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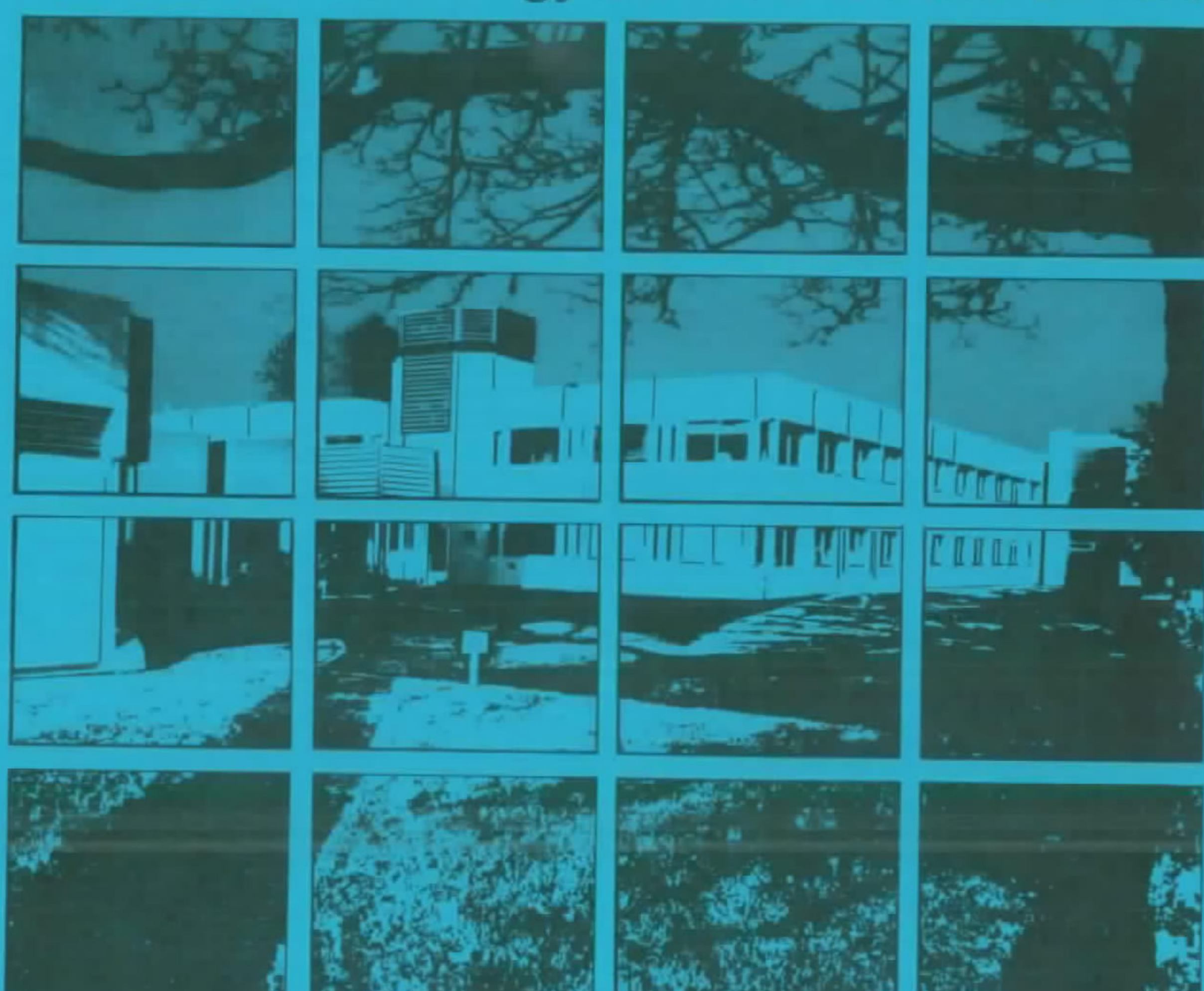
Instream Flow Requirements of Aquatic Ecology in Two British Rivers



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Instream Flow Requirements of Aquatic Ecology in Two British Rivers

Application and assessment of the Instream Flow Incremental Methodology using the PHABSIM system

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with contributions on

"Habitat preferences of target species for application in PHABSIM testing" by Armitage, P.D. and Ladle, M., Institute of Freshwater Ecology

and

"Habitat preference of river water-crowfoot (Ranunculus fluitans Lam.) for application in PHABSIM testing" by Mountford, O. and Gomes, N., Institute of Terrestrial Ecology.

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Preface

This report describes the application and assessment of the Instream Flow Incremental Methodology using the Physical Habitat Simulation system in two British rivers. The project was carried out by a collaborative research group headed by the Institute of Hydrology involving the Institute of Freshwater Ecology, the Institute of Terrestrial Ecology and Loughborough University. The work was commissioned by the Department of the Environment through Mr C. E. Wright of the Water Directorate under research contract No. PE.CD/7/7/210, which also includes *IH Report No. 107*, 'Impact of climatic variability and change on river flow regimes in the UK' and *IH Report No. 108*, 'Low flow estimation in the UK'. The opinions expressed are those of the authors and are not necessarily those of the Department. It is not an objective of this report to recommend flow regimes for the selected sites on the rivers Blithe and Gwash, nor to reassess the compensation flows from the Blithfield Reservoir or Rutland Water schemes.

Acknowledgements

The authors would like to thank the following contributors to the work which underpins this report: the Aquatic Systems Branch of the United States Fish and Wildlife Service in Fort Collins, Colorado who developed the Instream Flow Incremental Methodology and offered training and constructive advice in its application; Professor Geoff Petts of the Department of Geography at Loughborough University of Technology, for advice on reach selection, equipment provision and scientific issues and to Dave Forrow who contributed significantly to data collection; Patrick Armitage and Mike Ladle of the Institute of Freshwater Ecology at Wareham who undertook the construction of habitat suitability curves for fish and macroinvertebrate species; Owen Mountford and Noelle Gomes of the Institute of Terrestrial Ecology at Monks Wood, who contributed habitat suitability curves for river water-crowfoot and to the additional staff from Monks Wood who contributed to data collection, including Nick Greatorex-Davies, Tina Yates, Tim Parish, Dave Myhill, Elspeth Leeson, Catherine Haynes, Stuart Green, Sean Edwards and Amanda Carlin; Jon Bass of the Eastern Rivers Group of the Institute of Freshwater Ecology for advice on invertebrate sampling; staff of the Institute of Hydrology, particularly Rob Brown for his involvement at many stages of the project, Julia Dixon who assisted with data processing, and Sandra Smith who typed the manuscript. The authors and fieldstaff appreciate the access and cooperation granted by the landowners at the six study reaches.

Abstract

The Instream Flow Incremental Methodology (IFIM) allows the quantification of ecological species preferences for the range of discharges within a river. This is achieved on the basis that species exhibit preferences for certain habitat types, represented by physical variables, which vary with discharge. The relationship between physical habitat and river flow permits the negotiation and setting of flow regimes optimal for ecological management. Given a growing awareness of the need for ecologically-sound water management in Britain, this report is aimed at the application and assessment of IFIM under British conditions. Application of IFIM is on two rivers, the Gwash in Leicestershire/Lincolnshire and the Blithe in Staffordshire, with the objectives of gaining experience in IFIM, assessing the Physical Habitat Simulation (PHABSIM) component of IFIM, modelling the impact of reservoir construction upon aquatic ecology and to establish a long-term research programme to develop techniques for recommending ecologically acceptable flows. The report presents a review of the IFIM rationale and concepts, hydraulic and habitat data requirements of PHABSIM, the theory of the three hydraulic simulation routines IFG4, MANSQ and WSP, microhabitat suitability criteria and calculation of Weighted Usable Area. Application of IFIM at five reaches on the two rivers is discussed in terms of the collection of hydraulic data and of ecological data which comprise habitat preference curves for eight species of fish (brown trout, grayling, dace, chub, roach, bream, pike and perch), five species of macroinvertebrates (*Leuctra fusca, Isoperla grammatica, Rhyacophila dorsalis, Polycentropus flavomaculatus and Sphaerium corneum*) and one aquatic macrophyte (*Ranunculus fluitans* Lam.). Results of physical habitat simulations are presented as Weighted Usable Area against discharge relationships for each reach, and as Weighted Usable Area duration curves incorporating pre- and post-impoundment flow regimes at two sites for two species. Preliminary recommendations are made for future calibration and simulation of PHABSIM and a framework is proposed for research initiatives to further the development of IFIM in British rivers. The potential of habitat versus discharge relationships from IFIM for setting prescribed flows, reviewing compensation releases from impounding reservoirs and other ecologically acceptable flow regimes is clearly demonstrated by this investigation.

Executive Summary

Water use is generally divided into two primary classes - offstream use and instream use. Instream uses, which generally do not diminish the flow downstream of the point of use, include hydro-electric power generation, navigation, pollution dilution and biological, recreational and aesthetic requirements. The key tool in the management of instream water for the more traditional economic uses in the United Kingdom has been the prescribed flow, often based on the concept of the Dry Weather Flow. The concept of the Dry Weather Flow encompasses the setting of a fixed discharge, often a low flow statistic, at a maintained flow point. For biological uses a fixed discharge statistic, and the context in which the statistic is set, pays little cognisance to the instream flow requirements of biological species. It has long been demonstrated that ecological species exhibit preferences for certain habitat types. However, while quantitative models and design techniques are available for estimating discharge statistics in British rivers, there is a paucity of operational tools for managing aquatic communities in British rivers at a national scale. In this regard water management in this country lags behind the United States in the development of appropriate management models for recommending flow regimes which consider ecological demands.

Since 1974, development of the Instream Flow Incremental Methodology (IFIM) by the Aquatic Systems Branch of the U.S. Fish and Wildlife Service has allowed the quantification of species preferences for the full range of discharges that may be experienced within a river. This quantification of habitat preferences and the relationship with river flow permits the negotiation and setting of flow regimes optimal for ecological management, paying specific regard to the physical habitat requirements of selected target species. The Methodology has received wide international recognition and is the standard method for determining flow requirements below major water resource schemes in 38 states of the U.S. Given a growing awareness of the need for ecologically-sound water management in Britain, the immediate need is for the application and assessment of IFIM under British conditions. This report presents the results of the application of IFIM on two rivers, aimed at gaining experience in IFIM, assessing the validity of the modelling approach and developing an interface between engineering hydrologists and fisheries staff.

The principal aims of this study are:

* to gain experience in the use of the Instream Flow Incremental Methodology (IFIM), a technique developed for recommending flow regimes in the United States, on at least two British rivers;

* to assess the Physical Habitat Simulation (PHABSIM) component of IFIM and its applicability for British rivers;

* to assess the suitability of IFIM for quantifying the impact of changing compensation flows upon aquatic ecology below at least one upland and one lowland reservoir;

* to establish a long-term research programme to develop techniques for recommending flow regimes based upon the requirements of aquatic ecology.

Essentially, IFIM provides an estimate of habitat loss/gain with changes in discharge. IFIM itself is a concept, or a set of ideas, of which the fundamental basis is that aquatic species exhibit a describable and quantifiable preference for one or more of the physical habitat variables; velocity, depth, channel substrate or cover. This preference for each variable by a species is represented by an index of suitability, which can take the form of a binary function or univariate curve. A major component of IFIM is the Physical HABitat SIMulation (PHABSIM) system, a suite of computer programs aimed at combining simulated values of velocity and depth in a channel reach with the habitat suitability indices. Simulation of the physical variables is achieved by using any of three hydraulic simulation routines. Calibration of the hydraulic models is on a transect-defined cell-by-cell basis requiring field observation of channel cross-sectional profiles, water surface elevation, mean column velocity and application of substrate and cover classification schemes. Depth predictions across the transects at a range of flows can be based on stage-discharge relationships, the solution of Mannings equation or a step backwater model according to data availability and complexity. Velocities are predicted on a cell-by-cell basis by solution of Mannings equation. Cell values of each of the physical variables are combined with species-specific (and life-stage specific) preference curve information through a selected functional relationship to weight the total usable available habitat by its suitability for that species life-stage. Simulations at a range of discharge generate a Weighted Usable Area against discharge relationship. Optimal discharges for specific species can be identified from these habitat versus flow relationships, providing an estimate of habitat loss/gain with changes in discharge.

Selection of sites for IFIM application in two British rivers was determined by a requirement for the combined availability of pre- and post-reservoir impoundment river flow data and ecological data. The river Blithe below Blithefield Reservoir in Staffordshire and the river Gwash below Rutland Water in Leicestershire/Lincolnshire were selected as appropriate sites, each possessing long series of gauged river flow data on the Surface Water Archive, the Blithe being a biological sampling site in the River Communities Project and the Gwash in an Institute of Freshwater Ecology lowland reservoir data set. On each river three sites were selected in the vicinity of the reservoirs for field measurement of hydraulic data for PHABSIM calibration; Blithe Bridge, Blithe Dam, and Hamstall Ridware on the river Blithe, and Empingham, Ryhall and Belmesthorpe on the river Gwash. Each reach is represented by between 15 and 20 transects and each transect by around 30 cells. Up to 3 calibration flows were observed at each reach, involving observation of channel bed elevations, water surface elevations, cell velocities and values of substrate and cover. The development of microhabitat suitability curves for this study was undertaken by the Institute of Freshwater Ecology and the Institute of Terrestrial Ecology. Habitat preference curves were developed for eight species of fish (brown trout, grayling, dace, chub, roach, bream, pike and perch), five macro-invertebrates, *Leuctra fusca, Isoperla grammatica* (both stoneflies), *Rhyacophila dorsalis, Polycentropus flavomaculatus* (both caddis flies) *and Sphaerium corneum* (pea mussel), and one aquatic macrophyte, river water-crowfoot (*Ranunculus fluitans* Lam.). Different preference curves were developed for the adult, juvenile, fry and spawning life stages of the fish species and for the larval stage of the insect invertebrates and the adult stage of the mussel. Using the PHABSIM system, Weighted Usable Area (WUA) against discharge relationships are generated for each life stage of each species at five of the six sites, the assembled data at the Empingham site proving inadequate for model simulations. This report presents the output data in three ways; graphical representations of the WUA against discharge relationships; WUA duration curves for selected species at Blithe Dam and Ryhall; and pre- and post-impoundment duration curves at these two sites. Discussion focusses upon the different forms of WUA relationships with discharge, variations amongst different life stages and species, between sites and upon the impact of reservoir impoundment. It is clear from this report that a flow change which is beneficial to one life stage or species may be detrimental to another, and that more water does not necessarily mean more habitat. It is most definitely not an objective of this report to recommend prescribed flow regimes for the rivers Blithe and Gwash, nor to reassess the compensation flows from Blithefield Reservoir or Rutland Water. Instead, an example from Willow Creek, Idaho is used to illustrate how habitat-discharge relationships are used to recommend a seasonally-varying low flow regime.

The report concludes that the underlying concepts of IFIM can be validly transferred to the United Kingdom and recognises that there is a significant and growing demand for a habitat management model. The report makes specific recommendations on issues pertaining to field calibration, the use of ecological data, and hydraulic simulation routines for the development of the PHABSIM system. Overall, the project was successful in PHABSIM calibration, simulation and the generation of output, which although of a provisional nature, demonstrates that the methodology can be applied in British rivers. It is another issue whether those involved in water management accept the underlying concepts and limitations of the results, for the true assessment of the approach will be the extent to which it is taken up by water resource planners and environmental managers.

To this end, the report proposes a framework for future research initiatives in the development of IFIM in the UK which should include:

* use of appropriate data sets including those assembled during this study to explore the full scope of the PHABSIM system through the range of options available to the user, many of which were not used during this study;

* investigation of the minimum data requirements for calibration of the hydraulic simulation components of PHABSIM based on the sensitivity of output results to the reduction of the amount and type of input data. Work in this sphere has already been undertaken using the data assembled in this report (Petts, 1990);

* a review of substrate and cover classification procedures to develop a standard methodology for use in future IFIM studies in the United Kingdom. This could be best administered within a hierarchical framework of classification schemes based on the demands of a particular instream flow study. The framework must take account of the considerable research already undertaken in the sphere of ecological requirements for substrate and cover;

* collation of relevant data from literature sources and from existing ecological data bases to underpin and refine the derivation of habitat suitability curves. Where possible, and particularly where the available data support it, suitability curves should be upgraded to habitat utilisation and habitat preference curves. Experience should be gained in deriving suitability curves from field sampling techniques;

* consideration of the most appropriate, and most important, target species for future IFIM studies. Judgements should be based upon species importance to river management, conservation, restoration and recreation interests. Identification of a suite of key target species, perhaps with variations in regional application, would impose a sharper focus upon future research programmes;

* calibration of PHABSIM on a wide range of British rivers, ensuring experience of varied hydraulic and geomorphological environments, in order to identify and assess the limitations of the acquired data in simulating physical habitat. Diversity of study rivers will also allow evaluation of the value of the acquired data for the extrapolation to a more regional application.

The provisional application of the Instream Flow Incremental Methodology in this report has suggested the potential of habitat versus discharge relationships for setting prescribed minimum flows, reviewing compensation releases and other instream flow demands. With research developments in the identified areas offering greater ease of application and a more solid ecological foundation, and with the establishment of an appropriate negotiating framework, IFIM could become a standard operational tool for ecological management in British rivers.

Symbols, abbreviations and acronyms

A	Cross-sectional Area
BE	Bed Elevation
BOD	Biological Oxygen Demand
c	Channel index
CF	Conveyance Factor
cfs	Cubic feet per second
CSI	Composite Suitability Index
d	Depth
DWF	Dry weather flow
E	Energy
g	Gravitational acceleration
H	Head loss
HABTAT	Executable program within PHABSIM
IFE	Institute of Freshwater Ecology
IFG4	Instream Flow Group 4 hydraulic simulation routine
IFIM	Instream Flow Incremental Methodology
IH	Institute of Hydrology
ITE	Institute of Terrestrial Ecology
L	Reach length
MAM(7)	Mean Annual Minimum seven day low flow discharge
MANSQ	Mannings Stage Discharge hydraulic simulation routine
mps	metres per second
n	Mannings roughness coefficient
NERC	Natural Environment Research Council
O.S.	Ordnance Survey
P	Fluid pressure
PHABSIM	Physical Habitat Simulation
Q	Discharge through a transect
q	Discharge through a cell
QARD	Simulation discharge specified by the user in the hydraulic simulation routines when running PHABSIM
Q_{CAL}	Calibration discharge
Q_{SIM}	Simulation discharge
Q95	95 percentile exceedance low flow discharge
R	Hydraulic radius
RCP	River Communities Project
RIVPACS	River Invertebrate Prediction And Classification System
S	Longitudinal water surface slope
TFS	Terrestrial and Freshwater Sciences (Directorate of NERC)
U	Internal energy due to fluid temperature
v	Velocity
VAF	Velocity Adjustment Factor
WP	Wetted perimeter
WSL	Water surface elevation
WSP	Water Surface Profile hydraulic simulation routine
WUA	Weighted Usable Area
x	Horizontal distance across a transect
y	Surveyed elevation difference between bed and headpin
γ	Specific weight of fluid

Contents

1. Introduction

1.1 METHODS FOR SETTING INSTREAM FLOW REQUIREMENTS

Water use generally is divided into two primary classes - offstream use and instream use. In offstream use, water is withdrawn from the river or aquifer for use beyond its natural flow path and examples include irrigated agriculture, public and industrial water supply. Each offstream use decreases the volume of water available downstream of the point of diversion and increases availability downstream of the point of return. Instream uses, which generally do not diminish the flow downstream from its point of use, include hydro-electric power generation, navigation, pollution dilution and the environmental requirements of biological, recreational and aesthetic use. The key tool in the management of instream water for the more traditional economic uses in the United Kingdom has been the prescribed flow. A number of methods have evolved for estimating the increasingly recognised environmental flow requirements, of which the Instream Flow Incremental Methodology (IFIM) is at present the most sophisticated and widely recognised. IFIM is a collection of computer models and analytical procedures designed to predict changes in fish and invertebrate habitat due to flow changes. A major component of IFIM is the Physical HABitat SIMulation (PHABSIM) system (Bovee, 1986) which is a collection of computer programmes by which available habitat area is obtained as a function of discharge. This report describes the application of the Instream Flow Incremental Methodology to two British rivers using the PHABSIM system.

Water management in the United Kingdom has historically adhered to discharge-based methods in the setting of prescribed flows, being set according to the Dry Weather Flow. The Dry Weather Flow is itself an undefined discharge, but is indexed by a low flow discharge, typically either the 95 percentile flow duration statistic, or the mean annual minmum seven-day flow frequency statistic. It is only a recent phenomenon in the United Kingdom that cognisance is given by resource planners to the ecological value of low river flows; for example, the Yorkshire National Rivers Authority region now employ an environmental weighting scheme, which sets prescribed flows as a proportion of the Dry Weather Flow (DWF) weighted according to a range of environmental characteristics and uses (Drake and Sherriff, 1987). Thus the Environmental Prescribed Flow is set at 1.0 x DWF for the most sensitive rivers and at 0.5 x DWF for the least sensitive, which will determine the amount of water available for offstream uses, pollution dilution and environmental protection.

Recommendations from a review of compensation flows below impounding reservoirs in the United Kingdom (Gustard *et al.*, 1987) suggest that a re-evaluation of awards is warranted but that any negotiation of new awards should move away from simply setting prescribed flows as a fixed percentage of the mean flow. The review establishes that many reservoirs provide compensation flows which were determined by industrial and political constraints and which no longer apply. Furthermore, the majority of compensation flows were awarded when there were few or no hydrometric data to describe differences in catchment hydrology and little knowledge of the impact of impoundments on downstream aquatic ecology. It is the inheritance of this historical legacy that prompts a reassessment of current compensation flows. Equally, the recognition that aquatic ecosystems have specific flow requirements which perhaps bear little relation to existing compensation awards is a strong argument towards the reassessment of prescribed flows, moving away from discharge-based methods alone towards habitat methods.

However, while quantitative models and design techniques are available for estimating discharge statistics in rivers, for example Low Flow Studies (Institute of Hydrology, 1980), there is a paucity of operational tools for managing aquatic communities in British rivers at a national scale. A notable exception is the development of the RIVPACS (River Invertebrate Prediction And Classification System) technique, appropriate for modelling invertebrates. Fish management models tend to be more scheme-specific in nature, for example the fisheries study downstream of Roadford Reservoir which commenced in 1984 aimed at developing operating rules to minimise detrimental impacts upon salmonids in the Tamar and Torridge rivers. The recent development of the HABSCORE technique by the Environmental Appraisal Unit of the National Rivers Authority Wales establishes an operational tool for the management of salmonid populations in Welsh rivers. Essentially, both RIVPACS and HABSCORE adopt the same rationale - that the carrying capacities of streams are to a large extent dependent on channel structure and the environmental regime (hydrological, chemical, temperature) experienced within the stream. These characteristics can be measured by a combination of site features (width, depth, substrate, cover etc.) and catchment features (altitude, gradient, conductivity etc.). By measuring these features and species populations at a number of pristine sites which have variable habitat, multivariate models can be calibrated which predict species presence and abundance from the environmental variables. The predicted population sets an objective for the river reach based on the habitat which it provides. This type of model may be used to detect anomalies in observed ecological data in relation to the objective population, anomalies which may be attributable to impacting factors. What this type of model is not designed to achieve however is the recommendation of hydrological regime or prescribed flow.

Water management in Britain lags a considerable way behind the United States as regards the development of appropriate management models for recommending flow regime measures which consider ecological demands. In the United States procedures for evaluating impacts of streamflow changes were first developed and have advanced considerably in the period 1974-1989. Central to these advances has been the concept of instream flow requirements which recognises that aquatic species have preferred habitat preferences, with habitat defined by physical properties (flow velocity, water depth, substrate and vegetal/channel cover). Because some of these physical properties which determine habitat vary with discharge, so species have different preferences for different discharges. Development of the Instream Flow Incremental Methodology (IFIM) by the Aquatic Systems Branch of the U.S. Fish and Wildlife Service has allowed the quantification of species preferences for the full range of discharges that may be experienced within a river. This quantification of habitat preferences and the relationship with river flow permits the negotiation and setting of optimal flows for ecological management. Setting instream flows in this manner complements purely water-quantity or cost-management objectives by paying cognisance to the physical habitat requirements.

In the period since 1960 within the United States the importance of instream flows has become regarded more widely as essential to maintain and restore values and uses of water for fish, wildlife, ecological processes, and other environmental, recreational and aesthetic purposes (Jahn, 1990). By the mid-1980s, at least 20 states provided legislative recognition of instream flows for fish aquatic resources. Data from Lamb and Doersken (1987) in Table 1.1 illustrates that IFIM is now the most widely applied method for determining instream flow requirements for major resource schemes in the United States. The US equivalent of the Dry Weather Flow, the 7-Day, 10 Year (7Q10) Low Flow is used in just five states. Along with other simpler methods, such as the Tennant Method, 7Q10 would tend to be applied to minor schemes and basinwide planning purposes.

The essence of the Instream Flow Incremental Methodology is concisely stated by Bartholow and Waddle (1986):

> "The Instream Flow Incremental Methodology is a reasoned approach to solving complex streamflow allocation problems that are often characterised

Table 1.1 Methods for determining instream flow requirements in the United States, and number of States using each method

METHOD	NUMBER OF STATES USING METHOD
Instream Flow Incremental Methodology (IFIM)	38
Tennant method	16
Wetted perimeter	6
Aquatic Base Flow	5
7-Day, 10-Year Low Flow (7Q10)	5
Professional judgement	4
Single Cross-Section (R-2 CROSS)	3
USGS Toe-Width	2
Flow records/duration	2
Water quality	2
Average Depth Predictor (AVDEPTH)	1
Arkansas	1
Habitat quality index	1
Oregon fish-flow	1
US Army Corps of Engineers	1
Hydraulic Modelling (HEC-2)	1

Source: Lamb and Doersken (1987)

by uncertainty. Application of the IFIM requires an open and explicit statement of management goals, study objectives, technical assumptions, and alternative courses of action. IFIM provides a framework for presenting decision-makers with a series of management options, and their expected consequences, in order that decisions can be made, or negotiations begun, from an informed position. IFIM exposes for the decision-makers those areas where their judgement is necessary and presents the potential significance of the alternatives they might choose."

By relating ecological demands to discharge, the merit of IFIM lies in providing a quantitative basis which allows river ecologists to negotiate prescribed flows or flow regimes in equivalent terminology to other water resource demands.

The demand for a scientifically defensible method for both resource allocation and environmental impact assessment in the United Kingdom (Petts 1989) may be satisfied by IFIM when it is considered that the scientific rationale of IFIM has been successfully defended against legal challenges in the U.S.. There is therefore scope for the application of IFIM in the United Kingdom to yield long-term benefits to instream flow management. By relating ecological requirements to discharge, IFIM allows prescribed flows to be determined and set using values which complement quantity-based statistics. The method has received wide international recognition and has been extensively applied to real water resource problems in the U.S.. The immediate need, and the objective of this report, is the assessment of the suitability of the methodology in British rivers.

1.2 OUTLINE OF REPORT

This report presents the results of the application of the Instream Flow Incremental Methodology on two rivers in the UK using the Physical Habitat Simulation system. The project aimed to:

- gain experience in IFIM application

- assess the validity of the PHABSIM model

- develop an interface between engineering hydrologists and fisheries staff.

In Chapter 2 the rationale and concepts of the Instream Flow Incremental Methodology are explained, the requirements of hydraulic and habitat data are expressed and the theory of the hydraulic simulation routines, suitability criteria and habitat weighting are detailed.

The application of IFIM on two British rivers is detailed in Chapter 3. The rivers Blithe in Staffordshire and Gwash in Leicestershire/Lincolnshire were chosen because each possesses the necessary hydrological and ecological data but contrast the pool-riffle river Blithe and the ponded sections of the Gwash.

Chapter 4 presents the details of model simulations of physical habitat availablity for a variety of fish, macroinvertebrates and macrophyte (Table 1.2).

Results are presented as weighted usable area (WUA) versus discharge functions for each target species, as WUA duration curves based on observed river flow data from permanent gauging stations on the two rivers, and as pre- and post-impoundment WUA duration curves based on habitat availability before and after construction of Blithfield Reservoir and Rutland Water on the rivers Blithe and Gwash respectively.

Chapter 5 presents recommendations regarding the suitability of IFIM for modelling instream flows in British rivers, an assessment of the PHABSIM system and a proposed framework for research initiatives in the sphere of instream flows in Britain.

Table 1.2 Summary of target species used in the application of IFIM in the UK

FISH (in each case adult, juvenile, fry and spawning life stages are considered)

Brown trout
Grayling
Dace
Chub
Roach
Bream
Pike
Perch

MACROINVERTEBRATES

Isoperla grammatica - stonefly
Leuctra fusca - stonefly
Rhyacophila dorsalis - caddis-fly
Polycentropus flavomaculatus - caddis-fly
Sphaerium corneum - pea mussel

MACROPHYTE

Ranunculus fluitans - river water-crowfoot

2. IFIM rationale and PHABSIM data requirements

2.1 IFIM RATIONALE AND CONCEPTS

The IFIM procedure provides an estimate of habitat loss/gain with changes in discharge. IFIM itself is a concept or at least a set of ideas and PHABSIM is software (Gore and Nestler, 1988).

The underlying concepts of the Instream Flow Incremental Methodology are that:

- IFIM is habitat-based, with potential usable habitat being simulated for unobserved flow or channel conditions

- evaluation species exhibit a describable preference/avoidance behaviour to one or more of the physical microhabitat variables; velocity, depth, cover or substrate

- 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

- preferred conditions can be represented by a suitability index which has been developed in an unbiased manner.

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. 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 2.1. Hydraulic simulation is used to describe the area of a stream having various combinations of depth, velocity and channel index (cover or substrate) as a function of flow. Habitat suitability is based on the preference of species for certain combinations of physical parameters above others. Hydraulic and habitat data are combined to calculate the weighted usable area (WUA) of a stream segment at different discharges based on the preference of selected target species for the simulated combinations of hydraulic parameters.

Physical habitat suitability information for target species, and distinct life stages of those species, can be derived from existing empirical data (including the US Fish and Wildlife Service Curve Library), scientific literature, or direct field sampling.

Calibration of the hydraulic model components is achieved on a transect-defined cell-by-cell basis requiring field observation of channel bed cross-sectional profiles, water surface elevation, mean column velocity, and

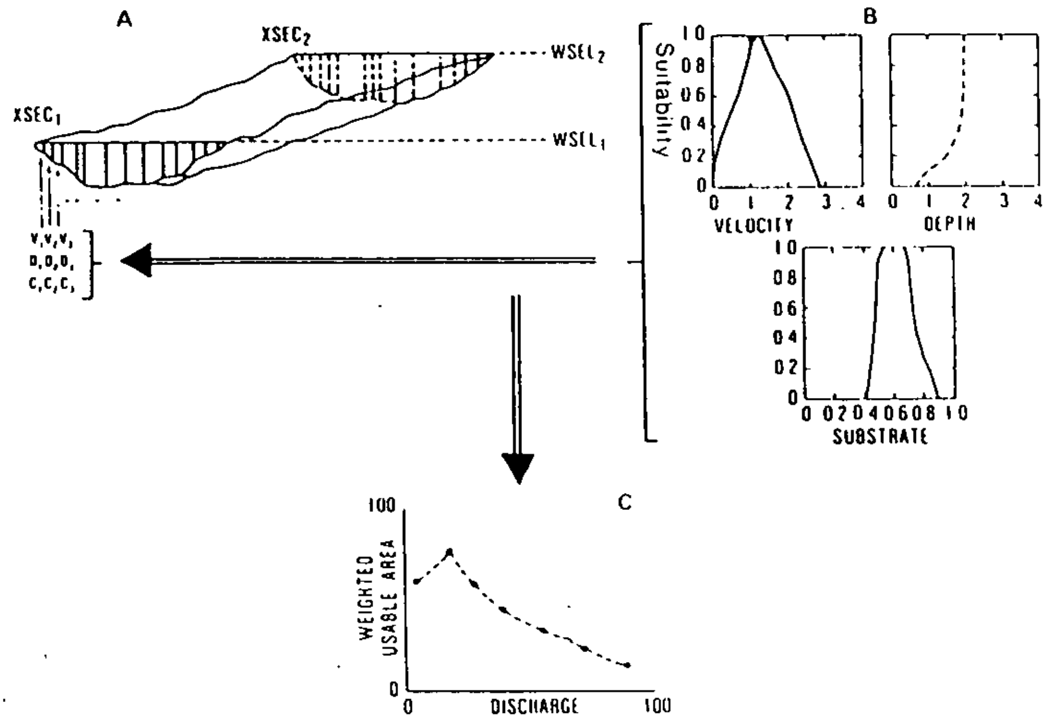


Figure 2.1 ***PHABSIM scientific rationale. Source: Gore and Nestler (1988). A schematic representation of the IFIM process. Velocity (V), depth (D), and cover/substrate (C) values from various cross sections (XSEC) are combined with water surface elevations (WSEL) at a steady discharge to drive the hydraulic model (steady or dynamic flow) which provides stage/discharge information to PHABSIM [A]. The habitat suitability information [B] is linked to the simulation of cell-by-cell hydraulics to predict (via HABTAT) the amount of weighted usable area at any proposed discharge [C].***

application of substrate and cover classification schemes. Cells are defined as the boundaries of the data represented by a single survey point, and are most commonly defined in the cross-channel directions as the mid-point between survey points, and in the downstream direction by the inter-transect midpoint.

Observations of these data at calibration flows are necessary to create the dataset from which the depth and velocity within cells is simulated at different discharges using the hydraulic programs. Observed channel index values are assumed to be independent of flow.

Cell values of each of the physical parameters are combined with species preference curve information through a selected functional relationship, termed the Composite Suitability Index (CSI), to develop the composite habitat index, termed weighted usable area. Typical CSI functional relationships are multiplicative, but any alternative can be devised. Weighted usable area, indexed by total surface area of the cell weighted by its relative suitability for a given species, simulates the amount of physical habitat within that cell at different discharges.

Summation of individual cell values within the river reach of interest can be achieved either by a representative reach approach or by habitat mapping and selective identification of field sites. In the representative reach approach, individual transects are assigned a weighting which represents a fraction of the distance to the next-downstream transect, according to the distance to the change in habitat type. In the habitat mapping approach, transects are assigned a distance weighting according to the frequency of occurrence of that habitat which the transect represents within the study river as a whole.

Once achieved, output comprises a graphical weighted usable area against discharge function for the particular target species under study. Optimal discharges for specific species can be identified from the WUA-discharge functions, but must be considered in the context of water availability, water management constraints and ecological objectives.

2.2 HYDRAULIC AND HABITAT DATA REQUIREMENTS OF PHABSIM

The Physical HABitat SIMulation (PHABSIM) system comprises a large number of separate programs which fall into two main categories; hydraulic simulation and habitat simulation. The hydraulic simulation programs, when calibrated with observed field data, are used to simulate depths and velocities at different discharges selected by the user at transects along a reach of river. To calibrate the hydraulic programs it is necessary to survey the bed profile of the river reach on a transect basis, to measure the distances between transects, and to observe water surface elevation and velocity on a cell-by-cell basis across each transect at a range of different flows. The flows at which the water surface elevation and velocities are measured are termed calibration flows. The discharge for each calibration flow (Q_{CAL}) must be calculated from the observed data. The flows selected by the user when running PHABSIM are termed simulation discharges, (Q_{SIM}).

There are three basic hydraulic simulation programs; IFG4, MANSQ and WSP. For the simulation discharges, IFG4 predicts the water surface elevation using a simple stage/discharge relationship and predicts velocities on a cell-by-cell basis using Mannings n and a simple mass balance adjustment. In IFG4 and MANSQ each transect is modelled independently. When IFG4 fails to sensibly predict water surface elevations due to the poor calibration of the stage-discharge relationship then water surface elevations can be predicted by MANSQ using the solution of Mannings equation. WSP is a standard stepbackwater model for the prediction of water surface elevations which considers transects as dependent and uses an energy balance model to project water levels from one known stage/discharge relationship to all transects upstream. Neither MANSQ nor WSP can predict velocities, so once a sensible downstream water surface elevation profile has been predicted for the simulation discharges, then IFG4 is used to predict velocities.

The output from the hydraulic simulation programs is predictions of depth and

Table 2.1 Minimum data requirements of PHABSIM

HYDRAULIC PROGRAMS

IFG4

1. Survey of x,y coordinates of the bed elevation (maximum of 100 data points) for channel cross-section transects. The x,y coordinates represent the horizontal distance and the elevation difference respectively from the headpin representing the start of the transects. These are converted by PHABSIM to a cross-sectional profile of channel bed elevations (BE). Substrate code or cover code value for each surveyed point. The transect which represents the downstream end of the study reach should be located at a hydraulic control, upstream of which there is a unique stage-discharge relationship.

2. Measurement of inter-transect distances and assigned upstream weighting factor

3. A minimum of three calibration flows at which water surface elevation and discharge through the transects are measured. The measurement of velocity at each survey point across the transect is essential during at least one calibration flow, preferably the highest of the three discharges. The three calibration flows should sample flows with differences of an order of magnitude. Data from a maximum of nine calibration flows can be accepted.

MANSQ

1. As (1) above

2. As (2) above

3. Minimum of one calibration discharge and water surface elevation

WSP

1. As (1) above

2. As (2) above

3. Minimum of one calibration discharge at all transects and a minimum of three calibration flows at the transect furthest downstream

ECOLOGICAL PROGRAMS

HABTAT

1. Set of suitability index curves for one or more of the following:
    - depth
    - velocity
    - substrate
    - cover

2. Set of hydraulic information describing the depth and velocity characteristics for each cell as a function of flow derived from the hydraulic programs

velocity for each cell for each simulation discharge. Cell values of the channel index (cover or substrate) remain independent of discharge.

The second category is the suite of programs for the simulation of physical habitat space. The input to this suite of programs are habitat suitability curves, which quantify the relative preference of a selected life stage of a target species for depth, velocity and channel index independently. Preference ranges from 0 to 1, with 1 being optimal and 0 being the most unsuitable. The programs, of which the principal is HABTAT, combine the habitat preference values for depth, velocity and channel index for life stages of target species with the predictions of the physical variables from the hydraulic simulations.

The minimum data requirements for the three hydraulic simulation routines and HABTAT are summarised in Table 2.1.

2.3 THEORY OF HYDRAULIC SIMULATION ROUTINES

2.3.1 IFG4

IFG4 simulates water surface levels and predicts velocities for any simulation discharges selected by the user, treating each cross-section independently. Water surface elevations are simulated by a stage-discharge relationship from which water depths in each cell and cell widths are calculated. Velocities are predicted by solving Mannings equation. A velocity adjustment factor is used to ensure that the discharges calculated from the predicted values of depth, width and velocity equal the simulation discharge. Because IFG4 uses a constant Mannings n at any simulation discharge, the theoretical relationship of decreasing n with increasing discharge at a point is contravened. Instead, IFG4 uses a variable velocity adjustment factor to account for variable Mannings n. The IFG4 routine is explained in more detail below.

Depth prediction

A stage/discharge relationship is calculated from the water surface elevation and discharge data measured at the three or more calibration discharges. The stage/discharge relationship allows water surface elevations to be predicted at any simulation discharge.

Once the water surface elevation has been predicted for a simulation discharge then the depths for all cells across the transect are calculated as the difference between the predicted water surface elevation and the channel bed elevation. This is illustrated in Figure 2.2 where for a single cell:

$$\hat{d}_i = \hat{WSL} - BE_i$$

where $\hat{d}_i$ = predicted depth at point i
$\hat{WSL}$ = predicted water surface elevation
BE_i = bed elevation.

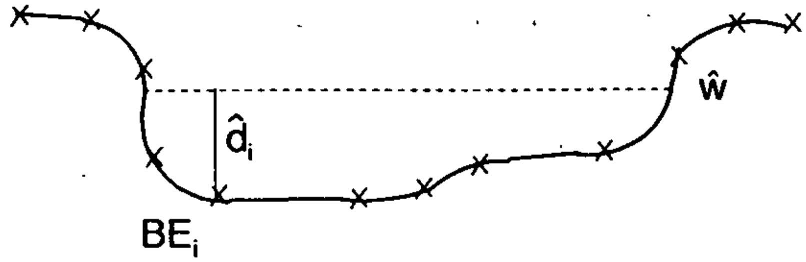


Figure 2.2 Prediction of water depth using IFG4

Velocity prediction - assuming constant Mannings n

To enable predictions of velocities at simulation flows to be made, data from one of the calibration flows are used to derive the value of Mannings n. If velocities have been measured at more than one calibration flow, then the user is free to select any one of the flows. Given a choice, it is preferable to select the highest calibration flow because more cells in the transect are likely to contain water. The parameters v_i, d_i and S are known (Figure 2.3), where:

v_i = measured mean column velocity at vertical i
S = measured average slope through transect
d_i = WSL - BE_i, where WSL is the measured water surface elevation,

allowing the solution of n_i where

$$n_i = \frac{1.49}{v_i} \; d_i^{2/3} \; S^{1/2}.$$

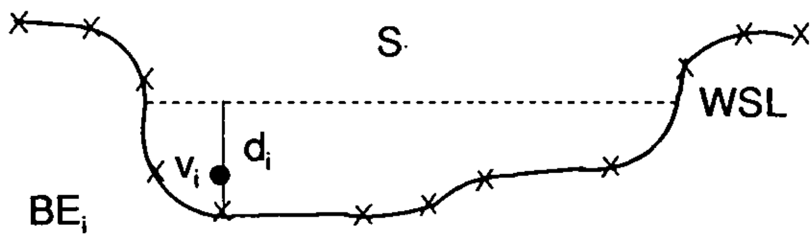


Figure 2.3 Calibration data necessary for velocity predictions in IFG4

It should be noted that the calculated values of n are not constrained to equal published n values (for example Gregory and Walling, 1973) for the stream bed types in the river reach when predicting velocity distributions, because n is being used in IFG4 as a velocity calibration coefficient rather than an index of energy dissipation. It would, however, give added confidence to the modeller if calculated n values were found to be close to typical n values for the river type being modelled.

For the prediction of velocity in cells at simulation flows $\hat{v}_i$ is predicted using predicted depth, $\hat{d}_i$, calculated n_i and constant S (Figure 2.4) as follows:

$$\hat{v}_i = \frac{1.49}{n_i} \hat{d}_i^{2/3} S^{1/2}$$

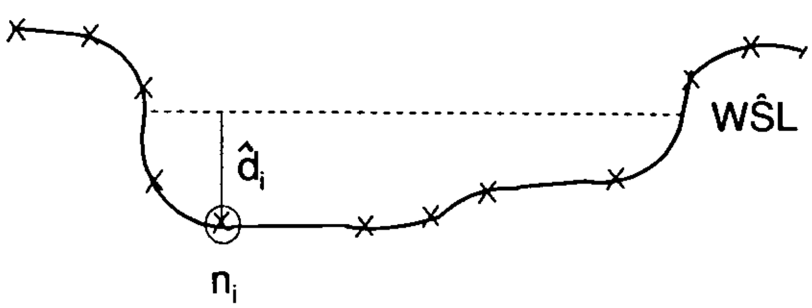


Figure 2.4 Prediction of velocity distributions at simulation discharges in IFG4

Velocity adjustment factor

Once $\hat{v}$ has been predicted then a velocity adjustment factor based on a simple mass balance is applied to ensure that the sum of the discharges calculated at all cells from the predicted values of n, $\hat{d}$ and $\hat{v}$ equals the simulation discharge initially selected by the user. Because in general terms discharge, Q, equals velocity times cross-sectional area, so for each cell the predicted discharge, $\hat{q}_i$, is calculated from

$$\hat{q}_i = \left[\hat{width}_i \times \hat{d}_i \right] \hat{v}_i$$

where $\hat{width}_i$ is the predicted width of the cell.

The predicted discharge through the whole transect, $\hat{Q}$, is the sum of all the individual cell discharges

$$\hat{Q} = \Sigma\hat{q}_{i...z}.$$

$\hat{Q}$ must equal Q_{SIM}, but may not when calculated as the sum of $\hat{q}_i...\hat{q}_z$ because of errors introduced by poor predictions of water surface elevations, water depth, cell widths or velocities within one, some or all of the cells. IFG4 uses a velocity adjustment factor, VAF, where

$$VAF = \frac{Q_{SIM}}{\hat{Q}}$$

to ensure that $\hat{Q} = Q_{SIM}$.

The VAF adjusts the predicted velocity in each cell, $\hat{v}_i$, such that

$$\hat{v}_i' = \hat{v}_i \times VAF$$

thereby ensuring that

$$\left[\hat{width}_i \times \hat{d}_i\right] \hat{v}_i' = \hat{Q} = Q_{SIM}.$$

It must be recognised that it is the predicted velocities alone which are adjusted and not predicted depths or predicted cell widths. However, poor measurement of water surface elevations at the calibration flows, and subsequently prediction of erroneous water depth by an incorrect stage/discharge relationship, can introduce a major source of error into IFG4 simulations, which can be partly overcome by ensuring that the calibration flows represent wide stage/discharge relationship.

Velocity preciction - variable Mannings n

So far Mannings n has been assumed to be constant and independent of discharge. In reality Mannings n at a point would be expected to decrease with increasing discharge, the relationship having form displayed in Figure 2.5.

To model variable Mannings n it is a condition of IFG4 that the VAF must vary with the simulated discharges and conform to the form shown in Figure 2.6, thereby mirroring the n/Q relationship. In the relationship between the VAF and simulated discharges the VAF equals one at the calibration discharge used to set the value of Mannings n (Q_{CAL}), and is < 1 for Q_{SIM} less than Q_{CAL} and > 1 for Q_{SIM} greater than Q_{CAL}. The decrease in VAF for discharges lower than that used to set Mannings n is the IFG4 solution to modelling the theoretically expected increase in Mannings n as discharge decreases. Typical values of the VAF range from 0.2 up to 2.5 - 3.0. The modeller must check that the VAF:Q_{SIM} relationship is conforming to this shape if variable Mannings n is to be adequately modelled.

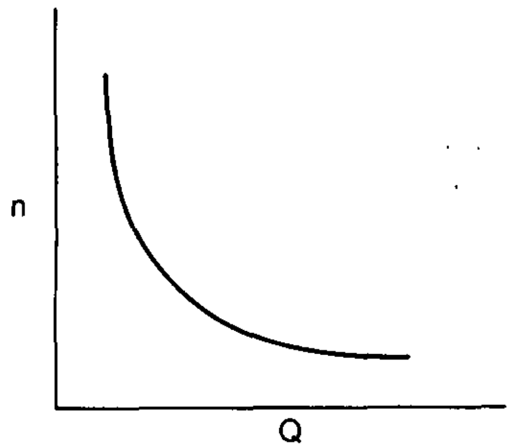


Figure 2.5 Relationship of Mannings n with discharge at a point

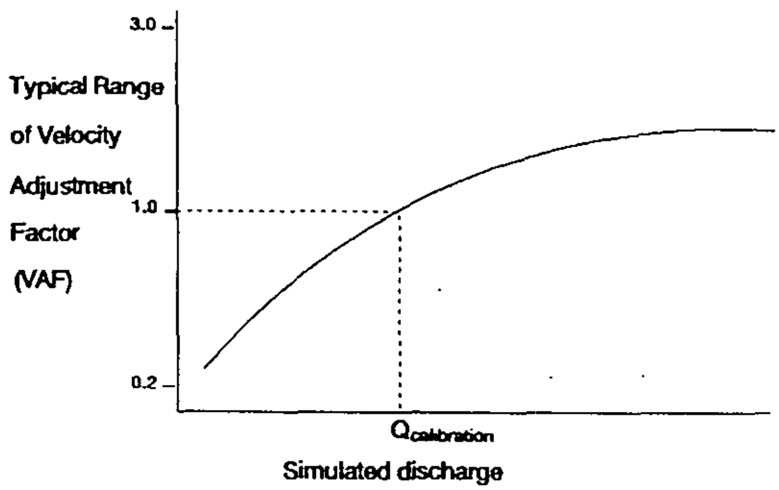


Figure 2.6 Relationship of the Velocity Adjustment Factor with discharge necessary to model variable Mannings n

2.3.2 MANSQ

MANSQ simulates water surface elevations only, treats each cross-section independently, and fails under conditions of backwater effects. MANSQ should be used to feed predicted water surface elevations into an IFG4-format data set when IFG4 fails because of internally poor rating equations.

MANSQ uses Mannings equation for predicting velocity, in which the terms n and S are considered as a conveyance factor, CF. The term CF is calibrated by solving Mannings equation using data from one calibration data set. The calibration of CF leaves the cross-sectional area and wetted perimeter known as a combined term but not known individually. At a simulation discharge, the individual values of A and R are solved by iterative calculation and comparison with their respective values in the calibration data set. Once A and R are known then the water surface elevation can be calculated from the channel bed profile.

Variable Mannings n with discharge is dealt with in MANSQ by varying CF. The relationship between CF and discharge is established by regression using three calibration data sets, from which the exponent, the Beta coefficient, is used. When only one set of calibration observations are available, then the value of the Beta coefficient should be based on empirical judgement of the channel bed material. The MANSQ routine is explained in more detail below.

The Mannings equation (in imperial units) for predicting velocity is given by

$$v = \frac{1.49}{n} R^{2/3} S^{1/2}$$

where v = velocity (ft/s)
n = Mannings n
R = hydraulic radius
S = slope of energy gradient (ft/ft)

and R = A/WP

where A = cross-sectional area (ft^2)
WP = wetted perimeter (ft)

Because $Q = vA$, so substituting Mannings equation

$$Q = \frac{1.49}{n} S^{1/2} R^{2/3} A.$$

When it is assumed that S and n are independent of Q and are constant, the term

$$\left[\frac{1.49}{n} S^{1/2}\right]$$

can be considered as a conveyance factor, CF, such that

$$Q = CF\ R^{2/3} A.$$

One set of calibration data is used to define the value of CF as explained in the following section. Later it is shown that CF is variable and three sets of calibration data are used to account for this.

Calibration of a constant conveyance factor

For any one calibration discharge Q_{CAL}, then the discharge Q, the water surface elevation WSL, and the x,BE coordinates of the channel bed profile are known. From these data the value of A can be derived and the value of R is calculated as follows:

$$WP = \sqrt{(\Delta x^2) + (\Delta BE^2)}$$

$$\text{and } R = \frac{A}{WP}.$$

Then, the constant conveyance factor, CF, is calculated from

$$CF = \frac{Q_{CAL}}{AR^{2/3}}.$$

Derivation of water surface elevations for simulation discharges

In the general equation

$$\frac{Q_{SIM}}{CF} = A\ R^{2/3}$$

the term $AR^{2/3}$ is known as a term but the terms A and R are not known individually. The derivation of the water surface elevation, w· for Q_{SIM} is achieved by iterative calculation of the values of A and R. In doing so the first step is to assume an arbitrary water surface elevation, $\hat{WSL}$, and calculate an arbitrary A and R, termed $\hat{A}$ and $\hat{R}$, and thence $\hat{A}R^{2/3}$. Calculate the corresponding $\hat{Q}_{SIM}$ and compare to Q_{SIM}. If $\hat{Q}_{SIM}$ is greater than Q_{SIM} then $\hat{WSL}$ should be decreased, or $\hat{WSL}$ increased if $\hat{Q}_{SIM}$ is less than Q_{SIM} until the unique solution of $\hat{WSL}$ is found where $\hat{Q}_{SIM} = Q_{SIM}$.

Calibration of a variable conveyance factor

Up to now MANSQ has assumed n and S to be constant, and therefore that CF is independent of discharge. However, whilst MANSQ continues to assume that S is independent of discharge, variations of n with Q (of the form shown in Figure 2.5) are accommodated by the Beta coefficient from a regression of CF against Q based on several calibration discharges. This is achieved as follows:

As shown in Fig. 2.5, $n = \alpha Q^{\beta}$. Because CF = f(n,S), so, providing S is assumed to be a constant, then $CF = aQ^b$.

By employing a data set with at least 3 calibration flows, for which $CF_{CAL1,2,3}$ and $Q_{CAL1,2,3}$ are known, then the Beta coefficient b can be derived by regression. For any simulation discharge, the value of the CF can be calculated from

$$CF_{SIM} = aQ_{SIM}^{b}.$$

MANSQ calculates and expresses the value of the CF to be used at a simulation discharge (CF_{SIM}) as a ratio to the constant CF derived from the single calibration data set (i.e. CF_{CAL}) as follows:

$$\frac{CF_{SIM}}{CF_{CAL}} = \frac{aQ^{b}_{SIM}}{aQ^{b}_{CAL}} = \left[\frac{Q_{SIM}}{Q_{CAL}}\right]^{b}$$

so

$$CF_{SIM} = CF_{CAL} \left[\frac{Q_{SIM}}{Q_{CAL}}\right]^{b} .$$

CF_{SIM} can be calculated for any discharge and replaces the constant CF during the calculation of A and R in the iterative calculation of water surface elevation.

If only one set of calibration observations are available, such that the Beta coefficient cannot be calculated by regression, then an estimated b value of 0.1 to 0.3 should be input, based on empirical judgement of the bed material. Generally, the larger the bed material then the larger the value of b. b is positive and typically exhibits an empirical range from 0.1 to 0.5, with a mean value of 0.22 (R. Milhous, pers. comm.).

2.3.3 WSP

WSP differs from both IFG4 and MANSQ which treat transects independently because WSP is specifically designed to consider backwaters and achieves this by considering water surface elevations at transects as dependent. In the same way as MANSQ, WSP is concerned only with the prediction of WSLs, which are then fed into an IFG4-format data set for velocity prediction. WSP is used where MANSQ fails due to the breakdown of the CF relationship with discharge caused by backwater effects.

A simple energy balance model through a channel reach takes the form

$$\begin{bmatrix}\text{ENERGY FLUX}\\ \text{INTO THE}\\ \text{CONTROL VOLUME}\end{bmatrix} - \begin{bmatrix}\text{ENERGY FLUX}\\ \text{OUT OF THE}\\ \text{CONTROL VOLUME}\end{bmatrix} + \begin{bmatrix}\text{TIME RATE OF}\\ \text{ENERGY CHANGE}\\ \text{WITHIN THE}\\ \text{CONTROL VOLUME}\end{bmatrix} = 0$$

Energy (E) at a point in a channel is the sum of the internal, kinetic and potential energies:

$$E = U + \frac{V^2}{2} + gBE$$

where U = internal energy due to fluid temperature

V = velocity of the fluid

g = gravitational acceleration

BE = Bed elevation above reference level.

Dividing through by g, then

$$E = \frac{P}{\gamma} + \frac{V^2}{2g} + BE$$

where P = Fluid pressure

γ = Specific weight of fluid.

