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Provisional assessment of the potential use of the Physical Habitat Simulation (PHABSIM) System to assess the impact of flow modification on juvenile fish habitat in the River Thames

Institute of Hydrology Report to Environment Agency Thames Region

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Executive Summary

This study forms part of an ongoing assessment into the environmental impact of future water resources development within the catchment of the River Thames. The study provides an initial examination of the potential ability of the Physical Habitat Simulation (PHABSIM) System to model the temporal and spatial physical habitat characteristics of the river, and to allow the prediction of changes in physical habitat for juvenile fish in relation to flow regime.

In liaison with staff of NRA Thames Region, a PHABSIM study reach was selected and a reduced-scale application of the model was carried out. The site, near Clifton Hampden, was selected to be generally representative of the sector of the Thames between Sandford and Benson weirs. Model calibration data were collected from study transects selected to sample a range of the general habitat types available within the river sector. Analyses were carried out to investigate the distribution and availability of low velocity habitats as well as habitat for life stages of a single, example, target species (roach, *Rutilus rutilus*) to assess the potential use of the model to investigate habitat availability for fry and juvenile coarse fish.

The results of the work indicate that PHABSIM is a potentially useful tool for the assessment of flow management impacts on the physical habitat of juvenile fish in the River Thames. However, significant limitations to any future application have been identified. With respect to this particular study, the tool cannot currently provide robust information to aid decision making and considerable development of the approach is required before any potential application. Model outputs have facilitated some provisional conclusions and the work has highlighted the need to examine several key issues if the model is to be applied on an operational basis. These include:

* The potential outputs from a PHABSIM study should be used as part of a wider framework of studies assessing other key factors which influence fish population in lowland rivers (e.g. temperature, water quality, food supply). The wider Instream Flow Incremental Methodology (IFIM) framework, of which PHABSIM is a part, is flexible and provides a tool for the development of such an approach.

* There is a key need to carry out an assessment of the type and distribution of marginal habitats within the sector of the river in question. This should be carried out with respect to both the availability of habitats and their location relative to weirs within the river sector in question.

* Modelling the hydraulic characteristics of a river such as the Thames presents challenges above those commonly experienced when applying PHABSIM, particularly when examining habitats in the channel margins of rivers where water levels are subject to variable artificial influences. The variability of water surface elevations within the study transects that results from weir management must be examined. Additionally, the calibration data collected in the course of this study may be affected by changes in weir levels, an issue which should be assessed and if necessary the model calibration should be reviewed.

* The simulation of low discharge velocities in the channel margin requires further investigation. Further work is required to improve velocity simulation in these key habitat areas. Further data are required to improve the resolution of data in the channel

margins above that already achieved. However, it is uncertain that model accuracy can be improved sufficiently given the sensitivity of fry and juvenile fish to changes in velocity, especially since the available velocity measurement techniques may not allow field data to be collected sufficiently accurately.

* Current information on the habitat requirements of coarse fish remains limited and no robust data are available for use with PHABSIM on the River Thames. The development of robust information on fish habitat requirements is a fundamental requirement for any future assessment of proposals for changing river management.

Nevertheless, the study has allowed some general conclusions to be drawn as follows:

* The physical habitat in the River Thames is largely determined by its management as an impounded navigation with water surface levels being determined by weir operation, particularly in the low to medium flow range. At the site studied, the physical habitat as defined by flow velocity, is also significantly determined by flow regime.

* Marginal habitats are very important in the provision of suitable fry habitat in relation to water velocity, cover and depth. A full assessment of the range of the comparative value of marginal habitats and their availability within the area of river in question is required.

* At the study site, the availability of habitat with water velocities suitable for fry was negatively related to flow with suitable habitat being associated with marginal zones. Habitat availability is also sensitive to flow in the range typical of dry to average summer flows. The study indicates that dry flow years are important in terms of the availability of habitat with water velocities suitable for fry.

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1: INTRODUCTION

1.1 Background

Future water resources development within the catchment of the River Thames may involve additional regulation of the flow regime of the main river, including augmentation of flow in the spring and summer period. Under studies commissioned by the National Rivers Authority (NRA) and its successor the Environment Agency (EA), work has been undertaken to assess the current status of fish populations and to identify the potential impacts of flow augmentation (Hughes, 1996).

A review of information on the fish populations of the River Thames and major influencing factors (Mann & Berrie, 1994) concluded that flow regime was one of the key factors. There is much evidence that bottlenecks to recruitment in coarse fish populations relate to the spawning and fry stages (Mills & Mann 1985, Mann 1996, Cowx *et al* 1995). Studies also demonstrate that the physical habitat requirements of coarse fish fry can be very specific. An important habitat requirement is for areas of very low flow velocity without which fry may become displaced and suffer high mortality rates.

The proposed future flow augmentation is of particular importance in relation to the River Thames due to three factors. Firstly, studies have shown that coarse fish populations may be dominated by strong individual cohorts, (i.e. that good recruitment years are infrequent and therefore very important) (Mills & Mann 1985, Cowx *et al* 1995). Secondly, the impact of flow augmentation on physical habitat may be exacerbated in heavily engineered rivers with reduced habitat diversity, such as the Thames. Thirdly, the timing of possible flow augmentation corresponds to the critical spawning and juvenile phases. As a result, there is a requirement to assess the impact of potential flow augmentation on physical habitat to help determine ecologically acceptable operating rules. Mann & Berrie (1994) recommended that further studies be undertaken on the River Thames to assess the distribution of low velocity refugia for fry.

Any study aiming to assess the physical habitat of fish within a river, and how this may be changed by river regulation, must adequately describe the spatial and temporal dynamics of the habitat in relation to the requirements of the fish. Techniques in the UK have generally consisted of transect methods to determine habitat characteristics (channel depth, flow velocity, substrate and cover type). These have been undertaken at various sites, times or flows and compared to the available definition of fish physical habitat requirements to provide a series of 'snap shots' of habitat availability. Such a method is the basis for the current study and will provide the same information at this basic level.

In addition, the study aims to apply a tool currently under development in the UK to model the temporal and spatial physical habitat characteristics of rivers, and to allow the prediction of changes in physical habitat for a target species in relation to flow regime. The tool, the Physical Habitat Simulation (PHABSIM) System, is a major component of the Instream Flow Incremental Methodology (IFIM), an organisational framework for evaluating and formulating water management options. PHABSIM has not been assessed for application to large, regulated, lowland rivers in the UK. This study is designed to examine the issues related to the use of the method in such rivers and in particular to its potential application to the assessment of the impact of flow modification on juvenile fish habitat in the River Thames.

1.2 The Instream Flow Incremental Methodology.

The Instream Flow Incremental Methodology (IFIM) (Bovee, 1982), was originally developed in the 1970s by the US Fish & Wildlife Service. It is a water resources management tool which has been developed for application in the UK by the Institute of Hydrology since 1989 (Bullock *et al*, 1991). A central part of the IFIM is the Physical Habitat Simulation (PHABSIM) model. The IFIM methodology was assessed for UK application under the national NRA R&D Project 282 "Ecologically Acceptable Flows" (Johnson *et al*, 1993 (1)). The methodology has been operationally applied to assess instream flow requirements on the River Allen (Johnson *et al*, 1993 (2)), Bray and Barle (Johnson *et al*, 1994) in NRA South Western Region, the River Glen in NRA Anglian Region (Petts *et al*, 1992) and the Water of Ae in Scotland (Maddock, 1993). The methodology is currently being employed to assess the impact of groundwater abstraction on habitat availability in the River Kennnet, Environment Agency (EA) Thames Region, and the rivers Tavy and Piddle in EA South Western region.

The PHABSIM model is a major component of the IFIM and provides a method of assessing changes in the amount of physical habitat available to aquatic species with changes in flow. During the Ecologically Acceptable Flows project the technique was applied to 11 different study sites, selected to represent the range of river types available within England and Wales. It was concluded that the method can be applied to a wide range of river types and provides a suitable tool to assist setting ecologically acceptable flows in most river types. However, it was not possible to achieve satisfactory calibration of the hydraulic models within PHABSIM on the site chosen to represent lowland river habitats (the Gt. Ouse), due to the close proximity of several automatic sluices and the resultant hourly variation in river stage and discharge. Thus, there is a need to assess the applicability of PHABSIM to lowland river habitats such as the main River Thames.

1.3 PHABSIM Physical Habitat Modelling

The PHABSIM computer model combines reach based hydraulic and morphological data with biological data in the form of Habitat Suitability Indices (HSIs). The model simulates the habitat area available to a target species, termed "Weighted Usable Area" (WUA), for a range of user-specified discharges. HSIs are defined for individual life-stages of target species of interest and key outputs from PHABSIM are unique WUA/discharge relationships for each target species life-stage in question.

The hydraulic models within PHABSIM are calibrated using observed values of water depths and mean column velocities. These depths and velocities are measured at points across transects which are placed to sample a representative (in terms of the habitat types present) reach of river. Observations are made at three or more flows, over as wide a range as possible to minimise extrapolation errors. Once the PHABSIM hydraulic models are calibrated, water depths and velocities can be simulated for a complete range of user-specified discharges.

Following calibration of the hydraulic models and subsequent flow simulation the habitat models within PHABSIM are used to combine the depth, velocity and substrate data with HSI data for each of the target species/life-stages to give corresponding WUA/discharge relationships. These outputs may then be combined with flow time series data to provide habitat time series information. This allows the analysis of changes in habitat availability both over time (e.g. using habitat duration curves) and also with changes in the level of artificial influences on flow.

1.4 Risks & Constraints

As outlined above, the PHABSIM model requires the input of calibration data, including hydraulic data in the form of water velocities and depths. The flow data necessary should be obtained over a range of flows wide enough to allow robust calibration of the PHABSIM hydraulic models over the range of flows of interest. As a result it was accepted that there was an element of risk within this study in that it may not have been possible to obtain all of the data required within the project timescale.

It was also accepted that the habitat suitability data available, for the target species under examination here, were preliminary, Category I (Bovee, 1986) data. The indices used represent the best data currently available but have limitations which are discussed later in this report.

2 PHABSIM PHYSICAL HABITAT SIMULATION

2.1 Study site selection

Through liaison with staff of NRA Thames Region, a study site was selected for physical habitat analysis using the PHABSIM model. A reach near Clifton Hampden was selected to be generally representative of the sector of the Thames between Sandford and Benson weirs. The location of the Clifton Hampden study site is shown in Figure 2.2 below (grid ref. SU 565 955). An advantage of the site is that it is relatively close to flow gauging stations at Day's Weir, approximately 3km downstream (No. 039002), and Sutton Courtenay some 6km upstream (No. 039046), which facilitates the examination of habitat availability over time and with changes in flow regime.

Day's Weir is a variable sluice weir which controls the water level in the study reach. For example, Figure 2.3 gives stage readings immediately above the weir with flow at 6 hourly intervals throughout 1995. It is clear that at flows below 140 m^3s^{-1} the stage may vary greatly with flow, especially over the 90-140 m^3s^{-1} range, where the level at a given flow may change by as much as 80 cm. At flows lower than this range, the figure suggests that changes in stage due to weir settings are much less, varying over 40 cm approximately at a given flow and are maintained at flows below 100 m^3s^{-1} to support navigation. Figure 2.4 illustrates how the effect of changes in weir settings vary with distance upstream of a weir. Using the stage readings obtained immediately downstream of Day's Weir as an example (since the water surface levels here may be controlled by the weir at Benson Lock approximately 5 km downstream). The figure still suggests that at flows between 90-140 m^3s^{-1} there is a large amount of variation in the water surface level for a given flow but at flows below this the variation in water surface level is limited to approximately 20 cm. It is also noteworthy that stage declines with discharge in a more consistent way than upstream of the weir since the weir's backwater effect will be reduced with distance upstream.

The implications of the above controls on the stage discharge relationships within the sector of the Thames in question, with respect to the simulation of flow depths and velocities, are considerable. Not only will these physical habitat variables change with flow, but they will also change with weir settings and the effect of changes in weir settings will decline with distance upstream of a structure. It would be expected, for example, that if the stage is raised at a given flow velocities may be reduced and vice versa. Consequently, any full assessment of flow related impacts upon instream physical habitat must examine these influences, both within the Clifton Hampden reach and within other reaches of interest. Since the study reach selected lies approximately 3 km above Day's Weir it may be expected that the relationship between stage and flow may lie somewhere between those shown in Figures 2.3 and 2.4, that is that the weir will maintain water levels at low flows to some degree, and under high flows the water levels may be reduced for flood defence purposes. Although a complete analysis of these issues is not possible within the context of this study, the work presented here includes an investigation of the sensitivity of physical habitat to the changes in water surface levels that may occur.

2.2 Study Transect Selection

Within the Clifton Hampden study reach, study transects were selected to sample a range of the habitat types available within the site. In particular, transects were selected to contain a range of marginal habitats present within the wider study reach. The location of each transect is given in Figure 2.2. In particular, transect 1 was selected to represent clear, steep sided marginal zones. Cross sections 2 and 3 both represent areas where the channel margins contain emergent vegetation, especially cross section 2 where extensive emergent vegetation was growing in a shallow area on the right bank of the river (looking downstream). Cross section 4 included an extensive *Nuphar* (yellow water lily) bed on the left channel margin. The cross section shapes are shown individually in Figures 2.11 to 2.14. Photographs of each cross section are presented in Appendix B.

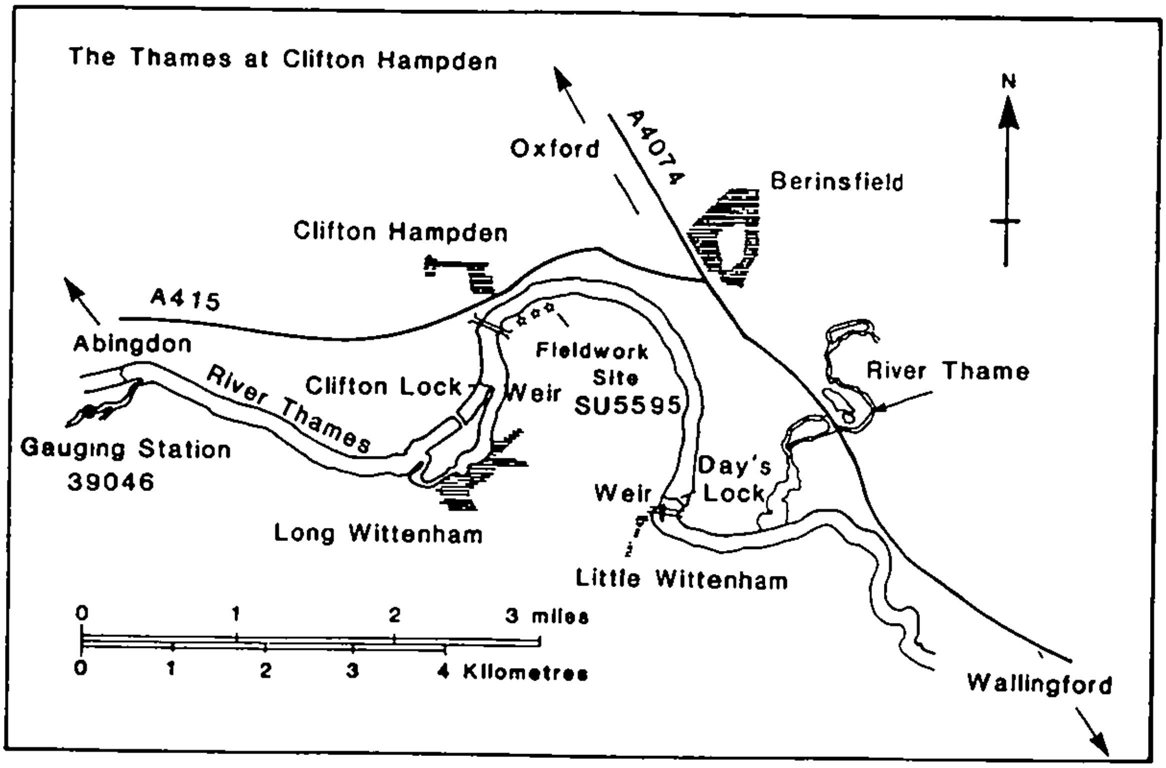


Figure 2.1: Location of Clifton Hampden Study Site

Since the work detailed here is a feasibility study, and it was necessary to constrain the resource input, only 4 study transects were selected. The study area of the river was approximately 340m in length with the river being approximately 45-50m wide. However, due to the heavily engineered nature of the Thames, and the reduced habitat diversity in this area, even this low number of habitat samples is sufficient to represent the general channel morphology in this sector of the river. The availability of the different marginal habitat types within the Clifton Hampden reach has not been fully quantified, and a full "habitat mapping" procedure (as outlined by Dunbar *et al* 1997) has not been undertaken for this preliminary study. In the absence of such information each of the transects was given an equal weighting in the habitat modelling procedure. The location of the study transects within the Clifton Hampden reach is given in Figure 2.2.

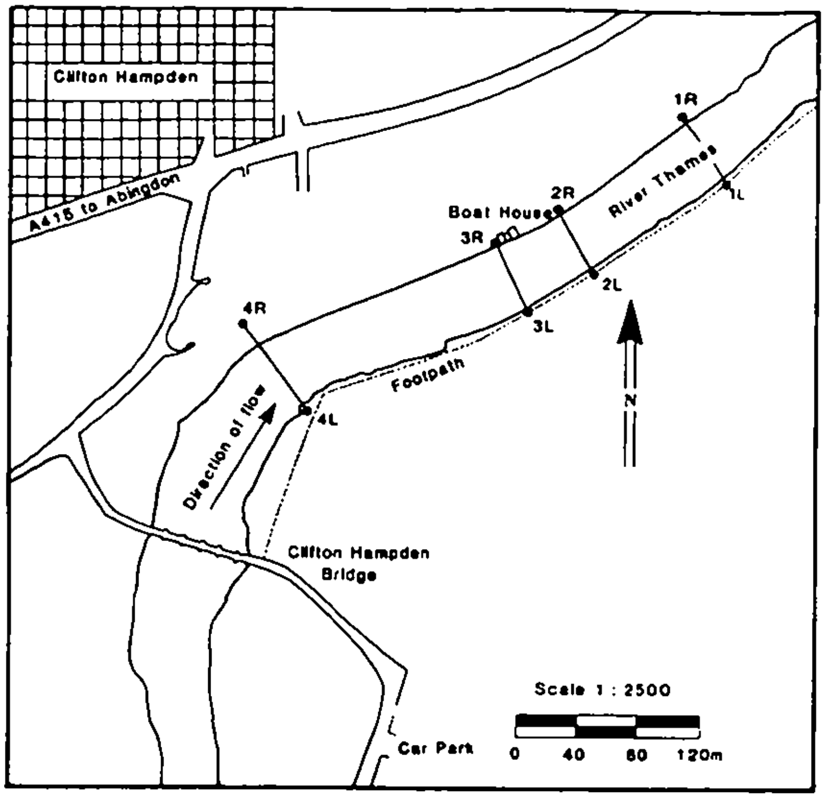


Figure 2.2: Location of PHABSIM Study Transects

2.3 PHABSIM calibration data collection

In collaboration with NRA Thames Region staff, the data required to calibrate the PHABSIM model were collected following the guidelines given in Johnson *et al* (1993(3)) with particular reference to issues relating to work on large rivers. Since a major concern of this study was the simulation of changes in marginal habitat with flow, additional survey points were selected in the marginal areas of the river to ensure that these zones were examined in detail. All survey data collected in the channel were measured from a small boat using a strong, tensioned, rope firmly anchored across each transect to allow the boat to be held in the correct location. At survey points across the transects, observations of depth, mean column velocity and dominant substrate type were recorded. Velocity measurements were obtained using a Valeport VEM003 electromagnetic current meter, suspended using either wading rods (under low flow conditions) or a cable and sinker weight (under high flow conditions). Due to the depth of the river in the central channel, observations of substrate in this zone were estimated by probing the bed of the river with a metal rod. The substrate classifications were recorded using the modified Wentworth particle size classification (after Trihey & Wegner, 1981) as given in Table 2.1 below.

