The role of hydro-ecological models in the development of sustainable water resources

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Abstract The development of groundwater and surface water resources for water supply, irrigation or hydropower will result in a modification of the natural flow regime of a river. Major advances in hydrological models and decision support systems have led to improvements in the design and operation of resource schemes. However, our ability to model these impacts on freshwater ecosystems has been developed relatively recently. The Instream Flow Incremental Methodology (IFIM) using the Physical Habitat Simulation (PHABSIM) system is now being used in the UK for the assessment of the sensitivity of the change in habitat (for a given species) to a change in flow regime. The paper describes this approach for modelling riverine habitats and presents examples of how the model has been used to assist in sustainable water resource development in the UK.

INTRODUCTION

A key element in the development of sustainable water resources is the assessment of resource development on freshwater ecology. This area of hydro-ecological modelling is a relatively new science requiring further development and validation of existing techniques. One approach is the Instream Flow Incremental Methodology (IFIM) (Bovee, 1982) which is a strategy for evaluating the suitability of different river flows for a range of uses, e.g. freshwater ecology, amenity value, recreation. The Physical Habitat Simulation (PHABSIM) (Milhous et al., 1984) software is used specifically for ecological modelling to predict the change in the physical habitat for an incremental change in discharge (for a particular freshwater species and life stage).

The IFIM and PHABSIM were originally developed to assist the ecologically sound management of rivers in western USA. However, the technique is generic and following its initial application in the UK (Bullock et al., 1991), the method has been developed for the very different hydrological and ecological regimes of British rivers (e.g. Johnson et al., 1993a). To date in excess of 65 study sites have been examined on more than 35 rivers (Fig. 1) for both research and operational applications of the method.

The research and operational application of the IFIM/PHABSIM in the UK have focused upon the assessment of water resource issues, although the model has also been used to examine the impacts of changes in channel morphology upon aquatic habitats due to both flood defence schemes (Johnson et al., 1993b) and habitat restoration works (Elliott et al., 1996).

MODELLING INSTREAM HABITAT USING THE IFIM/PHABSIM

The technique is a flexible tool allowing the assessment of changes in physical habitat with changes in flow regime, or channel morphology, for a wide range of rivers. Indivi-
dual application of the model will vary greatly depending on the issues involved, the river(s) in question and the target species being assessed. The most common application of the model in the UK has been to assist in the sustainable development of water resources by evaluating the impact of reduced flows (due to groundwater or surface water abstraction) on instream ecology.
Data collection and hydraulic modelling

(a) Identify the river sectors and aquatic species most affected by abstraction. Assess the availability of Habitat Suitability Indices for the appropriate target species/life stages (see below) and if necessary develop new relationships by carrying out a full data collection programme.

(b) Using a habitat mapping approach, identify the habitats (e.g. pools, glides, riffles) available within the appropriate river sectors and their relative occurrence. Define a "representative" reach, or reaches, which contain examples of these habitats which may then be used for PHABSIM modelling.

(c) Select study transects (cross sections) within each representative reach to characterize each habitat type and to satisfy the data requirements of the PHABSIM hydraulic and habitat models as necessary.

(d) Mark the position of each transect within the study reach, survey the relative elevation of each transect to a fixed datum level and measure the inter-transect distances.

(e) Survey the topographic shape of each transect using sufficient data collection points to represent rigorously the habitat available within the transect (all further observations refer to these same data collection points).

(f) Observe the dominant substrate (or other channel characteristics as necessary) at each data collection point and the cover (usually macrophytes or vegetation over-hanging the river).

(g) Under steady flow conditions, measure the mean column velocity at each wetted survey point and survey the water surface elevations relative to the fixed datum level.

(h) Repeat step (g) on further occasions (e.g. under high, medium and low flows) to provide sufficient data to allow simulation of the hydraulic properties of each transect over the full range of simulation flows required.

