ARCHIVE:

PLEASE DO NOT DESTROY

Institute of Hydrology

1996/075

Centre for Ecology & Hydrology

Natural Environment Research Council

Centre for Ecology and Hydrology

Component Institutes
Institute of Freshwater Ecology
Institute of Hydrology
Institute of Terrestrial Ecology
Institute of Virology & Environmental Microbiology

Natural Environment Research Council

Guide to undertaking a PHABSIM study in the UK

Informal Note

DRAFT

Institute of Hydrology
M.J. Dunbar, C.R.N. Elliott,
M.C. Acreman, A. Gustard

Institute of Hydrology
Wallingford
Oxon. OX10 8BB
UK

Tel: 01491 838800
Fax: 01491 692424

March 1996

Contents

List of Figures

Executive Summary

The Physical Habitat Simulation system (PHABSIM) is a hydro-ecological model which enables the assessments of impacts caused by changing flow regimes, or altered channel geometry, on physical instream habitat. It is calibrated by taking field survey measurements of channel geometry, plus water surface levels and velocities at two or more flows. Hydraulic simulation of the river is combined with criteria on physical habitat that aquatic species find 'suitable'. It is thus not a population or biomass model, but a widely-applicable means by which biological information may be introduced into the water resources planning process.

Development of PHABSIM was initiated in the 1970s, by an interdisciplinary team of scientists at the US Fish and Wildlife Service (Bovee 1995). PHABSIM is part of a wider framework, the Instream Flow Incremental Methodology (IFIM), a procedure designed to assess quantitatively the changes in river habitat that occur as a result of river management decisions. PHABSIM was first applied in the UK in 1989, and has been the subject of ongoing research since. The first operation application of the model was in 1993 on the river Allen in Dorset.

This paper is a general guide to the most important points to be considered when planning and conducting a PHABSIM study in the UK. It should assist those using the IFIM by providing a general guide to the requirements of the PHABSIM model and by detailing the issues that may need to be addressed during such work. This paper should also provide a useful check list for staff that must review the conduct and results of a PHABSIM study, although again it is not an exhaustive check list, as ideas on 'best practice' are continually being updated.

It is important to note that this is not an all-encompassing guide, or "rule book", to the application of the method, and it does not cover methodologies in detail. The reader is referred to Milhous (1990) and Elliott (1996) and other publications of the US Instream Flow Group as essential reading before conducting or reviewing a study.

Critical aspects of any PHABSIM study will be the study scoping process, selection of study site(s), development of habitat suitability data (or their transfer from other studies), the hydraulic modelling process, and the aggregation of habitat suitability indices to produce a composite index of how habitat varies with flow. Once the basic modelling procedures have been completed, combination of model output with flow time series, and analysis of spatial distribution of habitat may provide valuable additonal information should the study objectives require.

Individual applications of the model may require examination at lower or higher levels of detail than suggested here and a major consideration when applying the model is the resource input required and this should be reviewed alongside the issues that need to be addressed.

Also the IFIM and PHABSIM is the focus of ongoing research projects, both within the UK and internationally, and as a result the recommended approaches to using the model are subject to change as developments take place.

The Instream Flow Incremental Methodology

The Physical Habitat Simulation system (PHABSIM) is part of a wider conceptual framework, the Instream Flow Incremental Methodology (IFIM), which provides a problem-solving approach to water resource issues in streams and rivers.

As alterations in flow will change physical habitat in virtually any river, PHABSIM is probably the most common element of IFIM to be applied. However an IFIM study may also include models for water quality, water temperature or indeed any other model which simulates characteristic features which could influence habitat. It also includes mechanisms for analysing the institutional aspects of water resource issues, the study scoping and planning process, along with techniques for negotiation and resolution.

One of the most important aspects of any PHABSIM study is that it is adequately planned / scoped, and for all but the simplest studies, this will include setting the study within an appropriate IFIM or IFIM-like framework. The reader is referred to Bovee 1995 for more information on this topic.

PHABSIM

The Physical Habitat Simulation system (PHABSIM) is a hydro-ecological model which enables the assessment of impacts caused by changing flow regimes, on physical instream habitat. It may also be used to assess impacts from changes in channel morphology, such as those arising from flood defence or habitat improvement schemes. It is calibrated by making field survey measurements of channel geometry at transect sites on a river system, along with measurements of water surface level and stream velocities at two or more flows (Elliott *et al.* 1996). Output from PHABSIM is expressed as available habitat area (termed Weighted Usable Area or WUA) versus discharge, for each species/life stage of interest. Available habitat is usually modelled over a range of selected discharges to allow the representation of how habitat (represented by WUA) varies with streamflow. Further analysis of how habitat will vary on a spatial and temporal basis, for different species and their life stages provides valuable information to underpin future river management and water resources allocation.

Application of PHABSIM in the UK

The first UK use of the IFIM, focusing on the application of PHABSIM involved studies at five sites on the rivers Blithe and Gwash, under a commission from the DoE (Bullock *et al.* 1991) by the Institute of Hydrology. The study successfully demonstrated the potential of PHABSIM as a practical tool for the generation of habitat vs discharge relationships for IFIM studies on UK rivers. Following this application, work has continued on the assessment and development of PHABSIM for use in the UK. These studies include: the National Rivers Authority R&D project "Ecologically Acceptable Flows" a study examining the application of the towards the assessment of water resource issues, MAFF funded studies examining the application of the model to the assessment of river flood defence and habitat restoration/improvement schemes, and the NERC science budget project "Faunal and floral response to reduced flows and habitat loss in rivers". Following the success of Phase I of the Ecologically Acceptable Flows project, the first operation application of the IFIM & PHABSIM was carried out on two sites on the River Allen, Dorset, under a commission from the NRA (Johnson *et al.* 1993). To date the model has been applied to approximately 50 sites in the UK, both for research and applied purposes. This guide has been produced in response to the increasing use of the model to operational water resource issues and the resulting demand for information on how such work should be carried out.

The PHABSIM model

PHABSIM itself comprises the following elements:

- a hydraulic model that can be calibrated to the river in question.
- an ecological model, which combines information on what is and is not suitable habitat for a species with the output from the hydraulic model.

The underlying concepts of PHABSIM are:

- It examines physical habitat, data on which is collected across study transects at several flows.
- Physical habitat is simulated for unobserved flow conditions.
- Target species exhibit a quantifiable preference/avoidance behaviour to one or more of the physical microhabitat variables: velocity, depth, cover or substrate.
- Preferred conditions can be represented by a habitat suitability index which quantifies the suitability of flow depths and velocities and cover/substrate, for a specific species/life stage and which has been developed in an unbiased manner.

- Individuals select the most preferred conditions within a stream, but will use less favourable areas with decreasing frequency/preference.
- Species populations respond to changes in environmental conditions that constitute habitat for the species.

