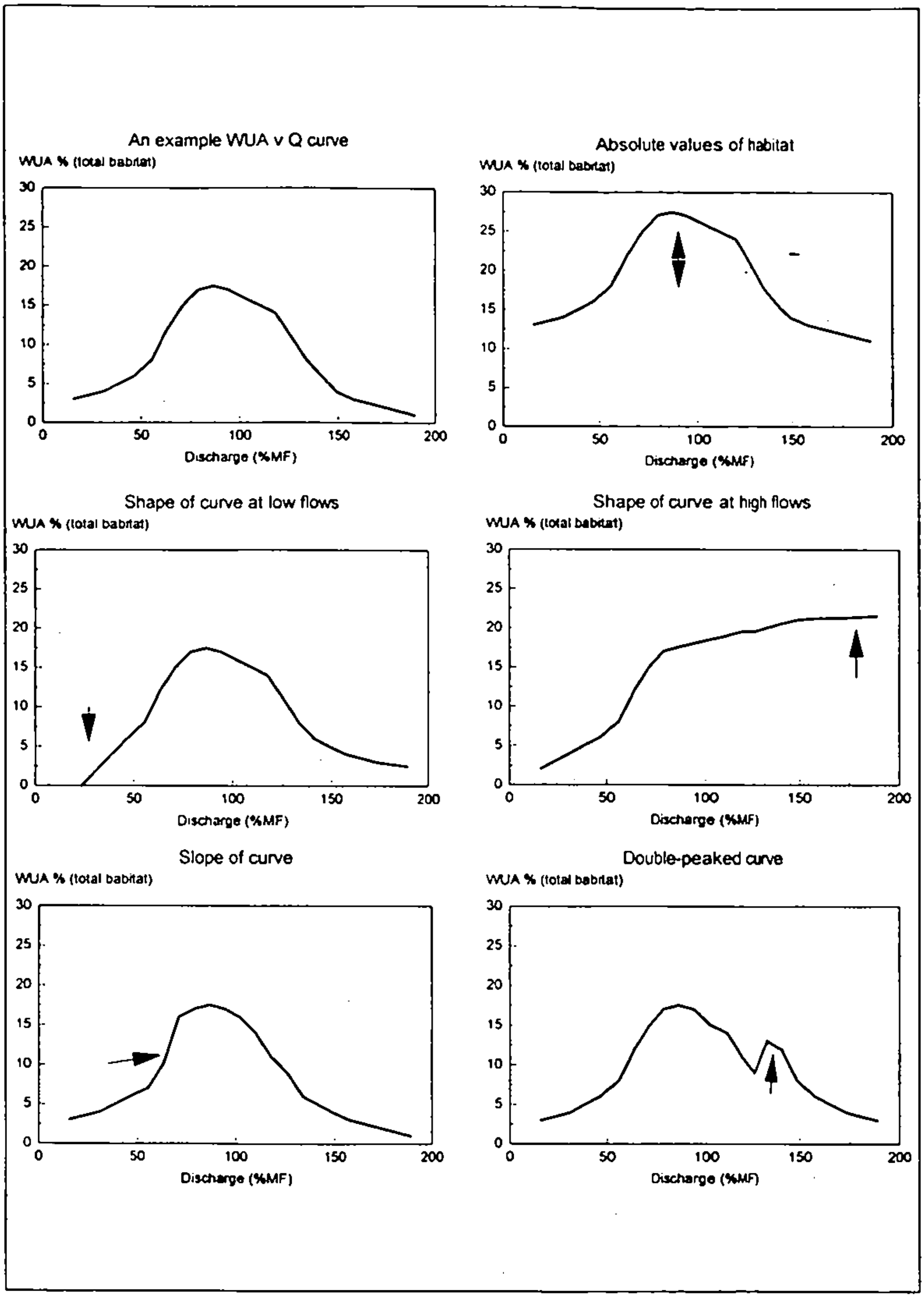


Figure 5.1. Variations in WUA v Q relationship

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APPENDIX A. SUMMARY OF GAUGED FLOW DATA AND HABITAT STATISTICS

	Summer X mean	X5	X50	X95	X5/X95	Winter X mean	X5	X50	X95	X5/X95
Exe (MF 0.183, X=flow)			31.7	8.2				100	27.9	
Trout (X=WUA)										
Adult	10.7	22.9	7.01	1.60	14	15.3	n/a	16.2	4.34	n/a
Juvenile	9.61	18.9	6.88	1.61	12	12.9	19.2	12.3	3.90	4.9
Fry	15.9	19.7	18.7	8.60	2.3					
Spawning (Nov-Dec)						*2.2*		*2.07*	*0.08*	
Wye (MF=1.7 cumecs, X=flow)	67.1		33.9	6.91		133		73.1	22.6	
Trout (X=WUA)										
Adult	15.3	20.0	15.8	8.96	2.2	14.9	20.0	14.3	10.0	2
Juvenile	13.5	19.4	12.2	7.04	2.8	12.0	19.4	10.9	5.84	3.3
Fry	14.0	18.1	15.0	7.37	2.5					
Spawning (Nov-Dec)						*2.06*	*4.04*	*2.06*	*0.04*	*100*
Blithe (MF 1.04 cumecs, X=flow)	*66.8*		*48.0*	*30.0*		*133*		*67.4*	*33.0*	
Dace (X=WUA)										
Adult	2.27	12.5	0.35	0.01	1300	6.33	30.3	1.60	0.03	1000
Juvenile	4.16	9.72	3.96	0.67	15	5.83	11.2	5.77	1.12	10
Fry	8.71	11.1	9.45	4.36	2.5					
Spawning (March-April)	*14.2*	*29.0*	*12.0*	*2.74*	*10.6*					
Roach (X=WUA)										
Adult	19.0	23.9	19.3	13.9	1.7	20.7	25.3	21.0	14.9	1.7
Juvenile	18.0	22.4	18.0	14.0	1.6	19.5	24.5	19.5	14.8	1.7
Fry	23.0	24.3	24.0	18.0	1.4					
Spawning (April-June)	*0.69*	*1.92*	*0.48*	*0.27*	*7.1*					
Itchen (MF 5.40 cumecs, X=Q%MF)	*90.5*		*84*	*53.0*		*110*		*105*	*59.0*	
Trout (X=WUA)										
Adult	23.6	25.9	25.0	17.7	1.5	22.8	25.9	24.3	16.4	1.6
Fry / Juvenile	17.1	21.5	19.3	8.21	2.6	15.5	21.5	16.9	7.13	3.0
Spawning (Nov-Dec)						*7.98*	*14.2*	*7.38*	*1.39*	*10*
Lymington (MF 1.01 cumecs, X=Q%MF)	*53.9*		*21.2*	*4.77*		*146*		*83.8*	*14.3*	
Trout (X=WUA)										
Adult	2.77	10.2	0.89	0.26	40	5.44	10.5	5.5	0.42	25
Juvenile	1.33	3.85	0.89	0.26	15	2.03	4.1	1.73	0.42	10
Fry	26.5	31.5	29.76	7.6	4.1					
Spawning (Nov-Dec)						*1.66*	*5.17*	*0.82*	*0.23*	*22*
Millstream (MF 0.93 cumecs, X=Q%MF)			*59.3*	*10.2*				*124*	*25.3*	
Dace (X=WUA)										
Adult	14.3	40.1	7.58	0.03	1300	24.9	40.4	32.0	0.45	90
Juvenile	7.06	13.3	7.14	0.45	30	6.13	13.0	7.45	0.44	30
Fry	5.51	8.2	5.76	2.82	3.0					
Spawning (March-April)	*43.2*	*50.2*	*47.6*	*18.3*	*2.7*					
Roach (X=WUA)										
Adult	17.0	20.6	18.4	7.39	2.8	15.1	20.4	17.2	6.97	2.9
Juvenile	16.5	20.9	18.1	7.44	2.8	14.3	20.7	15.3	7.09	2.9
Fry	16.0	23.2	19.0	4.92	4.7					
Spawning (April-June)	*0.635*	*1.08*	*0.57*	*0.44*	*2.5*					

Lambourn (MF=1.31 cumces, X=Q%MF)	105.3		99.4	34.1		94.9		76.1	40.2	
Trout (X=WUA)										
Adult	24.5	26.5	25.5	19.8	1.3	22.6	26.4	23.2	17.1	1.5
Fry / Juvenile	23.1	26.9	24.3	15.9	1.7	20.2	26.6	20.4	12.2	2.2
Spawning (Nov-Dec)						*12.1*	*14.2*	*12.0*	*9.99*	*1.4*
Gwash (MF=0.90 cumces, X=Q%MF)	85.1		69.8	30.7		115.5		85	31.9	
Trout (X=WUA)										
Adult	10.4	17.7	9.33	3.50	5.0	9.06	17.5	7.71	1.51	12
Juvenile	6.5	9.09	6.59	2.33	3.9	5.77	9.07	5.73	1.28	7.1
Fry	5.25	10.8	4.86	0.16	68					
Spawning (Nov-Dec)						*1.60*	*2.61*	*1.98*	*0*	*n/a*

APPENDIX B. RELATIONSHIPS BETWEEN WEIGHTED USABLE AREA (WUA) AND DISCHARGE (Q)

WUA (m^2/1000m) | **WUA (% total available habitat)**

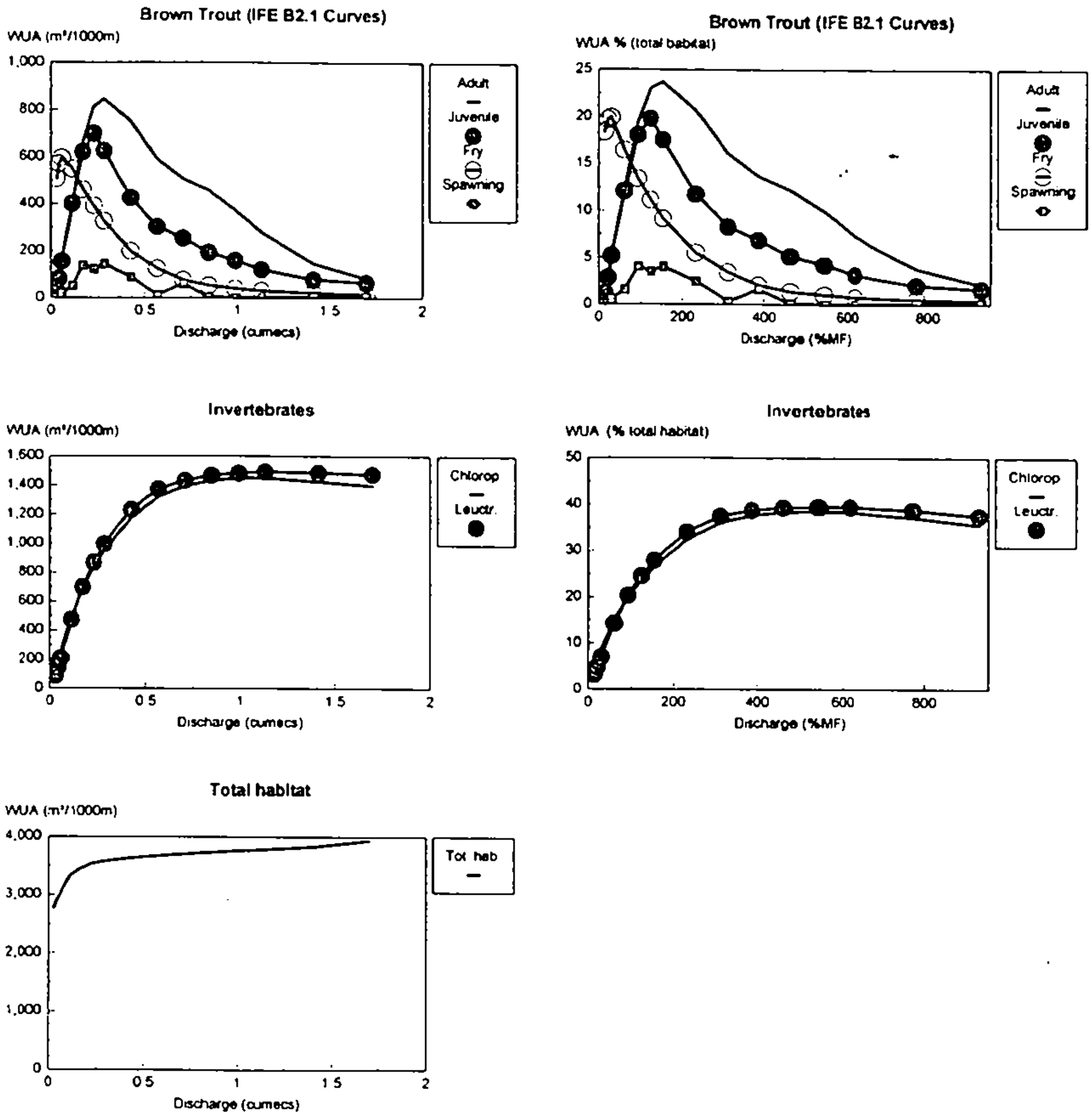

Figure B1. *River Exe: habitat vs discharge relationships*

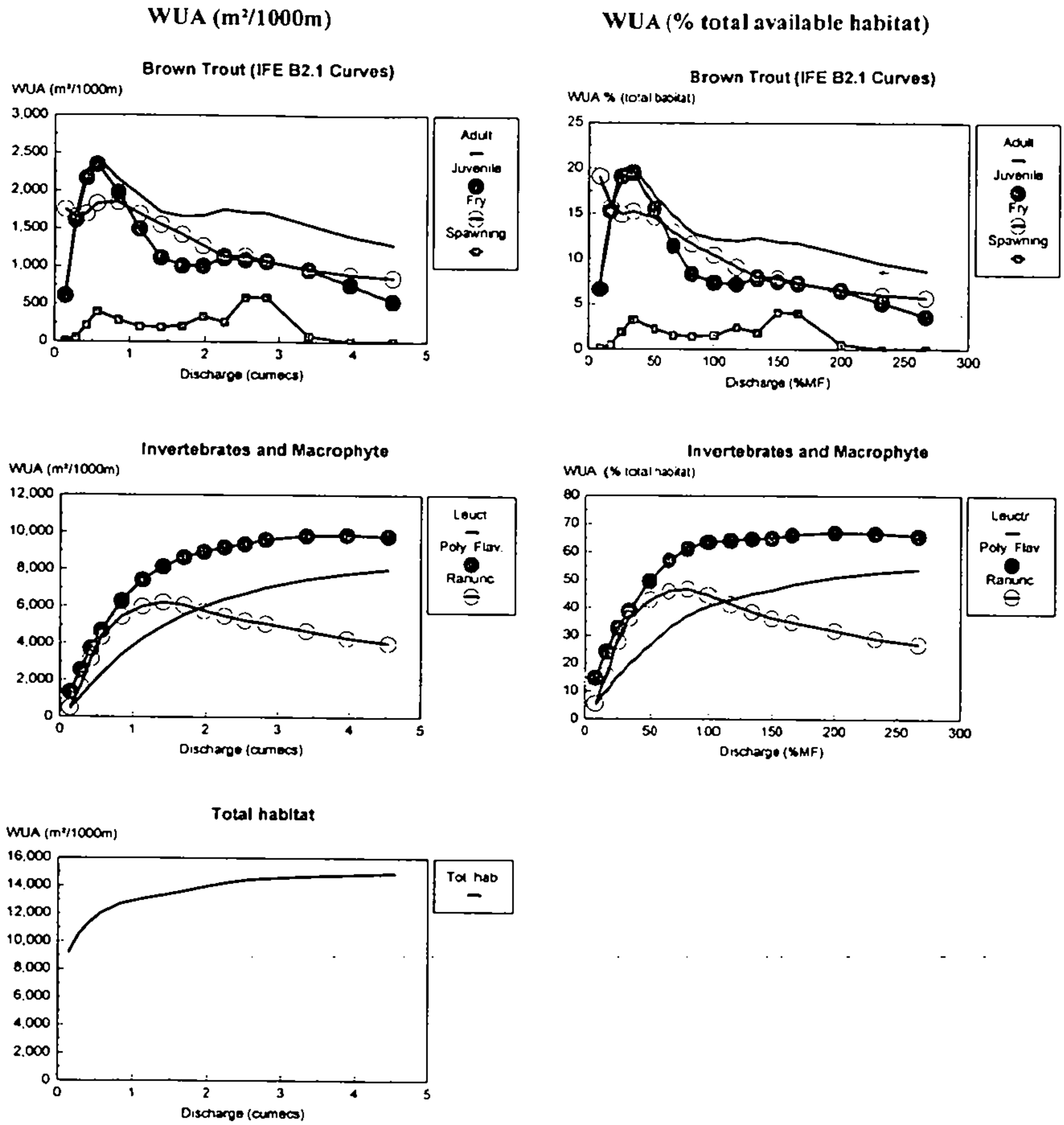

Figure B2. River Wye: habitat vs discharge relationships.

WUA (m^2/1000m) — WUA (% total habitat)

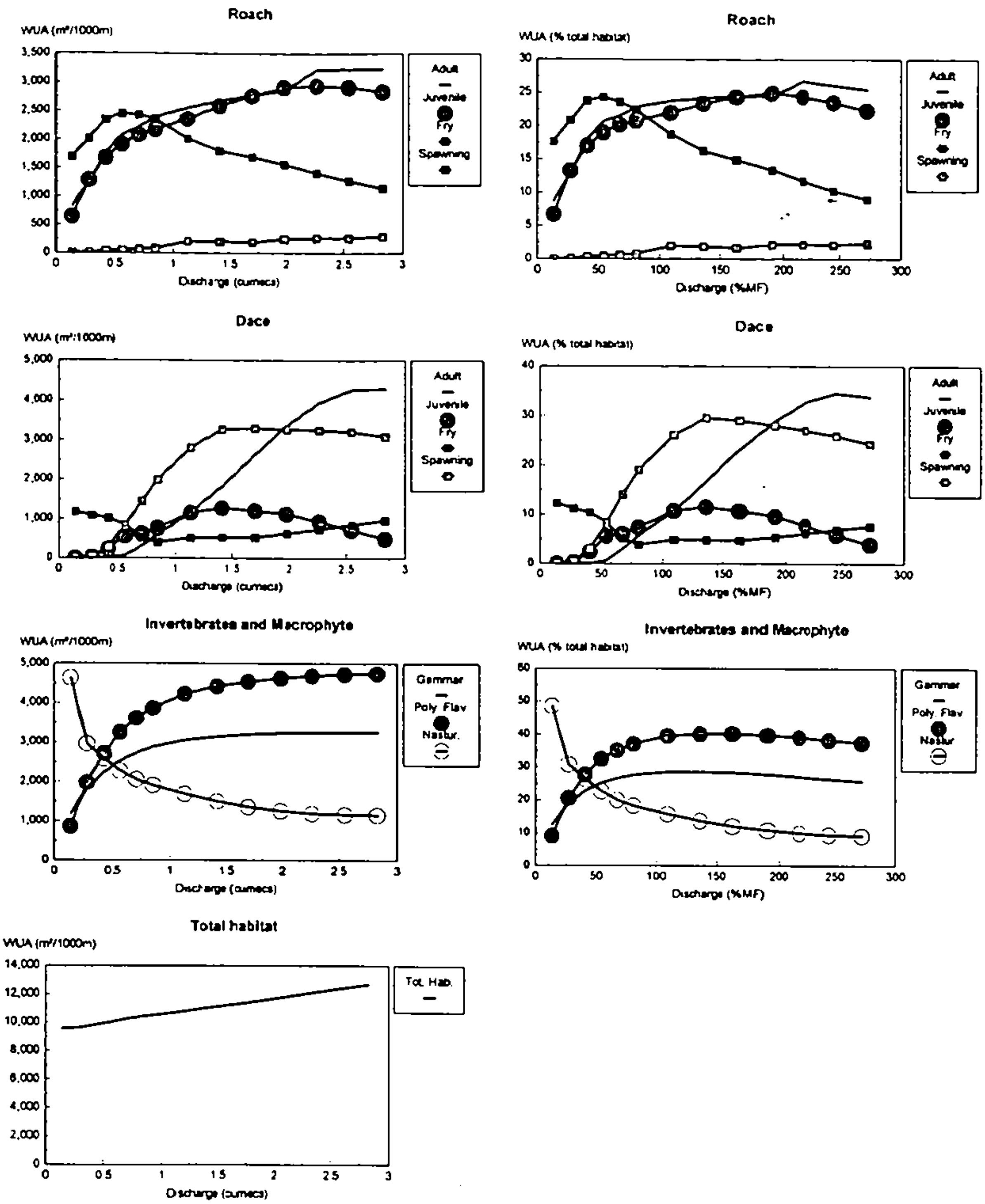

Figure B3. *Habitat vs Discharge Relationships: River Blithe*

WUA (m²/1000m) WUA (% total habitat)

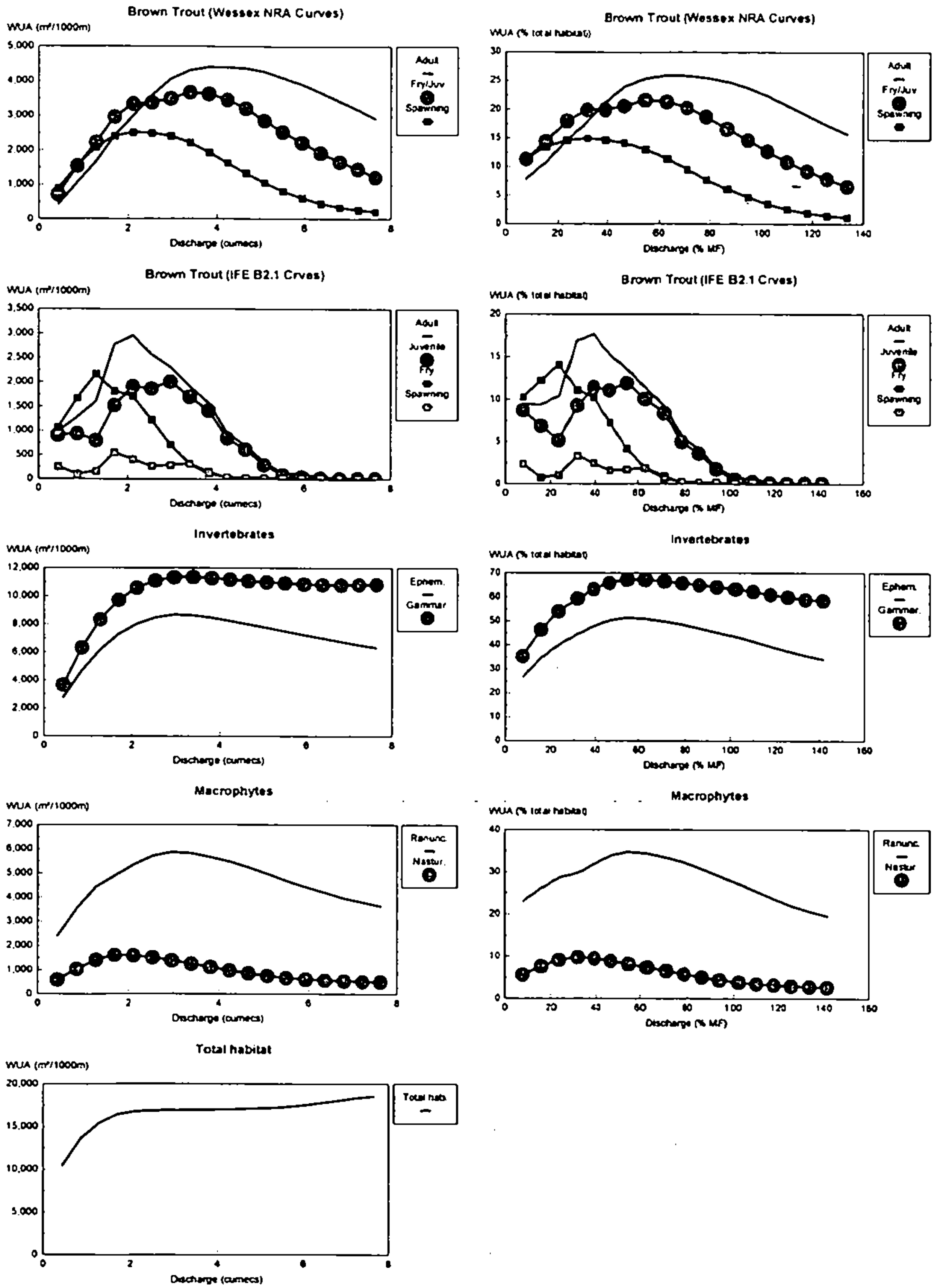

Figure B4. River Itchen: habitat vs Discharge Relationships

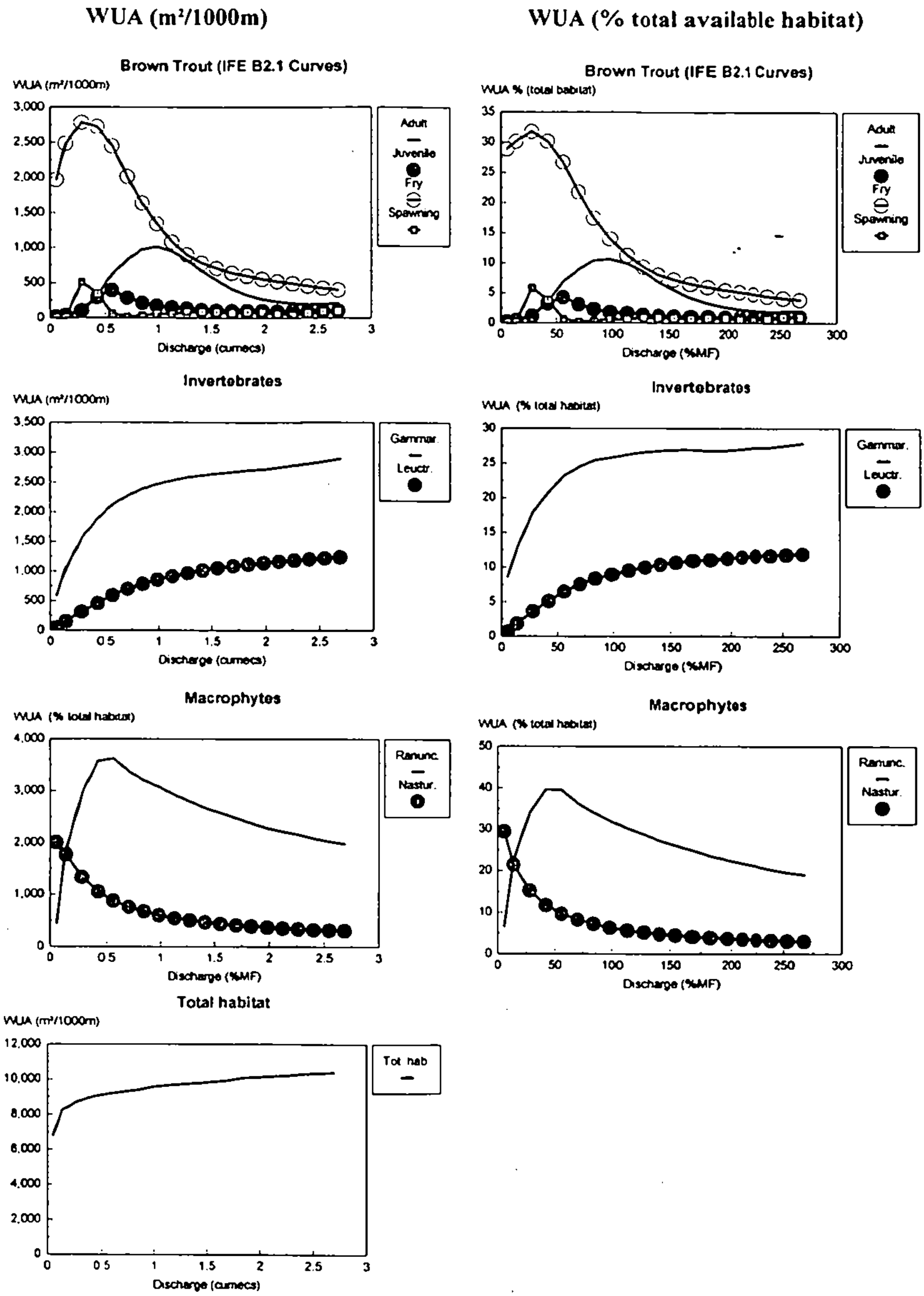

Figure B5. River Lymington: habitat vs discharge relationships

WUA (m²/1000m) WUA (% total habitat)