(i) Calibrate hydraulic models within PHABSIM (which may use a step-backwater model, Manning's equation or a rating curve simulation procedures based on each individual cross section) using the above data to simulate the flow depth and velocity characteristics at all survey points at each simulation flow.

Habitat modelling

**Habitat suitability indices** A fundamental assumption of PHABSIM studies is that the target species/life stages exhibit a quantifiable preference/avoidance behaviour to certain levels of one, or more, of the microhabitat variables, i.e. depth, mean column velocity, substrate and cover. These habitat requirements are represented by functions known as Habitat Suitability Indices (HSI). These are curves describing the suitability, ranging from 0 (unsuitable) to 1 (most suitable), of each of the microhabitat variables. Since individual target species and life stages may exhibit different habitat requirements, it is necessary to develop HSI relationships for each target species/life stage accordingly. This may be carried out using published data, expert opinion, or preferably by field observations. Figure 2 presents examples of HSI data developed by relating field observations of the position of a species to the physical conditions at that point. The relationships illustrated are for the fry/juvenile life stage of brown trout living in...
Habitat computations The habitat models within PHABSIM are used to calculate the area of habitat available within the study reach, for each species and life stage at each simulation flow. This available habitat is termed "Weighted Usable Area" (WUA) and is expressed in m² per 1000 m of river. The computation of WUA for a selected study reach at a given simulation discharge is based on the summation of individual cell values (WUAj) over a computational grid. This grid is defined across the river by the data points spaced across each study transect and along the river by the distance between each transect weighted to reflect the relative distribution of the habitat type represented by each transect. The values of depth (Dj), velocity (Vj) and substrate, (Sj) for each individual cell, at each simulation discharge, are predicted by the hydraulic simulation model.

For a given target species and life stage, the assessment of suitability is based on the computation of a composite suitability index (CSI) which combines estimates of suitability for three microhabitat variables: depth, mean column velocity and substrate (Johnson et al., 1995). For a given data point in the computational grid defined above the CSI is defined as:

\[
CSI(V_j, D_j, S_j) = HSIV(V_j) \cdot HSID(D_j) \cdot HSIS(S_j)
\]

where \(HSIV\), \(HSID\) and \(HSIS\) are the individual habitat suitability indices for velocity,
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The cell weighted usable area, $WUA_i$, associated with cell $i$ is defined by:

$$WUA_i = CSI(V_i, D_i, S_i) A_i$$

where $A_i$ is the area of the cell. The total $WUA$ for the study reach is then given by the sum of the individual $WUA_i$ values. In order to compare habitat area predictions from different reaches and different rivers, it is convenient to standardize the estimated $WUA$ by the reach length ($L$) and to express the $WUA$ in terms of habitat area per 1000 m length of river.

Figure 3 presents examples of the relationships between habitat areas and discharge for life stages of brown trout ($Salmo trutta$) and salmon ($Salmo salar$) in the River Allen in southern UK. These illustrate how the available habitat area for each target species/life stage changes with discharge, for example $WUA$ reaches a peak of approximately $4100 \text{ m}^2$ per $1000 \text{ m}$ at $1 \text{ m}^3\text{s}^{-1}$ for the fry/juvenile life stage of brown trout. At flows above and below $1 \text{ m}^3\text{s}^{-1}$, $WUA$ declines rapidly with no suitable habitat for brown trout at discharges below $0.1 \text{ m}^3\text{s}^{-1}$.

**Habitat time series analysis** Although the PHABSIM habitat model outputs provide key information showing how habitat for the target species/life stages changes with flow, it is important to assess these outputs with respect to the long term river flow regime, and any proposed changes to this regime. For example, this may be achieved by combining the $WUA$/discharge relationships (e.g. Fig. 3) with a time series of daily mean discharge data to produce a time series of daily habitat availability. Discharge time series are obtained from suitable flow gauging stations or from simulation models which may be simulated to include the effects of groundwater or surface water abstraction scenarios. An example of these data is provided in Fig. 4 which shows two sets of mean discharge and habitat availability curves.
monthly flow time series data under historical (including the effects of an abstraction) and naturalized (without the reductions in discharge caused by the abstraction) conditions. These data are combined with WUA/discharge relationships by calculating the available habitat for each target species/life stage for each mean monthly discharge. For example the WUA/discharge relationship for the fry/juvenile life stage of brown trout given in Fig. 3 may be combined with the two sets of flow time series data presented in Fig. 4 to produce the historical and naturalized habitat time series data also shown in Fig. 4.