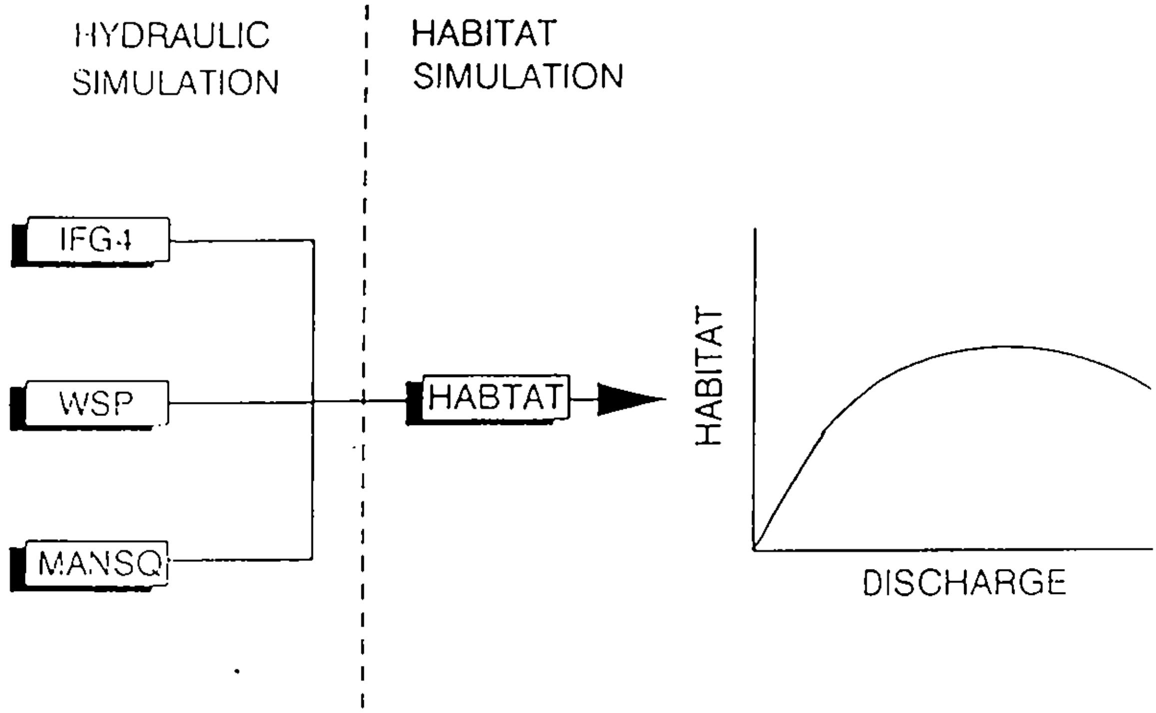

Figure 1: The PHABSIM model

The initial part of the PHABSIM modelling procedure is to model the hydraulic characteristics of chosen sets of linked river cross-sections (transects). The hydraulic simulation models within PHABSIM are calibrated using field survey data and are able to model both depths and velocities (along with substrate and/or cover as unchanging parameters), over a range flows. These data are then input into the PHABSIM habitat model which combines them with habitat suitability indices for the chosen target species / life stages. The habitat suitability information for the target species, and distinct life stages of those species, can be derived from one or more of the following methods: expert opinion, existing empirical data (including the US Fish & Wildlife Service curve library), scientific literature, direct field sampling. For each target life stage. the PHABSIM habitat model produces a single index, the Weighted Usable Area (WUA) at each simulation flow.

It is clear that in conducting a PHABSIM study, an ideal goal would be to relate changes in aquatic populations to changes in the flow regime. Although some studies have successfully demonstrated that PHABSIM may be capable of achieving this goal, it must be appreciated that PHABSIM alone is not generally capable of this task since it simulates the physical habitat area (WUA) available to aquatic species and not change in biomass. In some instances a linear relationship between biomass and WUA has been demonstrated (Milhous, 1988, Jowett, 1992). However it is clear that over a period of years this will not be the case in most rivers, since for some proportion of time, factors other than physical habitat will limit populations. In the absence of equivalent population models, it is essential that one accepts the limitations of using WUA as the key variable and attempts to take into account the factors which may also influence aquatic populations. Gore and Nestler (1988) make the following statement with regard to this issue in relation to the models use for assessing water resource issues:

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

A PHABSIM study will often involve significant expenses, in fieldwork, model calibration, interpretation of results, and not least the planning stages. Thus it is important from the outset to bear in mind the level of expenditure that is appropriate to the problem to be investigated. For example a major river basin management scheme may require the application of several different simulation models within an IFIM framework, the collection of new habitat suitability data and further simulation of spatial and temporal changes in habitat. However a small investigation into the potential impact of a new abstraction licence may involve the collection and analysis of relatively small amounts of data on physical habitat.

In assessing a PHABSIM study, one of the main objectives is to assess it against currently accepted 'best practice'. Ideas on what constitutes 'best practice' have changed over the last 20 years, and continue to change, so it is important that the reviewer keeps up to date.

A 'good' PHABSIM study will be an appropriate application of the model, use current best practice in study planning, data collection and manipulation, and be a robust application, leading to defensible conclusions.

Project scoping and study sector selection

Prior to the initiation of a PHABSIM project, a number of scoping activities are essential. However there is no one 'correct' way to perform a PHABSIM study and actual methodologies used will depend in part on the scope and objectives of the study. Major types of study include:

- Assessment of future project impact
- Assessment of impact of current water resources scheme
- Determination of instream flow requirements (management objectives) for a river system
- Use of the model as a research tool

Project scoping should follow a pragmatic approach based on the perceived importance of the issues to be addressed. The following sections are suggested as a guide only, each should include supporting evidence for the choices made.

1. A statement of study objectives (**why?**). The outputs, expectations and requirements of the project should be stated in as much detail as practicable and agreed before starting.

2. Identification of the impacted areas or areas to be studied (**where?**). Decision on the best approach to study site selection: critical reach or habitat mapping, and preliminary characterisation of study sector or sectors.

3. Identification of skills required and selection of personnel. Application of PHABSIM requires the skills of a multi-disciplinary team, including skills in aquatic biology, hydrology, hydraulic modelling, interpretation of the PHABSIM hydro-ecological models, and negotiation.

4. Confirmation that physical habitat is the main factor limiting target species populations. This may include characterisation of macrohabitat issues (e.g. quality and temperature) and consideration of further factors such as exploitation and stocking, food availability and competition, channel dynamics and sediment transport. Some of these aspects will be best addressed with other models, or using more conventional techniques such as multi-variate regression. Food availability for some fish species may be modelled using habitat suitability data for selected invertebrate species.

5. Selection of target species and life stages (**who?**). It will probably not be possible to evaluate effects on all species in a river. Management objectives, combined with advice from fisheries and conservation personnel will determine if the study is to concentrate on a broad range of species, or one specific species or even life stage. It should also be noted that an important component of the IFIM, is assessing trade-offs between the flow regimes required by different species / life stages.

   One method used to select species is to rank them numerically, according to various criteria, including their importance, vulnerability and extent of available information.
   Scoping should locate any existing sources of habitat suitability information, their 'transferability' (see below), as well as possible strategies for suitability curve development, should existing information not be available or comprehensive enough. The importance of characterising fish species by size / age class cannot be underestimated, as size will have a significant impact on habitat use. The classification to be used must of course be compatible with suitability data.

6. Construction of species periodicity charts, identification of hydrological regime **(when?)**
Consideration of location of gauging stations.

Habitat suitability curve selection or development

(main source Bovee 1986).

A vital part of a PHABSIM study is a knowledge of what provides favourable habitat for the target species being considered. (Micro)habitat in PHABSIM is defined by water depth, velocity and channel index, the latter representing substrate, cover, or any other similar variable which is important in defining the physical habitat requirements of an aquatic target species. This information is commonly known as habitat suitability curves or HSCs (suitability indices, suitability criteria and suitability data are also commonly-used terms).

It is important that consideration is given to HSC selection and / or development as early as possible into a PHABSIM study. Reasons for this include:

- It attaches an importance to HSCs, which is otherwise easy to overlook. Their simple nature when presented graphically belies the effort behind their development, and makes it all too easy simply to adopt whatever curves are available after hydraulic modelling is complete.
- It focuses the minds of the investigators on microhabitat variables in the stream in question.
- If no suitable habitat data exist, it may be necessary to a full suitability data collection programme, this may need to cover a long time period, even more so than the habitat hydraulics study.

A PHABSIM report will describe either the valid transfer of suitability curves developed for other similar streams, or refer to development of curves specifically for the study in question. Either way, reference to another report which describes the development of the HSCs is vital.

Types of suitability curve

Bovee (1986) provides a classification as follows:
Category I curves are based on information other than field observations made specifically for the purpose of suitability curve development. They can be derived from life history studies in the literature, or professional judgement. This latter case may involve round-table discussions, the Delphi technique (which overcomes some disadvantages of traditional committee meetings), or hybrid techniques such as 'habitat recognition', where the experts are taken to a stream and asked to assess the suitability of various habitats. This category also includes curves that have been based on one or more sets of source data, which experts have then 'modified' to account for differences between the source and destination streams.

Category II curves use data collected specifically for PHABSIM studies, based on frequency analysis of the actual microhabitat conditions used by different species and life stages in a stream. These are also called **utilisation** curves. Location of target species may be by one of a number of methods - direct observation (from the bank, snorkelling or scuba) video. telemetry, trapping / physical capture, electrofishing or explosives. Choice of method will have to be considered and justified, there is no one best method for all situations. Location of target species is accompanied by measurement of the relevant physical habitat variables at the point of observation.

Category III data combine a category II frequency analysis, with additional information on the availability of habitat combinations in the sampling reaches. These are also called **preference** curves. In the late 1980's it was thought that this methodology would correct for bias caused by habitat availability in the source stream(s), and thus make the curves more transferable.

