Urban regeneration and environment (URGENT)

Modelling River Corridors: Task 5 Report – Hydroecological Modelling

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Executive Summary

River corridors provide areas of biodiversity that play important aesthetical and economical roles in urban environments. Many urban rivers in the UK have been influenced by flow regulation, river channel alteration, effluent disposal and pollution. Urban rivers are particularly impacted as impermeable surfaces cause flashy runoff, concrete straightened channels provide poor physical habitat and contaminated land or effluent disposal create poor water quality. These alterations combine to determine the health of river corridor ecosystems. There is an economical and social benefit of urban regeneration including rivers and river corridors. The NERC URGENT "Modelling River Corridors: the scientific basis for rehabilitation of urban rivers" program was designed to carry out the science necessary to underpin cost effective urban regeneration.

The Physical Habitat Simulation (PHABSIM) model has been used to assess physical habitat of urban rivers at six sites in Birmingham. The PHABSIM model has been applied to pairs of reaches on the rivers Tame, Cole and Rea. Each pair of sites were selected on a space for time substitution basis with each pair representing different levels of habitat diversity in the particular river, but located within, at most, 0.75 km of each other. Field data have been collected to calibrate the hydraulic component of the PHABSIM model for all sites. Habitat suitability curves are then used to assess physical habitat quality and quantity within each of the modelled reaches for a range of flows. The modelling process allows assessment of the extent to which restoration of channel morphology may improve physical habitat in comparison to changes in flow regime. Results suggest that the poorest physical habitat occur in the more engineered channels at the highest flows implying that reduction of peak flows may be equally as beneficial to ecology as local restoration of channel morphology.

Physical habitat predictions were then used to calculate a Physical Habitat Assessment Score (PHAS). This score provides an objective assessment of physical habitat predictions. The modelling process allows assessment of the extent to which restoration of channel morphology may improve physical habitat in comparison to changes in flow regime. Scenarios of changes in flow regime, in the form of hourly time-series, were used to assess the impact that changes in flow may have on physical habitat. Results show that an increase in runoff would have detrimental effects in all cases, and that decreases in flow would benefit physical habitat. The less modified sites benefited marginally more than the more modified from decreases in flow. The benefit to physical habitat gained from three different scenarios, which all represented decreases in the flow regime, was assessed. Results showed that there was little difference in benefit received between these three scenarios.

Three-dimensional computational fluid (3D-CFD) dynamics modelling was also used to assess physical habitat suitability at high flows in urban rivers. A 3D-CFD code, called SSIIM, was used to simulate hydraulic conditions in two engineered river reaches of the River Tame, Birmingham, UK. These two sites represent channels with different levels of engineering. Models were calibrated and tested using field measurements. Results show that modelled water surface levels and velocity profiles are well simulated. Calibrated roughness heights are compared with those derived from field measurement of sediment size. Numerical experiments are used to assess the relationship between grid resolution in the vertical dimension and the form of the modelled velocity profiles. Biologists have used laboratory experiments to determine Maximum Sustainable Swimming Speeds (MSSS) of fish, often in order to assess what level of a particular pollutant may be tolerable. In this work, simulations of high flow hydraulic patterns are used to compare velocity patterns with fish MSSS. Results show that when the water levels rise to fill the first channel of the two-stage channels at the sites, which occurred 16 times in 2000, MSSS are surpassed in the majority of available habitat suggesting that excessive velocities at high flows are one factor that limits fish habitat. A comparison between the two reaches shows that there is less available habitat in the more modified reach. Conclusions suggest that an approach that integrates water quality issues and physical channel characteristics must be taken in river rehabilitation schemes, as improvements to water quality alone may not be sufficient to improve habitat quality to the desired level.

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Research paper submitted to Regulated Rivers

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Abstract

Prediction of changes to in-stream ecology are highly desirable if decisions on river management, such as those relating to water abstractions and effluent discharges or adjustments to the river channel, are to be justified to stakeholders. The Physical Habitat Simulation (PHABSIM) system is a hydro-ecological model that provides a suite of tools for the numerical modelling of hydraulic habitat suitability for fish and invertebrate species. Public policy emphasis on continual improvement of river water quality has given impetus to the consideration of physical habitat in urban river systems. In the UK, the most high-profile PHABSIM studies have focused on rural groundwater dominated rivers and have related to low flow issues. Urban rivers have been somewhat neglected in the development of predictive hydro-ecological models. This paper demonstrates elements of a best practice methodology for physical habitat modelling which deviate from those previously published. In urban rivers, lack of refuge habitat during high flows is often of key importance. This emphasises the need for accurate information relating to the response of fish and other organisms to high velocities, an area of research that has been neglected in the UK. Urban river flow regimes require simulation of hydraulics, and therefore habitat, over a wide range of flow conditions, a technically difficult task. The temporal resolution of both the input flow time-series and the subsequent habitat analysis procedures are important when considering flashy urban runoff regimes. Water quality issues may also complicate verification of physical habitat simulations. Results show that PHABSIM can be used to assess physical habitat health when applied to urban rivers provided that the appropriate methodology is employed.

Introduction

Application of river habitat models

Assessment of possible management options often involves assessing scenarios of future states that fall outside the range of present river conditions. This negates investigation using direct analysis of field observations and necessitates the use of predictive models. The Physical Habitat Simulation (PHABSIM) system is a suite of numerical modelling tools which allows at-site quantification of physical habitat defined in terms of the combination of depth, velocity and substrate/cover present in a river at a particular discharge (e.g. Johnson *et al.*, 1993; Elliott *et al.*, 1996). The system can be used to assess hydraulic habitat over a range of flows and therefore make predictions as to the effects of changes in flow regime or physical changes to channel structure such as those incorporated into river rehabilitation schemes. This system is most commonly used to describe physical habitat suitability for fish, although invertebrates and macrophytes which have measurable physical habitat requirements can also be assessed. In the past PHABSIM has been used to assess changes in physical habitat with changes in flow regime, for example, application to the Rivers Allen (Johnson *et al.*, 1995) and Piddle (Strevens, 1999). This type of study has often been undertaken to aid management decisions concerning future abstraction levels in groundwater dominated rivers. An example from the UK has been its use to support negotiation over the impacts of groundwater pumping on river flows, and thus the ecology of the River Kennet, an important Chalk stream (McPherson, 1997). PHABSIM has also been used to assess the impact of channel restoration on the River Wey (Acreman and Elliott, 1996).

The approach adopted in many PHABSIM studies was outlined by Elliott *et al.* (1999). This approach includes identification of river sectors and species of interest, identification of habitats that exist within the sectors of interest, selection of cross-sections which represent replicates of each habitat type and collection of model calibration data (water surface elevation, depth and velocity). This allows prediction of usable physical habitat for the species / life stage of interest. Usable physical habitat is commonly expressed as Weighted Usable Area (WUA) in m^2 per 1000m of river channel. WUA is an aggregate measure of physical habitat quality and quantity and will be specific to a particular discharge and species / life stage. Further details are provided in Johnson *et al.* (1995). Assessment of the changes in WUA which might occur as a result of any proposed changes in flow regime using time-series scenarios of any proposed changes in flow regime can then be made.

Elliott et al. (1999) demonstrated that the application of physical habitat modelling to groundwater dominated rivers was distinctive because of the physical characteristics and flow regime of this type or river. In previous studies on groundwater-dominated rivers, physical habitat at low flow has been the main area of interest. Physical habitat models have primarily been used to compare the implications of alternative flow regulation scenarios on habitat. This has lead to an emphasis on investigation of physical habitat for specific species at low flows conditions (i.e. the relationship between discharge and usable habitat given a distribution of relatively shallow depths and slow velocities).

Urban Rivers

Rivers corridors provide areas of wildlife habitat and play important aesthetic and economic roles in urban environments. Many urban rivers in the UK have suffered degradation of their hydro-morphological and physico-chemical habitat from a combination of flow regulation, river channel alteration, effluent disposal and pollution. It is the complex interaction between flow regime, water quality regime and channel structure that determine the health of river corridor ecosystems (May *et al.*, 1997; Walsh *et al.*, 2001). Urban rivers are particularly impacted as impermeable surfaces cause flashy runoff, engineered straightened channels provide poor physical habitat (Beavan *et al.*, 2001) and contaminated land (Flavin and Harris, 1991) or effluent disposal (Carr *et al.*, 2000) create poor water quality. This level of impact is not confined to highly urbanised areas. The River Habitat Survey showed that over 50% of lowland rivers in England and Wales were either obviously, significantly or severely modified (Raven *et al.*, 1998).

Environmental improvements to urban river corridors are possible through strategic action at different scales (Ellis, 1995). Potential areas for improvement to urban rivers include source control of runoff and pollutants, reduction of peak flows and physical enhancement of the channel structure. Management decisions require quantification of the relative improvements that might occur when each, or any combination, of these factors is affected in a catchment. For example, where the aim of a scheme is the restoration of fish stocks, improvements in water quality may not be able to improve river ecology to the desired state, if physical habitat remains inadequate.