In total three sets of hydraulic calibration data (flow depths and velocities) were collected and the dates of each survey, together with the measured discharges through the study reach, are given in Table 2.2 below. The hydraulic calibration data surveys were timed to give the widest possible range of measured data within the study period and thus minimise errors introduced by extrapolation in the hydraulic simulations. The relationship between the wide range of flows measured and the flow regime of the river (presented in Table 2.3) demonstrates that only minimal simulation of the flow conditions in the river outside the range of those measured would be required to carry out a full analysis of temporal changes in habitat.

Table 2.1 *Substrate Classification Coding System*

Code	Substrate Type
1	Organic Detritus
2	Clay
3	Silt
4	Sand
5	Gravel
6	Cobbles
7	Boulders
8	Bedrock
9	Terrestrial Vegetation
10	Man Made Bank Material

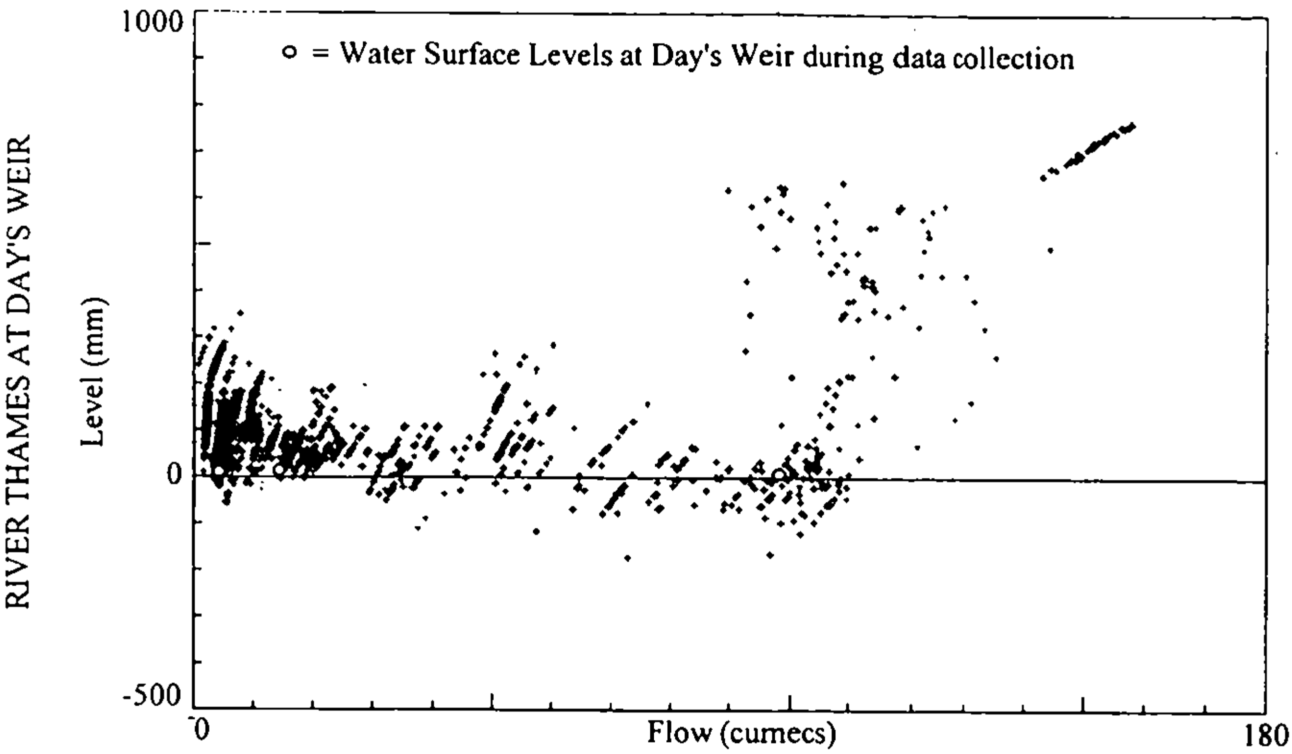
Table 2.2 *R. Thames at Clifton Hampden: Measured Calibration Flows*

Survey No.	Date	Flow (m^3s^{-1})
1	8.3.95	97.2
2	2.5.95	15.1
3	19.7.95	3.91

Table 2.3 *Monthly Flows Under Selected Conditions*

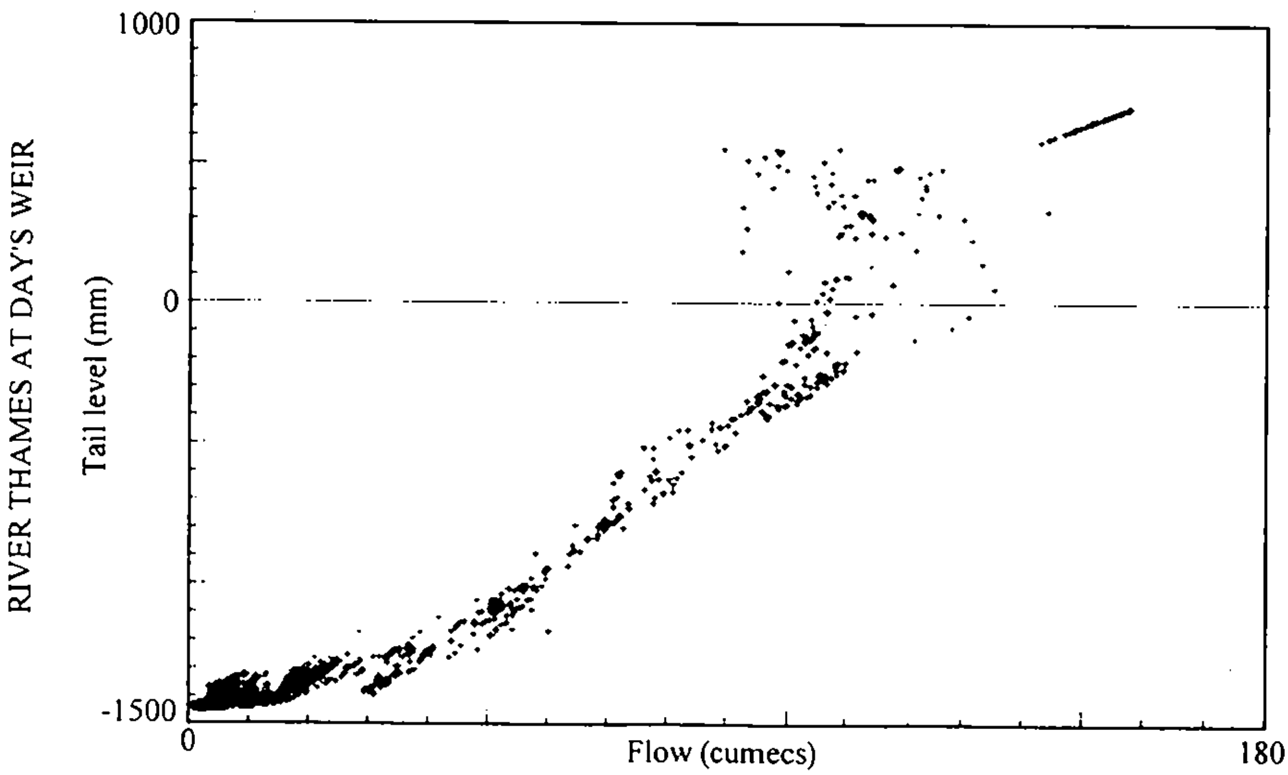
Month	Max Augmented	1990 (Dry Year)	1979 (Wet Year)
1	56.6	53.65	44.35
2	55.44	117.17	68.48
3	44.33	31.62	84.39
4	31.02	14.93	60.54
5	20.46	6.97	41.93
6	14.32	4.78	33.7
7	8.54	3.13	11.43
8	7.33	2.83	8.57
9	8.39	2.61	5.39
10	13.82	3.62	5.91
11	29.77	3.75	8.29
12	43.98	7.31	58.78

The water surface levels measured at Day's Weir when the three sets of calibration data were obtained are shown on figure 2.3. Comparison with the whole data set for 1995 suggests that the weir levels on the survey dates were relatively low in comparison with water surface elevations measured on other occasions at similar flows. The data also suggest that the weir level was reduced at the high flow, as may be expected for flood defence purposes, since the water surface level above Day's weir is lower than for the other two flows. However, this was not observed at the Clifton Hampden study site, where the water surface levels increase with discharge as detailed in Figure 2.7. Again, this indicates that the control that the weirs have on water surface levels within the river varies with distance upstream as outlined above. Although the data collected allows the calibration of the models, the effect of changes in stage at the study site (and elsewhere within the river sector) is not yet known and would require further data collection (i.e. measurements of stage at the study transects at particular discharge levels over a range of weir levels).



RIVER THAMES AT DAY'S WEIR
Data from 1/1995 to 12/1995 at 6 hourly intervals
NRA - Thames Region - Hydrological Services 15 March 1996

Figure 2.3 *Measured Water Surface Levels vs Discharge Above Day's Weir: 1995*



RIVER THAMES AT DAY'S WEIR
Data from 1/1995 to 12/1995 at 6 hourly intervals
NRA - Thames Region - Hydrological Services 15 March 1996

Figure 2.4 *Measured Water Surface Levels vs Discharge Below Day's Weir: 1995*

When working in large rivers health and safety issues must be given rigorous consideration since the dangers faced when undertaking such work should not be underestimated and may differ from those usually experienced when collecting PHABSIM calibration data in smaller rivers. This is especially important when obtaining data under high flow conditions and it is essential that the safety of the data collection personnel is not put at risk in order to obtain high flow calibration data. Lifejackets were worn by all survey staff at all times and dry suits were worn when collecting data from the survey boat. A safety boat was present at all times and at least 2 members of the survey team were qualified in first aid techniques.

2.4 Target Species and Habitat Suitability Data

In liaison with the NRA, the target species selected for investigation within this preliminary study was the roach (*Rutilus rutilus*). Roach was selected as an example of a typical lowland river coarse fish species known to be very common within the study reach. It is also a species for which a reasonable amount of information on habitat requirements is known and with Habitat Suitability Indices (HSIs) published for a range of life stages relating to the parameters of flow velocity, channel depth and substrate type.

Only one target species was selected as this was sufficient to provide an assessment of the potential of the method for the purposes of this project. Four life stages were examined: fry, juvenile, adult and spawning. Although the project was directed at fry and juvenile fish, the adult and spawning HSIs were also utilised to provide an overview of physical habitat assessment for roach in the study site.

The HSIs used were developed from the available literature by staff of the Institute of Freshwater Ecology. They were produced under NRA R&D project 282 (Johnson *et al*, 1993 (1) and are shown in Figure 2.5 below. They are classed as Category I (Bovee, 1986) as defined below:

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.

Category III: These are Category II curves in which the criteria are corrected for bias by factoring out the influence of limited habitat availability.

The indices represent the best HSIs detailing the physical habitat requirements of the target species available at the time of analysis. However, the authors of the HSIs advise that they are based on "very limited" information and it is considered that the indices are subject to a number of other limitations which are discussed later in this report. The HSIs were used as best available information to assess the use of the approach and identify requirements for further development.

In addition to the habitat suitability data discussed above, artificial HSIs were produced to assess the availability of areas of low flow velocities identified as being of particular importance to coarse fish fry. These were produced to allow the assessment of the extent of low velocity refugia throughout the range of flows. To achieve this a set of indices were produced where the only limiting factor on habitat area was flow velocity greater than a specified category (i.e. any flow depth and substrate were completely suitable). The flow categories assessed were <2cm/sec (i.e. 0-2cm/sec), <5cm/sec, <10cm/sec, <20cm/sec, and <30cm/sec.

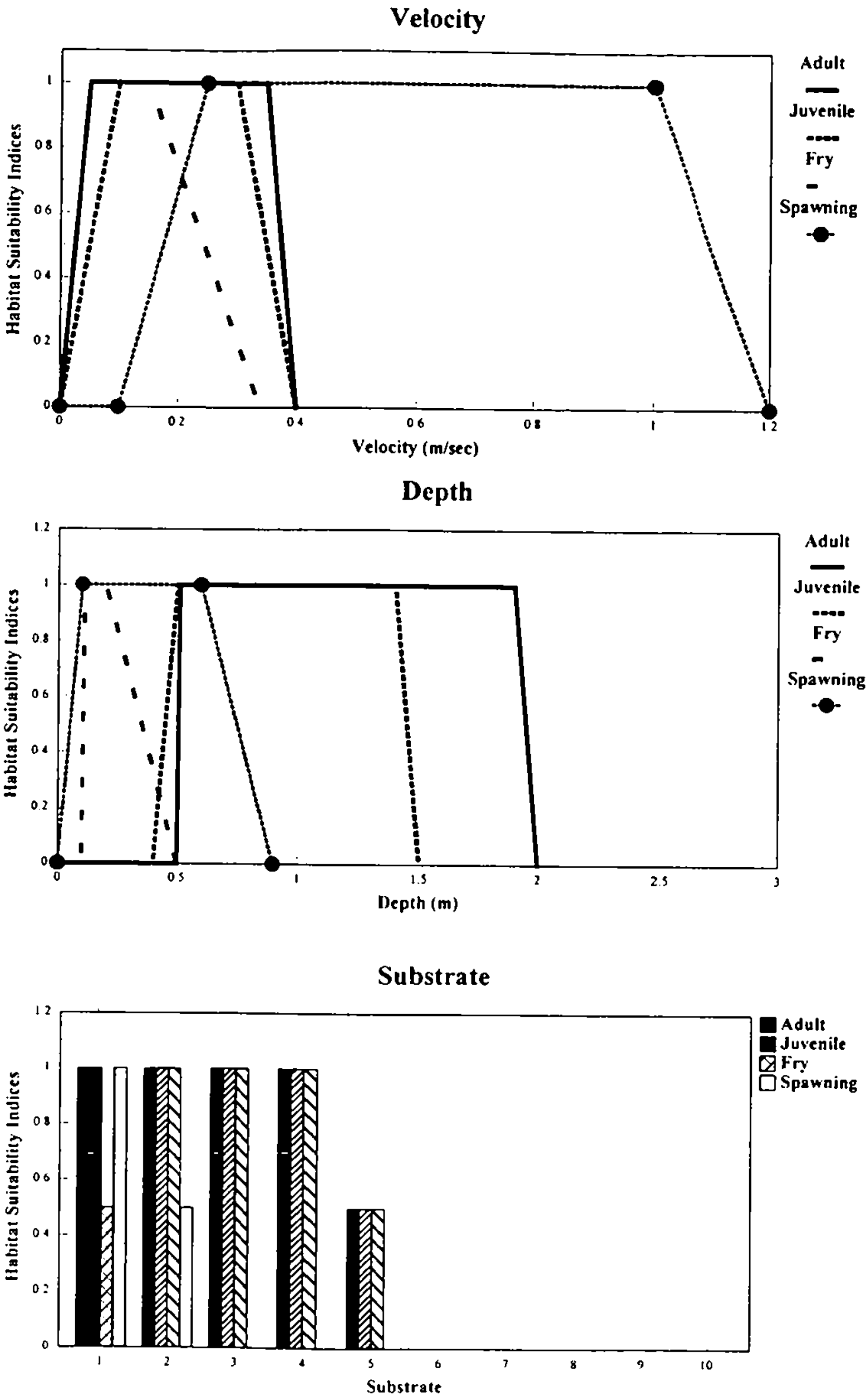


Figure 2.5 Roach Category I Habitat Suitability Indices

2.5 Hydraulic model simulations

Introduction

The application of the hydraulic models within PHABSIM to a river such as the Thames raises issues which are not usually encountered during applications of the model to less regulated rivers. In particular the issue of variable stage at a single discharge is of key importance and must be taken into account since this means that the stage/discharge relationship within the river is variable, and the amount of variability will change along the river. In previous applications of the model (Johnson *et al* 1993(1)) calibration of PHABSIM to a site of similar scale (the Gt. Ouse) proved impossible due to rapid changes in the stage/discharge relationship whilst collecting the model calibration data. In this study care was taken to ensure that this relationship remained stable when each set of measurements were collected. At this stage it was not possible to develop the empirical relationships necessary to properly link the stage/discharge relationships at the study site to those at Day's Weir since this would require the measurement of water surface elevations under consistent discharge conditions with variations in weir levels. However, the fact that the stage remained consistent when each calibration flow was measured, along with the wide range of calibration discharges surveyed, allowed an initial calibration of the PHASBIM hydraulic models and greatly facilitated the hydraulic model simulations.

The three sets of stage/discharge data collected (figure 2.6) show increases in stage with discharge, unlike those measured at Day's Weir where the stage at the time the high discharge was measured is lower than at the other two discharges (figure 2.3). This suggests that the influence of the weirs is reduced at the study reach. However, the reduced weir settings at the time of collecting the high discharge data is likely to mean that the stage is low in comparison to the other calibration data.

Flow depths and velocities were simulated within the four study transects over a range of discharges from 1.42 m^3s^{-1} to 95.18 m^3s^{-1}, a range selected to cover the flow time series data which could be used to examine the variation in habitat availability over time and with different flow regimes. At this stage in the application of PHABSIM to the river sector in question it is inappropriate to carry out the time series analysis as there are a range of issues that need further examination.

PHABSIM hydraulic model calibration and simulations are completed in two parts: water surface level (i.e. flow depth) and then velocity. As outlined above and in chapter 2.1, the possible changes in stage at a given flow are an important issue in this procedure and a sensitivity analysis was undertaken to examine the changes in model outputs that may result from the changes in weir settings. Following an initial calibration of stage and velocity distributions with flow using the calibration data, two further simulations were undertaken with the stage at a given discharge at each flow being raised by 40 cm and then lowered by the same amount. This procedure is described in more detail below.

Water Surface Simulations

The water surface simulations were carried out using the step-backwater model WSP. This model was calibrated using observed data and then used to simulate water surface levels over the full range of flows required. The calibration procedure is carried out in two phases. Firstly, Manning's "n" values are adjusted at each cross section in turn until satisfactory agreement is reached between predicted and observed WSLs at one of the calibration discharges. This procedure was carried out using the complete hydraulic calibration set (containing a full set of velocity and WSLs) obtained at a discharge of 15.1 m^3sec^{-1}. The "n" values produced were as may be expected in a channel of this type and were follows: C/S 1=0.025, C/S 2= 0.025, C/S 3=0.040, C/S 4=0.035.

The second phase of water surface level calibration is to adjust the "n" values using roughness modifiers to produce optimal agreement between the observed and simulated WSLs at the other calibration flows than used in phase 1. This procedure takes into account the relationship between "n" and discharge, where the roughness of a channel increases as flow decreases and again this part of the model calibration was straightforward with the roughness modifiers ranging from 1.5 at 1.416 m^3sec^{-1} to 0.75 at 97.2 m^3sec^{-1}.