However further statistical and practical work has shown that preference curves actually introduce additional bias, and that category III curves are in practice less transferable. Current thinking is that to construct the most realistic (and transferable curves) it is best to develop category II curves using source streams with the widest variation in microhabitat conditions. It is also important to note that curves should be developed on streams where artificial influences on physical habitat are not an issue.

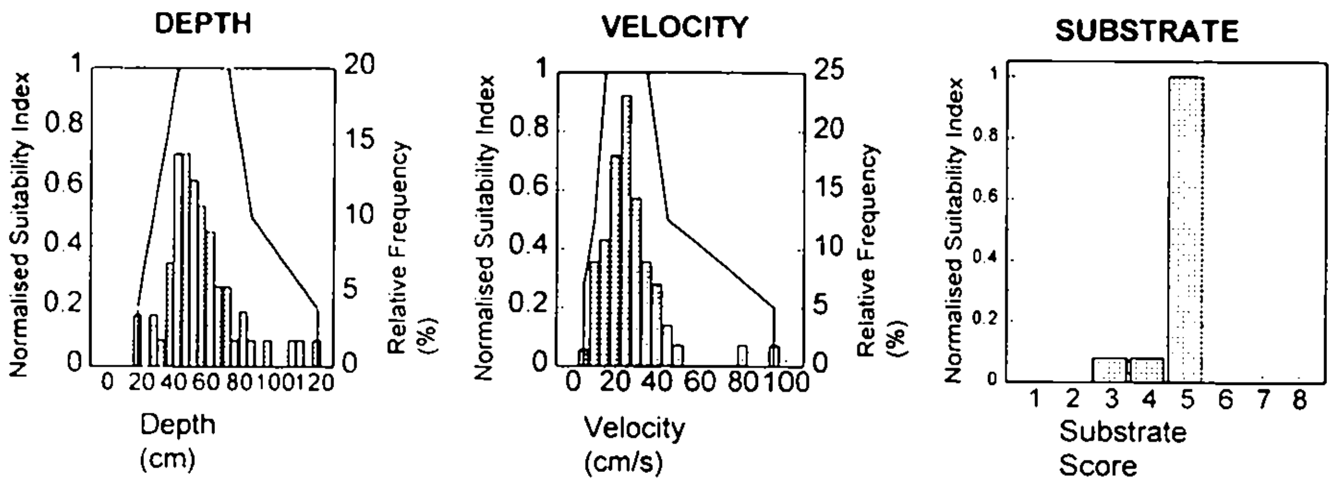

Figure 2: Suitability curves for adult brown trout in southern chalk streams

Transfer of suitability curves

However the data are collected, suitability curves will demonstrate some specificity to the stream(s) in which they were developed. However, well-developed curves may be transferable to studies on other similar streams. With limited resource availability, this is important. Naturally not having to develop HSCs in every stream leads to considerable cost savings. There are many instances of successful transfer of curves between streams, however it is important for the investigator always to apply professional knowledge, and to evaluate fully all aspects of the source curves for transferability.

This evaluation comprises two stages

1. Top level screening: check that available data includes all required species and life stages. Check the methodologies of the studies, were the data collected and curves constructed in a rigorous and defensible manner? - see the section on curve development below. Is there a full description of site(s), field and data handling techniques, with special regard to ensuring the absence of bias? Were all required variables sampled? Was the sampling procedure (e.g. for mean column velocity), and coding (e.g. for substrate) compatible with the proposed study? Do measurement units need to be converted? Problems may be encountered when transferring velocity measurements from smaller to larger rivers.

2. Evaluation of transferability

When considering the transfer of curves developed for other streams, consideration must be given to the additional factors which may influence microhabitat selection. For example: body size and size structure of population, risk of predation, competition, food availability, season, time of day, thermal regime, plus of course habitat availability. This leads to a basic assessment of the 'similarity' of the two streams - are the above factors sufficiently similar?

a. 'Rules of thumb'
There are also a number of 'rules of thumb' commonly used for assessing transferability:

- The more 'similar' the streams, the more likelihood of curve transfer being valid. It is important to consider whether differences between source and target streams create differences in target species / life stage microhabitat preferences? For example the fact that one stream may have a maximum velocity of 1 ms^{-1} and another 2 ms^{-1} is a major difference, but this may not be relevant if the target species only tolerates velocities below 0.75 ms^{-1}
- Curve convergence. If separate studies on similar streams have shown consistent results, this will add weight to the transfer of criteria to a new stream. Unfortunately we still have too little data to assess this in almost all cases.
- It is valid to transfer curves from a high diversity stream to a low one, but not vice-versa.

b. Statistical tests for transferability.
There are three methods:

- Convergence approach. Conduct a mini suitability study on the stream where the PHABSIM study is to take place, are the results consistent with other 'similar' streams?
- Habitat suitability overlay. Conduct a mini PHABSIM study on a reach in the target stream, ensuring each cell only contains one microhabitat type, and predict habitat quality at a simulated discharge. Conduct fieldwork at this discharge to ascertain whether fish are more likely to be found at the areas of high quality habitat.
- Monte-Carlo simulation. This uses the general methodology as above, but uses random number generation, combined with data from the source study on 'empty' cells. It allows for the fact that one will not necessarily find fish even in high quality habitat. Agreement between predicted and actual fish densities can be tested statistically.

If several source curves are available, which don't necessarily agree, but all are valid. Bayesian decision making theory can be used to produce a combined curve. In this approach, the researcher is able to place a weighting on the relative validity of each of the curves.

Stages in curve development

1. *Choice of species / life stages.*
2. *Choice of study site(s).* The final study report should contain a full description of the study site, including photographs. The site(s) should provide a high degree of microhabitat diversity to ensure the target organisms choice of habitat is not limited by availability.
3. *Sampling methodology.* These techniques are documented in Bovee (1982). adequacy of field measurement techniques must be ensured, as for other parts of a PHABSIM study. Is substrate and cover to be measured using standard techniques, to ensure ease of transfer by other researchers? What sort of velocities are to be measured (mean column - 0.4x or 0.2x & 0.8x depth), or nose velocities? The latter have not been applied in the UK.
4. *Sampling strategy* (important to eliminate bias). This should be chosen in conjunction with the methodology and fully documented.
   A stratified random approach can be used to ensure that all habitat types are represented. However care must be taken to ensure the true areas of the habitats are represented when data are collated, to avoid bias. Proportional sampling avoids this problem by dividing the

whole reach into a grid whose cell size varies with habitat homogeneity. Modified cluster sampling lies somewhere between these two approaches, with effort allocation based on habitat proportions.
Choice of sampling strategy will be dictated both by funding available and the characteristics of both the river and the target species.

5. *Data processing techniques.* The 'raw' data should be documented as well as the final 'curves'. The techniques used to fit curves to the data should be documented and justified, such techniques may include simple histogram analysis (perhaps with least-squares curve fitting), nonparametric tolerance limits, nonlinear regression or possibly multivariate regression.

Avoiding the introduction of bias when pooling data from different sources is a major issue in curve development. It is important to ensure that all combinations of microhabitat criteria are represented in a data gathering study and this may require different flows, reaches or even different streams to be sampled. There is a very real risk that bias could be introduced, in the form of over-representing particular data for non-statistical reasons. To this end it is important to correct for other sources of bias such as surface area sampled, time spent sampling and efficiency of different techniques.

The best way of eliminating pooling bias is to standardise effort between streams / sites. If microhabitat variables are always measured (including at sites where target organisms not found), then catch per unit effort (CPUE) can be calculated and used to correct for unequal effort.

Quality assurance in curve development

A great deal of care must be taken when developing HSCs for use with PHABSIM.

Possible sources of error in curve development fieldwork include:

- Precision error. How accurately can an organism be associated with a focal point of microhabitat? This is particularly important with more invasive techniques such as electrofishing.
- Disturbance error. This may be a problem in clear water or with particular species.
- Gear bias. Efficiency will vary with the methodology used, as well as under different sampling conditions. For example small fish are more able to evade electrofishing.

PHABSIM transect placement

There are two main approaches to selecting a study site or combination of sites in a stream: identification of one or more 'critical reaches', or placement of representative transects chosen through a 'habitat mapping approach'.

In the process of scoping an IFIM study, the length of river over which valid conclusions are required should be identified. Clearly, the more homogeneous the river is in terms of its hydrological and ecological characteristics, the more easily the results from simulations within the selected study reaches may be extrapolated to longer river sectors.