This paper addresses issues relating to the application of PHABSIM to urban rivers. Its aim is to outline, using specific examples, how the physical characteristics and flow regimes of urban rivers can be incorporated into the physical habitat modelling process. The physical habitat requirements of dace (*Leuciscus leuciscus L.*), roach (*Rutilus rutilus L.*) and chub (*Leuciscus cephalus L.*) have been used to illustrate these examples. The advantages and disadvantages of using PHABSIM in urban rivers are highlighted and should be considered when interpreting predictions of physical habitat suitability. The study is focused on the River Tame in the West Midlands, UK, where. Further contextual details are provided in Webster *et al.*, (2001).

Methods

Study site selection

In order to investigate the degree to which usable physical habitat for fish differs between river reaches with different levels of channel modification a pair of sites on the main River Tame was chosen. Table I gives a description and some summary information for each reach. The sites investigated for this study where chosen to represent channels with differing levels of geomorpohological diversity as a result of channel modification. Two sites were chosen which were 640m apart. The close proximity of the sites to each other ensured that the water quality and flow regime of the sites could be considered as the same. Measurement of substrate classes along each cross-section at the sites showed that the size distribution of substratum was not significantly different between the sites.

Investigation of urban river classification has shown that the level of channel modification ranges widely for rivers in the Tame catchment (Davenport *et al.*, 2001). Both sites investigated in this study were broadly representative of the type of river channels found in urban catchments in that they have been modified in order to improve flood conveyance.

However, neither of the sites was at the extreme extent of the channel modification scale. For example, the Tame below the M6 Motorway is completely concreted, whereas in other reaches of the Tame active channel processes (erosion/deposition) and fully developed pool-riffle sequences exist.

Table I. Description and summary of the two PHABSIM reaches.

River	Reach name	Description	National Grid Reference	Reach length	Average width	No. of cross-sections
Tame	Highly Modified	Highly straightened, highly channelised, two stage channel.	SP029927	90.4	11.1	4
	Less Modified	Straightened, two stage channel, some geomorphological diversity.	SP030925	137.7	9.4	5

Model calibration data

The procedure for site set up and collection of PHABSIM calibration data given by (Elliott *et al.*, 1996) was followed for both sites. This calibration data consisted of measurements of water surface elevation and depth-averaged velocity along several marked cross-sections. Table II shows the discharges at which calibration data were collected. The flashy nature of flow regimes in urban rivers made data collection at high flows particularly difficult as high flow events occur very rapidly in response to particular rainfall events and can recede quickly. Furthermore, collection of velocity data at high flows is hazardous unless procedures using cableways or gaugings from bridges are employed. Under these circumstances water surface elevations could be measured and a value of discharge obtained from the nearest Environment Agency gauging station. This was not seen as a problem as the reaches were located either side of a stage-logging gauging station and 4km downstream of a discharge-logging gauging station. In this respect the relatively large number of gauging stations in urban catchments can be seen as an advantage in terms of PHABSIM type applications. Trash marks (lines of debris left after a flood marking the maximum water surface elevation) were also used to indicate the maximum water surface elevation of a particularly large event ($35 m^3 s^{-1}$) during October 2000.

Table II. The discharges at which calibration data were collected at each site.

	Tame Highly Modified			Tame Less Modified		
Data set	Discharge (m^3s^{-1})	Water surface	Velocity	Discharge (m^3s^{-1})	Water surface	Velocity
1	2.53	✓	✓	1.46	✓	x
2	3.67	✓	✓	2.10	✓	✓
3	4.78	✓	✓	2.56	✓	✓
4				2.82	✓	x
5				4.37	✓	✓

Water level simulation

The calibration data were used to create simulations of the distribution of available depths and velocities for each site for a range of flows. For each site, water surface elevations at the most downstream cross-section were simulated using a simple rating curve approach. The form of these rating curves matched that derived from water levels obtained from spot gaugings taken at the gauging station in-between the sites (Figure 1). Stage increases slightly faster above $15m^3s^{-1}$ at the gauging structure, which is designed to be of constant width. Although there was some hysteresis in the stage-discharge relationship during flood events, this was minor and did not significantly affect the results of the physical habitat modelling.

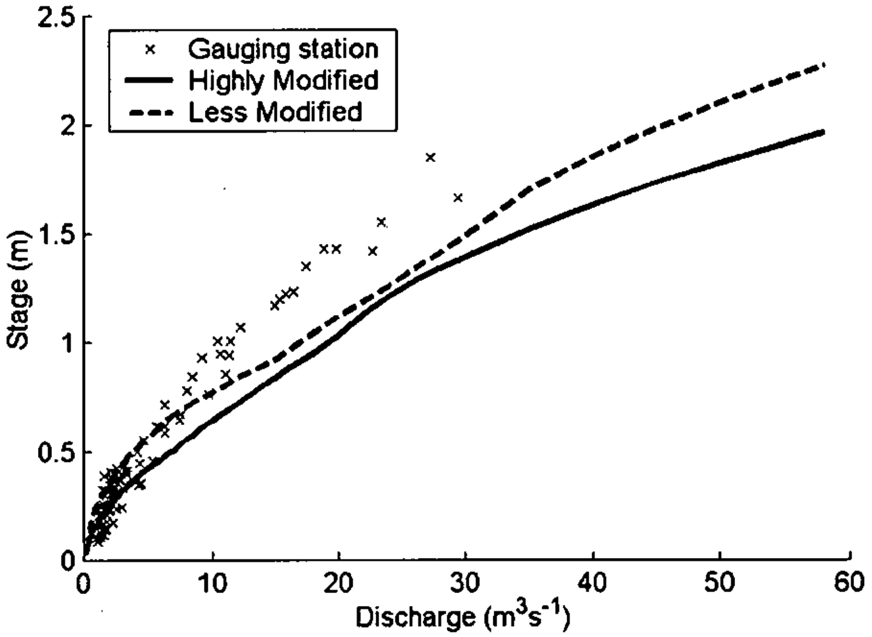

Figure 1. Stage-discharge relationships for the downstream cross-sections of each site compared with spot gaugings measured at a gauge structure located between the sites (stage is datum is specific to each site).

One-dimensional steady-state step backwater models were used to simulate water surface elevations upstream. For example, Figure 2 shows results of modelled water surface elevations for the most upstream cross-section at the River Tame Highly Modified site. This method of water surface modelling is the most physically-based approach available within the PHABSIM modelling suite. The approach provides the ability to include both spatial changes in roughness and variations in roughnesses that occur as discharge increases. In some respects the nature of urban channels was beneficial in the hydraulic modelling process. In general spatial variations in roughness within each site were small, reflecting the similarity in cross-sectional shape and homogenous nature of urban river channels due to a lack of roughness transitions such as those described by Robert *et al.* (1996) for more natural rivers with pools and riffles. Thus a lack of hydraulic controls simplified modelling of water surface elevations.

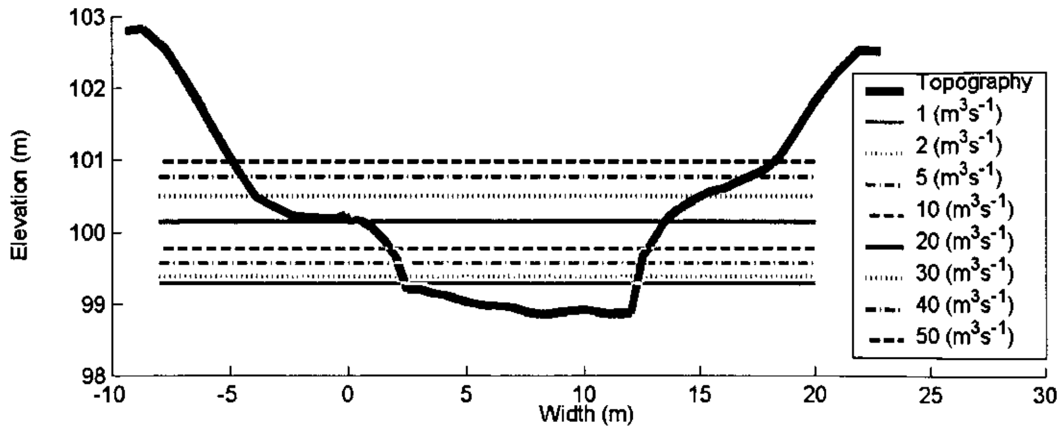

Figure 2. Modelled water surface elevations at different discharges (m^3s^{-1}), Tame Highly Modified site, Cross-section 4.

As the water surface elevation models were steady-state, it was assumed that for each specific discharge, the water surface slope did not change with time. This assumption is likely to be broken to some degree for flood waves travelling down the river. However the short length of each site, and the general lack of habitat at high discharges mean that any errors introduced into the habitat calculations from this assumption are likely to be small.

Velocity simulation

There are three methods of velocity modelling available in PHABSIM, each requires boundary conditions of topography, discharge and water surface elevation data. Cross-sections are treated independently and divided into discrete cells. The three methods are a) using a single calibration set, b) using no velocity calibration data, and c) simultaneous use of multiple calibration sets using regression. Combinations of these approaches may be used within a single model for different portions of the flow range. Choice of approach will depend on available data and channel complexity. These factors, plus the skill of the modeller will determine the accuracy of the modelling.