Following calibration of the WSP model to the measured data it is then necessary to carry out simulations of WSLs over a range of other flows. This procedure requires an estimate of the WSL at each of the simulation flows at the downstream cross section, along with estimates of the relevant roughness modifiers (RMOD). These data were calculated using regression analysis of the stage/discharge and RMOD/discharge relationships. The stage/discharge relationship as measured was not linear when transformed to log stage/log discharge (i.e. stage increased uniformly with flow). However, as the relationship between the two variables was linear without transformation, these data were used to minimise errors between the observed data and the WSLs predicted at the calibration flows using a simple linear regression formula.

The observed water surface levels (WSLs) are displayed in Figure 2.6, below, along with the simulated WSLs produced using the WSP model. The maximum error between the observed and simulated WSLs is small 47 mm (2.06 % of the water depth) occurring at the highest set of flow data on C/S 4. Figure 2.7, gives the simulated water surface levels simulated at selected flows, including the max. and min. flows. The level of simulation accuracy within the range of discharges of most interest 0-30 m^3s^{-1} is good with minimal differences between the simulated and observed data in this range. The overall range of simulation discharges was 1.4 to 97.2 m^3s^{-1}, selected to cover a wide range of flows with the minimum of extrapolation outside the range of the calibration data.

Velocity Simulation

The observed and simulated water surface levels produced above were combined with observed velocity data and used to calibrate the IFG4 model, which was then used to simulate velocities. This "mixed model" approach is often utilised where the stage/discharge relationships at each of the cross sections examined are not log/log linear as required to simulate water surface levels using the IFG4 stage/discharge regression model. The procedure used in velocity simulation was to input the highest complete velocity set (obtained at 15.1 m^3sec^{-1}) to the IFG4 model which then uses the data to estimate the roughness ("n") at each wetted survey point at the calibration flow in question. These are then used to distribute velocities within the channel at other simulation flows. Although "n" is not varied with discharge, the effect of increased roughness as flow is reduced is accounted for using a balancing technique. This uses a Velocity Adjustment Factor (VAF) to modify globally the velocities predicted at a given flow, at each cross section, so that the discharge calculated from the cross section area and simulated velocities matches the specified simulation discharge.

The observed and simulated flow velocities are displayed for each cross section in Figures 2.7-2.10, along with their cross section shapes and the observed WSLs at each flow. Note that for cross section 2, no high flow velocity data were obtained due to time constraints when the data was collected. As outlined above the WSLs simulated using WSP were combined with the most appropriate velocity data set for the simulation of velocities under medium discharge conditions (in this case the complete set of velocities measured at 15.1 m^3s^{-1}). These data were then used to calibrate the IFG4 model and to simulate velocities. To assess the errors involved in model calibration the simulated velocities were compared with the observed data at the two other calibration flows.

In absolute terms, the largest errors were found when comparing the observed and simulated data under the high flow calibration conditions (97.2 m^3s^{-1}) where the mean error between the observed and simulated data was 0.073 ms^{-1}. The maximum errors occurred towards the right bank (looking downstream) where the simulations under estimated velocity by up to 0.58 ms^{-1} in cross sections 1 & 3. This is due to slight differences in the relative distribution of flow across the channel as measured at the discharge used to calibrate the model and the high calibration flow. The model also appears to over estimate velocities at the extreme margins of the channel under high flow conditions, particularly in cross section 4 where the flow should be close to zero due the presence of the *nuphar* bed. This occurs when predicting velocity in cells where calibration data are not available (i.e. where the cells are only wetted at discharges above that used for calibration) and estimates of roughness are based on those calculated for neighbouring cells or default values. The mean error at the lowest calibration flow demonstrates that the simulations were relatively accurate with an overall error of less then 0.001ms^{-1} in absolute terms. However, velocity prediction errors may be relatively large at individual points, especially where these values are low in absolute terms, even small errors in velocities will be large when expressed as percentages.

A further check on the quality of the hydraulic modelling procedure is to assess the velocity adjustment factors (VAFs) used in the IFG4 model simulations as outlined above. The detailed theory behind the VAFs produced within the model is described in the US F&WS manual "Using the Computer Based Physical Habitat Simulation System (PHABSIM)" (1994). The VAF can serve as a general reference of the quality of hydraulic simulations. As flows decrease from the calibration flow, VAFs should uniformly decrease from 1.0. Usually if VAFs decrease up to the calibration flow there is a poor stage-discharge relationship for the transect in question. At simulated flows above the calibration flow, VAFs should increase at a decreasing rate. The VAFs produced in the IFG4 modelling procedure carried out here (Figure 2.11), provide no evidence of any problems with the hydraulic model simulations overall.

Sensitivity Analysis

As outlined above (Section 2.2) sensitivity analyses were carried out to examine the effect of changes in stage on flow velocities. This is designed to give an assessment of the importance of weir settings upon instream habitat, in particular upon low velocity refugia. This was achieved by taking the calibrated IFG4 input data file and adjusting the each of the simulation water surface levels specified using WSP by +/- 40 cm. The IFG4 model was then used to simulate velocities under both the high and low WSL settings utilising the same velocity calibration data as above to distribute the velocities within the channel. The balancing mechanisms within IFG4 will then adjust the simulated velocities according to the specified and calculated discharges as outlined above.

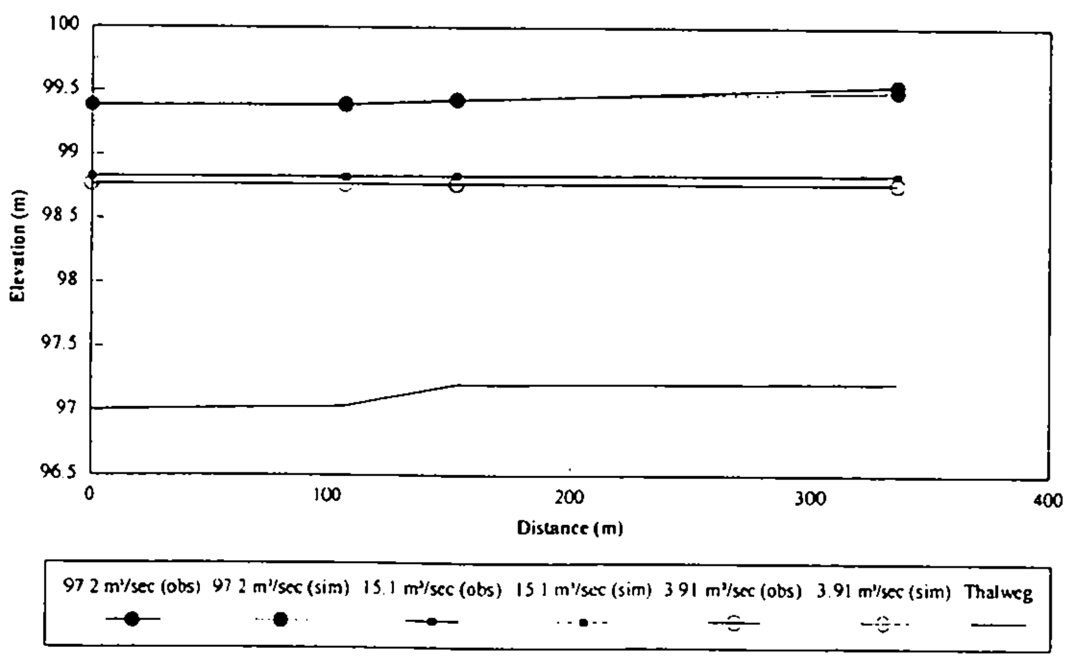


Figure 2.6 *Simulated and Observed Water Surface Levels at Calibration Flows.*

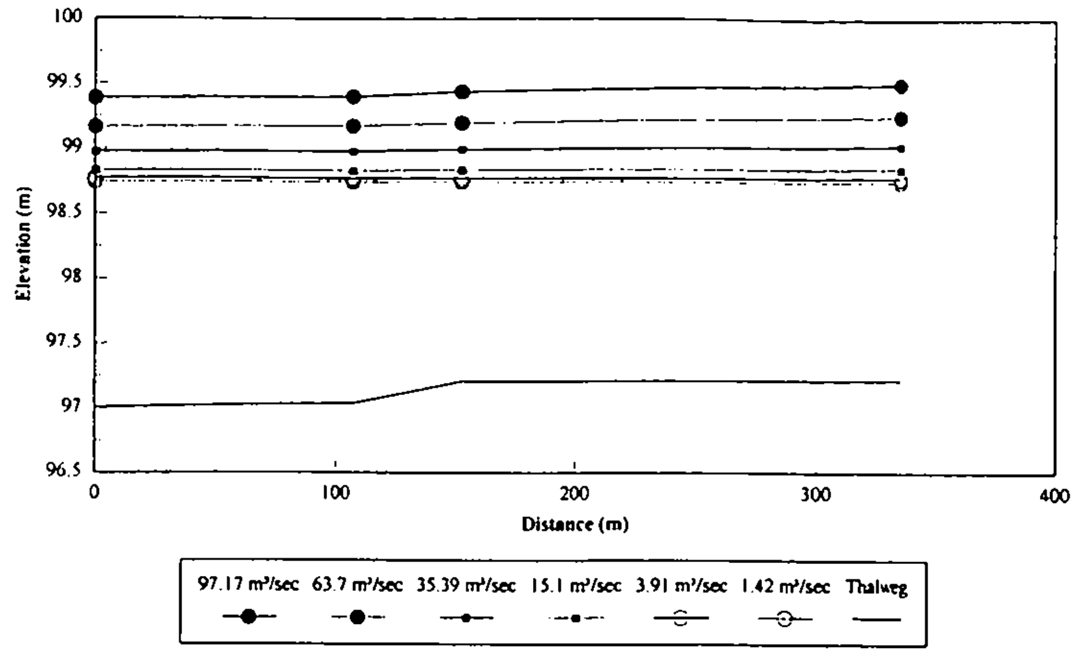


Figure 2.7 *Selected Simulation WSLs*

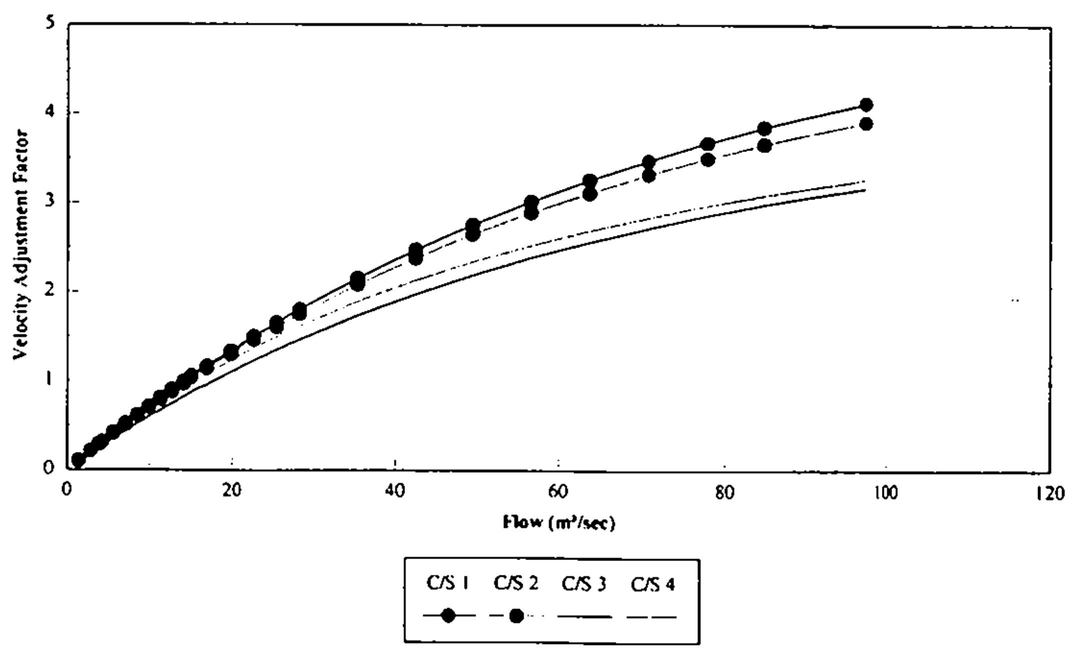
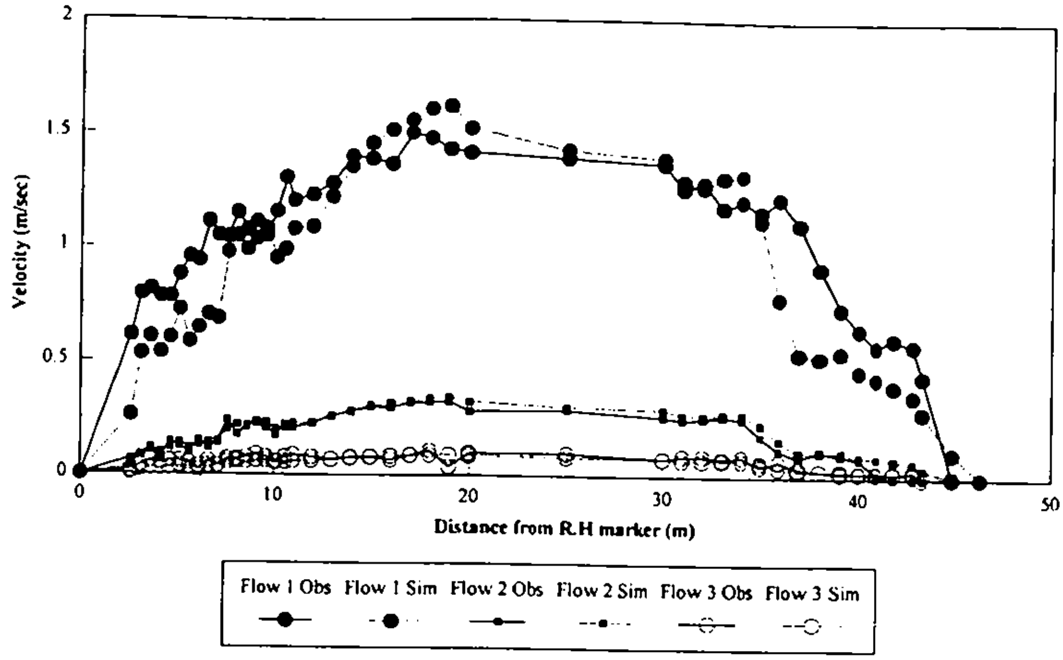


Figure 2.8 *Velocity Adjustment Factors (VAFs) Produced During IFG4 Model Simulations.*