Critical Reach
This approach is appropriate in a situation where it is possible to identify, through existing data, an area (or several areas) of the river which is known to be most sensitive to changes in flow, and critical to the success of a particular species life-stage. If for example, it is believed that the availability of spawning habitat is the limiting factor to recruitment of a particular fish species, then the selection of a reach covering the known spawning area would be most appropriate for a study designed to specify a flow regime optimal for recruitment of the species.

The critical reach should meet two basic criteria:

- The reach should be highly sensitive to changes in stream flow. The rate of change of width, depth and velocity with respect to discharge should be greater for the critical reach than for other portions of the river. Generally, the most sensitive reaches with respect to discharge are elevated portions of the channel, such as riffles and gravel bars.
- The critical reach must also act as a biological control. The target species in the study must be known to be directly limited by the type of habitat present in the critical reach for a particular life stage. For example, if the availability of spawning habitat is known to be limiting to trout populations, then a convex gravel bar could be an appropriate choice of critical reach.

If it is not possible to identify the availability of a particular habitat type to a particular species life-stage as the limiting factor to success of the species, the relationship between the flow regime and all of the different habitat types present in the length of river to which conclusions are to be applied must be sampled. For a single species, different habitat may be limiting to different life stages at different times of the year, and if the study addresses more than one target species, different habitat types may be limiting to populations of the different species. In either case, it becomes imperative that the study site(s) represents the full range of habitat types present in the larger length of river.

PHABSIM Study Sector Characterisation: Habitat Mapping
If a critical reach approach is not appropriate, the alternative is a 'habitat mapping' approach. Firstly, within the whole study area identified in the scoping process, river sectors are identified each comprising a different 'macrohabitat' type, for example defined by geomorphology and human influences. Within each sector, the species assemblages should naturally also be similar. Then persons familiar with the river, in conjunction with the PHABSIM investigators develop a classification scheme for habitat types in the river, roughly at the level of basic habitat types such as deep glide, shallow glide, pool, riffle and cascade. Personnel must also agree upon the flow under which the habitat mapping fieldwork must be carried out.

There are several levels at which the habitat mapping itself may be carried out. At the simplest level, personnel walk the study sectors and assess visually the types of habitat present. They then choose positions for PHABSIM study transects that represent these habitats. Clearly, the more homogeneous the stretch of river, the easier this task will become and it may be possible to represent the whole sector by one length of representative reach.

For more complex water resource impacts, a diverse study river, or simply where management information is required for a wide area, a more detailed approach may be appropriate. Zones of generally similar instream physical habitat are identified through a survey which takes spot measurements of habitat variables such as stream width, maximum velocity, depth, substrate and cover, along with a qualitative assessment of the habitat type. Analysis of the distribution of these habitat variables enables a finer classification of habitat types, for example it may highlight distinctive clusters of parameters showing different types of deep glide. In addition to identifying different geomorphological features, (e.g. pools and riffles) the distribution of areas having cover (e.g. overhead cover, undercut banks, or floating aquatic plants) and areas thought to be of special ecological importance (e.g. backwater refuges) should be identified.

Interpretation of stereoscopic aerial photographs of the river can be a valuable aid in this part of the study. Existing data, for example fish surveys and hydrological data plus expert local opinion may be used to supplement the visual survey.

Transect placement
PHABSIM transect sites are then chosen to represent the habitat types identified in the above mapping exercise. Where possible, series of hydraulically-linked transects are chosen as these can be modelled with greater accuracy. The total number of transects will depend on perceived habitat diversity, the extent of the study and resources available. The number of transects for each habitat type will generally be small, and in rough proportion to the contribution of that habitat type to the total make-up of the sector. However part of the habitat typing process may involve identification of 'critical habitat' such as chutes which occupy relatively small sections of river, but will constitute a disproportionate number of modelling transects due to their perceived importance.

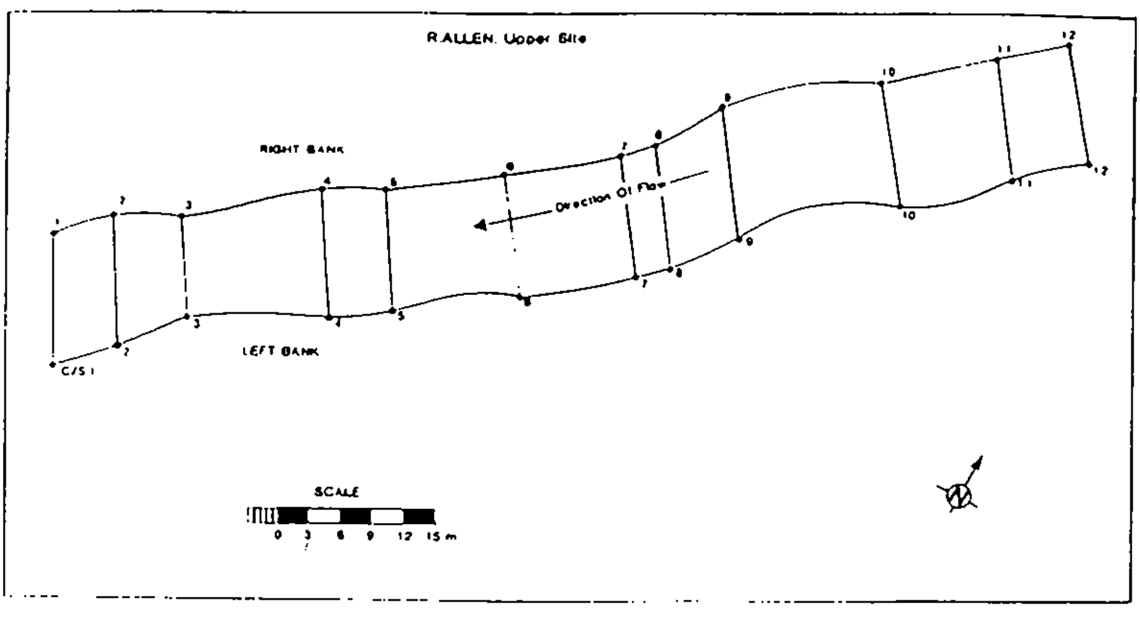

Figure 3: PHABSIM transect placement

In addition to the presence / importance of the habitat for transect choice, additional transects should be placed at all hydraulic controls within a study reach. These transects ensure optimum model performance. If these controls do not represent valuable habitat *per se*, then they do not contribute to the physical habitat calculations. The most downstream and upstream transects should also be at hydraulic controls.

Once hydraulic and habitat modelling have been completed, the area of available habitat for each whole sector is calculated by scaling the area for each habitat type (represented by one or more transects) by the proportion of the total sector river area that is represented by that habitat type. This procedure is carried outside the standard suite of PHABSIM programs, for example in a spreadsheet. It should be reported fully.

A further development of habitat mapping (e.g. Aquatic Systems Research 1992), involves mapping the changing proportions of the habitats (as mapped above) at different flows. This information is then included in the weighting of individual habitat WUAs to produce a composite WUA for all flows. For example a river may be 30% riffles at low flows, but only 10% at high flows. This methodology is only applicable to the most well-resourced studies.

Points to note in a report

- A full description of methods used for study site selection, including maps of locations of habitat types and table(s).
- Photographs of various habitat types.

Data collection and entry

PHABSIM data collection requires the following steps to be completed and reported:

- Units for measurement must be chosen (metric / imperial)
- The selection of flow discharges (usually 3) where field data are required. Identification of suitable conditions when these flows are occurring. Under particularly difficult conditions, for example a complex bed morphology or weed growth, data may be required from more than 3 flows in order to model the physical habitat correctly.
- Survey headpins are driven into the bank at each cross section. These must be placed a reasonable distance away from the water, but also where they are least likely to be disturbed.
- A topographic survey of channel morphology (bed elevation) at each cross section (selected above), relative to the fixed cross section headpin. The investigator should ensure an adequate number of readings to describe the channel cross section.
- A record of channel index parameters (substrate, and cover if required) at each of the points where bed elevation was taken above. PHABSIM considers substrate and / or cover to be unchanging throughout the flow range.
- At each flow, wading rod depths should be taken at these points.
- Field notes describing the river and in particular every cross section. It is important always to collect as much information as possible.
- For each set of linked transects, a closed-loop survey through all headpins showing elevations and distances.
- At each flow, a survey of water surface levels at each cross section, relative to the cross section headpin. Repeated staff readings on the left, centre and right of the channel provide best accuracy. This provides some data redundancy (wading rod depths are also taken) but provides an essential check on the survey techniques.
- At one or more flows, mean column velocities across each cross section, taken at bed elevation points as above. Measurements are usually taken at the highest flow, but this is not essential, conditions in the field may require a lower flow to be measured. Additional velocity sets taken at the other flows are desirable but not essential. Mean column velocity is usually taken at 0.4x depth, although for larger rivers, an average of readings at 0.2x and 0.8x may instead be taken.
- Any flow changes during fieldwork periods must be noted.
- Installation of a data logger for water surface level at a convenient point (usually the most downstream cross section) can provide valuable additional information.