For modelling using a single set of measured velocities (method a) for calibration, Manning's equation may be re-written as:

$$v_i = \left(S_e^{\frac{1}{2}} d_i^{\frac{2}{3}} \right) \Big/ n_i \quad . \tag{1}$$

Where v_i is the velocity at vertical i across a cross-section, S_e is the energy slope and n_i is a cell roughness coefficient. Depth of each cell, (d_i), is used as a substitute for hydraulic radius as cell width will be narrow compared to cell depth. In the calibration process, n_i is calculated using measured v_i and d_i for each cell at the calibration discharge. S_e can either be calculated from measured water level data or modelled water level data, or a default value may be assumed. As the n values are only used to distribute velocities across a cross-section, any assumption of S_e will not affect model results, although it would be important if the user wishes to compare n values between cross-sections.

Simulation at non-calibration discharges is undertaken by calculating v_i, given known d_i from the water surface model and the n values derived above. As the sum of all the cell discharges (calculated as velocity multiplied by area) will not exactly equal that of the original total conveyance used in the water surface level calculation, the ratio between the two is calculated (VAF) and used to derive an adjusted velocity value (v_{inew}) for each cell using

$$Q_{calculated} = \sum_{i=1}^{ncell} A_i v_i \quad , \tag{2}$$

$$VAF = \frac{Q_{calculated}}{Q_{simulated}} \quad , \tag{3}$$

and

$$v_{inew} = v_i VAF \quad . \tag{4}$$

Modelling of velocities using no calibration data (method b) proceeds in a similar fashion, the only difference being that the distribution of depths across each cross-section is used to derive n values. Modelling of velocities using three calibration data sets (method c) is quite different. For each cell a regression of the form

$$\log(v_i) = \log(c_i) + f_i \log(Q_i) \quad , \tag{5}$$

(where c_i and f_i are constants to be determined) is undertaken on the three velocities measured at different discharges.

For two sites on the River Tame velocity modelling was more uncertain at flows above the highest calibration data set as comparisons with real data could not be made. In these cases velocity was modelled as being proportional to depth with no calibration data. This type of modelling lacks the process representation of three-dimensional fluid dynamics modelling (e.g. Booker *et al.*, 2001). However, the approach is less problematic in relatively uniformly shaped urban rivers where sinuous planforms or pool-riffle sequences do not cause the more complicated flow patterns found in natural rivers. A sensitivity analysis showed that calculated physical habitat did not change significantly when the different methods were used to model velocity. This was largely because at these high discharges, the majority of the channel had velocities that were above the upper limit of usable physical habitat for any species or life-stage of fish. Previous work by Dunbar *et al.* (1997) demonstrated similar results in a post-project appraisal of a restoration scheme on the River Wey near Farnham, UK.

Modelling of usable physical habitat using habitat suitability indices

Physical habitat modelling requires quantification of the relationship between usable habitat for different life-stages and the physical conditions (such as depth, velocity and substrate). In PHABSIM applications these relationships are defined using Habitat Suitability Indices (HSIs) (Bovee, 1986). There has been a great deal of investigation into physical habitat use of Atlantic salmon (*Salmo salar L.*) and trout (*Salmo trutta L.*) (e.g. Kennedy and Strange, 1982; Belaud *et al.*, 1989; Heggenes and Saltveit, 1990; Milner *et al.*, 1998; Dunbar *et al.*, 2001). The physical habitat preferences of non-salmonids have been less well studied, but are receiving increasing attention (e.g. Garner, 1995; Winkler *et al.*, 1997). At one time the

River Tame and its tributaries were highly valued fisheries (National Rivers Authority, 1996), supporting brown trout in the headwaters and a mixed cyprinid fishery in the lower reaches. Degradation of both water quality and physical habitat has lead to the current status of an impoverished and transient coarse fish population in most stretches (National Rivers Authority, 1996). Fish population data provided by the Environment Agency showed that coarse fish such as chub have been present in the River Tame in recent years. HSIs are available for these species of coarse fish. For example, Johnson *et al.* (1993) provided HSIs for different life stages of roach and dace, while Armitage and Ladle (1991) illustrated indices for chub (Figure 3). These indices were all derived from expert opinion, supported by previous literature on habitat use.

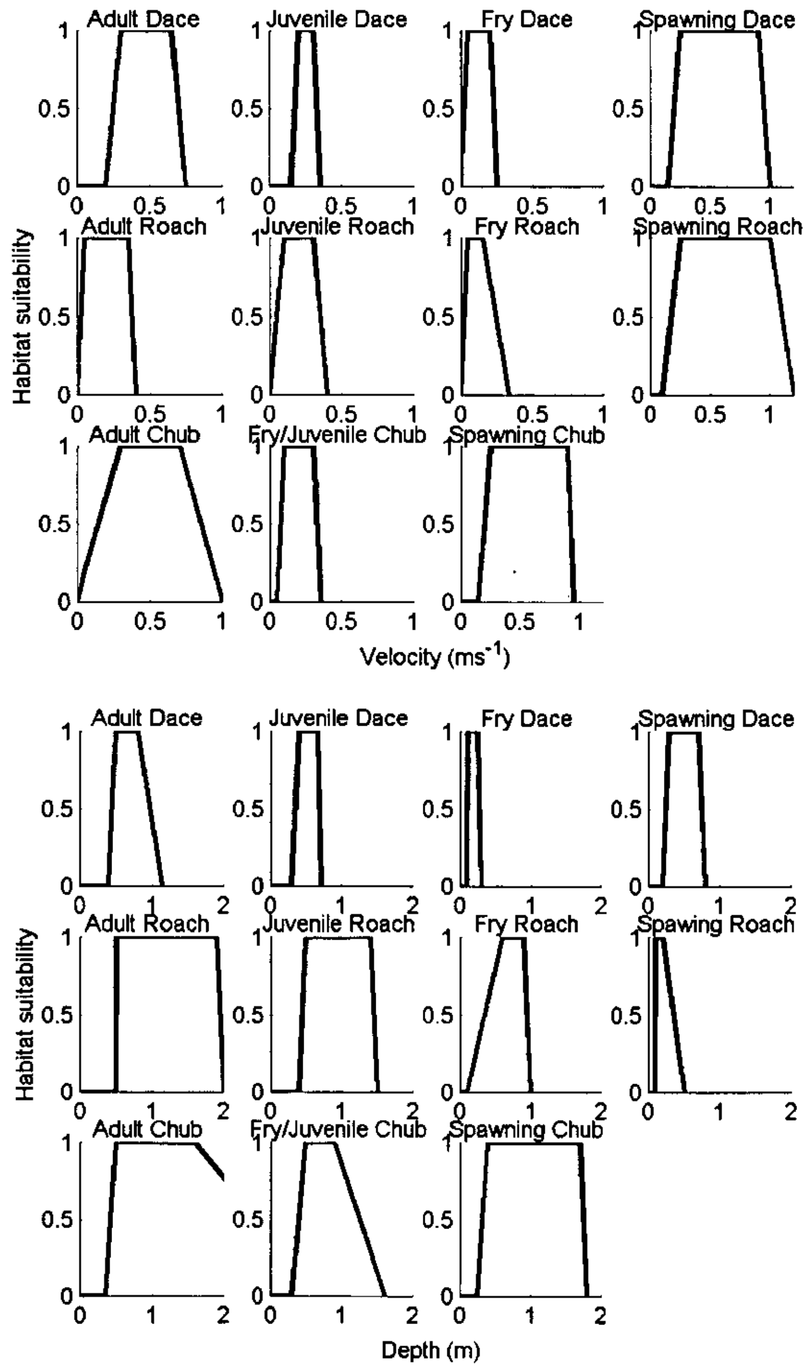

Figure 3. Habitat Suitability Indices for different life-stages of dace, roach and chub.

Subsequently suitability indices for juvenile roach have been published based on point abundance sampling in the field (Garner, 1995). These HSIs, developed specifically for the Great Ouse, took the form of polynomial equations describing the relationship between habitat suitability (in terms of frequency) and measurements of depth, velocity and substrate. The habitat suitability relationship for depth gained on the Great Ouse (see Figure 1 in Garner, (1995)) matches well with that shown in Figure 3, with habitat suitability falling rapidly at depths greater than 1.5m. The velocity data used by Garner was estimated using the displacement of the mesh of a dip net, rather than being quantified as mean column velocity using a current meter, and as such are not directly comparable with the HSI format used in this study. Critical water velocities for larval roach and dace were investigated by Mann and Bass (1997). These velocities were gained using laboratory experiments and equate to the velocity at which 50% of a group (6-10 individuals) of fish could not sustain for a 3minute period. Results showed that critical velocities for roach larvae (all less than 0.015m body length) were all less than $0.19ms^{-1}$. Critical velocities for dace (of a similar size) were only slightly faster (fastest - $0.22ms^{-1}$). These velocity values again relate well with the HSI curves illustrated in Figure 3, with roach and dace fry both selecting very slow velocities and dace tolerating slightly faster velocities than roach. It should be noted that even though the HSI shown in Figure 3 appear to agree well with the experiments conducted by Garner (1995) and Mann and Bass (1997) they are still a possible source of error in the final results.

HSIs gained using field data are considered desirable in any PHABSIM investigation (Bovee, 1986), although there is an on-going debate as to the applicability of generalised versus site specific HSIs (Dunbar *et al.* 2001). HSIs are commonly employed to define an overall envelope of habitat preference given good water quality and a wide range of available habitats. Thus, development of HSIs in the Tame was not desirable because of the ongoing poor water quality and lack of overall habitat diversity.