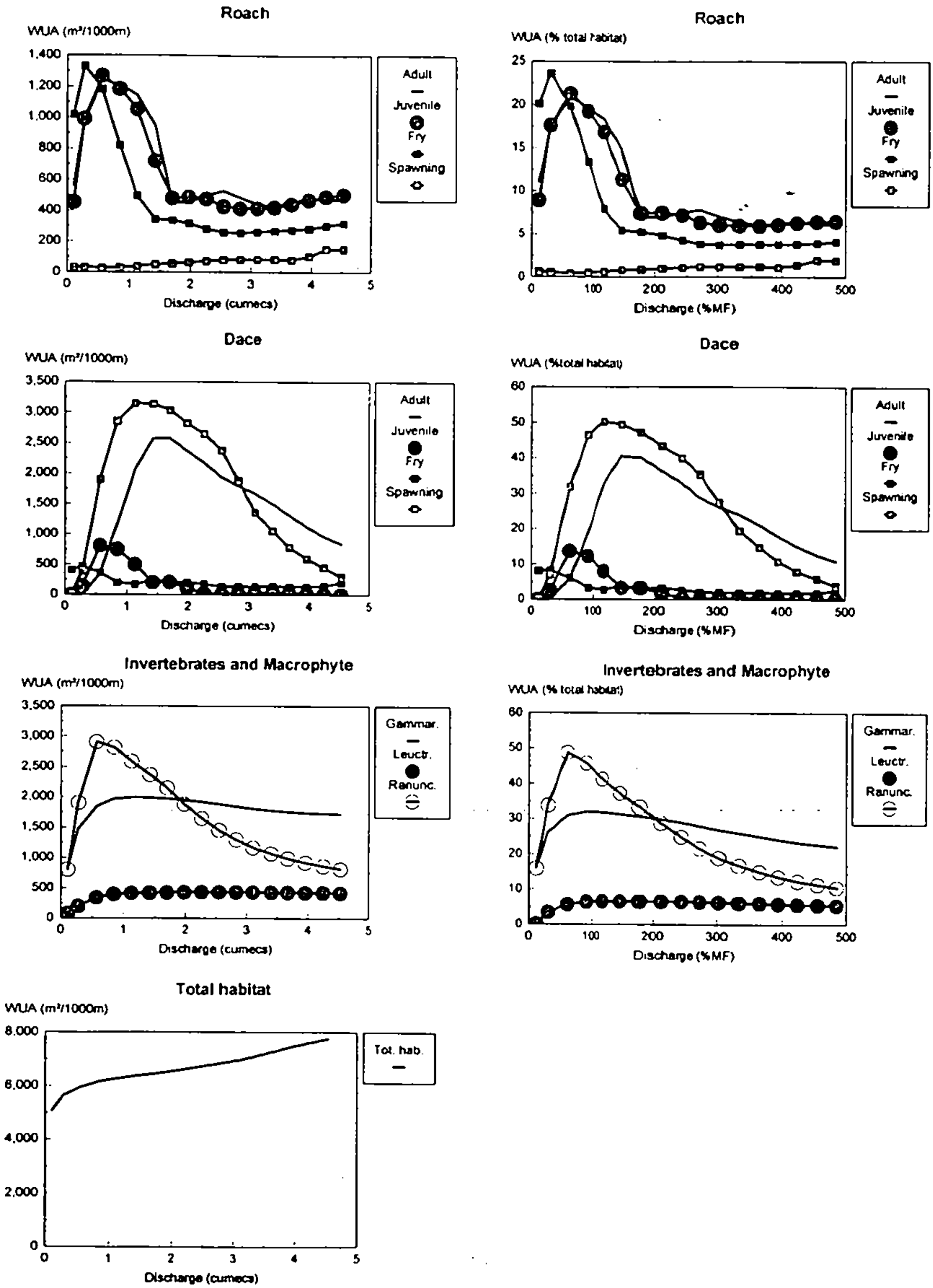

Figure B6. Millstream: habitat vs discharge relationships

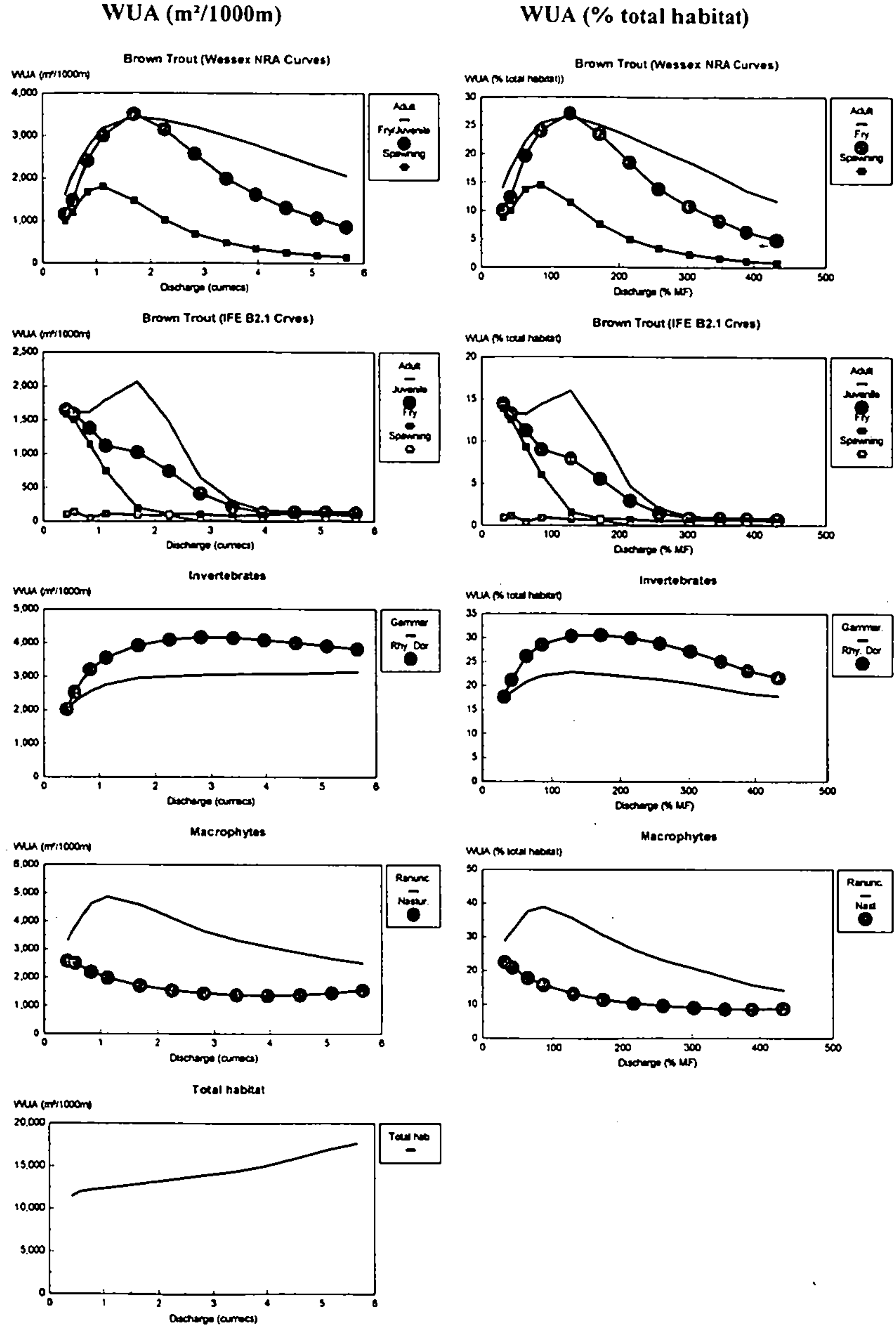

Figure B7. River Lambourn: habitat vs discharge relationships

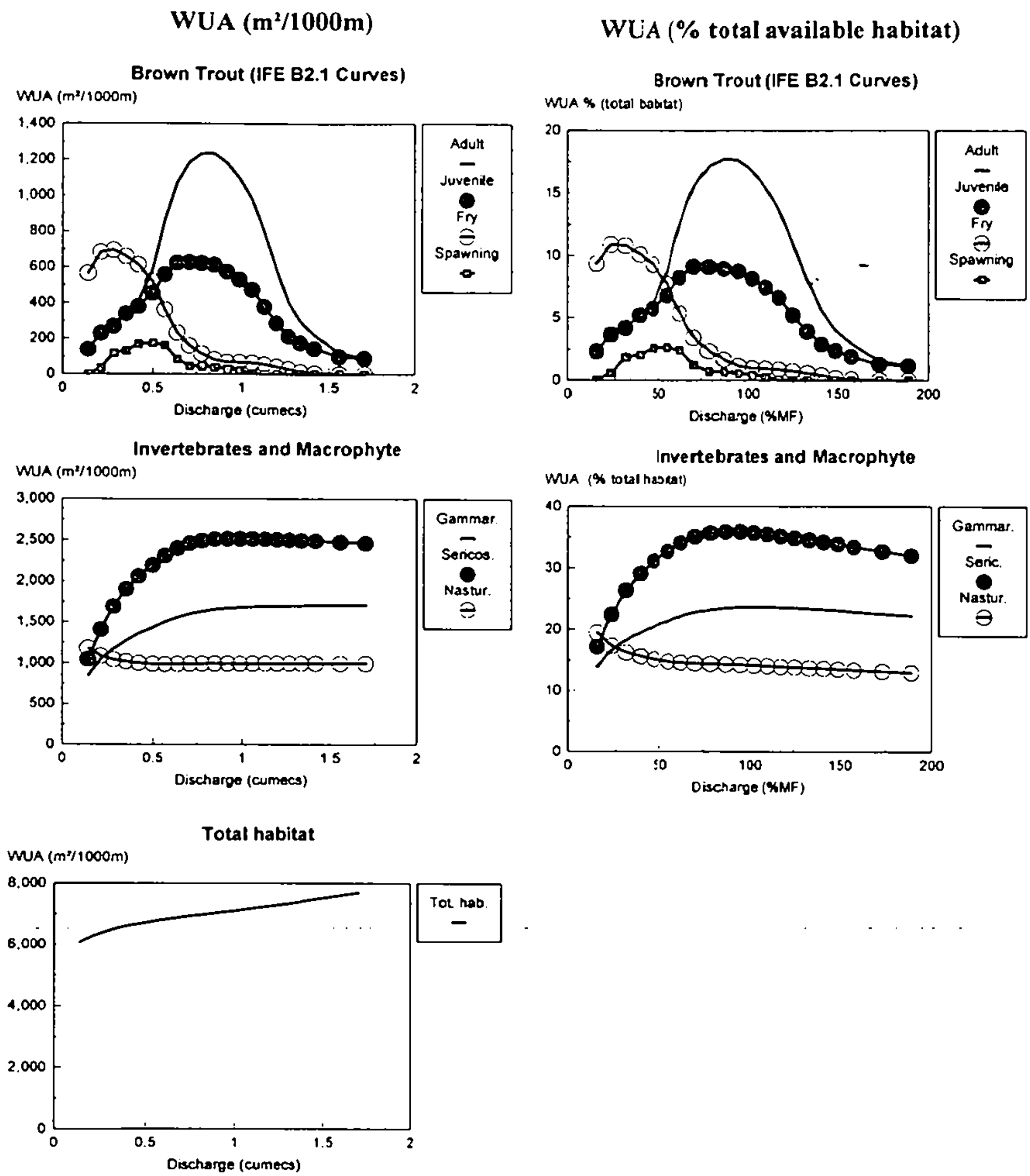

Figure B8. *Habitat vs Discharge Relationships: River Gwash*

APPENDIX C. HABITAT TIME SERIES AND DURATION CURVES

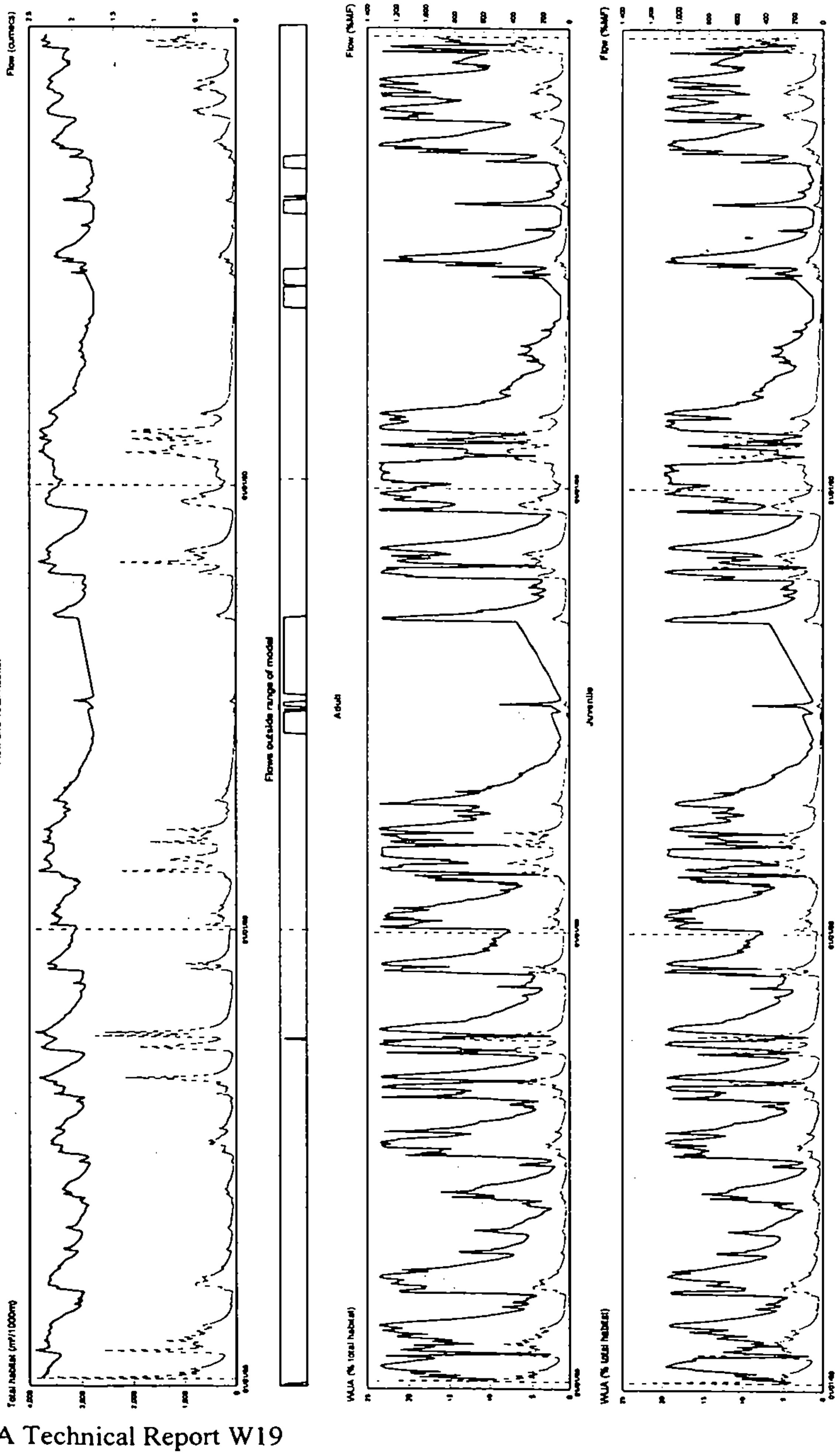

Figure C1.1. River Exe: total habitat and flow, habitat time series for brown trout (adult, juvenile)

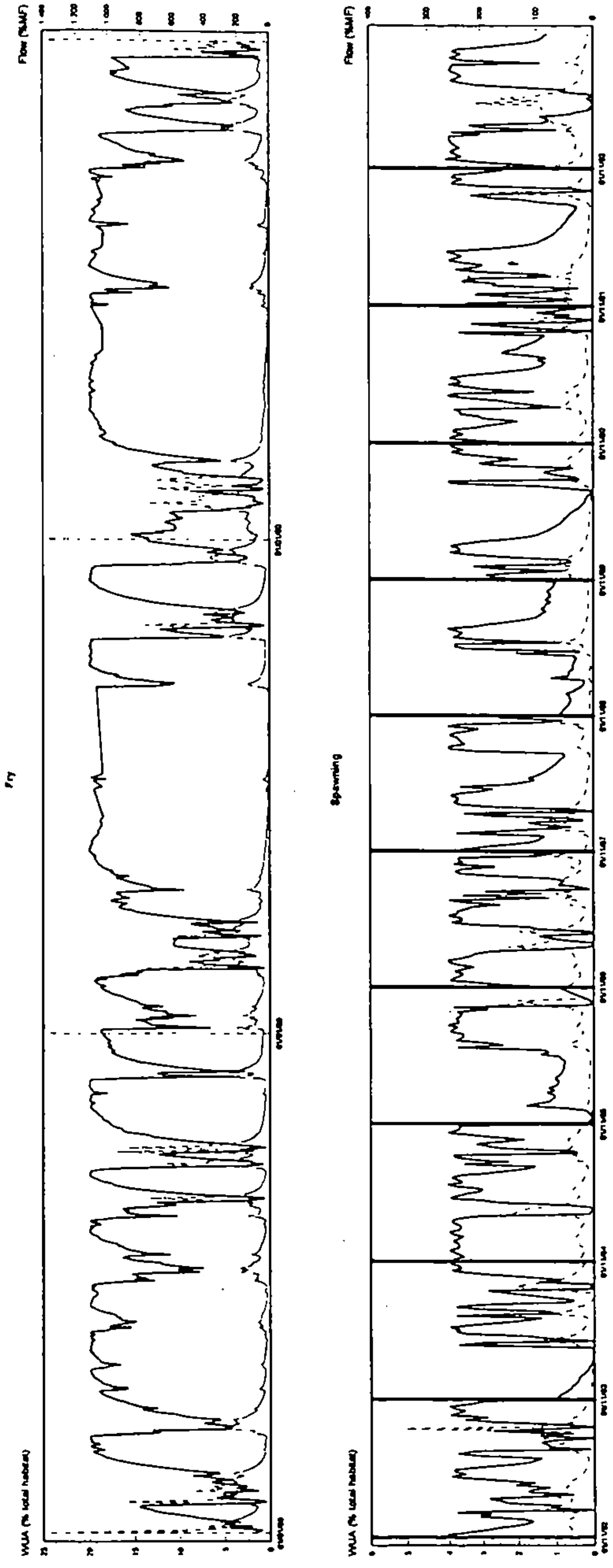

Figure C1.2. River Exe: habitat time series for brown trout (fry, spawning)

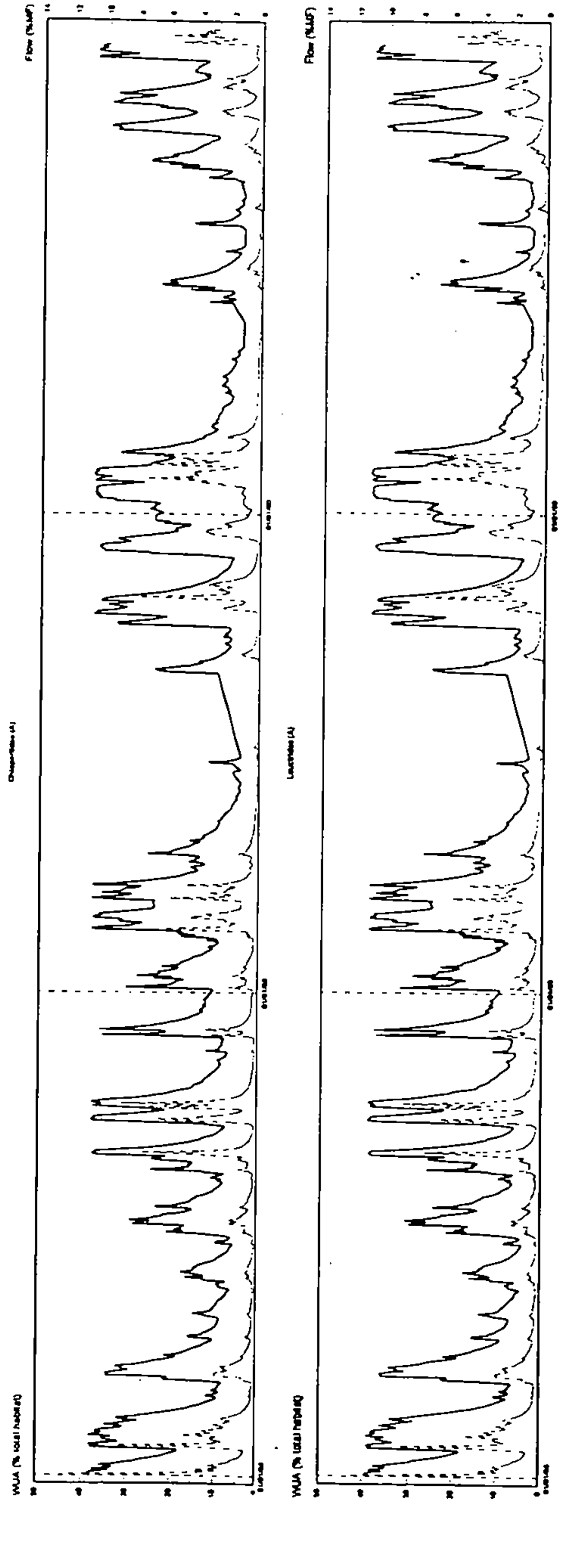

Figure C1.3. River Exe: habitat time series for invertebrates

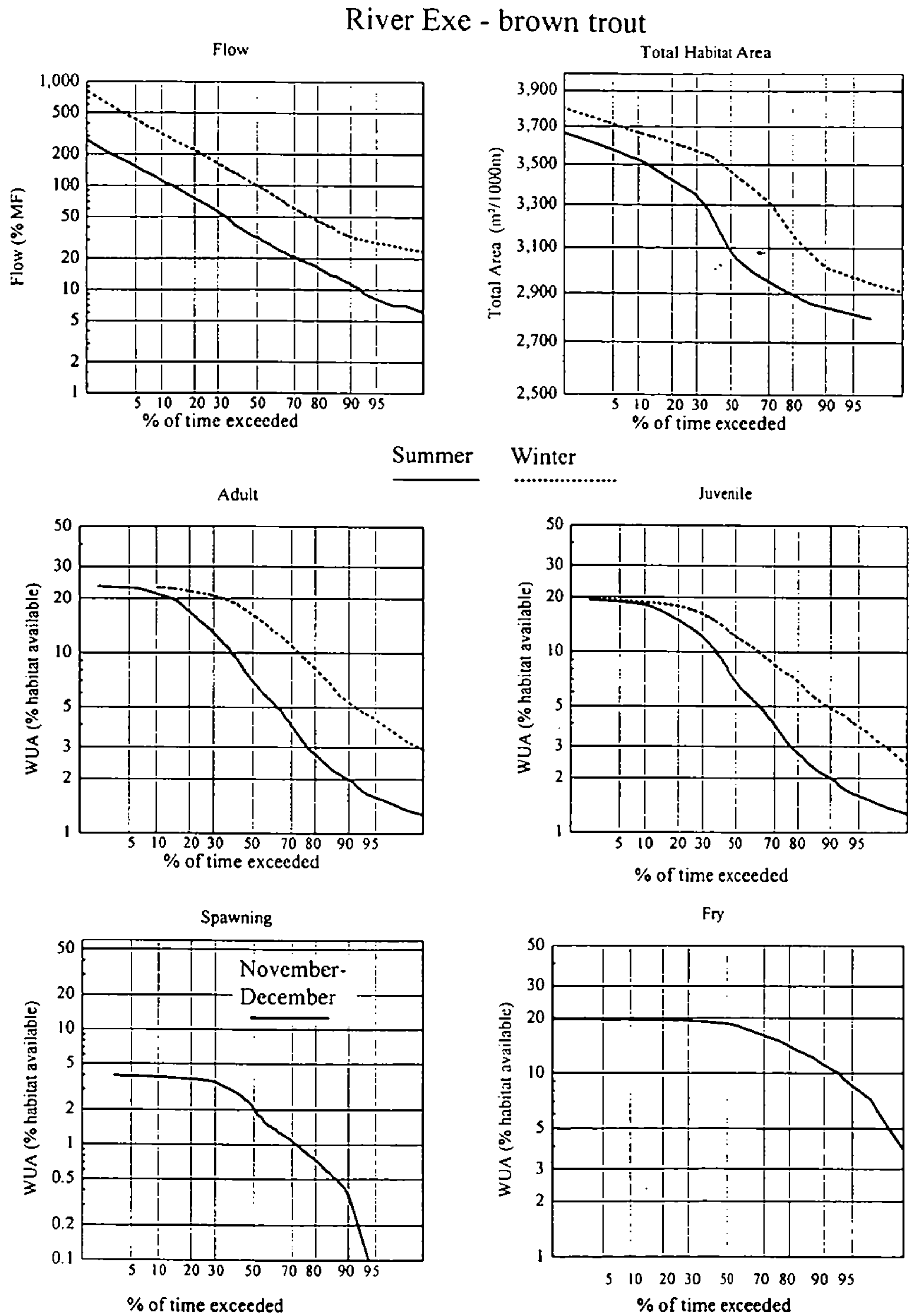

Figure C1.4. River Exe: Habitat duration curves for brown trout (all life stages) using 16 years of daily mean flow data (1966-1981)

River Exe - invertebrates

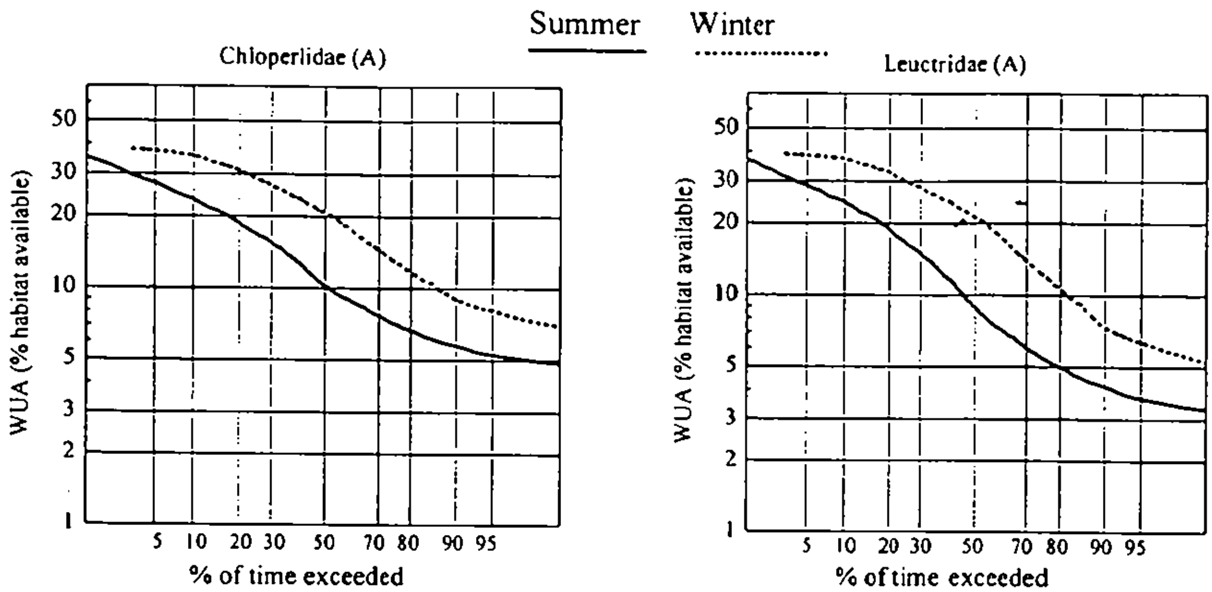

***Figure C1.5**. River Exe: Habitat duration curves for invertebrates using 16 years of daily mean flow data (1966-1981)*

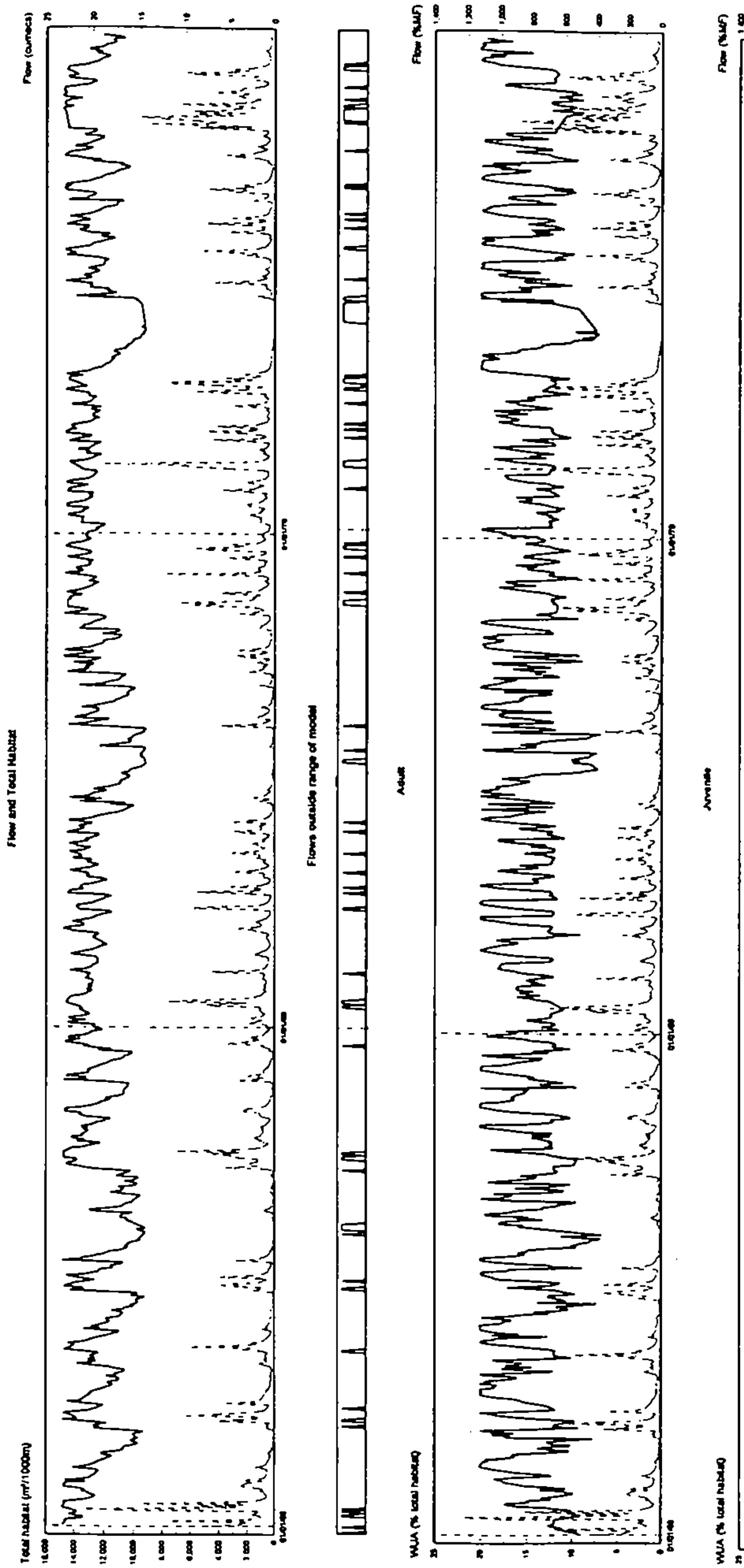

Figure C2.1. River Wye: total habitat and flow, habitat time series for brown trout (adult, juvenile)

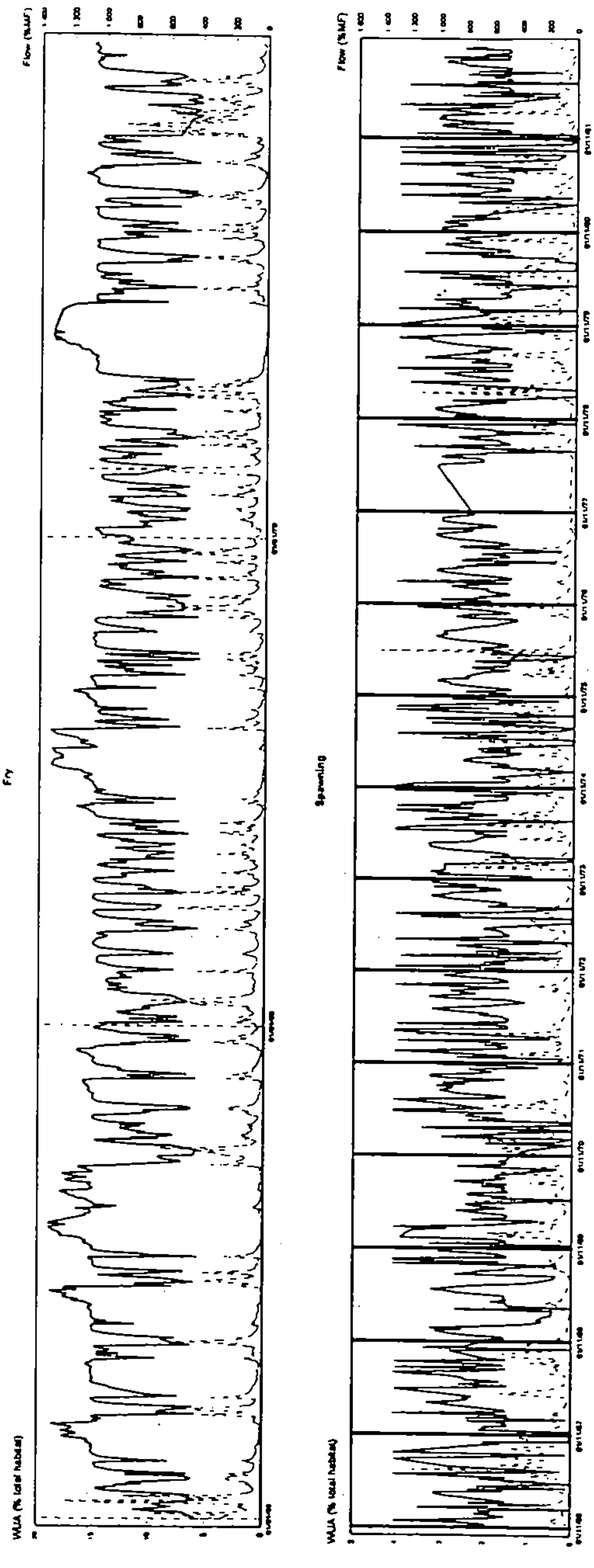

Figure C2.2. River Wye: habitat time series for brown trout (fry and spawning)