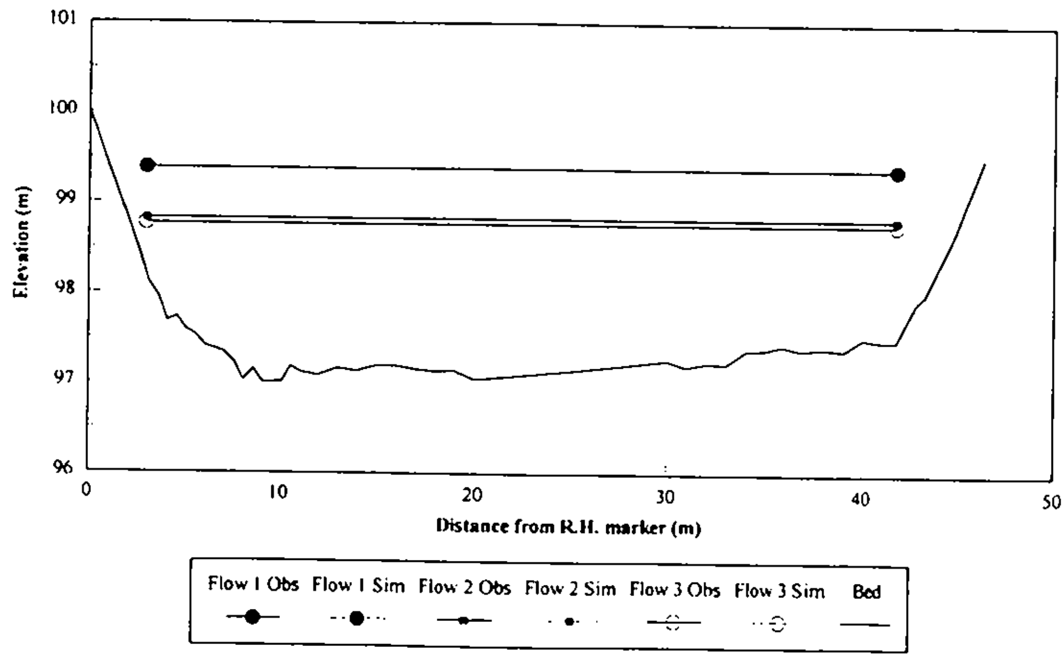


Figure 2.9 *Observed and Simulated Velocity Data C/S 1*

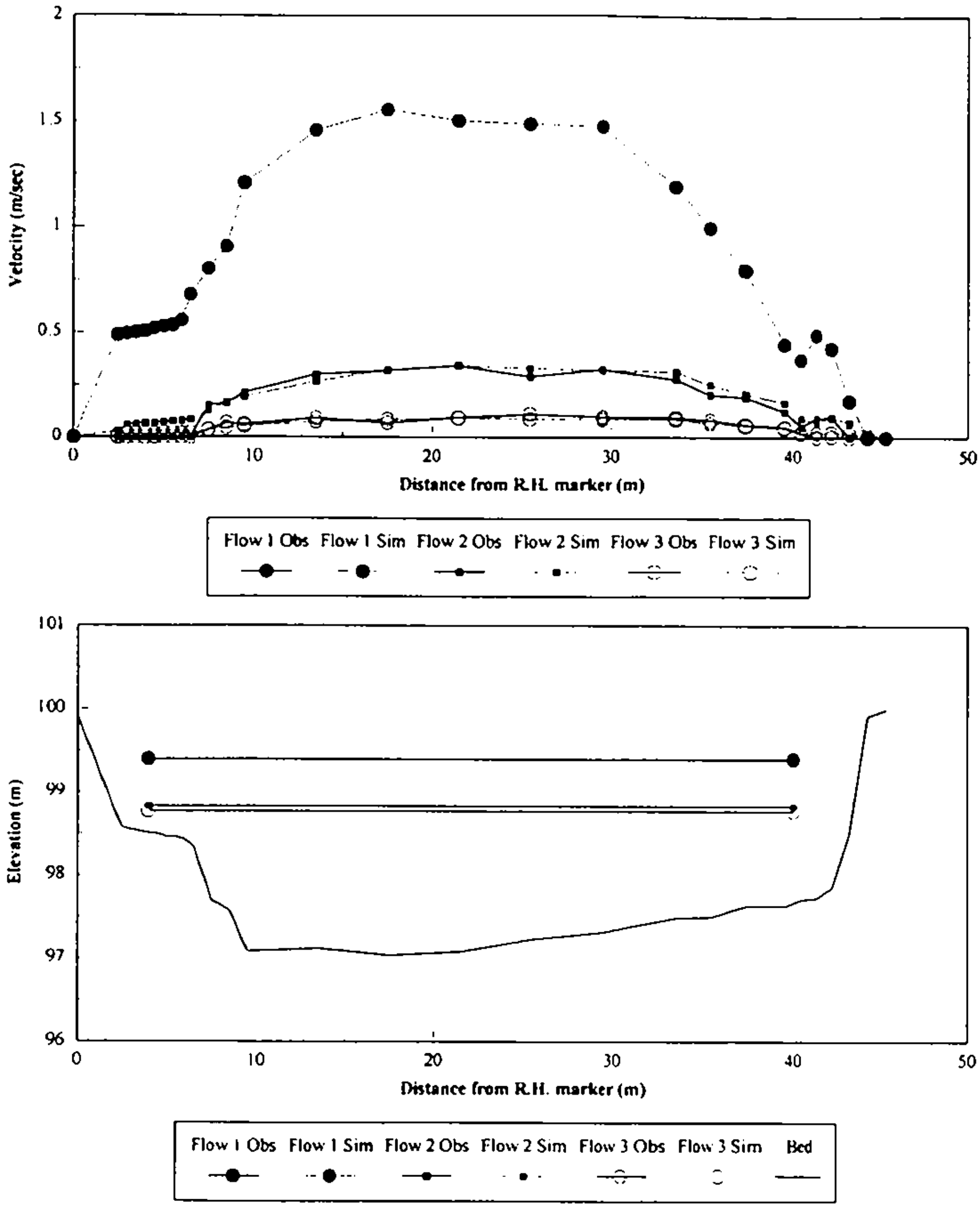


Figure 2.10 *Observed and Simulated Velocity Data C/S 2*

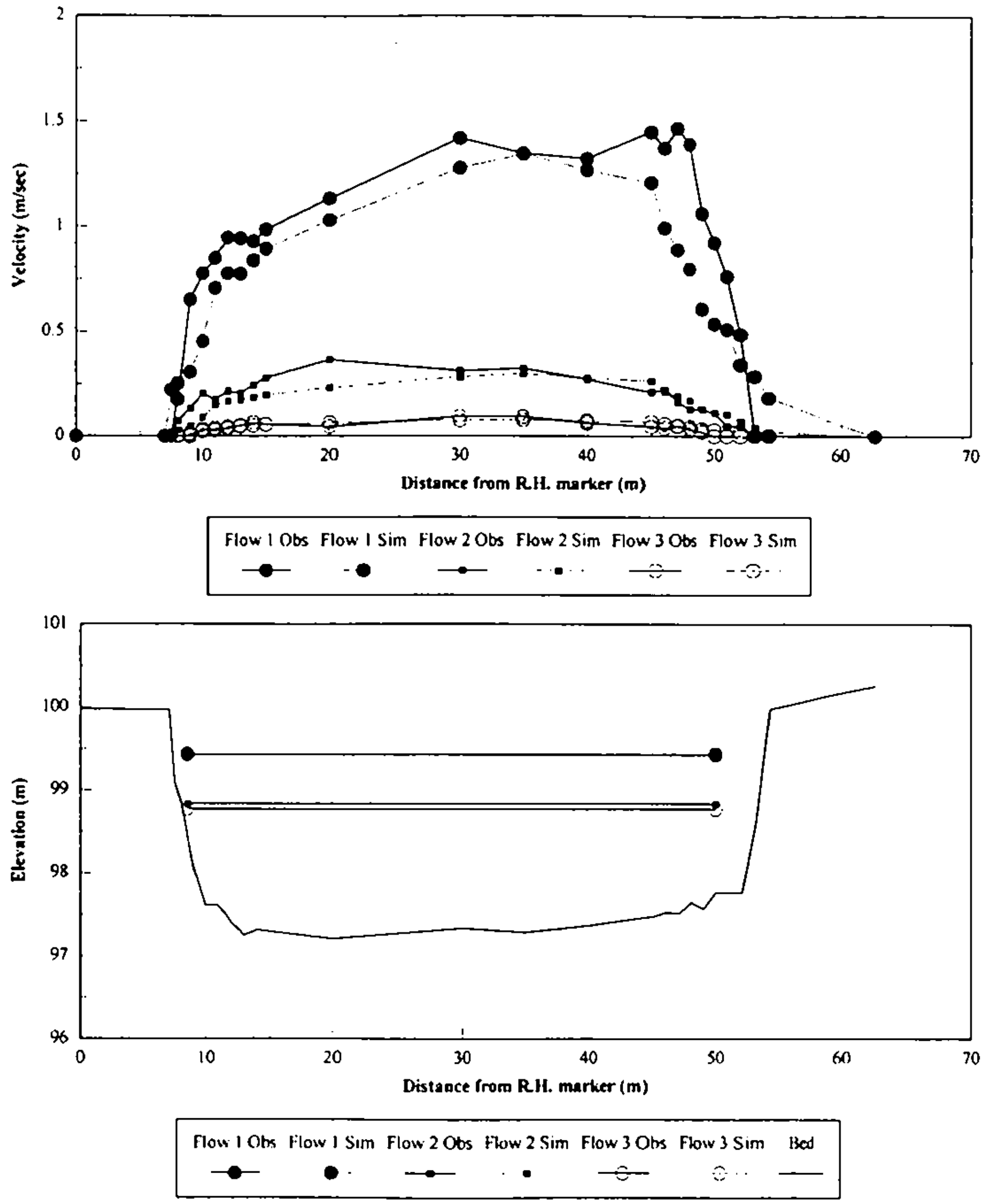


Figure 2.11 *Observed and Simulated Velocity Data C/S 3*

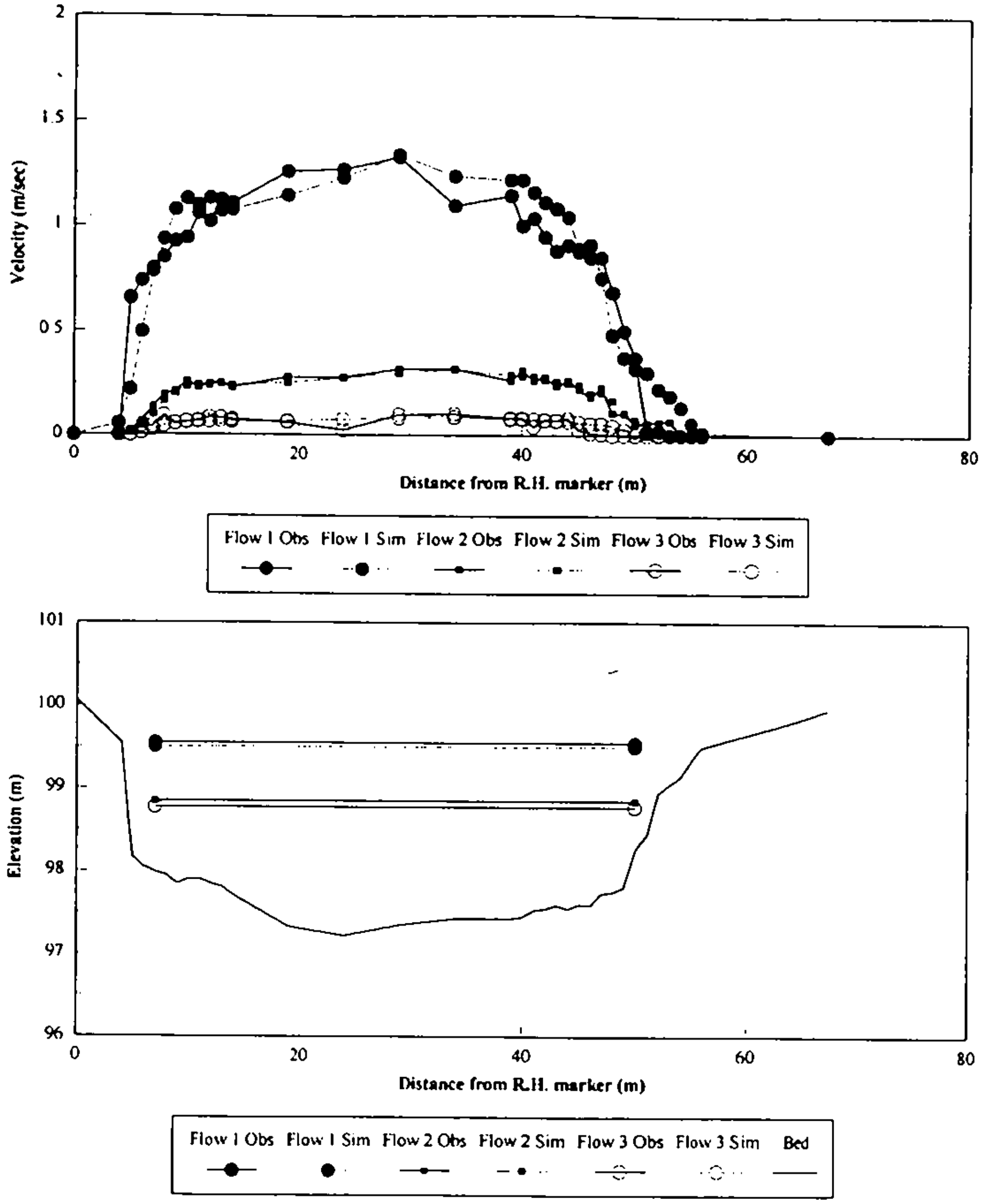


Figure 2.12 *Observed and Simulated Velocity Data C/S 4*

2.6 Habitat Model Simulations

Introduction

The velocities and depths, produced as output from the hydraulic model simulation procedure detailed above, along with details of the observed river substrate, were combined with the habitat suitability data for the target species and life stages in question using the PHABSIM habitat simulation model HABTAE. The results are expressed in terms of available habitat area termed "Weighted Usable Area" (WUA) expressed in units of square metres per 1000m of river length. As well as computing the WUA for each of the target species life-stages, the HABTAE model also calculates the total available physical habitat. This total habitat area vs discharge curve, shown in figure 2.13, shows little change with flow, increasing from some 45 000 m^2/1000m to 48 000 m^2/1000m over the range of flows modelled. This reflects the channelized nature of the river, with its relatively steep sides and that the wetted area changes little with flow as a result. It is important to note that each transect was given an equal weighting (0.5) within the habitat modelling procedure. This implies that each habitat type extends half way to the neighbouring cross section, an assumption which may not account for the spatial distribution of marginal habitats along the river rigorously.

The HABTAE simulations detailed here were carried out in four parts, the first was to look at the habitat availability with flow for the selected life stages of roach, the second was to look at the limiting factors behind the availability of habitat for the target species, thirdly an analysis of the availability of low velocity habitat was carried out. Finally, a sensitivity analysis of the impact of changes in water surface level, as may result from variations in the level of Day's Weir, was carried out on to assess possible changes in the availability of low velocity habitat and the available habitat for roach.

Habitat availability for selected target species/life stages

This technique is used to calculate the available physical habitat (Weighted Usable Area (WUA)) available to each species life-stage under investigation. The suitabilities of a species life stage for depth, velocity and substrate at a given flow are combined in a multiplicative manner to produce a composite suitability index which is then used to calculate habitat area or Weighted Usable Area (WUA) expressed in m^2 per 1000m of river. The interpretation of these issues is subject to the consideration of a number of issues which are discussed later in this report.

Habitat area vs flow

The WUA vs flow (Q) curves shown in Figure 2.14 show that the habitat available to the adult and juvenile life stages of roach are highly sensitive to changes in flow above and below the 5-15 m^3s^{-1} range. Within the 5-20 m^3s^{-1} flow range maximum WUA values are predicted for both life stages with adult roach habitat availability exceeding 40000 m^2/1000m and juvenile roach reaching 19000 m^2/1000m. The available habitat for both of these life stages declines markedly above and below the flow range producing peak habitat with WUA declining from less than 15000 to below 5000 m^2/1000m for both life stages over the 25-100 m^3s^{-1} flow range. Habitat for both the fry and spawning life stages is very limited over the whole flow range with fry habitat never exceeding 4000 m^2/1000m, however the amount of habitat is relatively stable over the 5-100 m^3s^{-1} range and no habitat is predicted for spawning roach.

Habitat distribution within the study reach

Figures 2.15 to 2.17 show the calculated suitability at each survey point along each transect for each of the three life stages that have available habitat within the study reach. A Combined Suitability Index (CSI) of 1 is optimal, showing that each aspect of physical habitat is optimally suitable for the target species/life stage. CSI values of 0 indicate habitat which is unusable for the target species because one, or more, of the physical habitat characteristics assessed is not suitable. The results are presented for the three calibration flows measured to give a "snapshot" of the physical habitat simulated at the calibration flows.

When assessing the predicted habitat distributions at this level it is important to remember that the predictions of habitat in each computational cell are defined by the averages of neighbouring point measurements of depth and velocity. The results show that the channel margin habitats for all three life stages of roach (adult, juvenile and fry) are extremely important, especially at high flows. The simulations suggest that adult roach is the only life stage which can make use of the centre of the channel and even then only under low flow conditions. This is likely to result from the unsuitably high velocity conditions found in the centre part of the channel as flow increases. In all cross sections, the simulations suggest that some marginal habitat is maintained at under high flow conditions although this should be interpreted with caution due to the averaging of depth and velocities as outlined above. Despite this, cross section 4 does appear to provide low velocity habitat at high discharges, indicated by the more extensive habitat availability which reflects the more sheltered nature of the channel margins here and the extensive *nuphar* bed.

Limiting habitat factors for selected target species/life stages

Velocity

The results presented in Figure 2.18 demonstrate that flow velocities limit the available habitat for the adult, juvenile and fry life stages of roach below flows of 2 m^3s^{-1}. At flows of less than 5 m^3s^{-1} there is also no habitat for spawning roach, reflecting their requirement for higher velocities since velocity only begins to limit the available habitat at flows above 60 m^3s^{-1}. Habitat is also restricted for the fry life-stage as flows increase above 15 m^3s^{-1} as velocity increases, this pattern is also followed by the adult and juvenile life stages at flows above 20 m^3s^{-1}.

Depth

Figure 2.19 suggests that habitat for the fry and spawning life-stages of roach is highly controlled by depth, although this changes little with flow since habitat for fry is limited to approximately 4000 m^2/1000m over the whole flow range and to 2000 m^2/1000m for spawning. Juvenile roach habitat becomes more limiting as discharge increases whilst adult habitat only becomes limiting at flows above 35 m^3s^{-1}.

Substrate

Figure 2.20 indicates that substrate is not at all limiting for the adult, juvenile and fry life stages since the available habitat area for all three life stages matches that for the total habitat area shown in Figure 2.13. Conversely the lack of suitable spawning substrate in the entire study reach means that there is no spawning habitat at all under any flow condition.

Low velocity habitat analysis

As detailed in section 2.4, WUA vs flow curves were produced to indicate the area of habitat containing flow velocities between 0-2 $cm.s^{-1}$, 0-5 $cm.s^{-1}$, 0-10 $cm.s^{-1}$, 0-20 $cm.s^{-1}$ and 0-30 $cm.s^{-1}$. These outputs are displayed in Figure 2.21, with the upper of the two graphs showing the output over the full range of flows, the lower showing the output from the lower half of the flow range modelled in more detail. The curves demonstrate that the availability of habitat with low flow velocities drops rapidly with increases in flow between 5-20 m^3s^{-1}. The remaining habitat at flows above 20 m^3s^{-1} consists of marginal areas near the river banks where low velocities may be found even at very high flows (as is shown by the flow calibration data given above). This demonstrates the importance of low flows and marginal river habitats to species which are unable to tolerate high current velocities, especially as over certain flow ranges, small increases in flow may lead to large reductions in WUA.

Effect of changes in stage upon habitat

Roach habitat

Figure 2.22 shows the predicted changes in the available habitat for adult, juvenile and fry roach resulting from changes in water surface level 40 cm above (high) and 40 cm below (low) the original simulation WSLs used above (med). The results suggest that all three life stages are sensitive to such variations in WSL (as may be caused by changes in weir settings) however, the level of sensitivity changes according to the life stage. Adult roach are, perhaps, the least affected since the functional relationship between flow and habitat remains similar under all three scenarios - peak habitat occurs under low flow conditions (5-20 m^3s^{-1}) and declines to a relatively constant level at flows above 40 m^3s^{-1}. The relationship between fry habitat, and to a slightly lesser degree juvenile, and flow changes dramatically with increases in stage over the flow range. Using the high WSL data set (producing deeper depths and lower velocities), reduces or removes the high levels of habitat found under low flow conditions and makes the available habitat area much less variable with flow.

Low velocity habitats

Figure 2.23 demonstrates that the impact of changes in stage upon the availability of low flow habitat can produce relatively large changes at a given flow, for example the amount of habitat containing flow velocities of 10 $cm.s^{-1}$ at 5 m^3s^{-1} can change from 10 000 to 35 000 $m^2 1000m^{-1}$. However, the general relationship does not change in the same manner as the WUA vs discharge functions for roach. This means that widespread areas of low velocity habitat only occur under low discharge conditions and are enhanced by increases in stage.

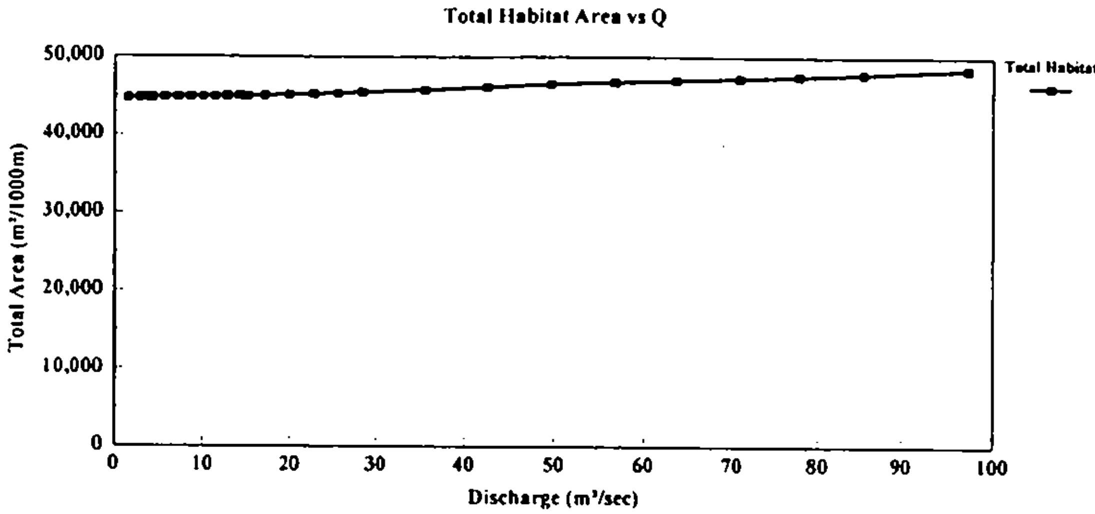


Figure 2.13 *R. Thames at Clifton Hampden, Total Habitat Area vs Discharge*

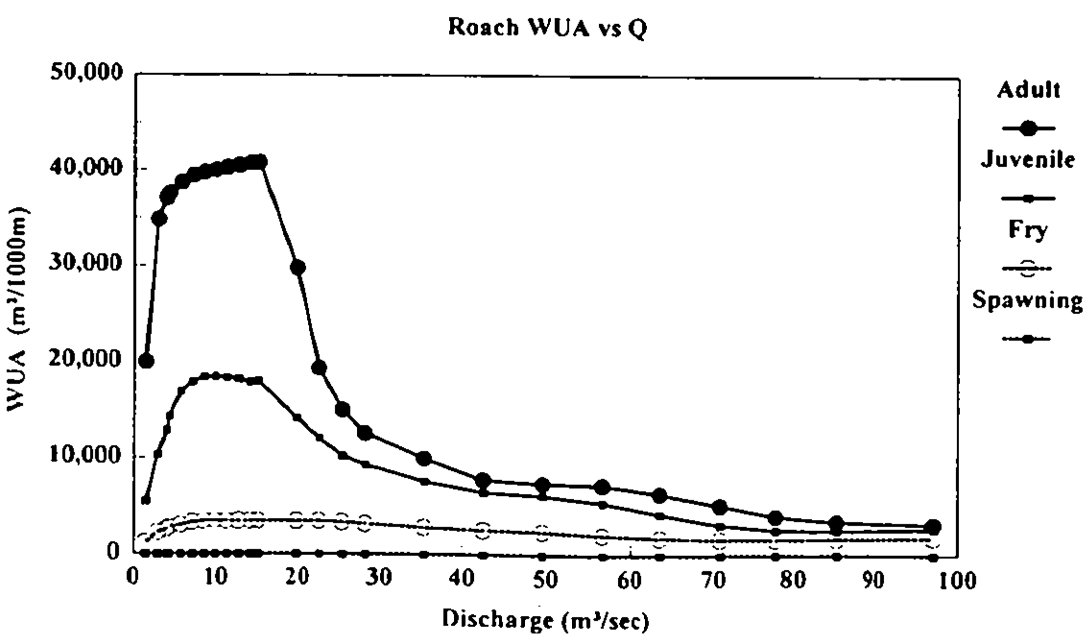


Figure 2.14 *WUA vs Discharge Curves for Roach Produced Using Composite Suitability Indices*