Garner (1995) suggested that the extremities of the curves were the most likely source of error. Information on swimming speeds, which are used to determine the upper bounds of the velocity suitability curves, were given by Clough and Turnpenny (2001). Comparisons between the swimming speeds of different sizes of fish and the velocity suitability curves given in Figure 3 are shown in Figure 4. The swimming speeds data shown in this figure are median values of maximum sustainable swimming speed (MSSS) for fish at 8°C. This represents the mean water velocity at which several individuals of each species were able to hold position for a period of over 200 minutes. Maximum sustainable swimming speed does vary with temperature. However, the data given by Clough and Turnpenny (2001) showed that maximum sustainable swimming speed increased by only $0.04ms^{-1}$ on average for dace, roach and chub for water of 12°C when compared to 8°C. Swimming speeds at 8°C are shown here as this was the coldest water temperature at which experiments were conducted. The figure shows that the HSIs derived from expert opinion and literature agree well with the experimentally derived swimming speeds for dace and chub. The maximum sustainable swimming speed of adult chub is particularly well replicated by the HSI derived from expert opinion. However, the roach HSI upper limit for velocity illustrates a sharp decline in suitability above $0.4ms^{-1}$, whereas the MSSS of larger roach is much greater. A comparison between MSSS and velocity HSI is not ideal: HSIs commonly indicate prolonged habitat suitability, while the MSSS indicate the maximum short-term velocities at which a fish may survive. Thus adult roach may be able to sustain swimming speeds greater than $0.4ms^{-1}$ for short periods, but water of this velocity may not necessarily represent suitable physical habitat.

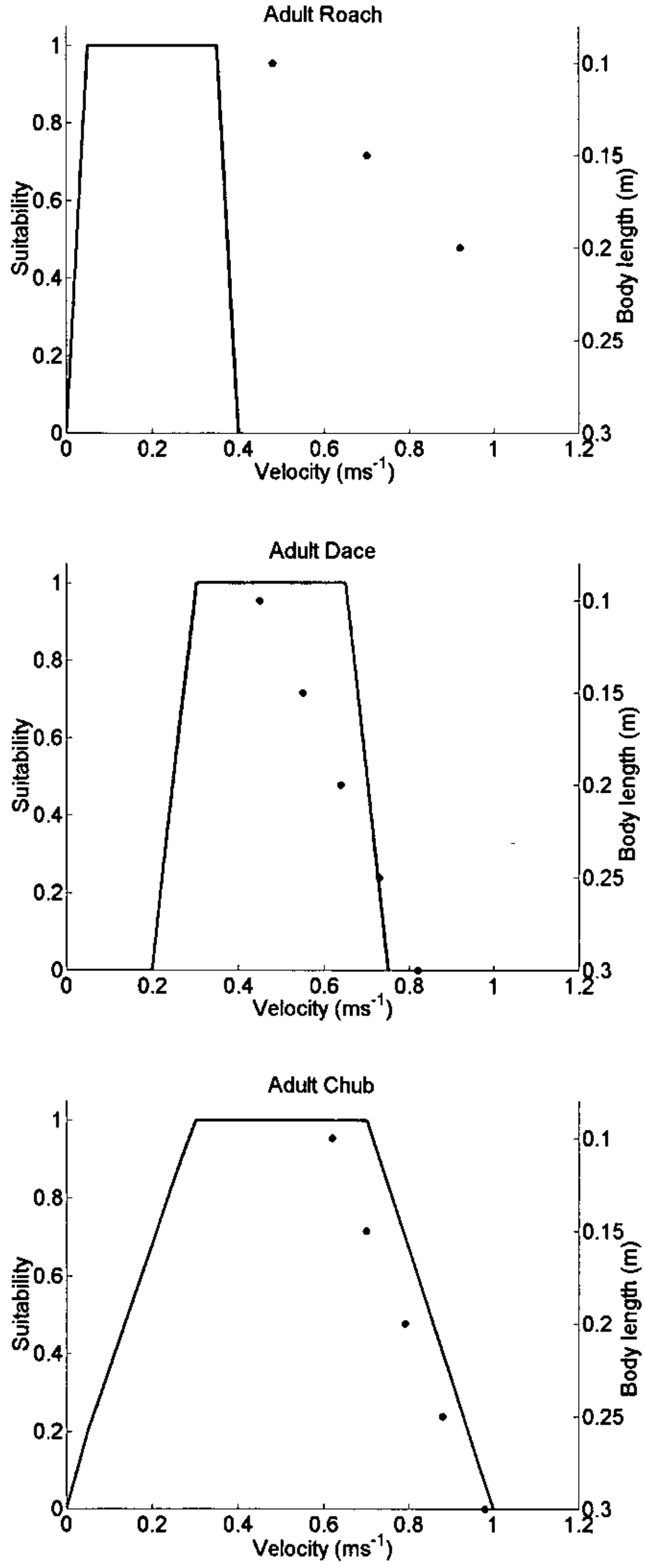

Figure 4. Velocity habitat suitability indicies (solid line) for adult roach, dace (Johnson *et al.*, 1993) and chub (Armitage and Ladle, 1991) in comparisons with median 'maximum sustainable swimming speeds' at 8°C for fish of different lengths (circles) (Clough and Turnpenny, 2001).

Results

Sensitivity of model results to shape of habitat suitability indices

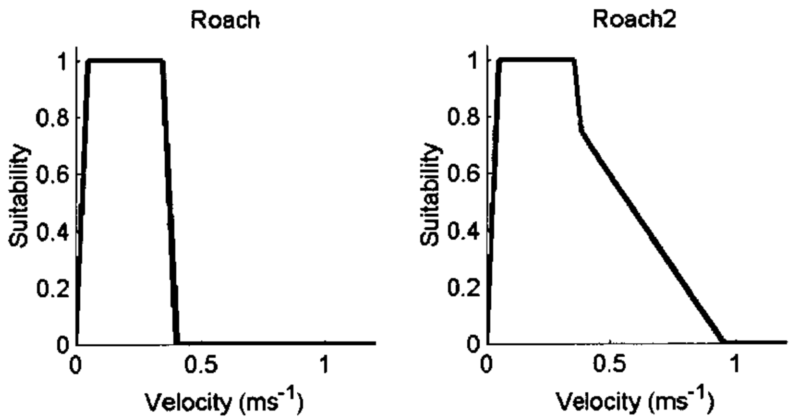

Figure 5. Two different HSIs for adult roach used in a sensitivity analysis.

Sensitivity of physical habitat predictions to alternative formulations of the adult roach HSI was assessed for the two Tame sites. Usable physical habitat (WUA) was simulated using the HSIs shown in Figure 5. 'Adult Roach' is the curve shown in Figure 3 and derived from expert opinion and previous literature. 'Adult Roach2' is an example of an amended curve, which includes more suitable habitat at higher velocities as indicated by the MSSS experiments conducted by Clough and Turnpenny (2001). Results show that at the Highly Modified site, usable physical habitat (WUA) calculated using the 'Adult Roach' HSI is zero at all flows (Figure 6). This is because the 'Adult Roach' HSI dictates that adult roach require slow flowing (less than 0.4ms^{-1}), deep water (greater than 0.5m) and, of the available habitat (i.e. the total river area), none falls into both of these categories. In comparison the 'Adult Roach2' HSI predicts some usable physical habitat for discharges between 2 and 6m^{3}s^{-1}. This is because there is some available habitat which is both deeper than 0.5m and is less than 0.9ms^{-1} in speed. However, the amount of usable physical habitat never rises above 3% of the total available habitat. The results therefore show that the difference in usable physical habitat predicted using the alternative "HSIs" from Figure 5 were minimal for the Tame Highly Modified site. Figure 6 shows a contrasting situation for the Less Modified site on the River Tame. Here there is an increase in usable physical habitat (WUA) produced by the alternative HSI formulations. Specifically, the WUA is more than doubled between 2 and 4 m^{3}s^{-1} and continues to exist for flows as high as 8 m^{3}s^{-1}. There is very little usable habitat above this discharge for either HSI formulation.

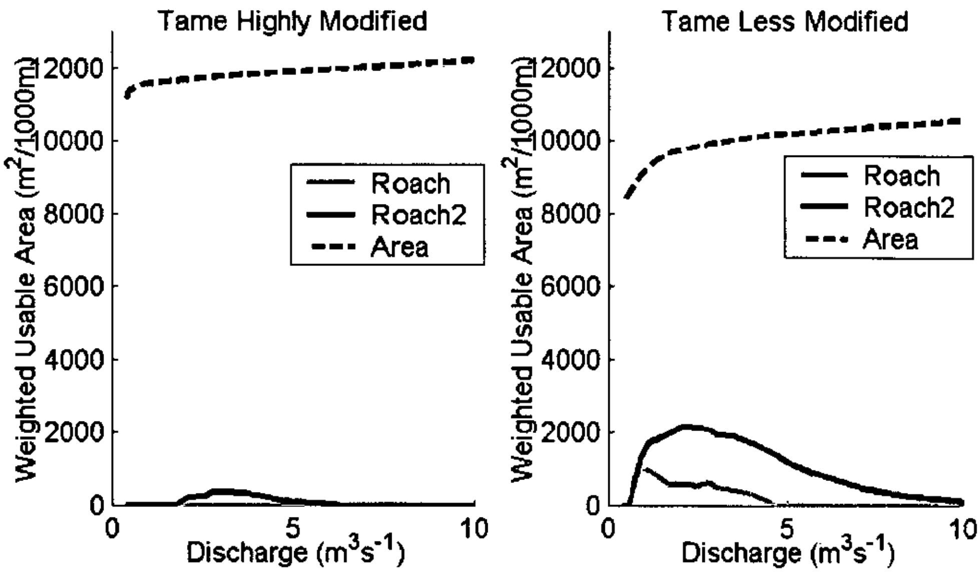

Figure 6. Usable physical habitat (WUA) at different discharges at two sites on the River Tame produced using different Adult Roach HSI's. Area refers to the total available area at each site.