Figure 4 illustrates the temporal analysis of changes in habitat for fry/juvenile trout in a reach of the River Allen between 1970 and 1992 and allows the identification of time periods when habitat is particularly low, as may occur under natural drought conditions or due to the impacts of abstraction. For example, in Fig. 4 the time period around month 71 indicates a period of extreme habitat loss (due to the groundwater abstraction) on fry/juvenile trout habitat in a study reach on the River Allen.

Habitat time series data also lend themselves to the production of summary habitat statistics (Dunbar et al., 1996) and other analysis techniques more commonly associated with flow analysis. In particular the production of habitat duration curves are useful for assessing the impacts of alternative flow regimes. For example, Fig. 5 illustrates flow duration curves produced for the River Allen under historical and naturalized flow regimes for the period 1970-1992, and equivalent habitat duration curves for brown trout.

Comparison of habitat availability under different flow regime scenarios using this technique provides a way of defining both the level of impact an abstraction has and the
amount of time that impact occurs. For example, the habitat level exceeded for 70% of the time (during 1970-1992) under naturalized conditions (i.e. without abstraction) is a WUA of approximately 2000 m$^2$ per 1000 m for fry/juvenile trout. Under historical flow (i.e. with abstraction) conditions the equivalent habitat exceedance level for the same species/life stage is less than 1000 m$^2$ per 1000 m. Thus for 30% of the time in the years 1970-1992, the abstraction reduced the natural level of trout habitat, in the reach of the River Allen, by more than 50%. As described below, in the example operational applications of PHABSIM, habitat duration analysis may also be carried out to assess seasonal changes in habitat. This allows the more detailed assessment of seasons where impacts may be particularly severe, or the examination of time periods of particular relevance to the life cycle of individual target species/life stages.

**APPLIED STUDIES**

**The River Allen, Dorset**

The River Allen is regarded as a classic example of a chalk stream and historically had a reputation as a high quality salmonid fishery. The development of groundwater abstraction from chalk boreholes within the catchment of the River Allen was initiated in 1946 and is detailed by Newman & Symonds (1991). Outputs from a catchment groundwater model for the period 1970-1992 concluded that the $Q95$ (flow exceeded for 95% of the time) flows in the area of maximum impact were reduced by up to 45% even with active stream augmentation. National Rivers Authority (NRA) fisheries data also demonstrated significant loss in fish populations, particularly brown trout and salmon.

PHABSIM studies carried out on the River Allen suggested that fry/juvenile trout were most affected by the abstraction, and seasonal habitat duration analysis indicated
that this impact was almost entirely confined to the summer months (Johnson et al., 1995). Figure 6 shows the habitat duration curves produced for the summer (April-September) and winter (October-March) months under three different flow scenarios, with the full groundwater abstraction (historical), with 50% of the abstraction, and with no abstraction (naturalized). The results of the study were used in negotiations between the NRA and Bournemouth Water Company to formulate an action plan for the river which included an agreed proposal to reduce current abstraction rates by 50%.

The River Wissey, Norfolk

The River Wissey is a chalk stream of high conservation value, and is adversely affected by groundwater abstraction. In particular it has a rich invertebrate diversity and a natural brown trout population (Petts & Bickerton, 1994). PHABSIM studies focused on seven study sites within the Wissey catchment and examined the adult, juvenile, fry and spawning life stages of seven species of fish, including brown trout, dace, chub and roach as well as four species of aquatic invertebrates.