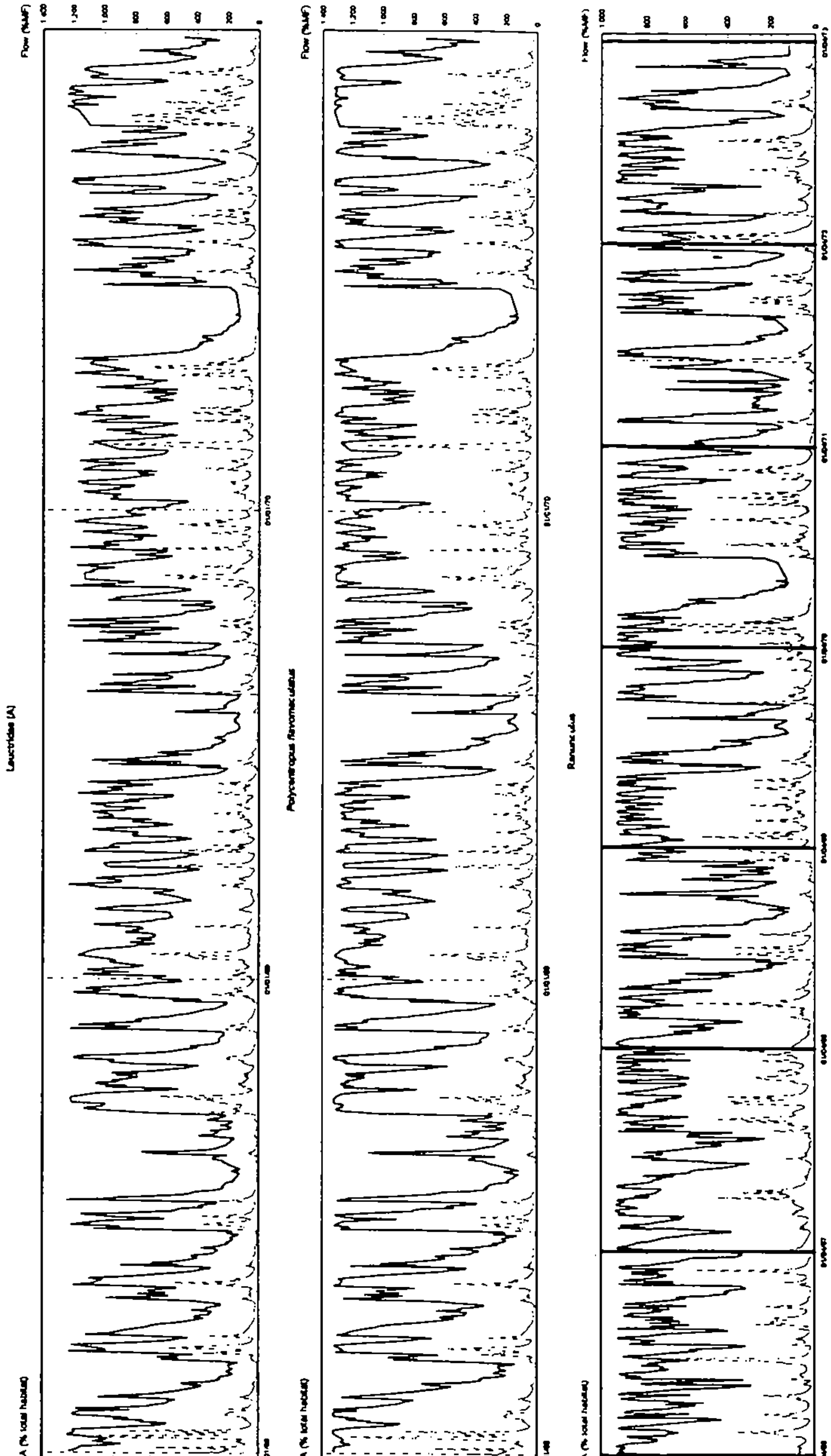

Figure C2.3. River Wye: habitat time series for invertebrates, plus ranunculus

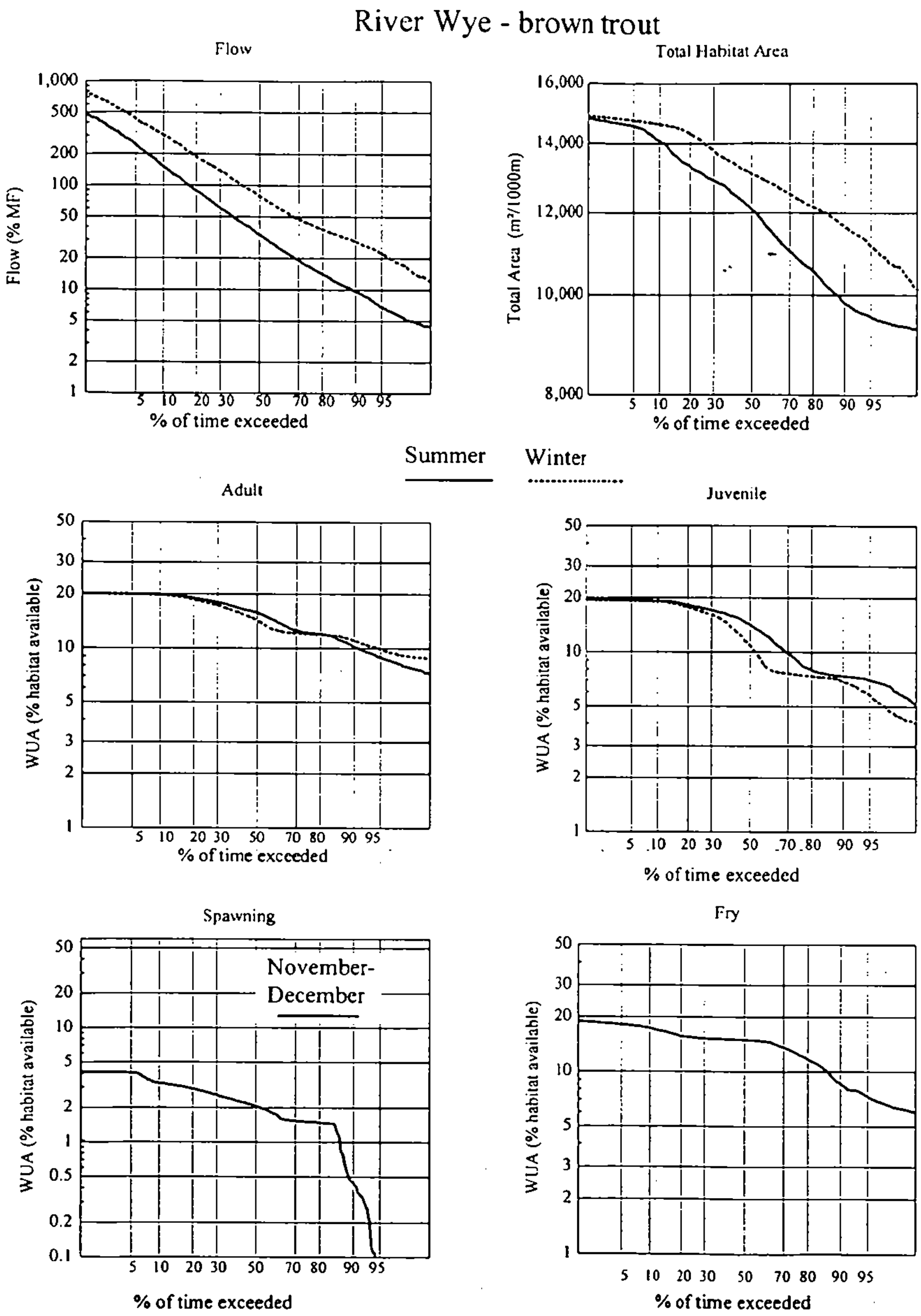

***Figure C2.4.** River Wye. Habitat duration curves for brown trout using 16 years of daily mean flow data (1966-1981)*

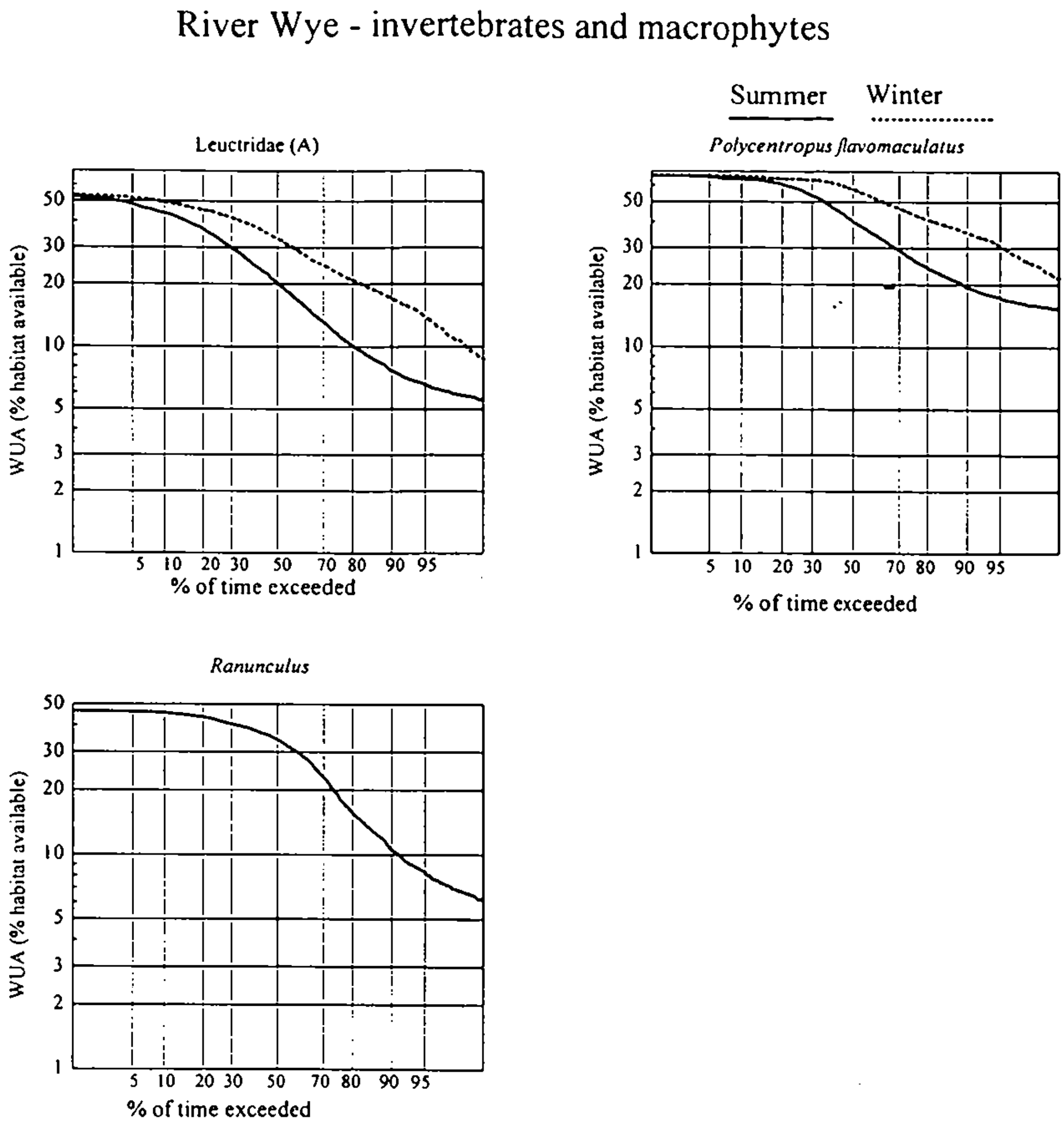

Figure C2.5. River Wye: habitat duration curves for invertebrates and macrophyte using 16 years of daily mean flow data (1966-1981)

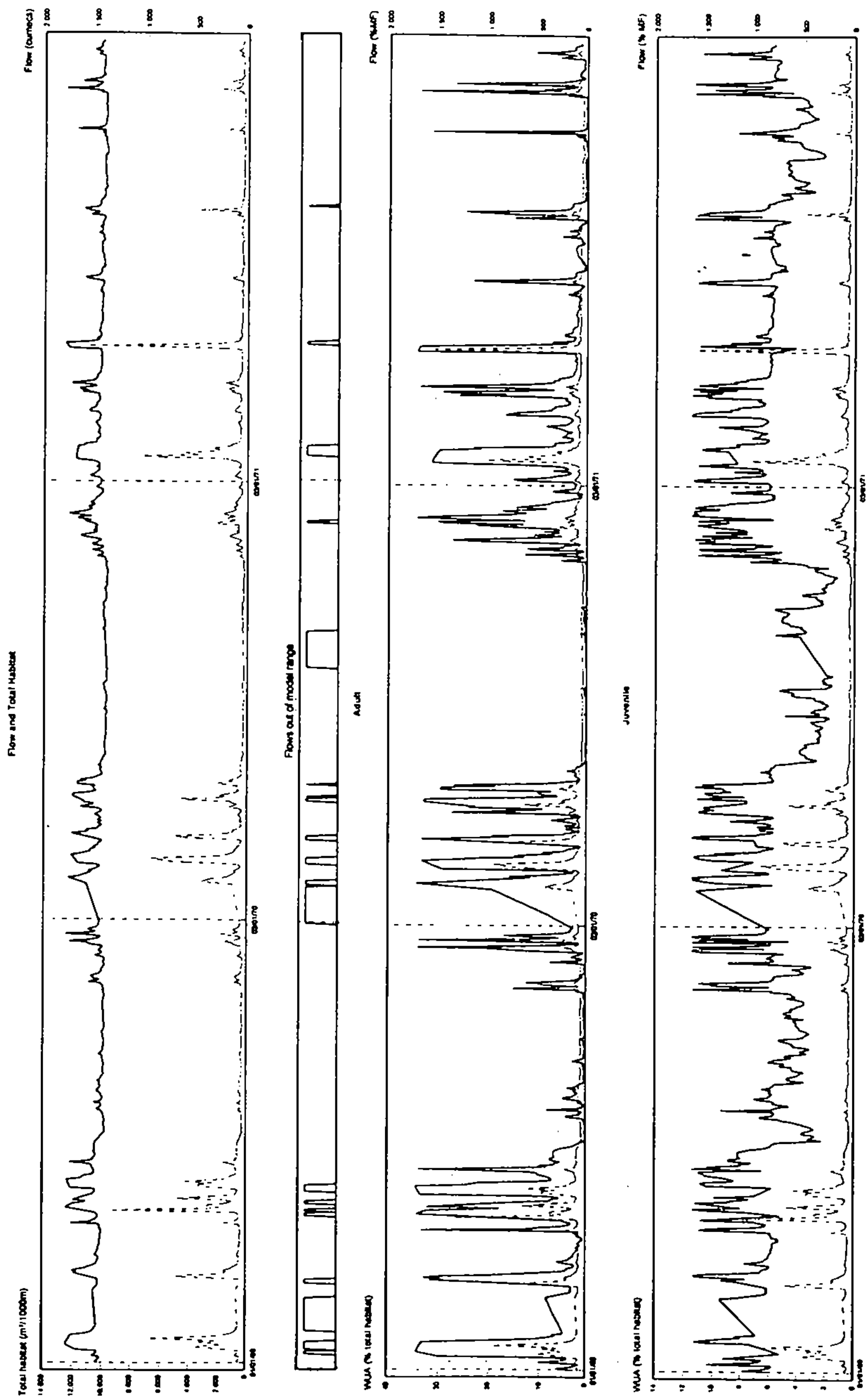

Figure C3.1. River Blithe: total habitat and flow, habitat time series for dace (adult and juvenile)

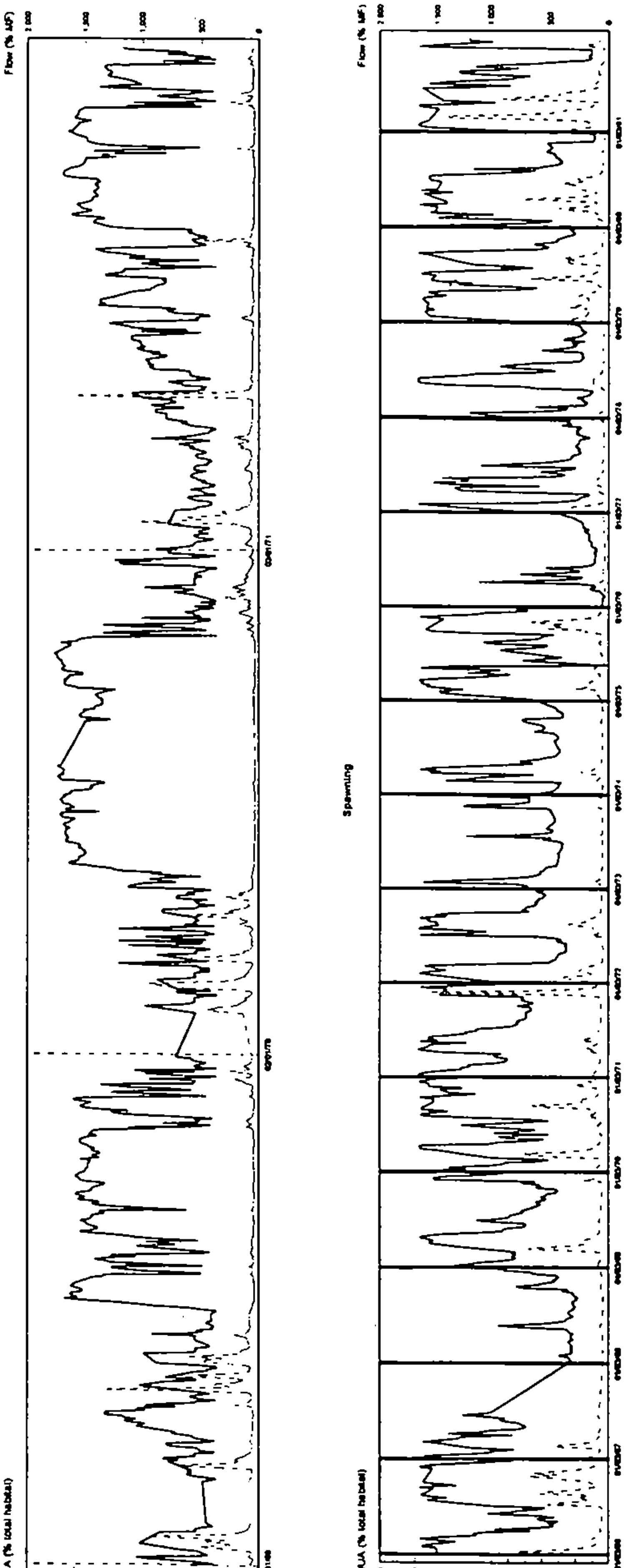

Figure C3.2. River Blithe. Habitat time series for dace (fry and spawning)

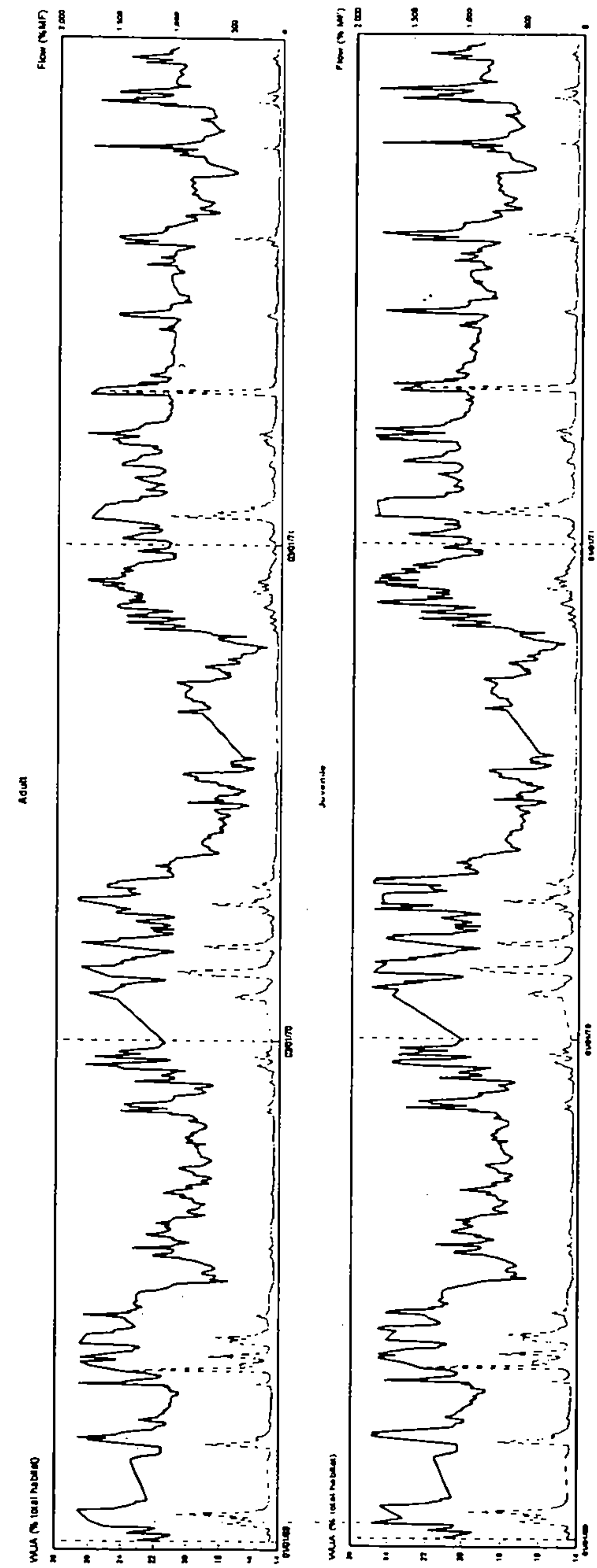

Figure C3.3. River Blithe: habitat time series for roach (adult and juvenile)

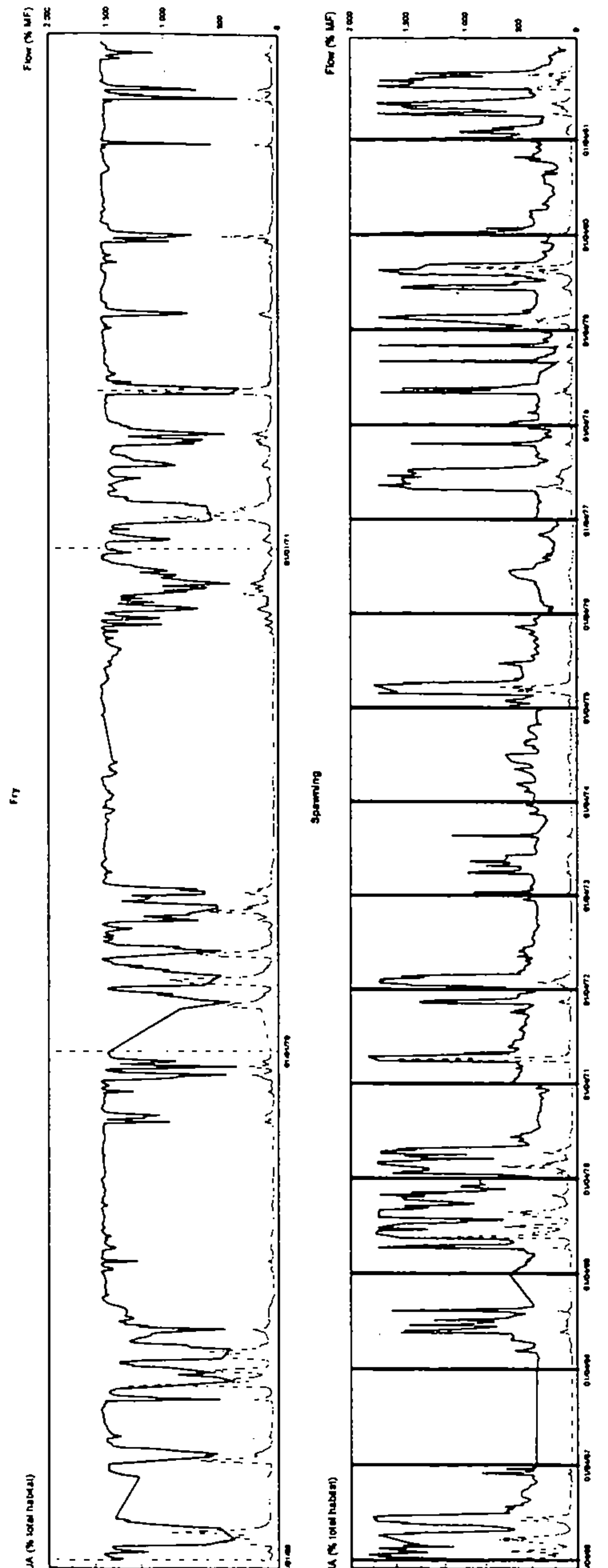

Figure C3.4. *River Blithe: habitat time series for roach (fry and spawning)*

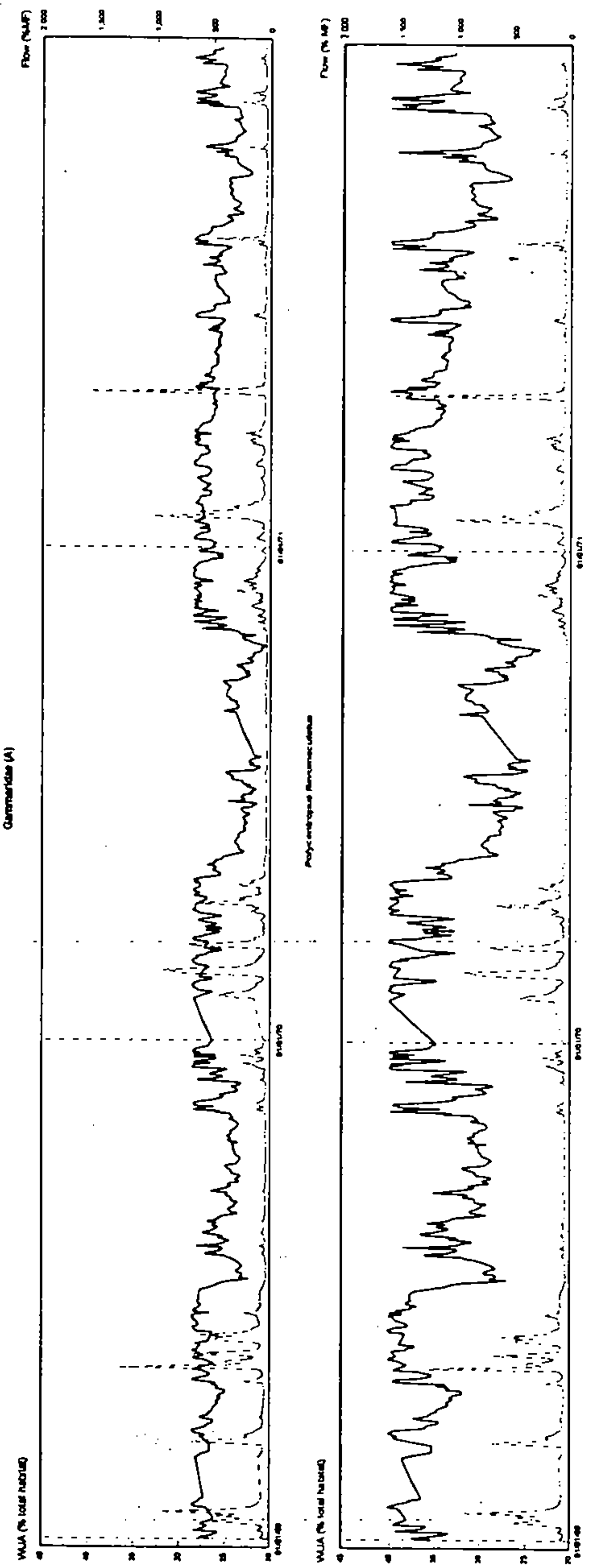

Figure C3.5. River Blithe: habitat time series for two genera of invertebrates

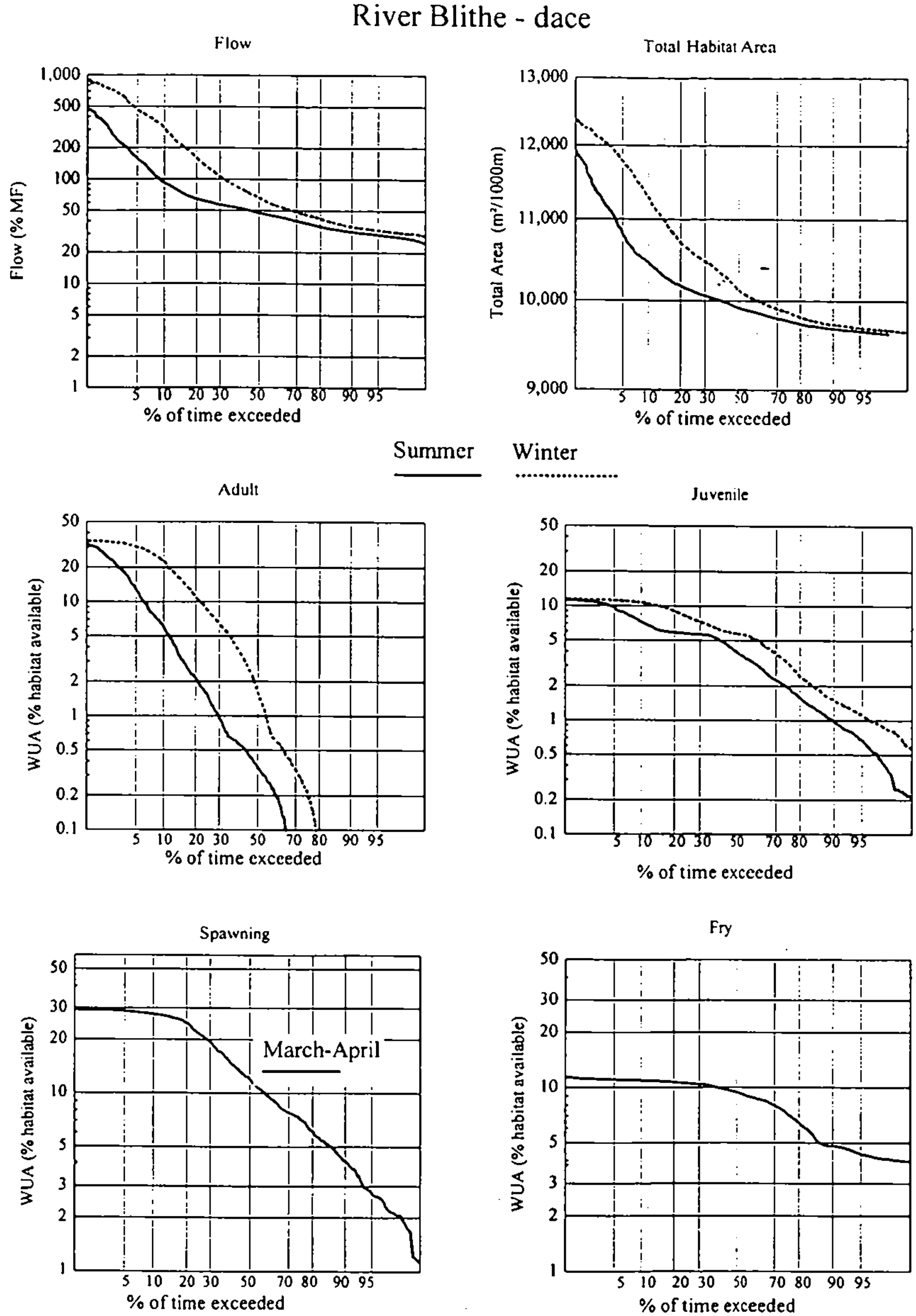

Figure C3.6. *River Blithe: habitat duration curves for dace using 16 years of daily mean flow data (1966-1981)*