Overall, this analysis shows that sensitivity to changes in HSI formulation is dependent on the site characteristics. In particular, the results show that the increase in habitat velocity suitability for adult Roach suggested by the swimming speed information only serves to increase the difference between the Highly Modified and Less Modified sites. Thus one conclusion, that a superficially more diverse urban channel does provide better habitat at both high and low discharges, is unchanged.

However, when the output is examined in more detail, the alternative HSIs will impact on the information provided to river managers. For example, Figure 6 illustrates that attempts to reduce prolonged high flow events to a maximum of $8m^3s^{-1}$ might improve physical habitat for adult roach at the site given the 'Adult Roach2' results. However, this conclusion would not be the same given the 'Adult Roach' results. This sensitivity analysis therefore shows how uncertainties in the habitat preference information can propagate into recommendations for managers.

Physical habitat for different fish life-stages

Figure 7 shows the relationship between WUA and discharge for different life-stages of chub, dace and roach. The figure demonstrates why all life-stages must be considered when analysing results. Results show that at the Highly Modified site, a large proportion of the river area is usable by adult chub. However, usable physical habitat (WUA) for fry/juvenile chub does not rise above $200m^2/1000m$ for any discharge. Similarly, the results also show that there is a large amount of usable physical habitat for spawning roach in the Highly Modified site but very little for the other three roach life-stages. This is because there is a greater range of suitable depth incorporated into the adult spawning roach HSI in comparison with the other roach life-stages. For the Highly Modified site results for different life-stages of dace are very similar to that for roach with very little usable habitat for any life-stage at any flow except for spawning dace. The more varied hydraulic conditions at the Tame Less Modified site creates less difference between suitable habitat for different life-stages of the same species than is the case for the Highly Modified site. The figure therefore demonstrates the importance of including all life-stages into the analysis. This is especially the case in urban rivers where both high and low flow extremes are likely to occur at any time of the year. The most detrimental effects of high flow events occurring during the early, post-hatch, stage of the fish life cycle (Pearsons *et al.*, 1992; Gozlan *et al.*, 1999).

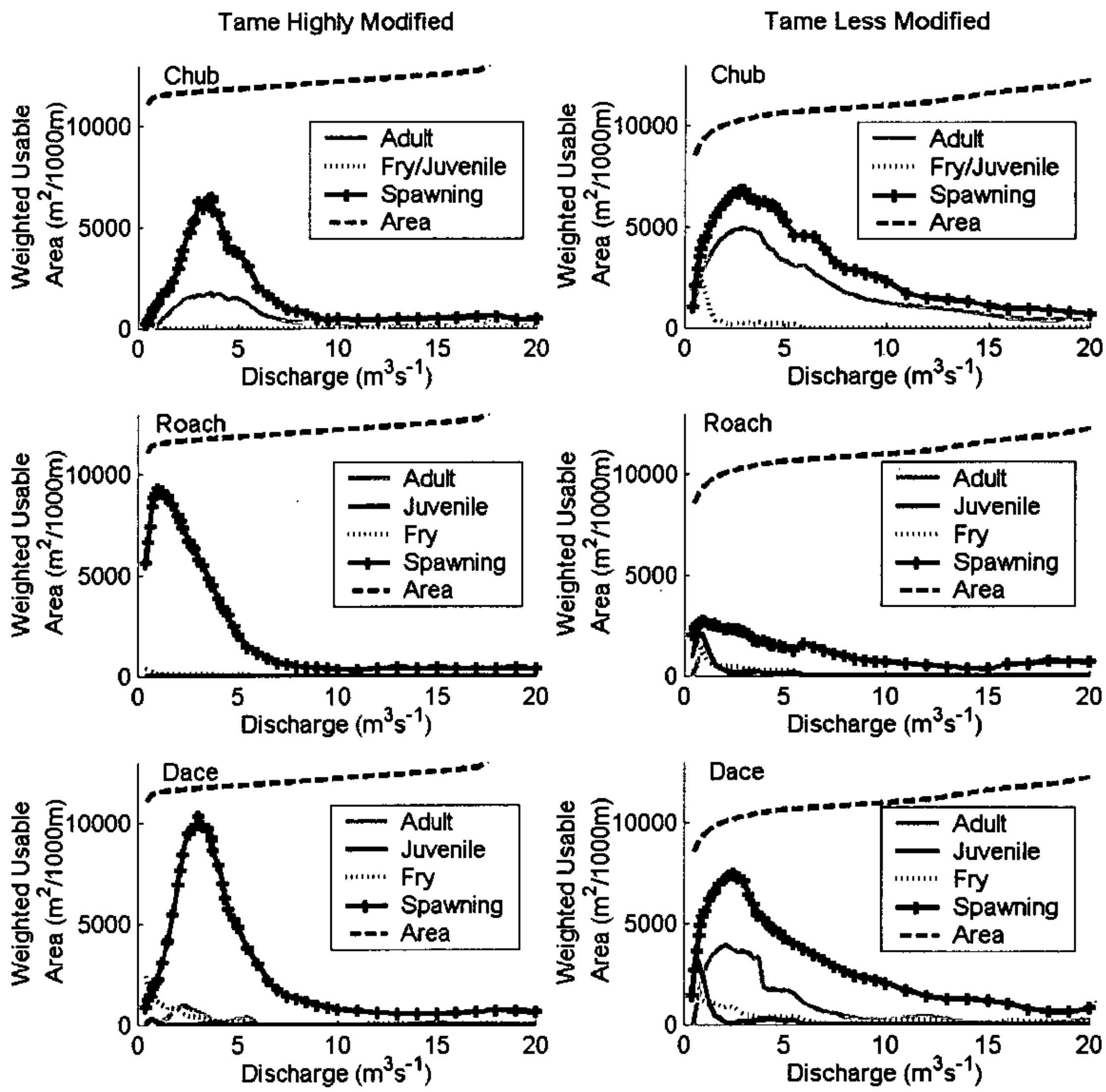

Figure 7. Usable physical habitat (WUA) for different life-stages of chub, roach and dace over a range of discharges at two sites on the River Tame. Area refers to the total area of available habitat.

Over-bank flow

At the two sites located on the River Tame the main river channel is contained within a two-stage channel. Out of bank habitat becomes available during very high discharges as shown in Figure 2. For a certain range of discharges, this habitat could become usable as it will contain velocities which are shallower and slower flowing than in the main channel.

Figure 8 shows an example of this hypothetical habitat for adult chub above $30m^3s^{-1}$. However, the actual situation will not be this simple, as to inhabit the marginal areas above 30 m^3s^{-1} during a high discharge event a fish would first have to endure low levels of habitat between 10 and 30 m^3s^{-1} during the rising limb of the hydrograph. Subsequently the fish may have difficulty re-entering the river channel as the flow recedes (akin to fish stranding observed in rivers with hydro-peaking operations (Saltveit *et al.*, 2001)). The falling limb of the hydrograph would then provide a longer period of low physical habitat as discharge drops from 30 back to $10m^3s^{-1}$.

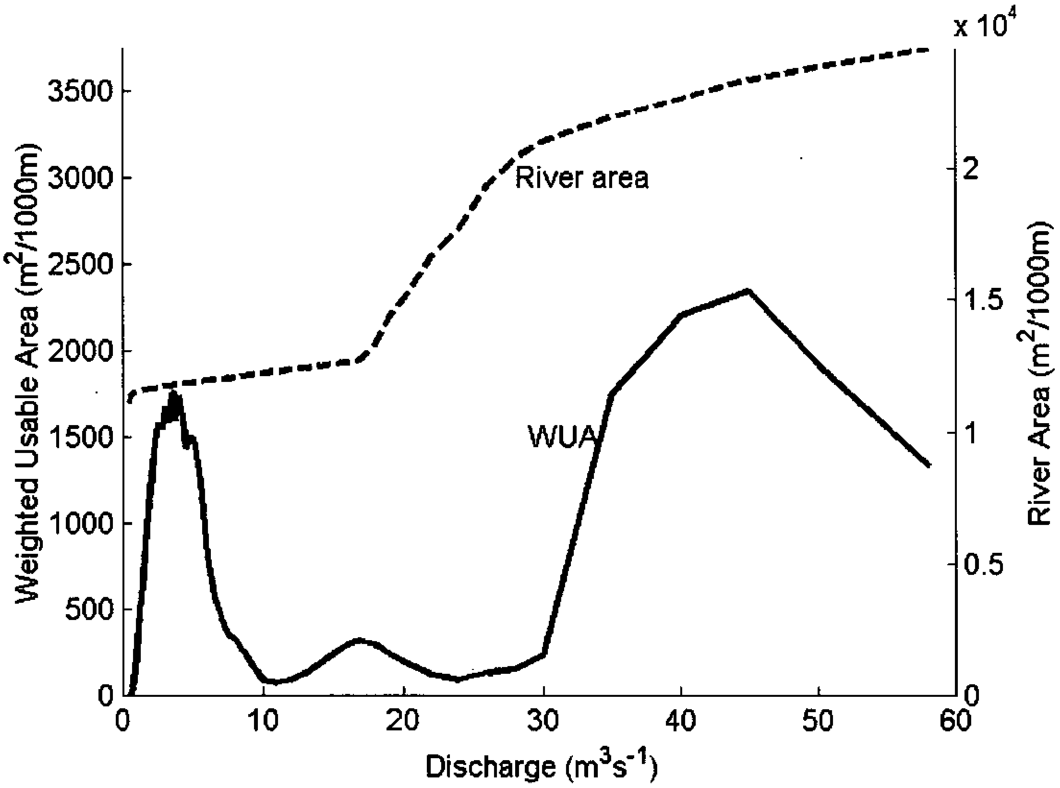

Figure 8. Usable physical habitat (WUA) for adult chub over a range of discharges at the Highly Modified site.