The energy balance model can then be written as

$$\left[\frac{P_1}{\gamma} + \frac{V_1^{\,2}}{2g} + BE_1\right] - \left[\frac{P_2}{\gamma} + \frac{V_2^{\,2}}{2g} + BE_2\right] + \left[H_L\right] = 0$$

where H_L = head loss, caused by the dissipation of energy to heat generation through the channel section.

Because pressure is specific weight times depth so

$$\frac{P}{\gamma} = \text{DEPTH}.$$

The energy balance simplifies to

$$\frac{V_1^{\,2}}{2g} + BE_1 + d_1 = \frac{V_2^{\,2}}{2g} + BE_2 + d_2 + H_L .$$

Employing this energy balance model as illustrated in Figure 2.7, then the head loss h_L between the two transects (A,B)

$$h_L = E_B - E_A .$$

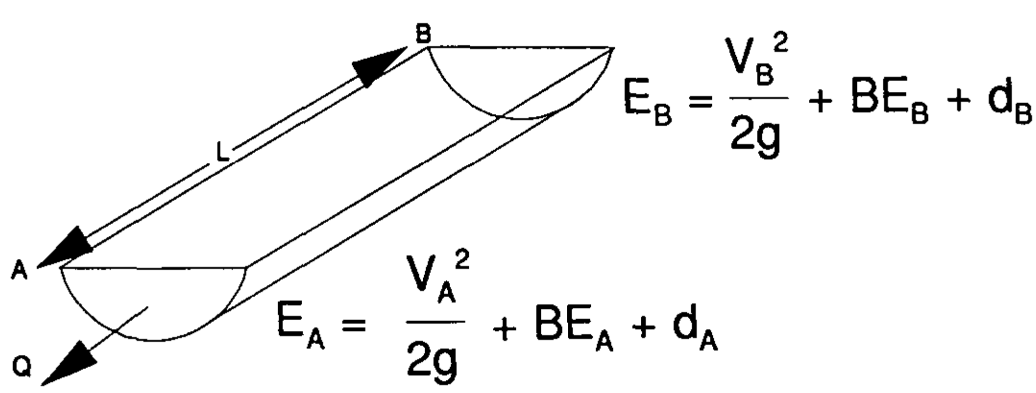


Figure 2.7 Energy balance model as the basis of WSP

The basis of WSP is the calibration of the head loss between transects, which is turned around to project changes in head, and hence water surface elevations, to upstream transects.

The solution of WSP is based on two definitions of the slope of the energy grade line, S:

DEFINITION 1

$$S_1 = \frac{h_L}{L}$$

DEFINITION 2 - Mannings equation can be solved for S such that

$$S_2 = \frac{n^2\ Q^2}{2.22\ R^{4/3}\ A^2}$$

in which the only unknown is Mannings n.

WSP projects the water surface elevation upstream from A to B to solve S_2 for the stretch A to B. To do so requires a starting value of Mannings n (initially an estimate), which is optimised iteratively until

$$S_1 = S_2 .$$

In the projection procedure, the projected water surface elevation at B may not be equal to that measured in the field due to an incorrect n, so the iterative optimisation adjusts n to achieve agreement. If the projected level is less than the observed level then Mannings n should be increased. Alternatively, if the projected level is greater than the observed level then Mannings n should be decreased.

Widely varying values of n should not be set at different transects, unless there is a strong physical justification for doing so. Rather, a constant n value should be used throughout a reach, essentially minimising the errors in under- or over-predicting water surface elevation at individual transects, similar to fitting a least squares regression line.

When projecting water surface elevations upstream it is necessary to know the stage/discharge relationship at the transect furthest downstream. A water surface elevation is calculated at this transect for the simulation discharge and the solution of S_1 allows the projection of water levels upstream to all other transects.

Again, it must be recognised that so far n has been assumed to be independent of discharge. Variable Mannings n is dealt with in WSP by roughness multipliers. Roughness multipliers are the values by which n must be modifed, and themselves vary with discharge. The values for a simulation discharge are derived by solving Mannings n for a range of calibration discharges, and identifying the ratio of n for the lower discharges to n for the highest discharge. This ratio is the roughness multipler, and when plotted against discharge allows the fitting of a best-fit relationship, thereby enabling the derivation of the multiplier for any simulation discharge. Roughness multipliers are greater than 1.0 for flows lower than the highest calibration discharge, and it is ideally the highest calibration discharges which should be used to solve S_2.

2.3.4 Mixed models

Since none of the hydraulic simulation routines can describe all possible channel conditions it is often necessary to use more than one model to simulate water surface elevations at all discharges at each cross section. The mixed model approach uses different hydraulic simulation models for the ranges of flow where each hydraulic model produces the best simulation results for that transect. 'Best' simulation results can be judged on the shape of VAF curves, on checking that water surface slopes are not negative (i.e. that water levels do not increase in a downstream direction), that in IFG4 the exponent of the stage-discharge relationship is between 1.5 and 3 and that the mean error of the Q against stage regression is low, and preferably less than 5%.

2.4 MICROHABITAT SUITABILITY CRITERIA

IFIM is based on the assumption that species exhibit discrete and quantifiable preferences for a range of velocities, depths and cover/substrate characteristics. A requisite input into the HABTAT component of PHABSIM is the numerical representation of the suitability of the physical variables for the specific species being studied. The basic form for the expression of suitability is a habitat suitability curve, or other categories of curve called utilization curves or preference curves. The distinction between the criteria is the base from which the curves are founded. Essentially, there are three categories (Bovee, 1986):

Category I: the habitat criteria are derived from life history studies in the literature or from professional experience and judgement, and are based on the adjudged suitability of physical habitat variables for target life stages.

Category II: the habitat criteria are based on frequency analysis of microhabitat conditions utilised by different life stages and species as identified by field observations. These criteria are termed 'utilisation curves' because they depict the conditions that were being used when the species were observed. Utilisation functions may not always accurately describe a species' preference because the preferred physical conditions may be absent or limited at the time of observation.

Category III: these are Category II curves in which the criteria are corrected for the bias by factoring out the influence of limited habitat availability. This correction is aimed at increasing the transferability of the criteria to streams that differ from those where the criteria were originally developed, or in the same stream at different flows.

A subsequent category, Category IV, has since been added, which are conditional curves, essentially Category III curves conditioned for variable factors such as cover and season.

There are three principal formats in which the microhabitat criteria (i.e. the suitability/utilisation/preference for depth, velocity and cover/substrate) can be expressed; binary criteria, univariate curves, or multivariate response surfaces, as depicted in Figure 2.8.

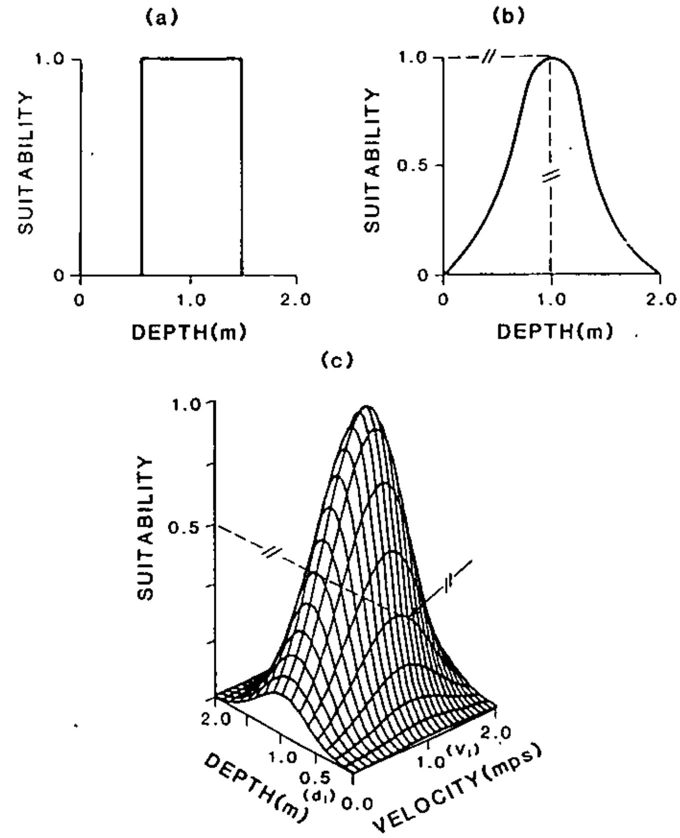


Figure 2.8 ***Examples of the three formats of habitat criteria: (a) binary, (b) univariate curve, (c) multivariate response surface***

The binary format establishes a suitable range of conditions for each variable as it pertains to a life stage of a species; within that range the suitability rating is 1.00, beyond it the rating is 0.00. Univariate curves developed from the concept that within the range of conditions considered suitable there is a narrower range that species select as preferred or optimal. The peak of the curve is the optimal value of the physical variable and the tails represent the bounds of suitability. The primary advantage of the multivariate response surfaces is the ability to express interactions among the variables.

2.5 WEIGHTED USABLE AREA AND COMPOSITE SUITABILITY INDICES

Total usable area is defined in terms of the plan area of the water surface within a river reach, expressed in $ft^2/1000$ ft of river length. Total usable area is the summation of the plan surface area of each of the individual cells within the river reach, some of which (principally the near bank cells) will vary in plan area with discharge. The net suitability of use of a given cell is quantified by the Weighted Usable Area (WUA). The suitability of a cell may be determined by one of four Composite Suitability Indices (CSI), as presented below, where A_i is the plan area of cell i, and f(v), f(d) and f(c) are the habitat suitability indices for velocity, depth and channel index (cover or substrate) respectively:

MULTIPLICATIVE CSI

$$WUA_i = A_i \times f(v) \times f(d) \times f(c)$$

GEOMETRIC MEAN CSI

$$WUA_i = A_i \times [f(v) \times f(d) \times f(c)]^{0.333}$$

MINIMUM CSI

$$WUA_i = A_i \times MIN[f(v), f(d), f(c)]$$

USER SUPPLIED CSI

$$WUA_i = A_i \times \text{USER SELECTED FUNC}[f(v), f(d), f(c)]$$

The multiplicative CSI, in which the gross area of the cell is multiplied by all suitability indices, is normally used and implies a 'cumulative effect' mechanism, a synergistic action whereby optimum habitat availability is achieved only if all variables are optimal (Gan & McMahon, 1990). The geometric mean CSI implies a compensatory mechanism, such that if two of the three variables are in the optimal range then the value of the third variable has little effect unless it is zero. The minimum CSI implies a 'limiting factor mechanism' such that when the cell area is multiplied only by the minimum of the factors the habitat is no better than its worst component. The user supplied CSI allows the PHABSIM modeller to define the nature of the CSI function according to the explicit interactions which are sought.

Weighted Usable Area is calculated cell by cell and summed for the whole reach. Under different flow conditions the values of the physical properties within a cell vary and consequently the habitat suitability indices may alter accordingly to calculate a new weighting factor. At different flows the plan area of certain cells will alter. The variations in these two factors combine to create a Weighted Usable Area relationship with discharge for a river reach.

3. IFIM calibration on two British rivers

3.1 FIELD SITES

Selection of sites for IFIM application in two British rivers was based on a requirement for the combined availability of pre- and post-reservoir impoundment river flow data and ecological data. Only three reservoirs in the UK were identified as possessing at least five years of gauged pre-and-post impoundment flow data by the Institute of Hydrology in 1987 (Gustard *et al.*, 1987), notably Derwent, Blithfield and Brenig Reservoirs. Acquisition of more recent flow data since 1987 appends Rutland Water to this group. Of these, Blithfield Reservoir and Rutland Water were selected as sites most appropriate for IFIM application, given that the river sites are also biological sampling sites, in the River Communities Project.

The River Blithe below Blithfield Reservoir was gauged 6km downstream at Hamstall Ridware (28002) between 1937 and 1984. Impoundment of Blithfield occurred in October 1952 giving a pre-impoundment period of 1937 - 1952 (16 years) and a post-impoundment period of 1953 - 1984 (32 years).

The River Gwash below Rutland Water has been gauged 13km downstream at Belmesthorpe (31006) since 1967. Rutland Water was impounded in February 1975, so the Belmesthorpe record contains pre-impoundment phase from 1968 to 1974 (7 years) and a post-impoundment phase of 1975 to 1989 (15 years).

In addition the two rivers exhibit contrasting geomorphological features, the river Blithe being an 'upland' pool-riffle river and the Gwash a 'lowland' river with ponded sections.

On the rivers Blithe and Gwash, three reaches were selected in the vicinity of the reservoirs for field measurement of hydraulic data. The location of these reaches are presented in Figure 3.1

RIVER BLITHE

Blithe Bridge SK 049 258 O.S. Sheet 128

Upstream of Blithfield Reservoir, located immediately downstream of the bridge on the minor road between Dapple Heath and Newton Hurst.

Blithe Dam SK 075 225 O.S. Sheet 128

Directly downstream of Blithfield Reservoir, with no intermediate tributaries between the outflow and the selected site.

Hamstall Ridware SK 110 188 O.S. Sheet 128

Downstream of Blithfield Reservoir, located immediately downstream of the

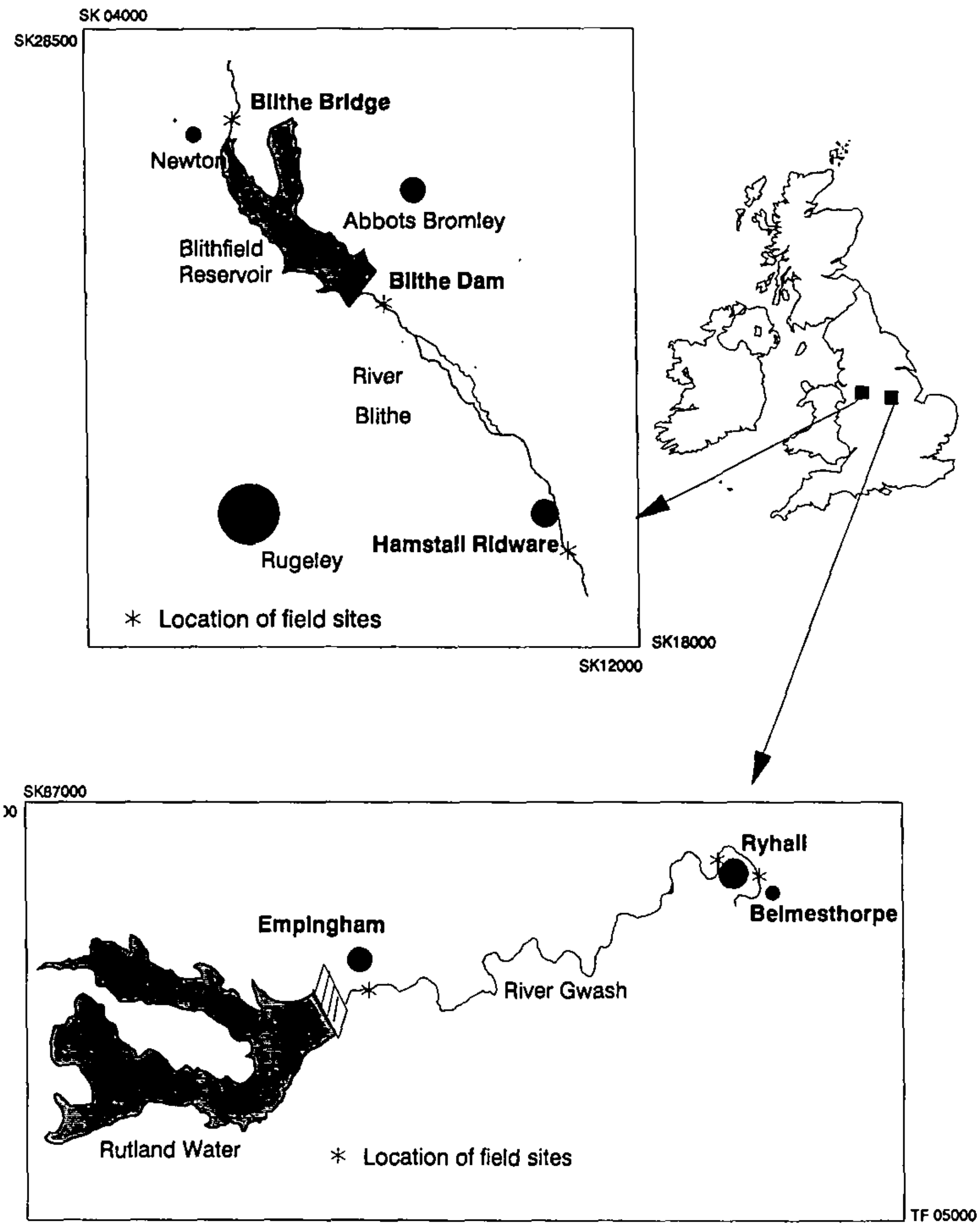


Figure 3.1 Site location map

bridge on the minor road between Hamstall Ridware and Olive Green. The gauging station (28002) is located some 100 metres upstream of this bridge, with no significant inflows in-between the gauge and the selected reach. Pur Brook and Ash Brook tributaries contribute to Blithe river flows between the reservoir outflow and the Hamstall Ridware site, increasing the catchment area by approximately $42km^2$ over the reservoir outflow.

Each reach on the Blithe possesses a well-developed pool-riffle sequence, and the first two contain a tight meander. Blithe Bridge is characterised by extensive overhanging vegetation.

RIVER GWASH

Empingham SK 954 084 O.S. Sheet 141

Immediately downstream of Rutland Water outflow, 500 metres below the A606 road bridge over the River Gwash, and above the confluence with the North Brook tributary above Mill Farm.

Ryhall TF 031 109 O.S. Sheet 130

Located 12km downstream of Rutland Water outflow, immediately upstream of the A6121 road bridge over the River Gwash at Ryhall. North Brook contributes river flow between the reservoir outflow and the Ryhall site, increasing the catchment area by approximately $85km^2$.

Belmesthorpe TF 041 104 O.S. Sheet 130

Located 13km downstream of Rutland Water outflow, and 1.5km downstream of the Ryhall site, adjacent to the minor road running north between Belmesthorpe and the A6121 north of Ryhall, immediately upstream of the minor road and dismantled railway juncture. North Brook contributes river flow between the reservoir outfall and the Belmesthorpe site, increasing the catchment area by approximately $90km^2$.

Empingham represents a well-vegetated ponded reach, Ryhall a pool-riffle sequence and Belmesthorpe a slow-flowing lowland 'drain'.

3.2 HYDRAULIC DATA

Actual study sites within these selected reaches are transects across the river channel, with each reach being represented by between 15 and 20 transects. Selection of transect sites was undertaken to represent the microhabitat variability within the reaches, specifically to ensure sampling amongst riffle, pool and straight channel typologies. Each transect is fixed in the field by two permanent survey marks, called headpins. The headpins on one bank are identified by a numerical sequence and the headpin on the other bank by the corresponding letter sequence. Headpin elevations were observed by field survey, and elevations related to an arbitrary benchmark of 100.000 metres assigned to one of the headpins. The headpin elevations, and distances between and across transects are presented schematically in Appendix 1.

Each transect is represented by between 23 and 33 cells, the boundaries of which are mid-point between the data observation points across the transect. The number of observation points per transect is presented in Table 3.1. Observation points were selected at points approximately equidistant across the transect, and thus each cell, with the exceptions of the marginal cells, is equal in width. The downstream dimensions of each cell are determined by the distance to mid-point between each transect and the transects immediately up- and downstream.

Table 3.1 Number of observation points per transect

Transect	Blithe Bridge	Blithe Dam	Hampstall Ridware	Empingham	Ryhall	Belmesthorpe
1A	30	31	30	24	25	26
2B	28	32	31	25	28	29
3C	31	33	32	30	26	26
4D	29	28	29	29	26	26
5E	28	27	28	29	27	26
6F	26	29	32	27	28	29
7G	31	34	31	31	30	30
8H	31	31	30	27	28	30
9I	30	29	24	28	27	25
10J	28	31	27	28	26	26
11K	29	29	28	24	26	29
12L	27	25	29	29	25	26
13M	26	32	32	27	29	29
14N	28	32	31	27	26	26
15O	27	30	32	26	27	29
16P	29	30	28		26	
17Q	27	30	28		28	
18R	26	26	29		26	
19S		27				
20T		32				
Max	31	34	32	31	30	30
Min	26	25	24	24	25	25

At each observation point across the transect, data were assembled of bed elevation using levelling. The data are processed to x,y coordinates, with x being the distance away from the transect headpin and y being the bed elevation. Cover and substrate codes were assigned to each cell using the conditional criteria scheme proposed by Trihey and Wegner (1981), presented in Tables 3.2 and 3.3 respectively. In the cover classification scheme, object cover is a combination of features within the channel, such as boulders, tree trunks or vegetation.

Under different flows, observations of mean column velocity were made at each observation point, and the mean water surface elevation measured. Flows at which these velocity and water surface elevations are made are termed

Table 3.2 Conditional cover classification scheme

Cover	Description
0.	No physical cover
1.	0 - 25% of the cell affected by object cover
2.	25 - 50% of the cell affected by object cover
3.	50 - 75% of the cell affected by object cover
4.	75 - 100% of the cell affected by object cover
5.	0 - 25% of the cell has overhanging vegetation
6.	25 - 50% of the cell has overhanging vegetation
7.	50 - 75% of the cell has overhanging vegetation
8.	75 - 100% of the cell has overhanging vegetation
9.	0 - 25% of the cell has undercut bank
10.	25 - 50% of the cell has undercut bank
11.	50 - 75% of the cell has undercut bank
12.	75 - 100% of the cell has undercut bank
13.	0 - 25% of the cell affected by object cover combined with overhanging vegetation
14.	25 - 50% of the cell affected by object cover combined with overhanging vegetation
15.	50 - 75% of the cell affected by object cover combined with overhanging vegetation
16.	75 - 100% of the cell affected by object cover combined with overhanging vegetation
17.	0 - 25% of the cell affected by object cover combined with undercut bank
18.	25 - 50% of the cell affected by object cover combined with undercut bank
19.	50 - 75% of the cell affected by object cover combined with undercut bank
20.	75 - 100% of the cell affected by object cover combined with undercut bank
21.	0 - 25% of the cell has a combination of undercut bank and overhanging vegetation
22.	25 - 50% of the cell has a combination of undercut bank and overhanging vegetation
23.	50 - 75% of the cell has a combination of undercut bank and overhanging vegetation
24.	75 - 100% of the cell has a combination of undercut bank and overhanging vegetation
25.	0 - 25% of the cell has a combination of object cover, undercut bank and overhanging vegetation
26.	25 - 50% of the cell has a combination of object cover, undercut bank and overhanging vegetation
27.	50 - 75% of the cell has a combination of object cover, undercut bank and overhanging vegetation
28.	75 - 100% of the cell has a combination of object cover, undercut bank and overhanging vegetation

SOURCE: Trihey E.W. and Wegner D.L. (1981)

Table 3.3 Substrate classification scheme

1.	Plant
2.	Mud
3.	Silt (<0.062mm)
4.	Sand (0.062 - 2mm)
5.	Gravel (2 - 64mm)
6.	Rubble (64mm - 250mm)
7.	Boulder (250mm - 4000mm)
8.	Bedrock (solid rock)

SOURCE: Trihey E.W. and Wegner D.L. (1981)

'Calibration Flows'. At each of the six reaches one observation was made per cell of bed elevations and cover/substrate. A variable number of calibration flows (up to three) were sampled, at which velocities and water surface elevation were reobserved. The frequency of observed data at each reach are summarised in Table 3.4.

Table 3.4 Frequency of observation of hydraulic and channel parameters

	Number of transects	Bed x,y	Substrate/ Cover	Calibration flows WSL	v
Blithe Bridge	18	1	1	3	3
Blithe Dam	20	1	1	3	3
Hamstall Ridware	18	1	1	3	3*
Empingham	15	1	1	1	1
Ryhall	18	1	1	2	2
Belmesthorpe	15	1	1	2	2

* at 5 transects only for one calibration flow

For each calibration flow, the observed values of bed elevation, water surface elevation and mean column velocities, were used to calculate the discharge using the velocity/area method within PHABSIM. The dates, water surface elevations and calculated discharges of the calibration flows are presented in Table 3.5.

3.3 ECOLOGICAL DATA

The development of microhabitat suitability curves for this study was undertaken by the Institute of Freshwater Ecology (Armitage & Ladle, 1989) and by the Institute of Terrestrial Ecology (Mountford & Gomes, 1990). The reports are presented in full in Annex 1 and 2 respectively and summarised below.

Habitat preferences of target species for application in PHABSIM testing (Armitage & Ladle, 1989).

Habitat preference curves for eight species of fish and five species of invertebrate are presented. The fish curves are based on expert and local knowledge of UK conditions, and fall into the Category I type of habitat suitability curves. Curves are developed for four life stages for each species (spawning, fry, juvenile and adult) and express habitat suitability for velocity, depth and substrate. Suitability for cover is expressed for a limited number of adult and juvenile species. The invertebrate curves are derived from analysis of the River Communities Project database, a large body of sampled information held at the IFE River Laboratory at Wareham. The curves were

Table 3.5 Date, water surface elevations (WSL) and discharges (Q) of calibration flows

Site: Gwash Empingham

X-sec	Date	WSL	Q
A1	21/2/89	322.59	4.5
B2	27/2/89	322.32	2.5
C3	23/2/89	322.45	2.1
D4	27/2/89	322.46	3.4
E5	24/2/89	322.42	5.4
F6	28/2/89	322.40	3.9
G7	22/2/89	322.37	1.0
H8	27/2/89	322.45	3.0
I9	24/2/89	322.52	4.2
J10	23/2/89	322.47	3.3
K11	28/2/89	322.37	1.6
L12	24/2/89	322.35	2.5
M13	23/2/89	322.28	2.6
N14	27/2/89	322.38	2.9
O15	22/2/89	322.34	2.7

Site: Gwash Ryhall

X-sec	Date	WSL	Q	Date	WSL	Q
A1	2/3/89	324.81	13.9	17/1/90	324.87	20.5
B2	3/3/89	324.63	14.9	17/1/90	324.80	21.2
C3	1/3/89	324.49	17.4	17/1/90	324.56	13.3
D4	2/3/89	324.28	10.6	17/1/90	324.50	24.1
E5	7/3/89	324.21	10.2	17/1/90	324.42	13.8
F6	2/3/89	324.19	10.5	17/1/90	324.40	21.7
G7	7/3/89	324.15	12.3	17/1/90	324.34	13.6
H8	3/3/89	324.15	13.1	17/1/90	324.29	22.1
I9	7/3/89	324.06	10.9	17/1/90	324.23	16.7
J10	1/3/89	323.96	14.7	17/1/90	324.15	18.6
K11	2/3/89	323.82	13.2	17/1/90	324.09	16.8
L12	3/3/89	323.88	16.0	17/1/90	324.09	18.4
M13	7/3/89	323.71	12.8	17/1/90	323.98	20.8
N14	2/3/89	323.58	9.4	17/1/90	323.90	18.2
O15	3/3/89	323.59	12.6	17/1/90	323.90	17.7
P16	2/3/89	323.51	12.5	17/1/90	323.86	20.5
Q17	7/3/89	323.50	12.8	17/1/90	323.82	21.0
R18	1/3/89	323.39	12.8	17/1/90	323.77	*

* Velocities not observed because transect x-section disturbed.

Table 3.5 continued

Site: Gwash Belmesthorpe

X-sec	Date	WSL	Q	Date	WSL	Q
A1	14/3/89	323.91	12.1	17/1/90	324.08	19.6
B2	08/3/89	323.94	10.4	17/1/90		*
C3	09/3/89		†	17/1/90	324.07	12.7
D4	13/3/89	323.85	11.0	17/1/90	324.07	20.0
E5	09/3/89	323.93	10.9	17/1/90	324.07	23.1
F6	13/3/89	323.87	9.3	17/1/90		⊕
G7	09/3/89	323.91	12.7	16/1/90	324.04	18.3
H8	08/3/89	323.86	10.1	16/1/90	324.04	20.9
I9	09/3/89	323.91	9.5	16/1/90	324.04	16.8
J10	13/3/89	323.77	7.8	16/1/90	324.02	22.6
K11	09/3/89	323.89	12.8	16/1/90	324.03	19.2
L12	13/3/89	323.84	8.5	16/1/90	323.03	22.0
M13	09/3/89	323.86	10.9	16/1/90	324.01	15.6
N14	08/3/89	323.83	9.5	16/1/90	324.00	19.7
O15	13/3/89	323.76	11.5	16/1/90	323.93	20.1

* Neither original headpin 2 or B could be relocated, therefore transect abandoned on 17/1/90.
† No sensible Water Surface Elevation can be calculated.
⊕ Neither original headpin 6 or F could be relocated, therefore transect abandoned on 17/1/90.

Site: Blithe - Blithe Dam

X-sec	Date	WSL	Q	Date	WSL	Q	Date	WSL	Q
A1	28/2/89	324.34	13.7	12/4/89	325.41	87.2	1/2/90	325.33	70.8
B2	01/3/89	324.23	12.6	12/4/89	325.34	85.3	1/2/90	325.39	81.8
C3	28/2/89	324.16	13.1	12/4/89	325.17	87.4	1/2/90		*
D4	01/3/89	324.20	11.5†	12/4/89	325.08	78.5	1/2/90	325.08	69.1
E5	28/2/89	324.00	12.3	12/4/89	325.10	78.2	1/2/90	325.09	64.7
F6	01/3/89	324.00	12.6	12/4/89	325.09	76.0	1/2/90	325.10	66.3
G7	01/3/89	324.02	12.3	12/4/89	325.08	84.5	1/2/90	325.03	66.0
H8	28/2/89	323.99	12.4	12/4/89	325.0	78.8	1/2/90	324.97	74.0
I9	27/2/89	323.96	11.3	12/4/89	324.97	72.8	1/2/90	324.91	65.6
J10	01/3/89	323.94	14.4	12/4/89	324.88	85.1	1/2/90	324.81	76.4
K11	01/3/89	323.86	18.4	12/4/89	324.85	75.1	1/2/90	324.79	76.1
L12	28/2/89	323.87	13.6	12/4/89	324.86	73.3	1/2/90	324.81	74.7
M13	01/3/89	323.85	20.1	12/4/89	324.63	90.8	1/2/90	324.68	81.8
N14	27/2/89	323.75	13.6	12/4/89	324.61	76.6	1/2/90	324.65	75.9
O15	28/2/89	323.72	12.9	12/4/89	324.60	80.2	1/2/90	324.58	79.6
P16	01/3/89	323.70	13.8	12/4/89	324.58	82.4	1/2/90	324.58	75.8
Q17	28/2/89	323.63	12.5	12/4/89	324.49	83.1	1/2/90	324.55	66.9
R18⊕	28/2/89	323.73	18.7	12/4/89	324.52	111.1	1/2/90	324.57	122.0
S19	01/3/89	323.67	12.9	12/4/89	324.38	75.8	1/2/90	324.45	72.9
T20	27/2/89	323.56	15.3	12/4/89	324.24	77.8	1/2/90	324.37	74.7

* Flows not observed: no explanation on data sheets.
† Original WSL data and calculated Q too low: corrected data represent adjustment made on basis of setting WSL to value between B2 and F6 to give a sensible calculated discharge.
⊕ All observed Water Surface Elevations and thus calculated Qs appear too high in this transect, with WSLs appearing to be approx 0.1ft too high. However, no error can be traced in the original head-pin elevation survey.

Table 3.5 continued

Site: Blithe - Blithe Bridge

X-sec	Date	WSL	Q	Date	WSL	Q	Date	WSL	Q
A1	02/3/89*								
B2	03/3/89	326.06	88.9	28/6/89	325.26	16.6	15/1/90	325.49	37.1
C3	08/3/89	325.44	39.6	28/6/89	325.22	12.4	15/1/90	325.45	33.6
D4	03/3/89	325.90	77.1	28/6/89	325.22	16.7	15/1/90	325.46	81.7⊕
E5	08/3/89	325.50	33.0	28/6/89	325.21	5.3	15/1/90	325.44	25.0
F6	02/3/89	325.95	102.5	28/6/89	325.17	11.3	15/1/90	325.40	34.7
G7	03/3/89	325.75	78.6	28/6/89	325.05	12.1	15/1/90	325.07	25.5
H8	07/3/89	325.31	43.3	28/6/89	324.84	11.1	15/1/90	325.06	22.7
I9	08/3/89	325.16	36.5	28/6/89	324.77	9.9	15/1/90	324.98	28.7
J10	07/3/89	325.29	58.4	28/6/89	324.71	5.5	15/1/90	324.96	32.3
K11	03/3/89	325.54	77.8	28/6/89	324.72	11.4	15/1/90	324.93	27.3
L12	07/3/89	325.10	46.6	28/6/89	324.68	10.9	15/1/90	324.91	26.8
M13	02/3/89	325.94	112.4	28/6/89	324.66	10.3	15/1/90	324.91	27.7
N14	03/3/89	326.01	102.0†	28/6/89	324.37	9.4	15/1/90	324.75	30.2
O15	03/3/89	325.45	96.3 ⊕	28/6/89	324.31	10.7	15/1/90	324.66	32.3
P16	07/3/89	324.87	42.9	28/6/89	324.25	9.6	15/1/90	324.50	27.2
Q17	03/3/89	325.32	77.3	28/6/89	324.25	8.5	15/1/90	324.51	28.6
R18	07/3/89			28/6/89	324.23		15/1/90	324.44	

* Transect A1 could not be relocated after 2/3/90, therefore transect abandoned after this date.
† Observed Water Surface Elevation and calculated discharge appears to be too high but no obvious solution can be traced.
⊕ Calculated discharge appears to be too high but no obvious solution can be identified.

Site: Blithe - Hamstall Ridware

X-sec	Date	WSL	Q	Date	WSL	Q	Date	WSL	Q
A1	21/2/89	325.03	22.9	13/4/89	325.54	83.8	2/2/90	326.12	136.3
B2	21/2/89	324.91	22.9	13/4/89	325.46	83.6	2/2/90	326.08	140.2
C3	22/2/89	324.88	26.3	13/4/89	325.41	81.5	2/2/90	326.08	140.2
D4	23/2/89	324.77	19.8	13/4/89	325.41	69.5	2/2/90	326.06	140.2
E5	24/2/89	324.73	20.4	13/4/89	325.40	88.8	2/2/90	326.05	141.8
F6	21/2/89	324.66	20.8	13/4/89	325.23	78.6	2/2/90	325.98	140.2
G7	22/2/89	324.64	19.7	13/4/89	325.20	80.9	2/2/90	325.97	140.2
H8	23/2/89	324.61	19.5	13/4/89	325.10	80.8	2/2/90	325.95	142.7
I9	24/2/89	324.48	27.1	13/4/89	324.95	88.3	2/2/90	325.91	140.2
J10	23/2/89	324.34	21.9	13/4/89	324.82	80.7	2/2/90	325.91	140.2
K11	22/2/89	324.09	23.0	13/4/89	324.74	75.2	2/2/90	325.87	145.4
L12	21/2/89	323.98	23.4	13/4/89	324.63	76.7	2/2/90	325.78	140.2
M13	23/2/89	323.90	22.9	13/4/89	324.58	75.3	2/2/90	325.78	137.1
N14	24/2/89	323.75	23.2	13/4/89	324.53	67.6	2/2/90	325.78	140.2
O15	22/2/89	323.72	23.2	13/4/89	324.49	70.6	2/2/90	325.78	138.1
P16	22/2/89	323.56	20.9	13/4/89	324.35	69.4	2/2/90	325.78	140.2
Q17	23/2/89	323.67	22.3	13/4/89	324.44	53.3	2/2/90	325.77	140.2
R18	22/2/89	323.50	21.5	13/4/89	324.27	73.8	2/2/90	325.71	140.2

Discharge observations on 2/2/90 for transects B2, C3, D4, F6, G7, I9, J10, L12, N14, P16, Q17 and R18 are estimated as the mean of the other six observed discharges.

based on the frequency of observed occurrence of the five invertebrates in the data set in relation to the physical variables. The invertebrate curves fall into the Category II type and represent habitat utilisation curves. Curves are developed for the larval stages of the insects and the adult stage for the pea-mussel, and express habitat utilisation for velocity, depth and substrate.

The eight fish species were selected because they represent the major fish populations of the rivers Gwash and Blithe at these sites. Invertebrates were selected to represent widely occurring species with narrow ecological limits. These consisted of three insects, (the two stoneflies *Leuctra fusca* and *Isoperla grammatica* and the caddis-fly *Rhyacophila dorsalis*) which are typical of high velocity reaches and two species, the *Polycentropus flavomaculatus* (caddis-fly) and *Sphaerium corneum* (pea mussel), which are characteristic of low velocity reaches.

Habitat preference of river water-crowfoot (*Ranunculus fluitans* Lam.) for application in PHABSIM testing (Mountford & Gomes, 1990)

Habitat preference curves are presented for the aquatic macrophyte *Ranunculus fluitans* Lam., commonly known as river water-crowfoot. This species was selected because of its abundance in both rivers. Category II utilisation curves were constructed as univariate curves from the observed abundance of the species in the river Blithe. No smoothing functions were applied to the observed data.

4. PHABSIM simulations and results

4.1 SIMULATIONS

Table 4.1 identifies the hydraulic simulation routines satisfied by data availability at each of the six reaches.

Table 4.1 Hydraulic simulation options satisfied by observed calibration data

	IFG4	MANSQ	WSP
BLITHE BRIDGE	*	*	*
BLITHE DAM	*	*	*
HAMSTALL RIDWARE	*	*	*
EMPINGHAM		*	
RYHALL		*	*
BELMESTHORPE		*	*

Figure 4.1 represents the flow of data through the PHABSIM system assuming three stage-discharge pairs and one velocity set. This path structure was employed during the simulations for each of the three Blithe sites and the Ryhall and Belmesthorpe sites. The amount of calibration data assembled for the Empingham site is inadequate to run any of the simulation routines with sensible verification options.

Because of data inadequacies and unresolvable problems certain transects were deleted from the calibration data sets prior to running the simulations, and these are detailed in Table 4.2.

As detailed in section 2.3, the hydraulic simulation routines predict values of the physical properties at flows which differ from the calibration flows. These simulation flows, so far termed Q_{SIM} for the sake of simplicity, are termed QARD flows within the PHABSIM system. The user is free to select values for the QARD flows, but the PHABSIM system does impose upper and lower bounds based on the magnitude of the calibration flows. These bounds are imposed to ensure that simulations are based upon realistic extrapolations of the observed data. The extrapolation limits depend upon the number of calibration sets which have been observed. The imposed extrapolation bounds are summarised in Table 4.3, and based on these values the recommended extrapolation limits for the five reaches are presented. The same lower and

Flow of Data through PHABSIM
(AssumesThree Stage-Discharge Pairs and One Velocity Set)

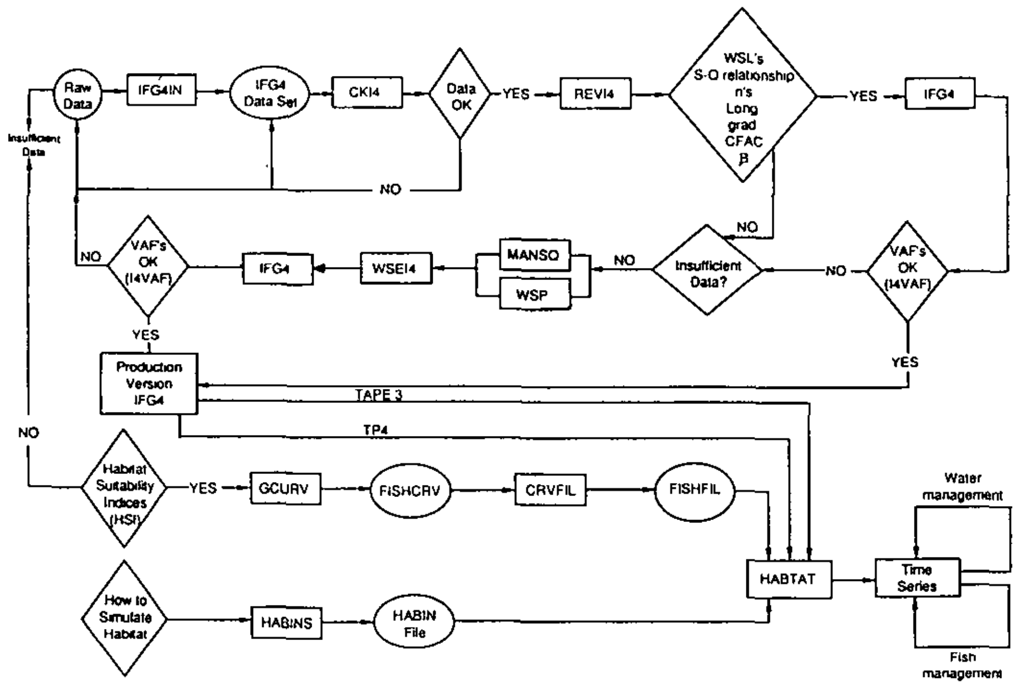


Figure 4.1 Flow of data through the PHABSIM system

Table 4.2 Transects deleted from analysis prior to simulation runs

	DELETED TRANSECTS	REASON
BLITHE BRIDGE	A1	Neither peg could be relocated after March 1989
	D4	Untraceable errors in bed elevation data
	R18	Transect at lowest end of reach
BLITHE DAM	C3	Highest calibration flow not observed; no explanation on field survey sheets
	R18	Untraceable errors in bed elevation data
	T20	Transect at lowest end of reach
HAMPSTALL RIDWARE	R18	Transect at lowest end of reach
EMPINGHAM	None	
RYHALL	R18	Transect at lowest end of reach
BELMESTHORPE	B2	Neither peg could be relocated in Jan 1990
	C3	Untraceable errors in one water surface elevation
	F6	Neither peg could be relocated after March 1989
	O15	Transect at lowest end of reach

Table 4.3 Extrapolation bounds imposed by PHABSIM upon the selection of simulation discharges

Hydraulic simulation extrapolation limits (all models)

No. of calibration sets	Lower limit	Upper limit
1	$0.4 \times Q_{measured}$	$2.5 \times Q_{measured}$
3	$0.4 \times Q_{lowest}$	$2.5 \times Q_{highest}$
5	$<= 0.4 \times Q_{lowest}$	$>= 2.5 \times Q_{highest}$

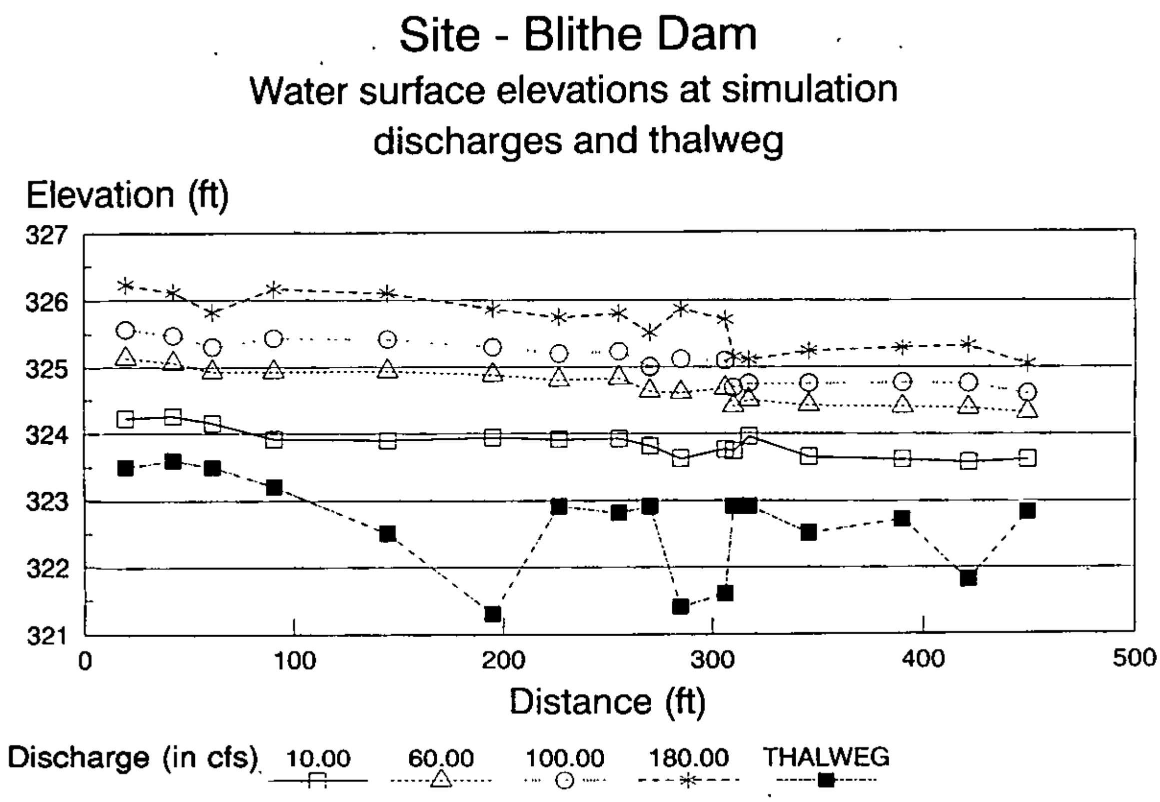
	Recommended lower limit	Recommended upper limit
Blithe Bridge	6.7	82.5
Blithe Dam	8.0	182.0
Hamstall Ridware	7.8	340.8
Ryhall	7.0	33.3
Belmesthorpe	5.1	39.0

Note
Lower limit calculated from 0.4 * the highest value of the lowest calibration discharge amongst the different transects.

Upper limit calculated from 2.5 * the lowest value of the highest calibration discharge amongst the different transects.

upper limit was applied to all transects in a reach, instead of each transect having a different range. Within the extrapolation limits the selection of QARD flows at each site was made to ensure a representation of the full flow range available for simulation.

Model simulations were run using IFG4 on the five sites, using MANSQ to simulate water surface elevations on transects where the VAF curves were theoretically unrealistic. The simulated longitudinal water surface profiles are presented in Figure 4.2. Despite the inconsistent prediction of water surface elevations in a downstream direction at certain reaches no attempt was made to improve the simulation output. In all simulations, substrate was used as the channel index and the channel cover classification values were not used in this study. A multiplicative Composite Suitability Index function was adopted throughout.



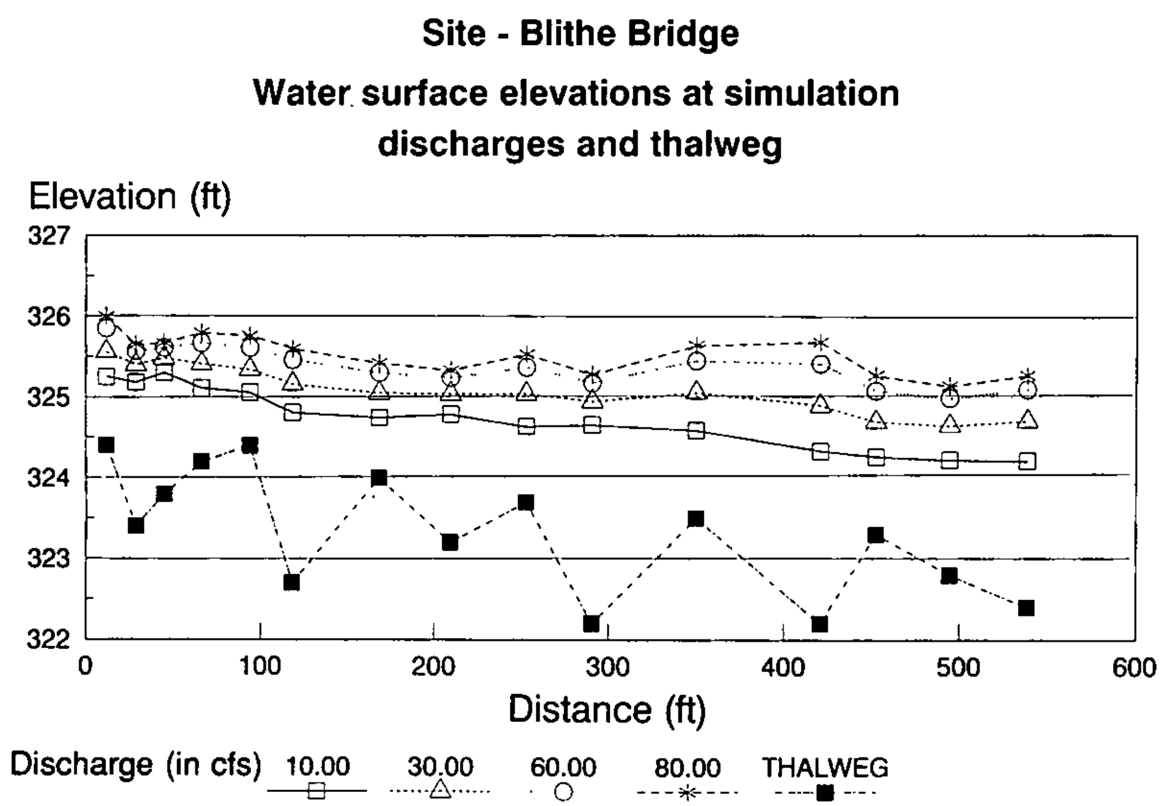
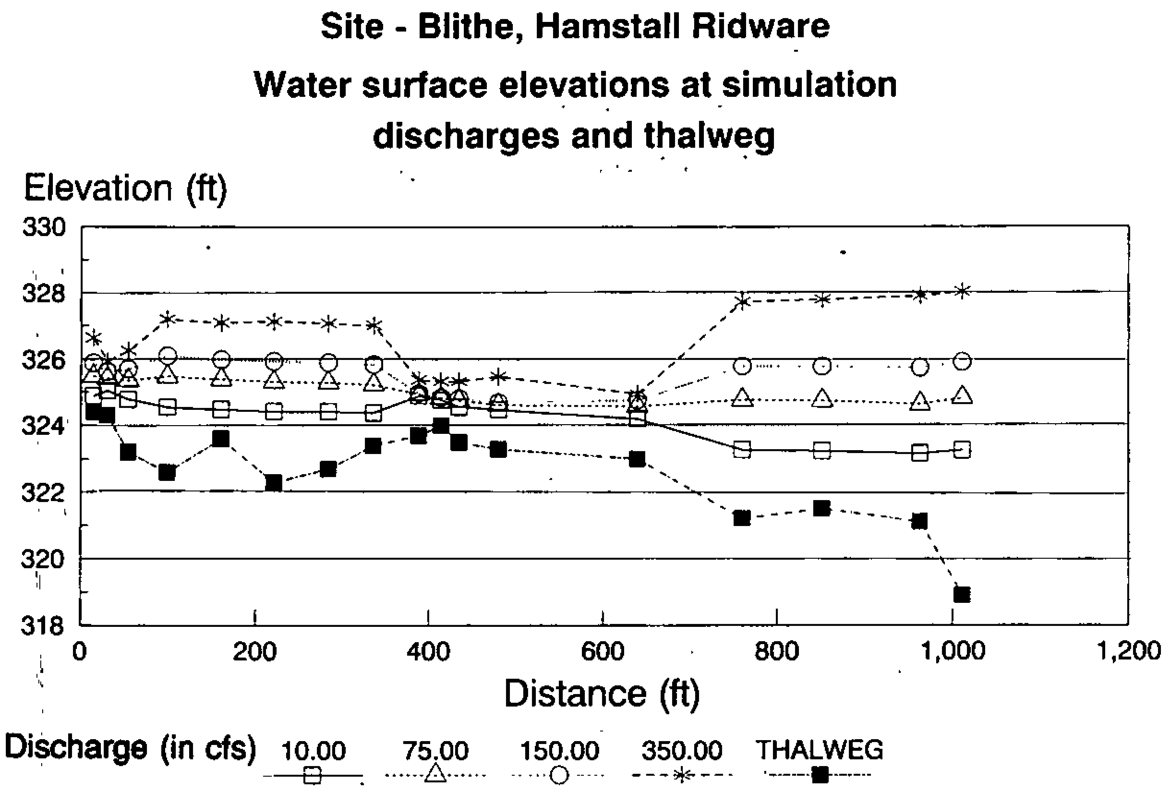