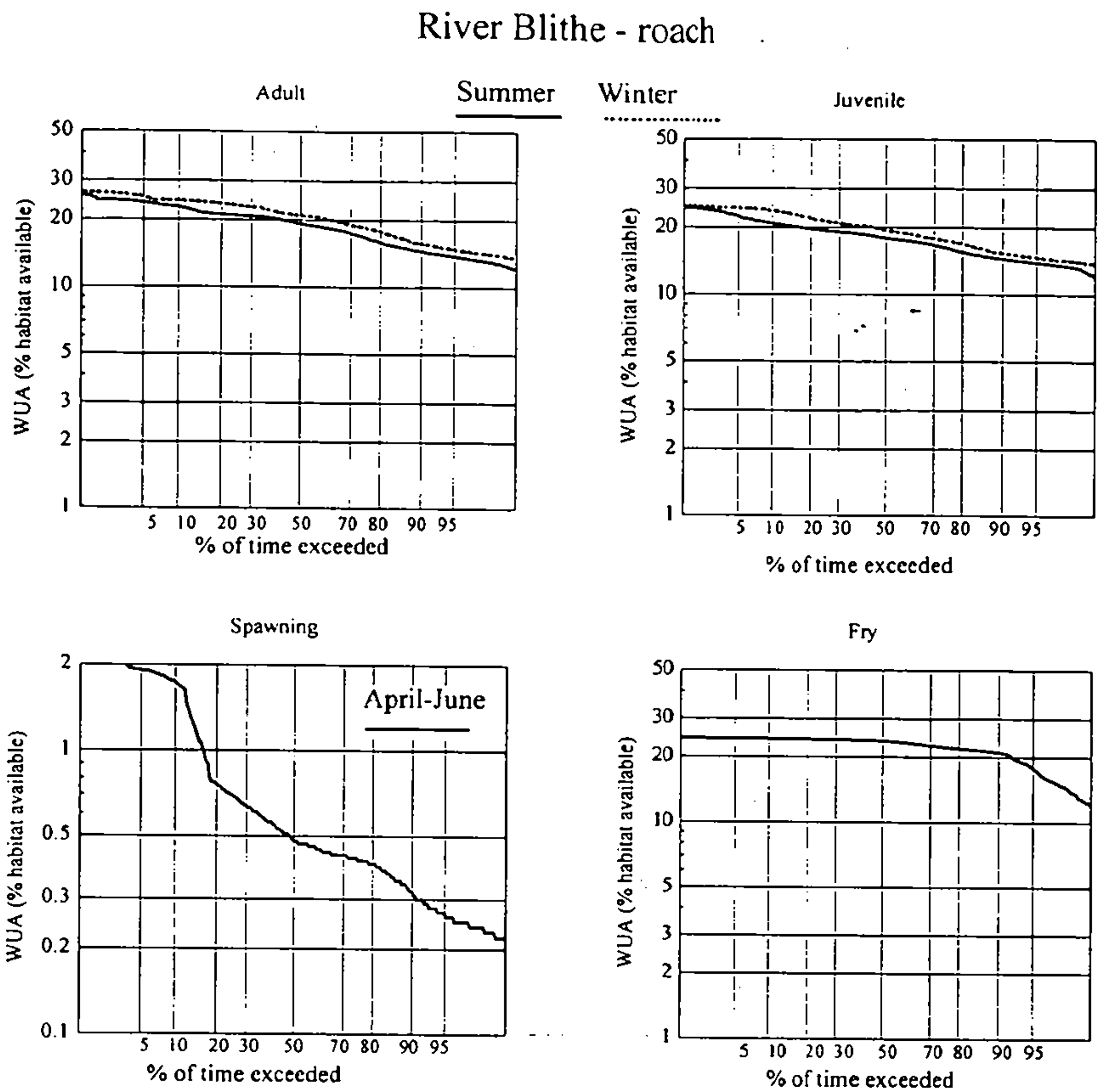

Figure C3.7. River Blithe: habitat duration curves for roach using 16 years of daily mean flow data (1966-1981)

River Blithe - invertebrates and macrophytes

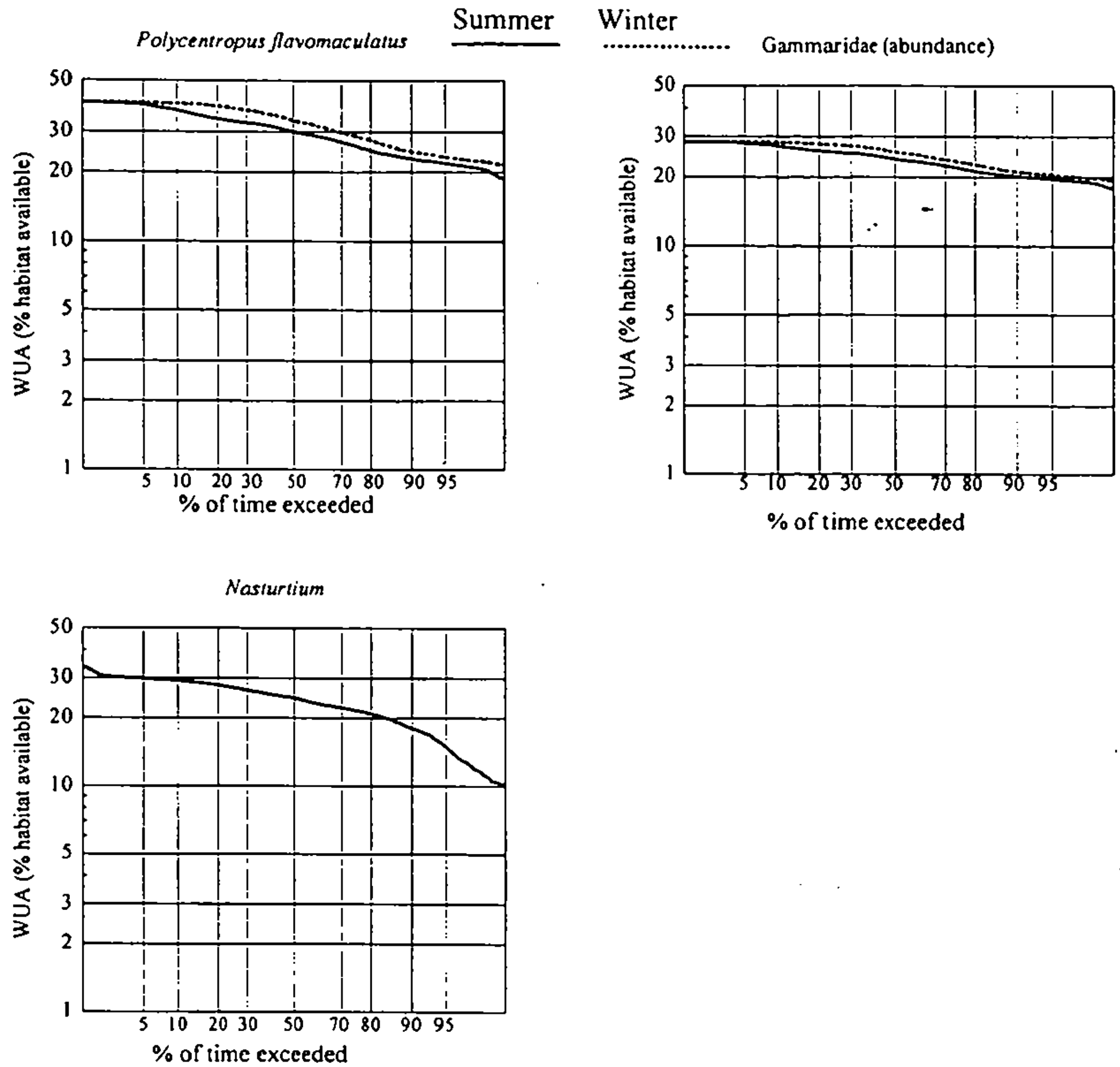

Figure C3.8. Habitat duration curves for invertebrates using 16 years of daily mean flow data (1966-1981)

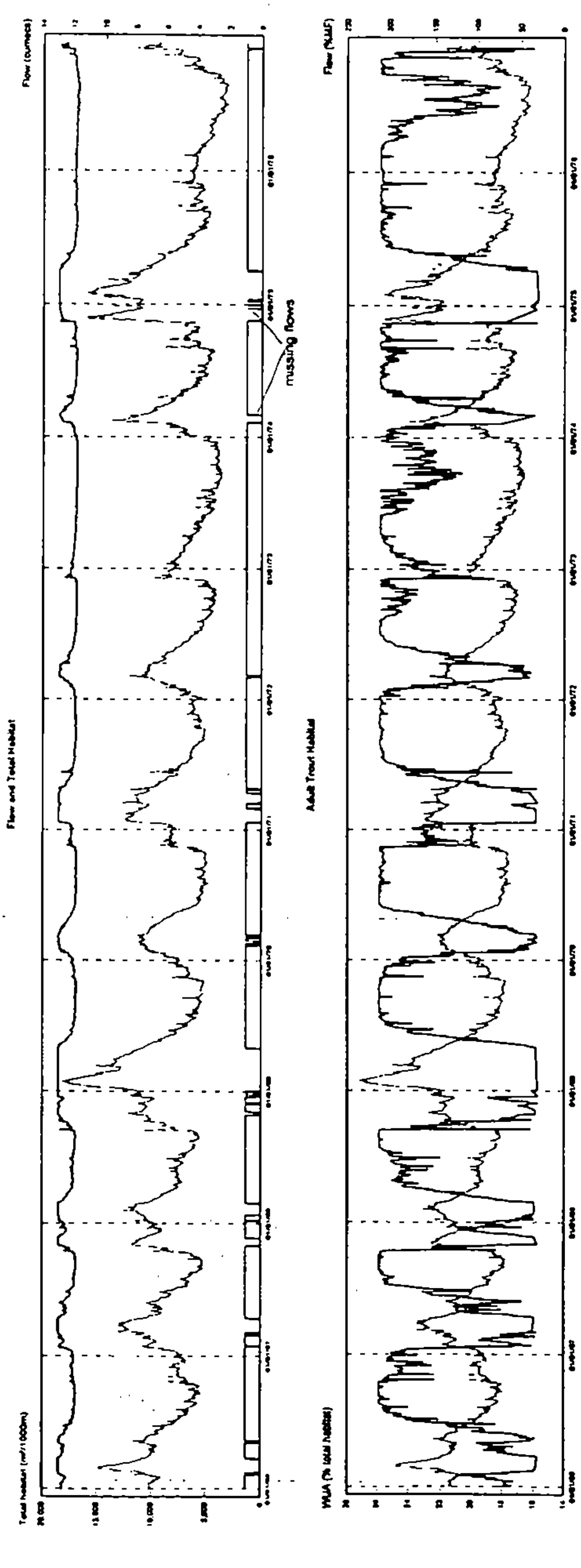

Figure C4.1. River Itchen: total habitat and flow, habitat time series for adult brown trout

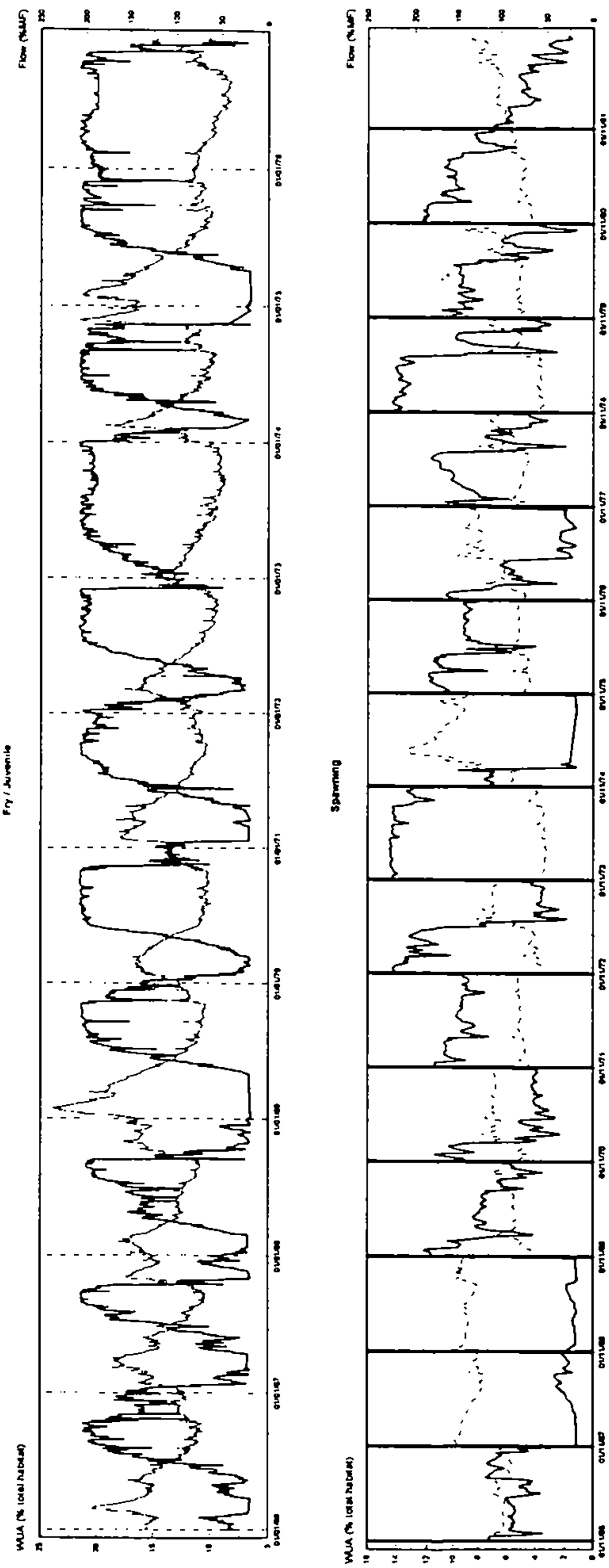

Figure C4.2. River Itchen: habitat time series for brown trout (fry/juvenile and spawning)

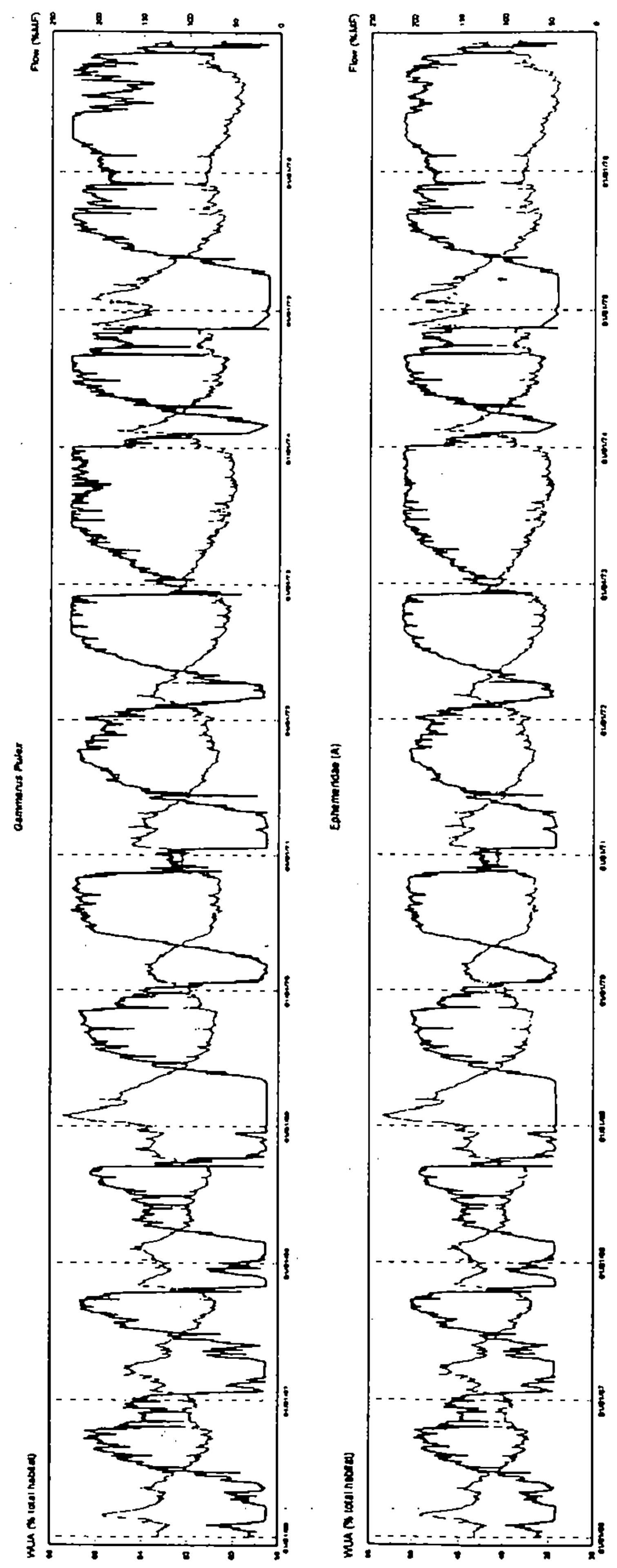

Figure C4.3. River Itchen: total habitat and flow, habitat time series for two genera of invertebrates

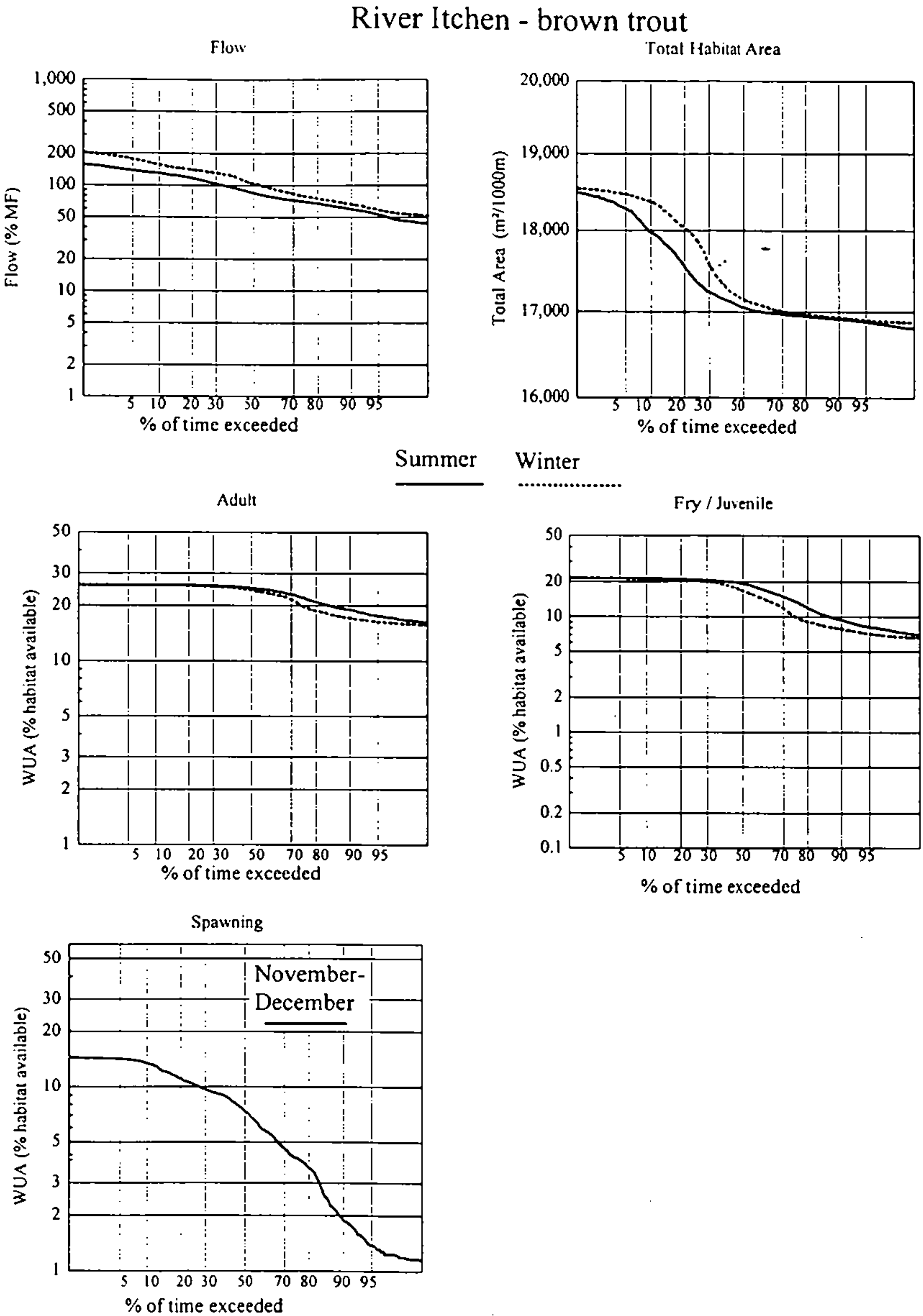

Figure C4.4. *River Itchen: habitat duration curves for brown trout using 16 years of daily mean flow data (1966-1981)*

River Itchen - invertebrates and macrophytes

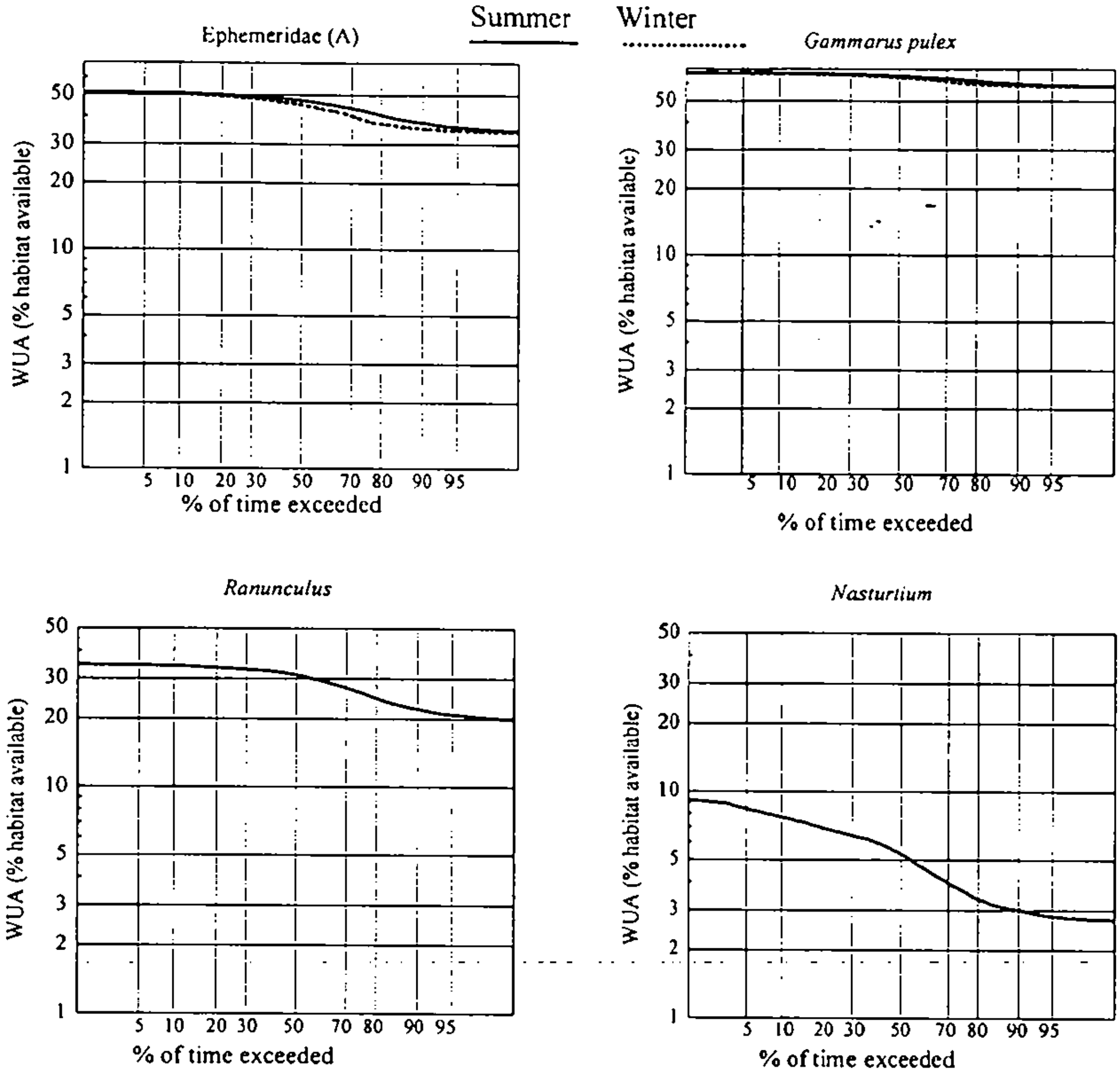

***Figure C4.5.** River Itchen: habitat duration curves for invertebrates and macrophytes using 16 years of daily mean flow data (1966-1981)*

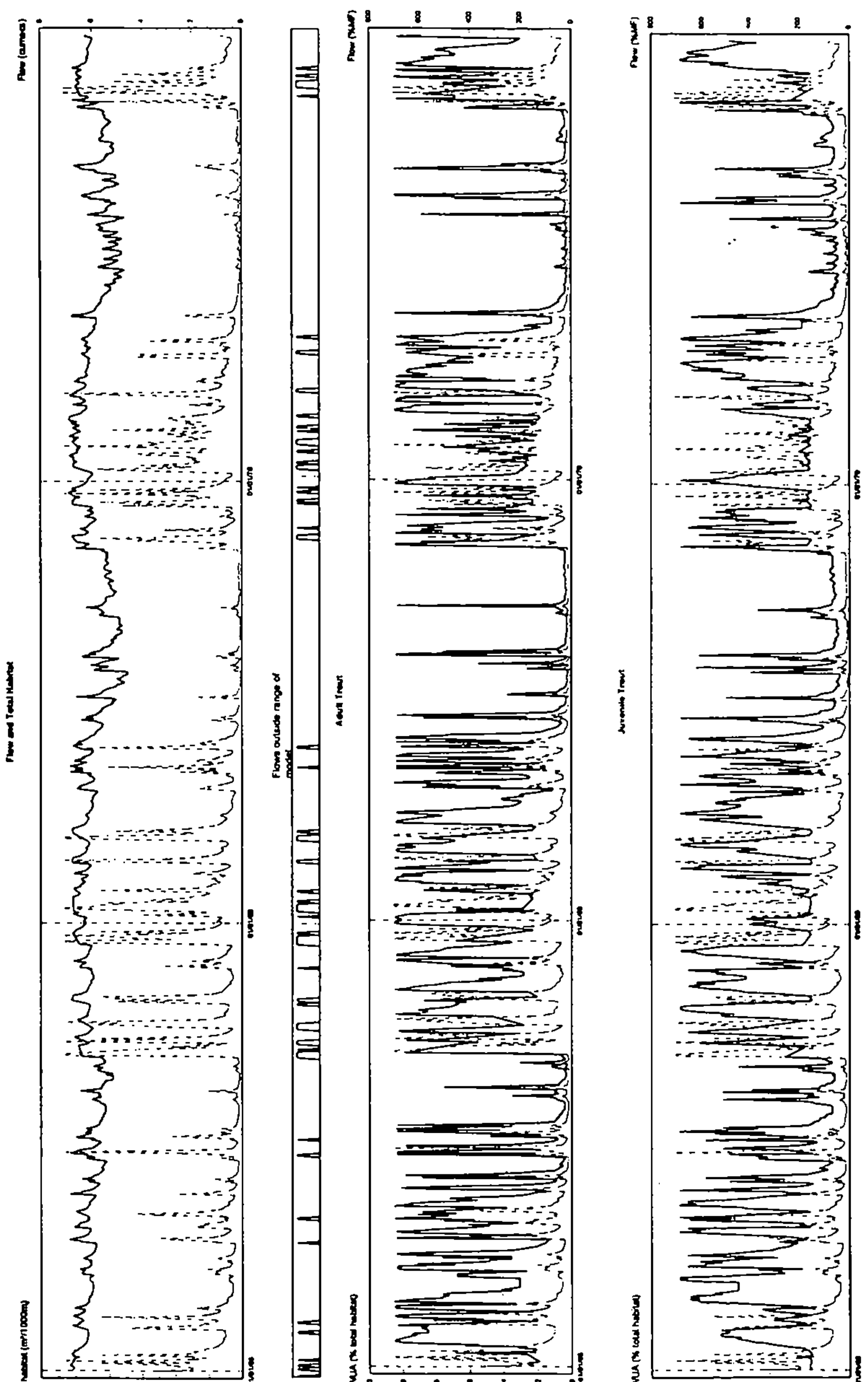

Figure C5.1. River Lymington: total habitat and flow, habitat time series for brown trout (adult, juvenile)