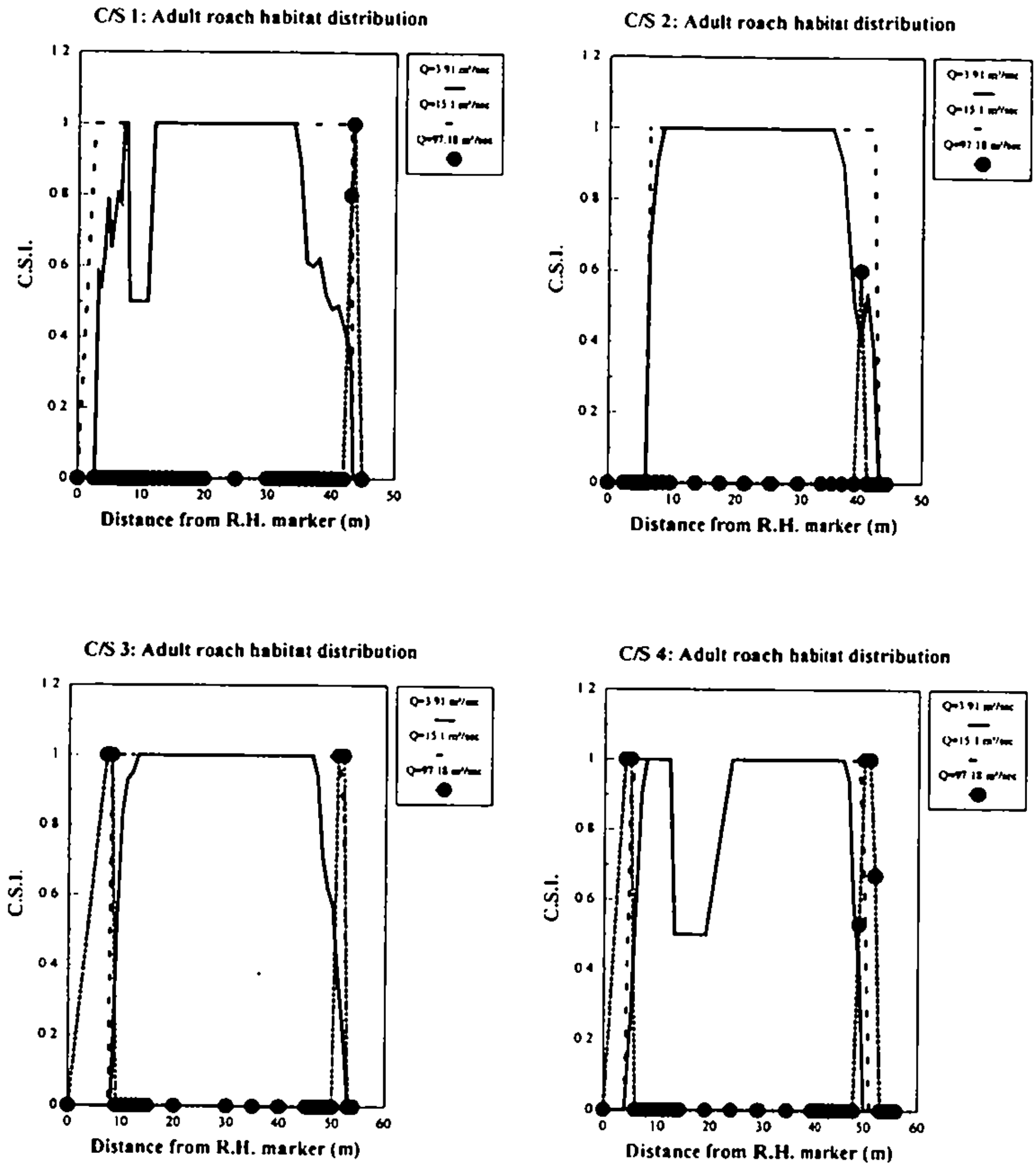


Figure 2.15 Distribution of Adult Roach Habitat Along R. Thames Study Transects at Calibration Discharges

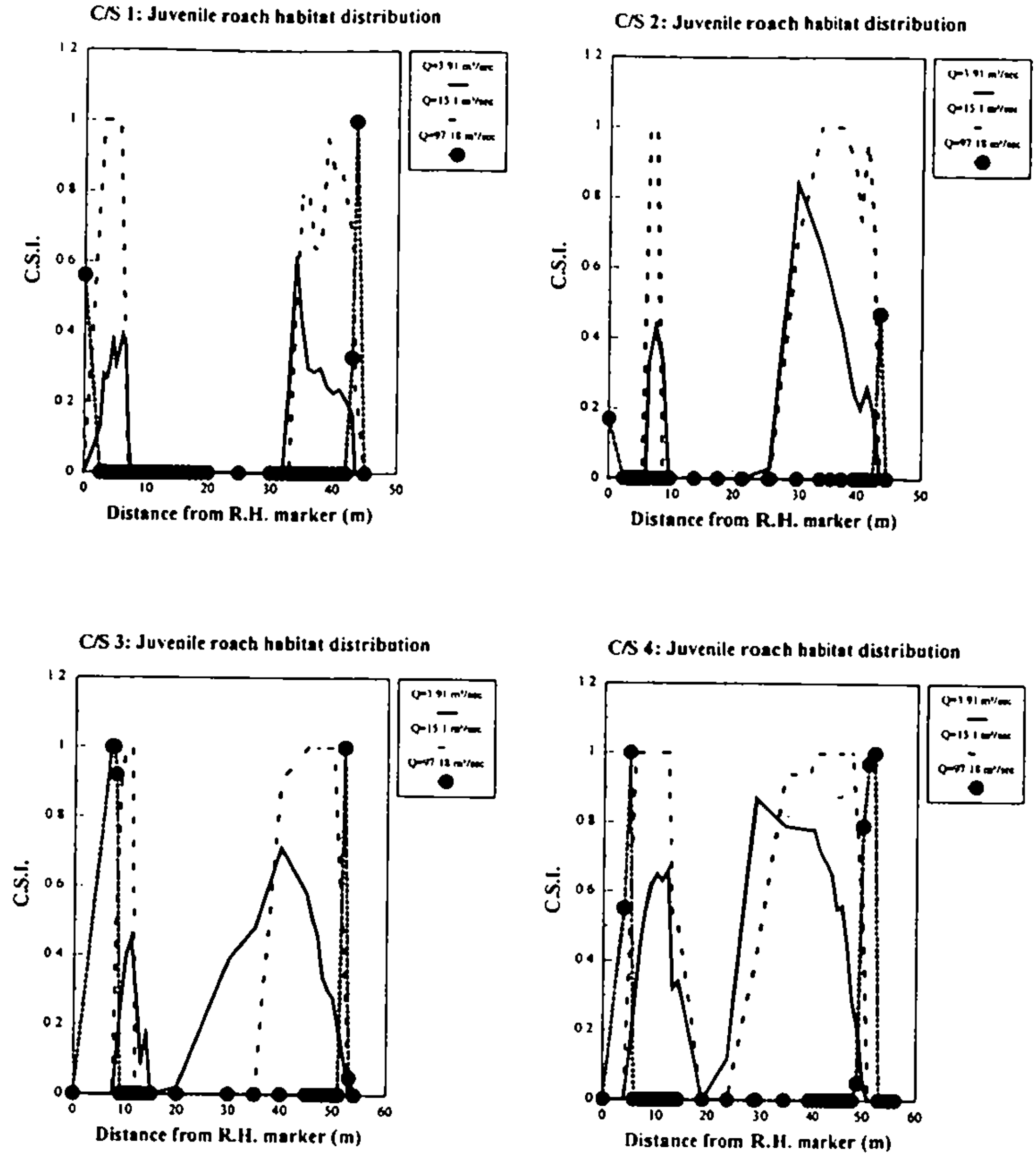


Figure 2.16 *Distribution of Juvenile Roach Habitat Along R. Thames Study Transects at Calibration Discharges*

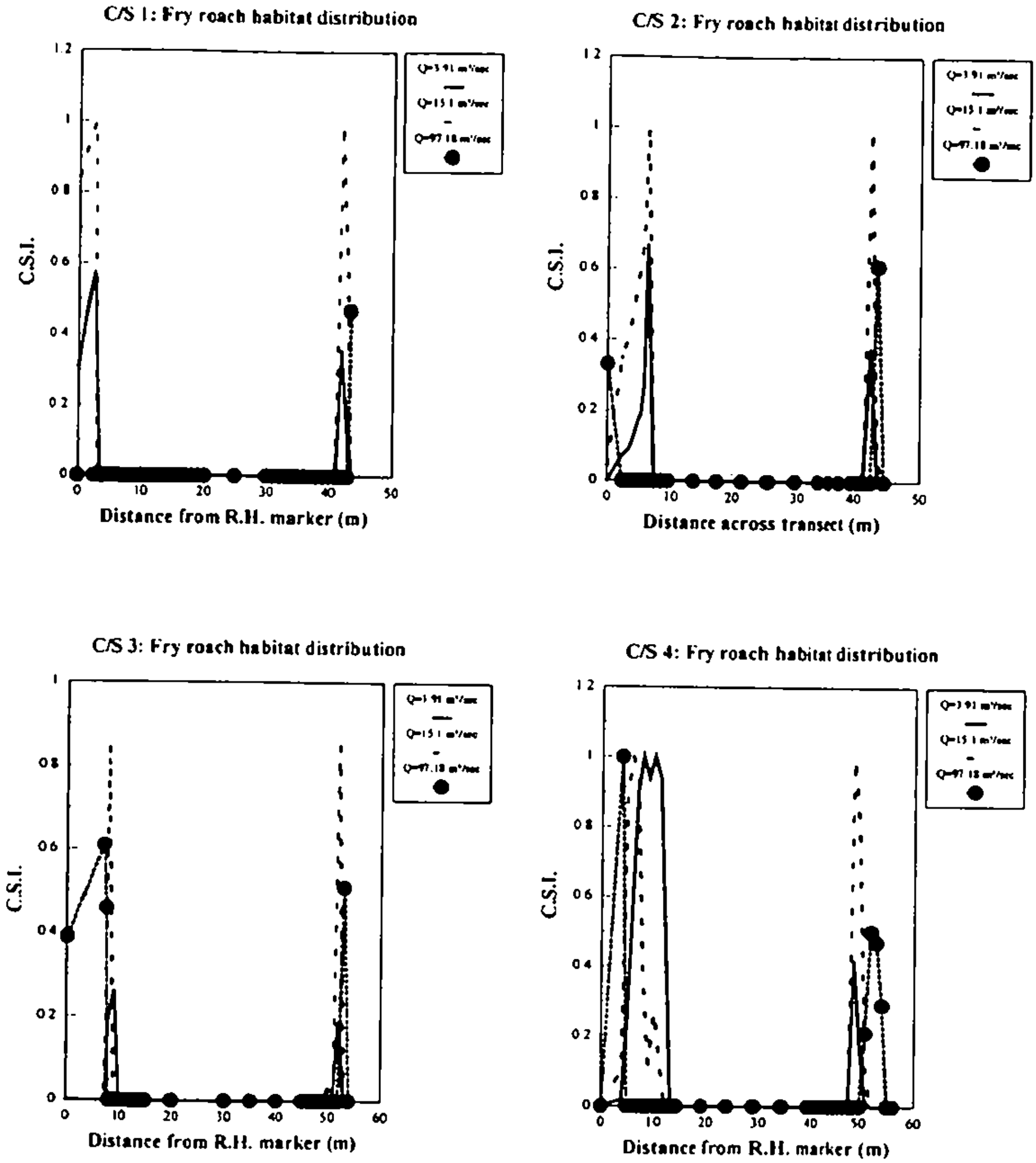


Figure 2.17 *Distribution of Fry Roach Habitat Along R. Thames Study Transects at Calibration Discharges*

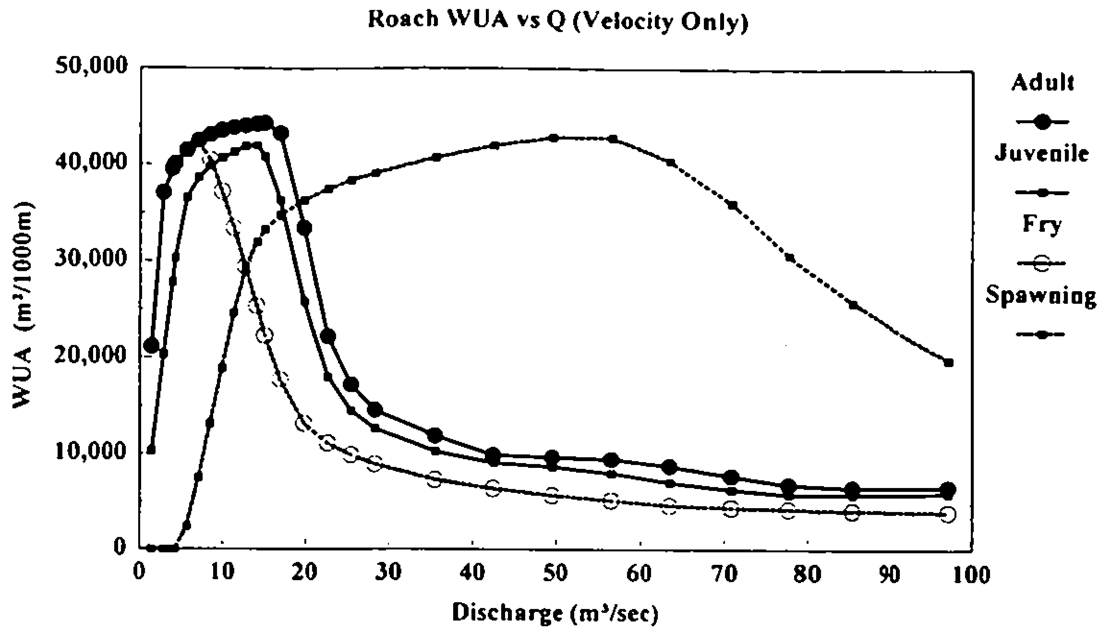


Figure 2.18: WUA vs Discharge Curves for Life Stages of Roach Produced Using Velocity Suitability Only

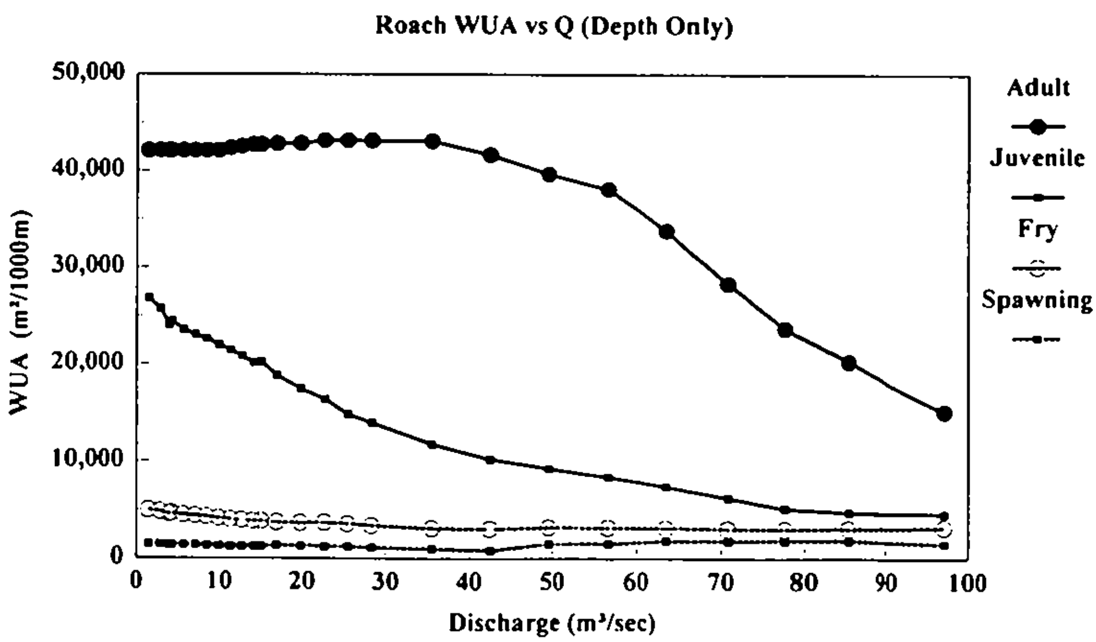


Figure 2.19 WUA vs Discharge Curves for Life Stages of Roach Produced Using Depth Suitability Only

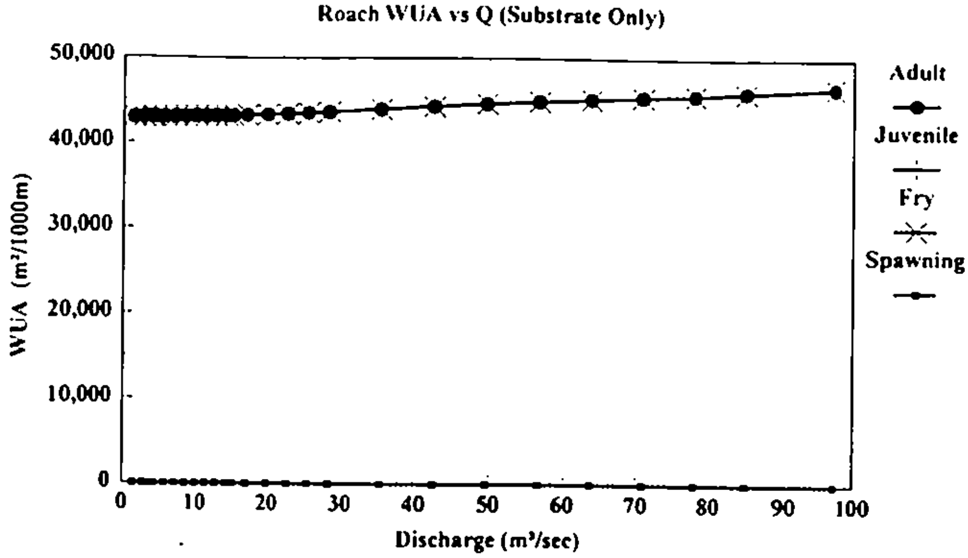


Figure 2.20 *WUA vs Discharge Curves for Life Stages of Roach Produced Using Substrate Suitability Only*