Figure 4.2 Simulated longitudinal water surface profiles for selected discharges



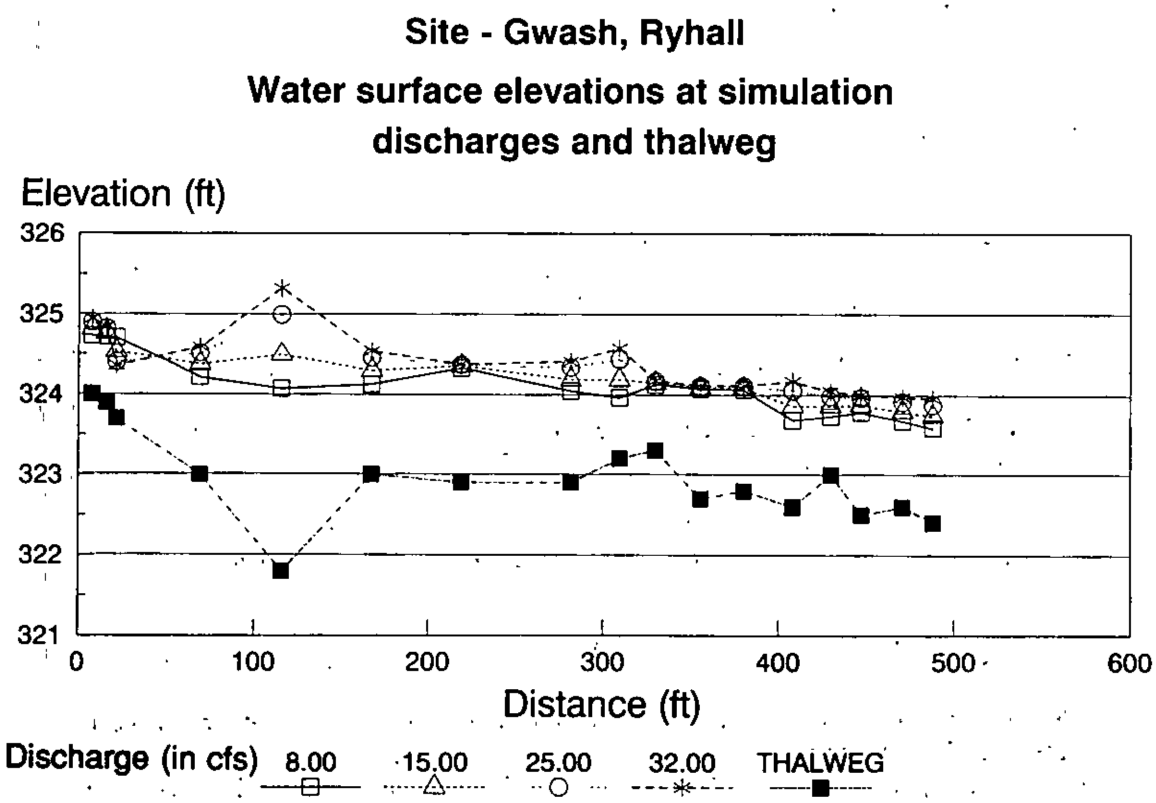


Figure 4.2 continued

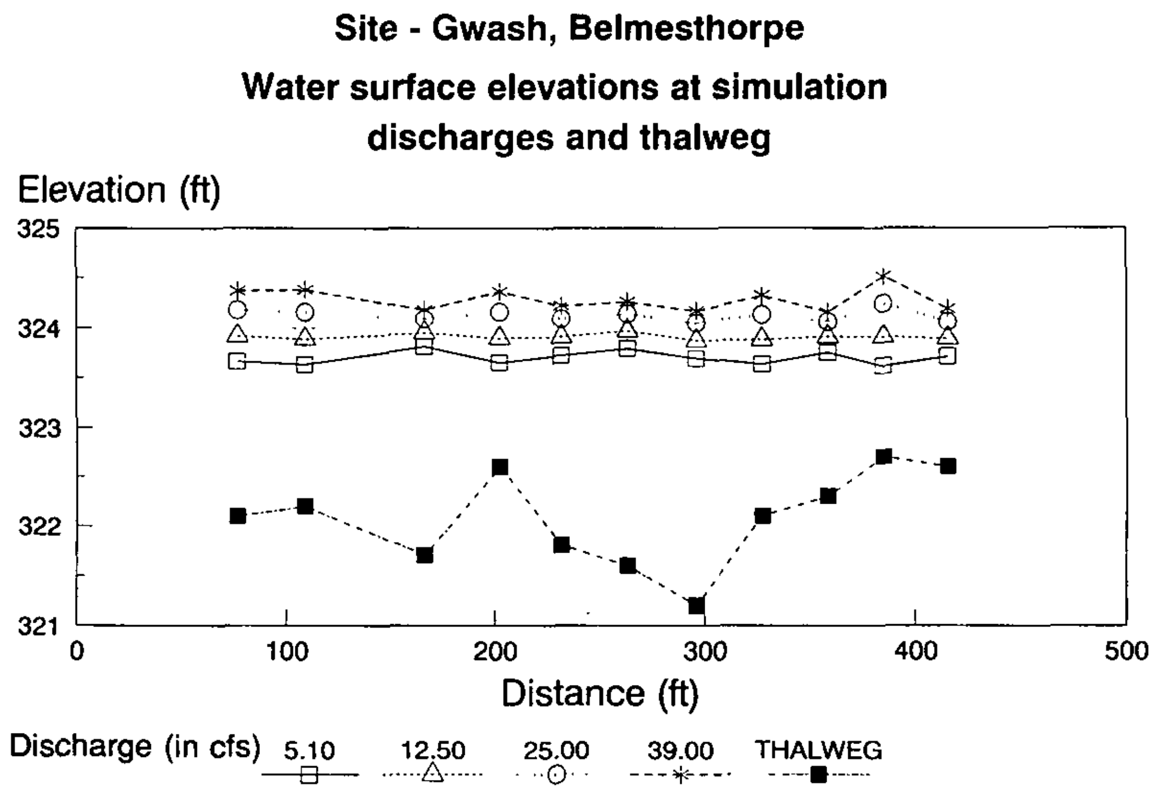


Figure 4.2 continued

4.2 RESULTS

PHABSIM simulations have been used to generate estimates of weighted usable area for each of the QARD flows for each life stage of each target species. This report presents these output data in three ways:

a) Weighted Usable Area against discharge functions for each reach;

b) Weighted Usable Area duration curves for the four life stages of brown trout and the stone-fly *Leuctra fusca* at Blithe Dam and Ryhall;

c) Pre- and post-impoundment Weighted Usable Area duration curves for adult brown trout and *Leuctra fusca* at Blithe Dam and Ryhall.

a) Weighted Usable Area against discharge functions for each reach

Weighted Usable Area versus discharge functions for each life stage of each target species are presented in Figures 4.3 for the Blithe Bridge site, and the equivalent figures for Blithe Dam, Hamstall Ridware, Ryhall and Belmesthorpe are presented in Appendix 2. In each case WUA versus discharge functions are compared with the total available habitat area. Habitat area, both total and weighted, is expressed in units of square feet/1,000 feet of river length. In

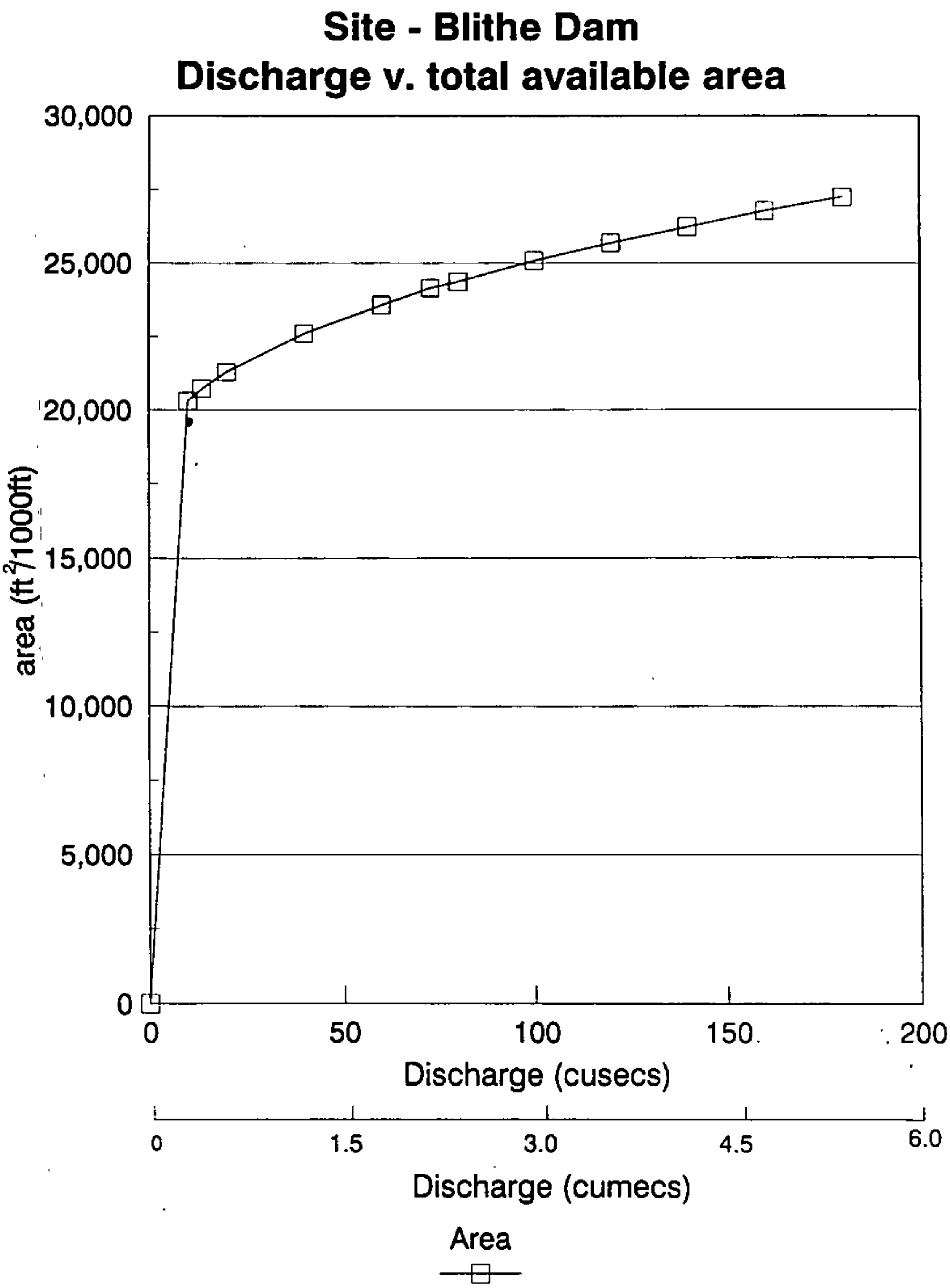


Figure 4.3 Weighted Usable Area against discharge relationships for all target species at Blithe Bridge

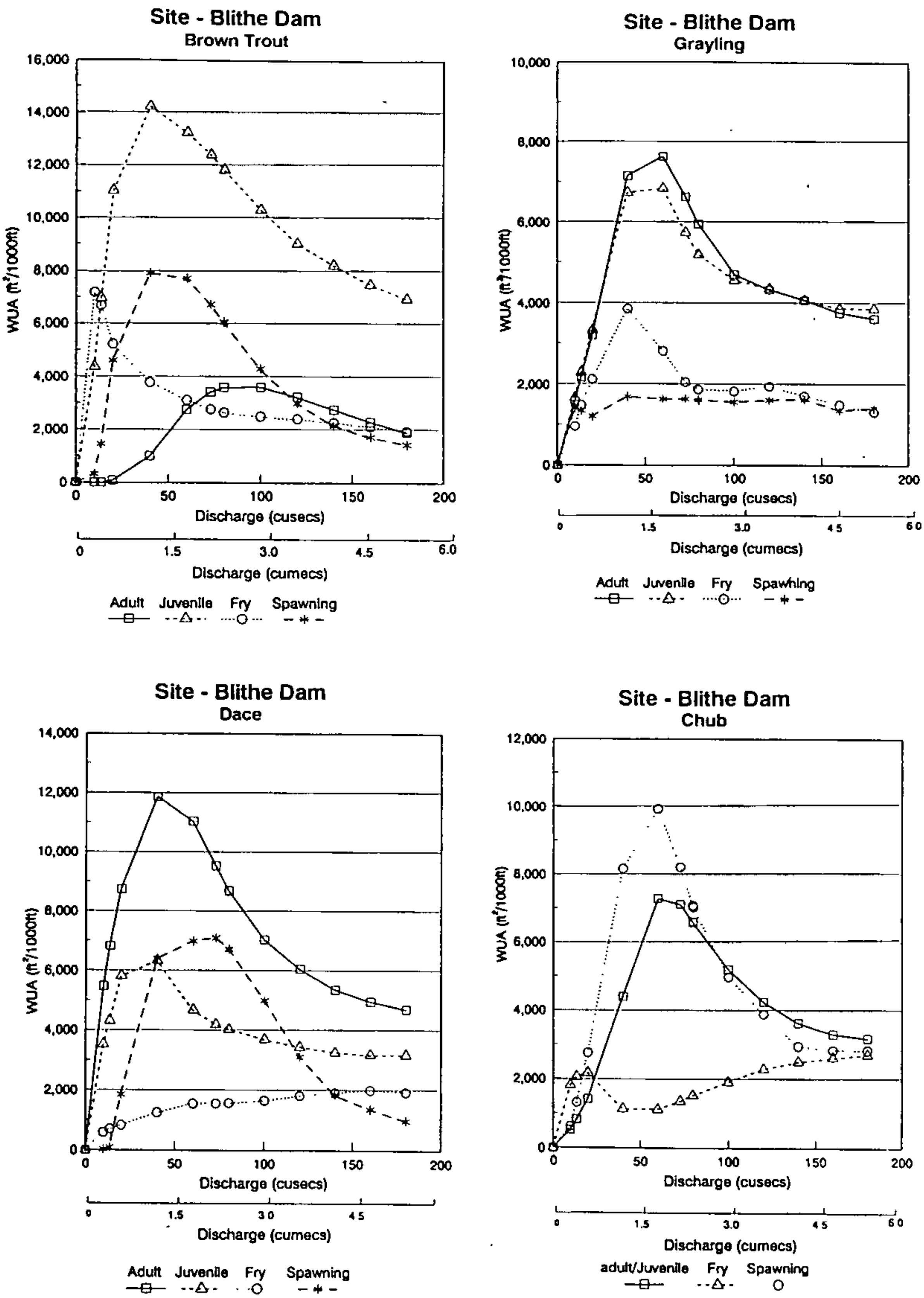
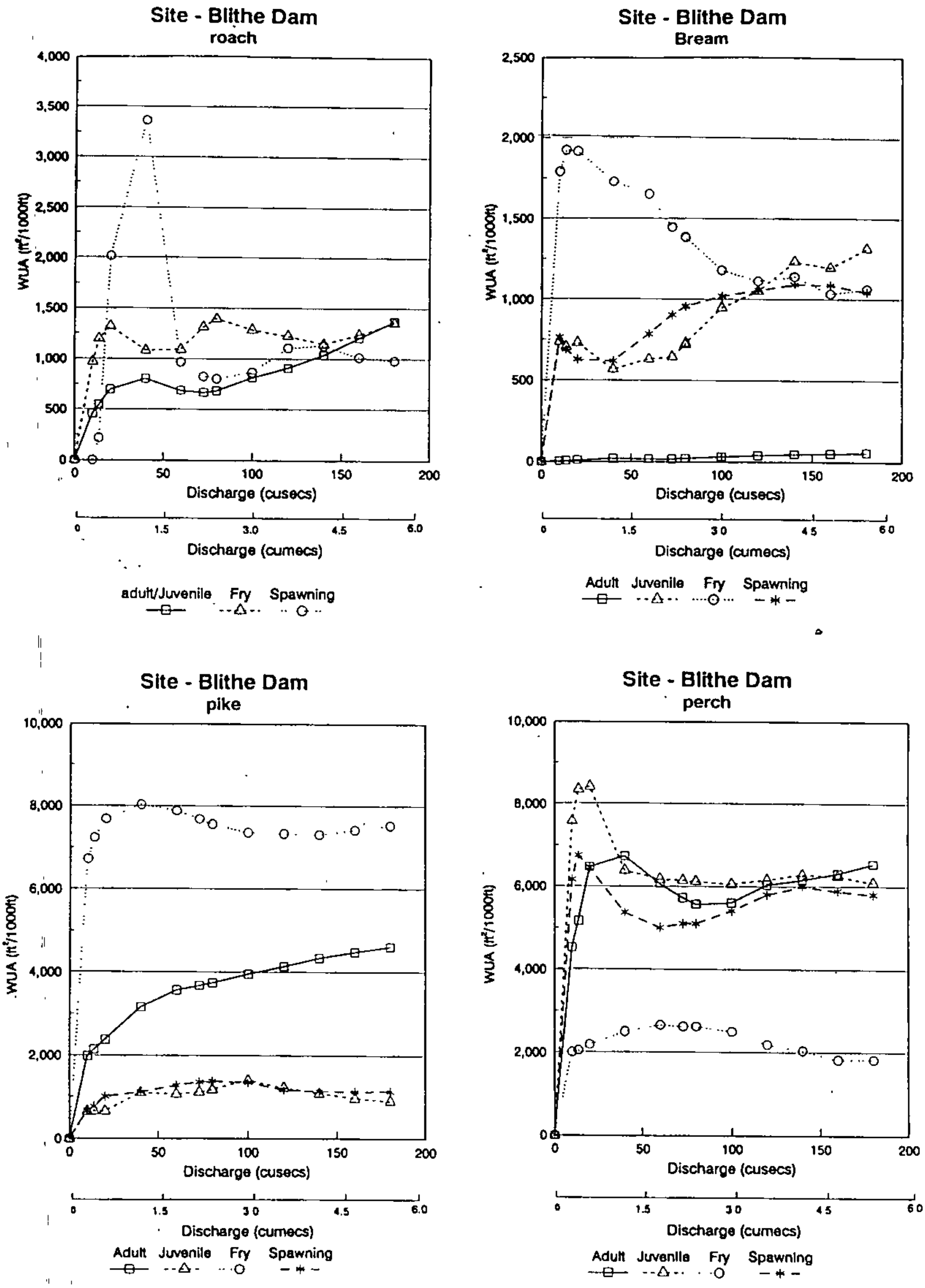


Figure 4.3 (Continued)



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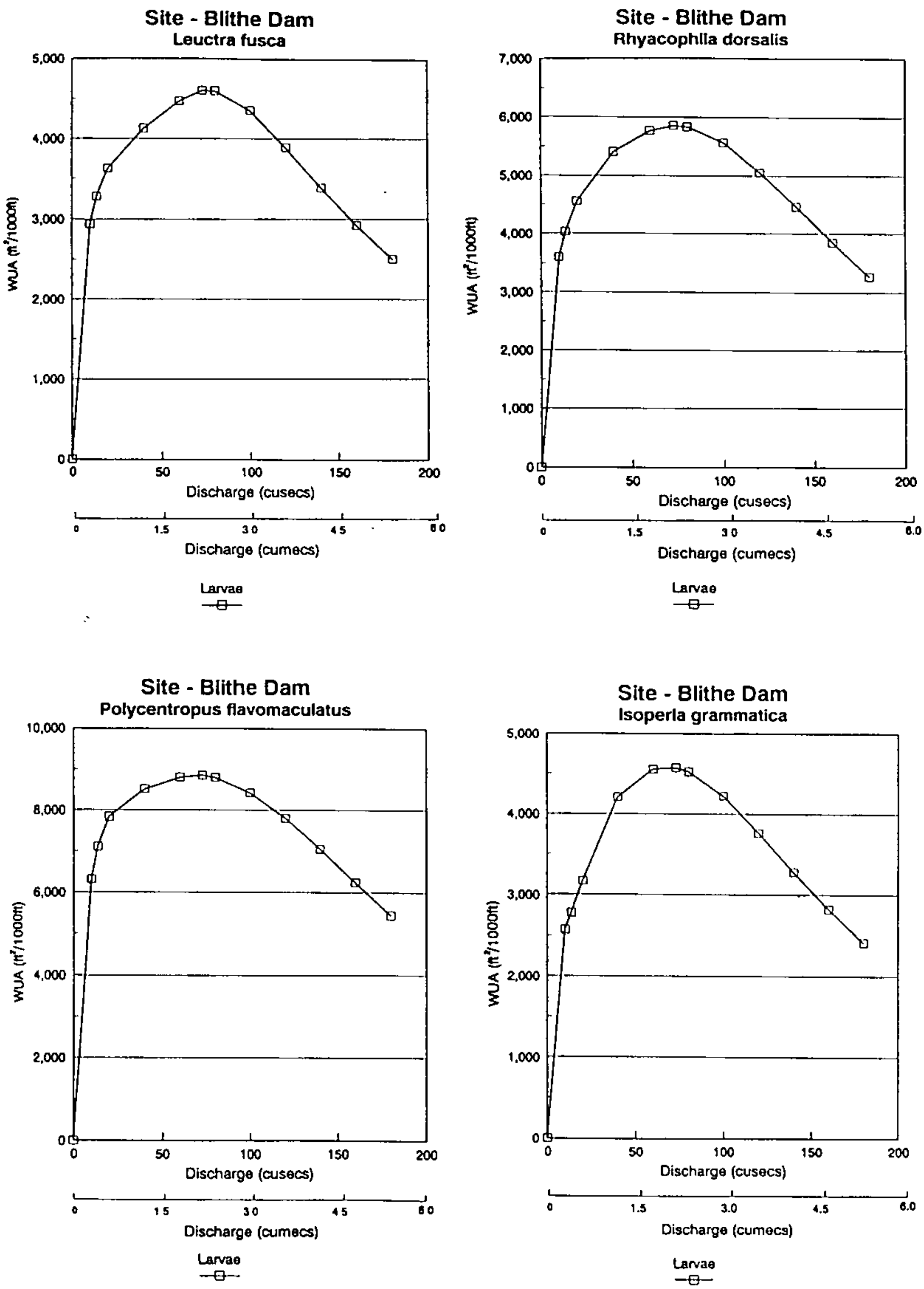

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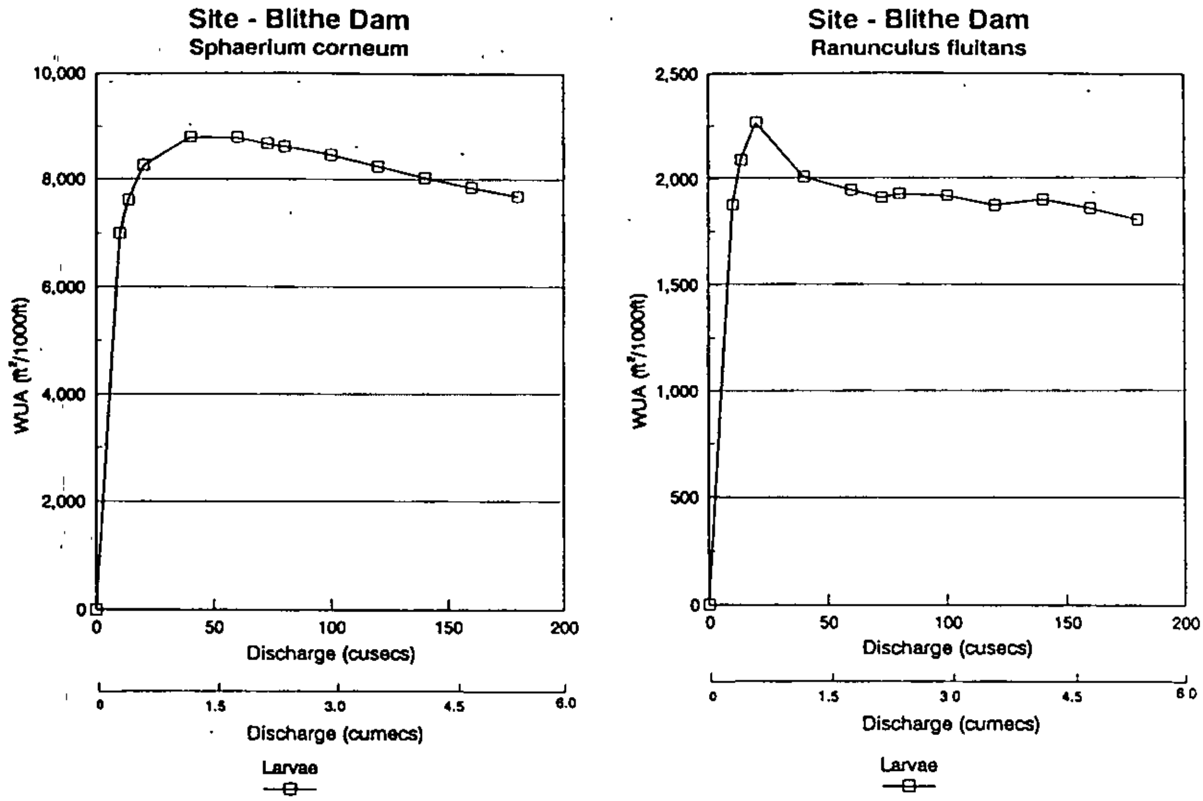


Figure 4.3 (Continued)

the case of total habitat area, these units represent the total plan area of water surface within the reach, and in the case of WUA the total habitat area has been multiplied by the Multiplicative Composite Suitability Index.

The total habitat areas available at each of the five sites are of approximately the same order, being 22,000 ft^2/1000 ft at $1m^3/s$ at Ryhall, Belmesthorpe and Blithe Dam, 27,000 ft^2/1000 ft at Blithe Bridge rising to 32,000 ft^2/1000 ft at Hamstall Ridware. Total habitat area increases with discharge at each site as the plan surface area of the river extends with rising stage over the sloping channel banks. The channel forms are largely rectangular in the sampled cross-sections and the increase in plan area is small for incremental stage rises compared with the increases one would anticipate from a channel with shallow sloping banks; a 400% increase in discharge from 0.25 m^3/s at Ryhall results in total habitat area increasing by less than 5%. The absence of marked within-channel features within the range of simulated stages and containment within bank-full capacity results in smooth total habitat area versus discharge relationships which lack significant inflections.

The Weighted Usable Area versus discharge relationships exhibit different forms and absolute values amongst different life stages of the same fish species. At Blithe Bridge, for example, physical habitat for the adult and juvenile life stages of each species exhibits essentially the same relationship to discharge, albeit differing in absolute amounts. Relative to the adult and juvenile stages, the fry stages of each species can possess very different amounts of physical habitat; either similar, as in the case of brown trout, roach, and perch or considerably less throughout the discharge range, as in the case of grayling chub and dace or considerably more (bream and pike). The spawning stages exhibit a similar diversity of relationships. There are also considerable variations amongst different fish species at the same site. For example, whilst there is considerable physical habitat available throughout the simulated flow range for chub, grayling, dace, perch, and in particular juvenile brown trout, there is less than 5% of the total habitat available for juvenile roach and pike and none at all for juvenile bream. In general, the relationships are similar between the five sites for each of the life stages, though comparisons are complicated by the different ranges of simulated flows. There are, however, notable differences in the amounts of physical habitat available in the River Gwash compared to the River Blithe, for example available habitat increases by at least an order of magnitude for pike and bream at Belmesthorpe compared to Blithe Bridge. The invertebrate relationships exhibit a much greater consistency in form and absolute values than the fish species. At Blithe Bridge macroinvertebrate species which prefer lower velocities, *Polycentropus flavomaculatus* and *Sphaerium corneum* possess greater amounts of available habitat than the species with preference for higher velocities. Indeed, habitat availability for *Sphaerium corneum* peaks at low flows and decreases with higher flows, whereas for the other species habitat increases at higher flows, and therefore higher velocities. Above a certain threshold, habitat availability for *Ranunculus fluitans* remains constant and insensitive to discharge.

The Weighted Usable Area versus discharge relationships displayed by the life stages can be said to accord to seven basic forms, as summarised in Figure 4.4. In interpreting the format of the curves one must be aware of the

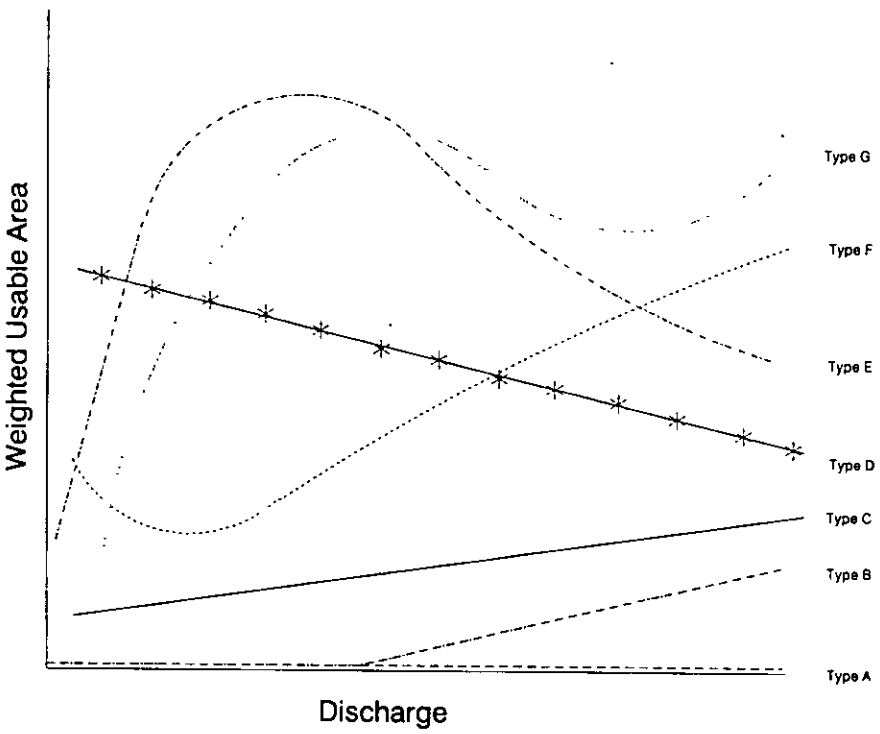


***Figure 4.4** Basic forms of Weighted Usable Area against discharge relationships*

tendency of the PHABSIM system to extrapolate the WUA versus discharge relationship below the lowest simulated flow to zero flow. This can introduce sharp inflections into the curve shapes so identification of the seven basic forms is founded upon the simulated flow range alone. The characteristics of each form, and an example from the Blithe Bridge relationships in Figures 4.3, are summarised as follows:

TYPE A: No physical habitat available throughout the simulated range of flows. Example: adult bream.

TYPE B: No physical habitat available in the lower range of simulated flows but above a certain threshold the amount of physical habitat increases with discharges. Example: spawning bream.

TYPE C: Physical habitat is available across the full range of simulated flows and the amount available continues to increase with higher discharges. Example: larval *Leuctra fusca*.

TYPE D: Physical habitat is available across the full range of simulated flows and the amount available continues to decrease with higher discharges. Example: fry brown trout.

TYPE E: Essentially a Type C curve which attains a peak of physical habitat availability followed by continuous declining habitat. Example: spawning roach.

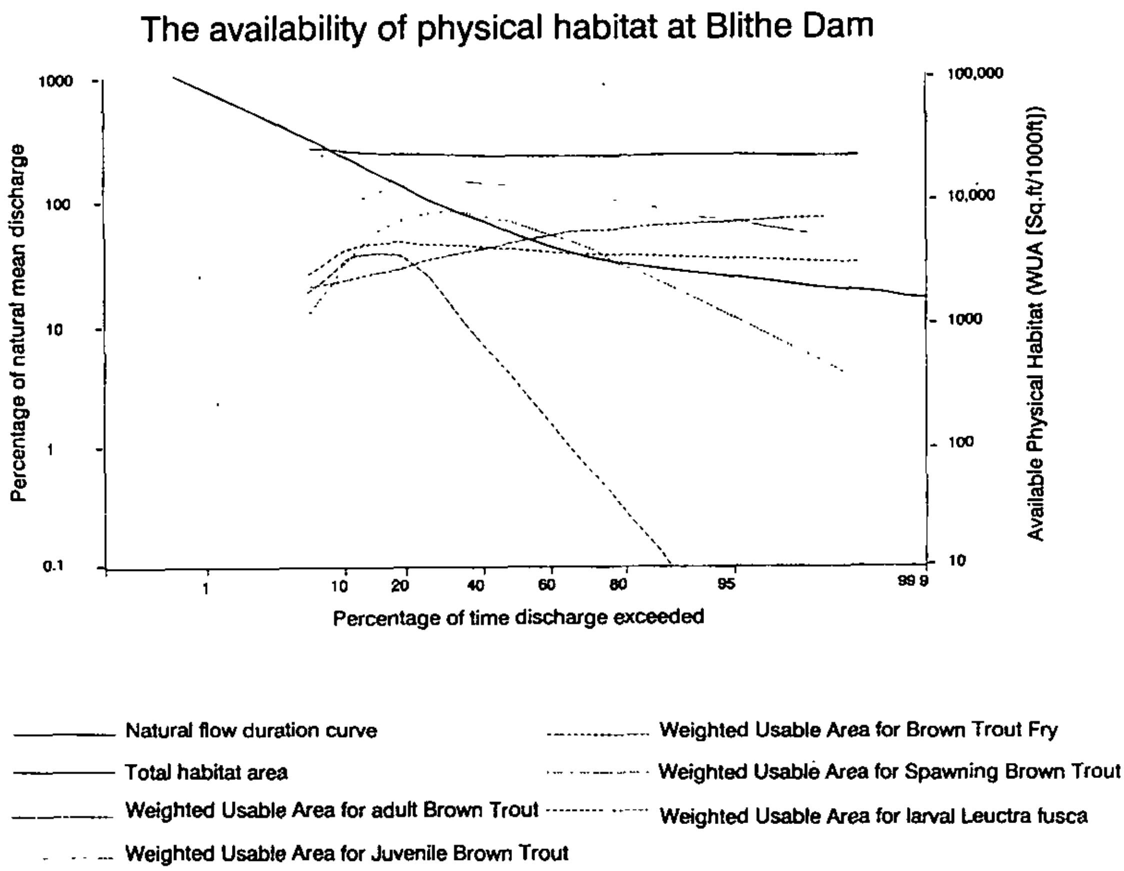
TYPE F: Essentially a Type D curve which attains a trough of physical habitat availability followed by continuous increasing habitat. No example at Blithe Bridge but refer to spawning bream at Hamstall Ridware.

TYPE G: Bimodal Type E or Type F. Example: fry roach.

It will be obvious that some of these Type curves are not in fact unique and that some could represent the sampled limb of another Type curve were the simulated flow range to be extended (for example Type C is merely the rising limb of Type E). However, the distinction is maintained because the form of the curve within the full flow range of a river reach is the critical aspect, even though this may, for example, represent only a single limb of a more complex curve.

b) Weighted Usable Area duration curves

The previous section presented WUA versus discharge relationships without reference to the frequency with which discharges occur in the river reaches. Any consideration of instream flows, and habitat availability, must consider the distribution of river flows over time to enable sensible interpretation and, in the longer term, feasible water management. This section represents a selection of the WUA versus discharge relationships superimposed upon a gauged natural flow duration curve at the Blithe Dam and Ryhall sites (Figure 4.5). In each case the flow duration curve represents the percentage of time that a given discharge (expressed as a percentage of the natural mean



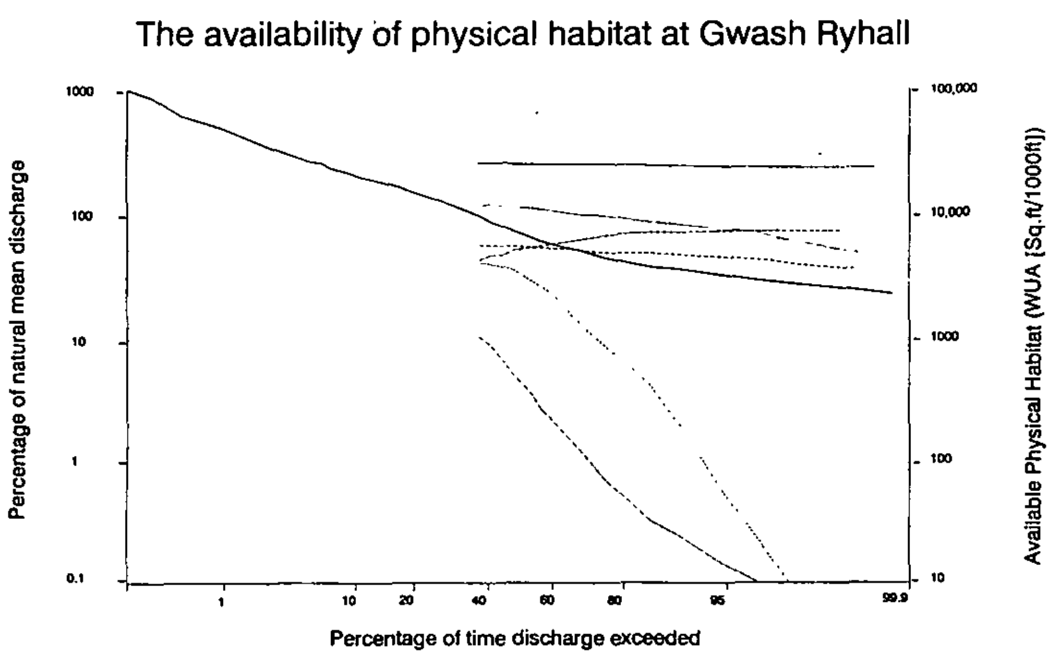


Figure 4.5 ***Weighted Usable Area against discharge relationships superimposed upon flow duration curves at Blithe Dam and Gwash Ryhall***

flow) is exceeded - for example the 95 percentile flow is the discharge which is exceeded 95 percent of the time - on all but eighteen days per year on average. Superimposed upon the flow duration curve is the total and weighted usable area versus discharge curves for selected species, in which the simulation discharges have been assigned an exceedance percentile. It is stressed that the habitat availability curves do not represent true habitat duration curves, for which the time series of daily flow data would have to be converted to a time series of daily habitat data.

The merit of superimposing WUA versus discharge curves upon the natural flow duration curve is the capability to associate key thresholds inflections or peaks and troughs of the habitat-discharge relationship with the probability of their occurrence. For example, it becomes evident that there is no physical habitat available for adult brown trout at Blithe Dam for 15% of the time on average per year, but that this frequency is less than 5% at Ryhall. The diagrams also identify that the discharge which provides the optimal physical habitat for the spawning, juvenile and adult life stages of brown trout is higher than the 40 percentile flow at both sites, but peaks between the 10 and 40 percentile flows at Blithe Dam.

c) Comparison of pre- and post-impoundment Weighted Usable Area duration curves

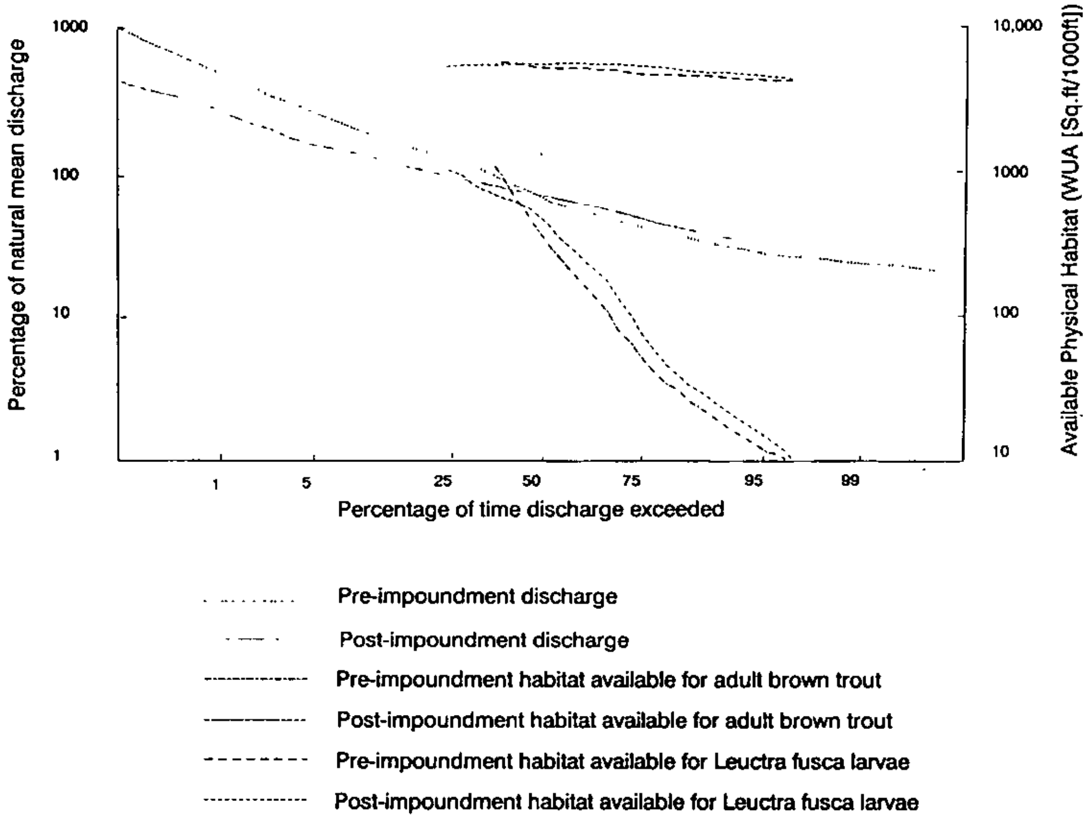
As detailed in Chapter 3, the available river flow data for the Rivers Blithe and Gwash represent the pre- and post-impoundment phases of Blithfield Reservoir and Rutland Water respectively. Both Blithe Dam and Ryhall sites are located downstream of the reservoirs and close to the permanent gauging stations. The data from this report enables a comparison of the pre- and post-impoundment river flow regimes (Gustard *et al.*, 1987) to be complemented by a pre- and post-impoundment comparison of available physical habitat for selected species.

Figure 4.6 presents pre- and post-impoundment flow duration curves for both the Blithe Dam and Rhyall sites, in which flow is expressed as a percentage of the natural (i.e. pre-impoundment) mean flow. Under the two different flow conditions, the simulation discharges (and hence WUA) are assigned different exceedance percentiles, which distinguishes the pre- and post-impoundment habitat availability curves.

In the case of Blithe Dam the post-impoundment discharges are lower than the natural flows through the full range, with the impact that less physical habitat is available at lower flows for adult brown trout and the *Leuctra fusca* stonefly after impoundment than previously. The greatest habitat loss occurs in the 75%-90% flow range for adult brown trout. Gustard *et al.* (1987) have illustrated the reduction of summer peak flows by Blithefield Reservoir, introducing more moderate and low flows into the flow record, with the result that the non-compensation flows are assigned a flow percentile of around 15% in excess of their natural percentiles. Because adult brown trout derive greater physical habitat from higher flows, it is this effect which shifts the post-impoundment habitat curve sharply to the left of the diagram. Because of their rather flat WUA versus discharge relationship, *Leuctra fusca* larvae do not significantly gain or lose physical habitat.

In the case of the impoundment of Rutland Water, the effect upon the flow

The impact of Impoundment upon the availability
of Physical Habitat at Gwash Ryhall



The impact of Impoundment upon the availability
of Physical Habitat at Blithe Dam

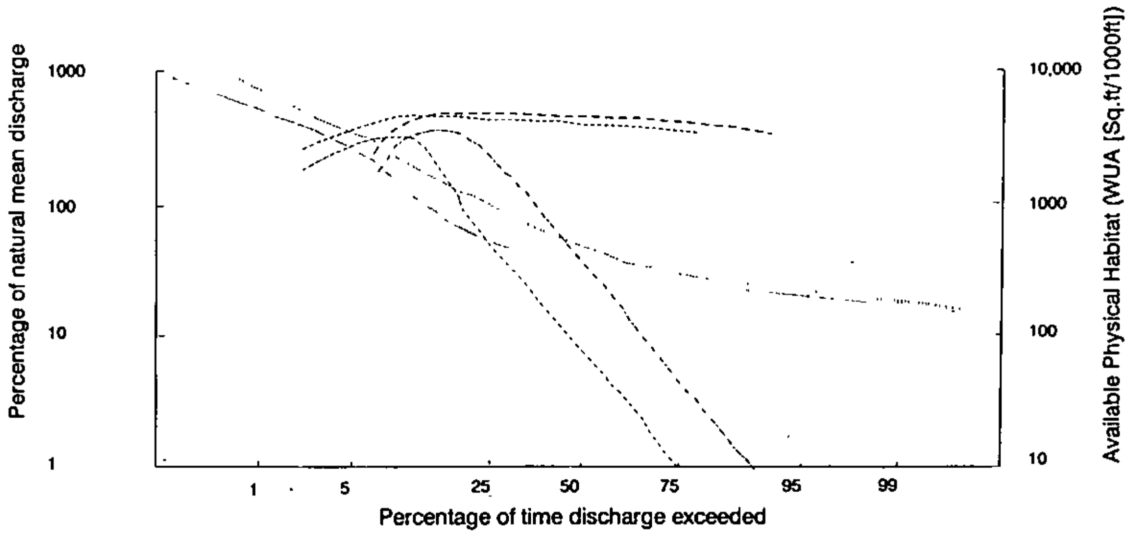


Figure 4.6 ***Pre- and post-impoundment flow duration curves and Weighted Usable Area for adult brown trout and Leuctra fusca below Blithfield Reservoir and Rutland Water***

regime is more complex. Flows in excess of the median (50 percentile flow) are reduced by impoundment, but the low flows are higher, with the exception of the extreme low flow events. Consequently, at lower flows (in the 50-95 percentile range) there is increased available physical habitat for adult brown trout at a given flow percentile after impoundment than previously. The gain in habitat, however, in absolute terms is of a smaller degree compared to the loss of habitat at Blithefield as the curves are displaced by 5 percentiles at a maximum. At flows in excess of the median, the available physical habitat is lower after impoundment and the disparity appears likely to widen at high flows given the divergence of the flow duration curves. Again *Leuctra fusca* do not significantly gain or lose habitat due to the flatness of their curves at these flows.

4.3 USE OF PHYSICAL HABITAT AVAILABILITY RESULTS

Optimal flows can be extracted from the habitat versus flow relationships, and it is seemingly most logical to argue for the peak of the function or significant thresholds or inflections. There are several concepts that must be borne in mind (Bovee, 1982):

* a flow change that is beneficial to one life stage may be detrimental to another life stage;

* a flow change that is beneficial to one species may be detrimental to another species;

* various life stages and species may require different amounts of water at different times of the year;

* a flow that maximises usable habitat in one part of the stream may not maximise, and may decrease, habitat in another part of the same stream;

* more water does not necessarily mean more habitat.

In addition, sensible interpretation and subsequent negotiations must consider, amongst others factors:

a) water availablity, and its seasonal distribution, within existing water management and institutional constraints;

b) that other biological factors, such as food supply, temperature or water quality may be more important than physical habitat;

c) how the biological population levels will respond.

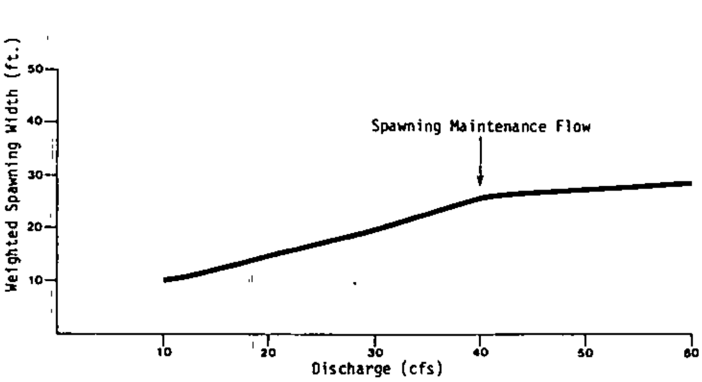
It is most definitely not an objective of this report to recommend flow regimes for the selected rivers Blithe and Gwash, nor to reassess the compensation flows from the Blithefield Reservoir or Rutland Water schemes. Indeed any interpretation of the presented results within a management context would be grossly misrepresentative. It is emphasized that these results are of a preliminary nature, being the result of the first application of IFIM in the United Kingdom, and should not be used on any account as an indication of habitat availability for design purposes.

However, in order to illustrate the practical application of the use of habitat/flow functions to recommend seasonal low flows, Table 4.4 presents the results of a case study of Willow Creek, Idaho (Pruitt & Nadeau, 1978). Habitat/flow relationships are presented (Figure 4.7) for the spawning, incubation and rearing stages of four trout species, rainbow, cutthroat, brown and brook. Rainbow and cutthroat trout are spring spawners while brown and brook trout spawn in the autumn. In combination with fish periodicity charts, the tabulated low flow regime was recommended to be released through controlled releases from upstream dams.

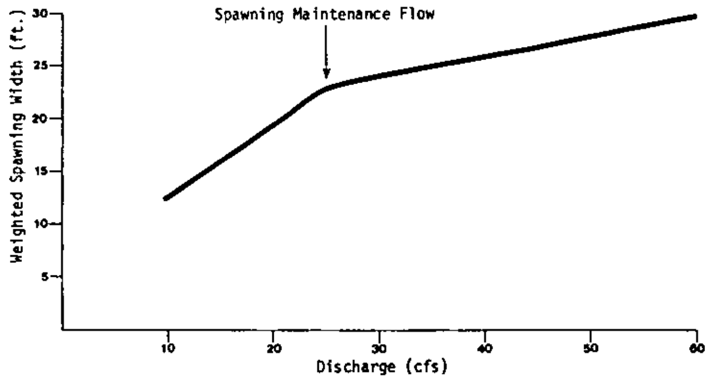
Table 4.4 Recommended low flow regime (in cfs) in Willow Creek, Idaho

Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainbow												
Spawning					40	40	40	40				
Incubation					27	27	27	27	27			
Cutthroat												
Spawning						25	25	25				
Incubation						17	17	17	17			
Brown trout												
Spawning										40	40	40
Incubation	27	27	27	27						27	27	27
Brook												
Spawning										23	23	23
Incubation	15	15	15	15						15	15	15
Rearing (all species)	25	25	25	25	25	25	25	25	25	25	25	25
Recommended Low Flow Regime	25	25	27	40	40	40	40	27	25	40	40	40

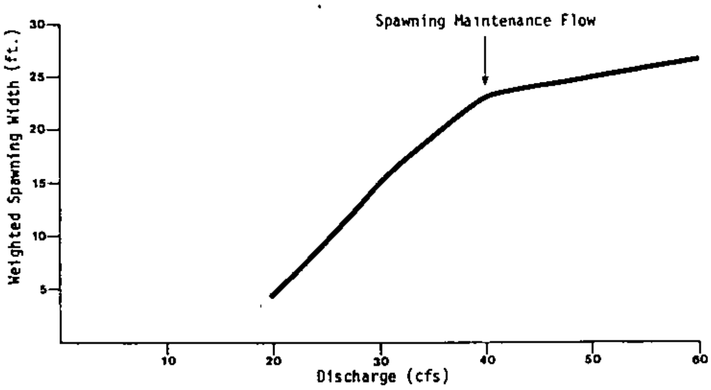
Source: Pruitt T.A. and Nadeau R.L. 1978. "Recommended stream resource maintenance flows on seven southern Idaho streams". Instream Flow Information Paper No.8



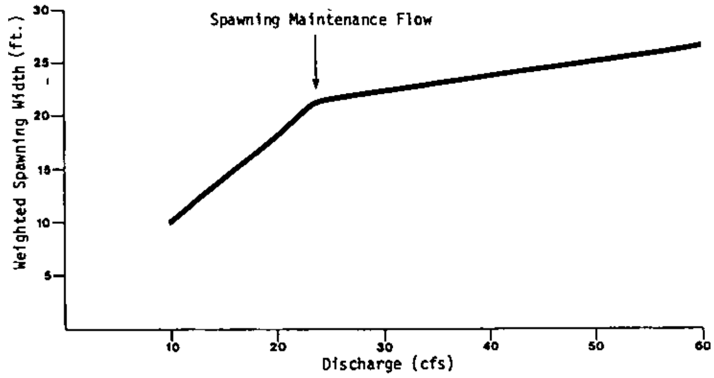
Rainbow trout spawning curve for Willow Creek below Ririe Dam.



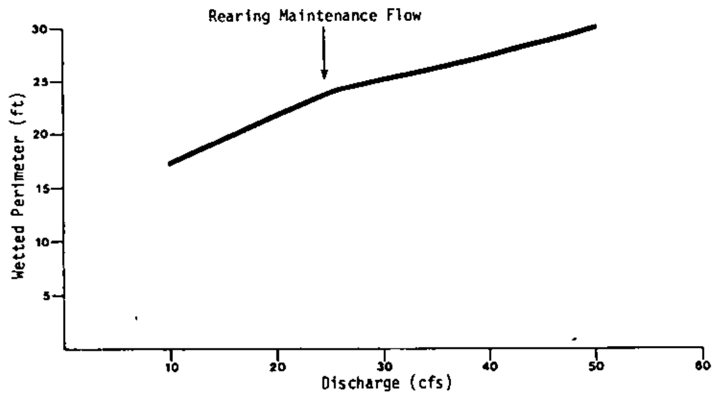
Cutthroat trout spawning curve for Willow Creek below Ririe Dam.



Brown trout spawning curve for Willow Creek below Ririe Dam.



Brook trout spawning curve for Willow Creek below Ririe Dam.



Wetted perimeter curve for Willow Creek below Ririe Dam.

Figure 4.7 Habitat preference (based on weighted channel width) against discharge relationships for Willow Creek, Idaho

5. Conclusions and assessment of the value of IFIM to modelling instream flows in British rivers

This chapter makes recommendations regarding the suitability of the Instream Flow Incremental Methodology for modelling instream flows in British rivers, the development of PHABSIM software and a proposed framework for research initiatives in the sphere of instream flows in Britain.

5.1 THE SUITABILITY OF THE INSTREAM FLOW INCREMENTAL METHODOLOGY FOR MODELLING INSTREAM FLOWS IN BRITISH RIVERS

The underlying concepts of the Instream Flow Incremental Methodology outlined in Chapter 2 - essentially that species exhibit a describable and quantifiable preference to physical microhabitat variables which can be simulated for unobserved flow or channel conditions - are equally as valid in the United Kingdom as in the United States. A requisite condition is that the user exerts considered judgement in the selection of evaluation species and in the correct fluvial environment. One cannot expect IFIM to simulate available habitat for species in a pond, lake, or estuarine environment where the physical variables of depth and velocity are not controlled by, or are very insensitive to, a discharge regime. IFIM applications must be recognised as being confined to strictly instream environments. The result of an IFIM application is the identification of the optimum stream flow or the range of flows where habitat is most sensitive to changes in discharges. In this regard, IFIM is eminently suitable as a contribution to the setting of prescribed flow and compensation flow in the United Kingdom, complementing traditional resource statistics such as Q95 and MAM(7) by a quantitative assessment of instream flow requirements. The following sections examine the suitability of PHABSIM for executing IFIM studies in British rivers, and propose a framework for future research initiatives in this topic area.

5.2 ASSESSMENT OF THE PHABSIM SYSTEM

5.2.1 Field calibration of PHABSIM

The following issues arose during field calibration:

a) Failure to relocate a headpin or indeed removal of a headpin means loss of valuable data from previous calibration flows. Investment in permanent headpins, and the use of detailed witness marks, is strongly recommended to restrict the loss of valuable data.

b) Survey data, especially levelled headpin surveys, should be checked on site using formal booking procedures and internal arithmetic checks. Compilation of full documentation pertaining to field data should be assembled, verified and processed at the earliest opportunity.

c) It is recommended that for research purposes reliance should not be placed upon the operation of water resource schemes for the variability of flows necessary to observe the full range of calibration flows required. This project experienced difficulties in observing calibration flows other than the compensation flows from Blithfield Reservoir and Rutland Water during the dry summer of 1989, leading to the eventual dropping of the Empingham site due to the total lack of variation in flow.

d) The Instream Flow Group of the U.S. Fish and Wildlife Service has assessed various approaches towards the incorporation of cover in PHABSIM in an attempt to find a balance between simple cover classifications which offer simplicity to the field observer and more complex schemes which represent a wide variety of cover combinations by a single index. However, difficulties with channel index were experienced during this project, primarily because the way the channel index is described is most dependent upon the biological function served by the feature. Substrate, as it is traditionally thought of, is most important to macroinvertebrates, fish eggs, and very small fish. Cover, which is sometimes included as a class in the substrate code is more important to larger fish. Whether a feature is called substrate or cover depends upon the species or life stage which is utilising it. Even for the same life stage, overhanging vegetation can become object cover at higher discharges. Application of a single standard substrate and cover classification in this study for species of variable size caused problems in the interpretation and then assignation of channel index codes by field staff.