We recommend that at least three complete sets of water surface level and velocity data are collected to ensure optimum model calibration. Available resources may limit time spent on data collection, so it is important to agree in advance the amount of data required to obtain a satisfactory model calibration.

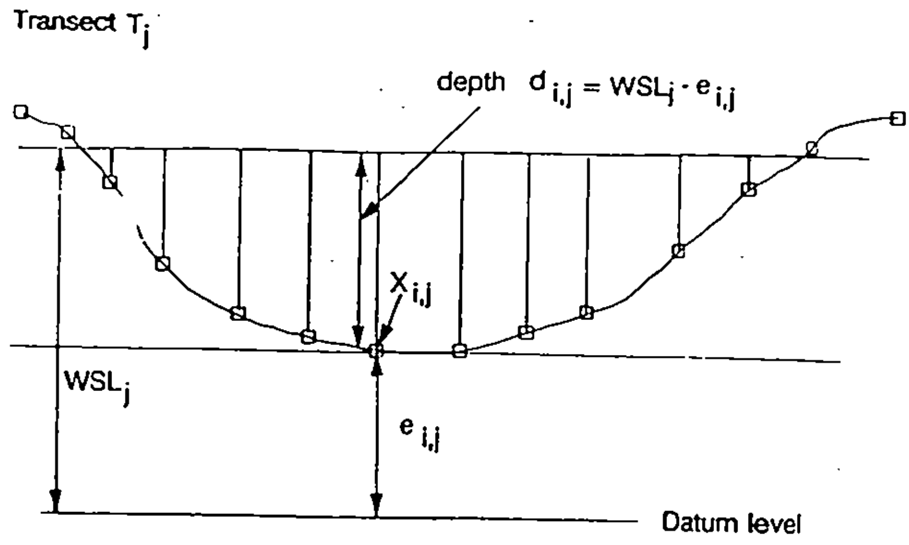

Figure 4: Collection of data across a transect

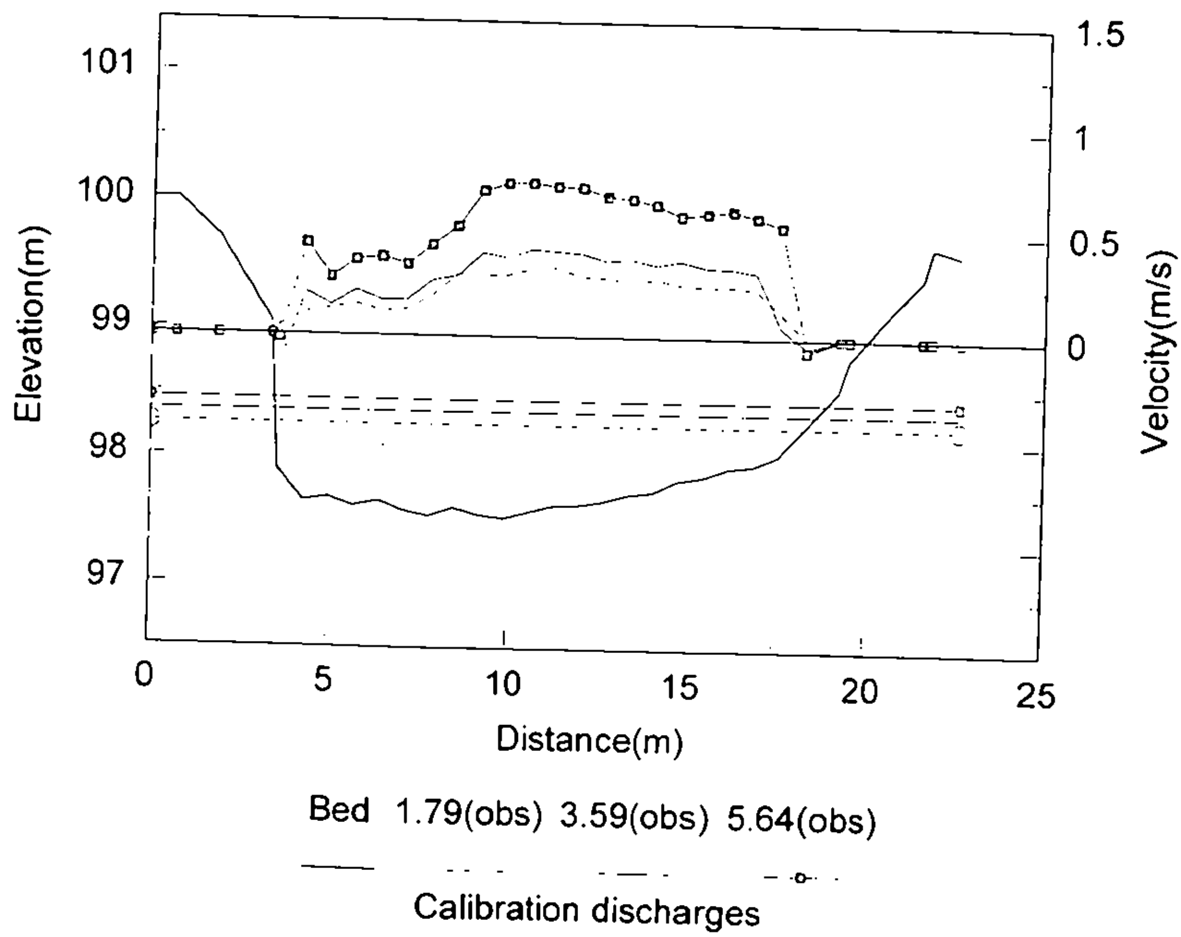

Figure 5: velocity, channel profile and water surface level measurement at three flows

Points to note when reporting data collection

The report should contain a full description of the data collection procedure. This includes:

- A description of any procedures for converting units of measurement. The main elements of the PHABSIM software only work in imperial units. The common practice outside the USA is to take all measurements in metric and convert to imperial at the last possible stage. Care must naturally be taken.
- Sketch maps of the reaches showing important features of the study sites, together with all transect locations. It can be particularly difficult to re-locate headpins without adequate documentation. Similarly, photographs of the transect sites are always useful.
- Field notes of features that may influence model calibration.
- Techniques used for quality assurance of the data entry (for example checking of all data input by another party).
- Techniques used for quality assurance of the data itself. Did water always flow downhill? Did water surface levels increase in a logical manner as flows increased?
- Checks on any variation in flow during each of the data collection periods, along with methods for correction of results if flows were not constant.
- The survey techniques and instruments used, including calibration checks.

The following should be presented in graphical and numerical (table) form:

- Cross section plots with water surface elevations at measured discharges.
- Cross section plots of velocities and channel index (cover and / or substrate). This enables a reviewer to check for unusual velocities and if they are justified.
- Longitudinal plots of thalweg and water surface levels.

Finally, the report should document and explain any adjustments made to the survey data to ensure consistency. For example on a wide river there may have been survey errors at points near the far bank, but these can be corrected for if an accurate survey is obtained to a known point on the far bank.

Hydraulic modelling

The techniques used to simulate hydraulic conditions in a stream can have a significant impact on the habitat versus streamflow relationship determined in the habitat modelling portion of PHABSIM. The correct choice of hydraulic models as well as proper calibration represents the most technically difficult step in the process of analysing instream flows.

Further details of the procedures for hydraulic modelling are contained in Elliott *et al.* (1995) and Milhous (1990).

NB it is important to note that the hydraulic simulation programs in PHABSIM assume that the shape of the channel does not change with streamflow over the range of flows being simulated.

The hydraulic models take as input the survey data collected above, this is processed so that all elevations for each set of hydraulically-linked transects are relative to a common datum. Each set of linked transects is modelled separately. The procedure is firstly model water surface levels, then to model cell velocities.