WUA/discharge relationships for the target species/life stages examined were used to derive specific monthly flow levels to achieve specific environmental objectives. These included:

(a) Desirable Ecological Flow (DEF), i.e. the flow providing at least a minimum area of suitable habitat for a given target species/life stage in every reach type within each sector of concern along the river;

(b) Ecological Minimum Flow (EMF), i.e. the flow providing at least a minimum area of suitable habitat for a target species/life stage in at least one reach type within each sector of concern along the river;
 Threshold Ecological Flow (TEF), i.e. the absolute minimum flow necessary to sustain refuges for biota associated with relatively high-velocity, clean substrate riffle and run habitats, below which there is no suitable habitat for target species.

Three seasonal flow regimes were defined using the above monthly flows (Table 1). The recommended DEF regime was calculated using WUA/discharge relationships for adult trout, juvenile trout and spawning trout, dace and chub. The study also recommended that river support should be used to maintain the EMF during one year droughts, and that if a drought extended into two or more consecutive summers the TEF should be maintained to protect the river against severe degradation.

Table 1 Ecological Flow regimes derived using PHABSIM for the River Wissey based on flows at Northwold gauging station (Petts & Bickerton, 1994).

<table>
<thead>
<tr>
<th>1956-1988</th>
<th>DEF (m³ s⁻¹)</th>
<th>EMF (m³ s⁻¹)</th>
<th>TEF (m³ s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>2.79</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>February</td>
<td>2.83</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>March</td>
<td>2.55</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>April</td>
<td>2.32</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>May</td>
<td>1.74</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>June</td>
<td>1.30</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>July</td>
<td>1.01</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>August</td>
<td>0.90</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>September</td>
<td>0.90</td>
<td>0.45</td>
<td>0.3</td>
</tr>
<tr>
<td>October</td>
<td>0.90</td>
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<tr>
<td>November</td>
<td>1.25</td>
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</tr>
<tr>
<td>December</td>
<td>2.07</td>
<td>0.4</td>
<td>0.3</td>
</tr>
</tbody>
</table>

 **The River Kennet, Wiltshire**

This study examined three reaches of the River Kennet to assess potential losses in habitat resulting from an abstraction by Thames Water Utilities at Axford near Marlborough, Wiltshire, UK (Maddock & Petts, 1995). These results indicated that there were spells of limited habitat availability associated with low discharge periods and that these were exacerbated by abstraction, both under the base licence, and with the historical conditions of the base licence which allowed greater abstraction at high flows. As part of this assessment, habitat loss duration curves were produced which show the amount of time a given percentage of reduction of habitat occurs. Figure 7 shows % habitat reduction curves for juvenile brown trout for both the base abstraction licence and the historical low flow conditions. This indicates that with the historical abstraction regimes a 10% (or more) loss in habitat occurred for 55% of the time. Based on this analysis (and assessments of fish populations, water quality flow modelling and cost/benefit analyses etc.), the Environment Agency proposed, subject to a public enquiry, a phased reduction in the current abstraction to a minimum prescribed flow of 1.2 m³ s⁻¹. This was based upon the flow rates below which the abstraction caused a habitat loss of 10% (Fig. 7) or more (Willis, 1996).
Loss of Brown Trout habitat due to abstraction scenarios at Axford Upstream

JUVENILE Trout when flows are less than 2.24 cumecs (193.5 Mld)

CONCLUSIONS

The three operational applications described in this paper demonstrate that the model provides an extremely useful tool to assist in assessing the ecological impacts of water resource development. The model is generic and subject to the development of appropriate Habitat Suitability Indices, can be applied to river systems where ecological response is determined by a change in flow regime and not by water quality. In developing sustainable water resources it is important to consider the ecological impact of both groundwater and surface water abstraction. PHABSIM facilitates this by providing a management model which enables the loss of instream habitat to be assessed.

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