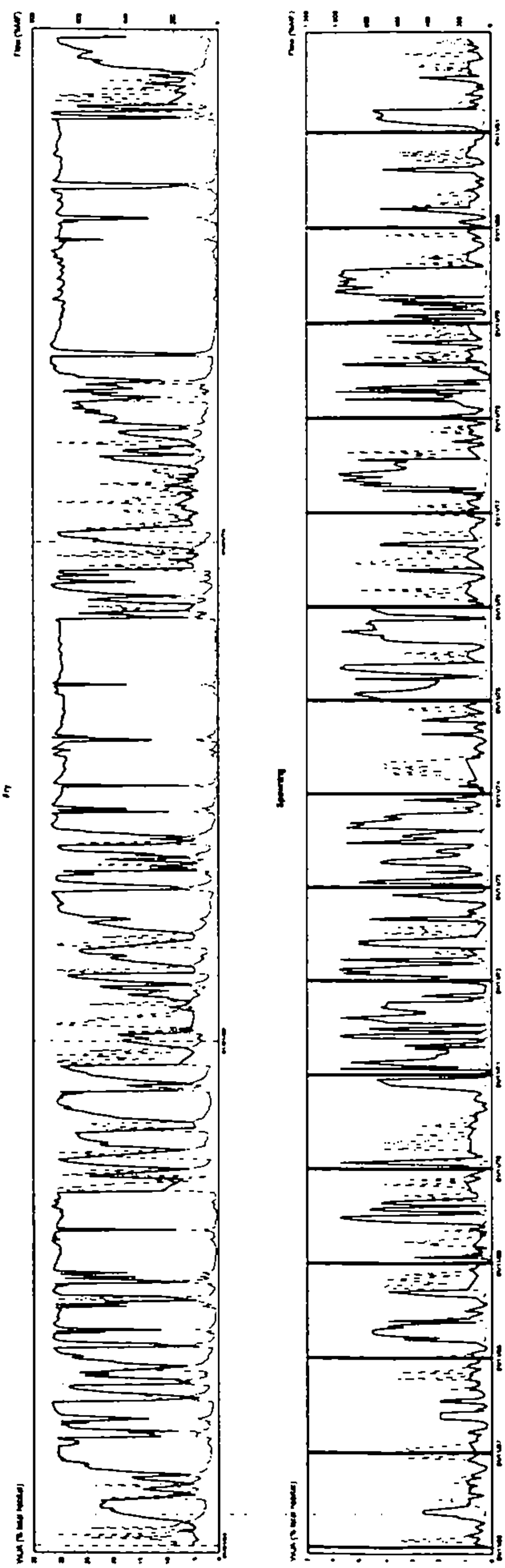

Figure CS.2. River Lymington: habitat time series for brown trout (fry, spawning)

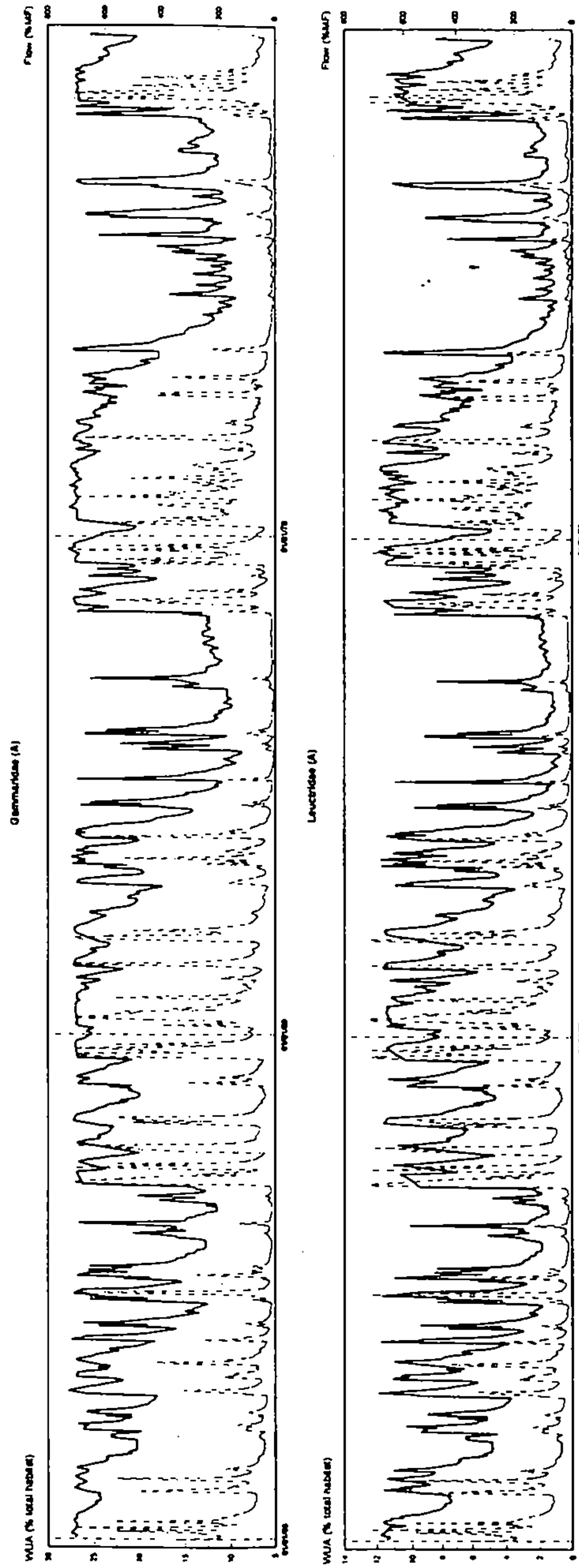

Figure C5.3. River Lymington. Habitat time series for two genera of invertebrates

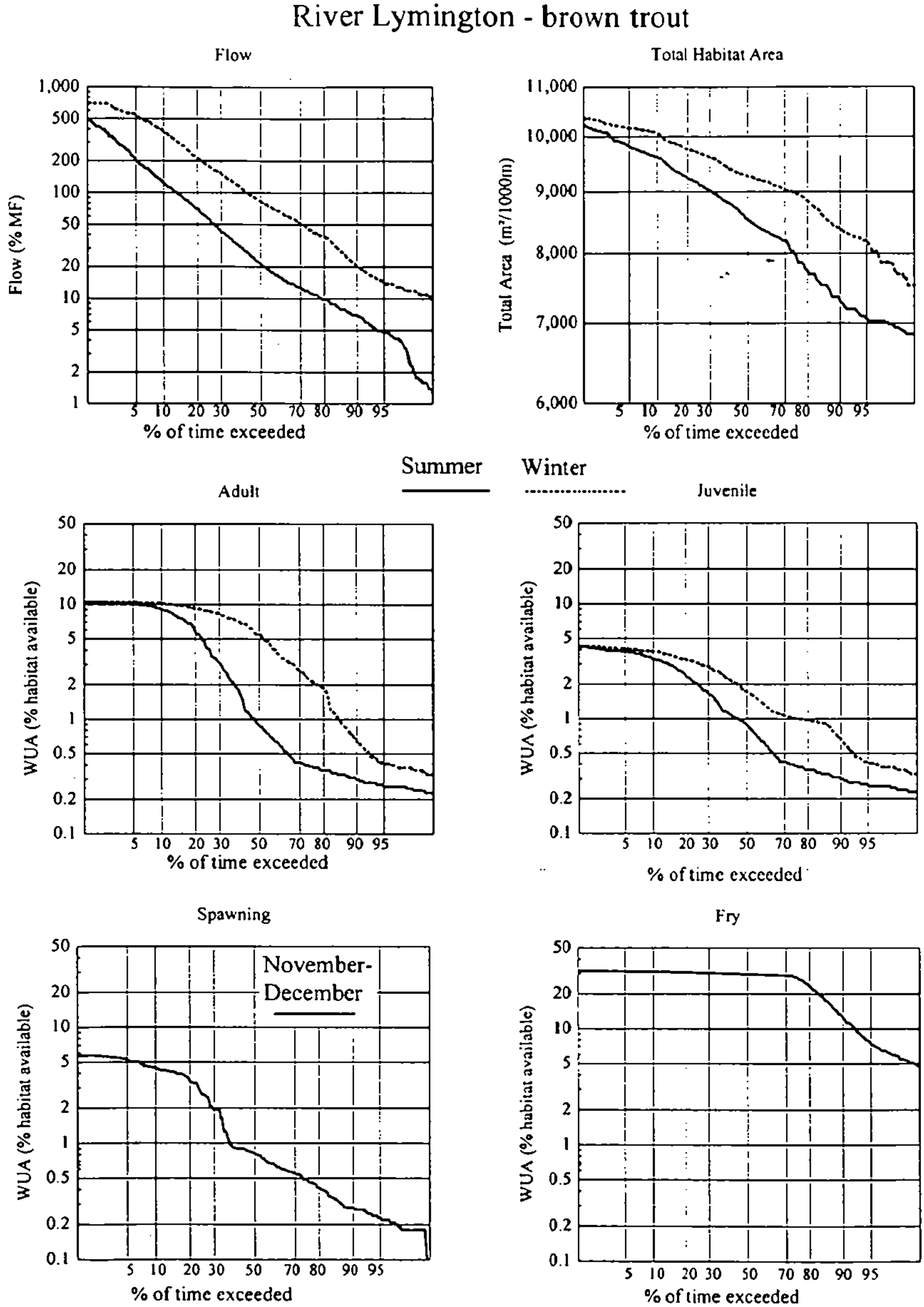

Figure C5.4. *River Lymington: habitat duration curves for brown trout using 16 years of daily mean flow data (1966-1981)*

River Lymington - invertebrates and macrophytes

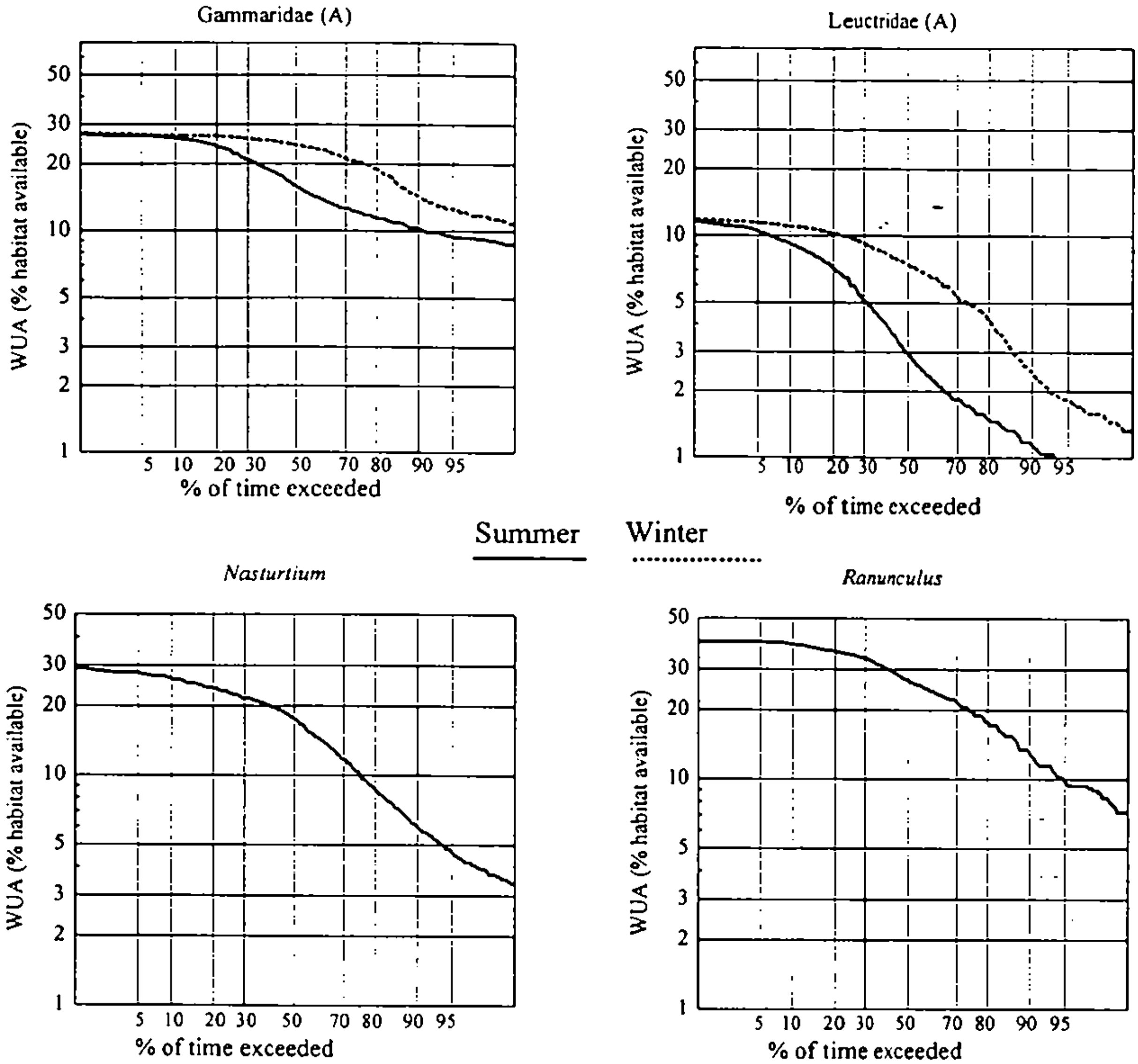

Figure C5.5. River Lymington: habitat duration curves for invertebrates / macrophytes using 16 years of daily mean flow data (1966-1981)

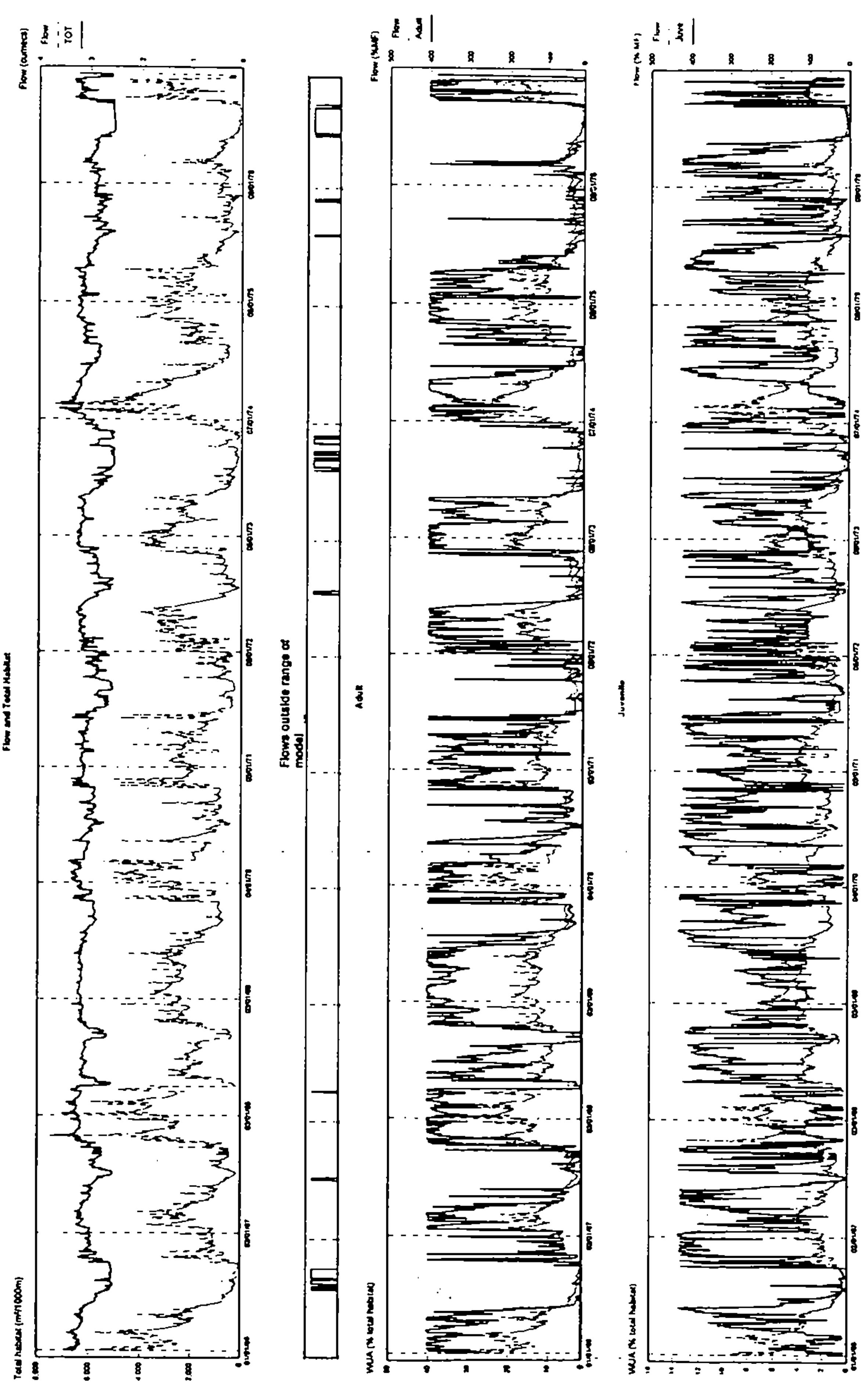

Figure C6.1. Millstream: total habitat and flow. Habitat time series for dace (adult and juvenile)

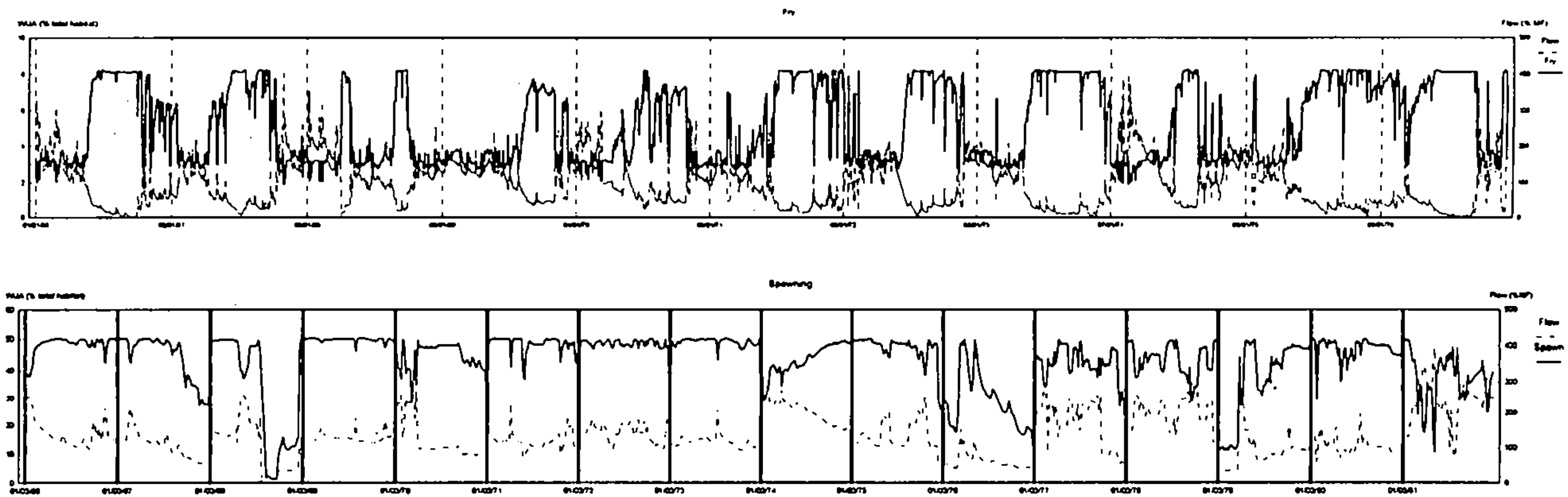

Figure C6.2. Millstream: habitat time series for dace (fry and spawning)

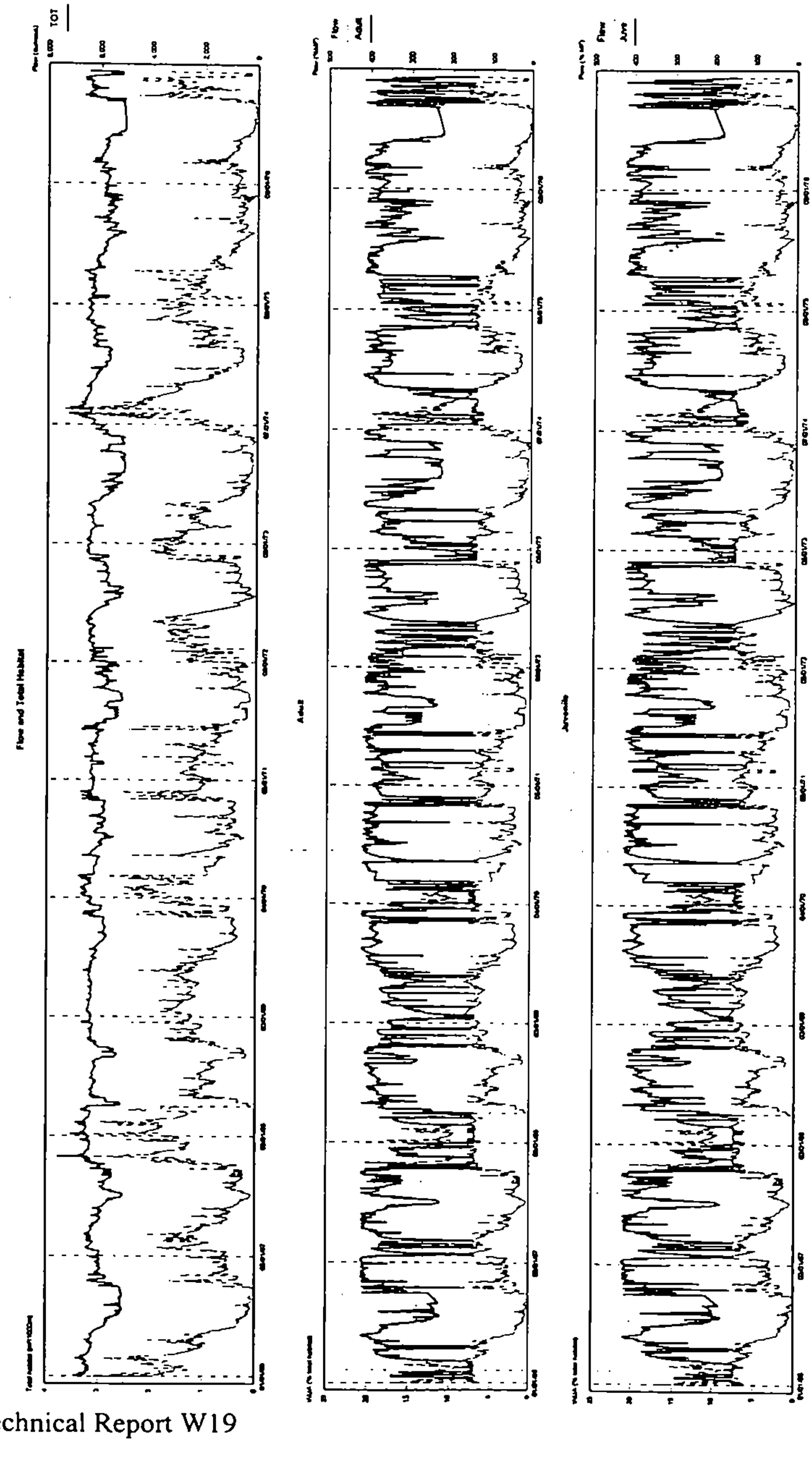

Figure C6.3. Millstream: total habitat and flow, habitat time series for roach (adult and juvenile)

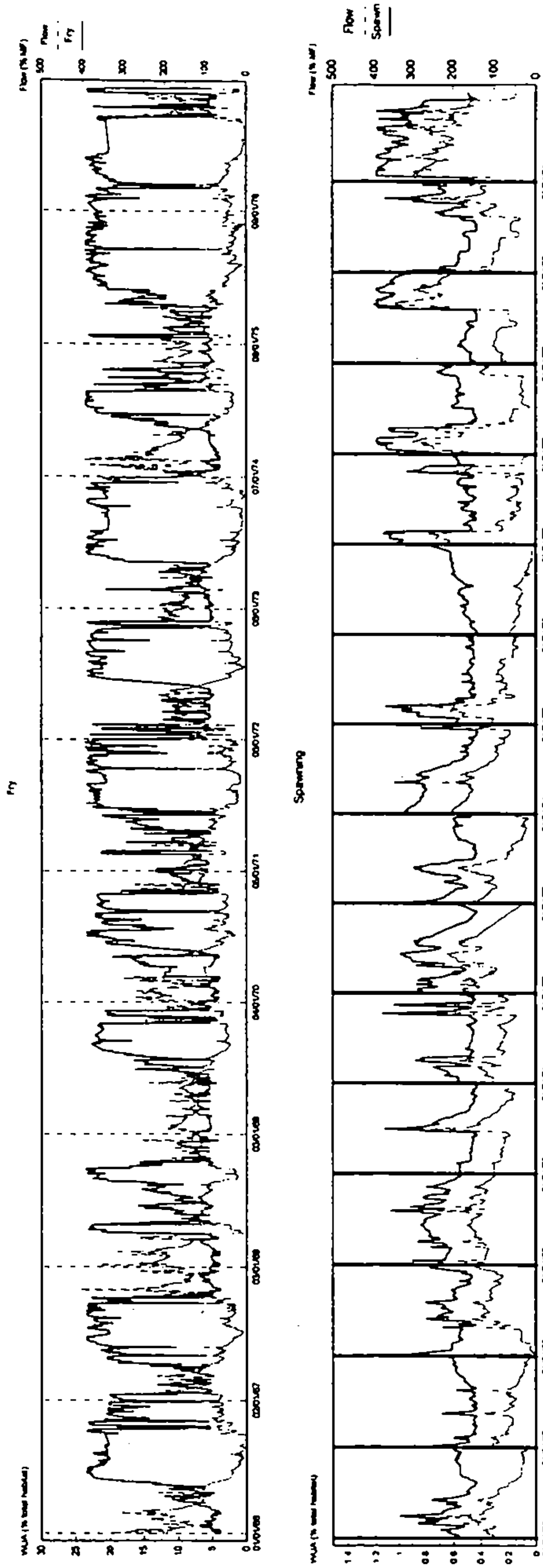

Figure C6.4. Millstream: habitat time series for roach (fry and spawning)

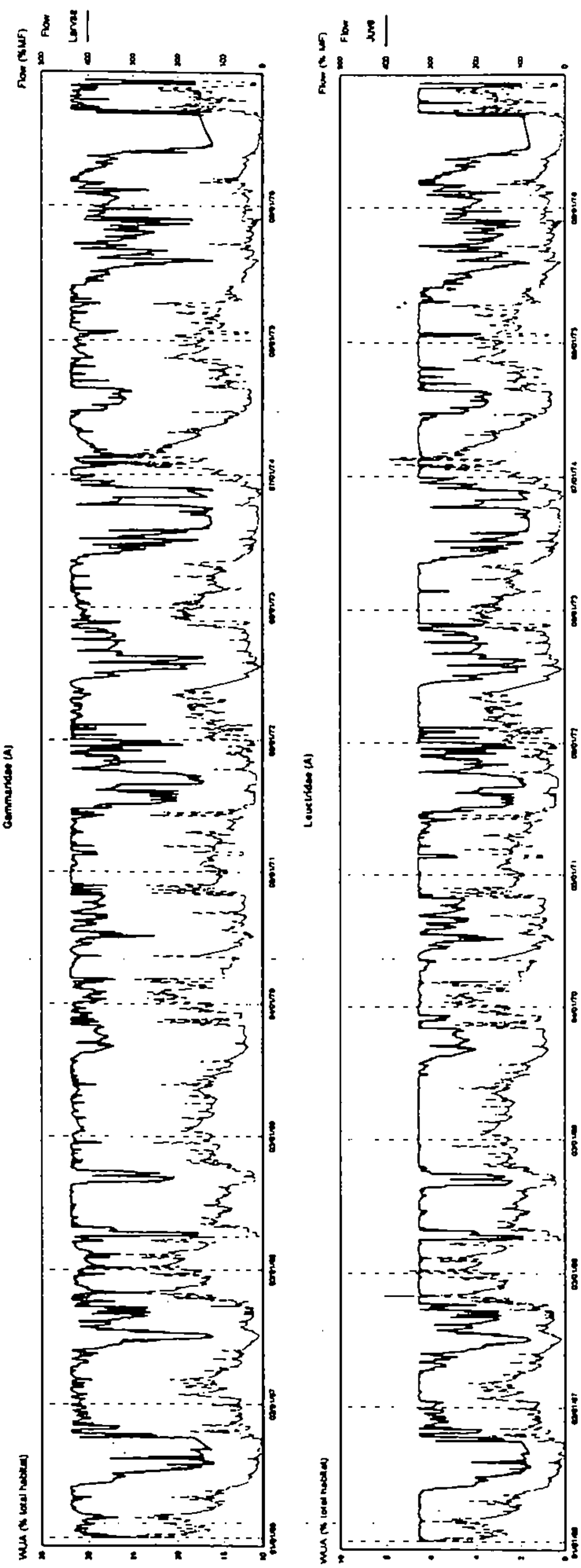

Figure C6.5. Millstream: habitat time series for two genera of invertebrates

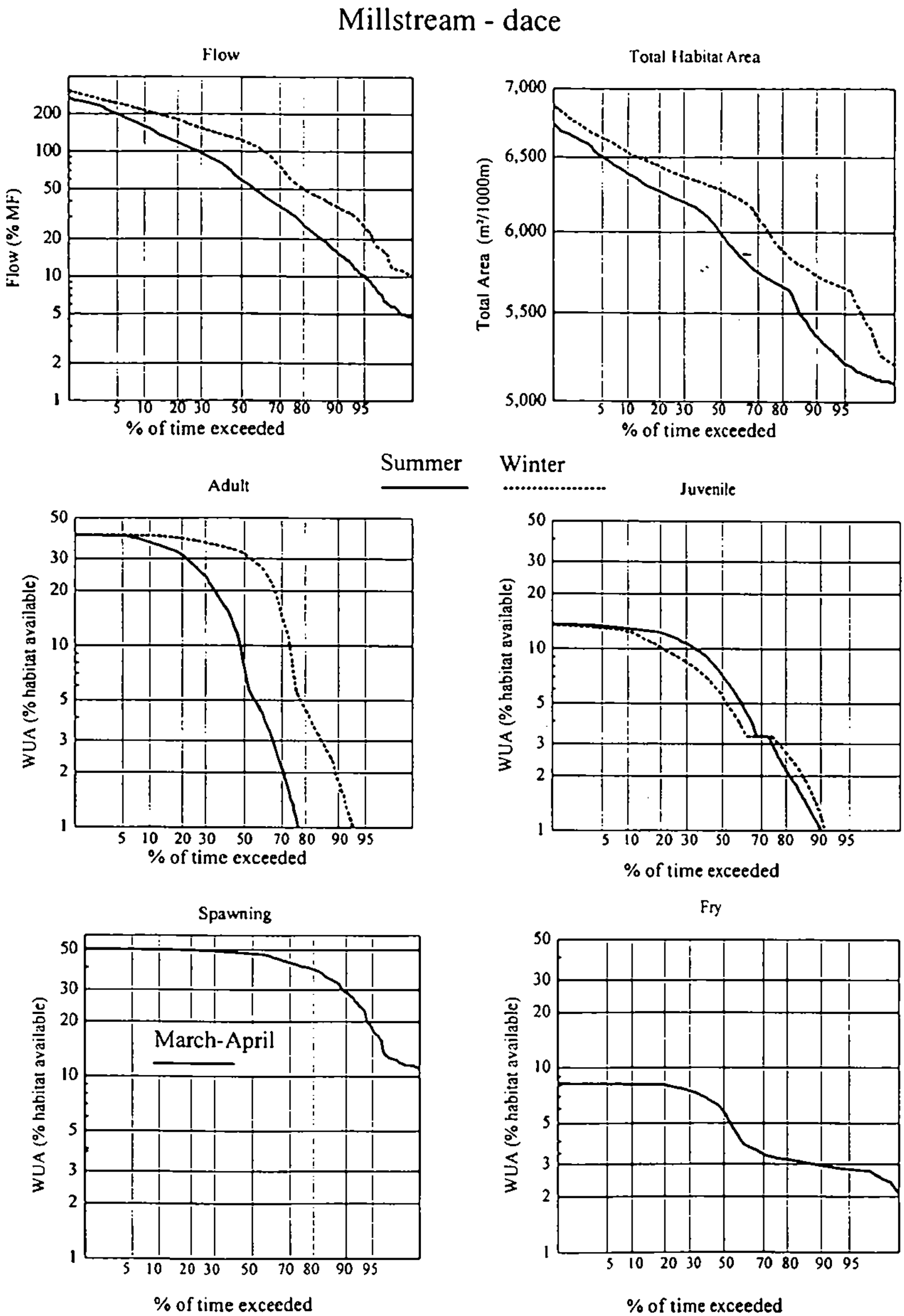

Figure C6.6. *Millstream: habitat duration curves for dace using 16 years of daily mean flow data (1966-1981)*