5.2.2 Ecological data

Habitat suitability/utilisation curves were developed for eight fish species, five macroinvertebrates and one aquatic macrophyte, though the base of data upon which they are founded is varied and there is much scope for refinement. In the case of the fish species, preliminary suitability curves were constructed by expert opinion. Significant improvements could be made by an exhaustive search of all the relevant literature for detailed information on habitat requirements. Furthermore, fish curves should be tested and developed by surveys of selected running waters covering the main stream and river types in this country. Where possible, selected sites should coincide with past fish monitoring sites.

Habitat utilisation curves were based on frequency of occurrence data in the River Communities Project database, and represent a gross assessment of habitat preference. More accurate assessments of habitat preferences require detailed analyses of microdistribution patterns in relation to flow velocity, depth and substrate.

The habitat utilisation curves for the aquatic macrophyte were based on observed occurrence on the River Blithe, and are thus very specific to that river. The utilisation curves are very jagged, which complicates the deterministic interpretation, and would require larger data sets or smoothing to ease their future use.

It is well recognised that extensive research programmes have examined the relationships between river flows, physical properties and aquatic ecology. The challenge facing the application of IFIM in the United Kingdom lies in developing the capability to collate the required data from the multifarious literature sources and databases in a format which can express habitat preference as a simple unambiguous curve. To achieve this, it must be recognised that IFIM maximises generality and precision at the expense, to some degree, of ecological reality (Gore & Nestler, 1988). The basis of ecological reality in the preference curves can nevertheless be strengthened by using different substrate and cover classifications, by recognising the seasonal variability of these classes, and by using the full scope of IFIM in simulating effective habitat to account for biological functions and behaviour such as competition, union, spawning, stranding and feeding.

5.2.3 Hydraulic simulation routines

a) The IFG4 hydraulic model routines predicted sensible water surface elevations at a transect, although the downstream profiles exhibit some element of inconsistency due to the transects being modelled independently. Greater precision is given to predictions of water surface profiles if the calibration flows are widely different. This places emphasis upon sampling the fullest range of flows as calibration flows. More complex channel cross-sectional forms will clearly require more than three calibration flows to construct a meaningful stage/discharge relationship, and an upper limit of nine calibration flows is allowed by the PHABSIM system.

b) The upper limit of 100 points to represent a cross-section is more than adequate to represent any anticipated cross-section in the UK.

c) Identification of channel hydraulic controls above which there is a unique stage/discharge relationship is likely to prove more difficult in some British lowland rivers, and this may restrict the number of reaches where PHABSIM can be calibrated. In addition it will restrict the application of the WSP routine which requires the establishment of a stage/discharge relationship at a channel control to predict water surface elevations in backwater areas.

d) Optimised beta coefficients generated within MANSQ exhibited a wider range within the Blithe and Gwash data sets than the empirical range of 0.1 to 0.5 experienced in the United States.

e) In considerations of the channel index it was found to be impossible to input both substrate and cover classifications simultaneously, forcing the user to select one or other during simulations. In this study, only substrate was used to the exclusion of cover.

5.2.4 Recommendations for the development of PHABSIM software

An improved menu structure would improve ease of use, removing the necessity to repeatedly rename input and output files and to set Input Output Control (IOC) options, particularly when dealing with mixed hydraulic models. Graphics routines, especially for the presentation of loaded data and output results, could be considerably enhanced.

Conversion to metric units would significantly overcome the inconvenience of conversion of all field data into imperial units, and the reconversion of output data and graphics.

The capability to enter both cover and substrate curves instead of only one would benefit analysis procedures.

5.3 A PROPOSED FRAMEWORK FOR RESEARCH INITIATIVES

A future framework for research initiatives in the development of the Instream Flow Incremental Methodology in British rivers should include:

* use of appropriate data sets including those assembled during this study to explore the full scope of the PHABSIM system through the range of options available to the user, many of which were not used during this study;

* investigation of the minimum data requirements for calibration of the hydraulic simulation components of PHABSIM based on the sensitivity of output results to the reduction of the amount and type of input data. Work in this sphere has already been undertaken using the data assembled in this report (Petts, 1990);

* a review of substrate and cover classification procedures to develop a standard methodology for use in future IFIM studies in the United Kingdom. This could be best administered within a hierarchical framework of classification schemes based on the demands of a particular instream flow study. The framework must take account of the considerable research already undertaken in the sphere of ecological requirements for substrate and cover;

* collation of relevant data from literature sources and from existing ecological data bases to underpin and refine the derivation of habitat suitability curves. Where possible, and particularly where the available data support it, suitability curves should be upgraded to habitat utilisation and habitat preference curves. Experience should be gained in deriving suitability curves from field sampling techniques;

* consideration of the most appropriate, and most important, target species for future IFIM studies. Judgements should be based upon species

importance to river management, conservation, restoration and recreation interests. Identification of a suite of key target species, perhaps with variations in regional application, would impose a sharper focus upon future research programmes;

* calibration of PHABSIM on a wide range of British rivers, ensuring experience of varied hydraulic and geomorphological environments, in order to identify and assess the limitations of the acquired data in simulating physical habitat. Diversity of study rivers will also allow evaluation of the value of the acquired data for the extrapolation to a more regional application.

The value of the Instream Flow Incremental Methodology lies in the generation of quantitative relationships between habitat and flows: the fact that IFIM is the only modelling tool that does so establishes the potential of the methodology in contributing to important water management issues in the United Kingdom. This report has applied IFIM to two British rivers and has generated quantitative relationships between habitat and flows for eight fish species, five macroinvertebrates and one aquatic macrophyte. The underlying concepts of IFIM, and the calibration requirements and hydraulic simulation routines of PHABSIM appear to be wholly appropriate for British conditions on the basis of this study. The results are provisional, largely due to the preliminary nature of the input data. The habitat versus flow relationships exhibit many facets of interest, including the different habitat relationships for different life stages of one species, for different species, variations between the two rivers and the different forms to which the relationships accord. The potential of habitat versus discharge relationships from IFIM for setting prescribed minimum flows, reviewing compensation releases and other instream flow demands is clearly demonstrated by this investigation.

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Appendix 1

Schematic representation of headpin elevations, and distances between and across transects

Headpin survey marks identifying the ends of each transect are represented by integer and alphabetic characters. The distance across each transect is presented horizontally between a pair of corresponding headpins. The elevation of each headpin is presented horizontally to the left of the integer headpins and to the right of the alphabetic headpins. Because some headpins were replaced or damaged, there may be more than one elevation associated with a headpin, each identified by the date of the survey from which elevation was calculated. Distances between headpins on adjacent transects are presented as a vertical sequence, and may be displayed as distances between the integer headpins alone or in addition to distances between the alphabetic characters.

Data are presented in metres.

Site: Gwash Empingham

MARCH 1989				MARCH 1989
100.000	1	11.62	A	99.698
	9.98			
99.647	2	9.61	B	99.470
	6.51			
99.720	3	10.52	C	100.054
	12.45			
99.661	4	11.00	D	99.663
	5.29			
100.018	5	12.50	E	99.464
	9.47			
99.710	6	10.50	F	99.503
	9.07			
99.527	7	11.19	G	99.503
	7.15			
99.562	8	10.10	H	99.226
	7.27			
99.701	9	9.62	I	99.531
	8.62			
99.580	10	8.61	J	99.586
	8.42			
99.453	11	7.68	K	99.284
	11.05			
99.501	12	9.14	L	99.613
	8.51			
99.514	13	8.75	M	99.466
	7.45			
99.168	14	9.50	N	99.461
	5.32			
99.513	15	9.25	O	99.265
99.513	16		P	

THALWEG = 97.962

FLOW DIRECTION

Site: Gwash Ryhall

MARCH 1989	JANUARY 1990				JANUARY 1990	MARCH 1989
100.025	100.023	A	9.26	1	100.000	100.000
		2.38		2.24		
99.872	99.871	B	9.94	2	100.028	100.028
		2.50		2.51		
100.246	100.254	C	10.08	3	99.832	99.832
		1.78		2.37		
99.896	99.900	D	9.56	4	99.768	99.768
		14.51		15.29		
100.211	100.215	E	9.71	5	99.998	99.998
		14.15		15.05		
100.109	100.105	F	10.87	6	99.803	(peg damaged) 99.936
		15.75		15.42		
100.146	100.149	G	11.68	7	99.880	(peg damaged) 99.893
		15.59		15.19		
In error 100.159 assumed 22/5/90	100.159	H	12.03	8	100.054	In error 100.054 assumed 22/5/90
		19.04		17.08		
99.736	99.739	I	10.10	9	99.731	99.731
		8.59		10.20		
99.809	99.815	J	10.00	10	99.756	99.756
		6.36		4.86		
99.849	99.850	K	10.78	11	99.686	99.686
		7.78		6.50		
99.504	99.504	L	9.77	12	99.783	99.783
		7.50		6.22		
99.544	99.547	M	9.37	13	99.657	99.657
		8.43		7.00		
99.941	99.945	N	9.71	14	99.511	(peg damaged) 99.526
		6.60		5.45		
99.590	99.591	O	9.00	15	99.464	(peg damaged) 99.450
		5.27		4.72		
99.439	99.440	P	9.16	16	99.403	99.403
		7.20		6.62		
99.342	99.340	Q	9.19	17	99.350	99.350
		5.25		5.42		
use 99.365	99.295	R	9.97	18	99.324	use 99.319

FLOW DIRECTION

NB: Pegs 6, 7, 14, 15, R: were found to be damaged on arrival in Jan 1990 and their peg heights were resurveyed.

Site: Gwash Belmesthorpe

MARCH 1989	JANUARY 1990				JANUARY 1990
AS JAN 1990	99.738	A	11.40	1	99.990
		A - C = 23.45		1 - 3 = 26.66	
99.973	MISSING	B	11.95	2	MISSING
99.978	99.795	C	11.44	3	99.763
		10.11		9.72	
99.946	99.901	D	11.81	4	99.866
		9.87		7.52	
99.747	99.793	E	11.38	5	99.866
		E - G = 17.40		5 - 7 = 16.74	
99.895	MISSING	F	13.76	6	MISSING
99.824	99.782	G	11.97	7	99.946
		10.95		9.85	
100.058	99.971	H	11.54	8	99.823
		8.96		8.95	
99.873	99.845	I	10.92	9	99.736
		9.59		9.57	
UNCERTAIN	99.832	J	11.18	10	99.743
		10.00		9.30	
99.782	99.809	K	11.64	11	99.709
		9.51		8.96	
99.786	99.872	L	11.10	12	99.665
		9.49		10.08	
AS JAN 1990	99.632	M	?	13	99.849
		8.03		10.68	
AS JAN 1990	99.540	N	8.65	14	99.876
		9.35		13.42	
AS JAN 1990	100.000	O	11.10	15	100.112

FLOW DIRECTION

NB: Distances between pegs refer to Jan 1990 measurements unless annotated otherwise.

NB: Pegs 1, C, D, G, H, I, K, L: New pegs were established in Jan 1990 as previous pegs could not be located.

NB: Pegs 4, 7, 9, 13, 15: Found to be damaged/bent over in Jan 1990 but resurveyed.

NB: Peg J: Discrepancy between 99.832 (Jan 1990) and 99.861 (Feb 1989); no evidence of damage but also no independent check on Feb 1989 height. Therefore use peg 10 in preference.

Site: Blithe Hamstall Ridware

MARCH 1989				MARCH 1989	MAY 1990
99.777	1	15.07	A	100.000	99.908
	4.35		3.05		
100.166	2	15.77	B	99.916	99.866
	4.90		3.40		
100.077	3	16.23	C	99.907	99.863
	7.20		3.35		
99.974	4	14.28	D	99.887	99.824
	13.65		14.45		
99.928	5	14.00	E	99.837	99.799
	18.80		16.20		
99.976	6	16.11	F	99.763	99.724
	18.40		17.80		
99.960	7	15.78	G	99.894	99.842
	19.20		16.60		
99.641	8	15.06	H	99.849	99.786
	15.90		17.20		
99.755	9	17.66	I	99.746	99.634
	15.80		12.55		
99.467	10	20.04	J	99.539	99.453
	7.80		10.95		
99.646	11	13.57	K	99.530	99.476
	6.30		11.10		
99.443	12	11.61	L	99.613	99.554
	13.75		10.80		
99.446	13	15.76	M	99.626	99.599
	48.80		46.10		
99.580	14	15.68	N	99.397	99.358
	36.75		33.70		
99.100	15	16.11	O	99.544	99.510
	27.55		31.30		
99.171 (E)	16	14.00	P	99.560 (E)	99.575
	34.20		40.05		
99.290	17	13.75	Q	99.581	99.513
	14.75		16.10		
99.271 (E)	18	14.28	R	99.547(E)	99.553

FLOW DIRECTION

Site: Blithe Dam

MARCH 1990				MARCH 1989
100.000 (2/90 99.891) Sunken	1	9.13	A	100.020
	6.25		5.90	
99.951	2	9.60	B	99.993 (New 2/90 .103 higher than Peg 2)
	6.90		6.90	
100.004	3	9.84	C	99.673
	7.00		7.30	
99.947	4	11.25	D	99.796 (New 2/90 .194 lower than Peg 4)
	5.95		5.45	
99.879	5	10.66	E	99.728 (New 2/90 .154 lower than Peg 5)
	7.40		10.40	
99.823	6	11.35	F	99.588 (New 2/90 .217 lower than Peg 6)
			16.60	
99.903 (New 2/90 .231 lower than Peg G)	7	10.15	G	99.644
			15.20	
99.789	8	9.24	H	99.828
	11.80		7.55	
99.702	9	11.60	I	99.803
	10.80		6.70	
99.642	10	12.52	J	99.559
	9.00		0.00	
99.736	11	11.75	K	99.561
	9.00		0.00	
99.733 (New 2/90 .157 higher than Peg L)	12	12.32	L	99.566
	9.65		3.10	
99.770	13	12.87	M	99.808
	2.40		0.00	
99.754	14	12.88	N	99.810
	2.30		2.10	
99.734	15	12.10	O	99.792
	7.30		10.00	
99.725	16	11.89	P	99.532
	7.80		19.45	
99.559	17	11.95	Q	99.717 (New 2/90 .234 higher than Peg 17)
	6.50		12.50	
99.570	18	10.40	R	99.726 (New 2/90 .188 higher than Peg 18)
	8.10		10.30	
99.512	19	10.84	S	99.687 (New 2/90 .258 higher than Peg 19)
	8.65		8.30	
99.455	20	12.57	T	99.578 (New 2/90 .205 higher than Peg 20)

FLOW DIRECTION

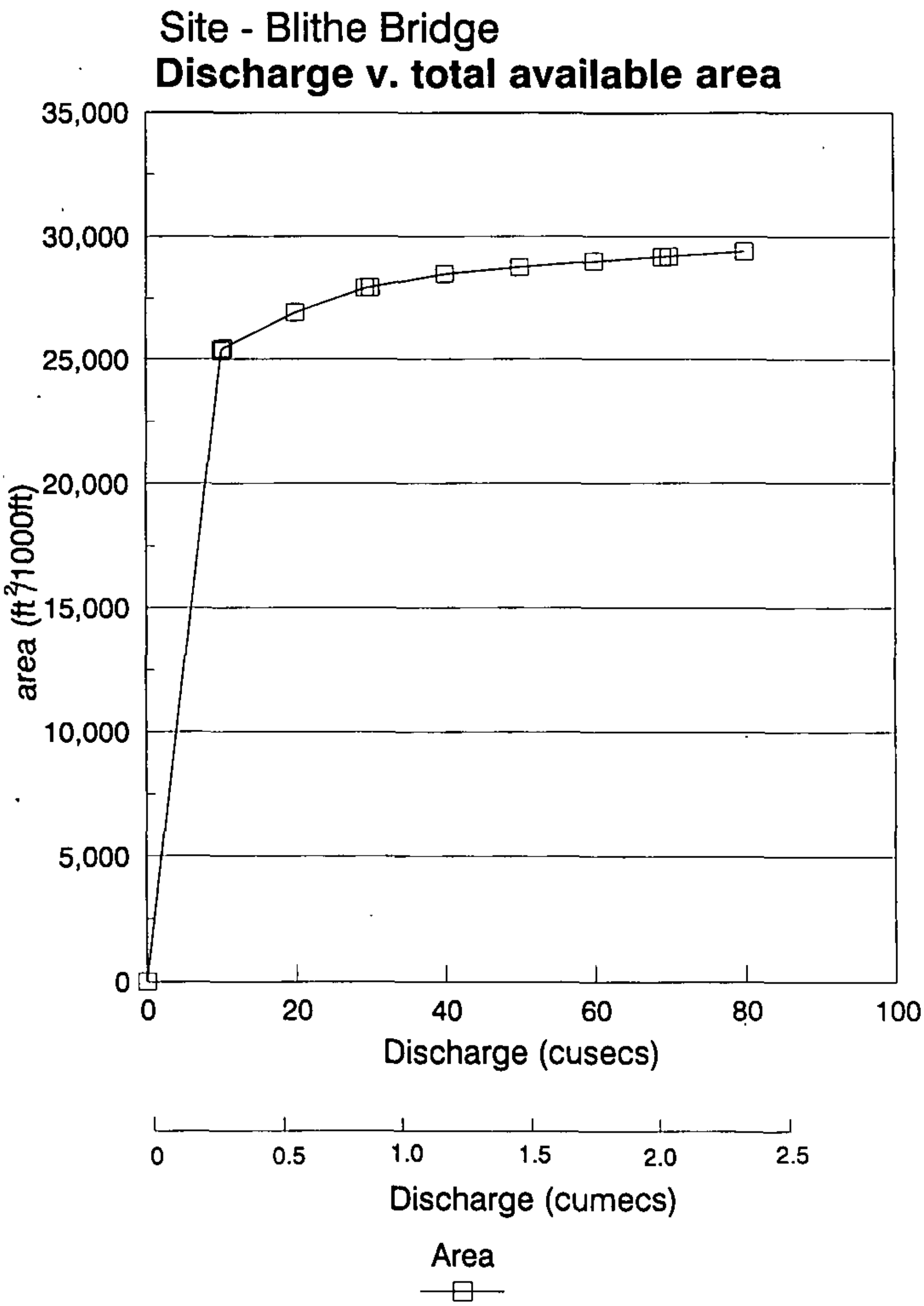
Site: Blithe Bridge

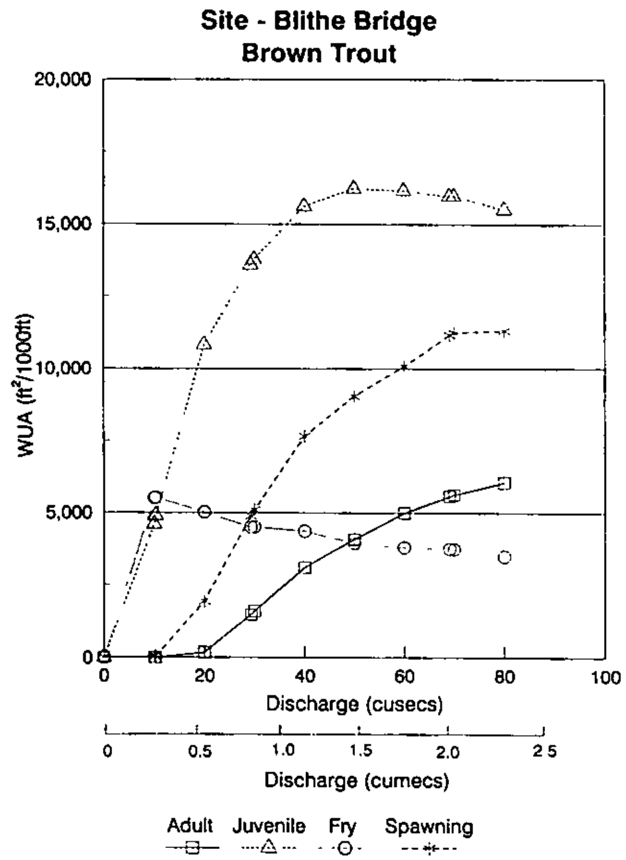
MAY 1990	MARCH 1989				MARCH 1989	MAY 1990
		1		A		
100.040	100.000	2	19.67	B	100.339	100.398
		3.60		8.70		
100.034	100.009	3	18.19	C	100.174	100.242
		5.20		7.90		
100.034	99.955	4	14.72	D	100.158	100.177
		5.30		7.80		
100.032	99.958	5	13.73	E	99.898	99.945
		4.90		5.70		
99.774	99.724	6	12.87	F	99.646	99.679
		6.50		7.00		
99.747	99.689	7	15.20	G	99.912	99.952
		8.40		8.40		
99.945	99.889	8	15.28	H	99.822	99.867
		7.50		4.80		
100.036	99.985	9	15.02	I	99.806	99.844
		15.20		12.80		
99.907	99.847	10	13.60	J	99.837	99.875
		12.40		10.30		
99.902	99.858	11	11.48	K	99.778	99.821
		13.30		13.00		
99.867	99.797	12	10.74	L	99.818	99.854
		11.50		11.70		
99.852	99.807	13	13.10	M	99.587	99.643
		18.10		28.10		
	99.738	14	14.00	N	99.684	99.736
		21.60		22.30		
99.664	99.630	15	13.33	O	99.709	99.732
		9.60		8.30		
99.677	99.659	16	11.34	P	99.646	99.712
		12.80		8.60		
99.716	99.658	17	10.80	Q	99.627	99.663
		13.40		15.40		
99.554		18	7.55	R		99.661

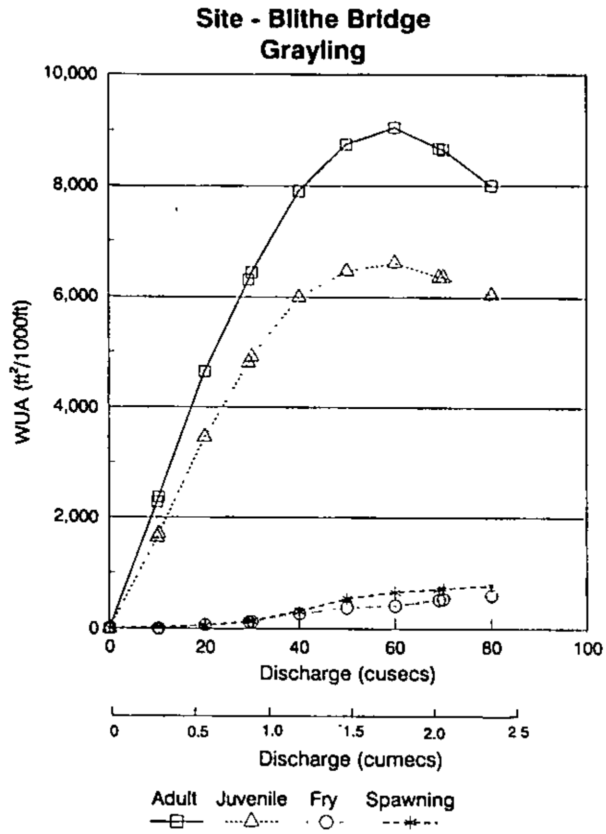
FLOW DIRECTION

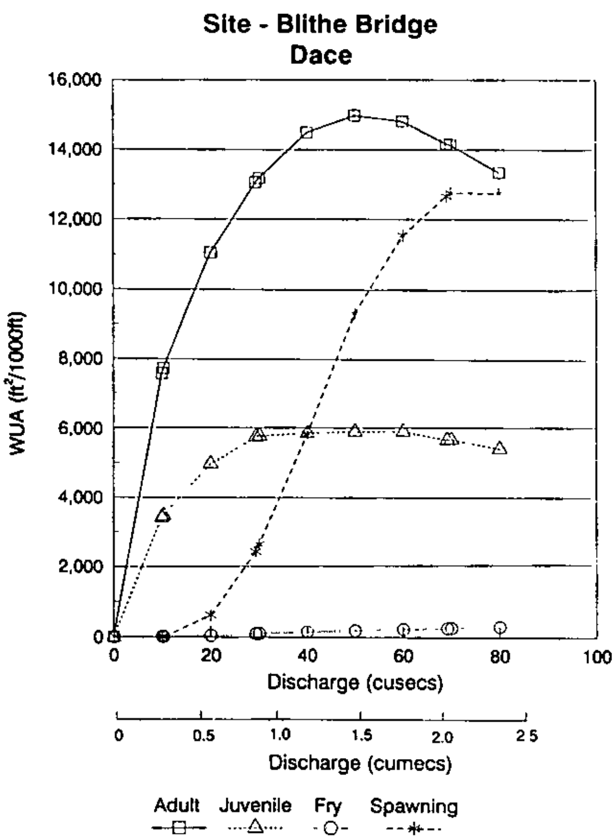
Appendix 2

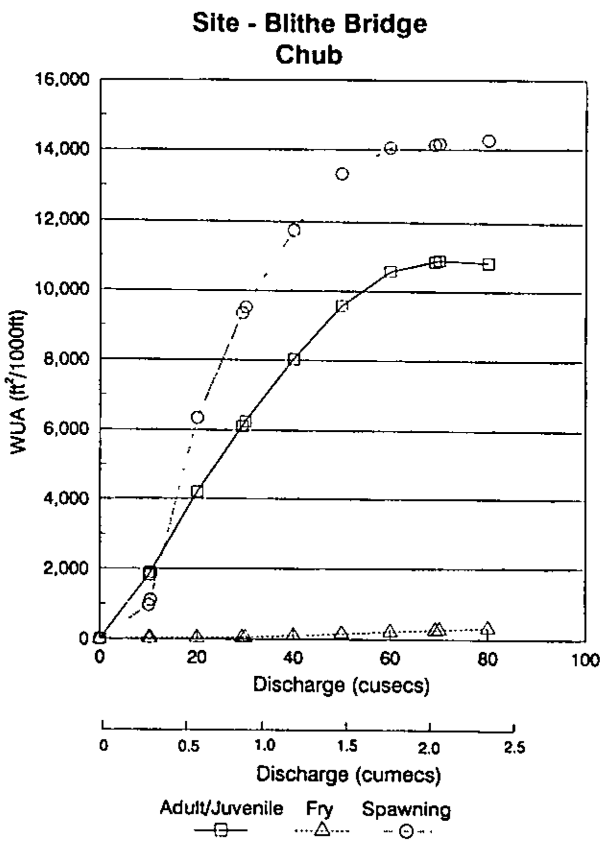
Weighted Usable Area against discharge functions for Blithe Bridge, Hamstall Ridware, Ryhall and Belmesthorpe

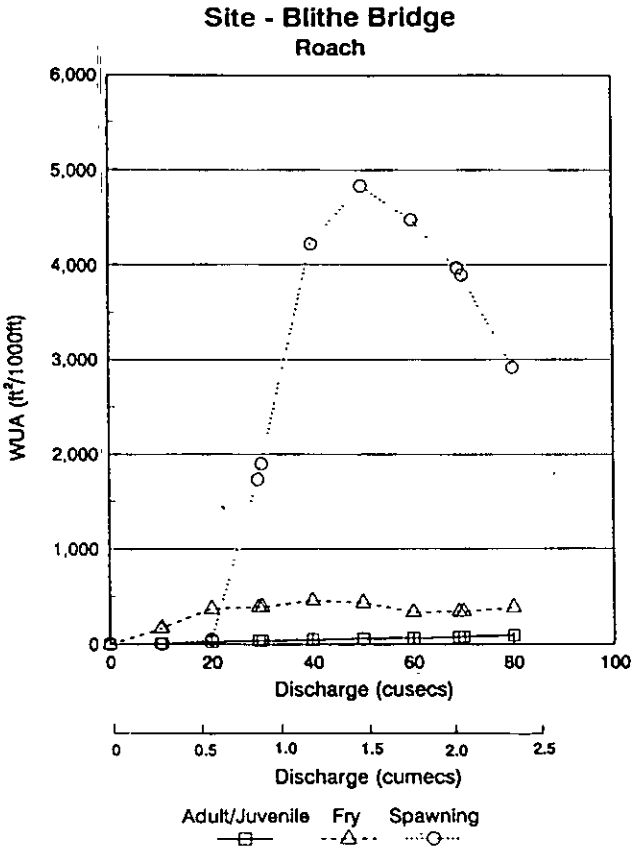

Site - Blithe Bridge
Discharge v. total available area
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
area (ft²/1000ft)
0
20
40
60
80
100
Discharge (cusecs)
0
0.5
1.0
1.5
2.0
2.5
Discharge (cumecs)
Area

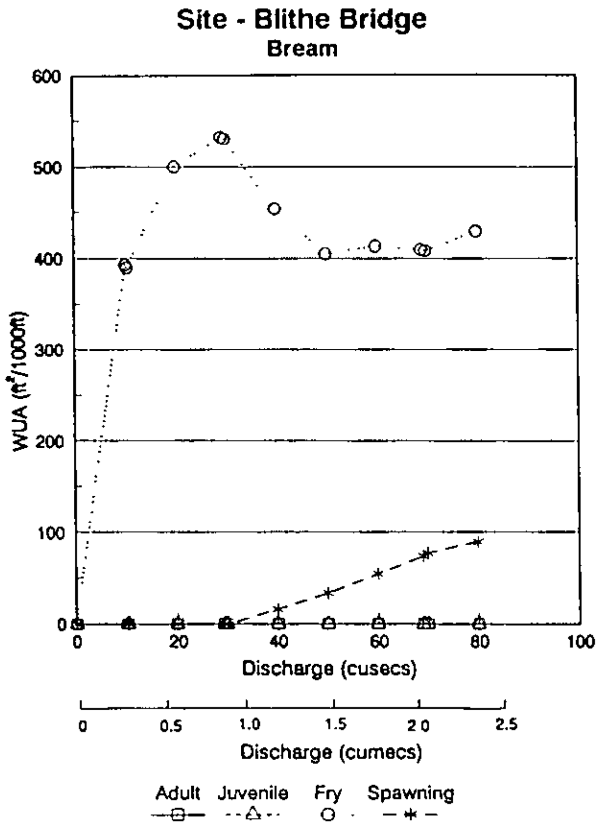

Site - Blithe Bridge
Brown Trout
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult Juvenile Fry Spawning

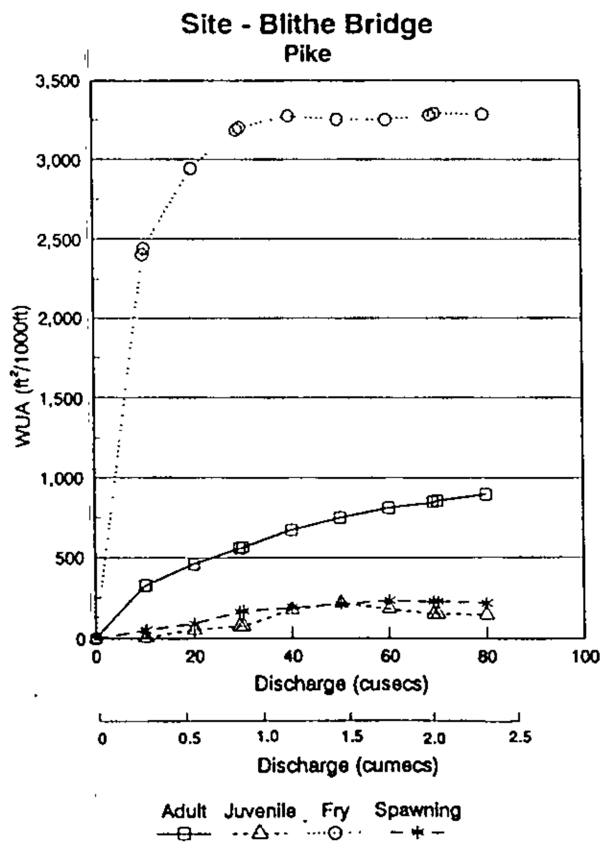

Site - Blithe Bridge
Grayling
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult Juvenile Fry Spawning

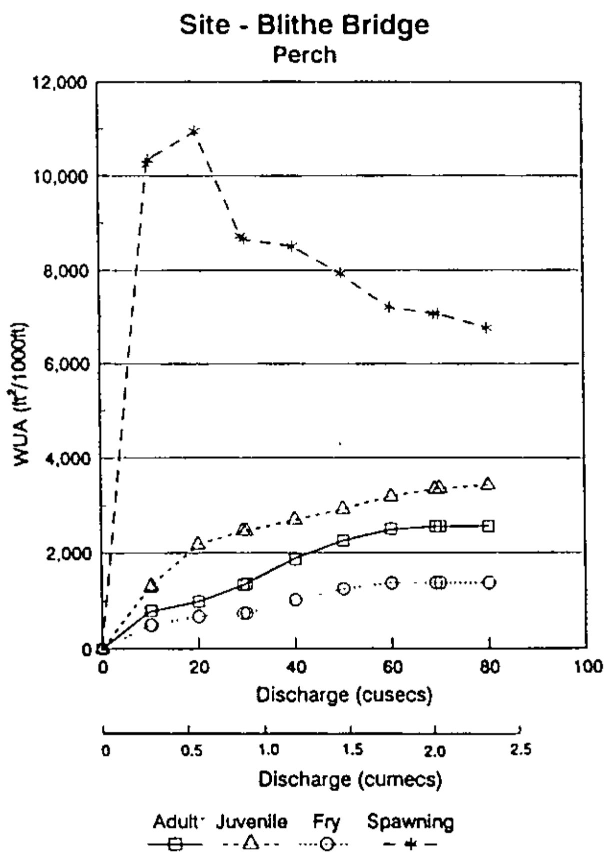

Site - Blithe Bridge
Dace
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult Juvenile Fry Spawning

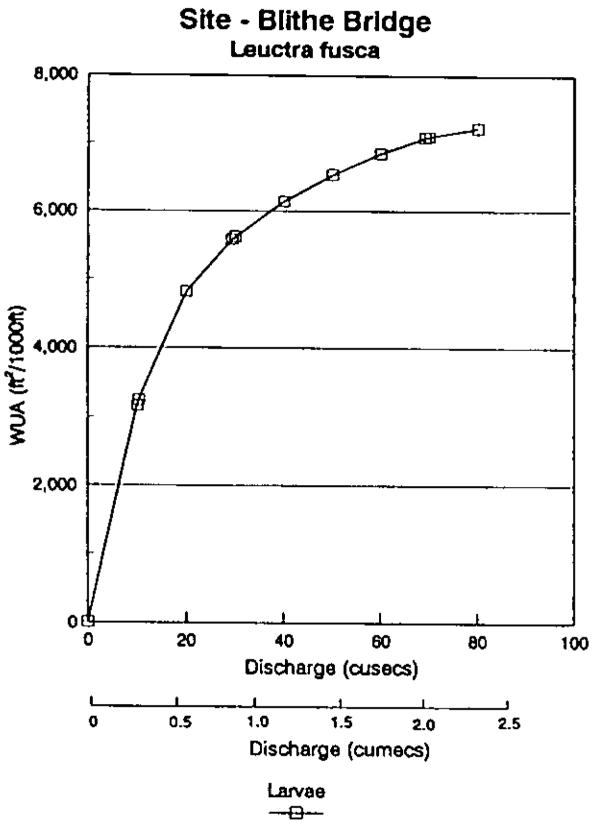

Site - Blithe Bridge
Chub
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult/Juvenile Fry Spawning


Site - Blithe Bridge
Roach
WUA (ft²/1000ft)
6,000
5,000
4,000
3,000
2,000
1,000
0
0 20 40 60 80 100
Discharge (cusecs)
0 0.5 1.0 1.5 2.0 2.5
Discharge (cumecs)
Adult/Juvenile Fry Spawning

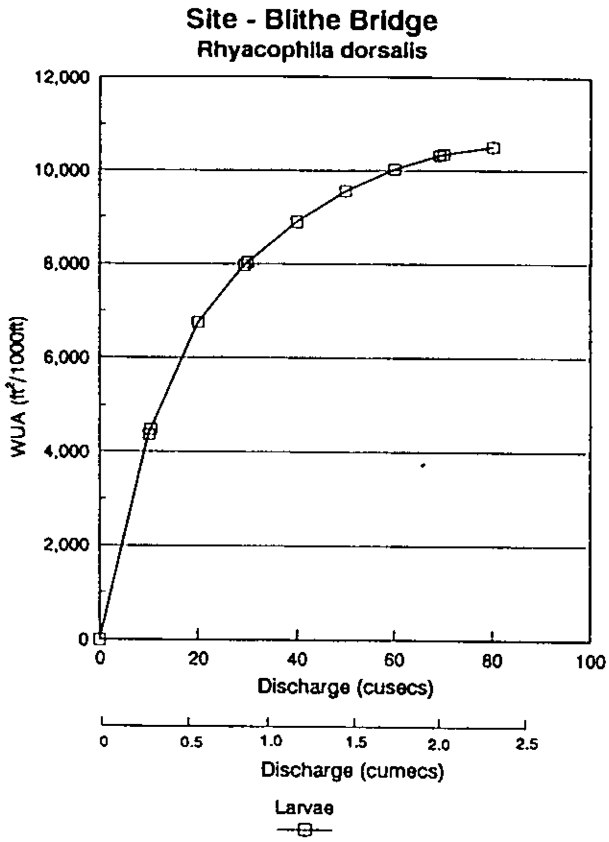

Site - Blithe Bridge
Bream
WUA (ft²/1000ft)
600
500
400
300
200
100
0
0 20 40 60 80 100
Discharge (cusecs)
0 0.5 1.0 1.5 2.0 2.5
Discharge (cumecs)
Adult Juvenile Fry Spawning


Site - Blithe Bridge
Pike
WUA (ft²/1000ft)
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0 20 40 60 80 100
Discharge (cusecs)
0 0.5 1.0 1.5 2.0 2.5
Discharge (cumecs)
Adult Juvenile Fry Spawning

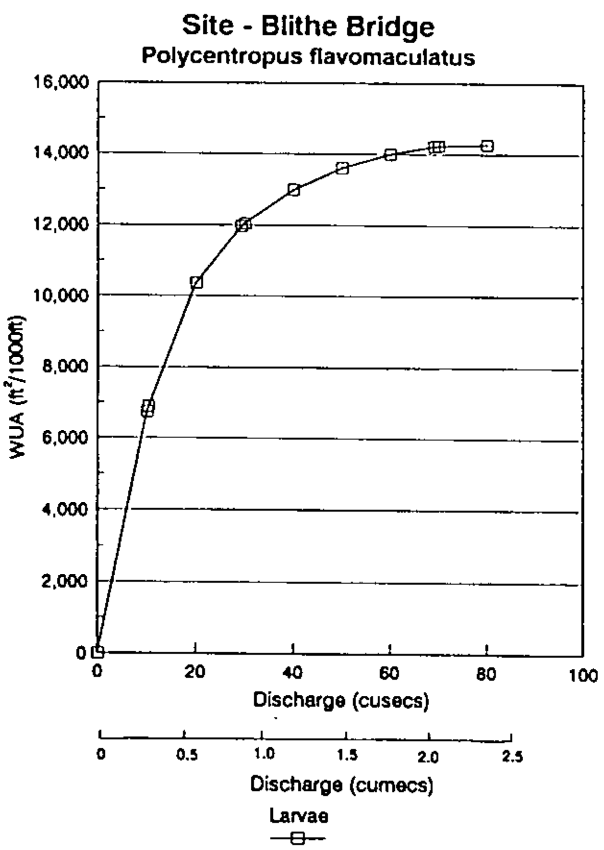

Site - Blithe Bridge
Perch
WUA (ft²/1000ft)
12,000
10,000
8,000
6,000
4,000
2,000
0
0 20 40 60 80 100
Discharge (cusecs)
0 0.5 1.0 1.5 2.0 2.5
Discharge (cumecs)
Adult Juvenile Fry Spawning



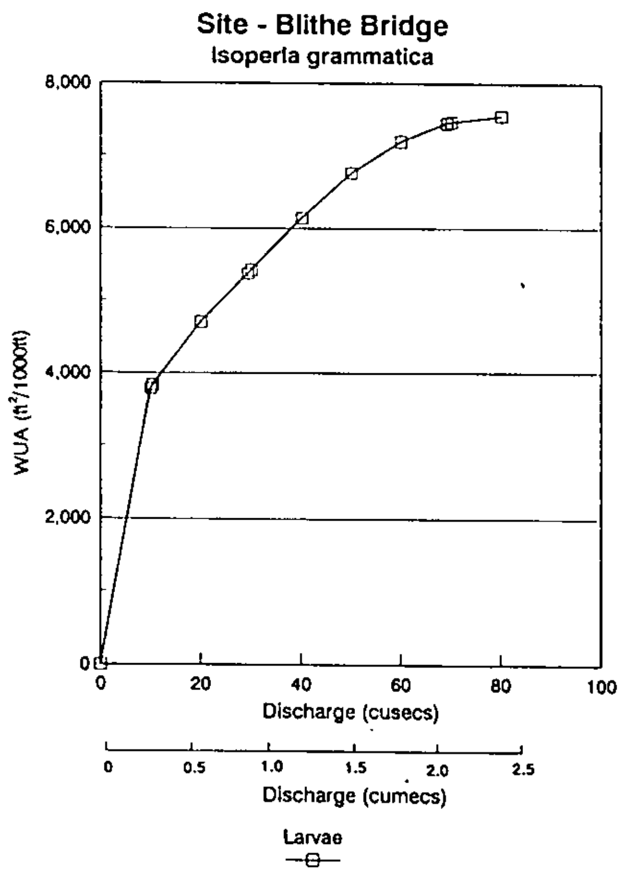
Site - Blithe Bridge
Leuctra fusca
WUA (ft²/1000ft)
8,000
6,000
4,000
2,000
0
0
20
40
60
80
100
Discharge (cusecs)
0
0.5
1.0
1.5
2.0
2.5
Discharge (cumecs)
Larvae



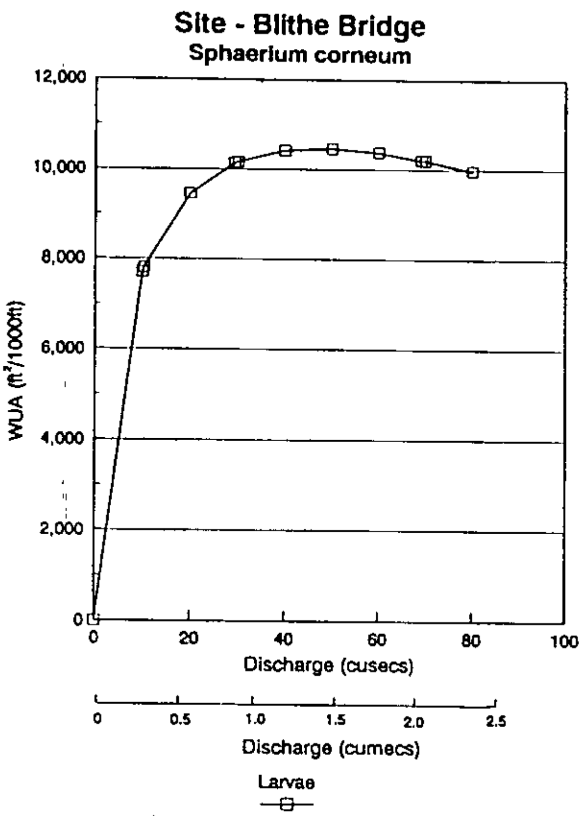
Site - Blithe Bridge
Rhyacophila dorsalis
WUA (ft²/1000ft)
12,000
10,000
8,000
6,000
4,000
2,000
0
0
20
40
60
80
100
Discharge (cusecs)
0
0.5
1.0
1.5
2.0
2.5
Discharge (cumecs)
Larvae

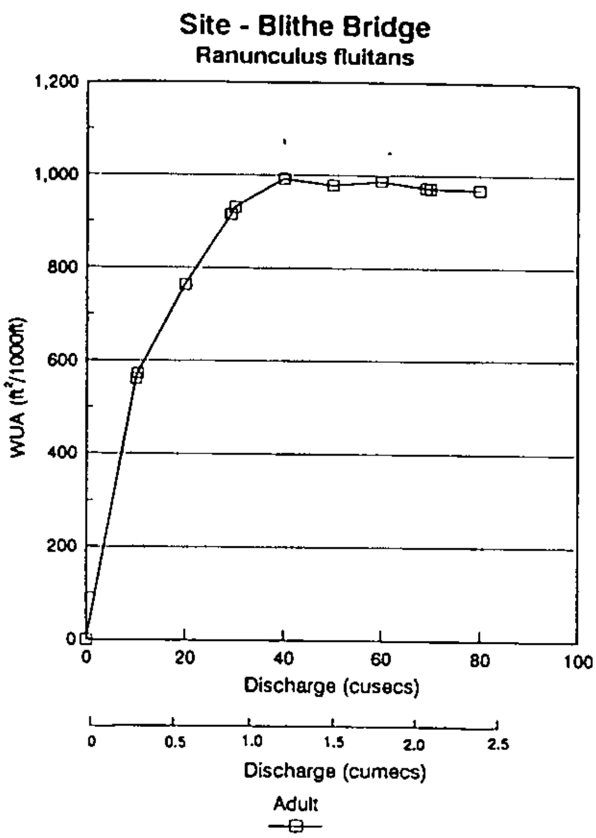


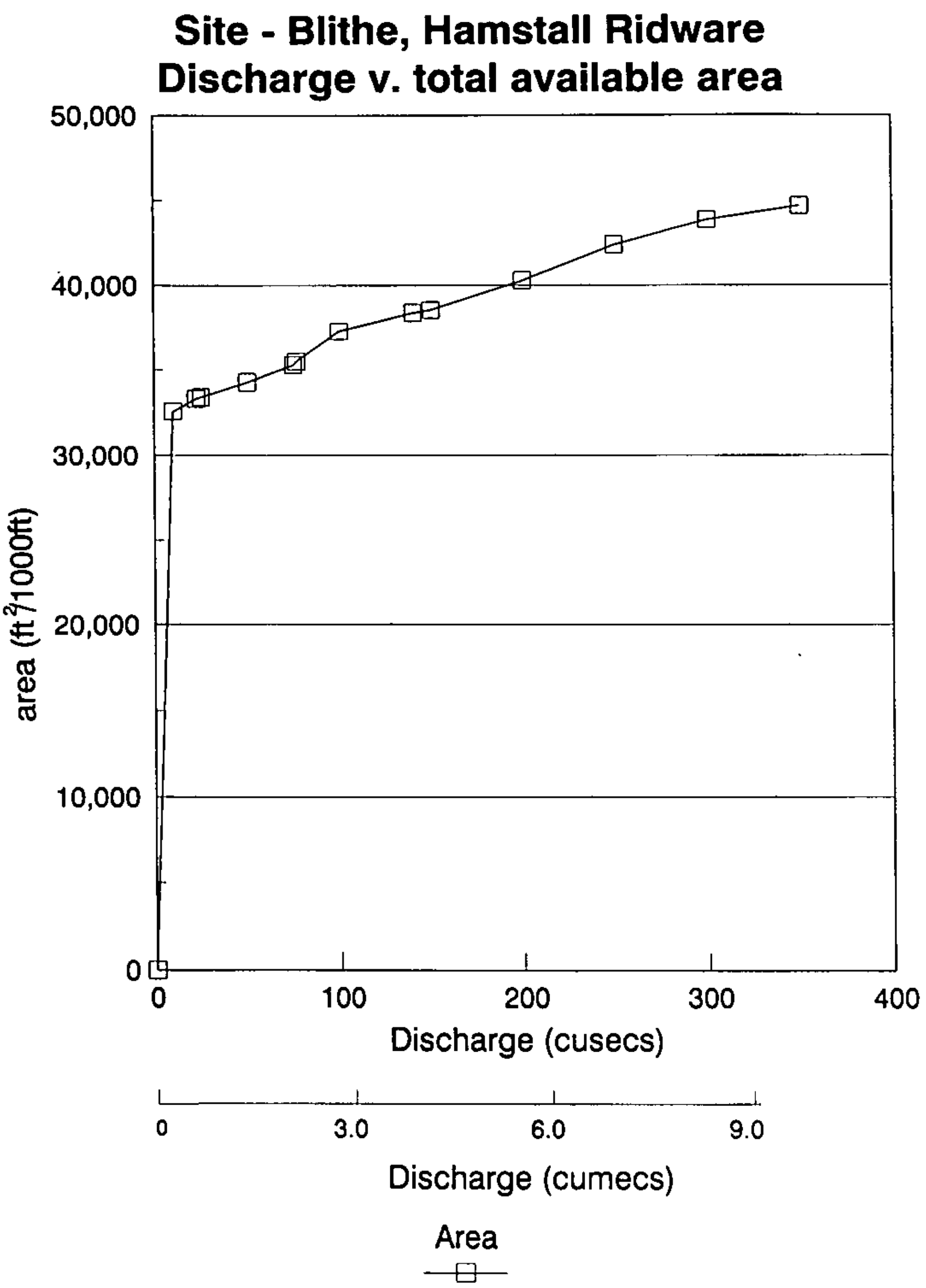
Site - Blithe Bridge
Polycentropus flavomaculatus
WUA (ft²/1000ft)
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
0
20
40
60
80
100
Discharge (cusecs)
0
0.5
1.0
1.5
2.0
2.5
Discharge (cumecs)
Larvae

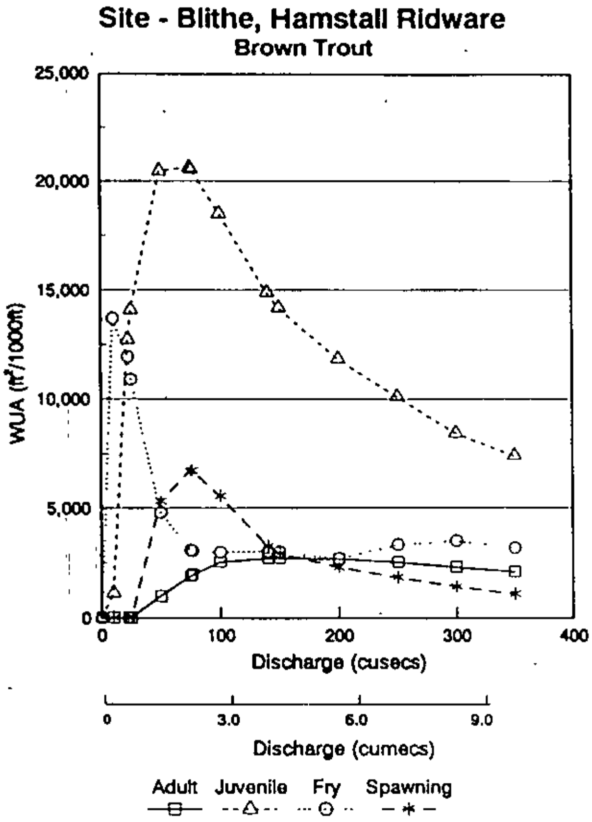


Site - Blithe Bridge
Isoperla grammatica
WUA (ft²/1000ft)
8,000
6,000
4,000
2,000
0
0
20
40
60
80
100
Discharge (cusecs)
0
0.5
1.0
1.5
2.0
2.5
Discharge (cumecs)
Larvae

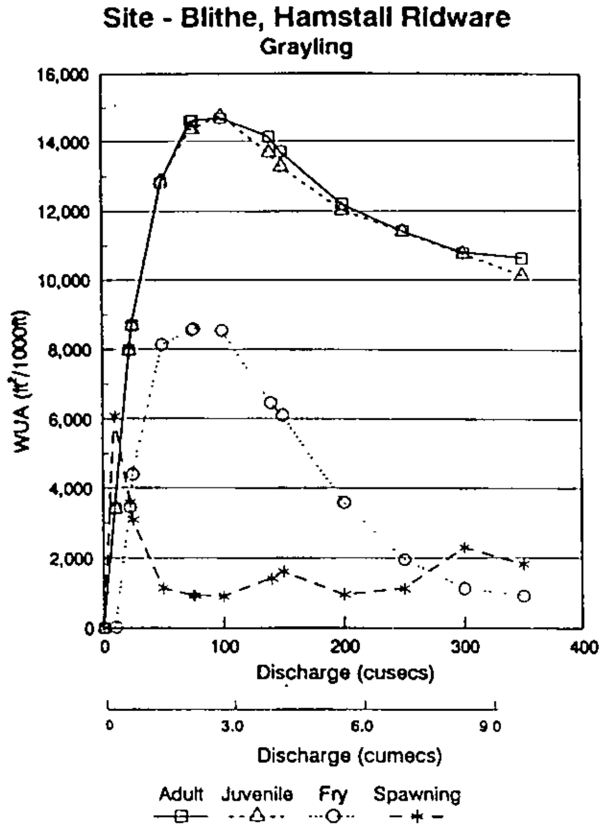

Site - Blithe Bridge
Sphaerium corneum
WUA (ft²/1000ft)
12,000
10,000
8,000
6,000
4,000
2,000
0
0
20
40
60
80
100
Discharge (cusecs)
0
0.5
1.0
1.5
2.0
2.5
Discharge (cumecs)
Larvae


Site - Blithe Bridge
Ranunculus fluitans
WUA (ft²/1000ft)
1,200
1,000
800
600
400
200
0
0
20
40
60
80
100
Discharge (cusecs)
0
0.5
1.0
1.5
2.0
2.5
Discharge (cumecs)
Adult

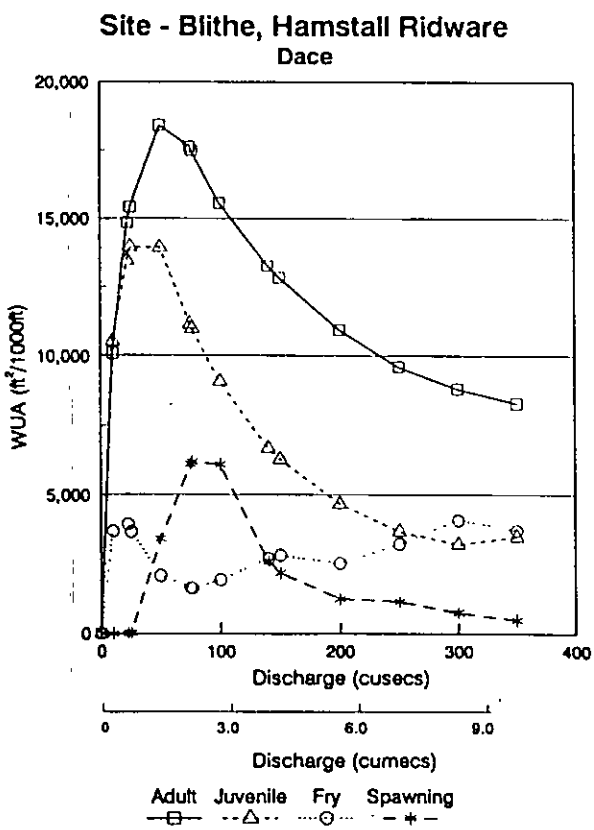

Site - Blithe, Hamstall Ridware
Discharge v. total available area
50,000
40,000
30,000
20,000
10,000
0
area (ft²/1000ft)
0
100
200
300
400
Discharge (cusecs)
0
3.0
6.0
9.0
Discharge (cumecs)
Area