The water surface elevations (WSLs) are one dimensional in that the same value for water surface elevation is used for any point on a cross section, and there is no flow between cells across a transect. Velocities vary from cell to cell across a cross section.

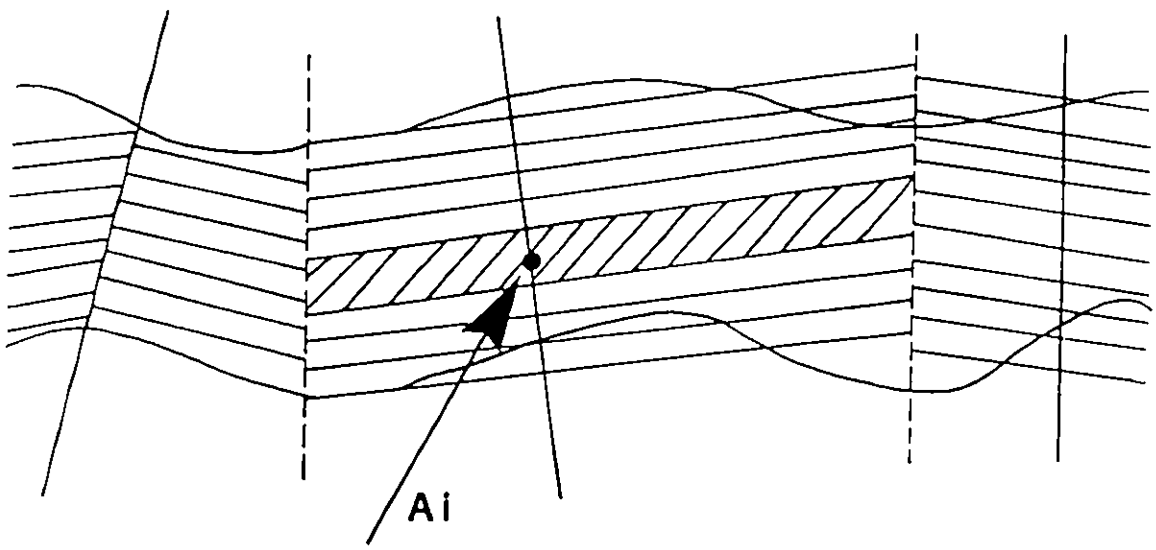

Figure 6: Cells used in PHABSIM calculations

Water surface level modelling

The approaches available for calculation of **water surface levels** are

Method	Model name	Sets of WSL data required	Notes
1. Stage-discharge using a log-log relationship	IFG4	2 (but 3 recommended)	Best for simple applications
2. Use of Manning's equation	MANSQ	1 (but 3 recommended)	Good for channel control
2. The step-backwater method	WSP	1 (but 3 recommended)	Good for backwater effects. Requires a starting set of WSLs from the downstream cross section.

Many rivers have compound control and it is possible for a PHABSIM application to use different models and different transects at different flows, in order to produce a robust model calibration. Available resources may limit the degree to which hydraulic modelling may be taken.

In a typical PHABSIM study, a first attempt is usually made at calibrating the IFG4 model, as this is the simplest procedure. IFG4 fits a straight line regression to a log-log graph of stage versus discharge. Examination of this relationship for the calibration flows at each cross section can clearly indicate if this assumption is valid. Two common reasons for it being invalid are more complex channel morphology (e.g. a stepped channel or uneven bottom) and backwater effects.

Once calibrated, IFG4 may then be used to simulate water surface levels within and outside the calibration flow range. Plots of these simulated flows provide a clear indication of model performance, again IFG4 works well in simple channels and has problems with backwater effects.

If IFG4 does not prove suitable (for example if it is clear that the stage-discharge relationship does not follow log-log form), one of the other models should be used. These use a greater combination of applied hydraulic theory in their calculations. Although these models may be used with less data with IFG4, best results use the same amount of data, i.e. water surface levels for at least three flows.

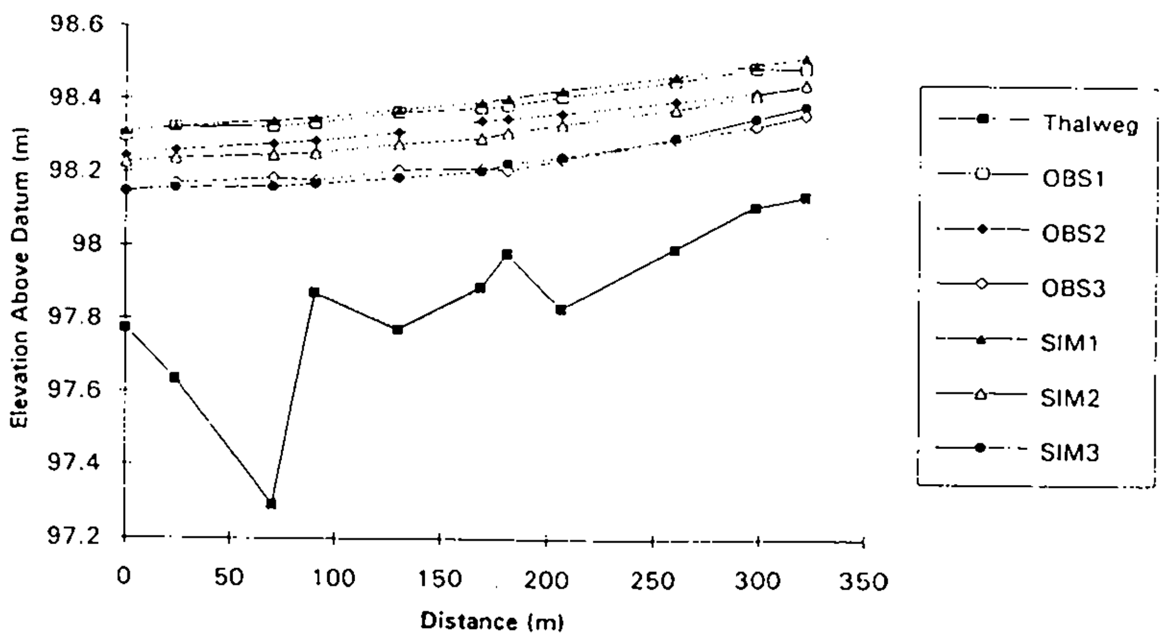

Figure 7: Observed and simulated water surface levels

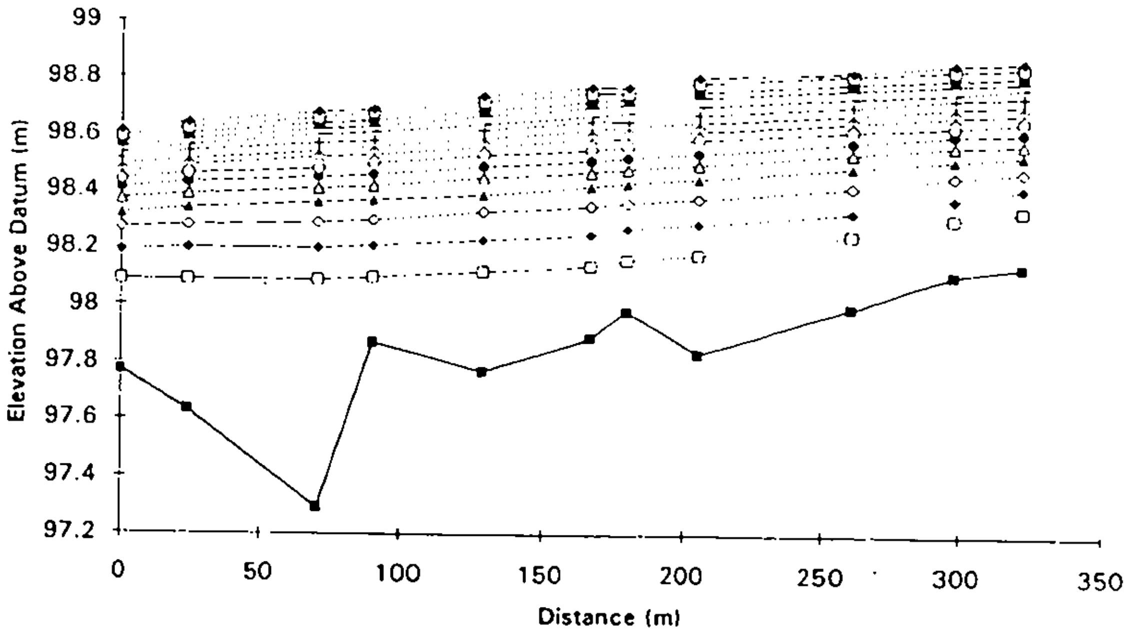

Figure 8: Complete range of simulated water surface levels

For complex situations, a MANSQ model of water surface levels, or ideally the stage-discharge relationship taken from a data logger at the most downstream cross section, combined with levels calculated by WSP at cross sections upstream is the usual way to proceed. Complex situations may also require a 'mixed model' approach, possibly using more than three sets of calibration data.