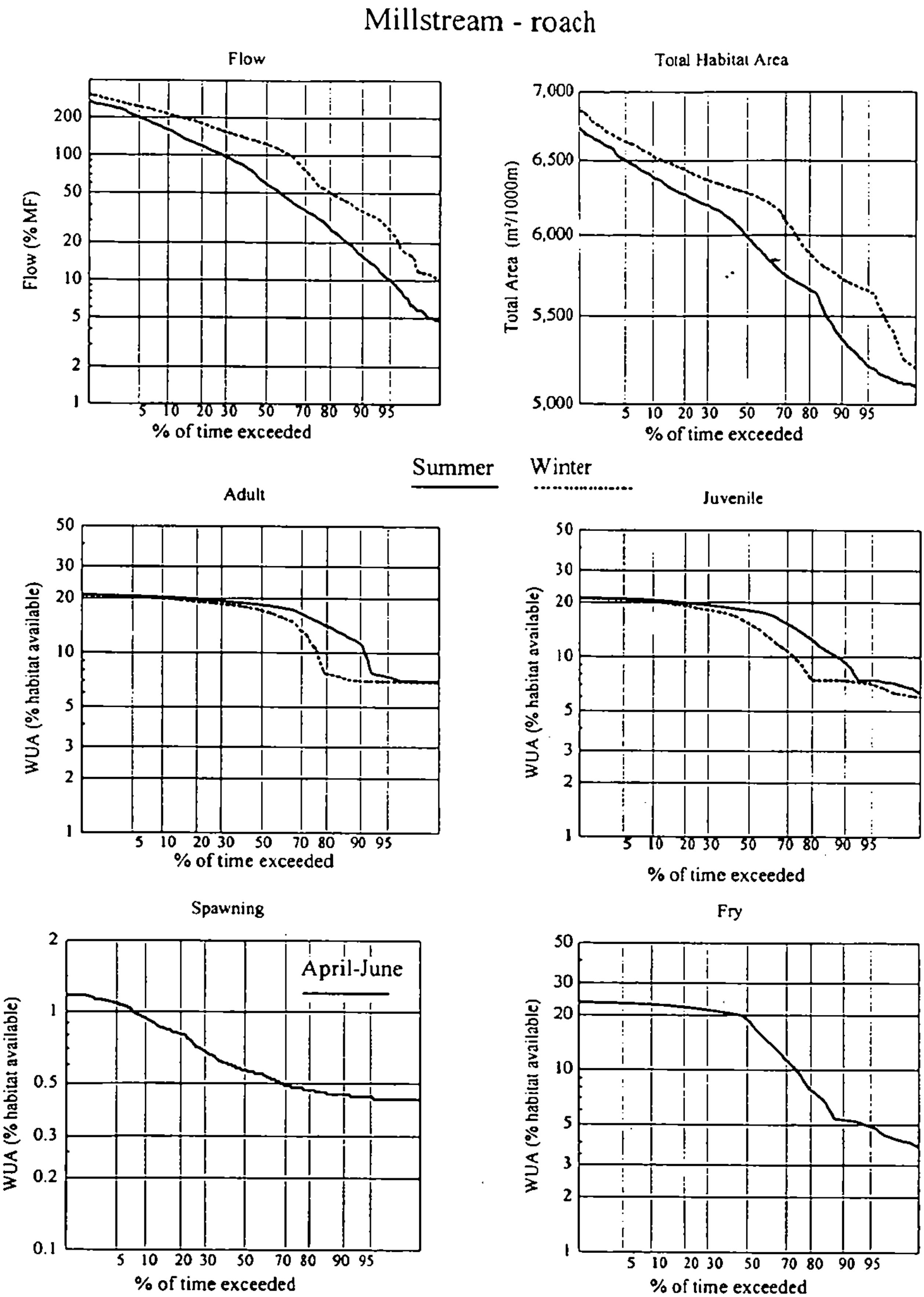

Figure C6.7. *Millstream: habitat duration curves for roach using 16 years of daily mean flow data (1966-1981)*

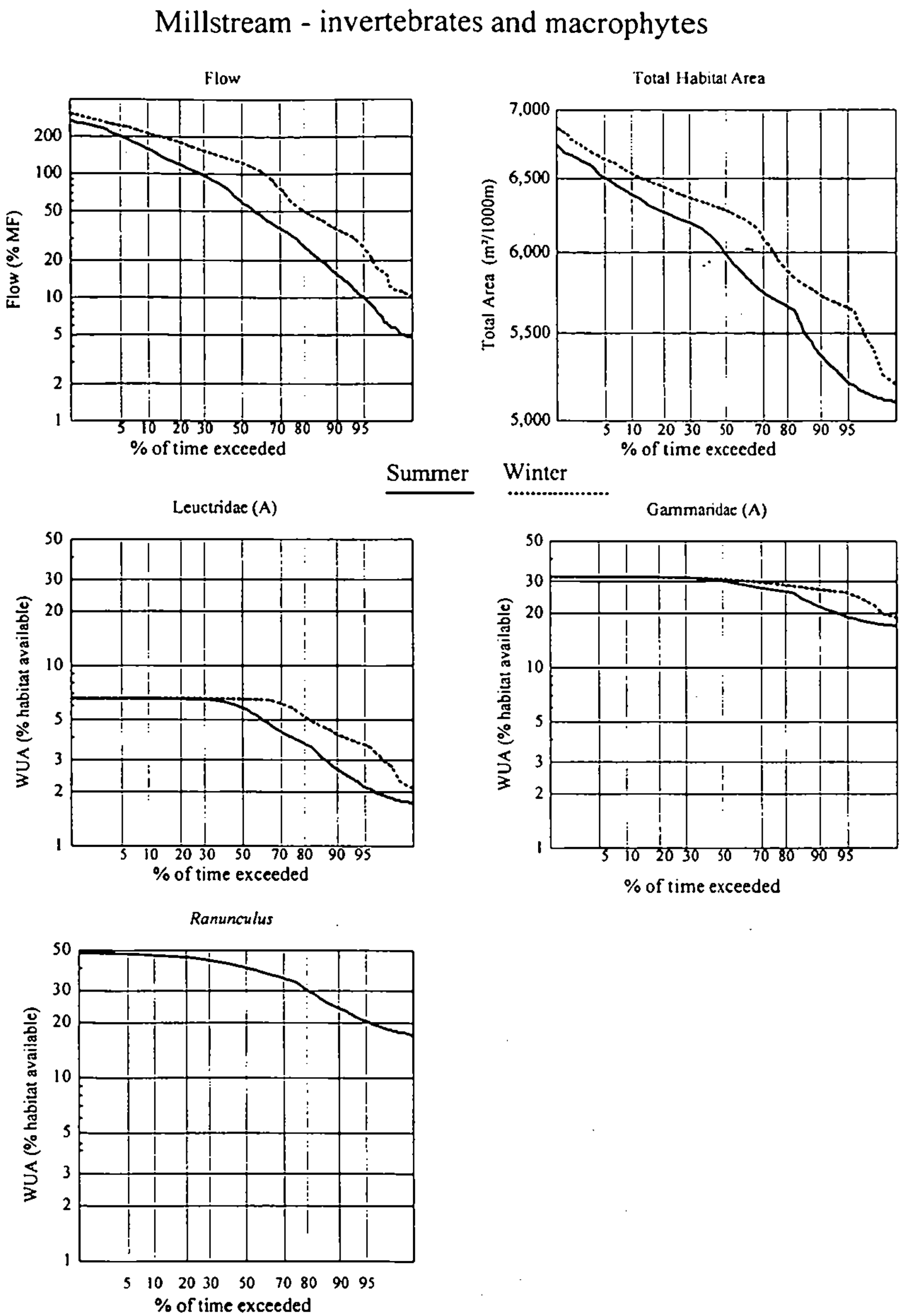

Figure C6.8. *Millstream: habitat duration curves using 16 years of daily mean flow data (1966-1981)*

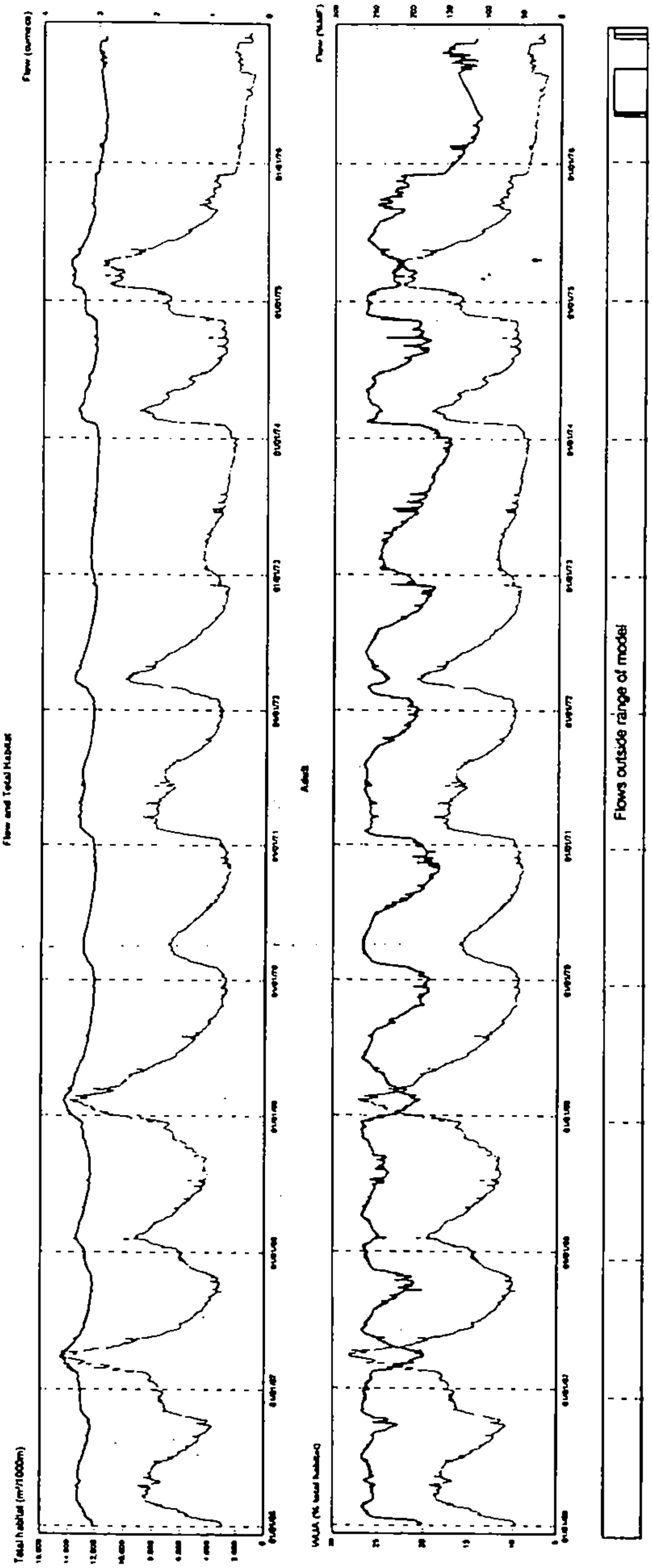

Figure C7.1. River Lambourn: total habitat and flow, habitat time series for adult brown trout

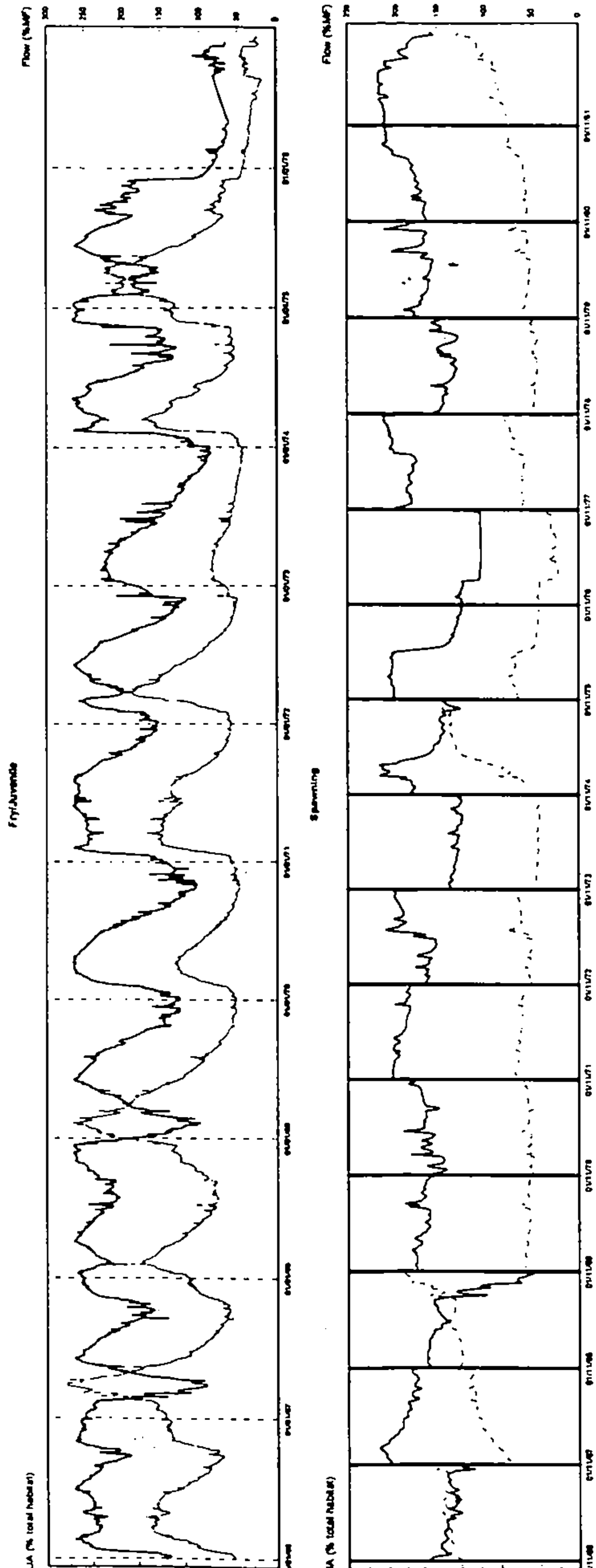

Figure C7.2. River Lambourn: habitat time series for brown trout (fry / juvenile & spawning)

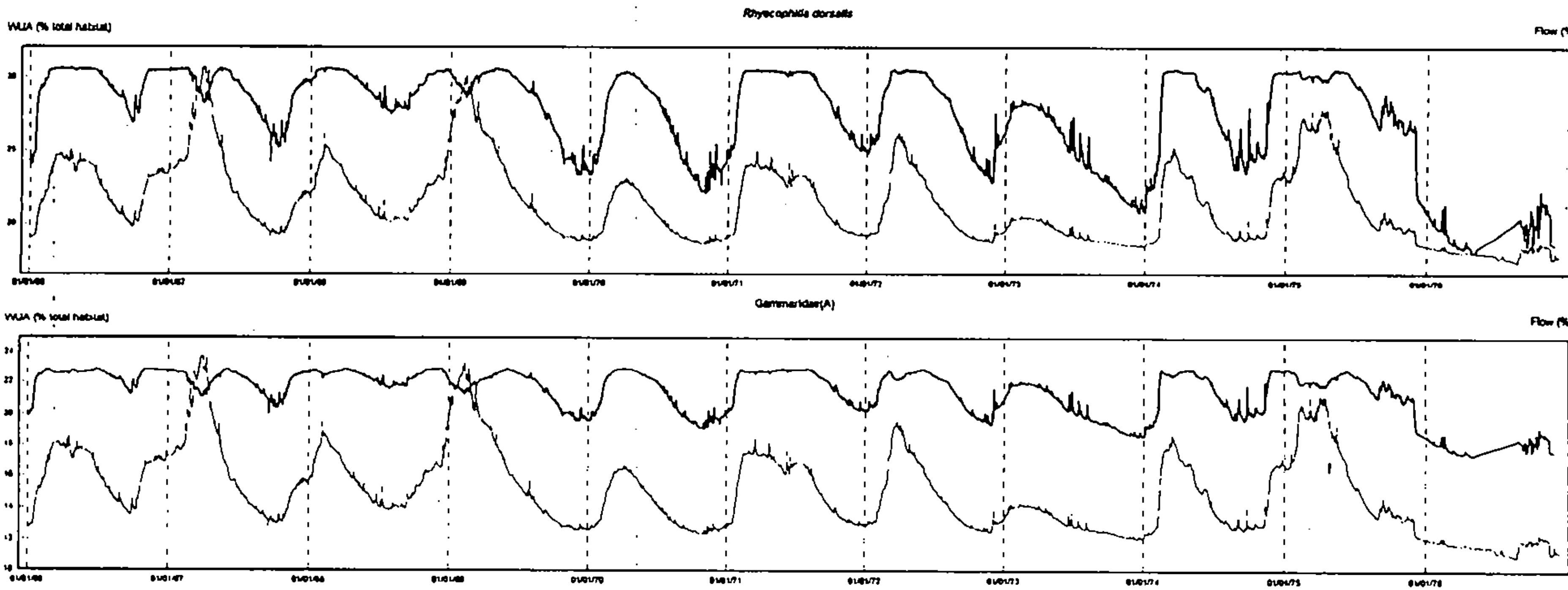

Figure C7.3. River Lambourn: habitat time series for two genera of invertebrates

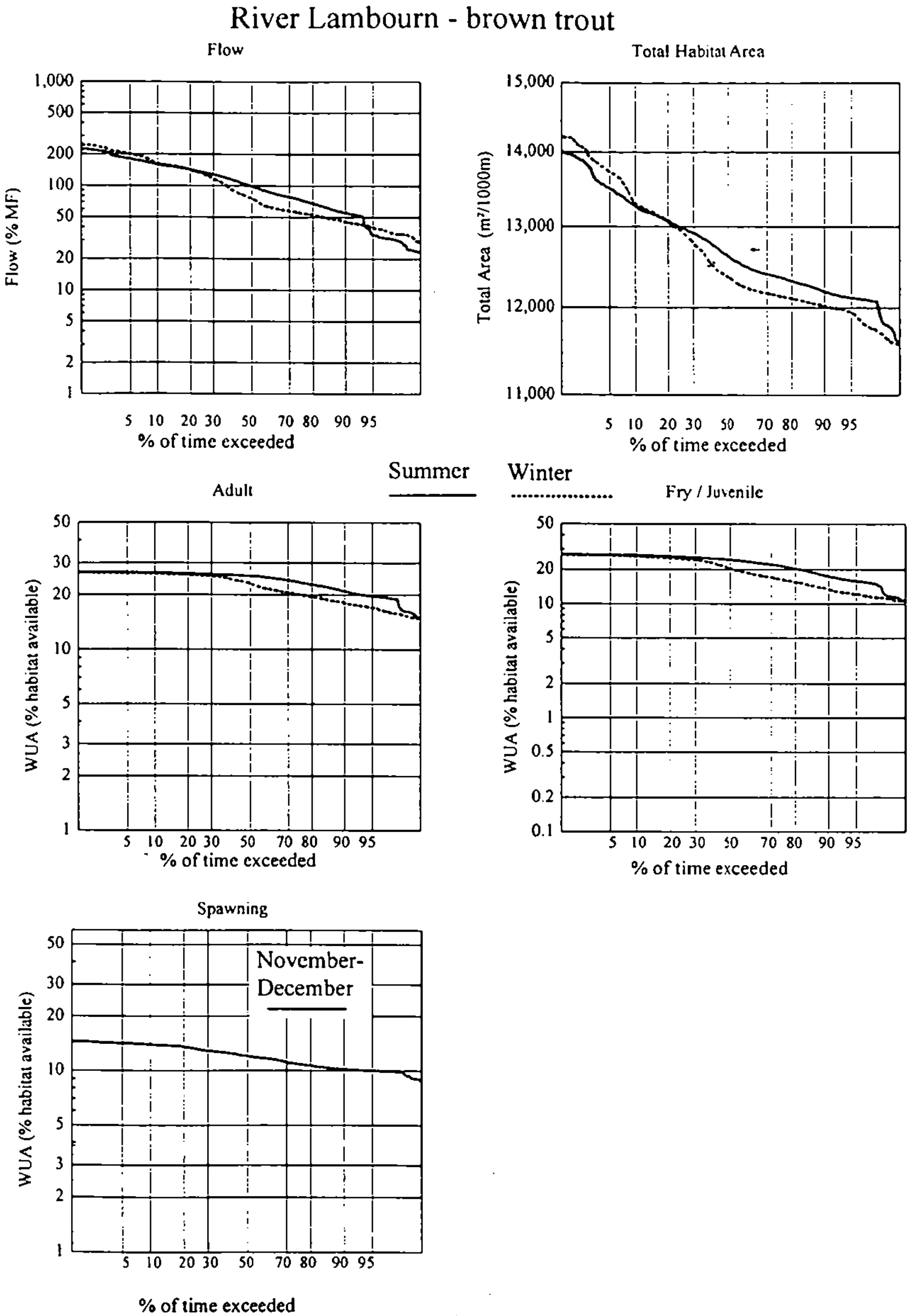

Figure C7.4. *River Lambourn, habitat duration curves for brown trout using 16 years of daily mean flow data (1966-1981)*

River Lambourn - invertebrates and macrophytes

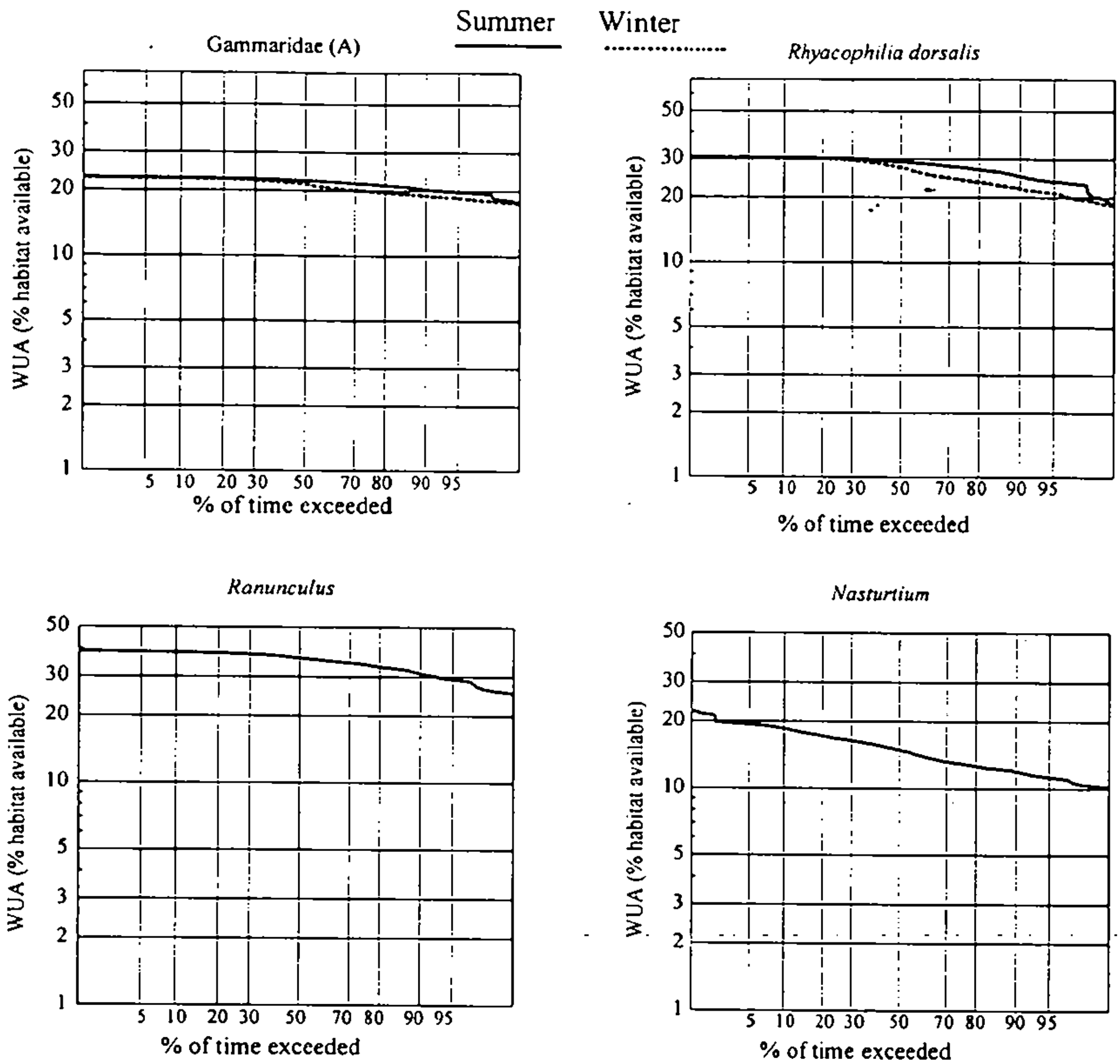

Figure C7.5. *River Lambourn, habitat duration curves for invertebrates and macrophytes using 16 years of daily mean flow data (1966-1981)*

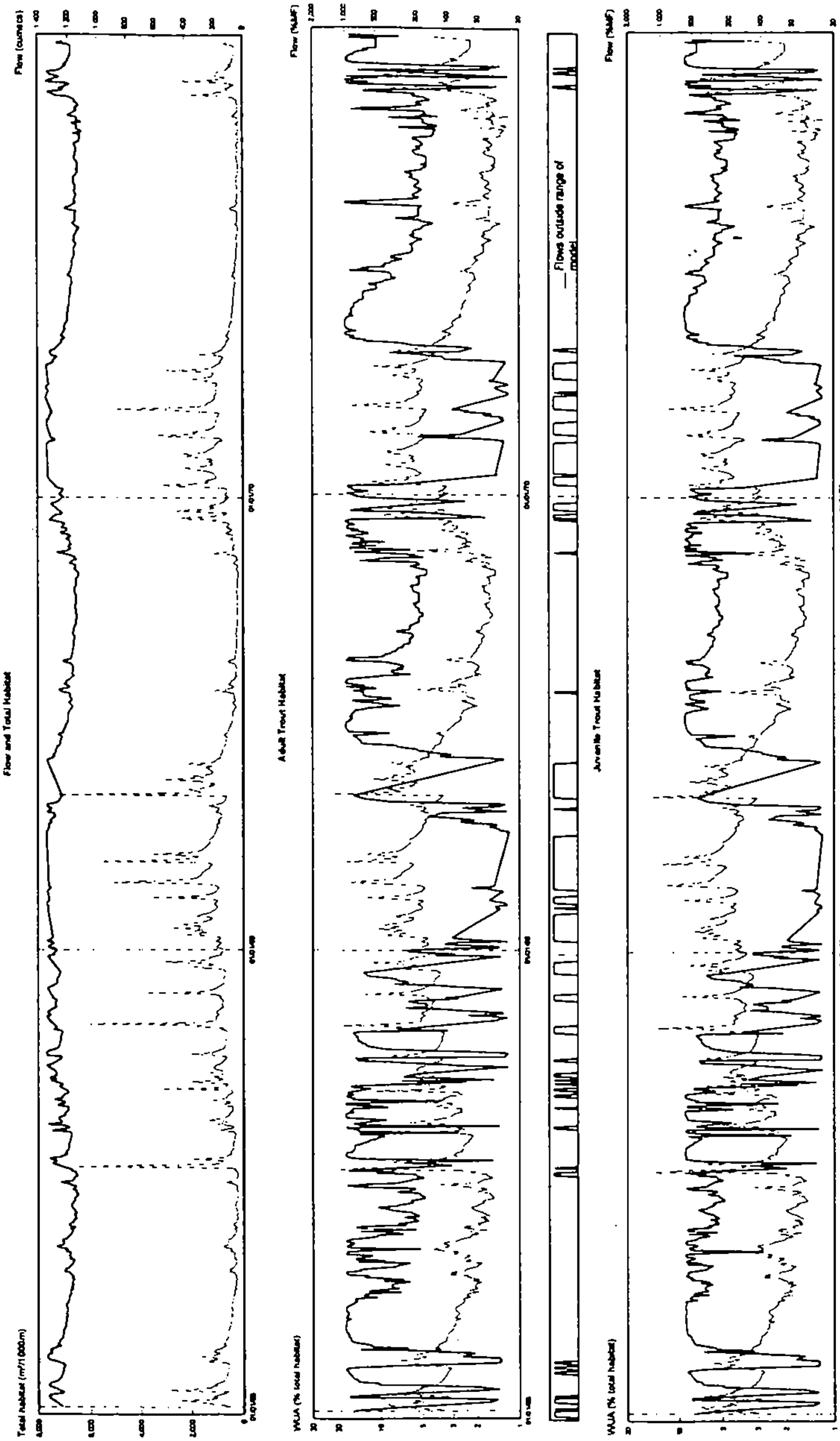

Figure C8.1. River Gwash at Belmesthorpe. Total habitat and flow. Habitat time series for brown trout (adult, juvenile)