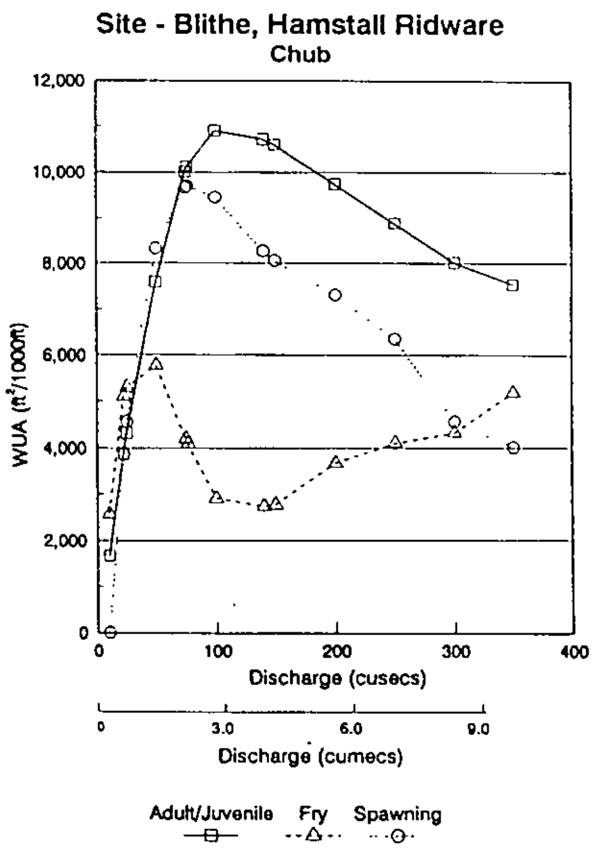
Site - Blithe, Hamstall Ridware
Brown Trout
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult Juvenile Fry Spawning



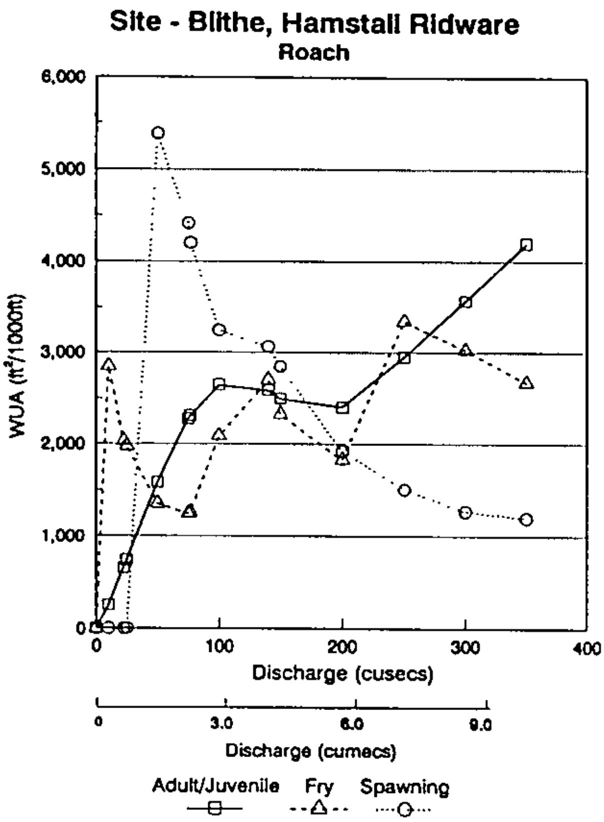
Site - Blithe, Hamstall Ridware
Grayling
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult Juvenile Fry Spawning

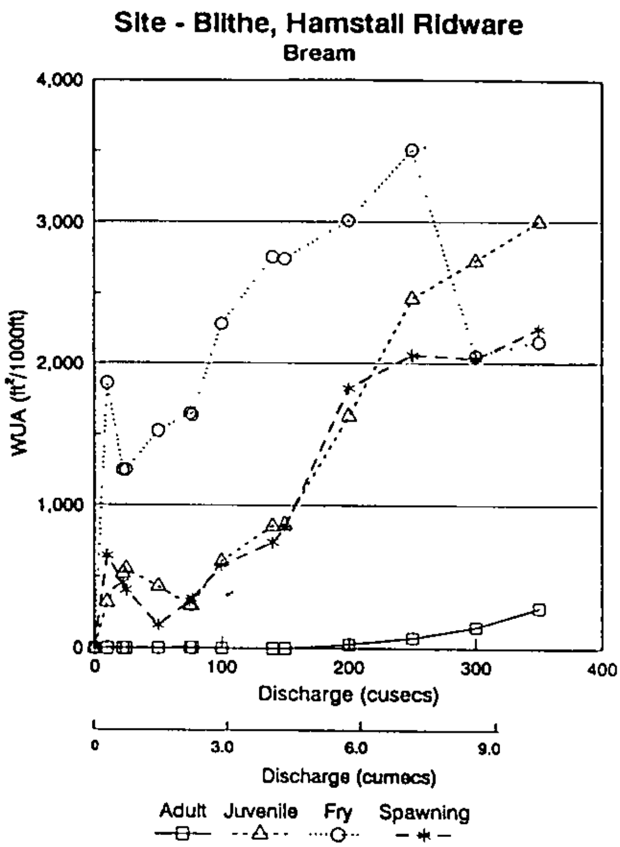


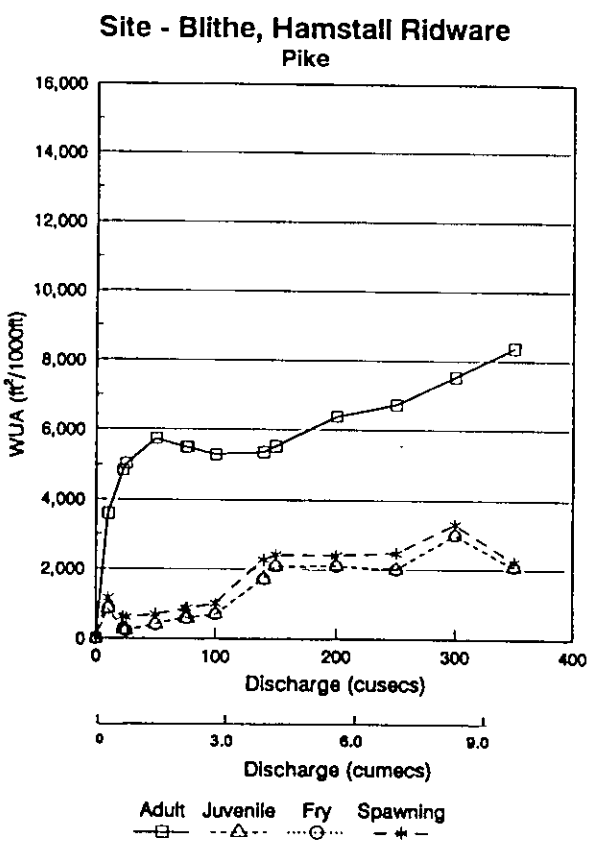
Site - Blithe, Hamstall Ridware
Dace
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult Juvenile Fry Spawning

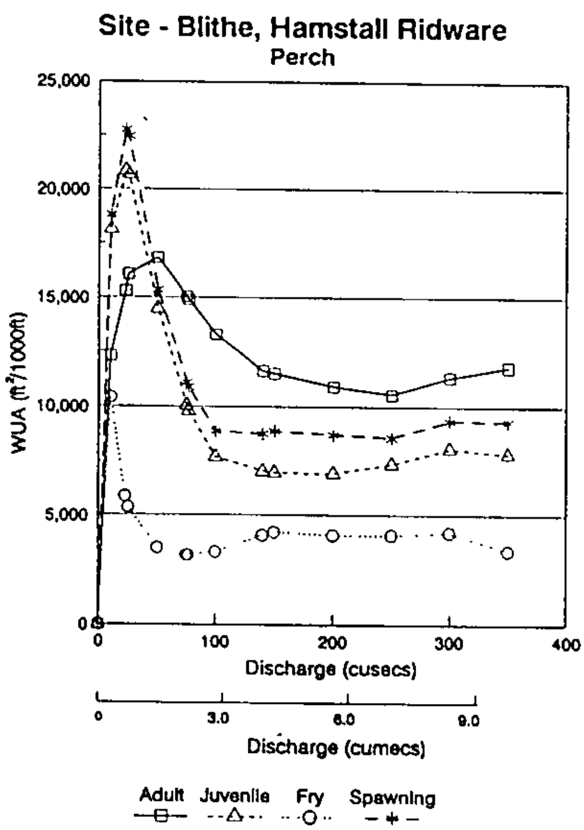


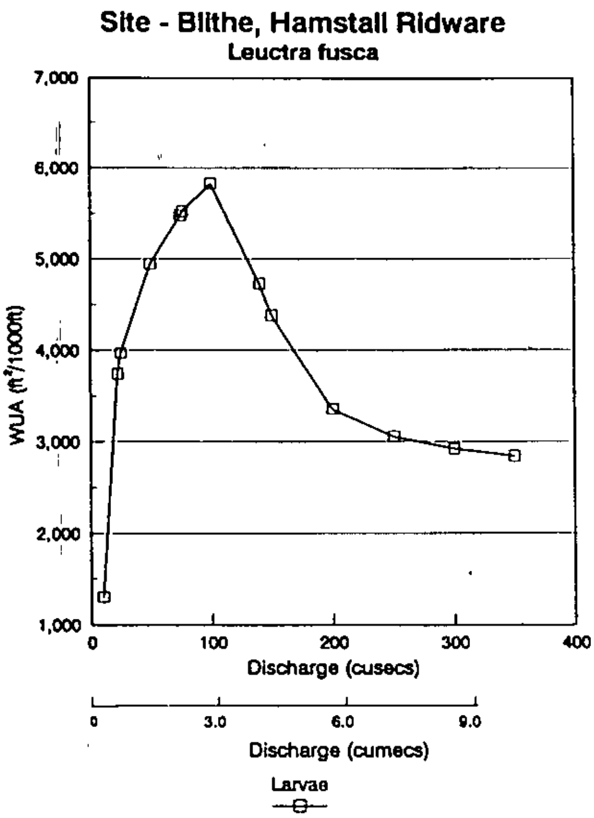
Site - Blithe, Hamstall Ridware
Chub
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult/Juvenile Fry Spawning


Site - Blithe, Hamstall Ridware
Roach
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult/Juvenile
Fry
Spawning

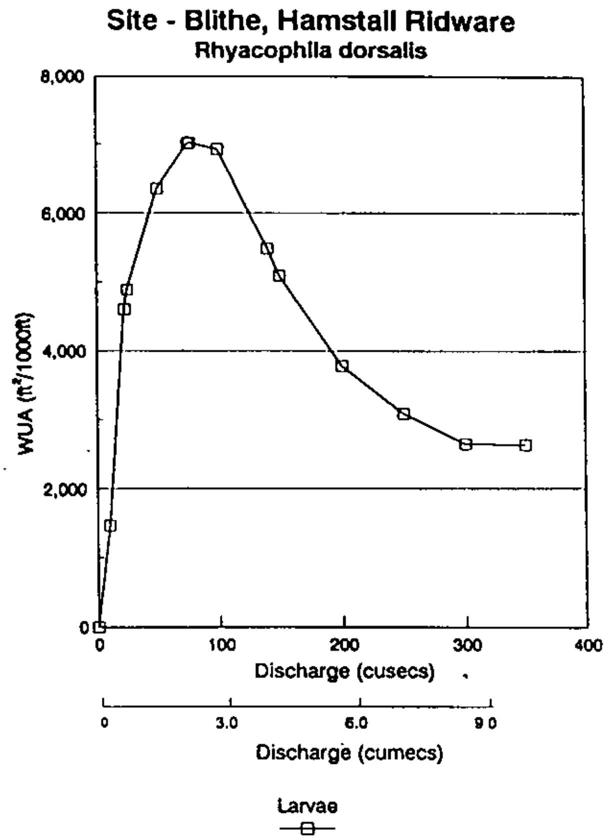

Site - Blithe, Hamstall Ridware
Bream
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult
Juvenile
Fry
Spawning


Site - Blithe, Hamstall Ridware
Pike
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult
Juvenile
Fry
Spawning

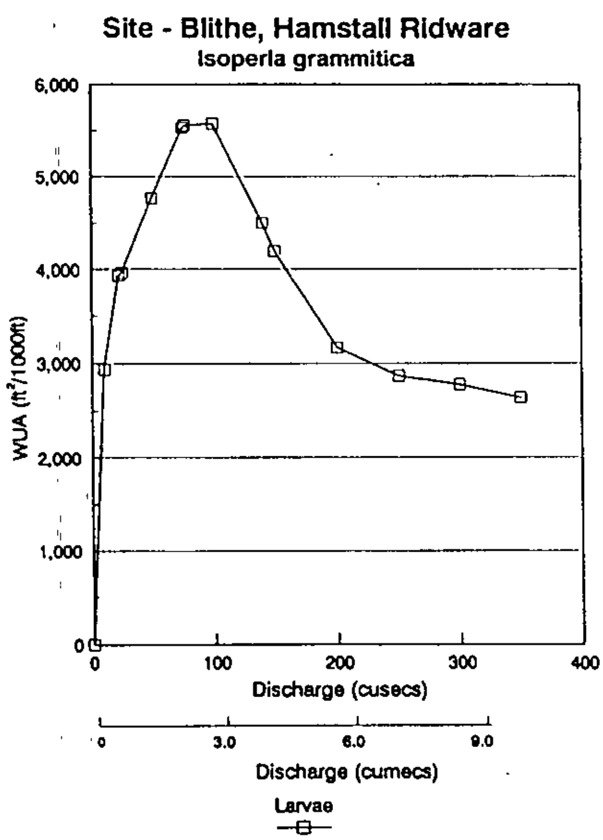

Site - Blithe, Hamstall Ridware
Perch
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult
Juvenile
Fry
Spawning



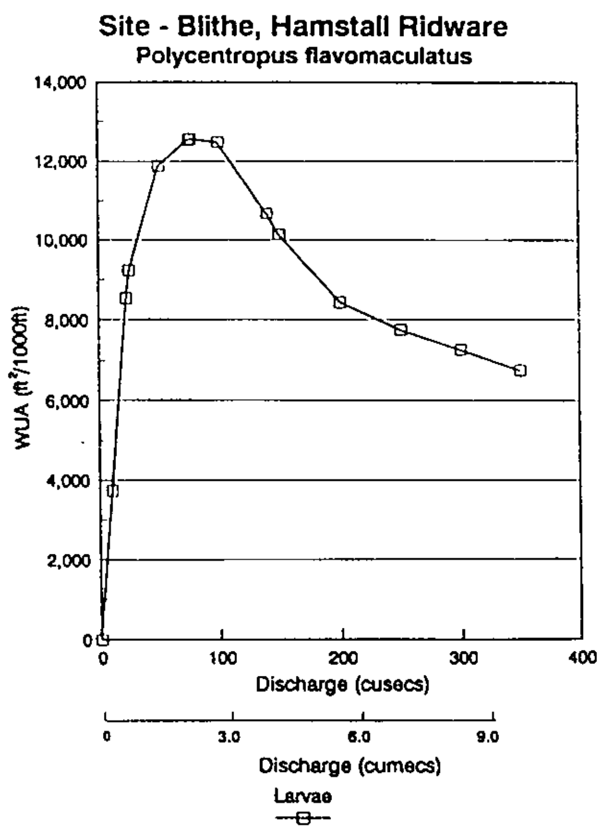
Site - Blithe, Hamstall Ridware
Leuctra fusca
WUA (ft²/1000ft)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
100
200
300
400
Discharge (cusecs)
0
3.0
6.0
9.0
Discharge (cumecs)
Larvae



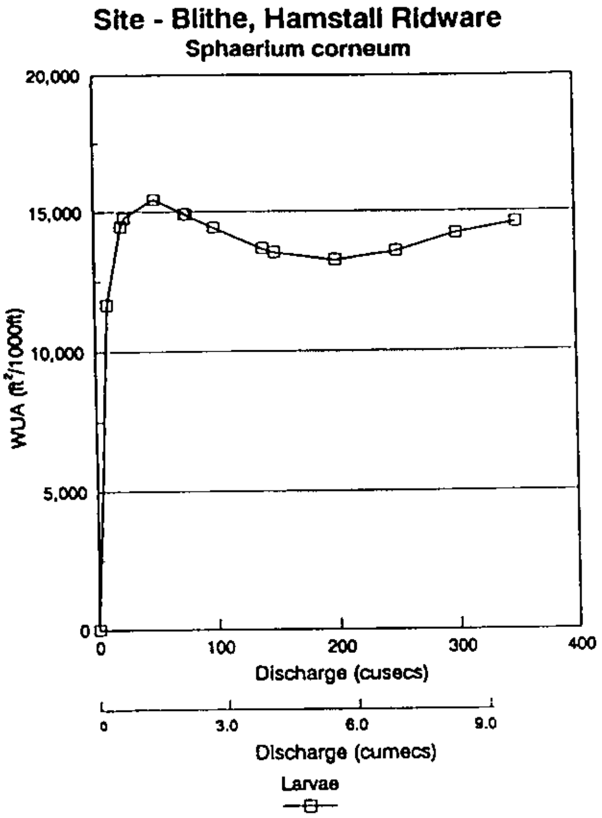
Site - Blithe, Hamstall Ridware
Rhyacophila dorsalis
WUA (ft²/1000ft)
8,000
6,000
4,000
2,000
0
0
100
200
300
400
Discharge (cusecs)
0
3.0
6.0
9 0
Discharge (cumecs)
Larvae

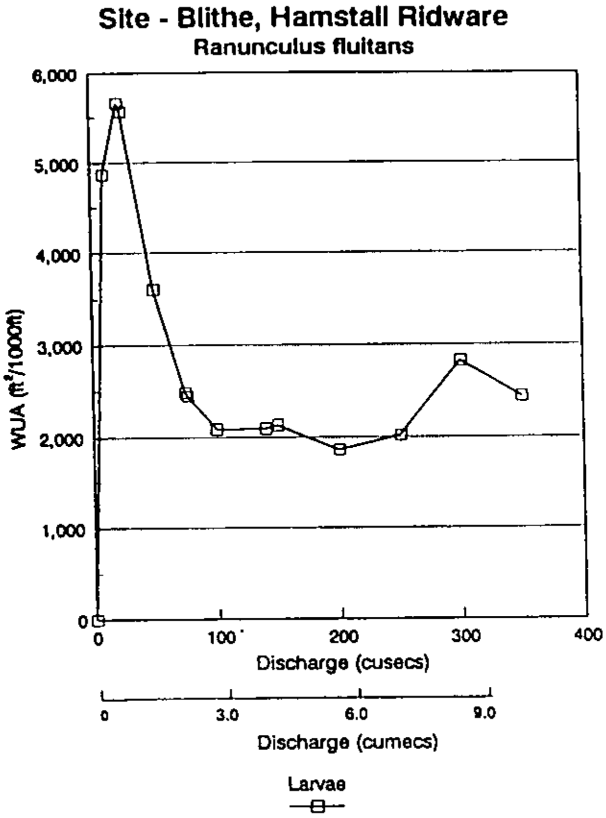


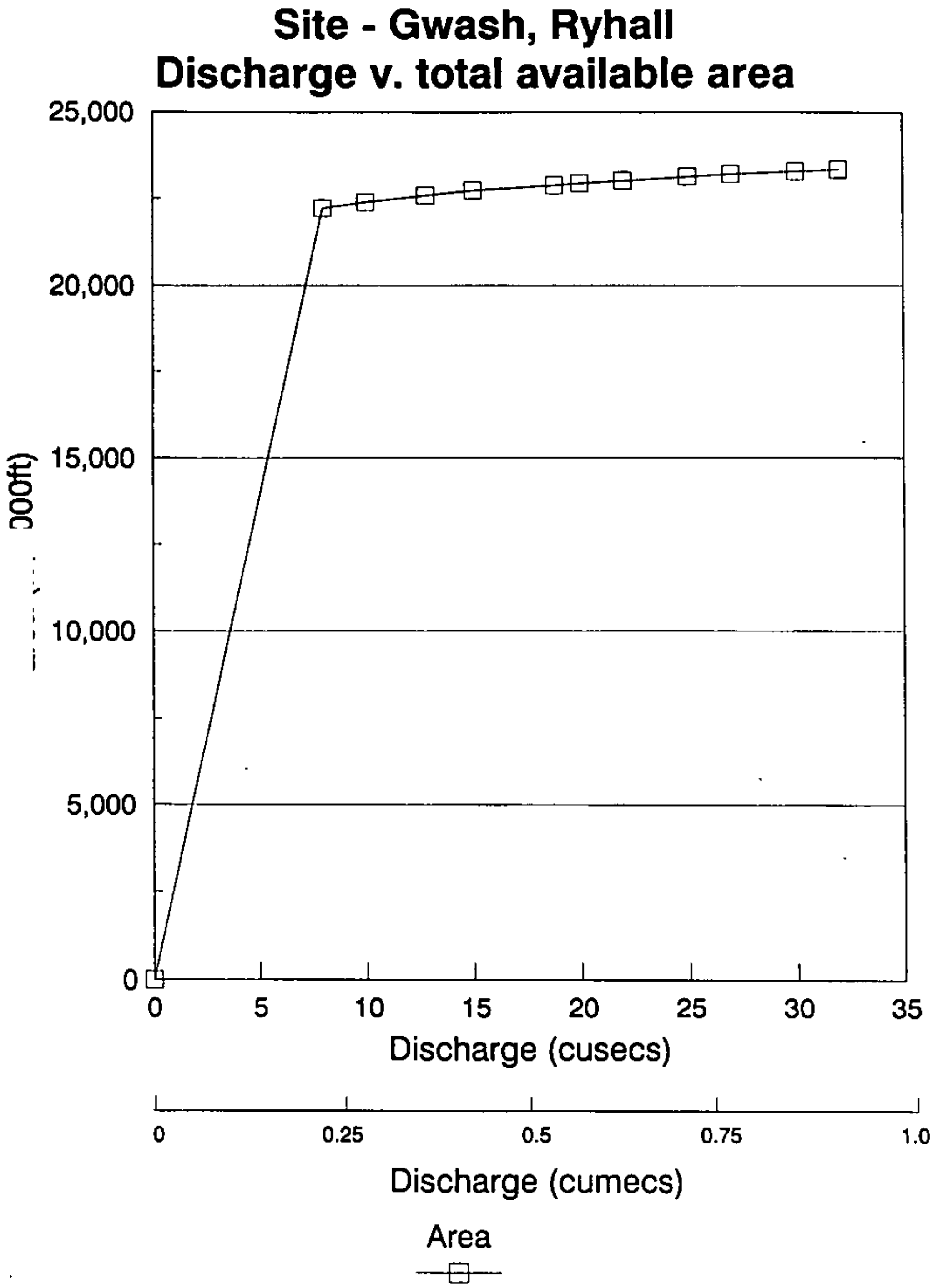
Site - Blithe, Hamstall Ridware
Isoperla grammitica
WUA (ft²/1000ft)
6,000
5,000
4,000
3,000
2,000
1,000
0
0
100
200
300
400
Discharge (cusecs)
0
3.0
6.0
9.0
Discharge (cumecs)
Larvae

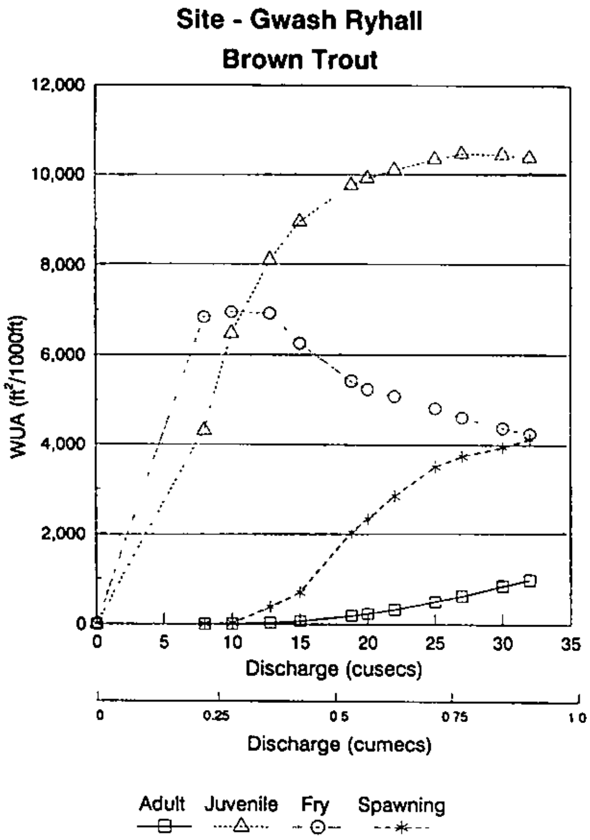


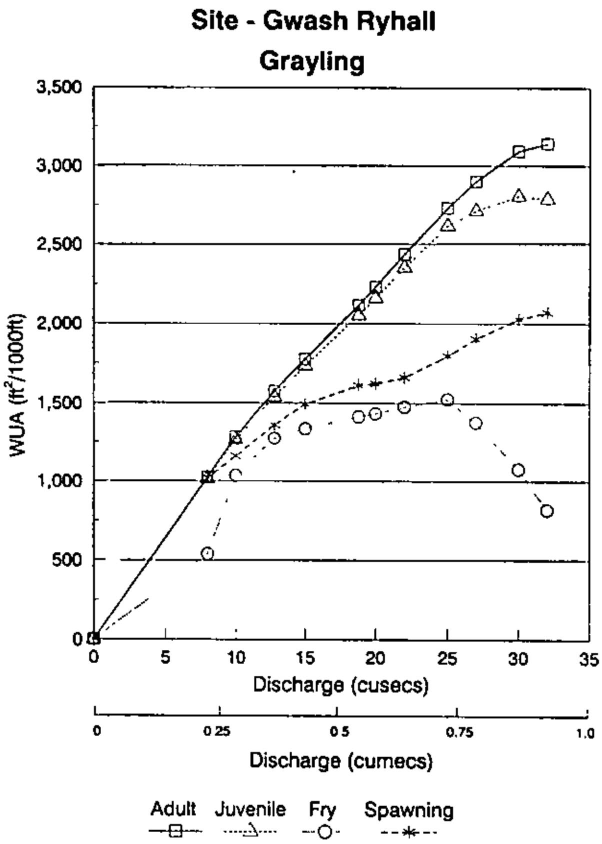
Site - Blithe, Hamstall Ridware
Polycentropus flavomaculatus
WUA (ft²/1000ft)
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
0
100
200
300
400
Discharge (cusecs)
0
3.0
6.0
9.0
Discharge (cumecs)
Larvae

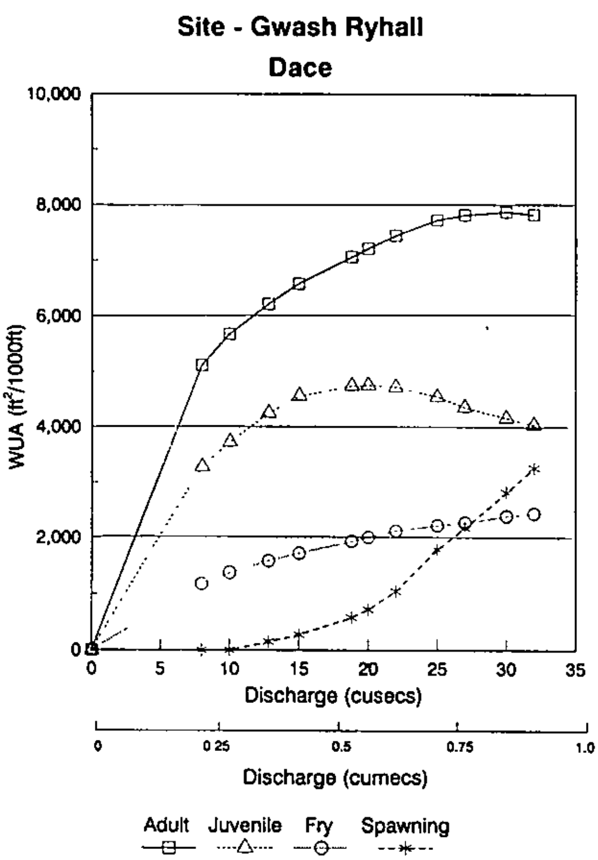

Site - Blithe, Hamstall Ridware
Sphaerium corneum
20,000
15,000
10,000
5,000
0
WUA (ft²/1000ft)
0
100
200
300
400
Discharge (cusecs)
0
3.0
6.0
9.0
Discharge (cumecs)
Larvae

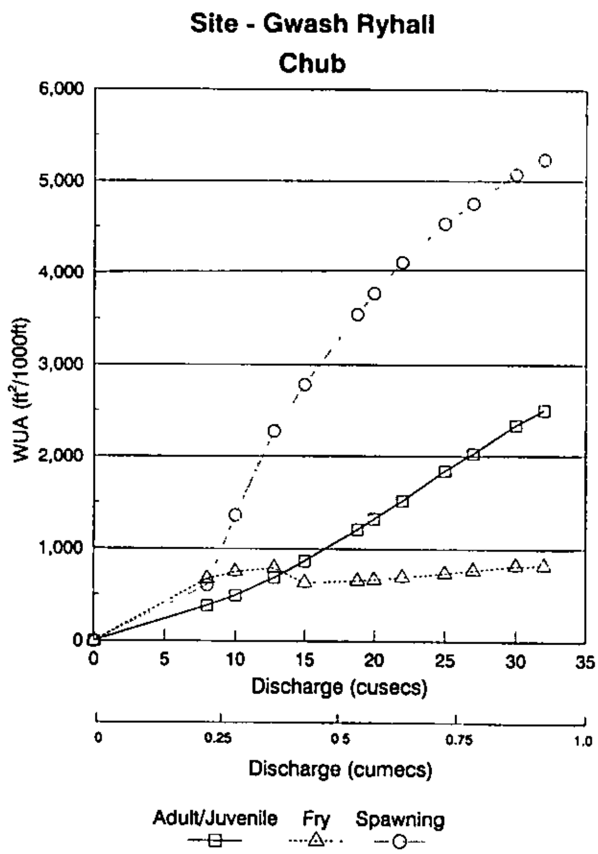

Site - Blithe, Hamstall Ridware
Ranunculus fluitans
6,000
5,000
4,000
3,000
2,000
1,000
0
WUA (ft²/1000ft)
0
100
200
300
400
Discharge (cusecs)
0
3.0
6.0
9.0
Discharge (cumecs)
Larvae

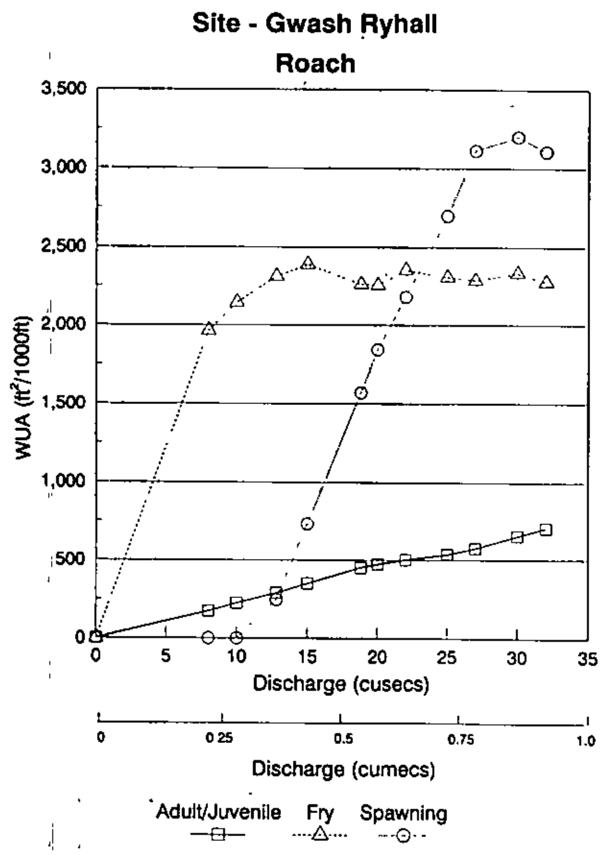

Site - Gwash, Ryhall
Discharge v. total available area
25,000
20,000
15,000
10,000
5,000
0
(000ft)
0
5
10
15
20
25
30
35
Discharge (cusecs)
0
0.25
0.5
0.75
1.0
Discharge (cumecs)
Area

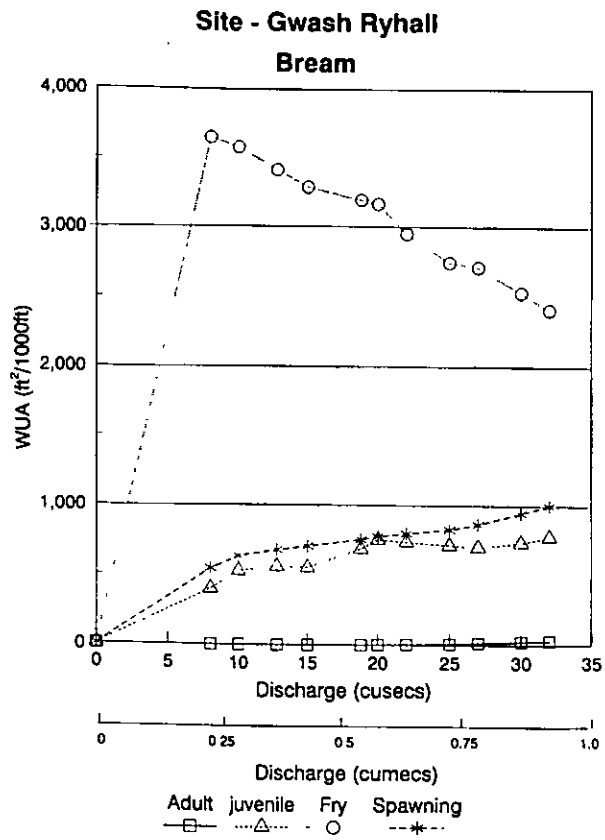

Site - Gwash Ryhall
Brown Trout
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult Juvenile Fry Spawning

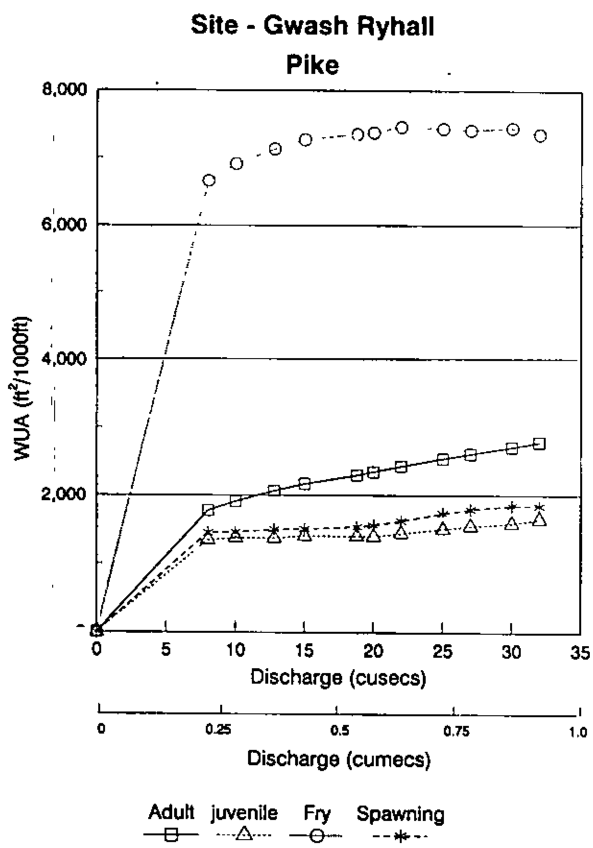

Site - Gwash Ryhall
Grayling
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult Juvenile Fry Spawning

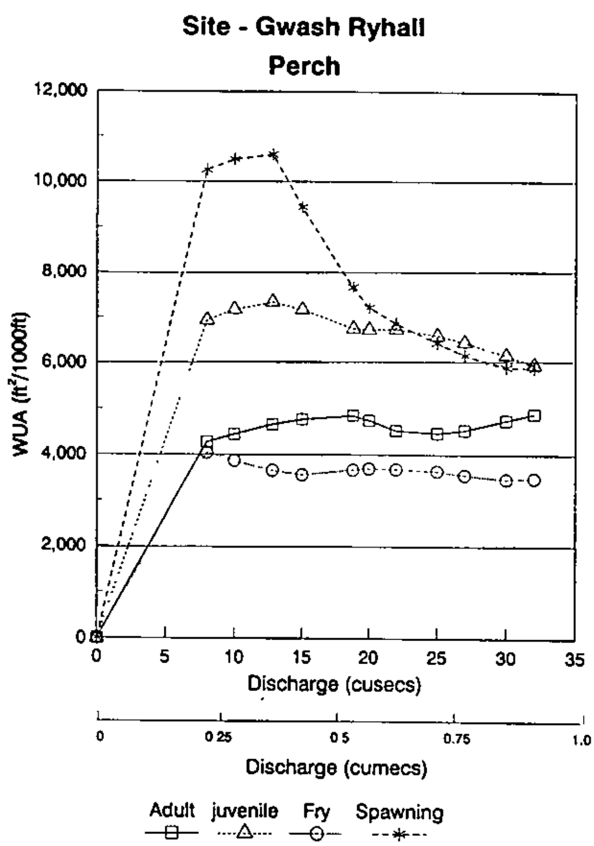

Site - Gwash Ryhall
Dace
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult Juvenile Fry Spawning

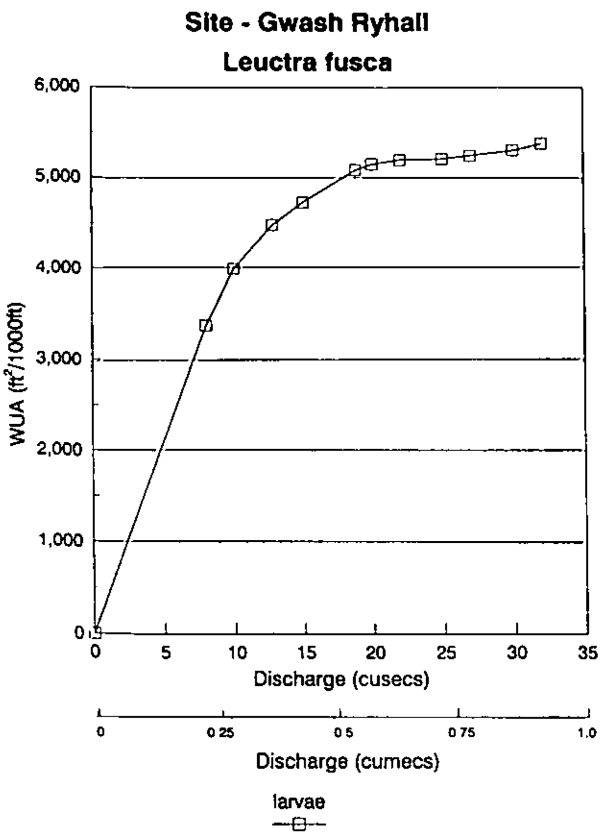

Site - Gwash Ryhall
Chub
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult/Juvenile Fry Spawning

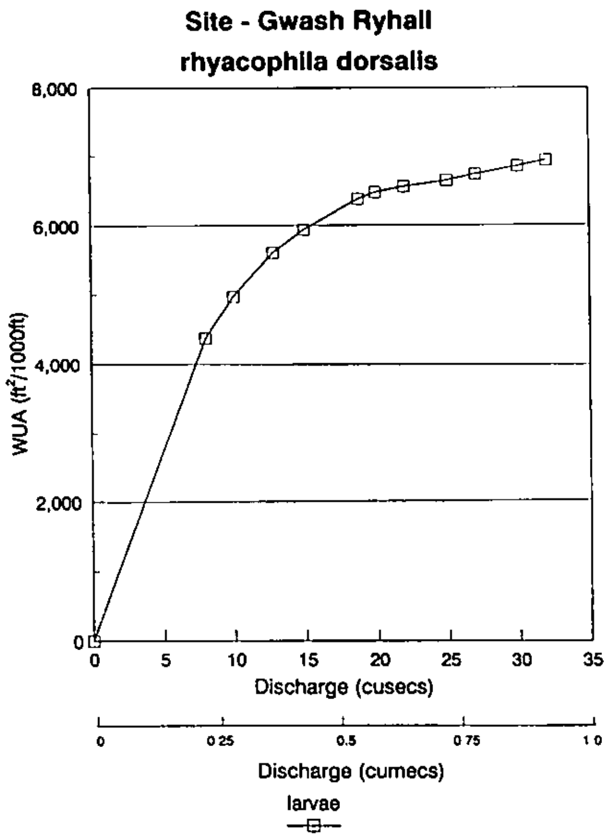

Site - Gwash Ryhall
Roach
WUA (ft²/1000ft)
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0 5 10 15 20 25 30 35
Discharge (cusecs)
0 0.25 0.5 0.75 1.0
Discharge (cumecs)
Adult/Juvenile Fry Spawning

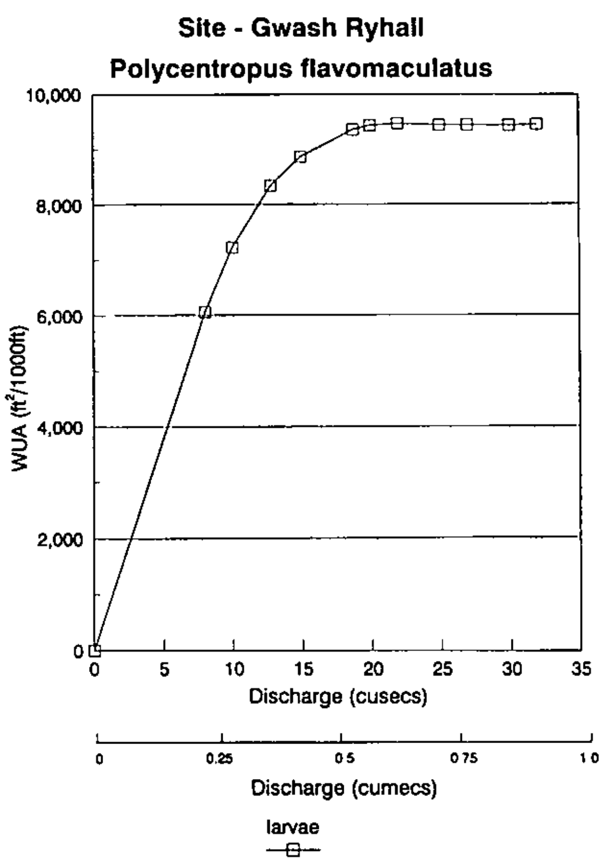

Site - Gwash Ryhall
Bream
WUA (ft²/1000ft)
4,000
3,000
2,000
1,000
0
0 5 10 15 20 25 30 35
Discharge (cusecs)
0 0.25 0.5 0.75 1.0
Discharge (cumecs)
Adult juvenile Fry Spawning

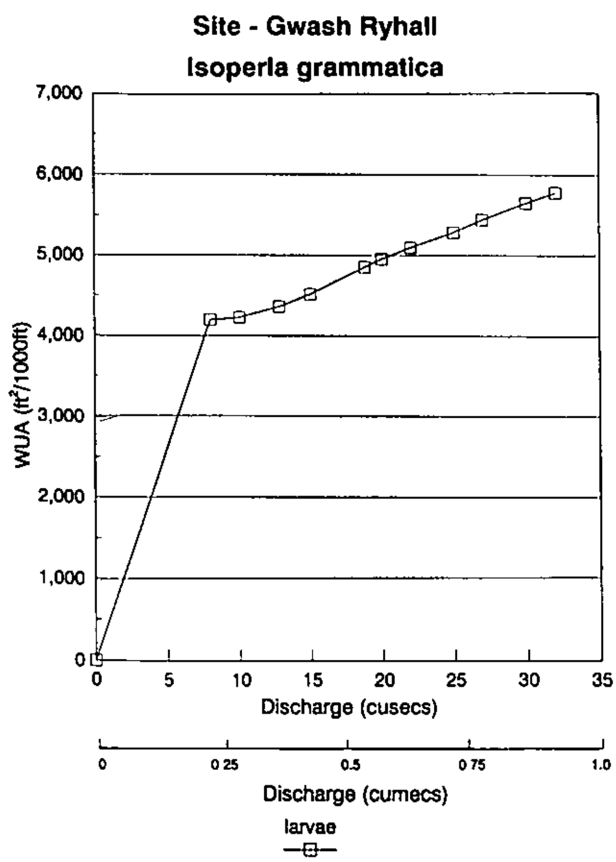

Site - Gwash Ryhall
Pike
WUA (ft²/1000ft)
8,000
6,000
4,000
2,000
0 5 10 15 20 25 30 35
Discharge (cusecs)
0 0.25 0.5 0.75 1.0
Discharge (cumecs)
Adult juvenile Fry Spawning

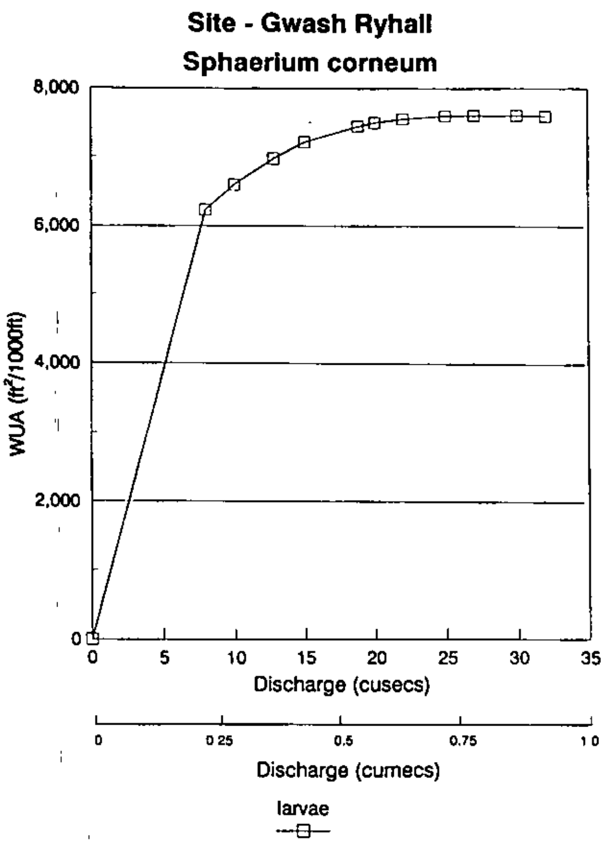

Site - Gwash Ryhall
Perch
WUA (ft²/1000ft)
12,000
10,000
8,000
6,000
4,000
2,000
0
0 5 10 15 20 25 30 35
Discharge (cusecs)
0 0.25 0.5 0.75 1.0
Discharge (cumecs)
Adult juvenile Fry Spawning

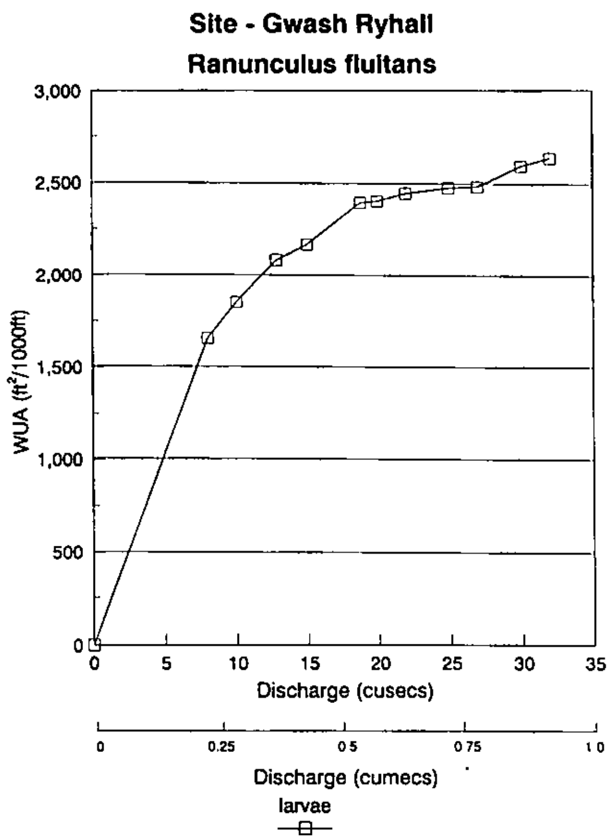

Site - Gwash Ryhall
Leuctra fusca
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
larvae

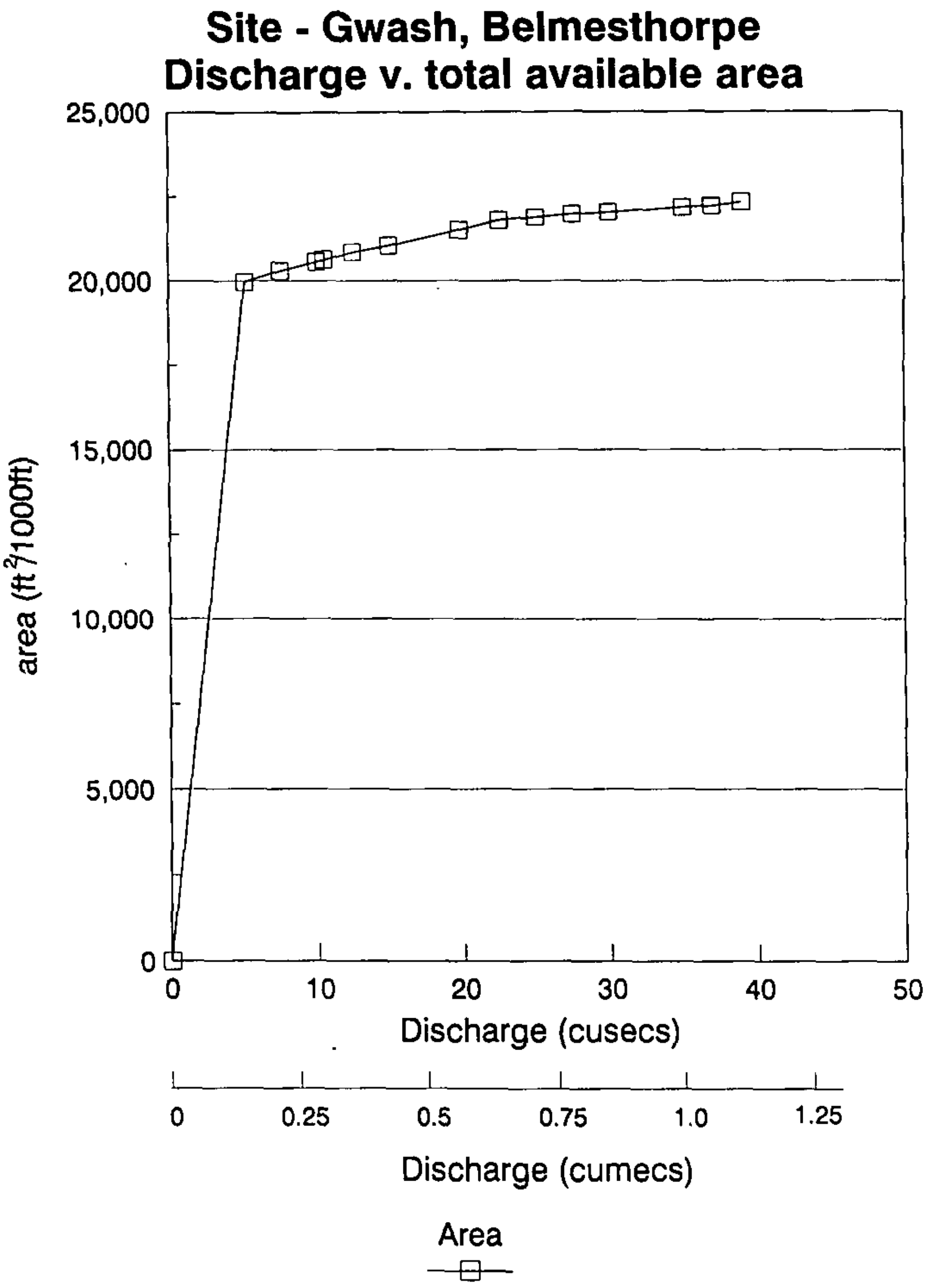

Site - Gwash Ryhall
rhyacophila dorsalis
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
larvae


Site - Gwash Ryhall
Polycentropus flavomaculatus
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
larvae

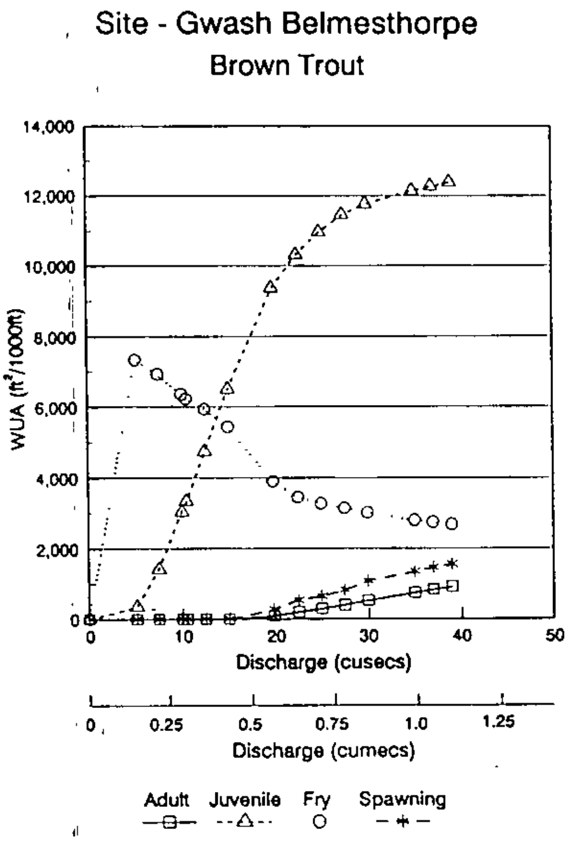

Site - Gwash Ryhall
Isoperla grammatica
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
larvae


Site - Gwash Ryhall
Sphaerium corneum
8,000
6,000
4,000
2,000
0
WUA (ft²/1000ft)
0
5
10
15
20
25
30
35
Discharge (cusecs)
0
0 25
0.5
0.75
1 0
Discharge (cumecs)
larvae