One method of analysing the extent to which this hypothetical habitat is actually usable is to relate the time taken for flow to rise from 10 to $30m^3s^{-1}$ during the rising limb of the hydrograph to the length of time which a fish can sustain its MSSS. Figure 9 shows a time-series of particularly high flows in November 2000 on the River Tame. The figure shows three different high flow events. Each event has its own distinctive time-series pattern of instantaneous physical habitat (WUA) for adult chub. The figure shows that an event with a peak magnitude of $60m^3s^{-1}$ (day 309-312) is no worse in terms of instantaneous physical habitat than the event with a peak magnitude of $32m^3s^{-1}$ (day 303-304). The hydrograph for each event rises rapidly; as a result usable physical habitat does fall sharply, but then rises again in an equally rapid manner as discharge increases above $30m^3s^{-1}$. In the case of the higher peak event, the period of time for which usable habitat is less than $1000m^2/1000m$ is less than the 200minute time period for which fish might be expected to sustain their maximum sustainable swimming speed (Turnpenny *et al.*, 2001). On the falling limb of both these events, physical habitat is poor for a prolonged time period as the flow drops slowly. Overall, the instantaneous physical habitat time-series for both these events falls below 300 m^2/1000m for the majority of a two-day period. Conversely, for the hydrograph event during day 306 (peak exceeded 0.08% of the time), its steeply receding limb caused a rapid return to high usable physical habitat. These results suggest that in this type of urban two-stage channel, attenuation of a flashy flow regime may not, on its own, be a productive restoration measure. However they do highlight the opportunities for the creation of refuge habitats by changes in the levels of the second stage areas on either bank.

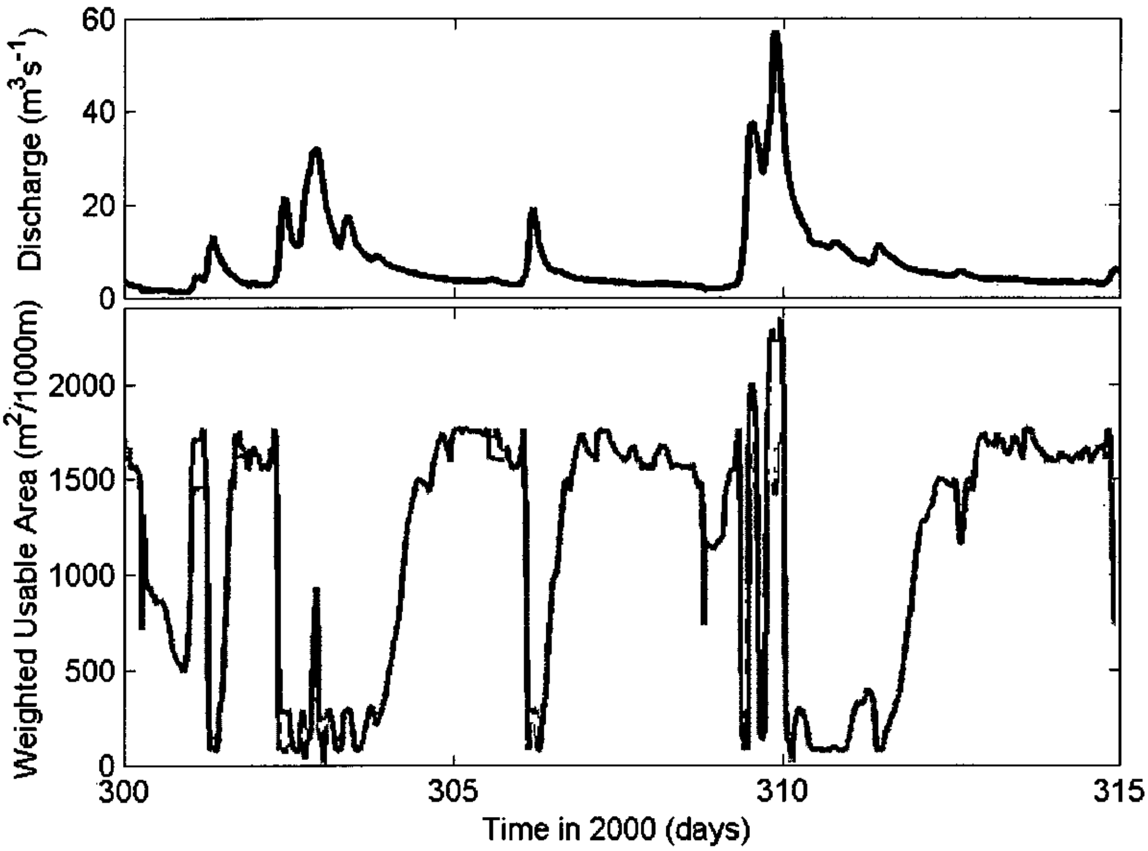

Figure 9. Time-series of flow and instantaneous usable physical habitat for adult chub at the Tame Highly Modified site during a period of very high flows.

Model time resolution

Impermeable surfaces, dense drainage networks and a lack of vegetation cover all contribute to creating flashy runoff conditions in urban catchments. The temporal resolution of flow time-series, which are used to model physical habitat, will therefore impact on the results of a PHABSIM study in urban rivers. Figure 10 shows the results for adult chub physical habitat for the two River Tame sites. The figure shows a comparison between modelled habitat using a 15minute flow time-series in comparison to a daily flow time-series. They demonstrate that there are considerable differences between results produced using hydrological input data of different temporal resolutions.

For example during days 258 and 261 of year 2000, high flow events occurred that lasted for a relatively short duration. The results derived from the mean daily time-series show relatively high levels of usable physical habitat during these storm events at both sites. However, when the 15minute time-series is employed, short periods with relatively low habitat are apparent. This difference occurs because physical habitat is poor at high flows as well as during low flows. When flow is averaged over each day different results are obtained. In an extreme example the first half of a day could have very low flows with a rainfall event causing very high flows for the second half of the day. The 15minute predictions would show poor habitat for the entire day. However, the corresponding habitat modelled from the daily time-series may predict better physical habitat than was actually the case.