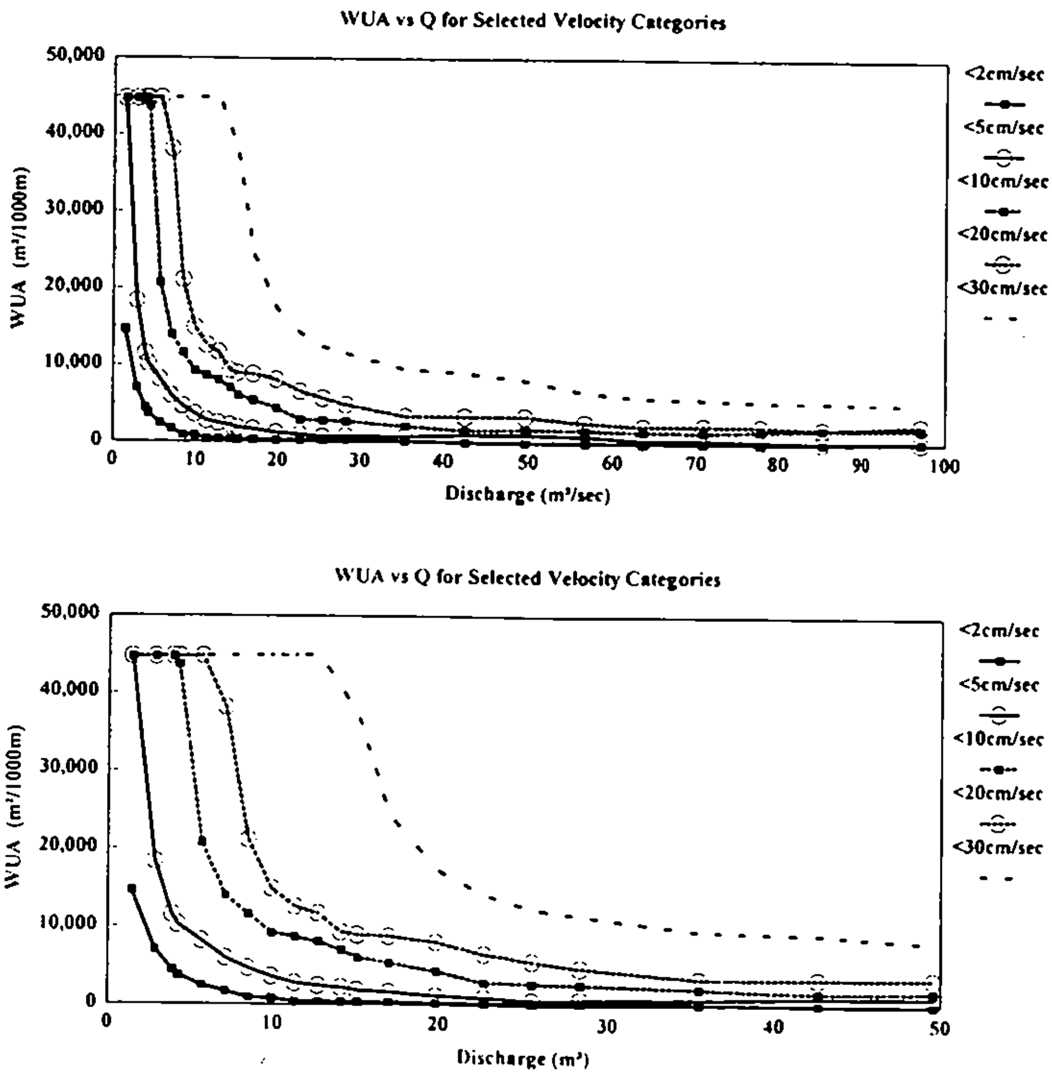


Figure 2.21 *WUA vs Discharge Curves for Selected Velocity Categories.*

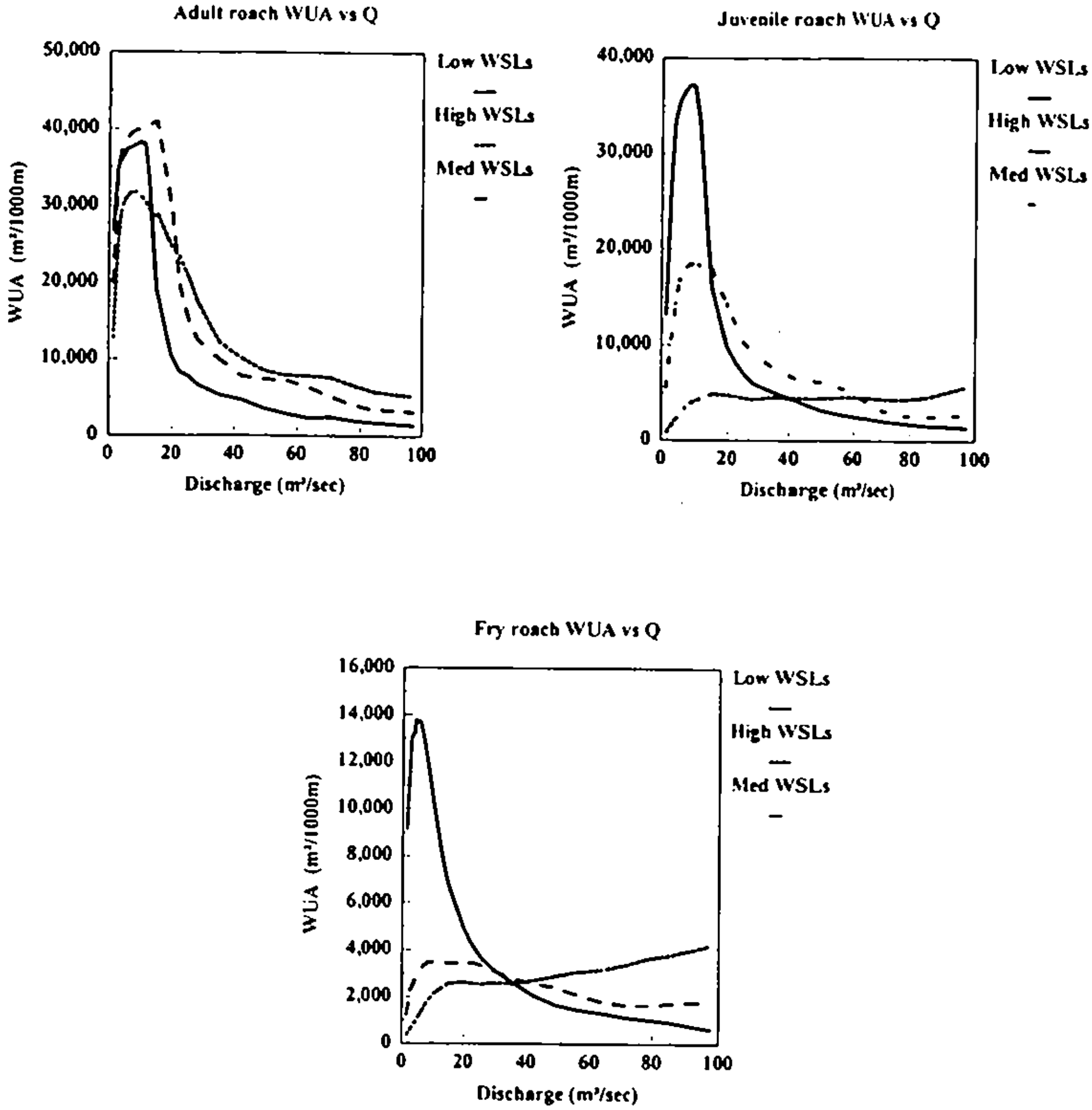


Figure 2.22 *Effect of Changes in Stage/Discharge Relationship on the Available Physical Habitat for Life Stages of Roach*

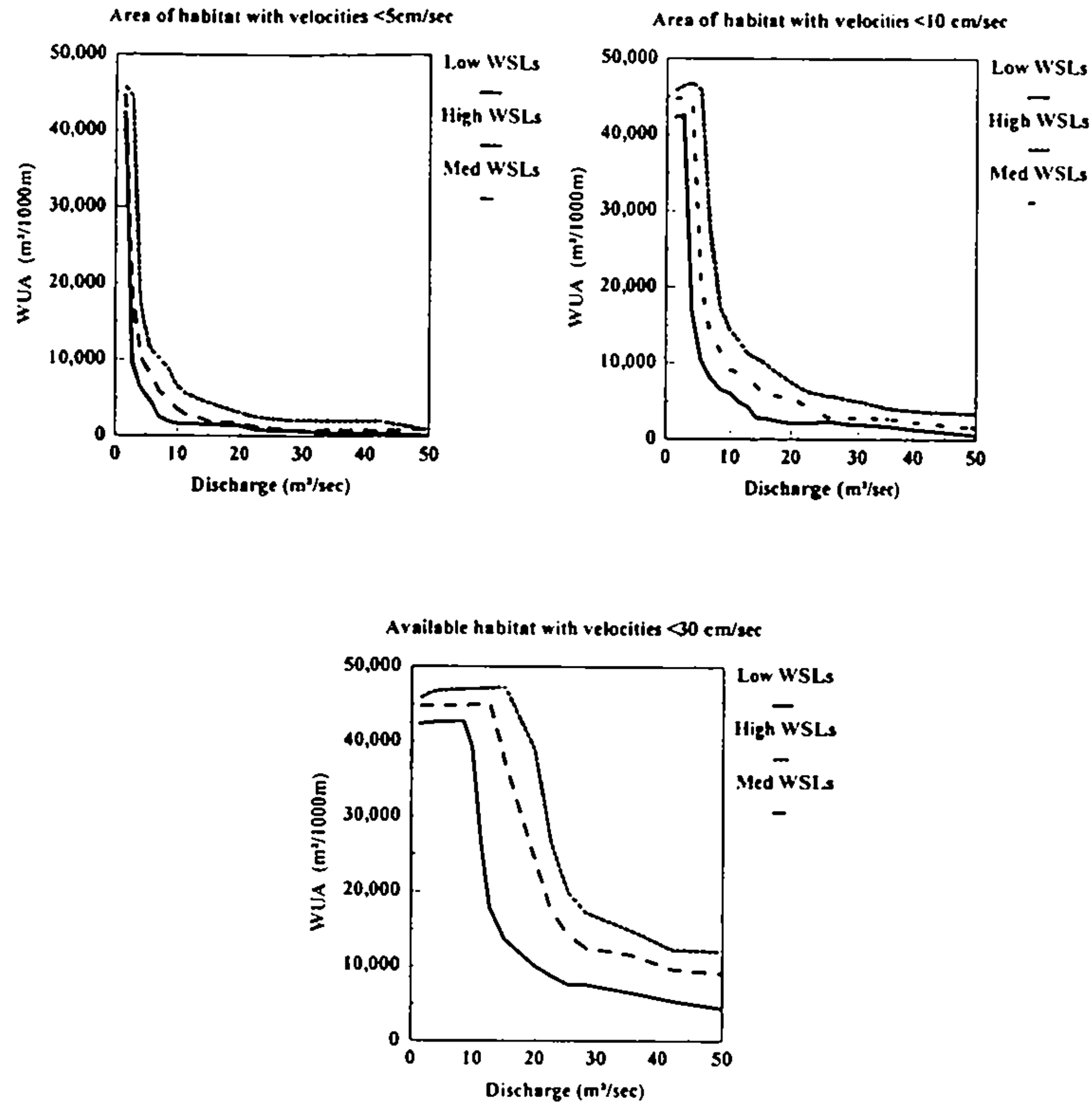


Figure 2.23 *Effect of Changes in Stage/Discharge Relationship on the Available Low Velocity Habitat*

2.7 Habitat Time Series Analysis

In order to use the output from the PHABSIM model in the development of strategies for the ecologically acceptable management of future flow augmentation schemes on the River Thames, it would be necessary to carry out habitat time series modelling to examine changes in available habitat with any proposed changes in flow. No habitat time series outputs are reported here as this is not yet appropriate given the issues discussed later in the report.

3. DISCUSSION

3.1 Selection Of Representative Habitats

As indicated in section 2.2, a limited number of survey transects (4) were selected for this preliminary assessment of the application of PHABSIM to the R. Thames. This number of transects is sufficient to represent the general channel morphology in the area of river in question because the main channel is heavily engineered and relatively simple in form. Although the study transects were also selected to include a variety of different marginal habitat types, the availability of such habitats has not been fully quantified and no habitat mapping has been carried out. Clearly a full application of the model will need to assess the impact of proposed changes in water resource management will need to address this issue. However, due to the size of the river and the issues related to weir management (as examined in section 2.5) this procedure is not as straightforward as would be the case on smaller, less regulated, rivers. In particular, a full habitat mapping study will need to assess the availability of habitats (in particular marginal habitats) on the basis of:

a: The number of different marginal habitat types present within the area of river in question (i.e. the Clifton Hampden reach and other reaches as required) and their relative availability.

b: The variable effect on marginal habitats of variations in water surface elevations due to changes in weir levels at given discharges.

The scale of the river and the variability, and frequency of change, in marginal habitat means that habitat mapping would present a considerable challenge and should make full use of existing data as well as any new approaches which may be required (e.g. using aerial photographs). As identified above, the variability in water surface elevations due to weir level changes with distance upstream of the weir, further complicates this procedure. This may be addressed by identifying the different marginal habitats and then mapping their distribution within the study area. This will highlight any need for further survey work to incorporate additional transects (representing particular habitat types) into the study. It will allow the relative availability of the habitats represented by each transect to be properly accounted for in the study results.

Secondly, the change in variability of water surface elevations at given flows with distance above each weir within the study area must be quantified, for example by using automatic stage recorders in conjunction with records of weir levels and gauged river discharges. These data may then be used to sub-divide the sections of river between weirs in to "zones of water surface variability" within which habitat sensitivity analysis to changes in weir levels may be carried out. The habitat distribution maps produced above should be included in this assessment so that model outputs correctly reflect the distribution of habitat within each "zone of water surface variability".

It should be noted that although this process is likely to require a large amount of resource input, it does not necessarily require large scale survey work to collect data from study transects representing the different habitats available AND the different level of variability in water surface levels throughout the reach. Having correctly identified the marginal habitats for assessment, and sampled them with additional representative study transects as necessary (the transects already surveyed may be included), analysis of the sensitivity of habitats within each "zone of water surface variability" to changes in water surface levels due to weir levels may be carried out using computer simulations.

3.2 Hydraulic Modelling Of Physical Habitat

In addition to the issues related to the variability of water surface levels with weir levels within the study area, there are several areas where further work is required if a fully robust application of the model is to be carried out. These can be separated into separate issues as discussed below.

1: Further data are required to quantify the variability in stage at each study transect that may result from changes in weir levels under steady flow conditions. For example, due to changes in weir levels, the maximum variability in water surface levels above Day's Weir is in the order of 40 cm at any flow between 0 and 90 m^3s^{-1} and water surface levels at each transect are likely to vary independently of discharge, since the weir provides a control on water surface elevations through the study reach. Consequently, at each study transect there is a need to fully quantify the variability in water surface elevations that may result from weir management, and to review the existing hydraulic calibration to account for any changes in water surface levels identified. This could be achieved relatively simply by installing automatic stage recorders at each transect and recording changes in stage with different weir levels. Following this review, the assessment of the effects of changes in variability in stage with distance above each weir may be carried out as identified in section 3.1 above.

2: The hydraulic simulations undertaken to date are adequate for an assessment of the general habitat characteristics of the river. However, further data/calibration work is necessary to develop the accuracy of the simulated velocities. This will enable a more detailed examination of marginal habitats for juvenile coarse fish. In particular, these target species/life stages require areas of negligible flow and may be very sensitive to small changes in velocity as discussed in section 3.3 below. Although the accuracy of simulated velocities in the channel margins can be improved, providing a better assessment of the general characteristics of the different marginal habitats, it is uncertain that they can be improved sufficiently to allow highly detailed investigations of these zones. One factor that may prevent this is the ability to obtain sufficiently accurate velocity calibration data in low velocity areas given the available flow measurement equipment and the natural variability in velocity that will occur at any measurement point. An additional issue is the spatial variability of low velocity habitat, although care was taken in this study to improve the resolution of the model in the marginal zones by increasing the number of survey points in these areas.

Any further studies should follow the same procedure or seek to increase the number of sample points in these key areas.

3: Although the issue of instream macrophyte growth within the River Thames has been taken into account intrinsically, since there was vegetation in the channel when the calibration data were collected, further work is required to investigate the temporal variability in habitat due to seasonal vegetation growth. Although it is expected that this will have a negligible impact on water surface levels within this river (relative to the effects of changes in weir levels), it is likely to cause significant changes in the pattern (and overall magnitude) of the velocities found in the channel margins. This issue may require calibration of the model on a seasonal basis if velocities are to be simulated with the required levels of accuracy outlined above.

In order to minimise the above issues it is clear that extreme care must be taken in simulating velocities and in particular those at the channel margin. This may be assisted by the collection of detailed velocity data at the channel margins at a variety of discharges and with different levels of marginal vegetation growth. These data would then determine the accuracy of the model outputs as well as allowing more accurate model calibration. However, it is clear that a full assessment of these issues in combination with the other issues raised in sections 3.1 and 3.2 will require considerable resource input over a period of several years.

3.3 Ecological Aspects

PHABSIM in relation to holistic coarse fish habitat requirements.

PHABSIM defines physical habitat using channel depth, flow velocity and substrate or cover. Whilst it is recognised that these factors are important aspects of fish habitat, they represent only a partial description of total habitat. As stated at the outset of the study, the model is utilised to assess some components of the physical habitat, available to a target species, in relation to flow regime.

Current knowledge of coarse fish habitat requirements identifies other important physical and ecological factors which need to be considered to provide a full assessment. These include energy (i.e. food supply), water quality, temperature and biotic interactions (predation, competition etc.) (Cowx *et al*, 1995). In relation to the River Thames, all of these wider habitat requirements need to be taken into account in order to assess current or future factors determining the fish populations.

The IFIM is a dynamic process which has the flexibility to include appraisal and modelling of all components of habitat. In reality the assessment of aspects such as microhabitat temperature and biotic interactions are still developing. As such, a common criticism of IFIM applications is that too little emphasis is placed on habitat components other than those assessed by PHABSIM (Orth 1987, Mathur *et al* 1985).

Components of fish population dynamics include growth, recruitment, mortality, immigration and emigration with factors other than physical habitat being very important (e.g. temperature for growth, predation for mortality). Assessment of physical habitat, which may be a limiting factor to the population at some stage(s), needs to be linked with other studies and new and more complex models are required.

Habitat Suitability Indices

Current knowledge relating to the specific habitat requirements of riverine coarse fish and factors determining population status is limited (Cowx *et al* 1995, Mann & Berrie 1994) and remains a key area requiring future research efforts.

The HSI data used in this study were accepted as being best available information but acknowledged to be limited in some respects including:

a: The indices were Category 1 (Bovee, 1986) being constructed from a review of the literature providing information on habitat use from a range of studies on many different river systems. Habitat utilisation is dependent on availability (Bovee, 1986) and as such the indices may be expected to be very broad in nature (i.e. a target species will have a wide range of suitable depths, velocities and substrates). However, the authors of the HSIs advise that the indices are based on 'very limited' information (i.e. a small number of published studies).

b: The HSIs used have not been validated for the River Thames or any other similar river. For example, recent work (published after the analysis undertaken for this study) by Garner (1995) on another regulated lowland river (the Great Ouse) and flume tank studies (Mann, 1996) demonstrate that early roach fry require negligible flow velocities. However, the indices used in this study contradict this information and identify 0 flow velocity to be unusable and velocities below $<5 cm.s^{-1}$ to be sub-optimal. Additional HSIs were constructed for this study to focus on a range of flow velocity requirements as discussed in section 2.4.

c: The life stages examined here were not specifically defined and require subjective assessments of 'fry' etc. This is a function of the poor definitions provided in the literature reviewed. Habitat utilisation of coarse fish fry is known to vary in relation to size (age) and thus specific definitions are required. There is also evidence that habitat utilisation is also dependant temperature and have diurnal variations, thus introducing a further limitation to current HSIs.

d: No indices for cover were available for roach at the time of the field data collection and analysis. This is a significant issue, particularly in relation to fry which have a close association with aquatic vegetation (Copp 1992, Garner 1995, Cowx 1995). The limitation of not having macrophyte cover HSI data available for use in relation to spawning habitat suitability is considerable given that the roach is a phytolithophil (primarily spawning on submerged plant surfaces) (Mann, 1996).