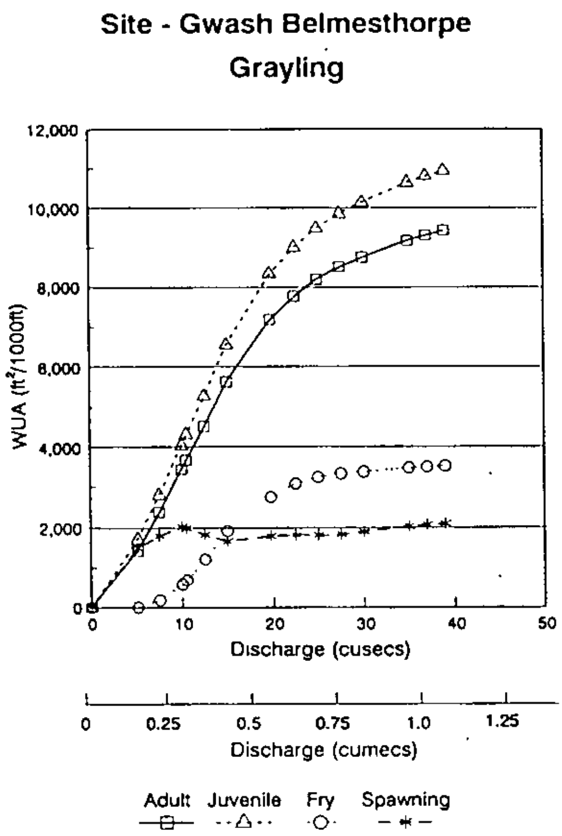

Site - Gwash Ryhall
Ranunculus fluitans
3,000
2,500
2,000
1,500
1,000
500
0
WUA (ft²/1000ft)
0
5
10
15
20
25
30
35
Discharge (cusecs)
0
0.25
0 5
0 75
1 0
Discharge (cumecs)
larvae



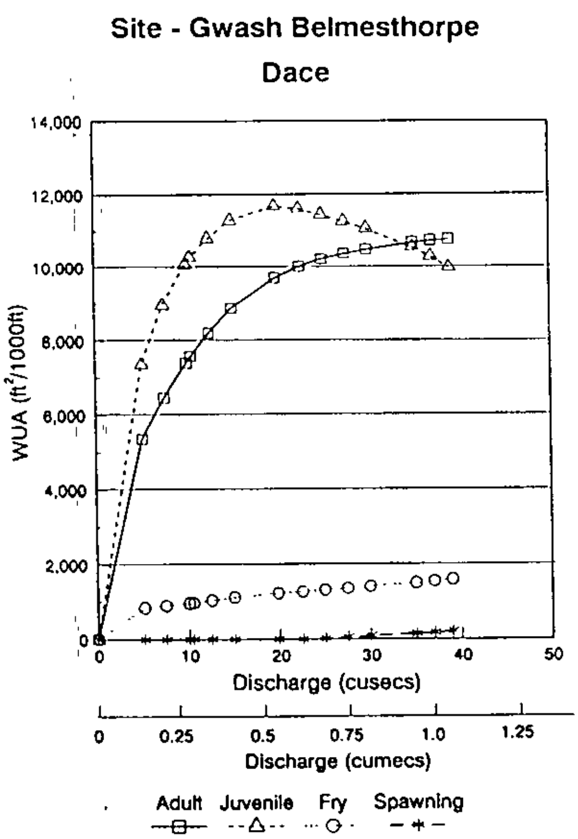
Site - Gwash, Belmesthorpe
Discharge v. total available area
25,000
20,000
15,000
10,000
5,000
0
area (ft²/1000ft)
0
10
20
30
40
50
Discharge (cusecs)
0
0.25
0.5
0.75
1.0
1.25
Discharge (cumecs)
Area



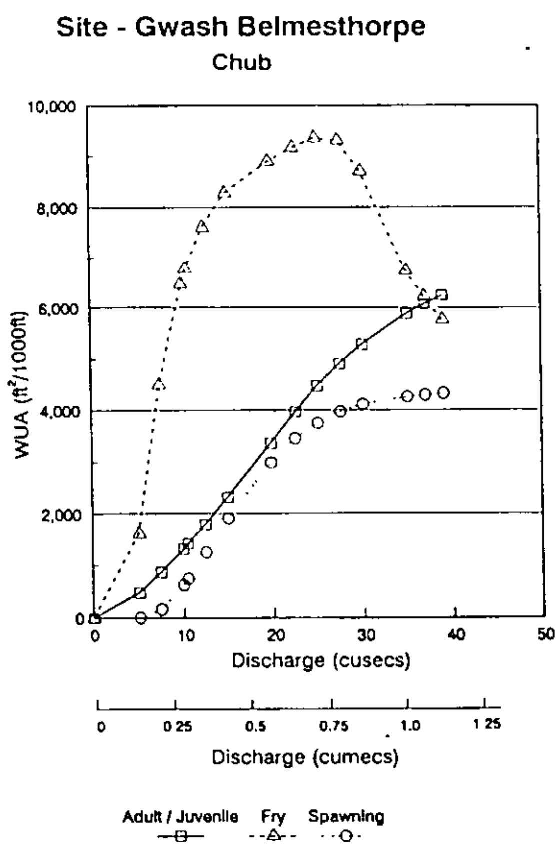
Site - Gwash Belmesthorpe
Brown Trout
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult
Juvenile
Fry
Spawning



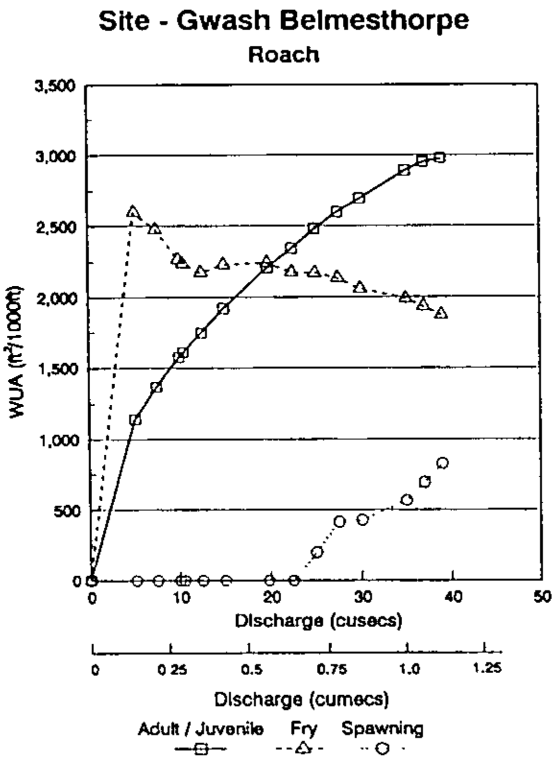
Site - Gwash Belmesthorpe
Grayling
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult
Juvenile
Fry
Spawning



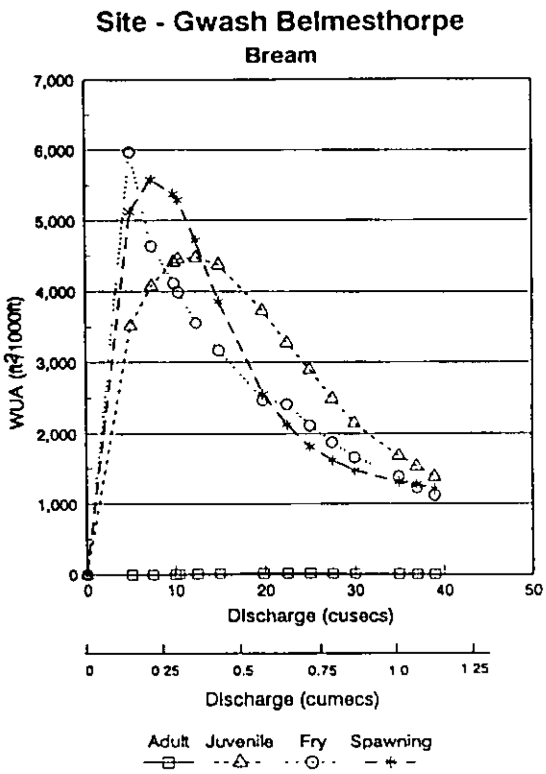
Site - Gwash Belmesthorpe
Dace
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult
Juvenile
Fry
Spawning



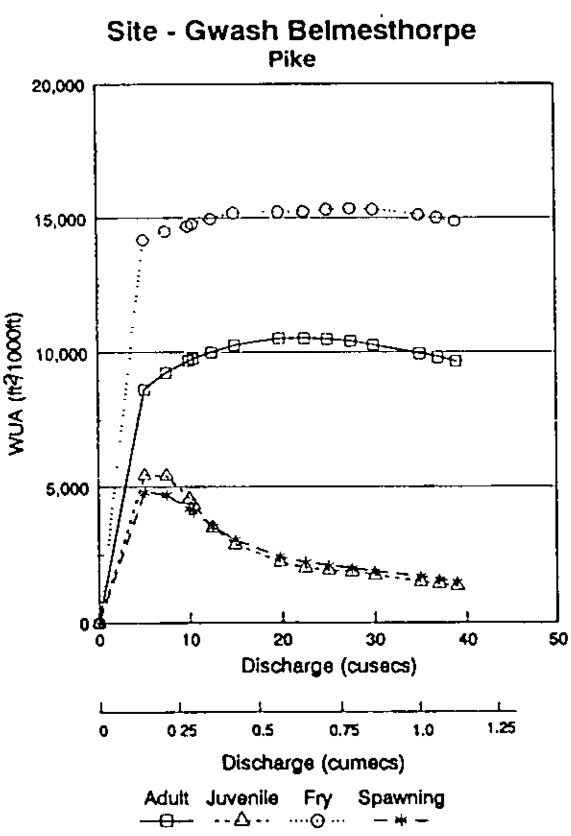
Site - Gwash Belmesthorpe
Chub
WUA (ft²/1000ft)
Discharge (cusecs)
Discharge (cumecs)
Adult / Juvenile
Fry
Spawning



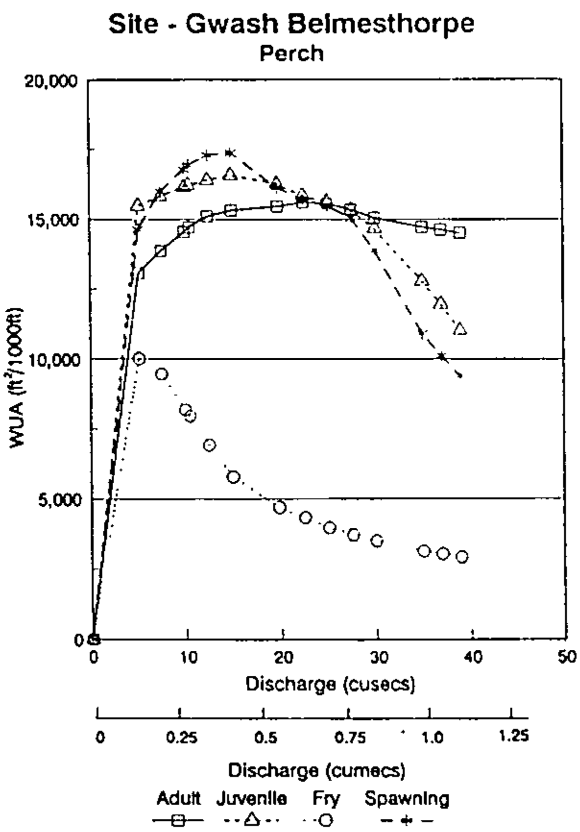
Site - Gwash Belmesthorpe
Roach
WUA (ft²/1000ft)
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
10
20
30
40
50
Discharge (cusecs)
0
0.25
0.5
0.75
1.0
1.25
Discharge (cumecs)
Adult / Juvenile
Fry
Spawning



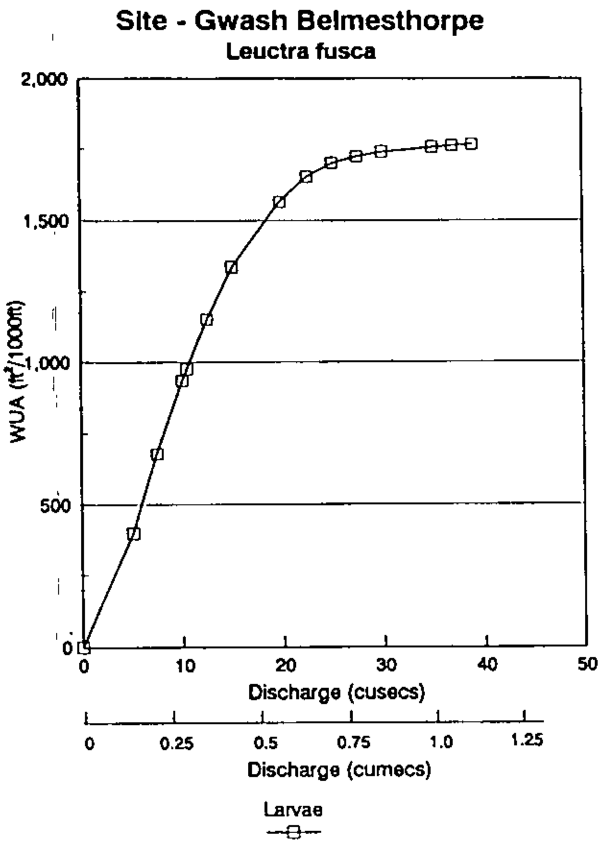
Site - Gwash Belmesthorpe
Bream
WUA (ft²/1000ft)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
0
10
20
30
40
50
Discharge (cusecs)
0
0.25
0.5
0.75
1.0
1.25
Discharge (cumecs)
Adult
Juvenile
Fry
Spawning

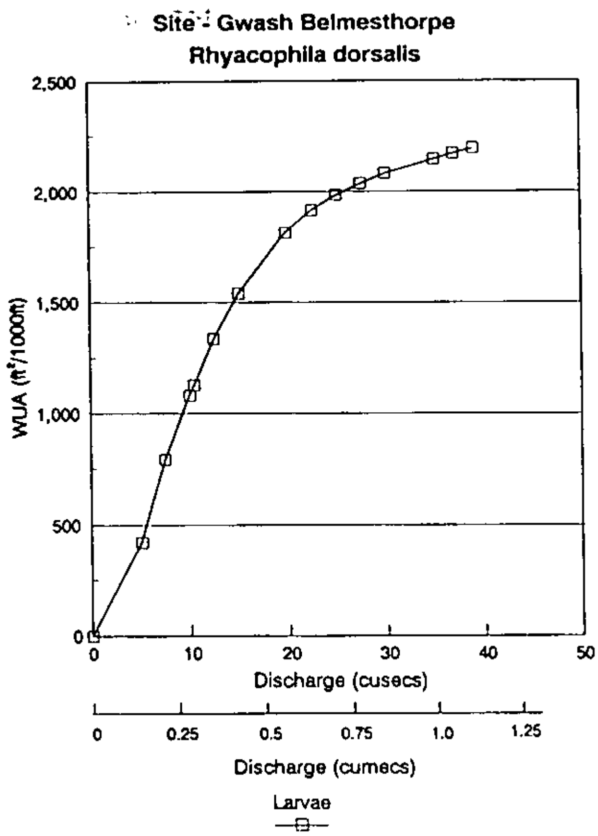


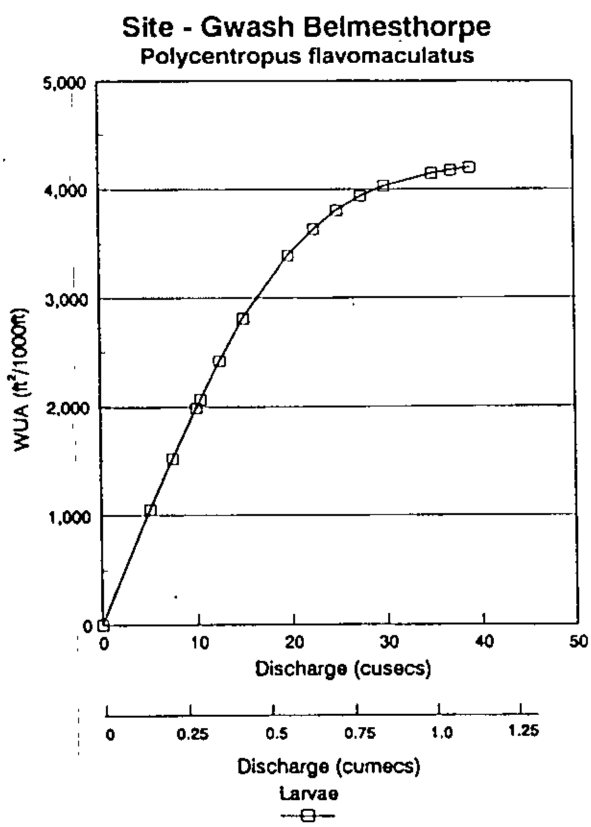
Site - Gwash Belmesthorpe
Pike
WUA (ft²/1000ft)
20,000
15,000
10,000
5,000
0
0
10
20
30
40
50
Discharge (cusecs)
0
0.25
0.5
0.75
1.0
1.25
Discharge (cumecs)
Adult
Juvenile
Fry
Spawning

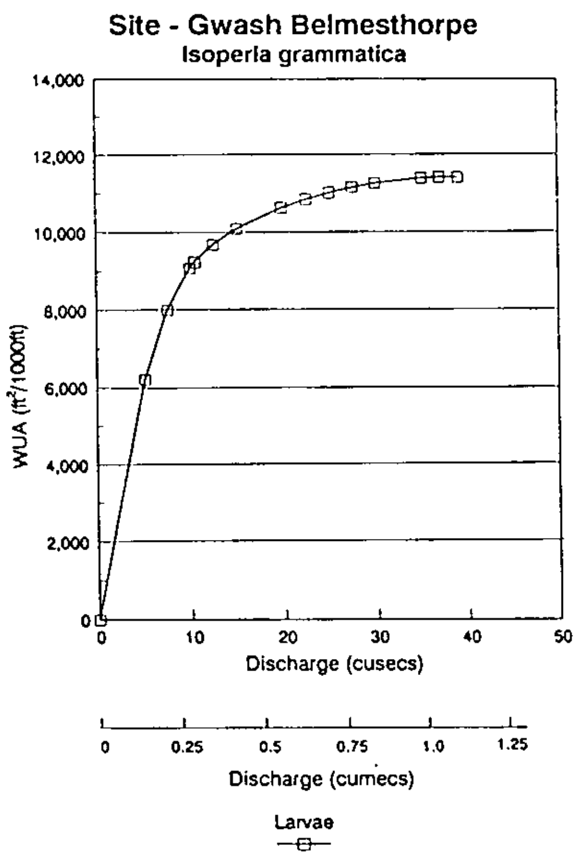


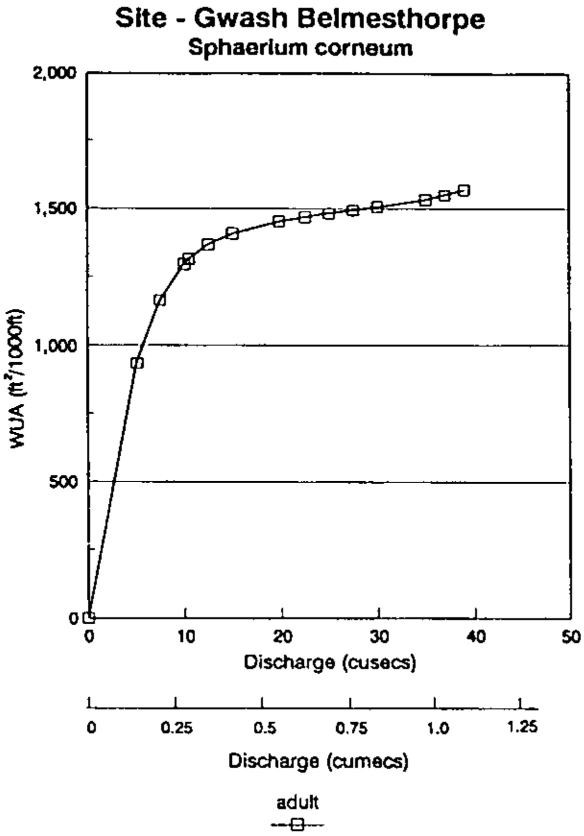
Site - Gwash Belmesthorpe
Perch
WUA (ft²/1000ft)
20,000
15,000
10,000
5,000
0
0
10
20
30
40
50
Discharge (cusecs)
0
0.25
0.5
0.75
1.0
1.25
Discharge (cumecs)
Adult
Juvenile
Fry
Spawning

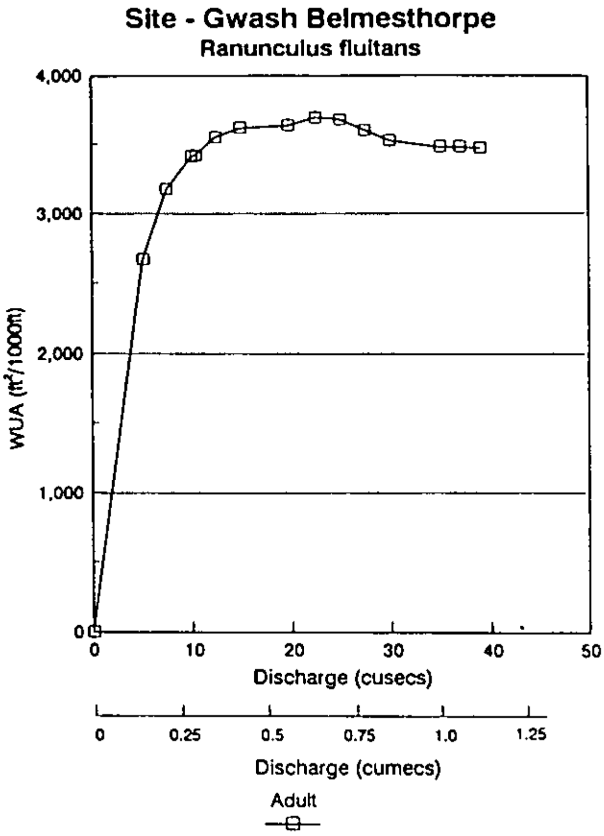

Site - Gwash Belmesthorpe
Leuctra fusca
WUA (ft²/1000ft)
2,000
1,500
1,000
500
0
0
10
20
30
40
50
Discharge (cusecs)
0
0.25
0.5
0.75
1.0
1.25
Discharge (cumecs)
Larvae


Site - Gwash Belmesthorpe
Rhyacophila dorsalis
WUA (ft²/1000ft)
2,500
2,000
1,500
1,000
500
0
0
10
20
30
40
50
Discharge (cusecs)
0
0.25
0.5
0.75
1.0
1.25
Discharge (cumecs)
Larvae


Site - Gwash Belmesthorpe
Polycentropus flavomaculatus
WUA (ft²/1000ft)
5,000
4,000
3,000
2,000
1,000
0
0
10
20
30
40
50
Discharge (cusecs)
0
0.25
0.5
0.75
1.0
1.25
Discharge (cumecs)
Larvae


Site - Gwash Belmesthorpe
Isoperla grammatica
WUA (ft²/1000ft)
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
0
10
20
30
40
50
Discharge (cusecs)
0
0.25
0.5
0.75
1.0
1.25
Discharge (cumecs)
Larvae


Site - Gwash Belmesthorpe
Sphaerium corneum
2,000
1,500
1,000
500
0
WUA (ft²/1000ft)
0
10
20
30
40
50
Discharge (cusecs)
0
0.25
0.5
0.75
1.0
1.25
Discharge (cumecs)
adult


Site - Gwash Belmesthorpe
Ranunculus fluitans
4,000
3,000
2,000
1,000
0
WUA (ft²/1000ft)
0
10
20
30
40
50
Discharge (cusecs)
0
0.25
0.5
0.75
1.0
1.25
Discharge (cumecs)
Adult

Annex 1

Habitat preferences of target species for application in PHABSIM testing

P.D. Armitage & M. Ladle
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SUMMARY

Habitat preference curves for five species of invertebrate and eight species of fish are presented. The invertebrate data are derived from a large body of information held at the IFE River Laboratory. The fish curves are based on experience and local knowledge of UK conditions.

The results are discussed and some suggestions for future studies are proposed.

1. INTRODUCTION

The PHABSIM model simulates a relationship between stream flow and physical habitat for various life stages of a species of fish, benthic invertebrates or for a recreational activity such as canoeing.

The model (which is still evolving) was developed in the USA and has been in use for about ten years as a management tool.

Its applicability to British waters has not been tested and the objectives of this present study are listed below:

i) establish a methodology for providing habitat preference curves for target species from field work, literature, and local knowledge for UK conditions;

ii) apply this method to provide habitat preference curves in tabular form and in the form of the attached figure for each of three variables: depth, velocity and substrate, for one or more species of fish and invertebrate, to be chosen by the IFE as being suitable for the following reaches selected for investigation: three reaches on the river Blithe, one upstream and two downstream of Blithfield reservoir (gauging station NGR SK 109192); two reaches on the river Gwash below Rutland water (NGR SK 951082); and two reaches on the river Derwent, one above and one below Ladybower reservoir (NGR SK 198851);

iii) plan and arrange invertebrate sampling in the study reaches selected for testing the PHABSIM model. The samples will be preserved and stored by the FBA to be processed when funds become available (Appendix 1).

2. METHODS

2.1 Invertebrates

The most accurate estimates of habitat preferences are derived from detailed analyses of distribution patterns of species with respect to specific variables measured at the point at which a faunal sample is taken. Such techniques are time-consuming and costly but are ultimately necessary for developing the model. In the absence of such data cruder estimates have to be used.

Large data bases which record both faunal occurrence and physical features at sites provide the raw material for preliminary assessments of habitat preference. The IFE River Communities Project (RCP) has, over the past ten years, identified about 600 species of macroinvertebrates from more than 400 substantially unpolluted sites throughout Great Britain. Physical and chemical information has also been collected from these sites. These two blocks of data (distributional biology, and physical characteristics) have been used in this study to assess the habitat preferences of selected species.

The results below are based on the first phase of the project when 273 sites had been sampled. The remaining data are not currently in a form which is readily available for assessment of habitat preferences.

At a site benthic fauna is taken from all available habitats, usually in proportion to their occurrence, and a sample comprises all the material collected in a three-minute period. This method therefore does not take account of distribution patterns within the site and the results express occurrence with respect to mean values of variables such as substratum, velocity, depth etc. This reduced precision is partly offset by the large number of records for the selected species.

The RCP data have been used to develop a model, RIVPACS, which uses environmental data to classify sites and predict the probability of capture of faunal taxa at unsampled sites. This model can also be used to determine habitat preferences mainly with respect to substratum. For example, it is possible to predict the fauna of the site Hamstall Ridware on the Blithe using actual physical data and then enter simulated substratum values and observe the effect on the probability of a species occurring at the site. This method is explored briefly in this report.

In addition to the presence/absence data for species in the RIVPACS model, information on the relative abundance of families is also available. This is important because changed physical habitat may affect both abundance and occurrence of benthic fauna.

Selection of taxa: Many invertebrate species have a relatively wide distribution and can tolerate a range of environmental conditions, for example the mayfly *Baetis rhodani* is very widespread occurring in about 85% of the sites sampled for the RIVPACS model. For such a species environmental changes would have to be very severe to cause a significant decline in its probability of occurrence at a site. In making the selection for this attempt at determining habitat preferences, species with narrower ecological limits were used. They include two stoneflies *Leuctra fusca* and *Isoperla grammatica*, two caddis-flies *Polycentropus flavomaculatus* and *Rhyacophila dorsalis*, and the pea mussel *Sphaerium corneum*. All taxa occur in at least 42% of the total sites sampled.

2.2 Fish

In relation to fish stocks the predictive characteristics applied vary in their relevance to the species. In general, water velocity and depth are appropriate features to consider at all stages of a fishes life cycle.

Because no factor operates in isolation from others which are under consideration it is considered that to assign values of suitability as high as 1 (presumably 'perfection') would be inappropriate and thus the figures are usually truncated at an arbitrary value of about 0.8 to permit scope for modification as the models are refined. Substrate type (sediment particle size/detritus content) is so closely related to depth, and in particular to velocity, that the relationships to habitat suitability are likely to be very similar.

Cover descriptions appear to have been designed purely for salmonid fishes since they include predominantly overhanging banks and vegetation which are known to increase the holding capacities of running waters for brown trout and other territorial species inhabiting mainly smaller, narrow, fast-flowing watercourses in which the significance of the marginal overhangs and trailing vegetation is much greater than in wide, deep rivers.

The present analysis covers those species known to inhabit the streams/rivers effluent from the three reservoirs under consideration (Appendix 2). Because many of these species are not salmonids the presence of aquatic plants is likely to be of greater importance to them. This factor is of twofold significance. Firstly, it will behave in a similar manner to 'instream cover' (rocks etc.) by sheltering fish from the direct effects of the flowing water, and secondly, it will provide a substratum on which prey organisms may live or to which the eggs of the fish may be attached. In practice the successful spawning of many cyprinids, esocids and percids is almost totally dependent on the presence of aquatic vegetation or of structurally similar 'cover' in the form of submerged tree roots, fallen tree branches, algae, bryophytes etc.

3. PRESENTATION OF RESULTS

3.1 Invertebrates

Tables 1-4 present data in tabular form which is repeated as curves for the selected species. Substrate data in the tables have been presented as phi values for increased accuracy and not as the code used in the PHABSIM model. Equivalent values have, however, been calculated for construction of the habitat preference curves. The highest weighted percentage value for each variable (Table 1), is considered as the most 'suitable', i.e. 1.0. Remaining 'suitability' values are calculated from the other percentages in relation to the highest value. Assessments based on existing knowledge of invertebrate distribution were used to supply missing values.

3.2 Fish

Figures and tables are used to describe a set of appropriate parameters within which each major species present in the rivers under consideration can be considered to lie. The tables are constructed on the basis of the modal range of each factor. Other species such as gudgeon, minnow, bullhead, three-spined stickleback and loach which are likely to occur are not listed in Table 5 and are of less direct relevance to water users, and under the constraints of time imposed on the present study have not been considered. However, these species may be excellent indicators of changing conditions and should be taken into account in any complete model.

The current PHABSIM model (as given) appears to have no provision for cover in the form of algae, bryophytes or angiosperms within the river. As mentioned above such plants are often critical to the spawning and/or feeding of coarse fishes so, in the absence of a definite directive, a '?' is used to indicate that this factor should be considered in future models.

4. RESULTS

4.1 Invertebrates

The following data are presented in figures and tables:

(i) Habitat preferences of the five invertebrate species based on frequency of occurrence data. Additional curves are presented for *Isoperla grammatica* which are based on relative abundance in the data set (Figs 1-5).

(ii) Substrate preferences of the families represented by the species *Isoperla grammatica* (= Perlodidae), *Leuctra fusca* (Leuctridae), *Polycentropus flavomaculatus* (Polycentropodidae), *Rhyacophila dorsalis* (Rhyacophilidae) and *Sphaerium corneum* (Sphaeriidae) based on predictions with the RIVPACS model applied to two sites, one on the R. Gwash, the other on the Blithe. Data are presented on both predicted occurrence (Figure 6) and relative abundance (Figure 7).

(iii) Substrate preferences of three species *L. fusca, I. grammatica* and *Sphaerium corneum* based on predictions with the RIVPACS model as in (ii) above (Figure 8).

4.2 Fish

In general each of the fish species listed is likely to have specific requirements at each stage of its life. Thus, while adult dace spawn in fast flowing, shallow water over gravel substrata (the eggs adhere to the hard bottom and are susceptible to damage by deposition of finer sediments) the fry stages are restricted to slow flowing, shallow, marginal areas in which the substratum may range from fine sand to silt or fragmented organic detritus. It will certainly be possible, with a greater input of research time, to prepare detailed information sheets for these and other species even though the limitations outlined above still apply.

5. DISCUSSION

5.1 Invertebrates

Most of the taxa tested were found over a wide range of conditions but were common only over a narrow range. To a degree the wide spread of occurrences reflects the composite nature of the samples but at the same time emphasises that species can be found in small areas of a site which otherwise may be totally unsuitable. This suggests that occurrence data are not suitable for defining habitat preferences. However, the results from the one case where relative abundance for a single species, *Isoperla grammatica*, were analysed indicate good agreement between occurrence and abundance data at a site.

Relative abundance data are readily available at the family level. Predictions of family response to substrate change also show good agreement between abundance and occurrence data despite the fact that the families contain more than one species. In a previous study specific variation has been examined and the response curves for occurrence are presented here for information (Fig. 39). It can be concluded that although there is good agreement in general between abundance and occurrence at family level individual species may show a wide range of responses. The family curve will be defined by the most common species within that family.

The data from predictions at the two sites for which environmental features were readily available showed an interesting phenomenon. Some species/ families appeared to have a greater tolerance to changing conditions in the Blithe (as indicated by their wider habitat preferences) than in the Gwash. This was particularly marked in those taxa which prefer coarser substrates. There was insufficient time available to study this further, but if the indications are true then it suggests something that might have been expected, that is that the fauna of some rivers will react less to environmental change than will that of more 'susceptible' streams.

The invertebrate community at a site is a dynamic complex of interactions and in consequence attempts to attribute change to three or four variables are not likely to be totally successful. A feature of major importance to benthos is the distribution and settlement of fine particulate material. This material which is partly biological in origin can determine the nature and abundance of invertebrates in rivers. It is important that attempts are made to establish the relationship between flow characteristics and channel morphometry and the dynamics of fines. The situation is complicated by the fact that managed flow changes may not be sufficiently great to alter the basic substratum type but would allow the deposition of a thin layer of the fines. This would result in faunal change.

Accurate assessments of habitat preferences require detailed analysis of micro-distribution patterns in relation to flow velocity and substrate. Data used in this study provide a gross assessment of preference and indicate the relative susceptibility of species to environmental change. It should be stressed however that most regulatory schemes in Great Britain do not have a *gross* effect on the physical characteristics, and faunal changes are frequently rather subtle involving shifts in dominance of species and increases or decreases in overall abundance. In order to predict these changes with accuracy in relation to physical habitat changes more basic work is needed on the factors controlling the distribution of individual species.

5.2 Fish

In many cases the application of the assigned habitat characteristics may vary with the time of day and the behaviour or physiological conditions of the species concerned. For example, the brown trout will, if disturbed, normally seek overhead cover and an adequate area of overhanging banks, trees etc. may be essential for a stream to support substantial populations of this species. Undisturbed fish which are feeding will require territories in which they are visually separated from their neighbours. The separation distances required may decrease in faster flowing water or in the presence of increased prey densities. In addition to these aspects it is probable that the majority of feeding activity takes place in the hours of darkness when the fish may move into shallower, faster flowing regions in order to take advantage of enhanced invertebrate drift rates at such times. In practice it can be seen that the optimal habitat for the adults of this species may not lie at a simple optimum for each habitat characteristic but could depend rather on the presence of a wide range of different conditions being present within the normal swimming range of the species and may vary in relation to the state of other factors. It follows that the values incorporated in the present report are simply one possible set, and that a substantial amount of research will be required before it is possible to assign values with confidence for rivers having different characteristics (e.g. chalk streams and upland streams).

6. FUTURE WORK

6.1 Invertebrates

The data presented in this report are based on the RCP data base. Further studies of habitat preferences could include the collation of information from exhaustive literature searches. However, it is clear that the most accurate information will come from detailed analyses of microdistribution patterns of selected species at different life-history stages in a range of river types.

It is worth considering the relative importance of each variable. Are they all given equal weighting in the model? Experience in the field has indicated that, for example, substratum and velocity are more important determinands of an invertebrate's distribution than depth.

The concept of cover requires investigation and its importance would seem to depend largely on the behaviour of the individual species and the niche-type that species occupies on the stream bottom.

An opportunity to compare predicted habitat preferences with observed preferences should be provided to determine the extent of agreement between the two methods. Such a study will help define more accurately the future needs in the calculation of habitat preferences.

6.2 Fish

The present attempt to provide data appropriate to PHABSIM suggests that, in future, the following approaches should be adopted.

* An exhaustive search of all the relevant literature for detailed information on the habitat requirements of both the larger species of fish and those lesser forms which, although of no interest to anglers, may be excellent indicators of changing conditions.

* The variables used in the construction of the PHABSIM model must be defined more clearly. In particular, cover must be defined with respect to the many functions of water plants and other characteristics relevant to British fishes.

* Findings should be tested with surveys of selected running waters covering the main stream and river types in this country. It is quite clear that much more information on the detailed habitat choices of fish is required.

* Application of habitat variables is, at present, too rigid and provision must be made for diurnal and other shifts in choice of factors by fish of a given species and group in relation to interactions with other parameters.

* Abundance data for certain fish in rivers is already available but a standard methodology should be implemented if PHABSIM is to be developed.

RIVPACS has been developed jointly by J.F. Wright, P.D. Armitage, M.T. Furse and D. Moss.

Table 1 ***Frequency of occurrence of selected species in a data set of 273 sites representing source to near mouth locations on a wide range of rivers in Great Britain. Occurrence (O) and weighted % (W%) in classes of surface velocity, depth and mean substratum particle size (MSUBST) are presented for Leuctra fusca, Isoperla grammatica, Rhyacophila dorsalis, Polycentropus flavomaculatus and Sphaerium corneum.***

Parameter classes	Total sites	L. fusca O	L. fusca W%	I. grammatica O	I. grammatica W%	R. dorsalis O	R. dorsalis W%	P. flavomaculatus O	P. flavomaculatus W%	S. corneum O	S. corneum W%
Velocity											
<10 cm s^{-1}	18	1	2	0	0	0	0	3	7	10	25
10-25	29	13	18	13	20	12	17	14	18	15	22
25-50	84	47	22	31	17	49	24	49	22	39	20
50-100	113	69	24	71	29	78	28	78	26	39	15
>100	29	25	34	22	34	22	31	20	26	13	18
Depth											
0-25 cm	117	74	32	67	30	82	36	70	21	37	12
25-50	97	61	32	51	27	56	29	60	22	47	18
50-100	36	14	20	15	22	21	30	24	24	18	19
100-200	19	6	16	3	8	2	5	8	15	11	22
200-300	4	0	0	1	13	0	0	2	18	3	29
MSUBST											
-8 -6 (phi)	64	55	26	54	30	57	27	52	19	11	4
-6 -4	60	45	23	41	24	54	27	39	16	15	6
-4 -2	56	28	15	22	14	26	14	32	14	33	14
-2 0	33	7	7	7	7	14	13	17	12	21	15
0 +2	18	8	14	6	12	7	12	6	8	9	12
+2 +4	15	2	4	3	7	2	4	7	11	11	18
+4 +6	11	4	11	2	6	1	3	6	13	7	15
+6 +8	14	0	0	0	0	0	0	0	0	9	15

Phi values used as PHABSIM code equivalents
(2 - 6 = 3; 2 - 0 = 4; 0 - -4 = 5; -4 - -6 = 6; -6 - -8 = 7)

Table 2 Abundance of Isoperla grammatica in classes of surface velocity, depth and mean substratum particle size based on actual numbers recorded in spring, summer and autumn samples at 273 sites

	Total sites	Total individuals	Mean no. per site
Velocity			
<10 cm s^{-1}	18	0	0
10-25	29	290	10
25-50	84	203	8
50-100	113	2713	24
>100	29	550	19
Depth			
0-25 cm	117	1987	17
25-50	97	1217	13
50-100	36	1004	28
100-200	19	38	2
200-300	4	4	1
MSUBST			
-8 -6	64	1999	31
-6 -4	60	1171	20
-4 -2	56	797	14
-2 0	33	161	5
0 +2	18	67	4
2 4	15	46	3
4 6	11	15	1

Table 3 Predictions of probability of occurrence (O) and relative abundance (A) of five families of invertebrates where a simulated substratum change is entered into the RIVPACS model (see text for details). (MSUBST = mean substratum particle size in phi units)

MSUBST	Perlodidae		Leuctridae		Polycentropodidae		Rhyacophilidae		Sphaeriidae	
	O	A	O	A	O	A	O	A	O	A
a) R. Gwash downstream of A606 road bridge										
-8	48.7	0.96	74.1	2.23	75.8	2.05	81.3	3.70	98.1	4.11
-6	28.0	0.56	48.4	1.33	67.8	2.01	65.0	2.64	98.5	5.16
-4	12.2	0.22	26.3	0.61	61.1	1.99	51.0	1.79	98.5	5.96
-2	5.8	0.09	17.4	0.34	58.2	1.97	44.3	1.45	98.0	6.17
0	3.6	0.05	13.4	0.25	56.9	1.95	38.7	1.22	97.4	6.17
2	2.6	0.03	9.6	0.17	56.1	1.93	29.9	0.89	96.5	6.14
4	3.2	0.03	6.8	0.11	51.3	1.72	20.0	0.46	95.4	6.03
6	4.4	0.04	8.6	0.10	35.7	1.04	19.4	0.25	95.0	5.48
8	3.7	0.04	12.3	0.13	22.8	0.47	25.1	0.26	96.2	4.86
b) R. Blithe at Hamstall Ridware										
-8	67.5	1.48	88.9	2.53	83.3	2.09	87.2	4.09	91.8	3.86
-6	61.8	1.33	84.3	2.28	82.2	2.11	83.6	3.77	93.7	4.19
-4	51.8	1.09	74.6	1.90	80.1	2.19	77.5	3.30	95.9	4.71
-2	37.1	0.75	58.1	1.38	77.3	2.35	68.0	2.70	97.7	5.39
0	21.0	0.40	38.3	0.86	76.3	2.55	53.1	1.98	98.8	6.05
2	8.3	0.15	22.3	0.51	77.7	2.63	30.9	1.07	99.3	6.47
4	2.4	0.04	15.0	0.37	75.9	2.48	14.7	0.39	99.2	6.49
6	1.2	0.01	13.9	0.31	61.8	1.89	14.0	0.19	98.8	6.01
8	1.1	0.01	15.0	0.23	38.3	1.00	22.8	0.23	98.8	5.18

Table 4 Predictions of probability of occurrence of three species at Hamstall Ridware on the Blithe and downstream of A.606 road bridge on the Gwash below Rutland Water following simulated substratum change (MSUBST = mean substratum particle size - phi values; O = probability of occurrence as %)

MSUBST	Leuctra fusca	Isoperla grammatica	Sphaerium corneum
a) River Gwash			
-8	70.8	48.5	55.2
-6	43.7	28.9	69.9
-4	20.5	12.2	80.9
-2	11.4	5.8	84.5
0	7.9	3.6	85.5
2	5.5	2.6	86.2
4	4.9	3.2	86.3
6	8.2	4.4	84.4
8	12.3	3.7	83.0
b) River Blithe			
-8	82.8	66.5	59.1
-6	77.9	61.2	64.7
-4	68.0	51.5	71.1
-2	51.6	37.0	77.3
0	32.2	21.0	83.5
2	18.2	8.3	89.8
4	13.4	2.4	92.9
6	13.5	1.2	91.8
8	0	0	86.9

Table 5 Estimated physical habitat preferences of 18 species of fish

Modal value	Velocity (cm/s)	Depth (cm)	Substrate (code)	Cover (code)
Species				
Brown trout				
Spawning	40-80	25-100	4-5	?
Fry	10-30	10-30	3.4	?
Juveniles	20-60	25-80	3-5	High
Adults	40-80	50-150	5.5-6.5	High
Grayling				
Spawning	20-60	40-120	3-4	0
Fry	10-20	10-30	1-3	?
Juveniles	20-60	50-200	3-5	?
Adults	20-60	50-300	3-5	?
Dace				
Spawning	55-100	20-80	4.5-5.5	?
Fry	5-25	10-30	0.2-1.7	?
Juveniles	15-35	30-70	2-4	?
Adults	20-70	50-100	3-5	?
Chub				
Spawning	25-90	40-170	3.5-5.5	?
Fry	5-30	50-90	1-3	?
Juveniles	30-70	50-160	3.5-6	High
Adults	30-70	50-160	3.5-6	High
Roach				
Spawning	40-80	30-300	1-2 5-8	?
Fry	0-20	25	1-2	?
Juveniles	0-40	100-300	1-2	?
Adults	0-40	100-300	1-2	?
Bream				
Spawning	0-10	50-100	1-2	?
Fry	0-5	5-50	1-2	?
Juveniles	0-10	50-300	1-2	?
Adults	0-10	170-300	1-2	?
Pike				
Spawning	0-10	20-80	1	?
Fry	0-10	20-90	1	?
Juveniles	0-20	10-70	1-2	High
Adults	0-20	40-290	1-2	High
Perch				
Spawning	0-30	30-150	1-8	High
Fry	0-10	10-50	1-3	?
Juveniles	0-30	20-80	1-4	High
Adults	0-40	30-250	1-4	High

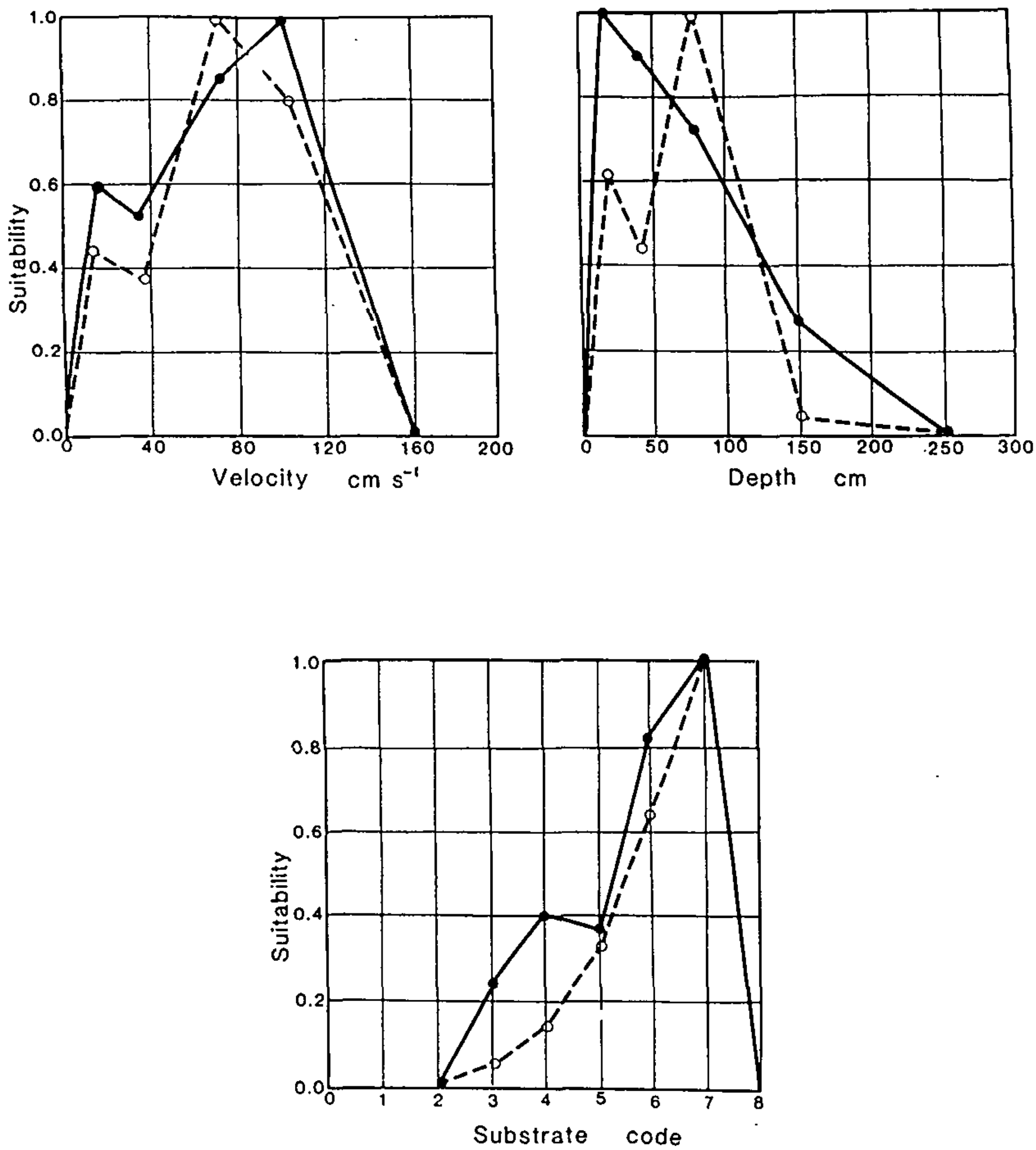

Figure 1a Habitat suitability curves for Isoperla grammatica based on observed occurrence (——) and relative abundance (----)