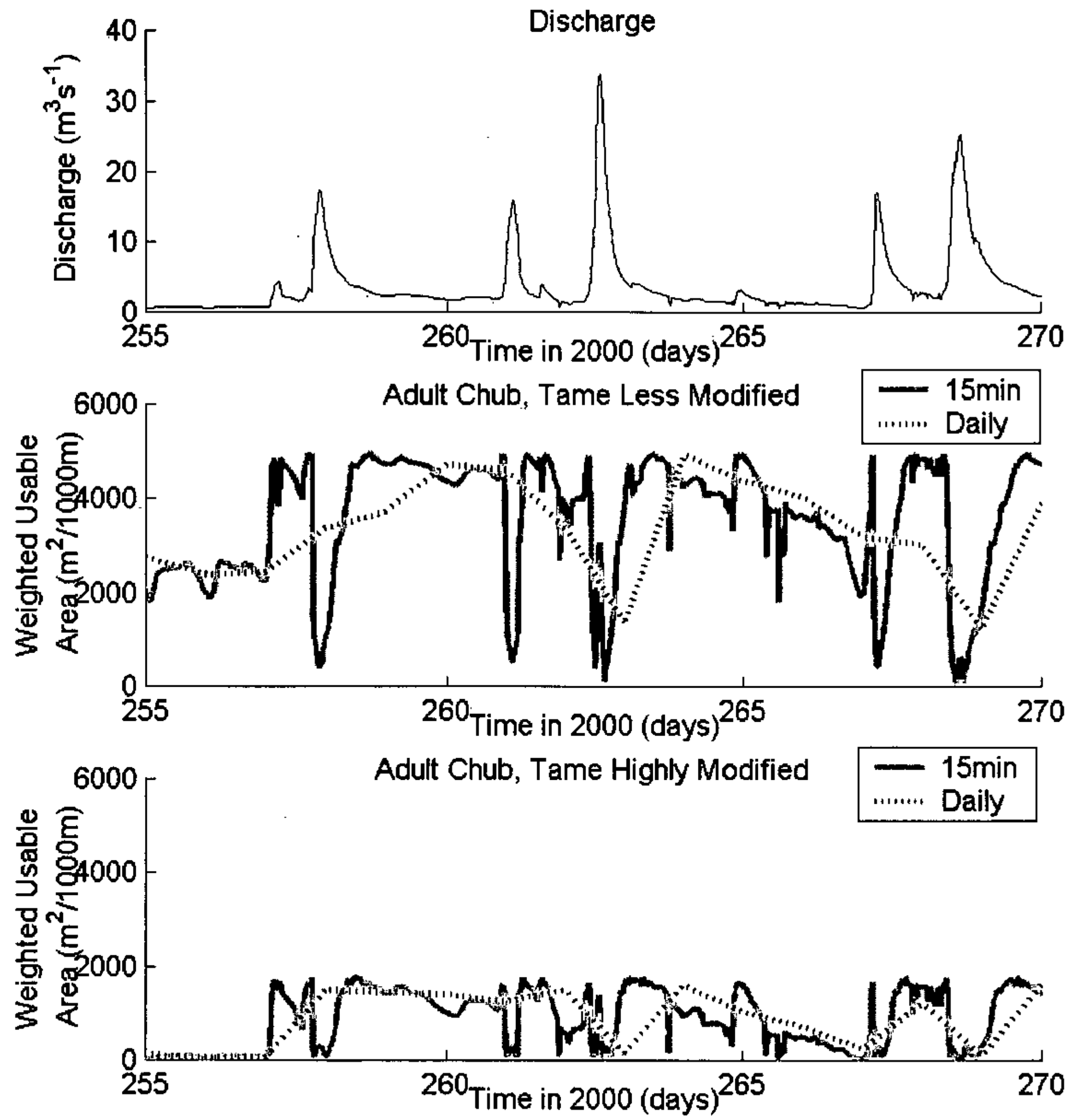

Figure 10. Time-series of flow and instantaneous usable physical habitat for adult chub modelled using mean daily and 15 minute time-series for the two Tame sites. Solid line is 15 minute resolution, dashed line is mean daily temporal resolution.

Investigation of temporal changes in physical habitat have been investigated in relation to hydro-peaking, which results from hydro-power production (e.g. Alfredsen *et al.*, 2000; Alfredson *et al.*, 1997; Valentin *et al.*, 1996). For some low-flow investigations of groundwater dominated rivers, physical habitat-duration curves have been the main analysis tool (e.g. Elliott *et al.*, 1999). This type of analysis is time independent, therefore temporal sequencing of events is lost. The total time of poor or good habitat availability is used in decision making. Critical limiting events arise from low discharges where improvement to habitat quality will be created by an increase in discharge. In urban rivers poor physical habitat can be caused by both low and high discharges. Thus habitat duration curves are unlikely to be a useful decision support tool in urban rivers because they do not distinguish between poor quality habitat resulting from high flows and poor quality habitat resulting from low discharges. This is important where changes in flow regime are being considered as a method of enhancing habitat quality (as might be the case if water quality improvements were the aim). Where a simple overview of physical habitat-discharge is required (for example for comparison of sites of different morphology), habitat suitability can be plotted onto corresponding (15min derived) flow-duration curve as shown in Figure 11.

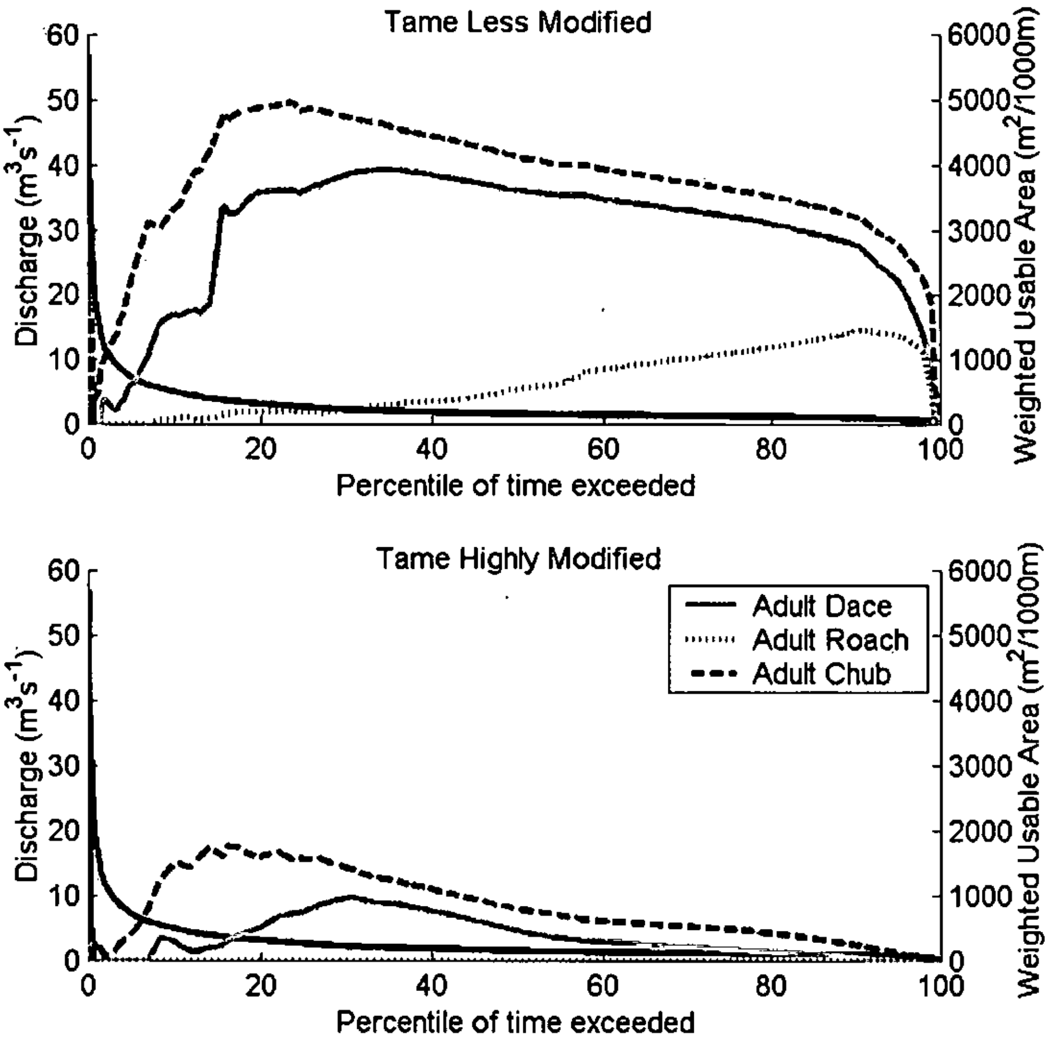

Figure 11. Flow-duration curve for the year 2000 (solid black line) instantaneous usable physical habitat adult dace, roach and chub at the Tame Highly Modified and Less Modified sites.

Figure 11 shows the differences in usable physical habitat of adult fish between the two sites for the year 2000. The figure shows that the worst habitat is at the Highly Modified site at flows exceeded approximately 7% of the time. At these high flows there is less than 500m^2/1000m of WUA for adults of any species. The impact of high flows on adult fish habitat availability is reduced in the Less Modified site where flows must be as high as those exceeded 1% of the time for the same situation to occur. A similar situation exists at the low flow end of the flow range. As flow decreases, usable habitat begins to reduce at higher flows for the Highly Modified site in comparison with the Less Modified. This is especially the case for roach, dace and chub, for whom usable habitat reduces steadily as flow drops from the 30 to 0% exceeded for the Highly Modified site. At the Less Modified site, usable habitat remains relatively high until the lowest 5% of flows whereupon a rapid drop occurs.

Conclusion

This research has shown that PHABSIM can be used to analyse physical habitat in urban river systems. However, the characteristics of urban rivers leads to a best practice methodology that deviates from that previously published. In urban rivers, poor physical habitat can occur during both high and low flows. Investigation of physical habitat in rivers with urban flow regimes therefore requires simulation of hydraulic conditions over a wide range of flows. This is a technically difficult task, which emphasises the need for accurate information on hydraulic patterns at high flows as well as the response of fish to high velocities. This subject has not received a great deal of attention in the UK and would benefit from further investigation.

The temporal resolution of flow time-series used in ecological applications is important for flashy urban runoff regimes. In particular the amount of time for which poor physical habitat can be endured is an issue of great importance. Physical experiments, which determine fish endurance and swimming speeds, may be used to aid analysis of results. This is an area of habitat modelling that requires further research in order to understand more fully the health of urban rivers. Water quality issues may also complicate verification of physical habitat simulations. This means that a prediction of good physical habitat needs to be put into the broader context of other factors such as poor water quality and longitudinal connectivity. It may be the case that fish of generally poorer health will have slower swimming performances and therefore have more restricted physical habitat tolerances. For example, McGeer *et al.* (2000) showed that swimming speeds of rainbow trout were significantly reduced when the fish were exposed to Cu (250 μgl^{-1}) in moderately hard water. This linkage of water quality to physiological state and physical habitat requirements is likely to be a fruitful avenue for future research.