The limitations of the HSI data were recognised at the outset of the study and they were used as best available information to assess the use of PHABSIM and to identify requirements for future development.

It is clear that considerable development of HSI information is required for use on the River Thames. Additional information on the microhabitat requirements of coarse fish is becoming available (0+ roach - Garner 1995, adult dace - Garner and Clough 1996) but high quality indices are not yet available for cyprinid fry or spawning which can be assessed for transferability to the River Thames.

There remains a clear need for the investigation of habitat utilisation by spawning and fry life stages of target species in the River Thames. The selection of target species and critical life stage/periods requires further assessment in relation to the assessment criteria (ecological, recreational value etc). This study will need to be made on the basis of existing information. The production of coarse fish habitat suitability indices for the River Thames would be limited by the potential range of methods which are suitable for the life stage, target species and river type. The size and turbidity of the river are particular constraints. One current method suitable for coarse fish fry in such systems is Point Abundance Sampling by Electric Fishing (PASE) (Persat and Copp 1988, Garner 1995). Further studies to develop HSI's for coarse fish on the River Thames would need careful consideration of the following:

* Target Area
* Target Species
* Target life stage
* Critical periods
* Chosen habitat factors (wider than PHABSIM parameters)
* Sampling methods for target species and habitat availability
* Method of HSI data analysis

Such a study would enable data requirements to be minimised by careful focusing. However, the current level of knowledge to enable such selection is limited and a range of species, life stages, periods and habitat factors would need to be investigated. Such a study would require significant resources over the medium term to enable the appropriate data to be collected. A rough approximation of required resources would be the equivalent to three person-years. Two significant factors should be raised at this point. Firstly, some level of targeting could be undertaken to provide phased development of HSI information for certain life stages of common species (e.g. roach fry). Secondly, the value of the HSI information would be dependant on linking it with appraisal or modelling of river habitats and management and any proposed changes. This essential factor is in itself a challenging issue as discussed in section 3.2.

The interpretation of model output

The interpretation of WUA (habitat availability) output from IFIM and PHABSIM is a complex but critical aspect of applying the tool. One of the most common criticisms of the tool is that the relationship between WUA and target species population is often not proven (Mathur *et al* 1985, Orth 1987). Studies confirming a relationship between WUA and fish populations, and thus the utility of the approach, have been published (e.g. those quoted in Hardy 1996). Other studies have not confirmed any such relationship (e.g. those quoted in Mathur *et al* 1985).

A key factor for any potential application on the River Thames is that studies confirming such a relationship have generally been undertaken on salmonids in cold water streams and that physical habitat, as defined by PHABSIM alone, will not necessarily be the dominant factor in determining coarse fish population status in cool or warmwater streams. It is highly probable that temperature is a key factor related to the River Thames coarse fish population and models of this and other habitat components will need to be assessed as discussed above. The use of IFIM incorporating PHABSIM and temperature models has demonstrated relationships between WUA and non-salmonid species populations in cool water streams in the US (Bovee *et al*, 1994).

Physical habitat as defined by PHABSIM may be limiting at specific periods for specific life stages of certain species (e.g. lack of low velocity refugia for coarse fish fry). Analysis of this issue would therefore need to take account of this important temporal factor and be carried out on an appropriate temporal scale. As a result, WUA may be a poor or inconsistent predictor of target species population due to other important factors even though low levels of physical habitat may limit the target species/life stage at certain times.

Outputs produced using the IFIM, including PHABSIM, are commonly used and defended without longer term studies confirming a relationship between WUA and target species populations. This is undertaken on the basis that it represents the best available information relating to the issue in question. In such cases, the robustness of the study will be carefully investigated to determine the probability that such a relationship exists and decisions may need to be reviewed as further information becomes available (i.e. adaptive management). Ideally, a full IFIM study on the River Thames would include a complex assessment of a number of habitat components and target species taking place over 3+ years. Additionally, a post assessment of model performance and adaptive management would be likely to require input over 5-10 years and perhaps beyond.

3.4 Coarse Fish Fry Habitat And Flow Regime On The River Thames

Given the above discussion on the current limitations of the modelling approach it is not possible to place a significant level of confidence in interpretation of the PHABSIM outputs. However, as identified when the study was initiated, the work carried out has reviewed and provided very useful information relating to the physical habitat of coarse fish fry and the relationship with flow regime in the River Thames.

Physical habitat requirements of coarse fish fry

There is good evidence that bottlenecks to recruitment in coarse fish populations relate to the spawning and fry stages within the first year of life (Mills & Mann 1985, Mann 1996, Cowx *et al* 1995). A review of information on the fish populations of the River Thames and major influencing factors (Mann & Berrie, 1994) concluded that flow regime was one of the key factors, particularly in relation to its influence on the physical habitat of fry.

Detailed information on the habitat requirements of different life stages of coarse fish species remains limited (Cowx *et al*,1995, Mann & Berrie, 1994) and further research is a high priority. Available information demonstrates that the physical habitat requirements of coarse fish fry can be very specific.

Recent studies in experimental channels (Mann, 1995) have provided information on critical velocities for roach and dace (*Leuciscus leuciscus*) fry with the best models incorporating size and temperature. Critical velocities at which 50% of roach fry become displaced after three minutes (CV50) are in the range of 5-40 $cm.s^{-1}$ given the size and temperatures expected in the River Thames (increasing with size and temperature). It is important to recognise that displacement velocities are much higher than preferred or foraging velocities which may be 70-80% lower (Mann, 1996) and thus be in the region of 0-10 $cm.s^{-1}$ The requirements of early fry (5-10 mm in length) when water temperature may be 10-15 degrees C will be in the range of 0-2 $cm.s^{-1}$ Other studies also confirm the importance of low velocity for coarse fish fry (Cowx *et al* 1995, Garner 1995).

The importance of size in relation to swimming ability has been proposed as being a mechanism for size selective mortality due to downstream displacement and thus a mechanism for limiting recruitment (Cowx *et al*, 1995). The availability of low velocity refugia is therefore a key habitat requirement for fry.

A further important aspect of physical habitat is cover, particularly from vegetation which may form the dominant category available. Depth and substrate type are also of importance (Mann 1996, Garner 1995, Cowx *et al* 1995, Copp 1992). In general the importance of shallower areas (<1m) and vegetation cover emerge as key factors.

Availability and distribution of fry habitat and relationship with flow

The study has provided information on the physical habitat availability at 4 transects selected to represent one river section. The river section is considered to be generally representative of the wider river sector. Physical habitat Information was collected on three different flows/occasions:

March	-	97 m^3s^{-1}, very high flows generally typical of a wet spring
May	-	15 m^3s^{-1}, moderate flows generally typical of May long term average
July	-	4 m^3s^{-1}, low flows generally typical of dry summer

Velocity

With respect to flow velocities (figs 2.8-11), the data show that the availability of areas of low velocity habitat (e.g. < 10cm.s^{-1}) is very restricted and exclusively associated with the margins at the moderate and high discharges. At the low discharge, the majority of the river area has flow velocities of approximately 10cm.s^{-1} or less. Areas of habitat with velocities of less than 5cm.s^{-1} remain exclusively associated with the margins.

The results demonstrate that the available fry habitat is extremely limited by flow velocities when river flows are typical of an average May and June. Early fry habitat (<5cm.s^{-1}) remains very limited at river flows typical of an average summer but may be significantly higher at flows typical of dry summers (e.g May-Sep 1990). The area of river with velocities <2cm.s^{-1} at average early summer (June) flow conditions is very limited, in the order of 1-2 %. Similar findings have been reported on other regulated lowland rivers such as the Frome (Mills, 1991) and the Great Ouse (Mann, 1996)

The sensitivity of areas of low flow velocity to river discharge has also been assessed by the use of the hydraulic model and defined habitat suitability indices. As discussed above, the hydraulic model was calibrated to simulate the observed water surface levels and velocity distributions. The issues relating to the accuracy of velocity simulation at very low velocities in the marginal zones is discussed above but the model is considered to provide an acceptable simulation of the general hydraulic behaviour of the river section given the weir management at the times of the data collection. Fig 2.21 shows the relationship between area of river below defined velocity values and flow. The results indicate that the area of river with velocities below 10 cm.s^{-1} is very sensitive to flow increases from 5-10 m^3s^{-1} and that the area below 5 cm.s^{-1} is sensitive to increases from 1-10 m^3s^{-1}.

In the context of the historical river flow regime, the flow range with high sensitivity to fry habitat loss is consistent with that between an average and dry flow year in the May-September period. In essence the results indicate that significantly more fry habitat (as defined by velocity requirements only) would be available in a dry flow year (e.g. 1990) when compared to a average flow year.

Depth

Channel depth is determined by both flow and weir management as discussed above. With the current river management, water surface level is largely determined by weir management, particularly in the flow range of interest to this study (0-30 m^3s^{-1}). A further important factor is that the engineered nature of the channel morphology, which in combination with the weir management, provides a navigable channel approximately 1.5-2 m deep. Areas where depth is <1m are almost exclusively limited to the margins under any flow condition.

The information on depth requirements of fry are limited and somewhat contradictory, particularly in relation to the issue of utilisation of depths in excess of 1m. This is an important issue for the Thames study as the question of the value of the deeper non-marginal zones when flow velocities are suitable is significant (i.e. non marginal zones may not be usable fry habitat even if velocities are suitable).

Cover

The availability of cover for fry (other than water depth) is almost exclusively associated with submerged, floating and emergent vegetation in the marginal habitats. This is largely due to the management of a deep and impounded river for navigation. The relationship between cover and flow has not been assessed as part of this study but there may a negative relationship (e.g. more extensive cover of *Nuphar* when flow velocity is lower in a dry flow year). As such, further assessment of the relationship between flow and marginal vegetation is required.

Substrate

This study has not fully assessed the complex relationship between substrate and flow since PHABSIM treats substrate as an unchanging parameter within the river. Substrate preference is known to be exhibited by coarse fish fry and has not been investigated specifically, other than as a factor defining the overall available habitat to the target species/life stages examined, consequently it remains an issue for further examination.

The overall picture is one which identifies the marginal zones to be very critical and potentially limiting habitat types for fry in terms of low velocity refugia, cover and shallower depths. The importance of such marginal habitats is enhanced in a regulated lowland river with reduced channel diversity due to management as an impounded navigation. The comparative value and abundance of different types of marginal habitat has not been investigated as part of this study. However, a preliminary assessment indicates clear differences in the depth, velocity and vegetation characteristics of different marginal habitats at a given flow. Further examination of this issue in relation to value as spawning and fry habitat is identified as a future requirement.

The potential impact of flow augmentation.

Little information has been provided on the details of any potential augmentation and any impact will clearly be dependant on such factors as magnitude, timing, duration, frequency etc. However, the preliminary indications are that the proposed augmentation may occur in the season associated with critical spawning and fry life stages (April-August) and may occur on a regular basis in years with below average flows, raising discharges to the monthly average.

This study has discussed the importance of the fry life stage to coarse fish population dynamics and the importance of physical habitat for fry. The study has also demonstrated a relationship between flow and fry habitat requirements, particularly in relation to water velocities. The potential sensitivity of fry habitat availability to an increase in river flow in critical periods by augmentation in dry flow years has been demonstrated.

The study has identified and discussed one potential mechanism for an augmentation scheme to adversely impact on a component of the coarse fish population. Significant limitations relating to the appraisal and possible validation of this mechanism have been identified and discussed.

It must be emphasised that the management of the river as an impounded navigation is the dominant factor determining physical habitat and that factors other than habitat are important in determining the fish population. The current water level management of the river does not include operating rules for ecological reasons. The sensitivity analysis undertaken within this study indicates the significant effect of weir management on physical habitat and the potential for some mitigation of the impacts of further flow regulation does exist. In addition other potential mitigation techniques such as extensive scalloping of marginal zones or Off River Supplementation Units (ORSU's) need active consideration and may have wider conservation and amenity benefits.

4 CONCLUSIONS

a: PHABSIM is considered to be a potentially useful tool in relation to the assessment of the impact of flow management on the physical habitat of juvenile fish in the River Thames but significant limitations to any future application have been identified. With respect to this particular study, the tool cannot currently provide robust information to aid decision making and considerable development of the approach is required before any potential application.

b: Although this study has examined the general patterns of habitat change with discharge in the River Thames, it has not considered the full range of marginal habitats available within the area of river in question. This is of key importance with respect to the target species/life stages that may be investigated in an operational application of the model and the variability and availability of such habitat should be quantified. It is also important that these issues are considered when collecting/reviewing model calibration data to ensure that the resolution of the model (which is partially defined by the number of data collection points surveyed across each study transect) is sufficient to take this into account.

c: The physical habitat in the River Thames is largely determined by its management as an impounded, navigable, river with water surface levels being determined by weir operation, particularly in the low to medium flow range. At the site studied, the physical habitat as defined by flow velocity, is also significantly determined by flow regime.

d: Modelling the hydraulic characteristics of a large, regulated, river such as the Thames presents challenges above those commonly experienced when applying PHABSIM. Issues include the fact that water surface elevation within the river is controlled by both discharge and weir management, and that the effects of weir management vary with distance above a weir. As a result further data are required to review the calibration of water surface levels in the existing hydraulic model of the river. Further data is also required to quantify the variability of water surface elevations, with respect to different weir levels, with distance above each weir in the area of the Thames in question.

e: In addition to paragraph d: above, velocity simulations must be carried out with consideration for the importance of accurate simulation in the marginal zones of the river and the habitat requirements of the target species/life stages. These issues are likely to require more data collection than would otherwise be the case in a "standard" PHABSIM study if they are to be addressed in a robust manner. In particular the resolution of the model simulations of low velocity marginal habitats should be reviewed and if necessary improved. Further data would also allow improvements in the accuracy of velocity simulations in low flow habitats in the channel margin. However, it is not yet certain if these can be developed sufficiently with respect to the sensitivity of fry and juvenile fish to small changes in low magnitude velocities.

e: The assessment of impact on physical habitat must be within a wider framework of studies assessing other key factors which influence fish population in lowland rivers (e.g. temperature, water quality, food supply). The wider IFIM framework is flexible and provides a tool for the development of such an approach.

f: Given the current state of knowledge, there is evidence that the physical habitat requirements of key life stages such as fry may be very specific and that suitable habitat is potentially sensitive to flow regime. This may be a potential mechanism for influencing population status.

g: Current information on the habitat requirements of coarse fish remains limited and no robust habitat suitability indices are available for use on the River Thames. The best available information used in this study is considered to suffer from several significant limitations. The development of robust information on fish habitat requirements is a fundamental requirement for any future assessment of proposals for changing river management. Further assessment of a strategy for the development of this data is needed.

h: At the site studied, the availability of habitat with water velocities suitable for fry was negatively related to flow with suitable habitat being associated with marginal zones. The availability of habitat with water velocities suitable for fry is sensitive to flow in the range typical of dry to average summer flows. The area of river suitable for fry is extremely limited by velocity when river flows are typical of an average June, being in the order of 1-2%. The study indicates that dry flow years are important in terms of the availability of habitat with water velocities suitable for fry.

i: Marginal habitats are very important in the provision of suitable fry habitat in relation to water velocity, cover and depth. Further studies are required to assess the comparative value and abundance of different marginal habitat types.

5 RECOMMENDATIONS

Further studies to develop the ability to appraise the impact of proposed flow management on the physical habitat of fish in the River Thames, will require considerable resources over the medium term. The requirement for this needs to be carefully considered in the context of the proposed management and the information requirements to consider such a proposal. If such development is considered necessary, the following recommendations are appropriate:

a: Any future study assessing the impact on physical habitat must be within a wider framework of studies assessing other key factors which influence fish populations in lowland rivers (e.g. temperature, water quality, food supply). The wider IFIM framework is flexible and provides one tool for the development of such an approach.

b: A full habitat mapping study of the area of river in question is recommended to identify and quantify the availability of different marginal habitat types. In addition data should be collected to quantify the variability in water surface elevations, due to different weir levels, with distance above each weir within the study area. These data will identify the need to survey additional study transects, allow PHABSIM habitat simulations to properly reflect the distributions of habitat within the river and allow the sensitivity of habitat availability to changes in weir levels to be assessed. If any additional study transects are examined, care must be take to survey sufficient data points to robustly model the marginal habitats (or any other important habitats identified).

c: Refinement of the hydraulic calibrations on the existing study transects is required if these are to be used to develop the tool further. Data should be collected to quantify the variability of stage with weir levels at each of the study transects to account for variations in weir levels between water surface level calibration data sets. The existing hydraulic model calibration should then be reviewed and if necessary adjusted prior to carrying out any further analysis of habitat changes due to variations in water surface level resulting from weir management.

d: Studies should also be carried out to refine the accuracy of the simulated velocities in the channel margins. Further data is required to assess the variability of velocities in the channel margins and this information should examine the key marginal habitats in more detail. Additional sets of velocity data should be obtained from the channel margins to confirm or improve model outputs. These should also be obtained on a seasonal basis to allow the incorporation of variations in macrophyte density in the assessment. The availability of data collection techniques to measure velocity data at a level of accuracy commensurate with the sensitivity of fry and juvenile fish to flow velocities under low flow conditions in the River Thames must be examined.

e: The development of robust information on fish habitat requirements is a fundamental requirement for any future assessment of proposals for changing flow management. Further assessment of a strategy for the development of this information on the River Thames should be undertaken.