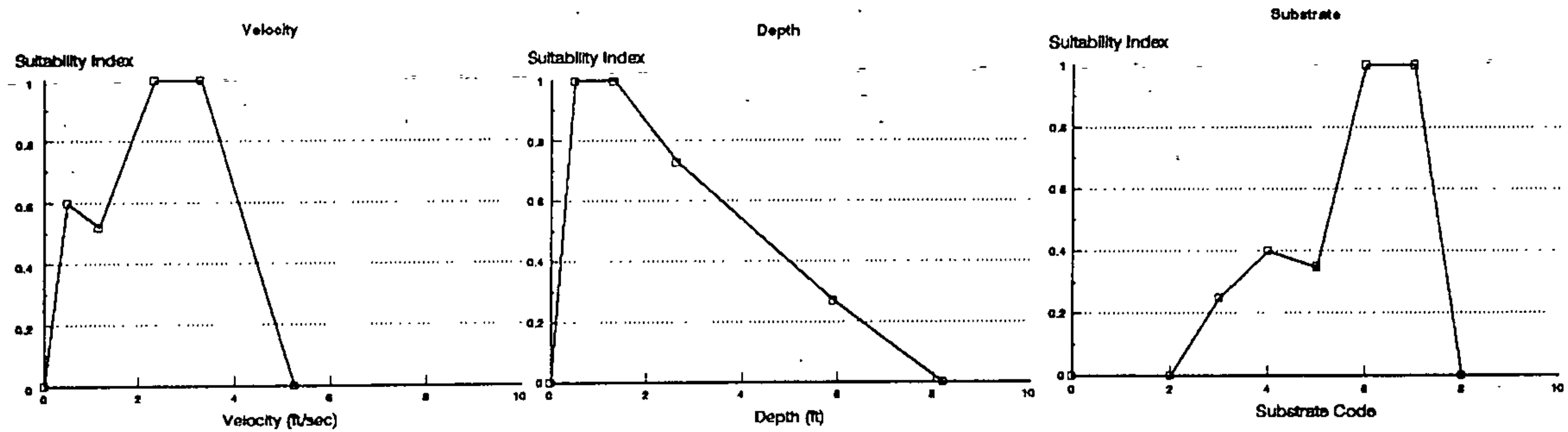

Figure 1b Habitat suitability curves for Isoperla grammatica

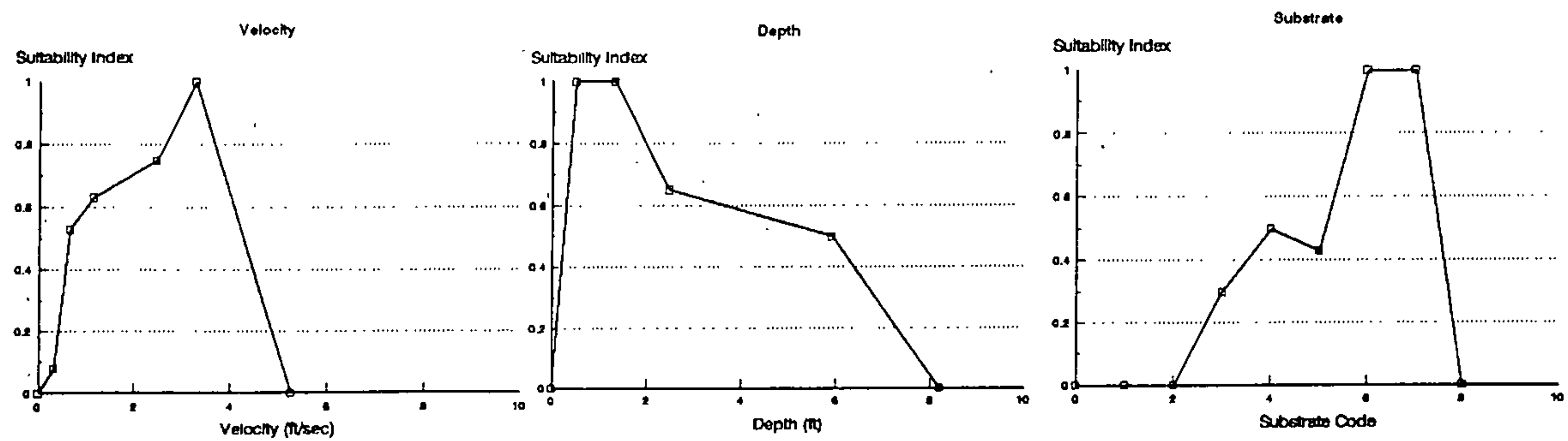

Figure 2 Habitat suitability curves for Leuctra fusca

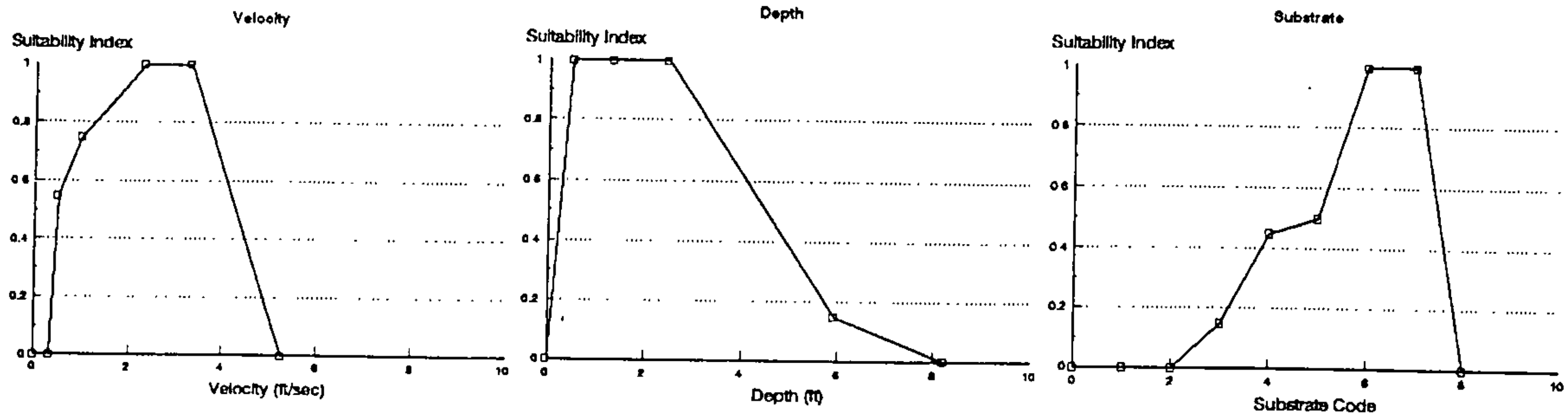

Figure 3 ***Habitat suitability curves for Rhyacophila dorsalis***

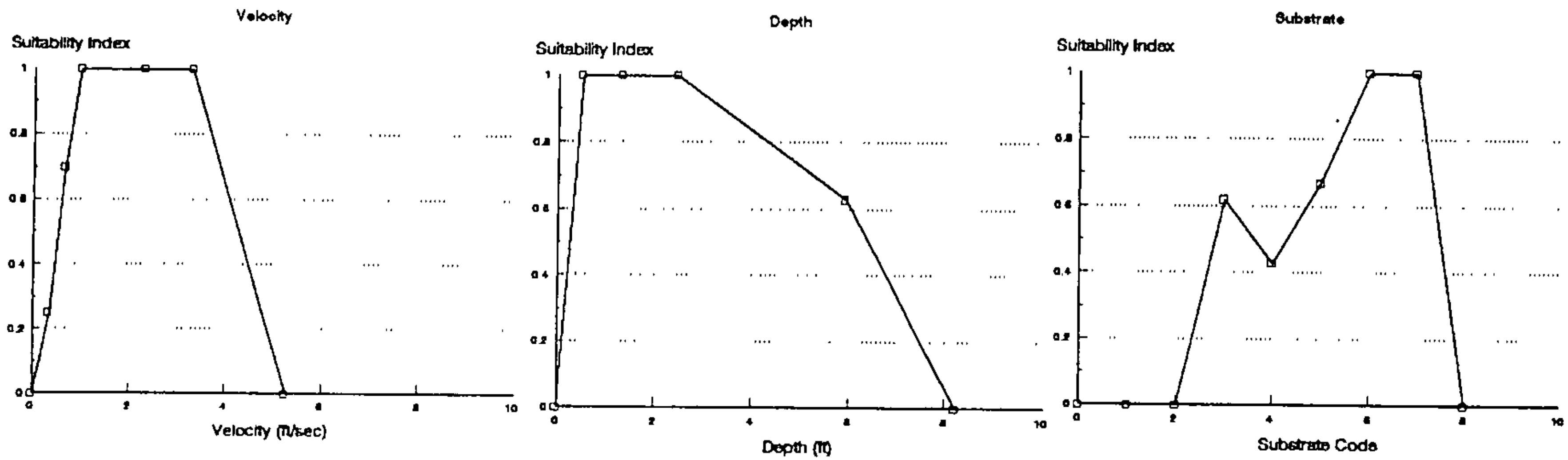

Figure 4 ***Habitat suitability curves for Polycentropus flavomaculatus***

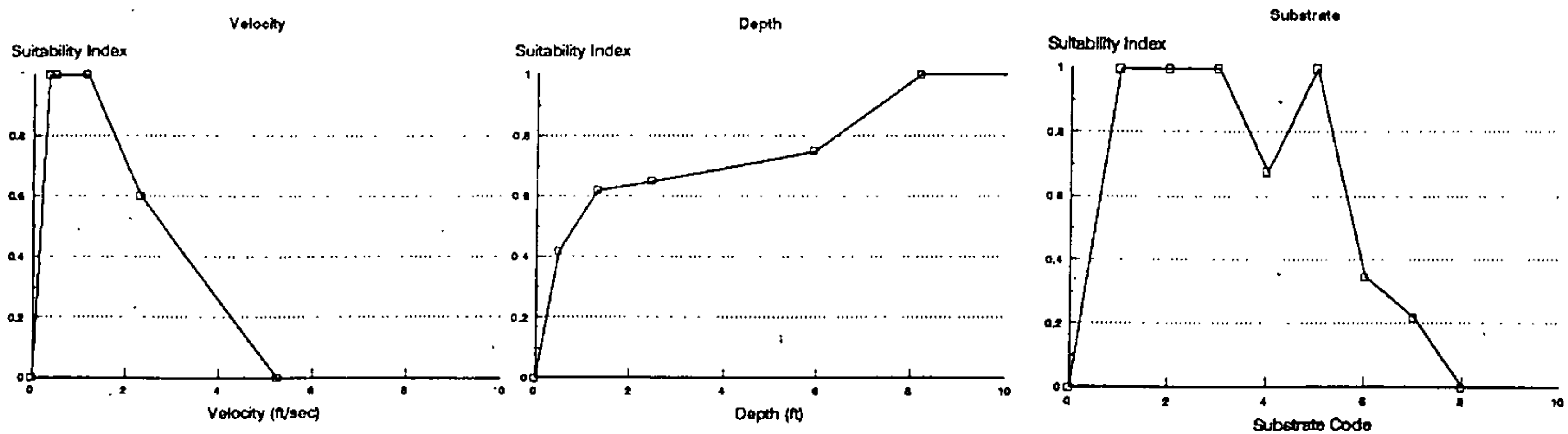

Figure 5 Habitat suitability curves for Sphaerium corneum

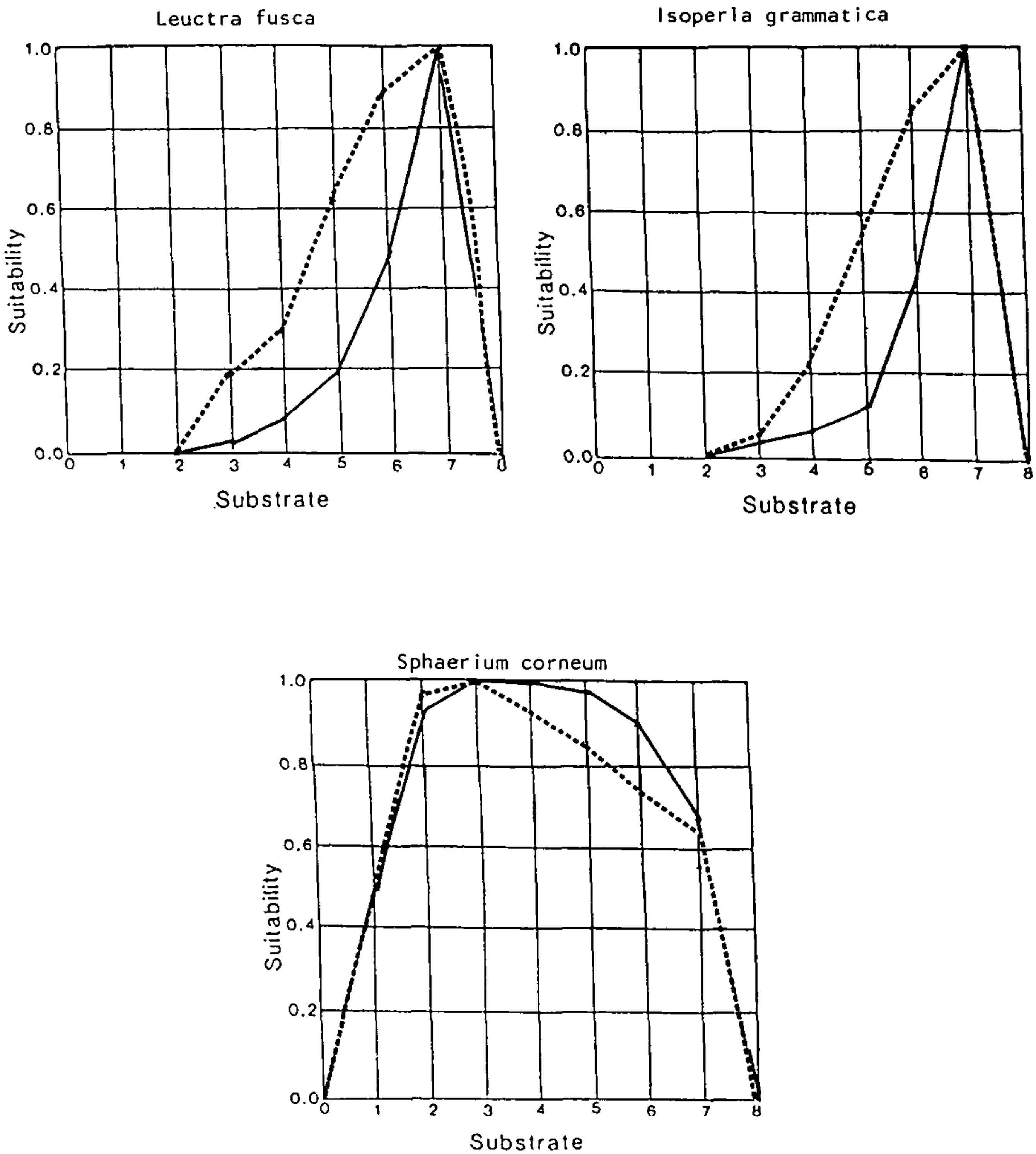

Figure 6 *Habitat suitability curves based on predictions of the probability of occurrence of 3 species of invertebrate at 2 sites (—— Gwash, ----- Blithe) where a simulated substratum change is entered into the RIVPACS model. (See text for details.)*

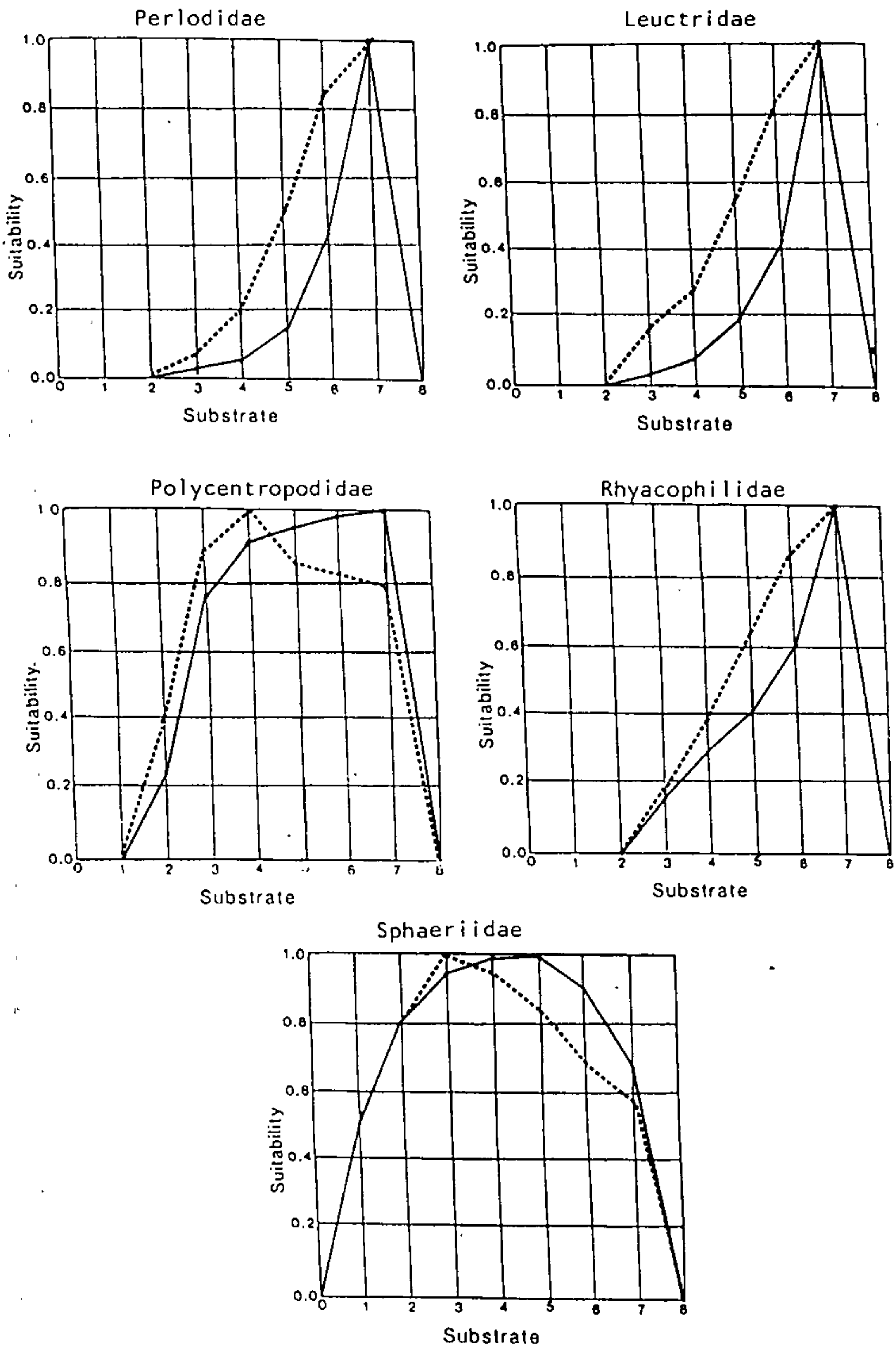

Figure 7 *Habitat suitability curves based on predictions of relative abundance of selected families at 2 sites (—— Gwash, ---- Blithe) where a simulated substratum change is entered into the RIVPACS model.*

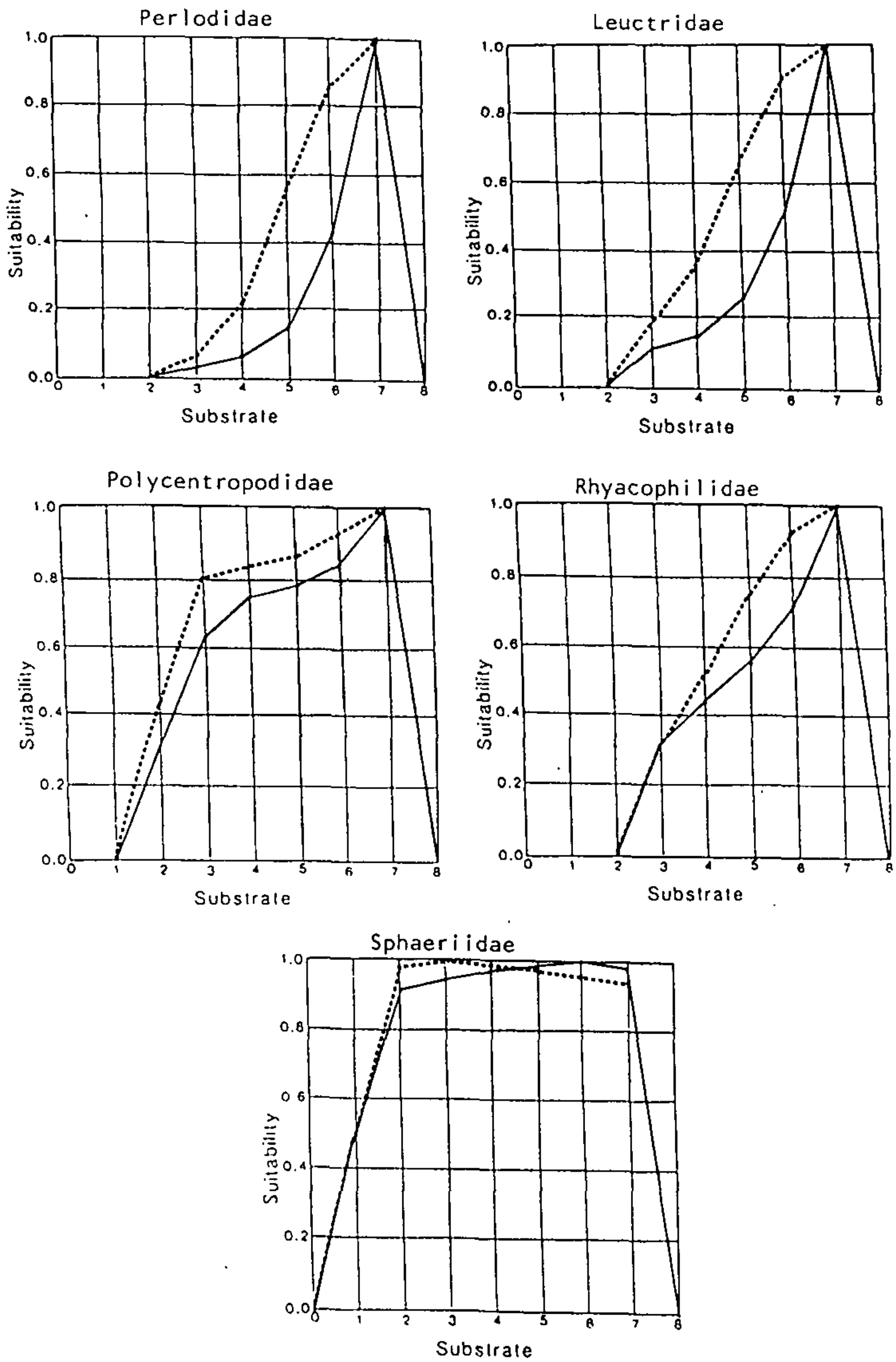

Figure 8 *Habitat suitability curves based on predictions of the probability of occurrence of selected families at 2 sites (—— Gwash, --- Blithe) where a simulated substratum change is entered into the RIVPACS model. (See text for details.)*