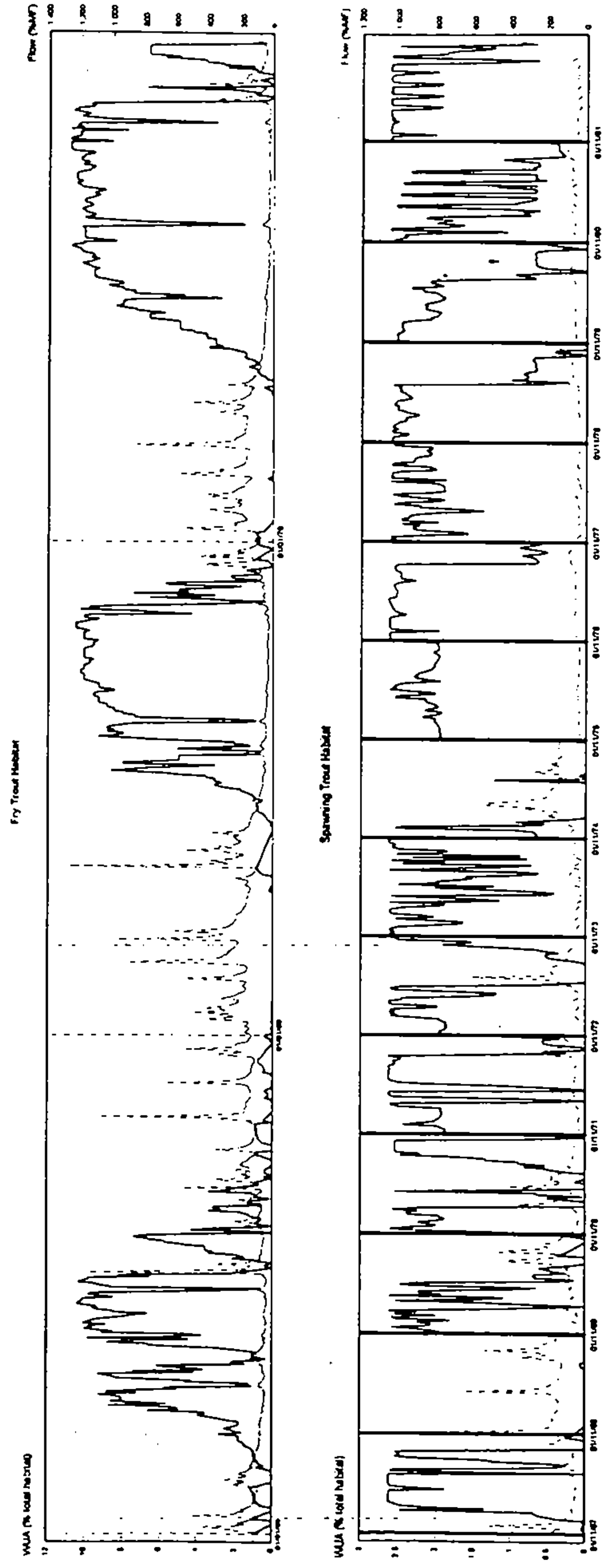

Figure C8.2. *River Gwash at Belmesthorpe. Total habitat and flow. Habitat time series for brown trout (fry, spawning)*

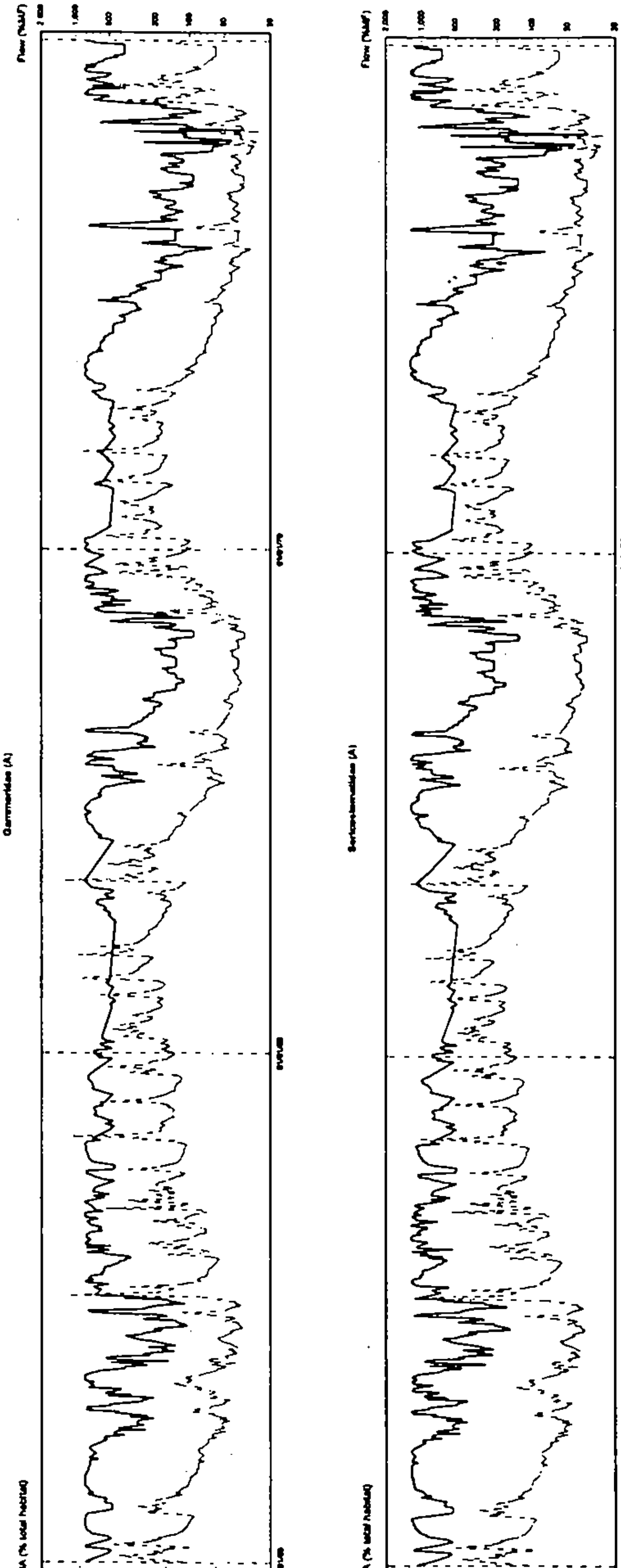

Figure C8.3. River Gwash at Belmesthorpe: total habitat and flow, habitat time series for invertebrates

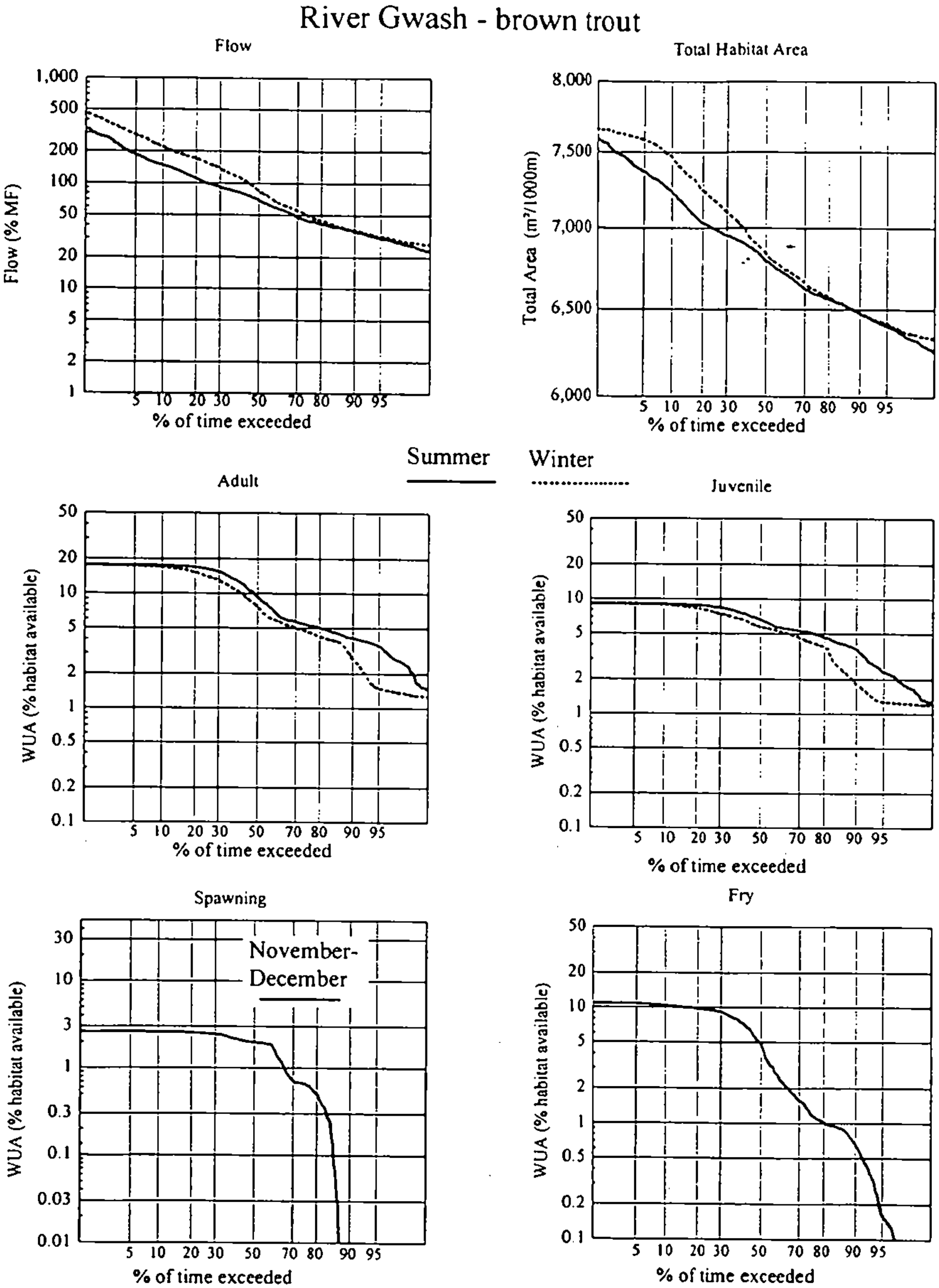

Figure C8.4. River Gwash: habitat duration curves using 16 years of daily mean flow data (1966-1981)

River Gwash - invertebrates and macrophytes

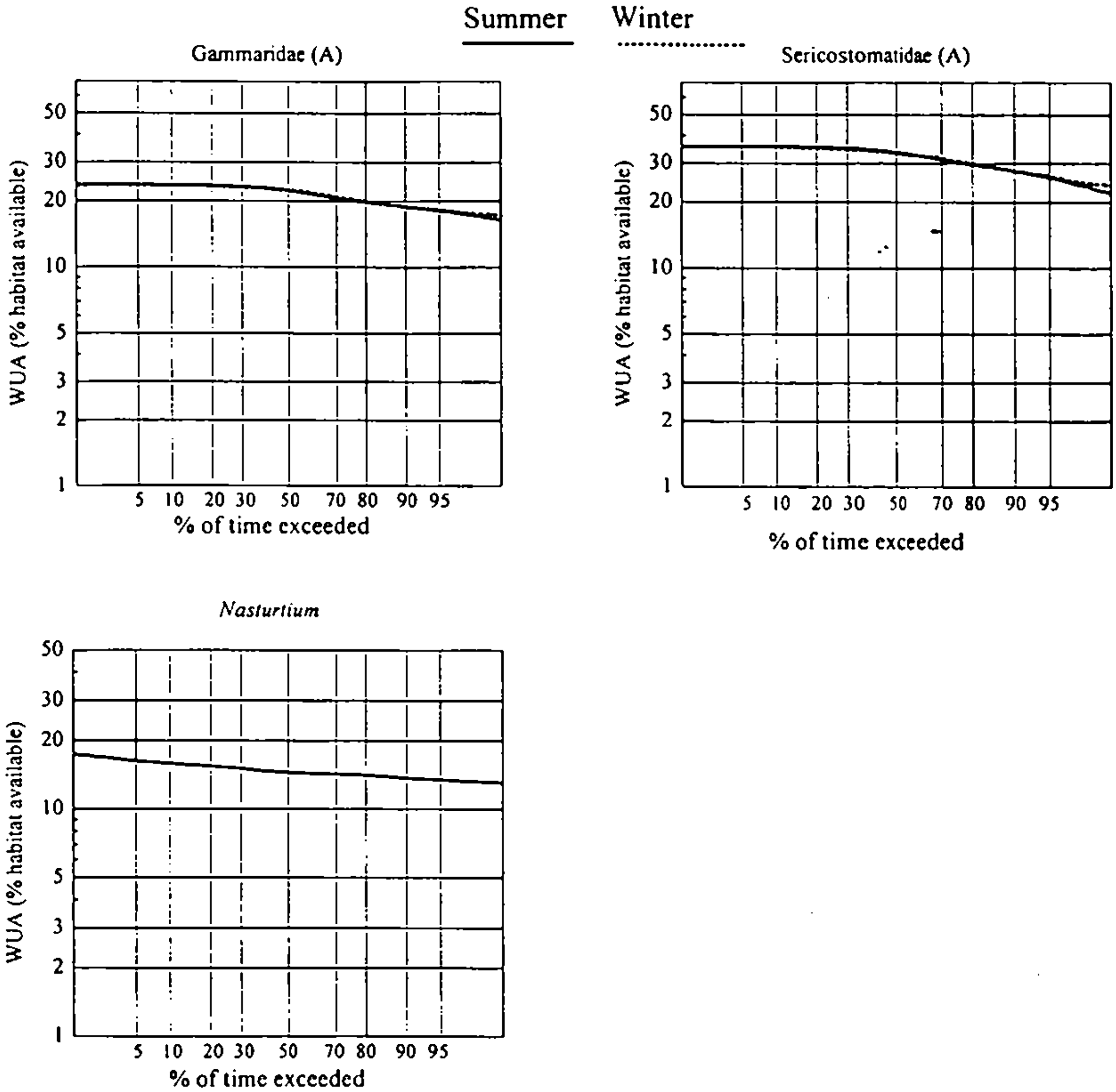

Figure C8.5. River Gwash: habitat duration curves for invertebrates and macrophytes using 16 years of daily mean flow data (1966-1981)

APPENDIX D. FURTHER ANALYSIS: MISSING VALUES, ADDING FLOW TO A HABITAT DURATION CURVE, SINGLE-YEAR DURATION CURVES AND FLOW & HABITAT SPELL ANALYSIS

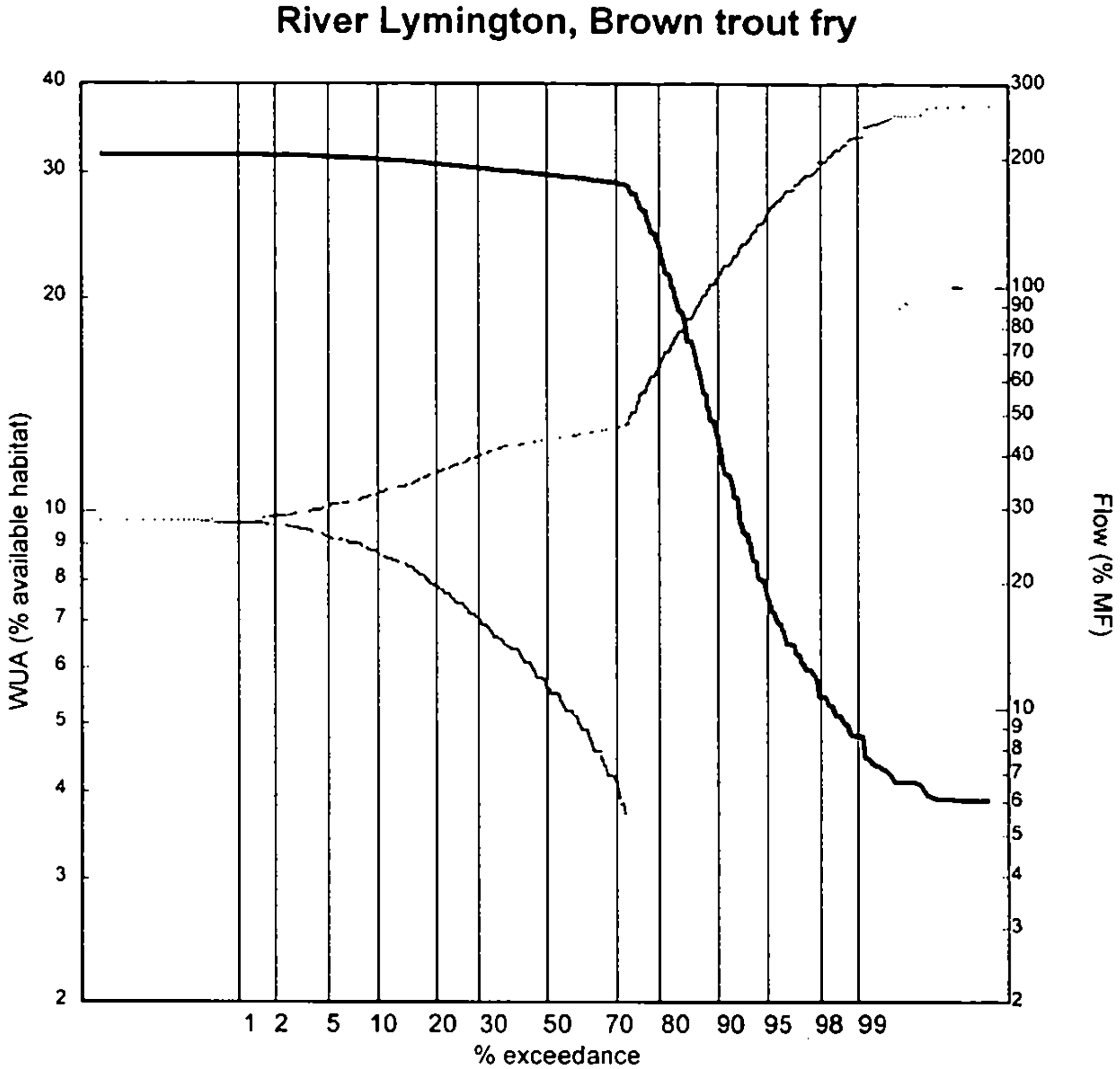

Figure D.1a. River Lymington: habitat duration curve with flows corresponding to habitat also plotted Note that this does NOT show flow exceedance percentiles.

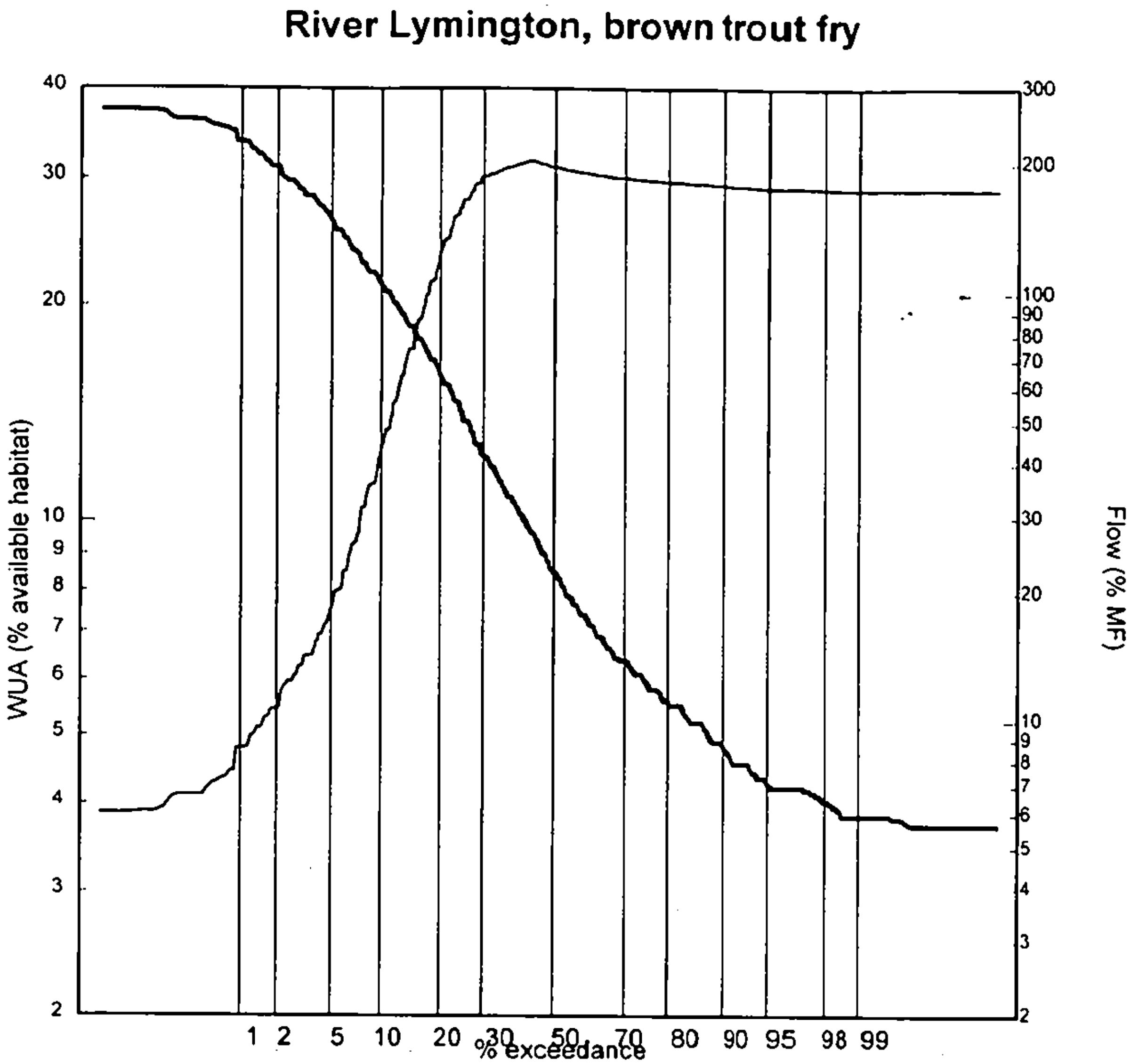

Figure D.1b. *River Lymington: flow duration curve with corresponding habitat values for brown trout fry*

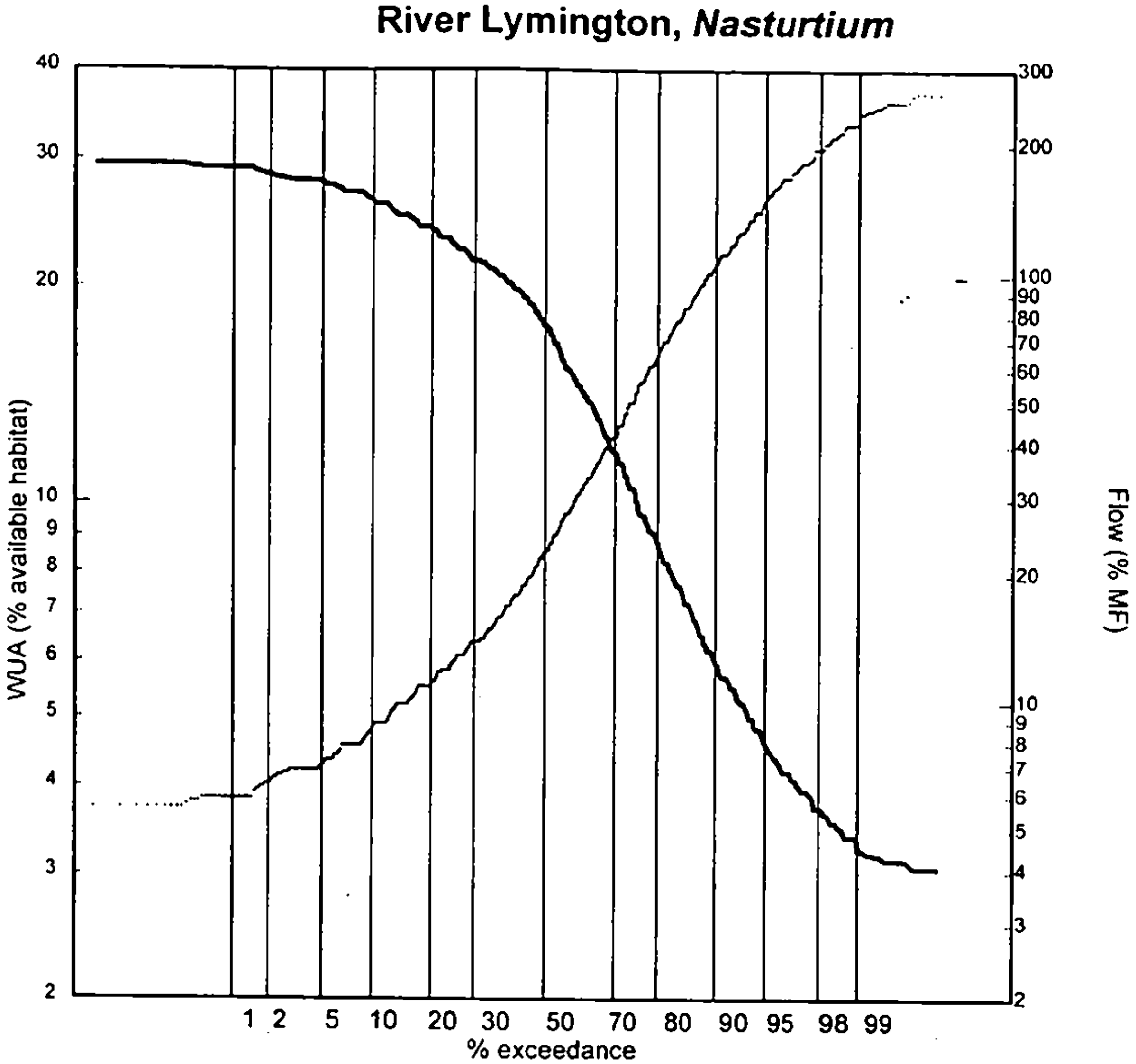

Figure D.2a. River Lymington: habitat duration curve with corresponding flows for Nasturtium Note that this shows habitat, exceedance percentiles, not flow exceedance percentiles.

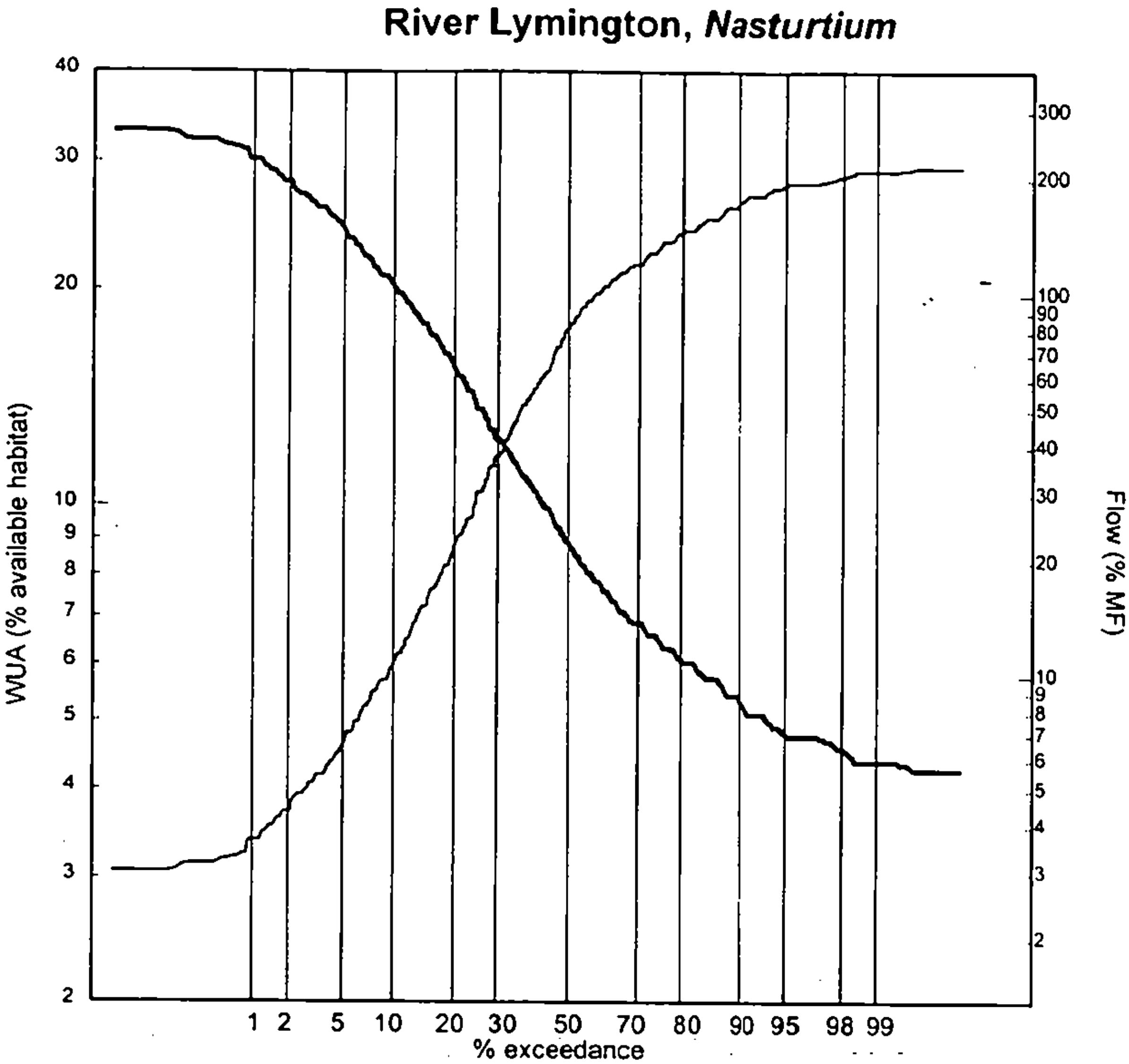

Figure D.2b. River Lymington: flow duration curve with corresponding habitat values for Nasturtium

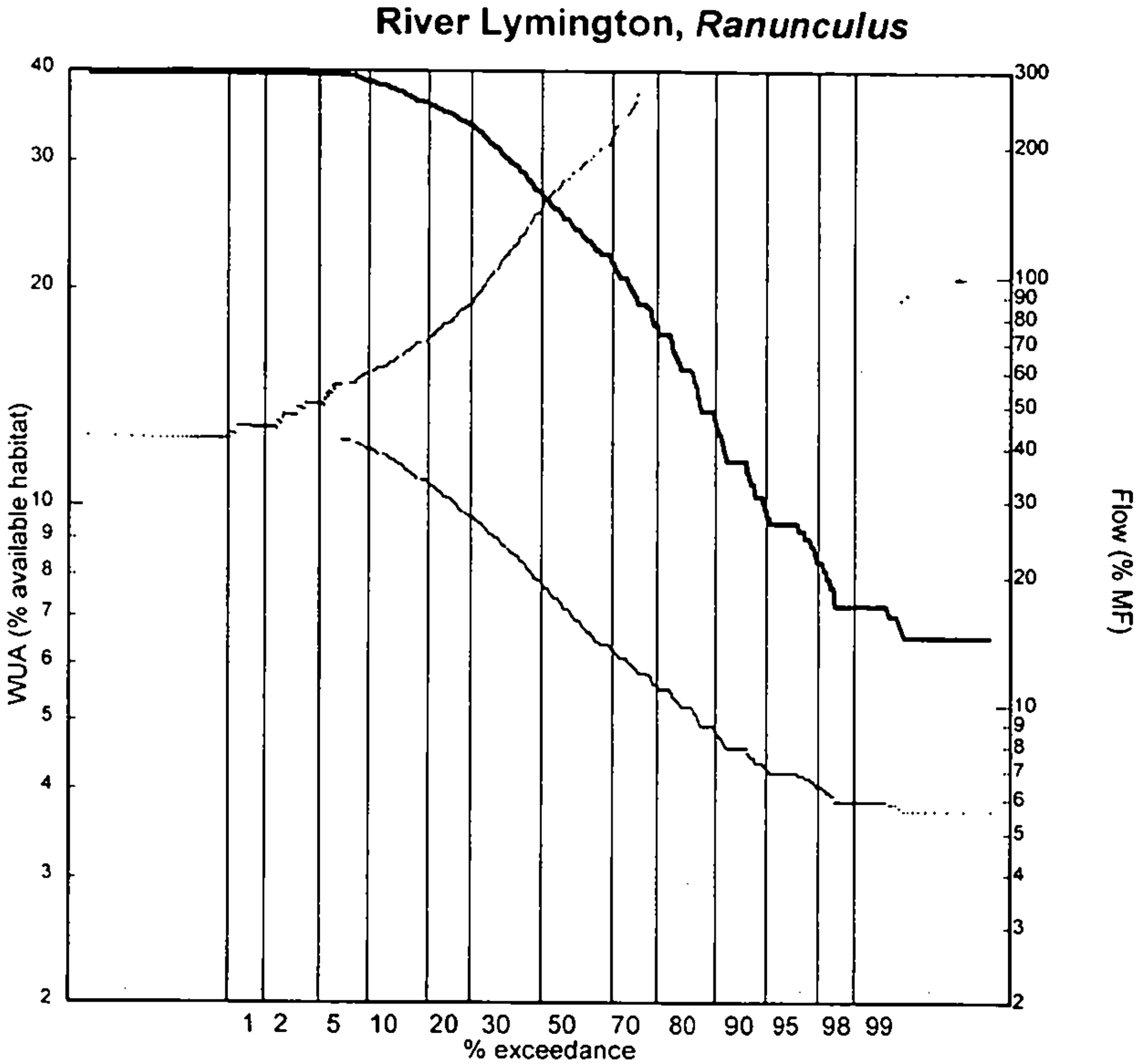

Figure D.3. River Lymington: habitat duration curve with corresponding flows for Ranunculus Note that this shows habitat exceedance percentiles, not flow exceedance percentiles.