Points to note when reporting on water surface level simulation

- Model calibration can produce a great deal of output. Some of this can be vital in assessing the adequacy of the model calibration. Effort should be made to present this in a way that is easily referred to, but does not interrupt the flow and arguments of the main report.
- The report should document the performance of the model in simulating water surface levels within and beyond the calibration flows. There are many options within the model that can be used to improve calibration for more complex situations. All options used should be explained and justified.
- The modeller should consider possible hydraulic effects of summer macrophyte growth. Unexpected effects may be minimised by careful timing of data collection.
- It is possible to simulate WSLs outside the range of the calibration flows. How far the model can be extrapolated depends very much on the particular situation and the skill of the modeller. Typical figures from the US Instream Flow Group are either 0.2x low flow to 1.5x high flow, or 0.4x low flow to 2.5x high flow, but it must be stressed that individual circumstances always dictate. The main influence is the physical structure of the river. In the longitudinal direction, this includes flows where control features are overridden. In the transverse direction, channel complexity is again important.
- Sometimes the model can be reliably pushed beyond the calibration flows with confidence, with others it breaks down just above the high calibration flow. Simulating below the low calibration flow is generally far more reliable than simulating above the high flow. WSP is also more reliable at simulating beyond the high calibration flow than the other models.
- The report should present longitudinal graphs of water surface levels simulated by the model at each extreme, plus representative levels in-between. A graph should compare simulated discharges at the calibration flows with the actual measured values. Agreement should be

good, but one can never expect an exact match. The reviewer should always view differences between predicted and actual values relative to the actual water depths.

- The report should present graphs of stage versus discharge at each cross section and account for the shape of the graph from a knowledge of open channel hydraulics and the morphology of the channel at and around the cross section.

Velocity simulation

The IFG4 model is normally used to simulate velocities across each cross section. The channel is divided up into the measurement cells as described above, and velocity measurements from current metering are used to calibrate a model based on Manning's equation. It assigns an 'n' value to each cell (strictly speaking a roughness modifier), based on water surface level and calibration velocity.

To compensate for the fact that effective roughness of the river changes with discharge, IFG4 also assigns velocity adjustment factors (VAFs) to each cross section at each calibration flow. It does this by calculating a theoretical discharge flow from summing velocity multiplied by area for each cell across a cross section and comparing this to the known discharge. A VAF for each simulated flow and cross section is calculated, and used to ensure a mass balance of water between cross sections at all simulated flows.

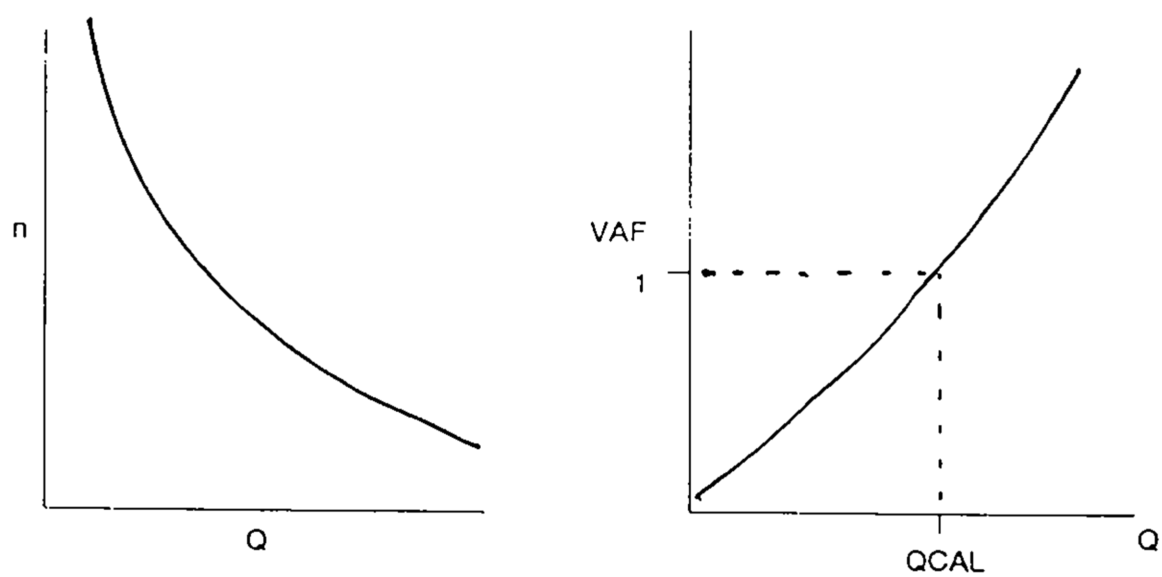

Figure 9: variation in n (roughness) and VAF with discharge

The recommended 'best practice' approach is to calibrate the model on just one set of velocity data. The choice of which calibration discharge to use the velocity set from (and thus to collect field data for) should be documented. Generally the highest velocity set is used, because this allows roughness modifiers to be calculated over the maximum area of river. Sometimes, field conditions will prevent current metering at high velocity, so the medium discharge can be used. This requires some educated guesswork in assigning roughness modifiers to areas of channel which are infrequently inundated, but this is still acceptable. It is not generally considered sensible to extrapolate up from the lowest velocity set, but it is stressed that each situation will be different and should be considered on its own merit.

Other calibration velocity sets should be compared with simulation outputs, if inaccurate. the modeller should consider simulating ranges of flow using other velocity sets, and combining results.

Points to report on velocity simulation:

- Tables and plots of individual cell velocities across each cross section for low to high simulated flows provide a useful check of model performance.

- Roughness modifiers across each cross section should also be examined for consistency. It is important to remember that the relative distribution of velocities across a cross section at the calibration flow will be repeated for all other modelled flows.

- Velocity adjustment factors should be documented and plotted against discharge. For each cross section the VAF will be 1 at the velocity calibration flow, and decrease below 1 at lower flows (to compensate for the fact that roughness commonly increases at lower flows), and increases at higher flows. Any deviation from this should be explained in the report. A common reason for deviation is a stepped channel with a wide berm and the calibration velocity above the step. At lower flows, because the channel is much narrower, effective roughness might in fact decrease.

Physical Habitat Modelling

In contrast to hydraulics, habitat modelling is generally a more straightforward process. Basic habitat modelling (using the HABTAT model) takes information on channel structure and modelled water surface levels and velocities and combines this with habitat suitability information to produce a Weighted Usable Area (WUA), for each cell across each transect at each modelled flow. The cell values are then summed to produce a composite WUA (measured in m^2 per 1000m of river), for each separate species or life stage. This enables a relationship to be built up between discharge (Q) and aggregate suitability for the whole study site. However the options used in habitat modelling will affect the predicted habitat area to some extent. Thus the modeller should select the options in a reasoned manner, and should be consistent when modelling habitat at different sites if the results are to be comparable.

Points to watch and report on in habitat modelling

- The report should document WUA vs discharge for all species / life stages. Both graphs and tables should be shown. WUA vs discharge for individual habitat types, and individual reaches (if appropriate) is a very useful addition. Techniques for differential weighting of habitat mapping transects at different flows should be considered.

- Mapping WUA on a plan view of the river is a useful technique. Results should be validated on the river itself. For example by observing areas that are predicted as good spawning habitat to see if they are actually used in this way by spawning fish.
- The habitat model is only as accurate as its input data, so it is vital to ensure accurate hydraulic calibration.
- There are many habitat model options - selection should be documented and justified.
- The habitat model has a limit of 25 flows for simulation.