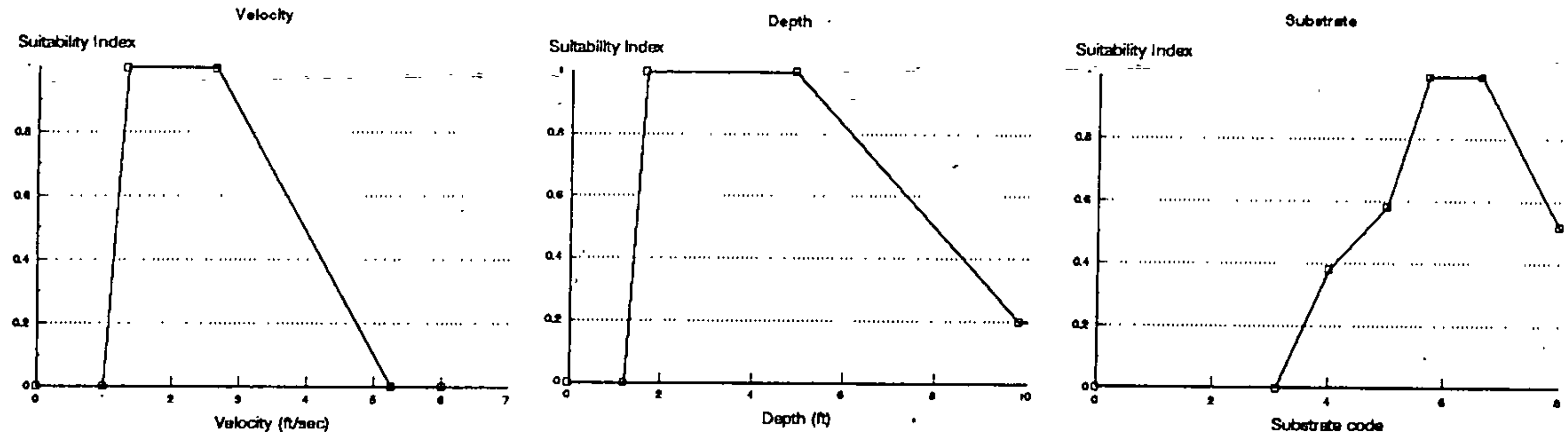

Figure 9 Habitat suitability curves for Adult Brown Trout

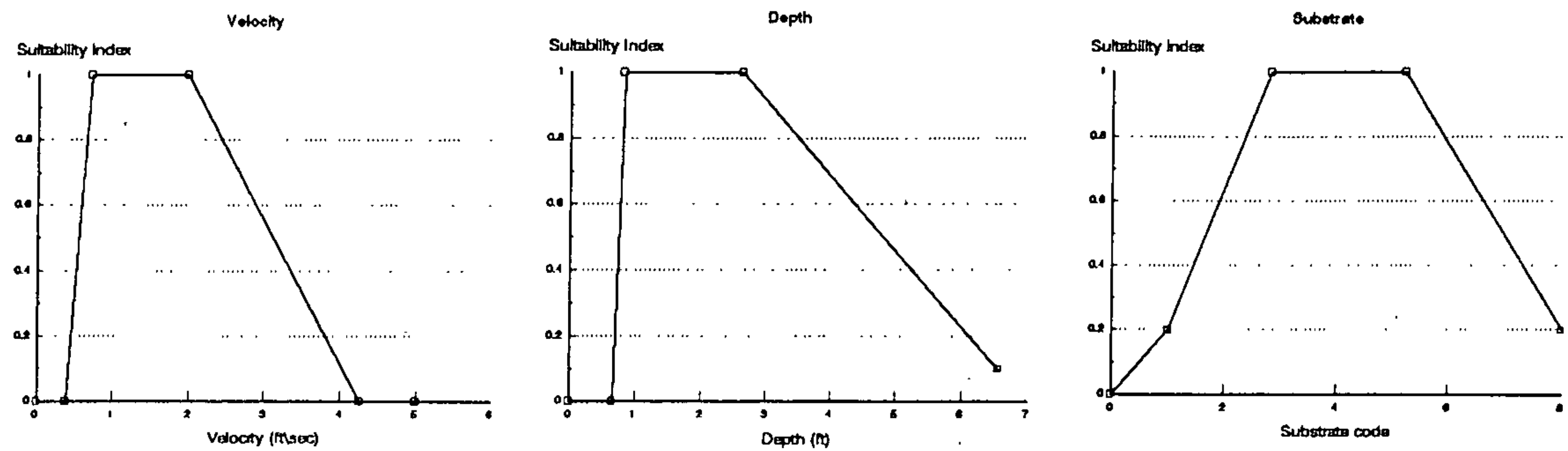

Figure 10 Habitat suitability curves for Juvenile Brown Trout

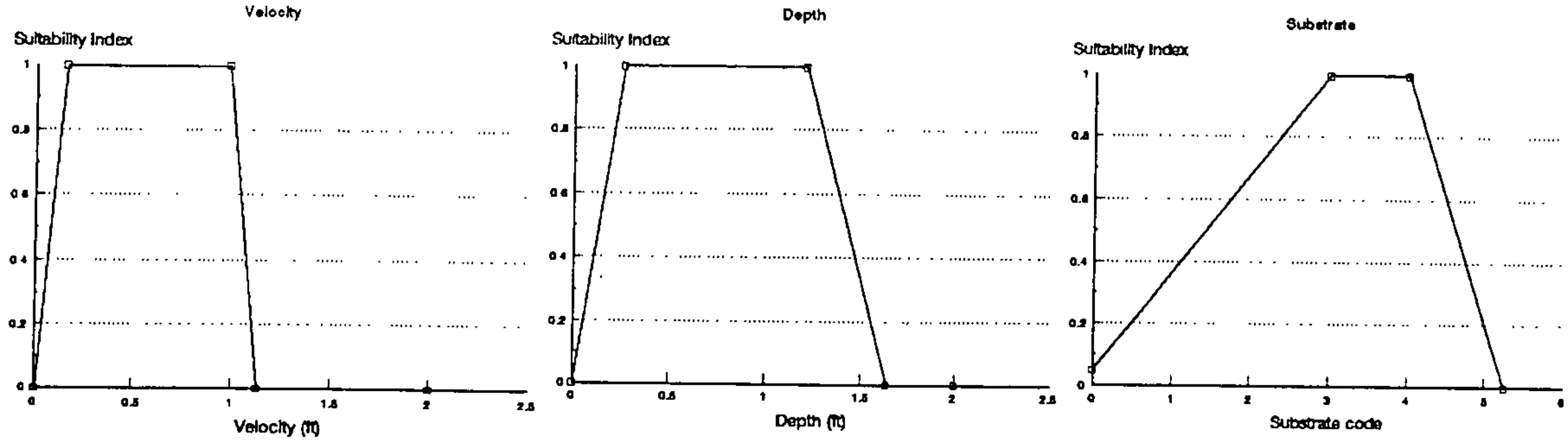

Figure 11 Habitat suitability curves for Brown Trout Fry

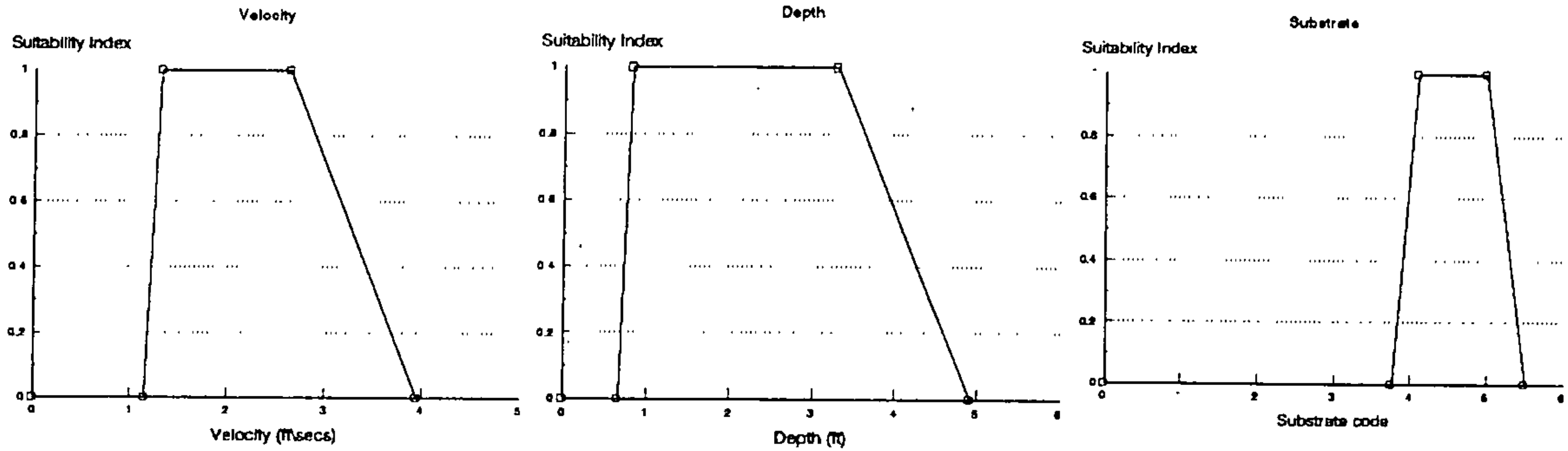

Figure 12 Habitat suitability curves for Brown Trout Spawning

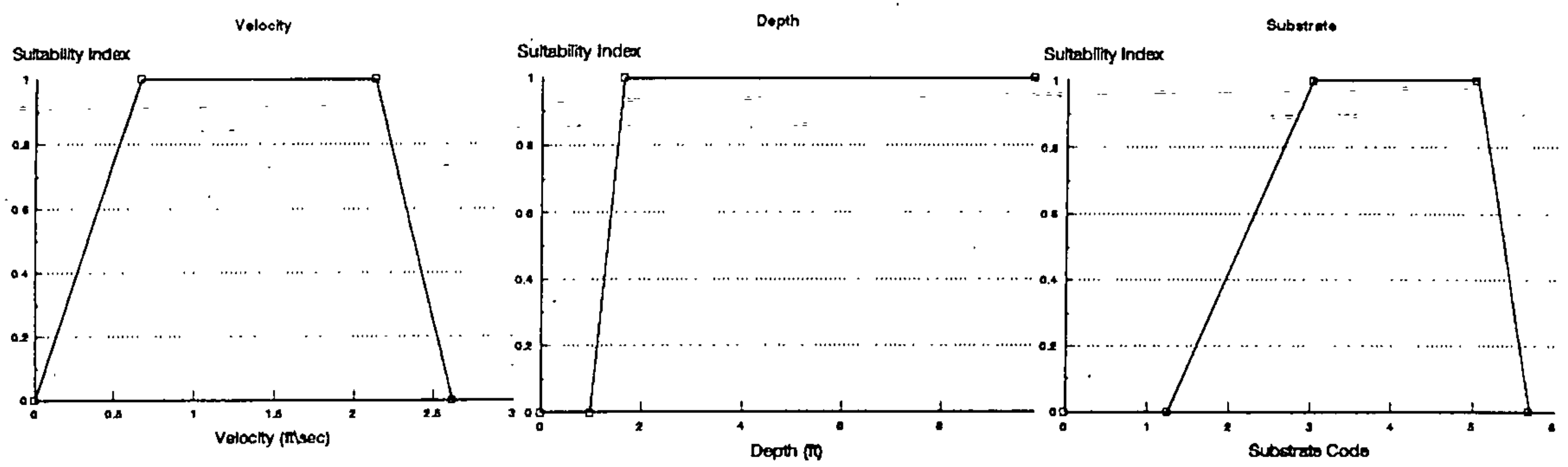

Figure 13 Habitat suitability curves for Adult Grayling

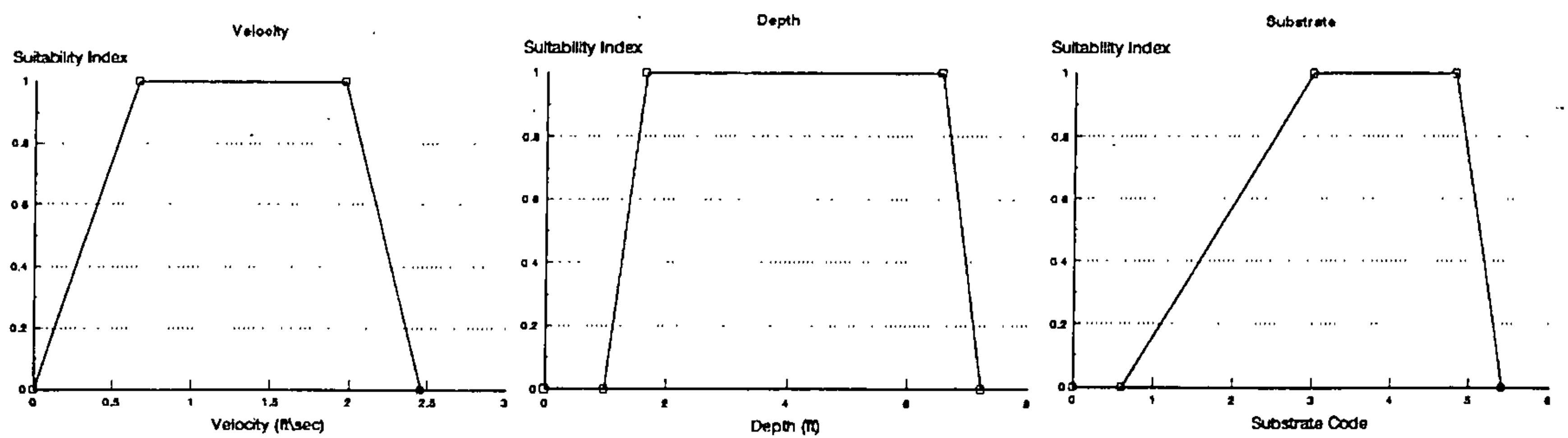

Figure 14 Habitat suitability curves for Juvenile Grayling

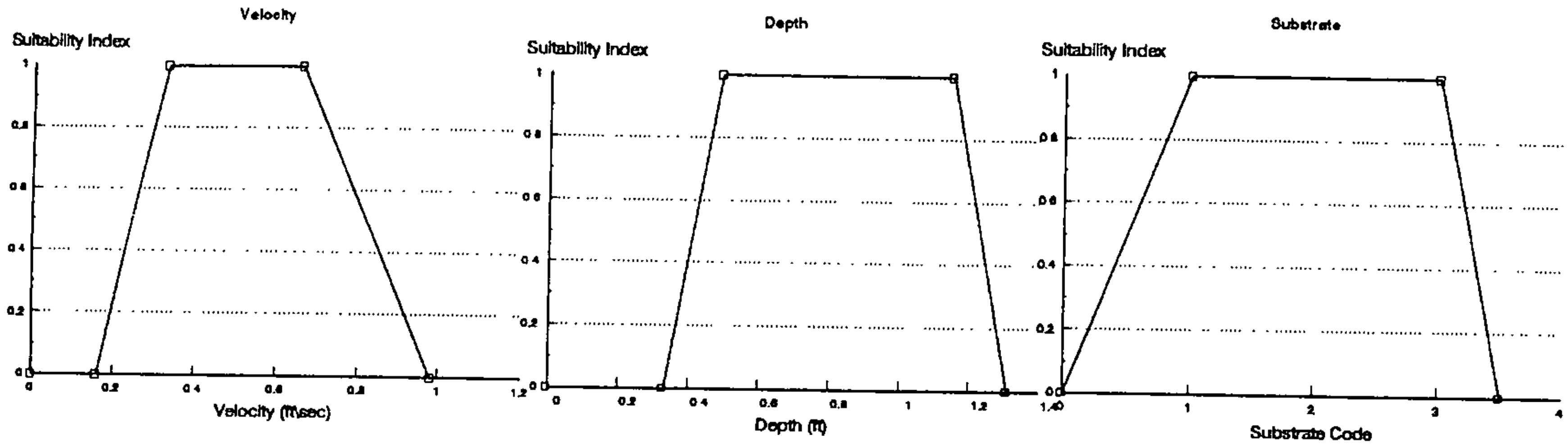

Figure 15 Habitat suitability curves for Grayling Fry

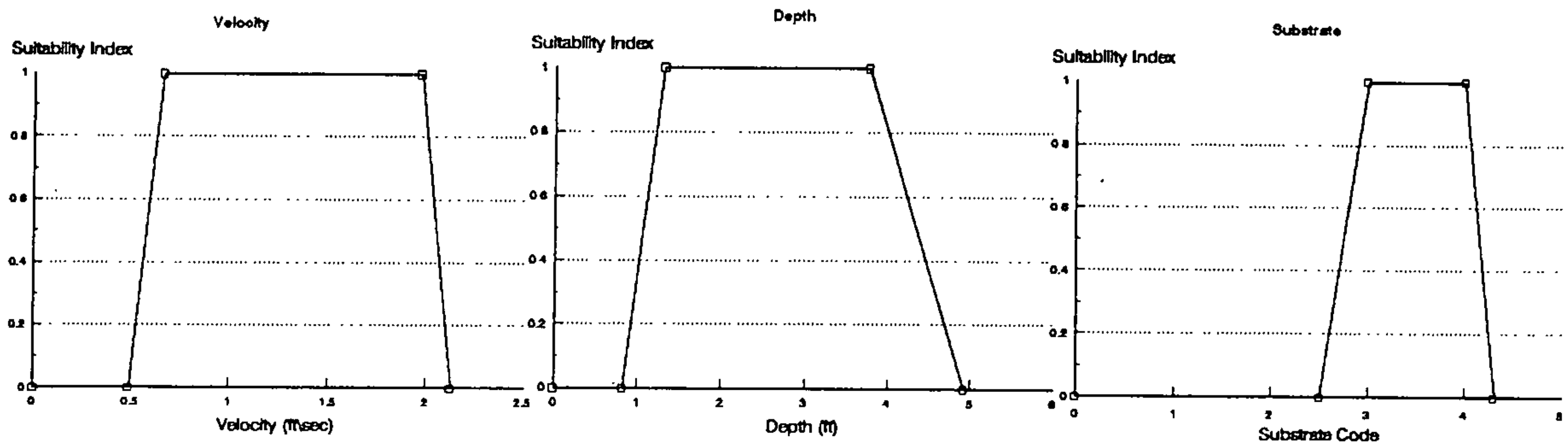

Figure 16 Habitat suitability curves for Grayling Spawning

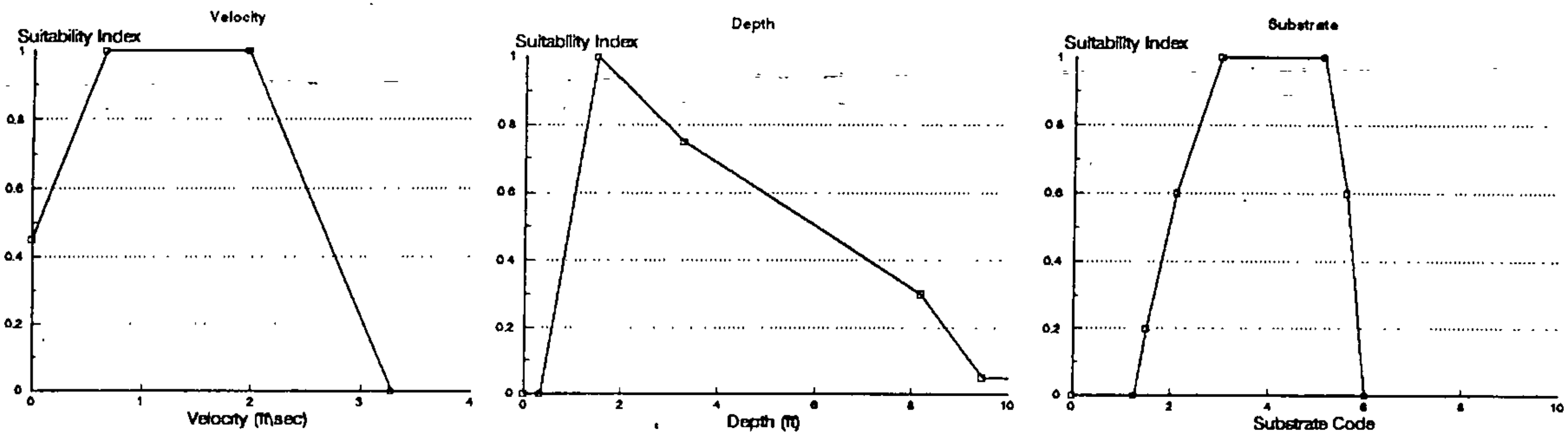

Figure 17 Habitat suitability curves for Adult Dace

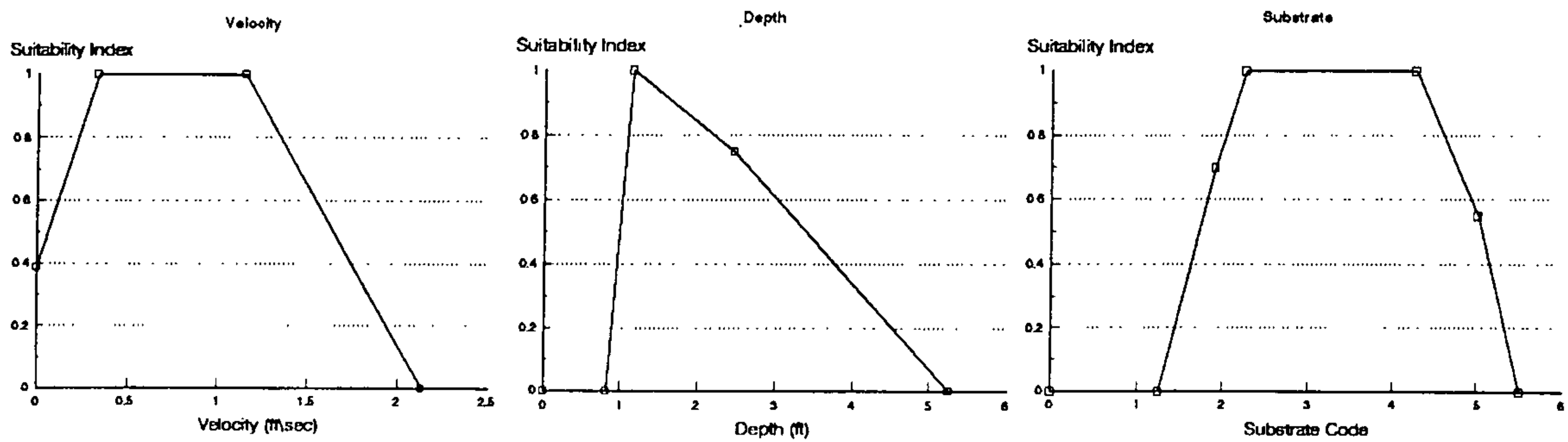

Figure 18 Habitat suitability curves for Juvenile Dace

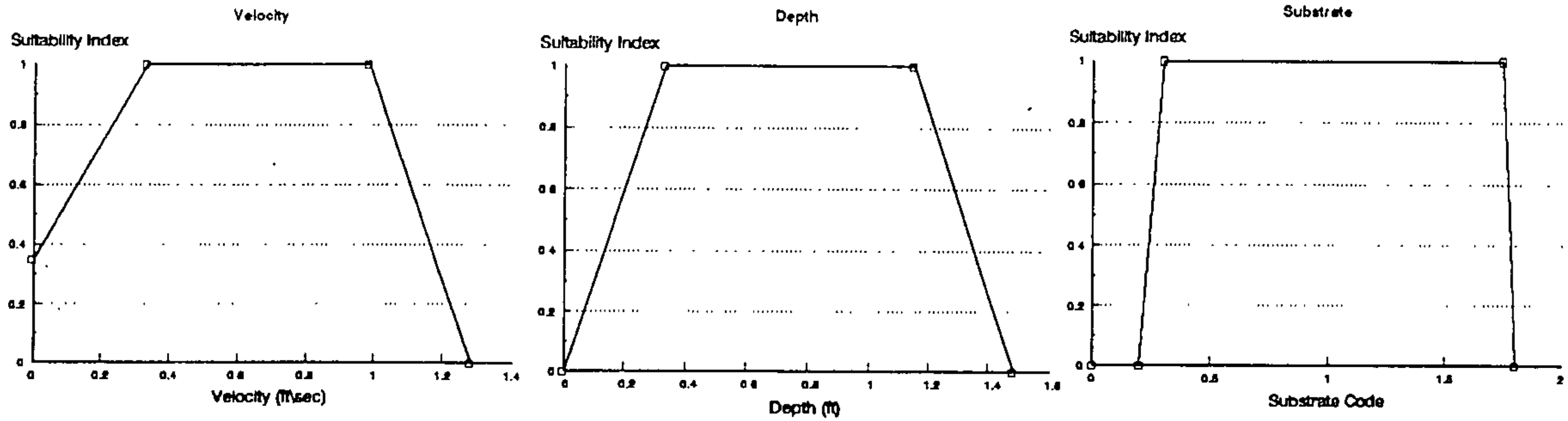

Figure 19 Habitat suitability curves for Dace Fry

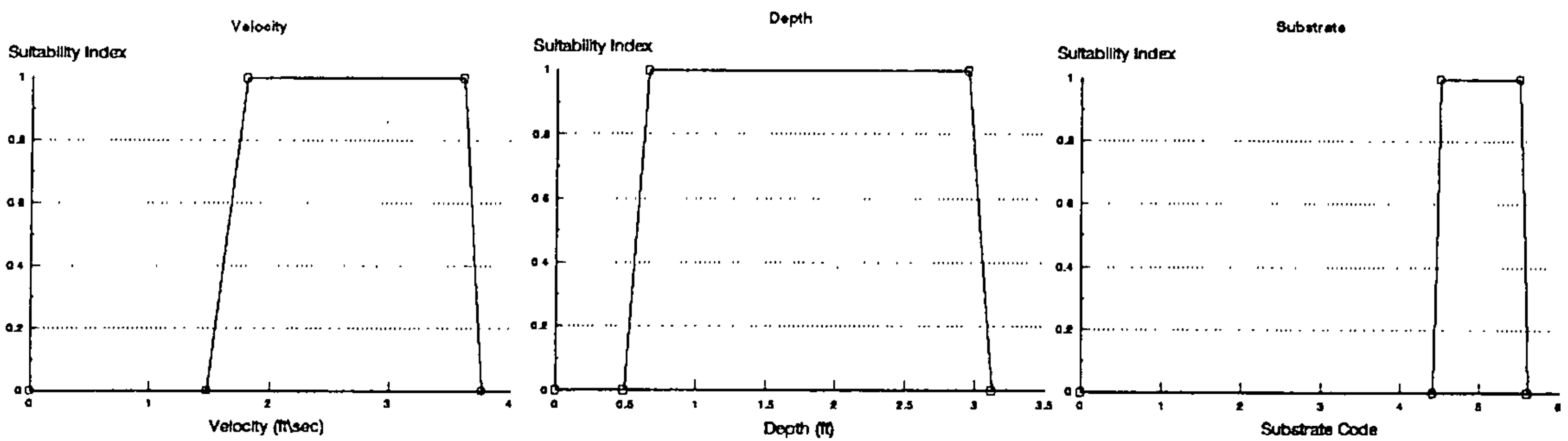

Figure 20 Habitat suitability curves for Dace Spawning

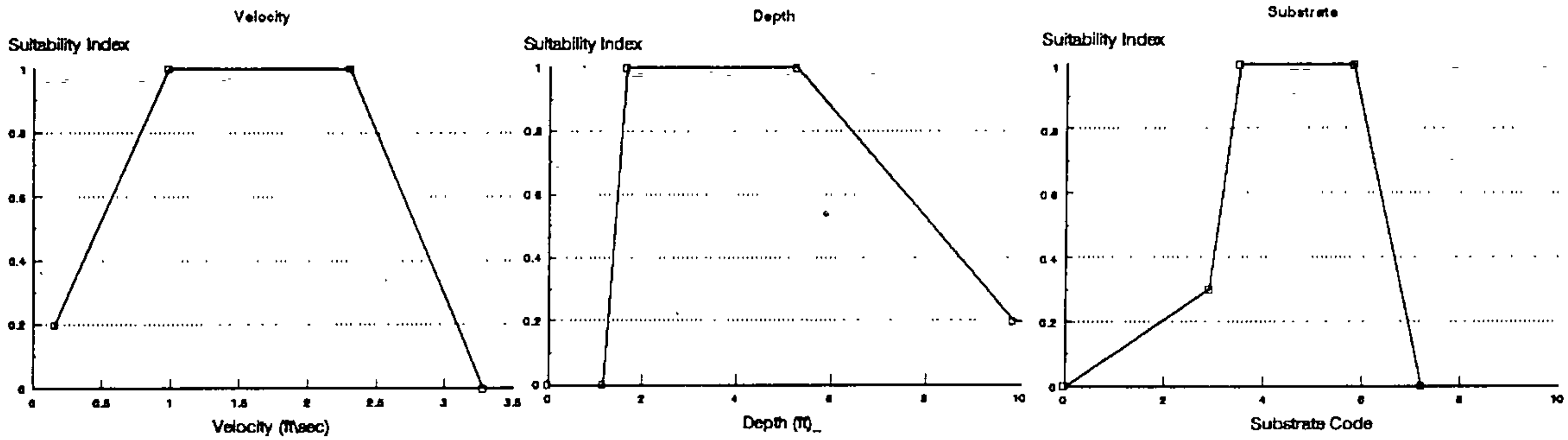

Figure 21 Habitat suitability curves for Adult and Juvenile Chub

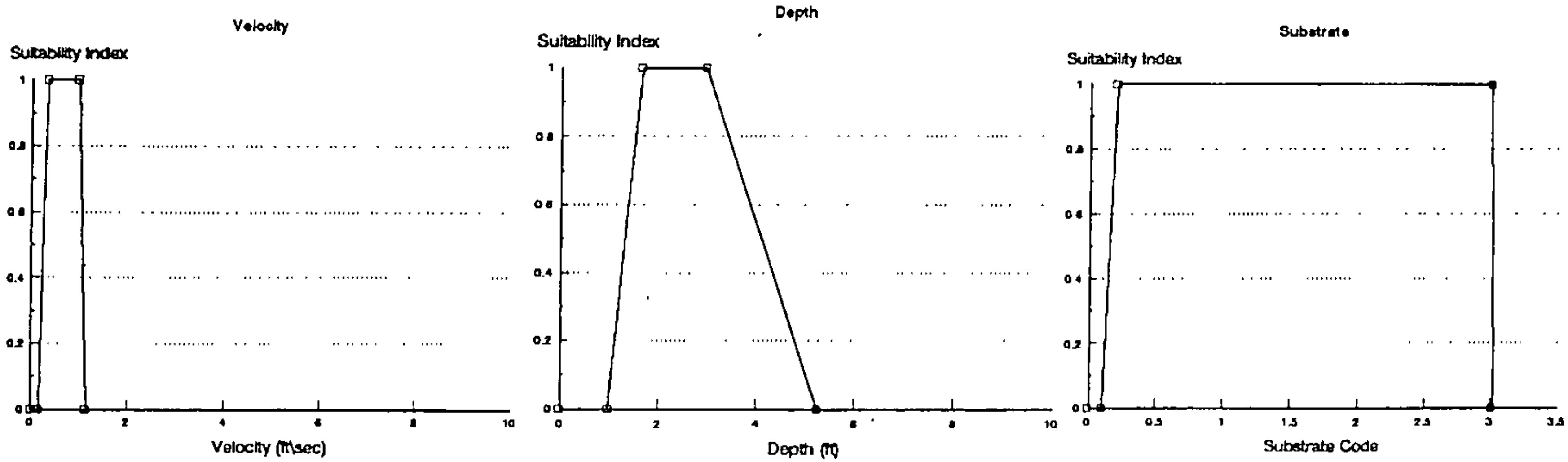

Figure 22 Habitat suitability curves for Chub Fry

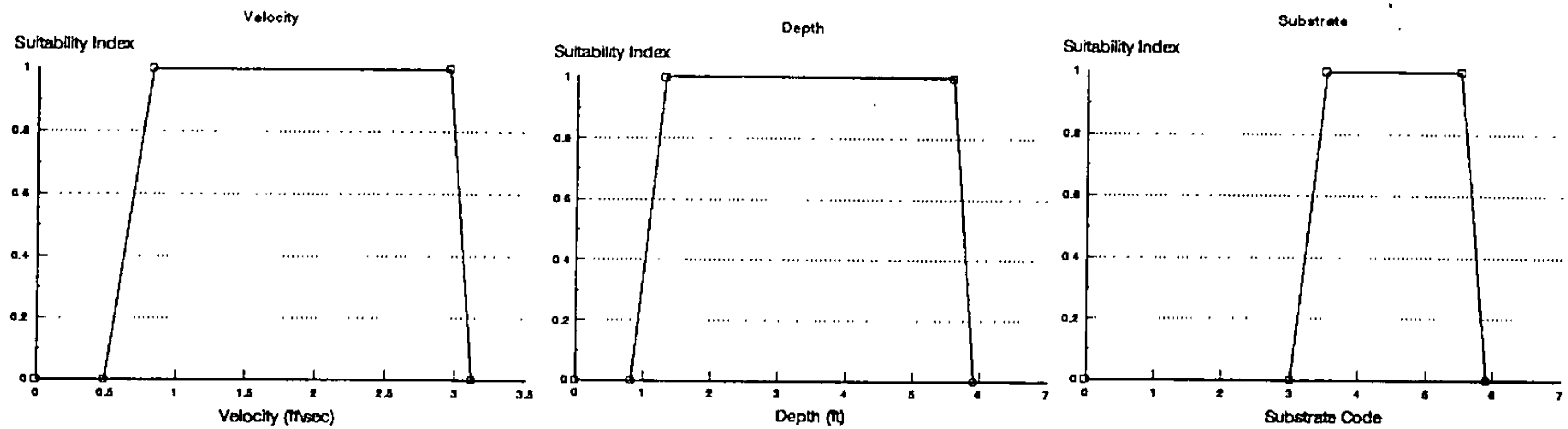

Figure 23 Habitat suitability curves for Chub Spawning

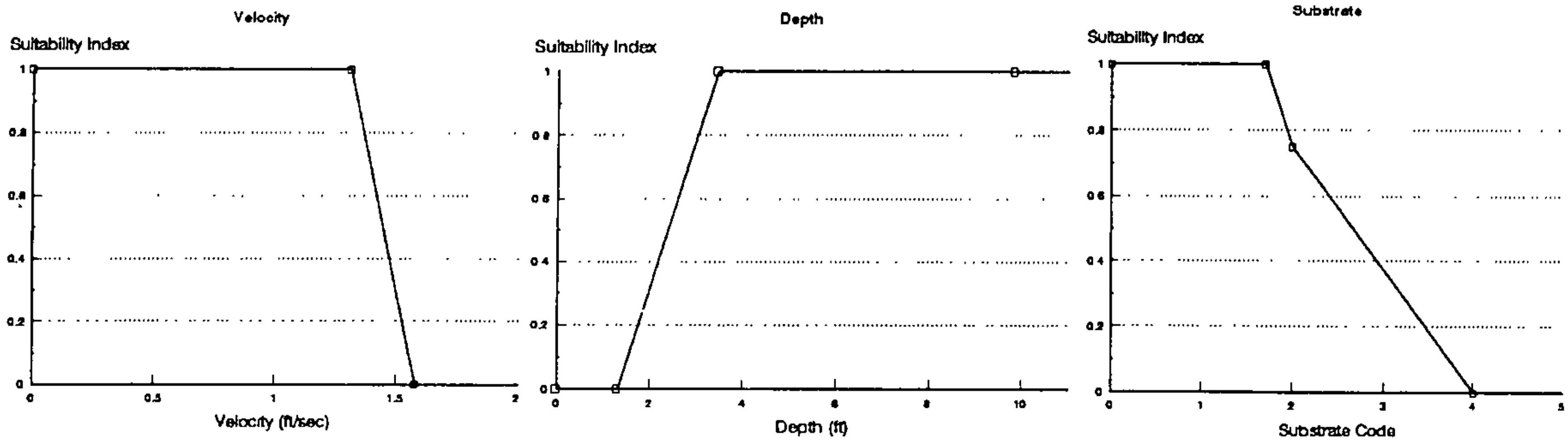

Figure 24 Habitat suitability curves for Adult and Juvenile Roach

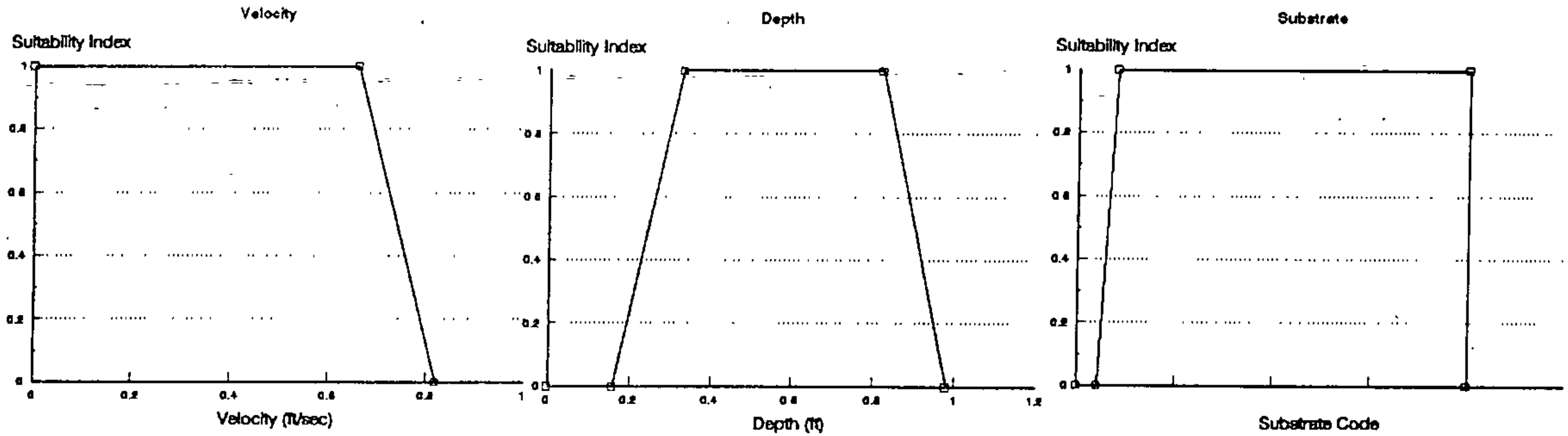

Figure 25 Habitat suitability curves for Roach Fry

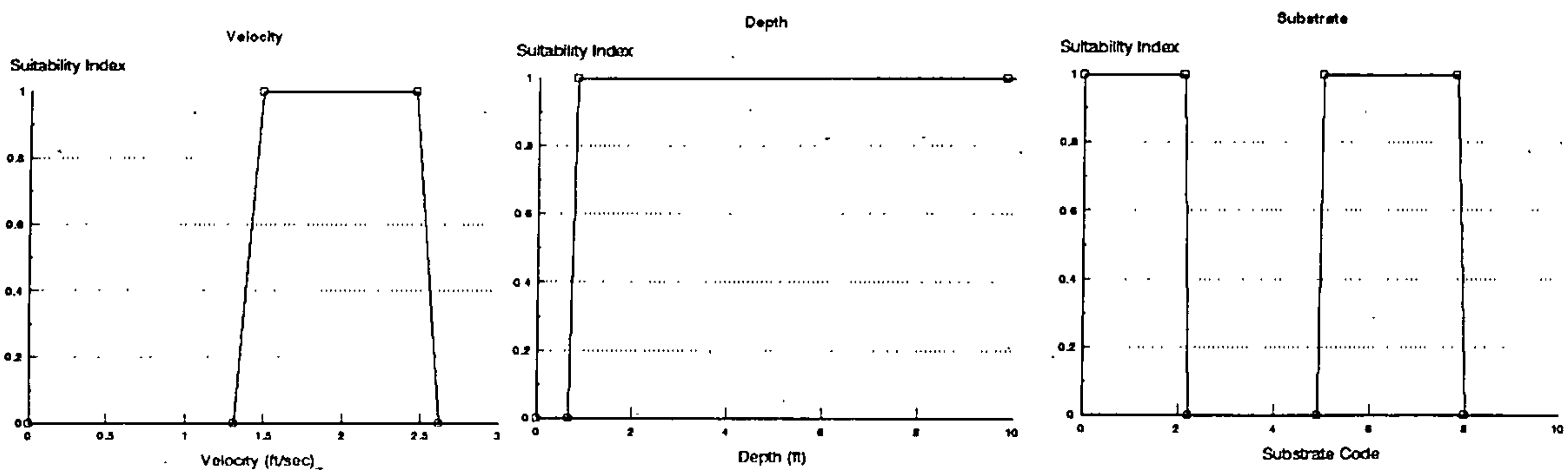

Figure 26 Habitat suitability curves for Roach Spawning

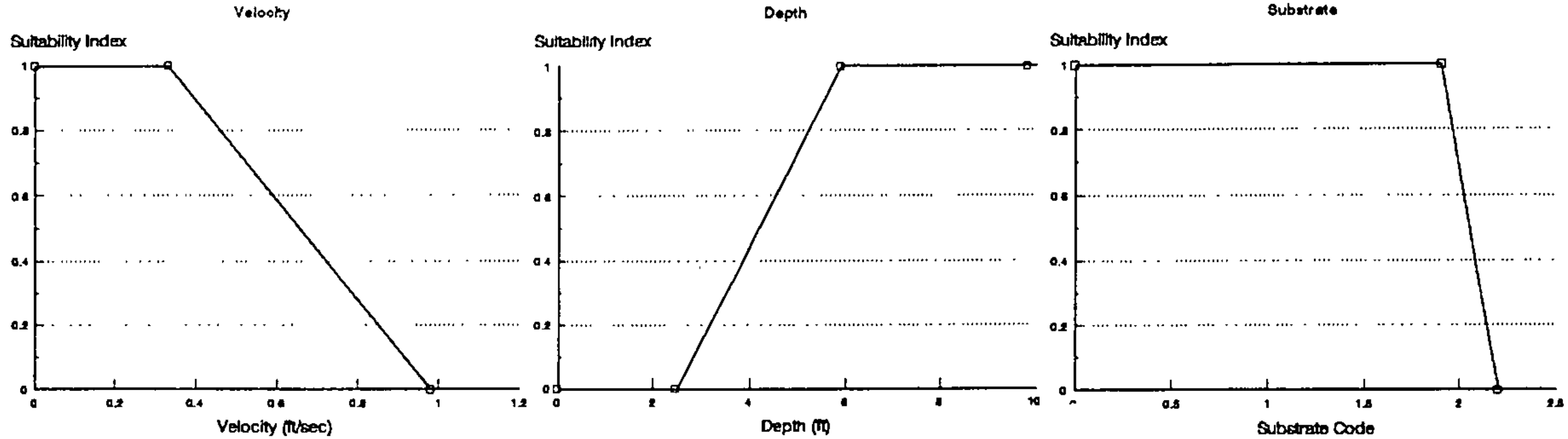

Figure 27 Habitat suitability curves for Adult Bream

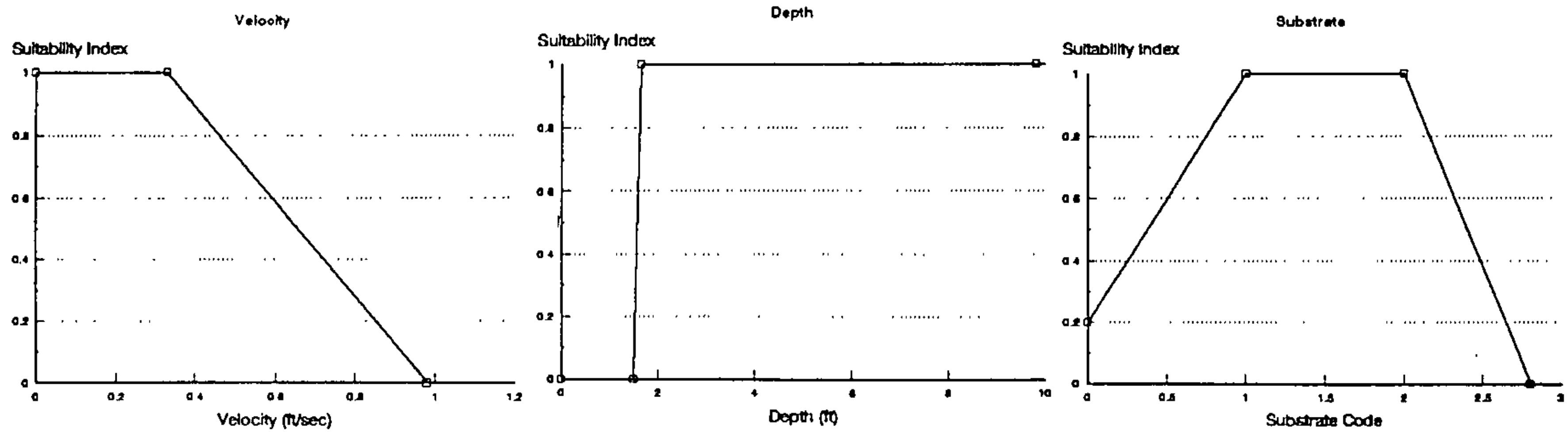

Figure 28 Habitat suitability curves for Juvenile Bream

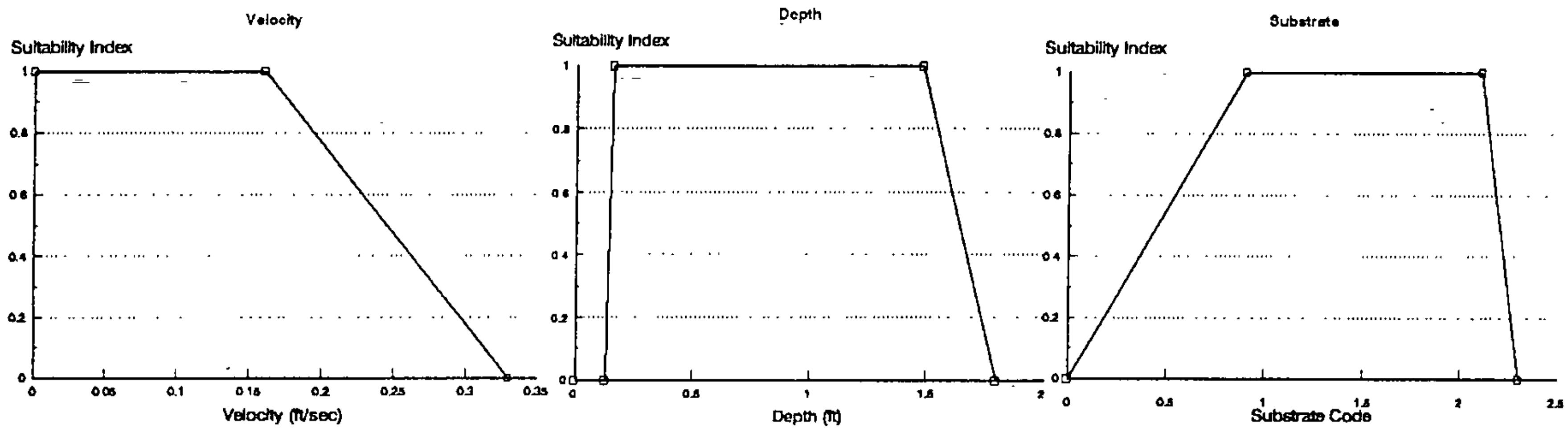

Figure 29 Habitat suitability curves for Bream Fry

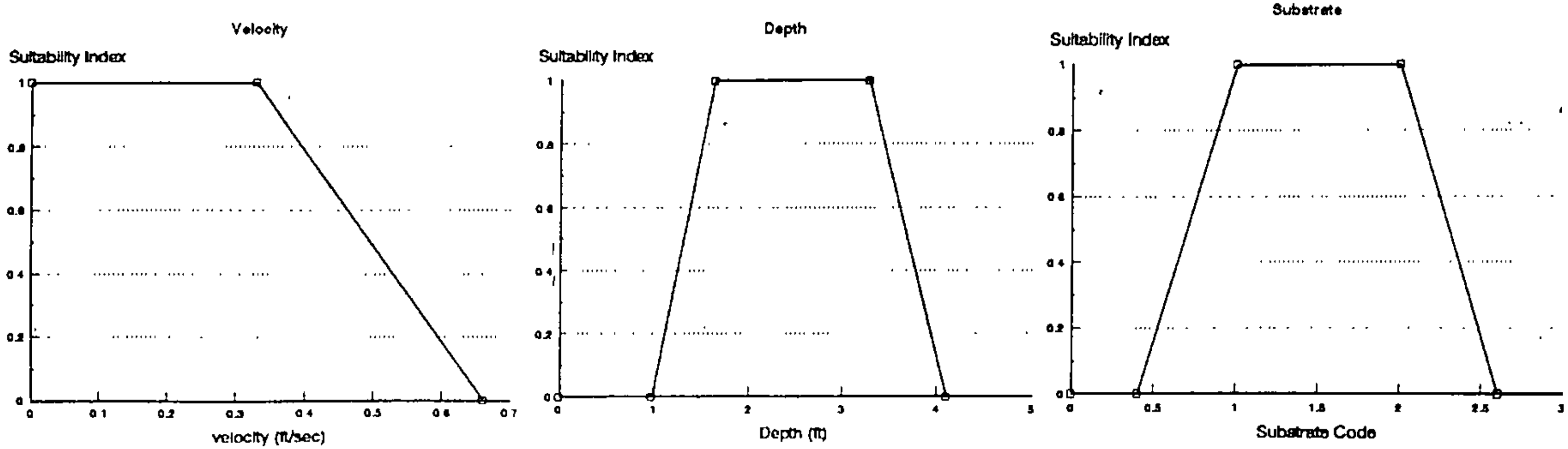

Figure 30 Habitat suitability curves for Bream Spawning

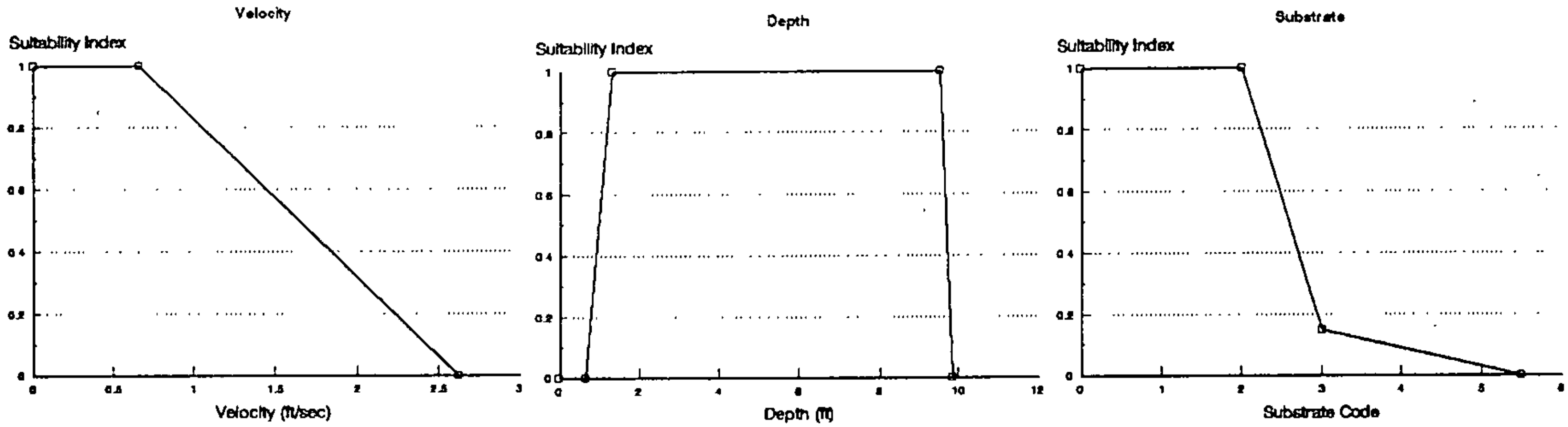

Figure 31 Habitat suitability curves for Adult Pike

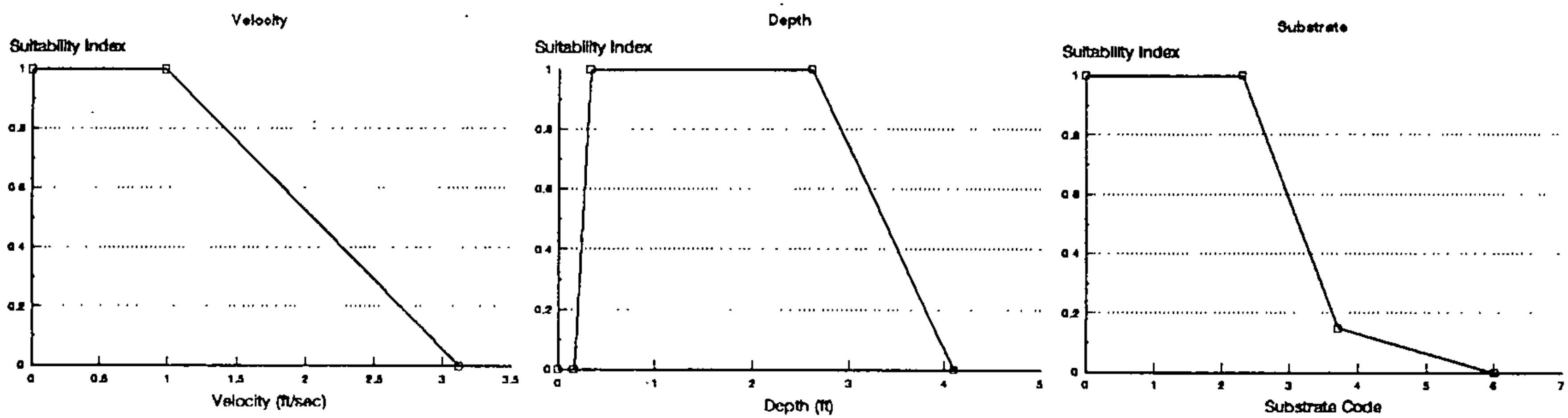

Figure 32 Habitat suitability curves for Juvenile Pike

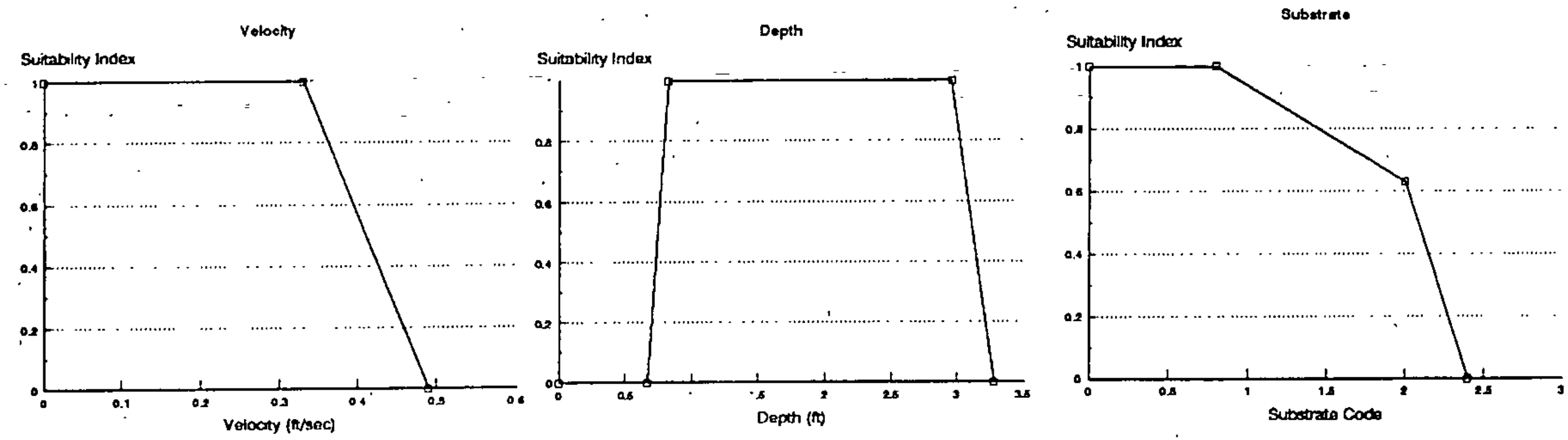

Figure 33 Habitat suitability curves for Pike Fry

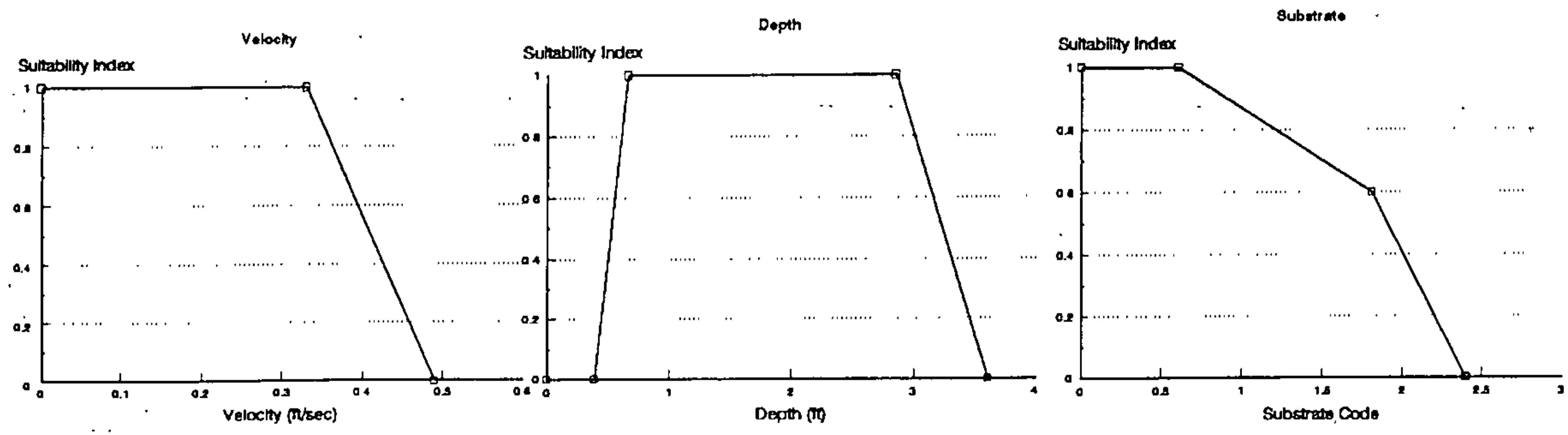

Figure 34 Habitat suitability curves for Pike Spawning

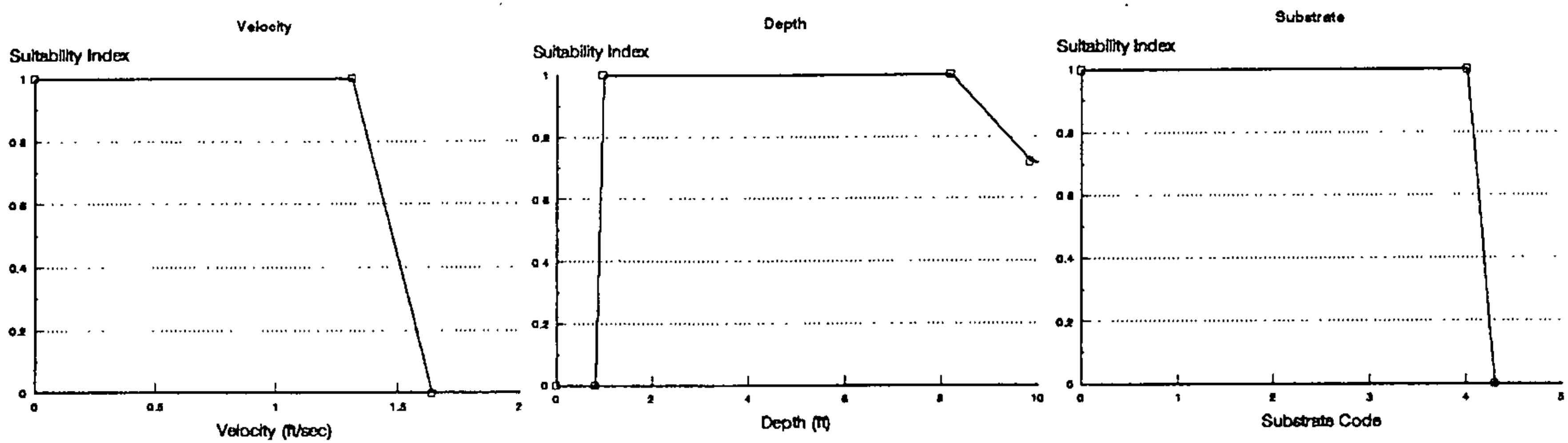

Figure 35 Habitat suitability curves for Adult Perch

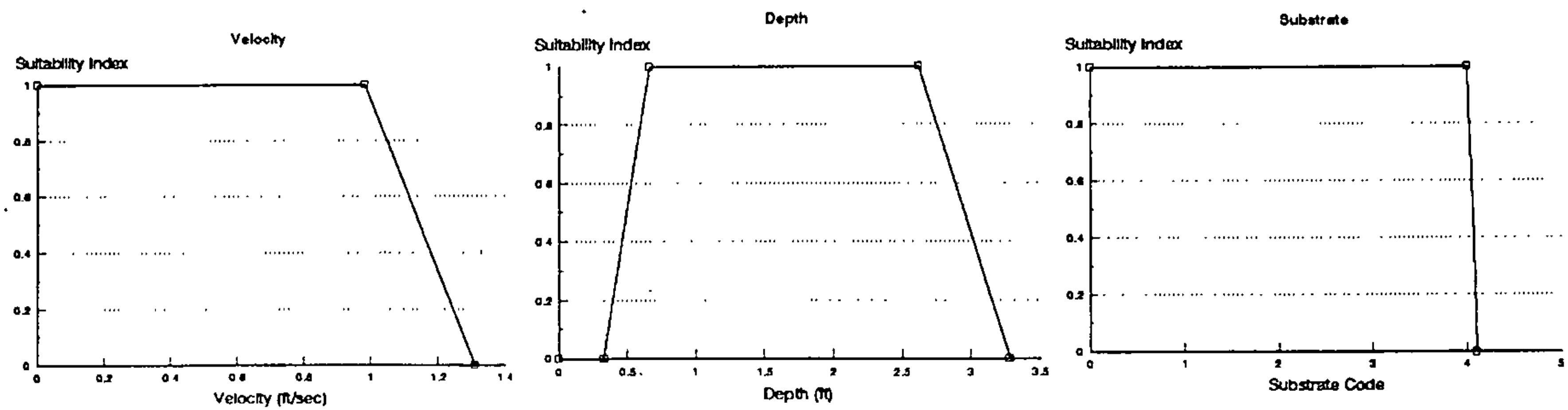

Figure 36 Habitat suitability curves for Juvenile Perch

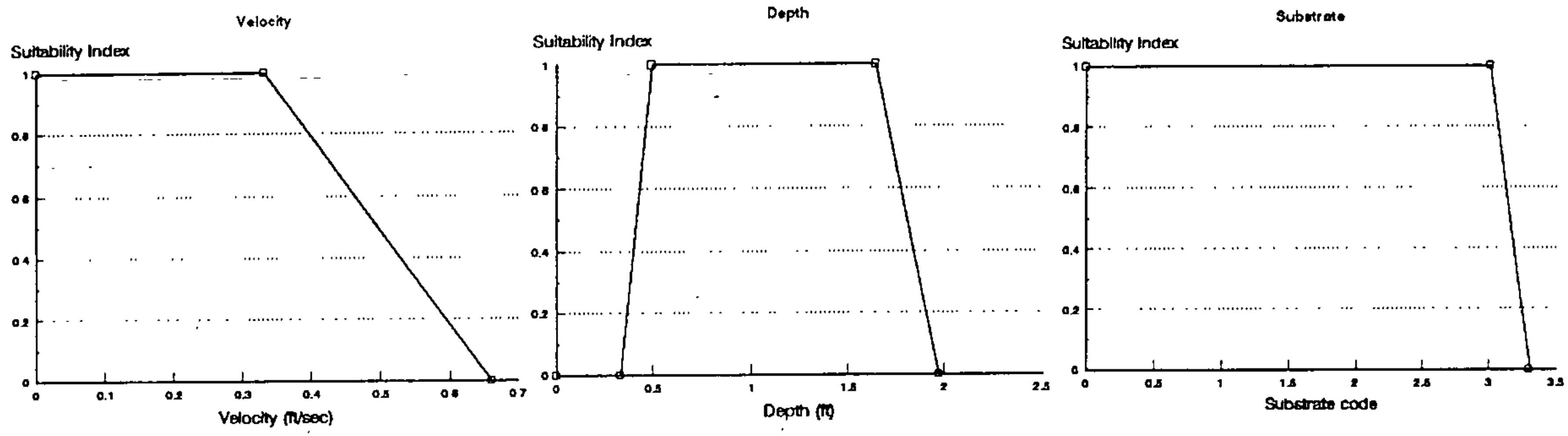

Figure 37 Habitat suitability curves for Perch Fry

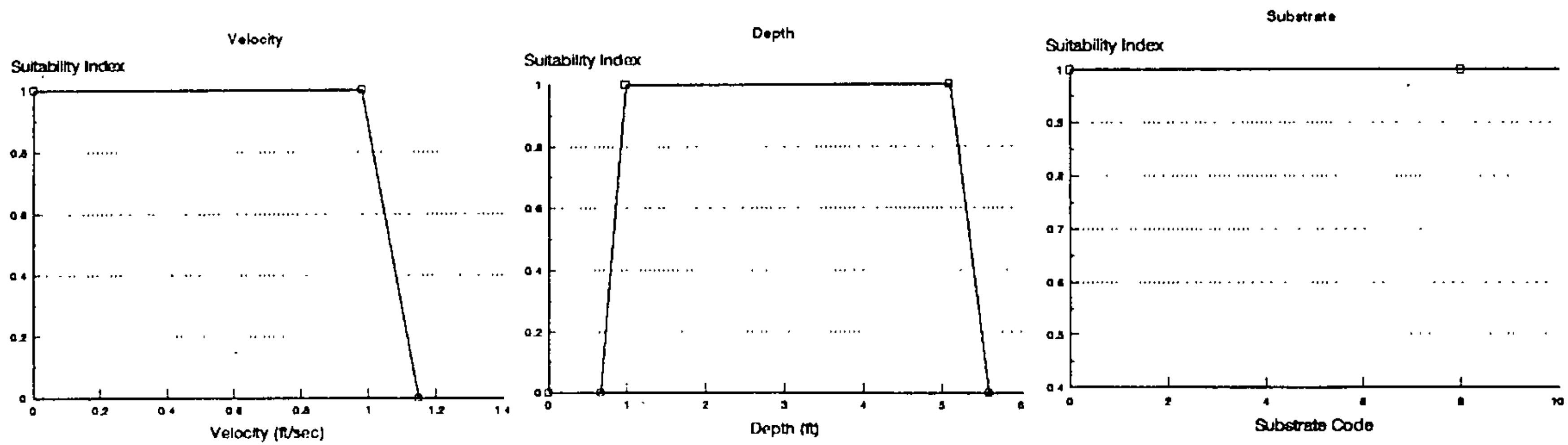

Figure 38 Habitat suitability curves for Perch Spawning

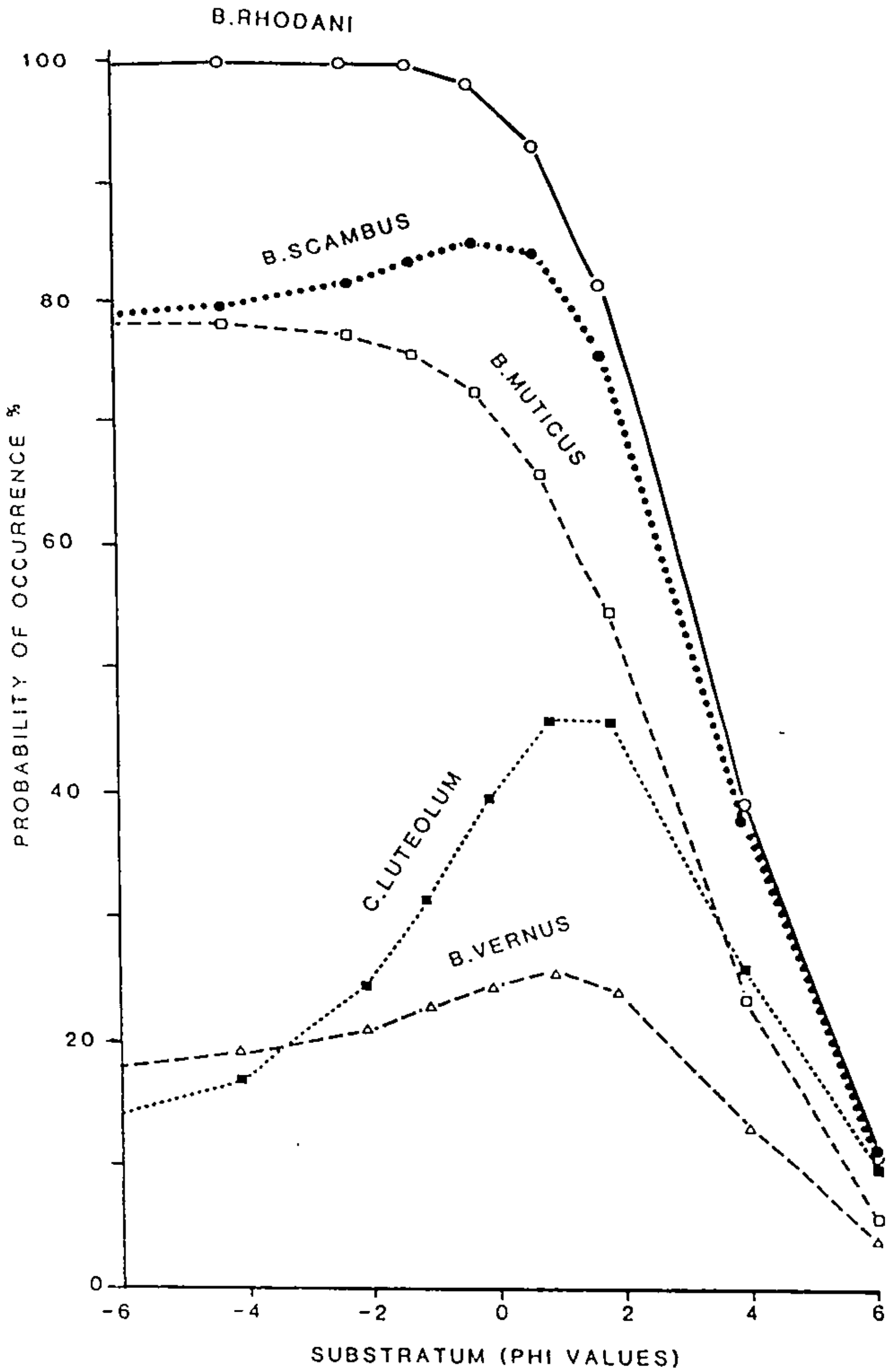

Figure 39 *The effect of simulated change in mean substratum particle size on predictions of the probability of occurrence of 5 species in the family Baetidae*

Annex 2

Habitat preference of river water-crowfoot (Ranunculus fluitans Lam.) for application in PHABSIM testing

O. Mountford & N. Gomes
(Institute of Terrestrial Ecology)

1. SUMMARY

Habitat preference curves are presented for the aquatic macrophyte *Ranunculus fluitans* Lam. These curves are derived from observations on the River Blithe.

The results are discussed in the context of the PHABSIM model, with suggestions for future research.

2. INTRODUCTION

The PHABSIM model seeks to simulate the relationship between stream flow and available physical habitat for fish (particularly Salmonids) at various life stages. It has been extended to examine benthic macroinvertebrates and human use of the river e.g. boating.

The model was developed in the USA (Bovee, 1982; 1986) and has been used throughout the 1980s as a means of determining compensation flows and impacts of their adjustment on downstream habitat.

The model had not been applied to the British situation and it was to test the viability of PHABSIM in the UK and to calibrate it for our rivers that the present study was set up.

The Institute of Hydrology was commissioned to assess the model and other component Institutes of NERC's Terrestrial and Freshwater Sciences Directorate (ITE(S) and IFE) were sub-contracted to help with fieldwork and particular biota. In addition the University of Loughborough co-operated with IH in the recording of the physical habitat. The habitat preference curves for five macroinvertebrate and eight fish species are presented in a separate report by IFE (Armitage & Ladle, 1989).

No attempt had been made in the USA to introduce an aquatic macrophyte component and it was suggested that ITE produce habitat reference curves of the type used in PHABSIM for any plant species that proved frequent in the surveyed rivers.

ITE conducted fieldwork on two English rivers during February and March 1989. Only one species, the river water-crowfoot (*Ranunculus fluitans* Lam.), proved at all frequent and hence was selected to test the practicality of the model. Habitat preference curves for four variables (depth, velocity, substrate and cover) were constructed.

3. METHODS

3.1 Resources

During February and March 1989, ten scientists from Monks Wood Experimental Station contributed to the field recording of elevations, depth, flow velocity, substrate and cover on two rivers in the English Midlands. Equipment for recording were provided by IH and Loughborough University.

3.2 Sampling

Three reaches of the River Blithe in Staffordshire were recorded, one upstream and two downstream of the Blithfield reservoir (gauging station: SK109192).

Three reaches of the River Gwash in Rutland etc. were also recorded, below Rutland Water (SK951082).

Within each reach, between 18 and 20 cross-sections were recorded. At regular intervals on each cross-section the following were recorded:

- distance from a fixed peg
- elevation of the bed
- depth of water
- flow velocity
- substrate
- cover

The substrate and cover were recorded using a standard coding list derived from the American model. Elevation, including that of the water surface, was measured relative to bench marks. The flow velocity was measured in terms of metres/second.

At each survey point the presence of macrophyte vegetation was noted. In all 1014 points within the water were noted in the River Blithe reaches. Macrophytes were observed in 107 of these, of which all except 18 were *Ranunculus fluitans* (*Veronica beccabunga* L. and *Agrostis stolonifera* L. are prominent in these remaining 18, though *Ranunculus repens* and the aquatic moss, *Fontinalis antipyretica* were also seen).

3.3 Data analysis

The data from the Blithe were tabulated and analysed using SAS statistics on the MicroVax computer at Monks Wood.

To date the frequency of *Ranunculus fluitans* in equal increments of depth, flow velocity, substrate and cover has been used as a simple direct method of relating macrophyte growth to physical habitat.

The distribution diagrams produced are a close approximation to habitat suitability curves, though clearly very specific to the river studied.

4. HABITAT SUITABILITY CURVES

4.1 General outline

Tables 1 to 4 summarise the frequency of *Ranunculus fluitans* in classes with equal range, of each measured variable. The depth range is divided into increments of 0.1 m and the velocity into classes of 0.05 m/sec. Substrate is divided into classes of 0.5 of a unit and cover is listed using the standard codes as recorded in the field.

The depth, velocity, substrate and cover classes are not evenly distributed within the three reaches of the River Blithe e.g. there are many more samples with a depth 0.1-0.199 m than between 0.9 and 0.999m. The fourth column of Tables 1 - 4 thus transforms the data (class by class within each environmental variable), giving the percentage of each class where *Ranunculus fluitans* was observed.

From these values which reflect the realtive abundance of the macrophyte in each class of each variable, the habitat suitability curves were constructed. The highest percentage value was considered to be the most suitable for the water-crowfoot and thus given a 'suitability' of 1.0. The other 'suitability' values were calculated as percentages of this highest value. Table 5 lists the 'suitability' values calculated in this way and used to construct the curves.

4.2 Depth

The depth of the River Blithe within the three sample reaches varies between zero and c.1.5 m, although difficulty of access, due to rapid flow and unstable riverbed, to the one or two deepest samples makes this upper figure an estimate. Almost 60% of the sample points within the river occur in depths between 0.1 and 0.399 m.

A habitat suitability curve based on observed occurrence within the River Blithe is presented in Fig. 1.

Over 80% of the occurrence of *Ranunculus fluitans* are in this same depth range (0.1 - 0.399 m).

The highest ('optimum') percentage of sites in a depth class with the water-crowfoot is 18.7% of samples in the range 0.2 - 0.299 m. This was allotted the suitability value of 1.00 and the remaining values calculated as percentages of this maximum. In all almost half the water-crowfoot observed grows within this depth class.

4.3 Velocity

The flow velocity of the River Blithe varies between zero and 1.25 m/sec. In contrast to the depth, there is more even distribution of flow values, though most are below 0.75 m/sec.

A habitat suitability curve for flow velocity, based on observed occurrence of the river water-crowfoot in the Blithe, is presented in Fig. 1.

An 'optimum' flow velocity cannot be precisely estimated but samples in the slow to moderate range (0.05 - 0.099 m/sec) provided the highest proportion of samples with macrophyte growth. It is possible that the crowfoot itself might reduce stream velocity as measured.

4.4 Substrate

This was scored on an eight-point scale: 1 (plant detritus); 2 (mud); 3 (silt); 4 (sand); 5 (gravel); 6 (rubble); 7 (boulder) and 8 (bedrock). The samples within the River Blithe include all these except bedrock, though the boulder category is always mixed with finer material, thus reducing the sample score. Over 60% of samples are composed of sand or coarser material.

A habitat suitability curve for *Ranunculus fluitans* is also presented in Fig. 1, based on observed occurrence in the River Blithe.

The water-crowfoot grows in a wide range of substrate material but is commonest in finer silts and mud. The presence of the crowfoot itself will produce plant detritus which will reduce the substrate score somewhat.

4.5 Cover

The scoring of cover was achieved using a 28-point scale that recorded varying amounts of object cover, overhanging vegetation and undercut bank as well as combinations of two or more of these factors. Most samples in the river itself were characterised by a simple cover of one factor only (particularly object cover and overhanging vegetation: codes 1 - 8) but a small number combined these two factors (codes 13 - 16).

A habitat suitability curve derived from observations on the River Blithe is given in Fig. 1.

Much the majority of samples with water-crowfoot were coded as 2, 3 or 4 indicating 25 - 100% of object cover. It must be borne in mind that the crowfoot itself was scored as object cover, thus influencing the results. However, the rarity of crowfoot object cover in combination with overhanging vegetation (codes 13 - 16), an undercut bank (codes 17 - 20) or both (codes 25 - 28) is significant.

5. DISCUSSION

The relationship between macrophyte growth and depth or substrate has been researched in detail, though most attention has been paid to lake habitats (Spence, 1967; Collins *et al.*, 1987; Anderson & Kalff, 1988).

The dimension of cover as understood in PHABSIM is difficult to relate to published work, other than that on the contribution of shade to the control of submerged weed cover (Dawson, 1978; Dawson & Haslam, 1983).

The relationship between flow and macrophyte growth in rivers has received more attention. Watson reviewed the existing literature on the hydraulic effects of aquatic weeds (Watson, 1987) but his conceptual model is addressed to predicting the effect of macrophyte growth on channel roughness, flow depth and flow stage rather than the manner in which macrophyte distribution is determined by flow velocity.

Although no attempt has been made in the past to make use of data on the cover of macrophytes in PHABSIM some allied studies on marginal emergents and the riparian zone exist. Kondolf *et al.* have examined the impact of diversion of flow due to hydroelectric development upon the vegetation lining streams in the Sierra Nevada (Kondolf *et al.*, 1987). As well as being less relevant to submerged macrophytes such as *Ranunculus fluitans*, this study deals with 'vegetation' in the broad sense rather than named species whose ecology may be compared with the UK examples.

The ecology of *Ranunculus fluitans* has not been studied in sufficient detail in Britain though some German studies have shown that it is relatively tolerant of pollution, being found where high concentrations of phosphorus, nitrogen compounds and a high BOD are noted (Monschau-Dudenhausen, 1982).

It is not covered in the work of the Unit of Comparative Plant Ecology at Sheffield (Grime *et al.*, 1988), and indeed the vegetation of flowing water is poorly represented in the species selected for that study. *Ranunculus penicillatus* (Dumort.) Bab. is described, though information on flow, substrate and depth is summary and insufficient to contribute to PHABSIM. They quote Cook's monograph on Batrachian Ranunculi, stating that *Ranunculus fluitans* tends to replace *R. penicillatus* where the substrate is silty (borne out by the Blithe observations). This is said to be due to the fact that it produces roots only during the winter and thus requires a stable silty bottom (Cook, 1966).

This lack of detailed data on the species of flowing water which could be adapted to the PHABSIM model has effectively circumscribed the choice of macrophytes on which to produce habitat suitability curves. The curves as constructed derive entirely from the Blithe observations and in concert with the physical parameters measured there may produce a consistent data set for PHABSIM. It is possible that curves on other species could be produced, notably the brooklime (*Veronica beccabunga* L.) though this data set is so small that errors are likely to be magnified.

To incorporate a macrophyte component into future uses of PHABSIM requires a large data set comparable with that gathered by IFE in their River

Communities Project (Armitage & Ladle, *op.cit.*). There are good data on the relationship between certain aquatic macrophyte's growth and management soil type, depth, channel width and water quality (Ham *et al.*, 1982; Haslam, 1987; Mountford & Sheail, 1989). However, the level of detail is as yet of a level inappropriate for use in PHABSIM.

It is suggested that existing data sets held by the component Institutes of TFS Directorate are searched for appropriate data on depth, flow, substrate and cover; that sites be revisited where present data are inadequate to produce the missing values that PHABSIM requires: and that further field work is undertaken on rivers where submerged macrophytes are prominent and where they exist in some taxonomic diversity.

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Table 1 Frequency of Ranunculus fluitans Lam. in classes of water depth

DEPTH (Classes of 10 cm)	NUMBER OF SAMPLES IN DEPTH CLASS	NUMBER OF SAMPLES WITH R. FLUITANS	PERCENTAGE OF CLASS WITH R. FLUITANS
0 - 0.099 m	99	3	3.03
0.1 - 0.199 m	247	14	5.67
0.2 - 0.299 m	230	43	18.70
0.3 - 0.399 m	113	15	13.27
0.4 - 0.499 m	94	3	3.19
0.5 - 0.599 m	90	5	5.56
0.6 - 0.699 m	59	1	1.695
0.7 - 0.799 m	33	2	6.06
0.8 - 0.899 m	23	1	4.35
0.9 - 0.999 m	4	0	0
1.0 - 1.099 m	3	1	33.33*
1.1 - 1.199 m	4	0	0
1.2 - 1.299 m	6	1	16.67*
1.3 - 1.399 m	4	0	0
1.4 - 1.499 m	5	0	0
1.5 - 1.599 m	0	0	0

* Data discarded due to small sample size

Table 2 Frequency of Ranunculus fluitans Lam. in classes of flow velocity

FLOW VELOCITY (Classes of 5 cm/sec)	NUMBER OF SAMPLES IN FLOW VELOCITY CLASS	NUMBER OF SAMPLES WITH R. FLUITANS	PERCENTAGE OF CLASS WITH R. FLUITANS
0 - 0.049 m/sec	199	12	6.03
0.05 - 0.099 m/sec	63	9	14.29
0.1 - 0.149 m/sec	60	10	16.67
0.15 - 0.199 m/sec	59	10	16.49
0.2 - 0.249 m/sec	56	9	16.07
0.25 - 0.299 m/sec	61	10	16.39
0.3 - 0.349 m/sec	62	6	9.68
0.35 - 0.399 m/sec	53	8	15.09
0.4 - 0.449 m/sec	38	3	7.89
0.45 - 0.499 m/sec	57	4	7.02
0.5 - 0.549 m/sec	50	0	0
0.55 - 0.599 m/sec	61	1	1.64
0.6 - 0.649 m/sec	39	2	5.03
0.65 - 0.699 m/sec	29	0	0
0.7 - 0.749 m/sec	30	3	10.00
0.75 - 0.799 m/sec	21	1	4.76
0.8 - 0.849 m/sec	20	1	5.00
0.85 - 0.899 m/sec	11	0	0
0.9 - 0.949 m/sec	11	0	0
0.95 - 0.999 m/sec	10	0	0
1.0 - 1,049 m/sec	3	0	0
1.05 - 1.099 m/sec	7	0	0
1.1 - 1.149 m/sec	5	0	0
1.15 - 1.199 m/sec	4	0	0
1.2 - 1.249 m/sec	5	0	0

Table 3 Frequency of Ranunculus fluitans Lam. in classes of substrate

SUBSTRATE CODE	NUMBER OF SAMPLES IN SUBSTRATE CLASS	NUMBER OF SAMPLES WITH R. FLUITANS	PERCENTAGE OF CLASS WITH R. FLUITANS
1.0 - 1.499	40	12	30.00
1.5 - 1.999	47	16	34.04
2.0 - 2.499	70	12	17.14
2.5 - 2.999	62	17	27.42
3.0 - 3.499	95	11	11.58
3.5 - 3.999	85	11	12.94
4.0 - 4.499	101	6	5.94
4.5 - 4.999	246	3	1.22
5.0 - 5.499	232	1	0.43
5.5 - 6.000	36	0	0

Table 4 Frequency of Ranunculus fluitans Lam. in classes of cover

COVER (Standard codes)	NUMBER OF SAMPLES IN COVER CLASS	NUMBER OF SAMPLES WITH R. FLUITANS	PERCENTAGE OF CLASS WITH R. FLUITANS
0	291	3	1.031
1	186	19	10.22
2	75	19	25.33
3	42	23	54.76
4	58	23	39.65
5	21	0	0
6	27	0	0
7	31	0	0
8	87	0	0
9	1	0	0
10	1	0	0
11	0	0	0
12	0	0	0
13	70	0	0
14	48	2	4.17
15	24	0	0
16	11	0	0
17	5	0	0
18	3	0	0
19	0	0	0
20	2	0	0
21	6	0	0
22	1	0	0
23	1	0	0
24	1	0	0
25	12	0	0
26	0	0	0
27	9	0	0
28	1	0	0

Table 5 Suitability values for Ranunculus fluitans Lam. calculated from percentage occurrence in environmental variable classes

DEPTH CLASS	SUITABILITY VALUE	FLOW CLASS	SUITABILITY VALUE
0 - 0.099	0.16	0 - 0.049	0.36
0.1 - 0.199	0.30	0.05 - 0.099	0.86
0.2 - 0.299	1.00	0.1 - 0.149	1.00
0.3 - 0.399	0.71	0.15 - 0.199	0.99
0.4 - 0.499	0.17	0.2 - 0.249	0.96
0.5 - 0.599	0.30	0.25 - 0.299	0.98
0.6 - 0.699	0.09	0.3 - 0.349	0.58
0.7 - 0.799	0.32	0.35 - 0.399	0.91
0.8 - 0.899	0.23	0.4 - 0.449	0.47
0.9 - 0.999	0	0.45 - 0.499	0.42
1.0 - 1.099	0*	0.5 - 0.549	0
1.1 - 1.199	0	0.55 - 0.599	0.10
1.2 - 1.299	0*	0.6 - 0.649	0.31
1.3 - 1.399	0	0.65 - 0.699	0
1.4 - 1.499	0	0.7 - 0.749	0.60
1.5 - 1.599	0	0.75 - 0.799	0.29
		0.8 - 0.849	0.3
		0.85 - 0.899	0
		0.9 - 0.949	0
		0.95 - 0.999	0
		1.0 - 1.049	0
		1.05 - 1.099	0
		1.1 - 1.149	0
		1.15 - 1.199	0
		1.2 - 1.249	0

* Data discarded due to small sample size

Table 5 (Continued) Suitability values for Ranunculus fluitans Lam. calculated from percentage occurrence in environmental variable classes

SUBSTRATE CLASS	SUITABILITY VALUE	COVER CLASS	SUITABILITY VALUE
1.0 - 1.499	0.88	0	0.02
1.5 - 1.999	1.00	1	1.19
2.0 - 2.499	0.57	2	0.46
2.5 - 2.999	0.81	3	1.00
3.0 - 3.499	0.34	4	0.72
3.5 - 3.999	0.38	5	0
4.0 - 4.499	0.175	6	0
4.5 - 4.999	0.04	7	0
5.0 - 5.499	0.01	8	0
5.5 - 6.000	0	9	0
		10	0
		11	0
		12	0
		13	0
		14	0.08
		15	0
		16	0
		17	0
		18	0
		19	0
		20	0
		21	0
		22	0
		23	0
		24	0
		25	0
		26	0
		27	0
		28	0

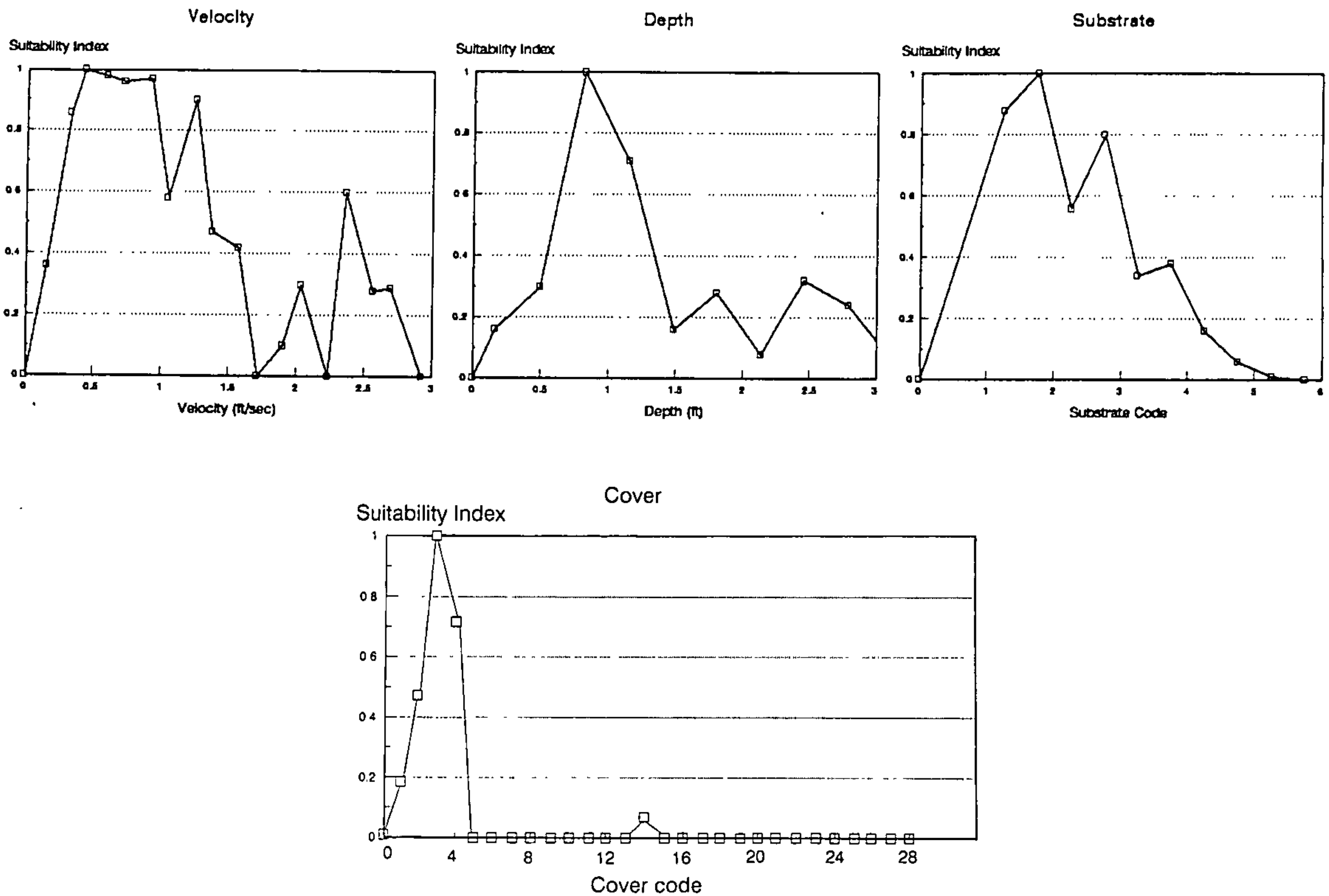

Figure 1 Habitat suitability curves for Ranunculus fluitans