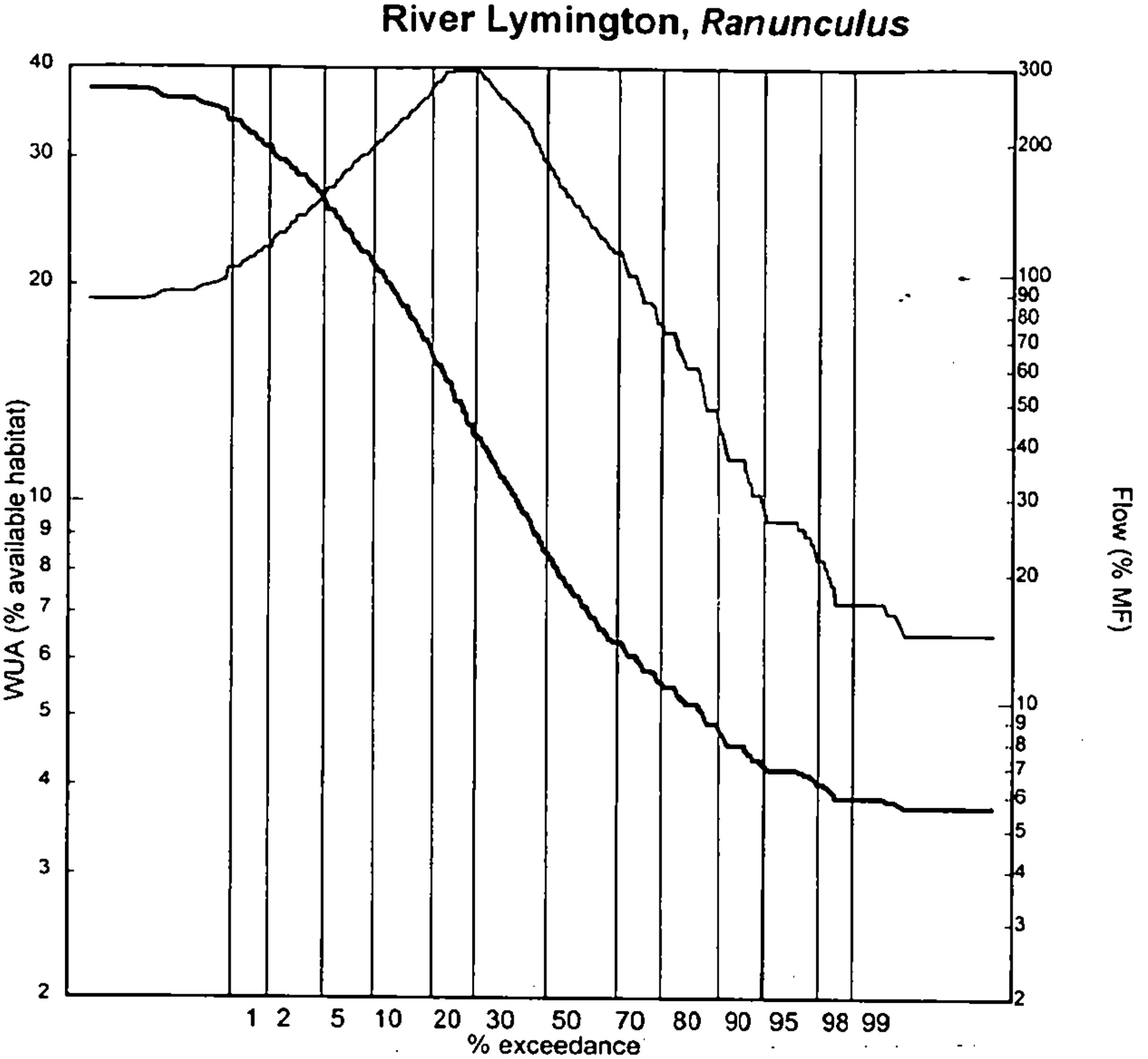

Figure D.3b. River Lymington: flow duration curve with corresponding habitat values for Ranunculus

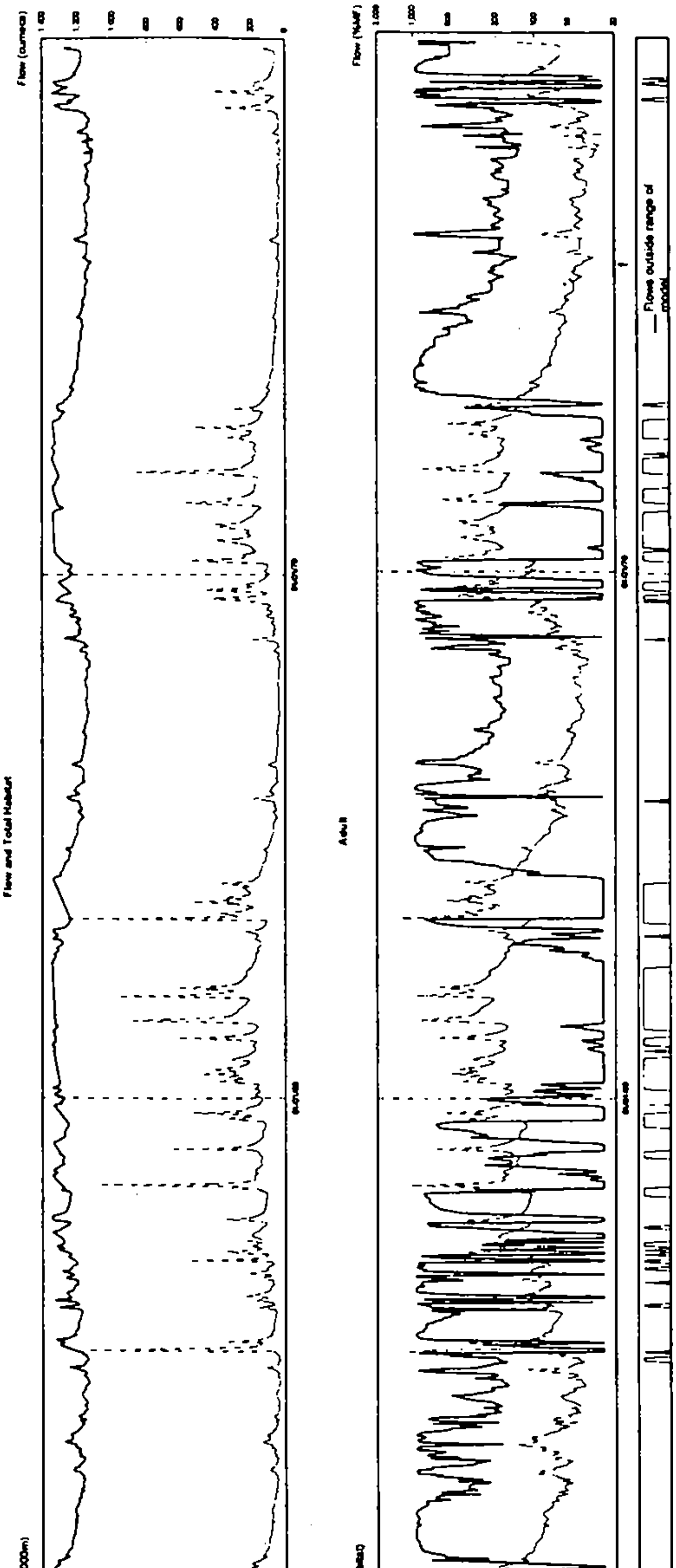

Figure D.4. River Gwash at Belmesthorpe. Total habitat and flow. Habitat time series for brown trout (adult)
Values outside range of model are taken as the values at the limits of the model

Summer Winter

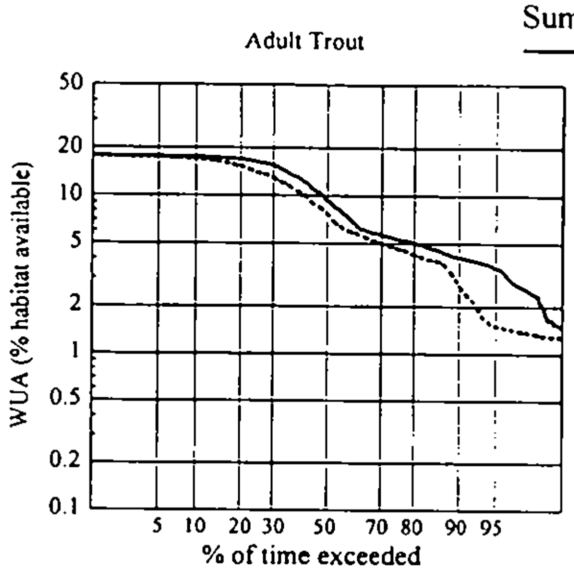

Figure D5.1. This chart created by ignoring missing values

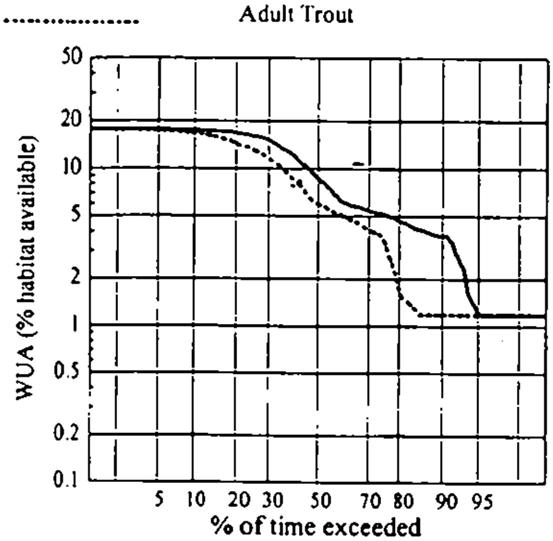

Figure D5.2. This chart created by setting all WUA values corresponding to flows outside range of the model to the WUAs at the respective limits of the model

Figure D5. River Gwash: duration curves for adult trout, examining effects of missing values

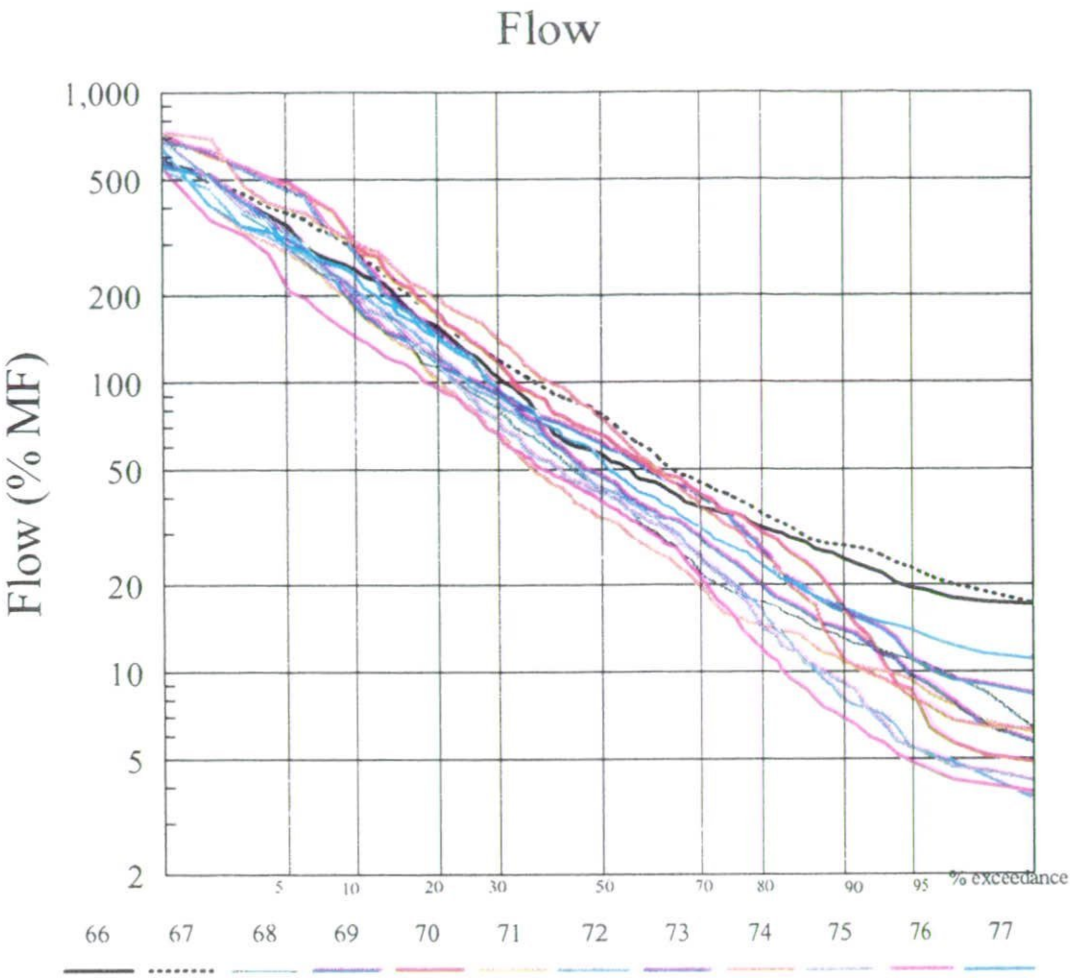

Figure D6. *River Wye Yearly flow duration curves*

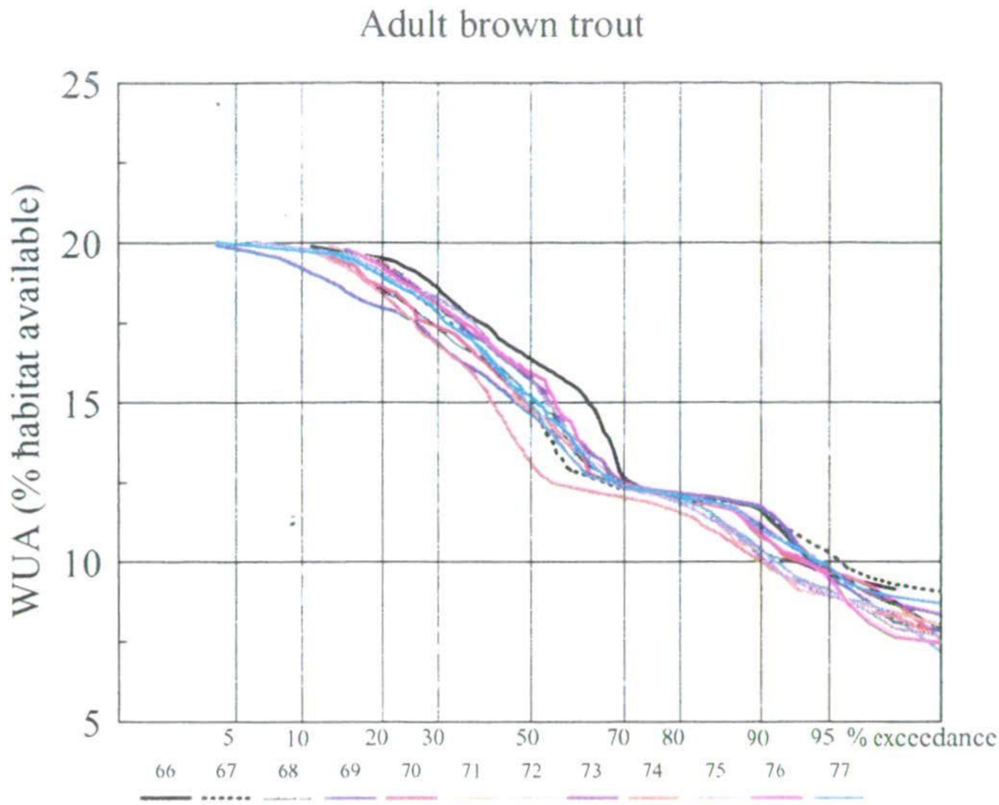

Figure D7. *River Wye Yearly habitat duration curves*

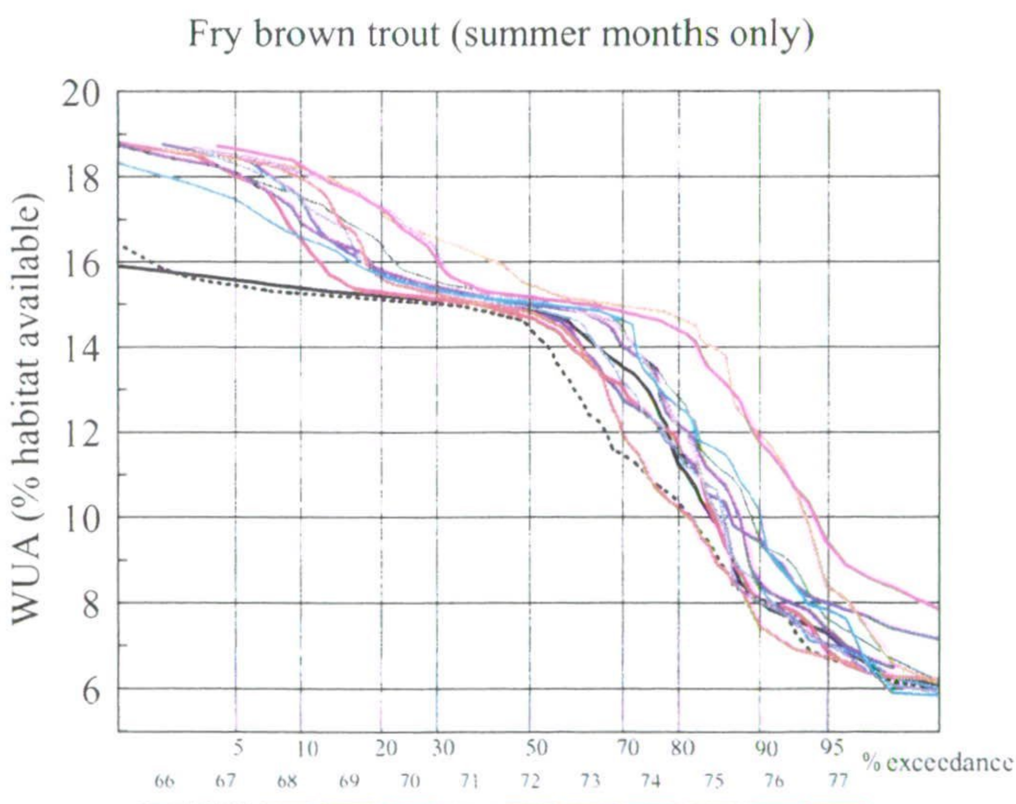

Figure D8. *River Wye Yearly habitat duration curves*

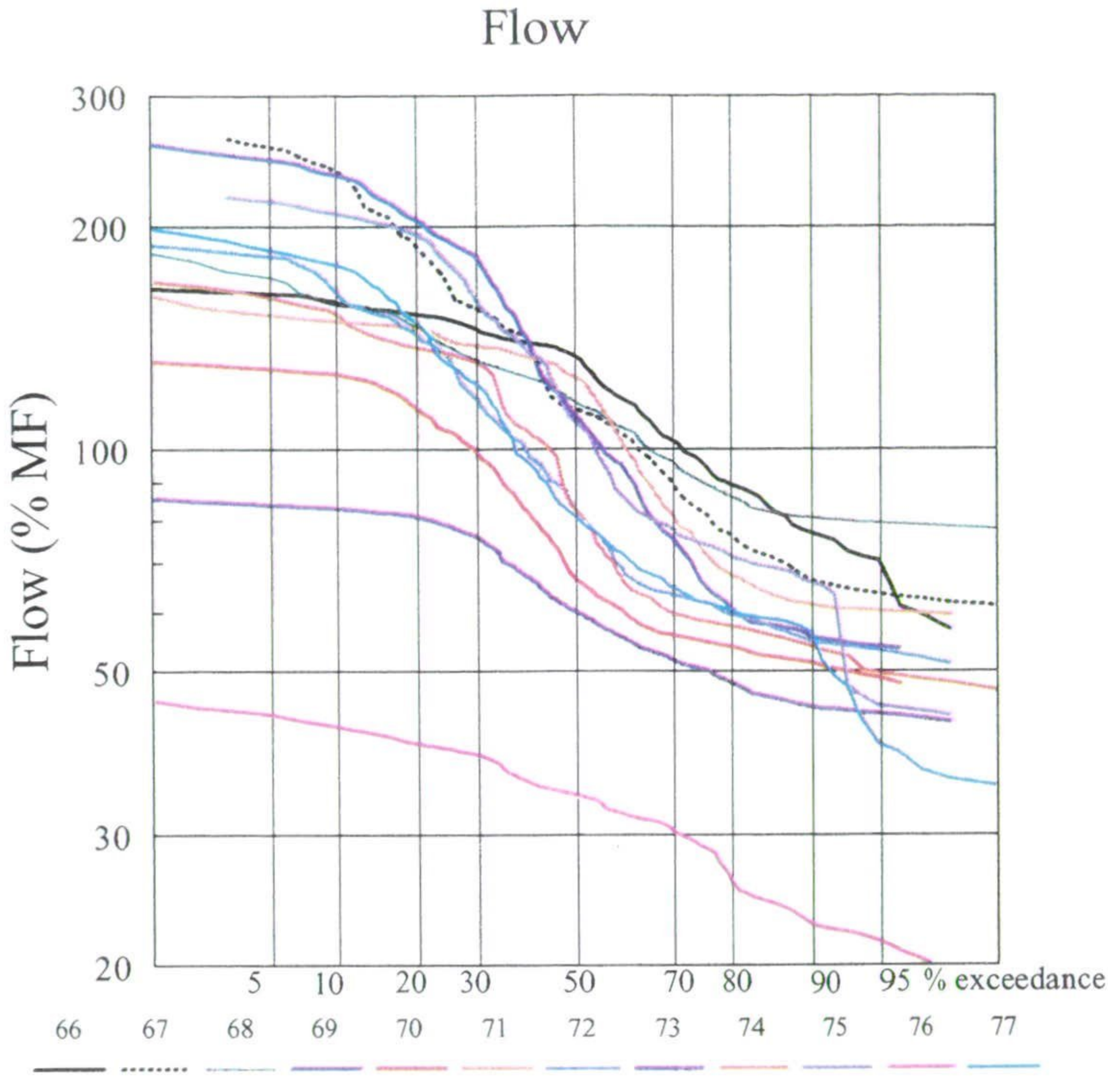

__Figure D9.__ River Lambourn: yearly flow duration curves

Figure D10. *River Lambourn: yearly habitat duration curves*

Figure D11. *River Lambourn: yearly habitat duration curves*

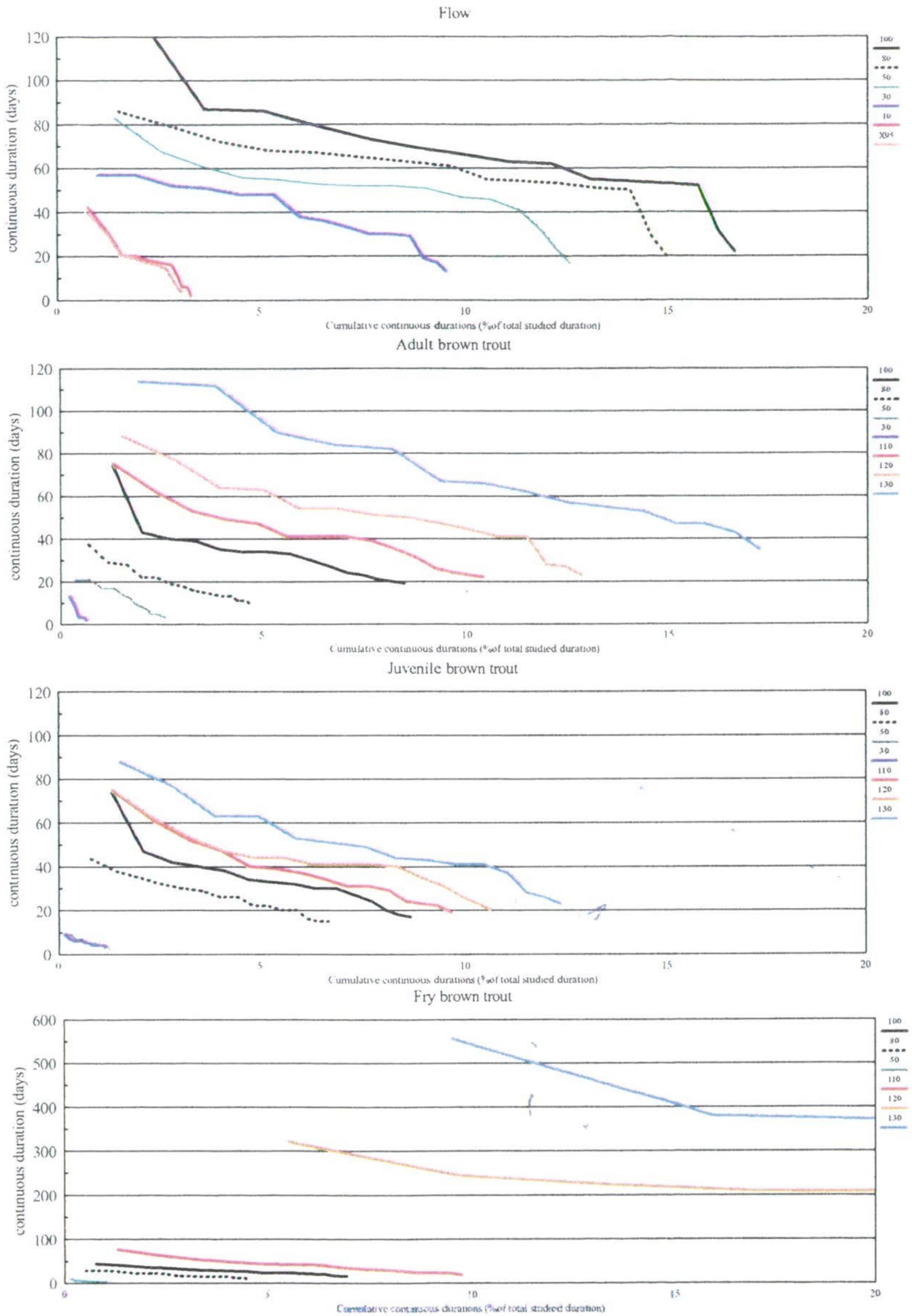

Figure D12. River Wye. Flow spell analysis of 16 years of daily flow / habitat data

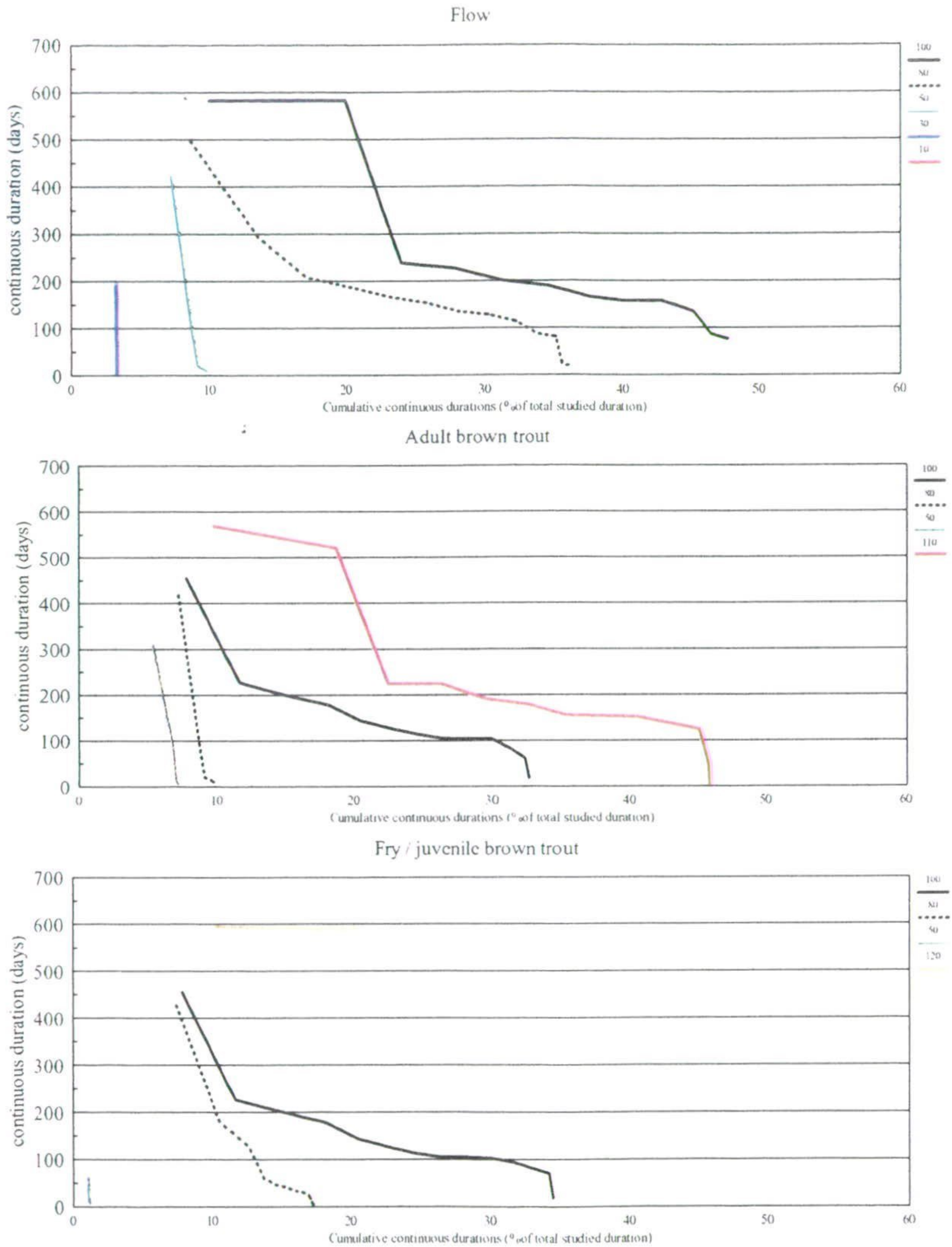

Figure D13. River Lambourn: flow spell analysis of 16 years of daily flow / habitat data