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Appendix A: Gauging Station Summary Sheets for Day's Weir and Sutton Courtenay

National River Flow Archive Data Retrieval Service

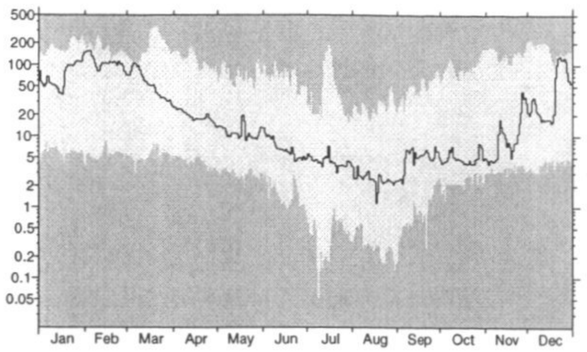
River Flow Measuring Station Information Sheet

Thames at Days Weir

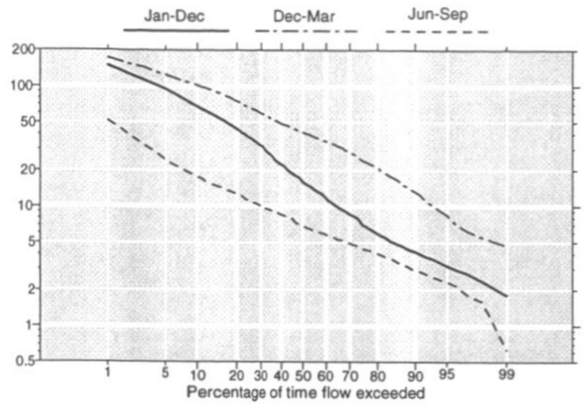
Measuring Authority:	Environment Agency	Gauged Flows and Rainfall:	1938-1996
Grid Reference:	41 (SU) 568 935	IH Station Number:	39002
Station Type:	Miscellaneous	Local Number:	1900

Daily Flow Hydrograph

Max. and min. daily mean flows from 1938 to 1996 excluding those for the featured year (1995; mean flow: 29.50 m^3s^{-1})



Flow Duration Curve



Flow Statistics

(Units: m^3s^{-1} unless otherwise stated)

Mean flow	28.00	
Mean flow (ls^{-1}/km^2)	8.14	
Mean flow ($10^6m^3/yr$)	885.0	
Peak flow / date		
Highest daily mean / date	349.0	17 Mar 1947
Lowest daily mean / date	0.050	7 Jul 1976
10 day minimum / end date	0.163	15 Jul 1976
60 day minimum / end date	0.338	2 Sep 1976
240 day minimum / end date	2.704	25 Sep 1976
10% exceedance (Q10)	67.810	
50% exceedance (Q50)	15.940	
95% exceedance (Q95)	3.181	
Mean annual flood	147.9	
IH Baseflow index	0.64	

Rainfall and Runoff

	Rainfall (1938-1995) mm					Runoff (1938-1996) mm				
	Mean	Max/Yr		Min/Yr		Mean	Max/Yr		Min/Yr	
Jan	68	132	1948	13	1987	44	104	1939	5	1976
Feb	47	135	1950	3	1959	40	85	1977	4	1976
Mar	53	152	1947	5	1961	35	127	1947	4	1976
Apr	47	99	1961	4	1984	23	64	1951	3	1976
May	58	131	1979	7	1990	16	48	1983	2	1976
Jun	54	124	1985	5	1942	11	31	1955	1	1976
Jul	53	117	1950	5	1955	7	38	1968	0	1976
Aug	64	149	1977	3	1940	6	15	1977	0	1976
Sep	62	129	1974	5	1959	7	29	1946	1	1959
Oct	64	163	1949	6	1978	12	58	1960	2	1959
Nov	70	178	1940	8	1945	23	96	1960	3	1990
Dec	73	316	1985	16	1991	35	100	1960	4	1975
Year	713	973	1960	492	1964	257	471	1960	92	1973

Station and Catchment Characteristics

Station level	(mOD)	45.8
Sensitivity	(%)	
Bankfull flow		
Catchment area	(km^2)	3445.
Maximum altitude	(mOD)	330
FSR slope (S1085)	(m/km)	0.37
1961-90 rainfall (SAAR)	(mm)	690
FSR stream frequency (STMFRQ)	(junctions/km^2)	
FSR percentage urban (URBAN)		

Station and Catchment Description

Adjustable thin-plate weir (5.48m wide) plus 15 radial gates, replaced a barrage of radial and buck gates in 1969. Rating formulae based upon gaugings - tailwater calibration applies for flows > 70 cumecs; above 100 cumecs overspill occurs. Daily naturalised flows available for POR (equal to gauged flows up to 1973) - allow for Didcot P S losses only.

Mixed geology (Oolitic Limestone headwaters, Oxford Clay below). Predominately rural with development concentrated along the valley.

Factors Affecting Runoff

- Runoff reduced by public water supply abstraction.
- Runoff reduced by industrial and/or agricultural abstraction.
- Runoff increased by effluent returns.

Summary of Archived Data

Gauged Flows and Rainfall

Key:	All rainfall	Some or no rainfall
All daily, all peaks	A	a
All daily, some peaks	B	b
All daily, no peaks	C	c
Some daily, all peaks	D	d
Some daily, some peaks	E	e
Some daily, no peaks	F	f
No gauged flow data	=	-

	0 1 2 3 4	5 6 7 8 9
1930s	- - - - -	- - - f C
1940s	C C C C C	C C C C C
1950s	C C C C C	C C C C C
1960s	C C C C C	C C C C C
1970s	C C C C C	C C C C C
1980s	C C C C C	C C C C C
1990s	C C B A A	A e

Naturalised Flows

Key:	
All daily, all monthly	A
Some daily, all monthly	B
Some daily, some monthly	C
Some daily, no monthly	D
No daily, all monthly	E
No daily, some monthly	F
No naturalised flow data	=

	0 1 2 3 4	5 6 7 8 9
1930s	- - - - -	- - - C A
1940s	A A A A A	A A A A A
1950s	A A A A A	A A A A A
1960s	A A A A A	A A A A A
1970s	A A A A A	A A A A A
1980s	A A A A A	A A A A A
1990s	A A A A A	A D

Institute of Hydrology, Wallingford, Oxon OX10 8BB, UK.Tel. (01491) 838800.

20th March 1997

River Flow Measuring Station Information Sheet

Thames at Sutton Courtenay

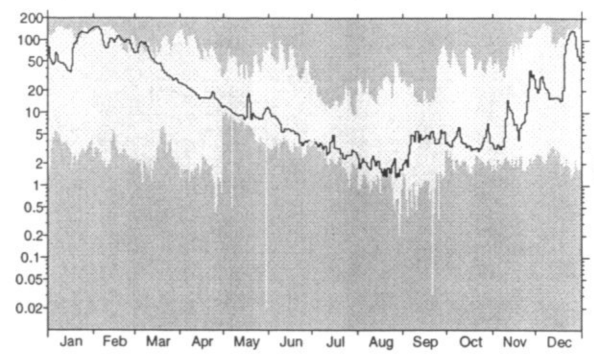
Measuring Authority: Environment Agency
Grid Reference: 41 (SU) 516 946
Station Type: Ultrasonic

Gauged Flows and Rainfall: 1973-1996
IH Station Number: 39046
Local Number: 1800

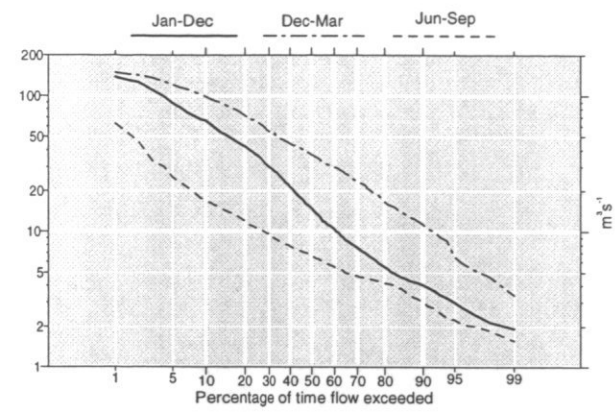
National River Flow Archive
Data Retrieval Service

Daily Flow Hydrograph

Max. and min. daily mean flows from 1973 to 1996 excluding those for the featured year (1995; mean flow: 28.50 m^3s^{-1})



Flow Duration Curve



Flow Statistics

(Units: m^3s^{-1} unless otherwise stated)

Mean flow	24.80	
Mean flow (ls^{-1}/km^2)	7.25	
Mean flow ($10^6m^3/yr$)	782.0	
Peak flow / date	221.0	18 Nov 1973
Highest daily mean / date	170.0	5 Dec 1992
Lowest daily mean / date	0.020	29 May 1976
10 day minimum / end date	0.794	30 Aug 1975
60 day minimum / end date	1.469	28 Sep 1990
240 day minimum / end date	2.437	16 Mar 1976
10% exceedance (Q10)	66.990	
50% exceedance (Q50)	12.280	
95% exceedance (Q95)	2.062	
Mean annual flood		
IH Baseflow index	0.62	

Rainfall and Runoff

	Rainfall (1973-1995) mm					Runoff (1973-1996) mm				
	Mean	Max/Yr		Min/Yr		Mean	Max/Yr		Min/Yr	
Jan	70	122	1995	22	1976	43	81	1994	3	1976
Feb	52	125	1977	8	1993	38	79	1990	2	1976
Mar	62	128	1981	15	1990	29	61	1979	2	1976
Apr	42	95	1983	4	1984	23	45	1987	11	1990
May	56	129	1979	7	1990	15	32	1979	5	1990
Jun	52	124	1985	10	1995	12	29	1985	3	1990
Jul	45	94	1978	11	1977	6	9	1977	2	1974
Aug	55	148	1977	4	1995	5	14	1977	1	1990
Sep	71	127	1981	14	1977	6	24	1992	1	1990
Oct	60	111	1976	5	1978	10	32	1992	2	1975
Nov	62	127	1984	28	1990	13	41	1974	2	1978
Dec	78	141	1979	16	1991	29	50	1989	5	1973
Year	705	864	1992	537	1990	229	305	1979	142	1991

Station and Catchment Characteristics

Station level	(mOD)	44.9
Sensitivity	(%)	
Bankfull flow		
Catchment area	(km^2)	3414.
Maximum altitude	(mOD)	330
FSR slope (S1085)	(m/km)	
1961-90 rainfall (SAAR)	(mm)	691
FSR stream frequency (STMFRQ)	(junctions/km^2)	
FSR percentage urban (URBAN)		

Station and Catchment Description

Multi-path ultrasonic gauging station replaced original (first in the UK) single path device in 1982; early data of lower precision. Rectangular channel in straight, navigable reach. Levels, and velocity profile relative to the four ultrasonic flightpaths, influenced by d/s sluices. Some negative flows in 1976 (dmfs not archived). All but highest flows contained. Station between offtake and discharge for Didcot P.S. (naturalised flows available).

Mixed geology: Oolitic Limestone headwaters, Oxford Clay below. Mainly rural with development concentrated in the valleys.

Factors Affecting Runoff

- Runoff reduced by public water supply abstraction.
- Runoff reduced by industrial and/or agricultural abstraction.
- Runoff increased by effluent returns.

Summary of Archived Data

Gauged Flows and Rainfall

	0 1 2 3 4	5 6 7 8 9
1970s	- - - e A	E E E E A
1980s	E = = = E	D d d a D
1990s	D A D D A	D e

Key:

	All rainfall	Some or no rainfall
All daily, all peaks	A	a
All daily, some peaks	B	b
All daily, no peaks	C	c
Some daily, all peaks	D	d
Some daily, some peaks	E	e
Some daily, no peaks	F	f
No gauged flow data	=	-

Naturalised Flows

	0 1 2 3 4	5 6 7 8 9
1970s	- - - D A	D D D D A
1980s	D - - - D	D D D D D
1990s	D A D D A	D D

Key:

All daily, all monthly	A
Some daily, all monthly	B
Some daily, some monthly	C
Some daily, no monthly	D
No daily, all monthly	E
No daily, some monthly	F
No naturalised flow data	=

Appendix B: Photographs of the Clifton Hampden Study Reach

Photograph 1: Clifton Hampden Study Reach Under High Discharge Conditions (97.2 m^3s^{-1})

Photograph 2: Clifton Hampden Study Reach Cross Section 1

Photograph 3: Clifton Hampden Study Reach Cross Section 2

Photograph 4: Clifton Hampden Study Reach Cross Section 3

Photograph 5: Clifton Hampden Study Reach Cross Section 4

Appendix C: PHABSIM calibration data

Cross Section 1

Reach Length	=	0	WSL at 97.2 m^3s^{-1}	=	99.387
WSL at 15.1 m^3s^{-1}	=	98.828	WSL at 3.91 m^3s^{-1}	=	98.769

Distance From R.H. Peg (Looking D/S)	Relative Elevation	Velocity at 97.2 m^3s^{-1}	Velocity at 15.1 m^3s^{-1}	Velocity at 3.91 m^3s^{-1}	Dominant Substrate
0	100.000	0	0	0	Silt
2.6	98.487	0.613	0.068	0.02	Silt
3.1	98.127	0.795	0.087	0.04	Silt
3.6	97.957	0.817	0.117	0.06	Silt
4.1	97.687	0.784	0.076	0.05	Silt
4.6	97.727	0.784	0.147	0.06	Silt
5.1	97.587	0.882	0.124	0.06	Silt
5.6	97.527	0.96	0.098	0.05	Silt
6.1	97.407	0.944	0.153	0.02	Silt
6.6	97.377	1.115	0.121	0.06	Sand
7.1	97.337	1.054	0.147	0.04	Silt
7.6	97.227	1.048	0.241	0.07	Silt
8.1	97.027	1.154	0.179	0.07	Sand
8.6	97.157	1.08	0.218	0.08	Gravel
9.1	97.007	1.041	0.229	0.09	Gravel
9.6	97.007	1.056	0.21	0.08	Gravel
10.1	97.017	1.161	0.177	0.06	Gravel
10.6	97.187	1.311	0.223	0.08	Gravel
11	97.127	1.209	0.209	0.09	Gravel
12	97.087	1.234	0.229	0.08	Gravel
13	97.167	1.286	0.263	0.07	Sand
14	97.137	1.403	0.28	0.08	Sand
15	97.197	1.392	0.302	0.08	Sand
16	97.197	1.37	0.301	0.07	Sand
17	97.157	1.505	0.321	0.09	Sand
18	97.137	1.482	0.323	0.11	Sand
19	97.147	1.434	0.327	0.04	Sand
20	97.047	1.418	0.285	0.1	Sand
25	97.147	1.397	0.291	0.1	Sand
30	97.267	1.373	0.264	0.08	Sand
31	97.197	1.263	0.251	0.09	Sand
32	97.237	1.291	0.256	0.09	Sand
33	97.227	1.183	0.266	0.08	Sand
34	97.377	1.212	0.256	0.09	Sand
35	97.387	1.165	0.182	0.05	Sand
36	97.437	1.224	0.121	0.07	Sand
37	97.387	1.113	0.089	0.04	Sand
38	97.407	0.92	0.117	0.03	Sand
39	97.387	0.741	0.099	0.02	Sand
40	97.517	0.65	0.083	0.02	Silt
41	97.487	0.577	0.019	0.02	Silt
42	97.487	0.61	0	0.02	Silt
43	97.917	0.582	0	0.03	Silt
43.5	98.007	0.444	0	0	Silt
45	98.715	0	0	0	Silt
46.4	99.526	0	0	0	Silt

Cross Section 2

Reach Length (from C/S 1) = 107.20 WSL at 97.2 m^3s^{-1} = 99.391
WSL at 15.1 m^3s^{-1} = 98.828 WSL at 3.91 m^3s^{-1} = 98.769

Distance From R.H. Peg (Looking D/S)	Relative Elevation	Velocity at 97.2 m^3s^{-1}	Velocity at 15.1 m^3s^{-1}	Velocity at 3.91 m^3s^{-1}	Dominant Substrate
0	99.915		0	0	Silt
2.5	98.578		0	0	Silt
3	98.548		0	0	Silt
3.5	98.528		0	0	Silt
4	98.508		0	0	Silt
4.5	98.498		0	0	Silt
5	98.458		0	0	Silt
5.5	98.458		0	0	Silt
6	98.428		0	0	Silt
6.5	98.338		0	0	Silt
7.5	97.698		0.152	0.036	Silt
8.5	97.578		0.161	0.067	Sand
9.5	97.088		0.211	0.059	Sand
13.5	97.118		0.299	0.09	Sand
17.5	97.038		0.317	0.068	Sand
21.5	97.078		0.342	0.095	Sand
25.5	97.228		0.29	0.111	Sand
29.5	97.318		0.325	0.098	Sand
33.5	97.488		0.275	0.093	Sand
35.5	97.498		0.203	0.082	Sand
37.5	97.628		0.192	0.061	Sand
39.5	97.628		0.122	0.048	Sand
40.5	97.708		0.052	0.02	Sand
41.5	97.728		0.092	0.001	Silt
42.5	97.848		0.096	0.006	Silt
43.5	98.502		0	0	Silt
44.5	99.915		0	0	Silt
45.5	99.995		0	0	Silt
46.5	99.995		0	0	Silt

Cross Section 3

Reach Length (from C/S 2)	=	45.77	WSL at 97.2 m^3s^{-1}	=	99.425
WSL at 15.1 m^3s^{-1}	=	98.834	WSL at 3.91 m^3s^{-1}	=	98.771

Distance From R.H. Peg (Looking D/S)	Relative Elevation	Velocity at 97.2 m^3s^{-1}	Velocity at 15.1 m^3s^{-1}	Velocity at 3.91 m^3s^{-1}	Dominant Substrate
0	99.979	0	0	0	Silt
7	99.97	0	0	0	Silt
7.5	99.100	0	0	0	Silt
8	98.835	0.177	0.075	0	Silt
9	98.045	0.652	0.134	0	Silt
10	97.605	0.777	0.206	0.035	Silt
11	97.605	0.849	0.174	0.028	Silt
12	97.405	0.946	0.216	0.037	Sand
13	97.245	0.943	0.206	0.052	Sand
14	97.315	0.929	0.245	0.065	Sand
15	97.295	0.985	0.279	0.057	Sand
20	97.205	1.133	0.366	0.045	Sand
30	97.335	1.419	0.312	0.094	Sand
35	97.285	1.347	0.325	0.094	Sand
40	97.365	1.321	0.274	0.064	Sand
45	97.475	1.45	0.212	0.047	Sand
46	97.525	1.374	0.224	0.04	Sand
47	97.515	1.469	0.165	0.047	Sand
48	97.645	1.393	0.129	0.033	Sand
49	97.565	1.063	0.129	0.021	Sand
50	97.765	0.924	0.111	0	Silt
51	97.765	0.763	0.05	0	Silt
52	97.765	0.487	0.047	0	Silt
53	98.615	0	0	0	Silt
54	99.979	0	0	0	Silt
62.6	100.257	0	0	0	Silt

Cross Section 4

Reach Length (from C/S 2)	=	183.89	WSL at 97.2 m^3s^{-1}	=	99.547
WSL at 15.1 m^3s^{-1}	=	98.844	WSL at 3.91 m^3s^{-1}	=	98.771

Distance From R.H. Peg (Looking D/S)	Relative Elevation	Velocity at 97.2 m^3s^{-1}	Velocity at 15.1 m^3s^{-1}	Velocity at 3.91 m^3s^{-1}	Dominant Substrate
0	100.064	0	0	0	Silt
4	99.547	0	0	0	Silt
5	98.167	0.655	0.021	0	Silt
6	98.047	0.738	0.067	0.042	Silt
7	97.987	0.795	0.136	0.042	Silt
8	97.947	0.849	0.192	0.094	Silt
9	97.847	0.926	0.21	0.054	Silt
10	97.897	0.941	0.256	0.061	Sand
11	97.897	1.059	0.229	0.068	Sand
12	97.847	1.019	0.247	0.084	Sand
13	97.807	1.123	0.25	0.082	Sand
14	97.707	1.108	0.227	0.074	Gravel
19	97.327	1.259	0.277	0.061	Gravel
24	97.217	1.271	0.278	0.025	Gravel
29	97.347	1.329	0.318	0.098	Gravel
34	97.427	1.096	0.319	0.103	Sand
39	97.427	1.145	0.264	0.083	Sand
40	97.447	1	0.312	0.083	Sand
41	97.527	1.036	0.263	0.041	Sand
42	97.547	0.946	0.278	0.076	Sand
43	97.587	0.88	0.237	0.072	Sand
44	97.547	0.909	0.261	0.081	Sand
45	97.597	0.892	0.22	0.026	Sand
46	97.587	0.851	0.185	0.01	Silt
47	97.727	0.852	0.229	0.006	Silt
48	97.747	0.685	0.109	0	Silt
49	97.807	0.5	0.104	0	Silt
50	98.247	0.371	0.051	0	Silt
51	98.447	0.013	0.058	0	Silt
52	98.947	0.02	0.064	0	Silt
53	99.047	0	0.068	0	Silt
54	99.147	0	0	0	Silt
55	99.347	0	0	0	Silt
56	99.497	0	0	0	Silt
67.7	99.949	0	0	0	Silt