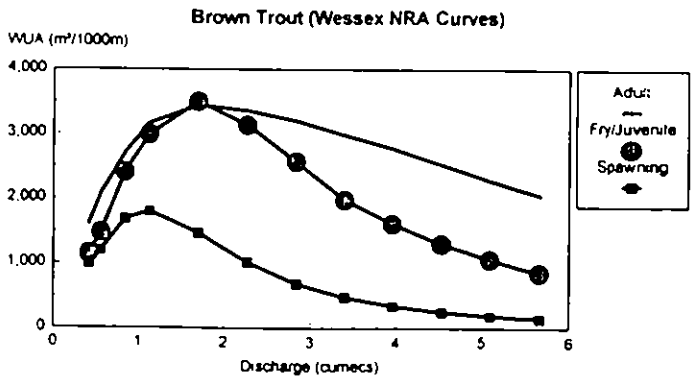

Figure 10: relationship between habitat and discharge (Lambourn study site)

More advanced habitat modelling

There are many additional analyses that can be performed once initial habitat modelling is completed. The rationale and aims of the project will very much influence the extent of analysis at this stage.

- For example a project looking at impacts of an abstraction will detail how habitat is affected by different levels of abstraction.

- A study aimed at setting management objectives for a river might look more closely at WUA for each separate habitat type.
- A study may look at how habitat quality is influenced by streamflow, and whether a WUA curve for high quality habitat only, follows a different shape.
- A common analysis would be an analysis of the requirements of differing species or life stages, attempting to produce advice on the optimum trade-off in terms of flow regime.

Other habitat models have been developed to address more specific problems, although so far these have not been widely applied in the UK.

- HABTAV uses information on velocities in adjacent cells to model suitability of feeding stations of drift feeding fish.
- HABTAM uses information on suitability of habitat in cells a user-defined distance from each modelled cell to try to predict suitability for organisms with limited mobility under conditions of rapidly varying flow (e.g. hydropeaking).
- HABEF takes data from one of the above models at two flows or for two species or life stages to model stranding, competition / overlap or spawning.

Time series analysis

In all but the simplest studies, a graph of weighted usable area against discharge will be insufficient grounds on which to base the conclusions of a study. However combination of this information with figures on past flow regimes can provide a wealth of additional data on which to make decisions on future flows. Analysis of alternative time series may be particularly valuable (Capra *et al.* 1995, Dunbar, 1995).

It is logical to assume that future population levels in an instream aquatic community will be influenced not only by physical habitat at that future time, but also by the patterns of physical habitat leading up to it. Thus extending the 'traditional' PHABSIM model results (the Weighted Usable Area versus Discharge curve) to temporal predictions of habitat is a crucial step in relating changes in flow regime to changes in fish and invertebrate populations. The non-linear relationship between habitat and discharge has profound influence on the form of a habitat time series.

A fundamental method for analysis of time series of river flows is to derive a cumulative frequency diagram, this is often known as the flow duration curve. Following this concept, habitat duration curve analysis may also be undertaken. These methods are of particular use in the analysis of how alternative flow regimes affect habitat available to individual life stages of a species.

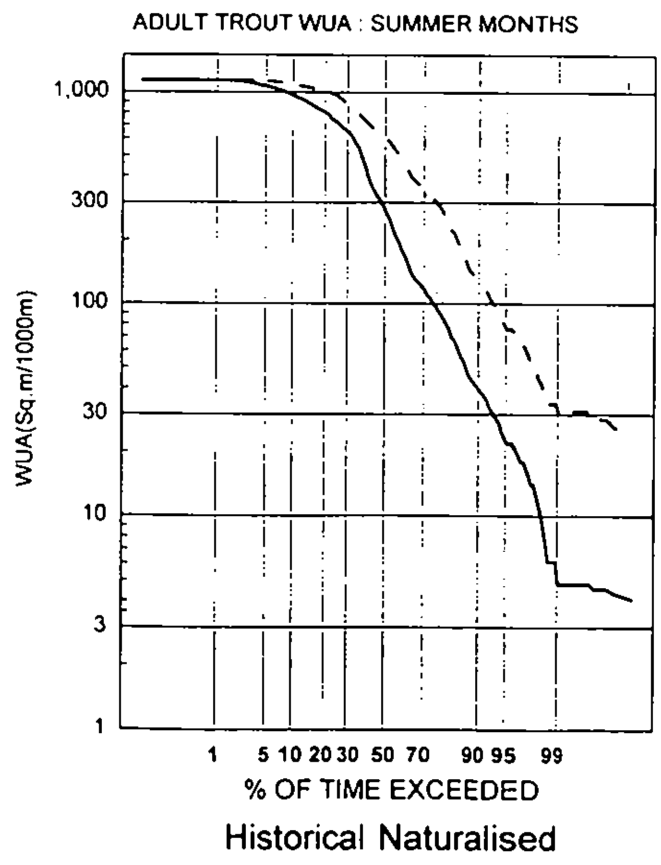

Figure 11. Habitat duration curve for historical and naturalised flow time series

Issues to bear in mind include:

- The significance and choice of time series
- The basic measurement unit - daily, monthly or yearly
- Their accuracy, for gauged and synthetic series
- The period of record

Analysis of habitat time series is a rapidly-developing area of study, and in the UK, the Institute of Hydrology should be contacted for the most up-to-date guidelines.

Reporting and interpretation of results

Finally, the following points should be considered when drawing conclusions from an applied PHABSIM study.

- Throughout the study, was the degree of detail appropriate to the requirements from the conclusions? The level of detail will also be influenced by the level of resources available.
- Do the conclusions and management advice agree with the science that is presented in the report? Have all species and life stages been adequately considered? Do the conclusions take into account any temporal requirements of life stages?
- Has the report included and compared related information from outside the study, for example previous fish surveys, rod catches, other historical data?
- Are the arguments clear and logical, easily understood, and justified by the data presented?
- It is up to the authors to produce a report that is acceptable to both laymen and a highly technical audience. The study will produce a vast amount of information which must be distilled into a report, while at the same time including all supporting data.
- Is there enough technical information for a technical reader to understand exactly what was done?
- Does the report propose a clear list of management options and their consequences? Alternatively, is it clearly inconclusive?
- Does the report contain recommendations for future monitoring?

References

Aquatic Systems Research. 1992. Instream flow requirements for brown trout in Lee Vining Creek, Mono County, California. Draft Final Report.

Bovee, K.D. 1986. Development and Application of Habitat Suitability Criteria for Use in The Instream Flow Incremental Methodology, US Fish & Wildlife Service Instream Flow Information Paper No. 21.

Bovee, K.D. (editor), 1995. A comprehensive overview of the Instream Flow Incremental Methodology. National Biological Service, Fort Collins, Colorado.

Bullock, A., Gustard, A. and Grainger, E.S. (1991) Instream Flow Requirements of Aquatic Ecology in Two British Rivers. IH Report No. 115.

Capra H., Breil, P. and Souchon, Y., 1995. A new tool to interpret magnitude and duration of fish habitat variations. Regulated Rivers: Research and Management, Vol. **10**, 281-289.

Dunbar, M.J., Elliott, C.R.N., Acreman, A., Gustard A. 1995. Ecologically Acceptable Flows Phase II: Time Series Analysis. Institute of Hydrology Draft Report to the National Rivers Authority.

Elliott, C.R.N., Johnson, I.W., Sekulin, A.E., Dunbar, M.J., Acreman, M.C. 1996. Guide to the use of the Physical Habitat Simulation System, NRA Release Version. Institute of Hydrology Draft Report to the National Rivers Authority.

Heggenes, J. 1990. Habitat utilisation and preferences in juvenile Atlantic salmon (*Salmo salar*) in streams. Regulated Rivers, Research and Management 5, 341-354.

Jowett G. 1992. Models of the abundance of large brown trout in New Zealand rivers. North Am. J. Fish. Manage. **12**, 417-432

Johnson, I.W., Elliott, C.R.N., Gustard, A., Clausen, B. (1993) River Allen instream flow requirements, Final Report, Institute of Hydrology report to the National Rivers Authority.

Milhous, R.T. 1990. User's Guide to the Physical Habitat Simulation System - Version 2. Instream Flow Information Paper No. 32. U.S.D.I. Fish and Wildlife Service Biol. Rep. 90

Nestler, J.M., Milhous, R.T. and Layzer J.B. 1989. Instream Habitat Modeling Techniques. In: Alternatives in Regulated River Management. Gore, J.A. and Petts, G.E. (eds) Florida, CRC Press.

Thomas, J and Bovee K.D. 1993. Application and testing of a procedure to evaluate transferability of habitat suitability criteria. Regulated Rivers, Research and Management **8**, 285-294.