Overall results show that the Highly Modified site provided less suitable habitat, despite being wider and therefore having more total area. At the Highly Modified site poor habitat caused by high flows occurred at lower discharges and poor habitat caused by low flows occurred at higher discharges. In this respect the Less Modified channel proved to be more robust to changes in discharge providing suitable habitat over a wider range of flows. These results indicate that water quality may not be the only factor controlling the health of urban river ecosystems. A successful urban rehabilitation scheme must therefore consider physical habitat as well as water quality in an integrated approach to environmental management. Artificially wide channels with poor geomorphological diversity can provide some suitable fish habitat. However, the time for which this is present at a site may be limited to a narrow range of discharges. More diverse channel morphology, which incorporate an undulating bed profile provide better quality physical habitat over a wider range of flows. This is because different areas of the channel can provide suitable habitat at different levels of flow. This research suggests that refuge areas that reduce velocities during high flow events would benefit the physical habitat of fish in urban rivers. This is especially the case in straightened channels where geomorphological diversity is poor. The challenge is to create morphologically diverse urban river channels that are able to remain stable and convey floods.

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Part II) Hydraulic modelling of fish habitat in urban rivers during high flows.

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Key words: Computational fluid dynamics; fish swimming speeds, habitat suitability, urban rivers, engineered river channels.

Abstract

In urban rivers, flow regime and channel morphology are the drivers of physical habitat quality for aquatic species. Peak discharges are increased at high flows as a result of impermeable catchments and channel engineering for flood protection schemes. Hazardous conditions and flashy hydrographs mean that measurement of velocities at high flows is a difficult task. This research uses a three-dimensional Computational Fluid Dynamics (3D-CFD) model to simulate hydraulic patterns in two urban river channels. A 3D-CFD code, called SSIIM, was used to simulate hydraulic conditions in two engineered river reaches of the River Tame, Birmingham, UK. These two sites represent channels with different levels of engineering. Models were calibrated and tested using field measurements. Results show that modelled water surface levels and velocity profiles are well simulated. Calibrated roughness heights are compared with those derived from field measurement of sediment size. Numerical experiments are used to assess the relationship between grid resolution in the vertical dimension and the form of the modelled velocity profiles. Biologists have used laboratory experiments to determine Maximum Sustainable Swimming Speeds (MSSS) of fish, often in order to assess what level of a particular pollutant may be tolerable. In this work, simulations of high flow hydraulic patterns are used to compare velocity patterns with fish MSSS. Results show that when the water levels rise to fill the first channel of the two-stage channels at the sites, which occurred 16 times in 2000, MSSS are surpassed in the majority of available habitat suggesting that excessive velocities at high flows are one factor that limits fish habitat. A comparison between the two reaches shows that there is less available habitat in the more modified reach. Conclusions suggest that an approach that integrates water quality issues and physical channel characteristics must be taken in river rehabilitation schemes, as improvements to water quality alone may not be sufficient to improve habitat quality to the desired level.

Introduction

River corridors support aquatic ecosystems, provide areas of biodiversity and play important aesthetic and economic roles in urban environments. Many urban rivers in the UK have been influenced by flow regulation, river channel alteration, effluent disposal and pollution. These alterations combine to cause an interaction between flow regime, water quality regime and physical habitat that determines the health of river corridor ecosystems. Urban rivers are particularly impacted as impermeable surfaces cause flashy runoff, concrete straightened channels provide poor physical habitat and contaminated land or effluent disposal create poor water quality. This level of impact is not confined to highly urbanised areas. The River Habitat Survey showed that over 50% of lowland rivers in England and Wales were either obviously, significantly or severely modified (Raven *et al.*, 1998).

There are economic and social benefits of urban regeneration including rivers and river corridors. The NERC URGENT (urban regeneration and environment) programme was designed to carry out the science necessary to underpin cost effective urban regeneration. This is reflected in the URGENT modelling river corridors main hypothesis: "Cost effective rehabilitation of urban rivers depends not only upon scientifically sound improvements in water quality, but also on improvements in flow regime and physical habitat". This work comprises a small part of the project as a whole and aims to assess the quality of physical habitat for fish at high flows in channelised rivers through investigation of two reaches of the River Tame, Birmingham.

Fish can only live in rivers in which they can swim upstream or hold their position against the current. Comparisons between river velocities and swimming speeds can therefore be used as an indicator of physical habitat quality. This method is one that is more physically based than using habitat suitability curves derived from expert opinion (e.g. Johnson *et al.*, 1993; Dunbar *et al.*, 1996) or sampling at locations where fish have been observed (e.g. Bird *et al.*, 1995). Attainable fish swimming speeds are related to endurance (Peake *et al.*, 1997a; Peake *et al.*, 1997b). Due to the difference between aerobic and anaerobic swimming metabolism, and the relative contributions of red and white muscle fibres at different swimming speeds, slow speeds may be maintained for long periods while the fastest speeds may only be sustained for tens of seconds (Turnpenny *et al.*, 2001). In this paper modelled hydraulic patterns have been compared with sustainable fish swimming speeds to assess the quantity of physical habitat available to different sizes of three fish species during high flows. Flow time-series are used to assess the duration for which fish MSSS are surpassed.

CFD Modelling

Computational Fluid Dynamics (CFD) modelling can be used to simulate hydraulic patterns in natural river channels allowing improved simulation of key hydraulic and geomorphological processes (Lane, 1998). Numerical models, tested using field data, are capable of replicating velocity patterns and secondary flow structures in complex natural channels (Olsen and Stokseth, 1995; Lane and Richards, 1998, Hodskinson and Ferguson, 1998; Nicholas and Sambrooke-Smith, 1999; Booker, 2000). CFD simulations of flow in natural river channels have been related to geomorphological applications. For example, creation of shear stress maps (Lane *et al.*, 1999) or analysis of near-bed flow direction (Booker *et al.*, 2001). An alternative application of CFD is modelling of physical habitat (e.g. Crowder and Diplas, 2000). Spatially continuous, multi-dimensional hydraulic modelling can provide improvements over cross-sectional/cell based habitat modelling tools such as PHABSIM (Elliott *et al.*, 1996). This is because CFD modelling allows simulation of the river as a spatially continuous system and includes any habitat niches or flow refugia.

The CFD model used to simulate patterns of flow for this investigation was SSIIM (Olsen, 1996). The program solves the Navier-Stokes equations with a k-ε turbulence closure model on a three-dimensional non-orthogonal grid. SSIIM employs the Navier-Stokes equations for turbulent flow in a general three-dimensional geometry

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = \frac{1}{\rho} \frac{\partial}{\partial x_j}\left(P\delta_{ij} - \rho\overline{u_i u_j}\right) \qquad (1)$$

to obtain the water velocity. Non-compressible, constant density flow is assumed. Symbol notation is illustrated in Table I. Subscripts *i* and *j* are used to indicate dimensions in the computational plane.

Table I. Notation for SSIIM numerical symbols.

C_μ $C_{\varepsilon 1}$ $C_{\varepsilon 2}$ = constants in k-ε model	U = average velocity
g = gravitational acceleration	u = fluctuating velocity
Δh_{ij} = vertical movement for water surface calculation	u_* = shear velocity
K = constant in wall function	v_T = turbulent eddy viscosity
k = turbulent kinetic energy (per unit mass)	x = horizontal coordinate
k_s = roughness height	y = horizontal coordinate
l = difference in height of water surface at P_{ij}, and P_{ref}.	z = coordinate in vertical direction
P = pressure (P_{ij} is extrapolated pressure at each cell, P_{ref} is the reference pressure)	ε = dissipation rate for k
P_k = term for production of turbulence	∇ = gradient operator ($\delta/\delta x$, $\delta/\delta y$)
t = time	δ_{ij} = Kronecker delta
	ρ = density
	σ_k, σ_ε = constant in the k-ε turbulence model
	τ = boundary shear stress

A control-volume approach is used for discretisation of the equations. The default mechanism for pressure correction is the SIMPLE method (Patankar, 1980). This is used for coupling of all cells except those closest to the surface and allows calculation of a free water surface. The water surface is fixed at the downstream boundary where the pressure, P_{ref}, is taken as a reference pressure. A pressure deficit at each cell is then calculated by subtracting this reference pressure from the extrapolated pressure for each cell and used to move the water surface (Olsen and Kjellesvig, 1998a).

$$\Delta h_{ij} = \frac{l}{\rho g}(P_{ij} - P_{ref}) \qquad (2)$$

The power law is used in the discretisation of the convective terms. Further explanation of these numerical methods is given in Patankar (1980), Melaaen (1992) and Olsen (1991;2000).

The k-ε model is used to calculate turbulent shear stress for three-dimensional simulations within SSIIM. The eddy-viscosity concept with the k-ε model is used to model the Reynolds stress term as illustrated in Equation 3 (where the first term on the right hand side of the equation forms the diffusive term in the Navier-Stokes equation)

$$\overline{u_i u_j} = \mathrm{v}_\mathrm{T} \frac{\partial U_i}{\partial x_j} + \frac{2}{3} k \delta_{ij} \quad . \tag{3}$$

The k-ε model simulates the eddy-viscosity as

$$v_T = \mathrm{C}_\mu \frac{k^2}{\varepsilon} \tag{4}$$

where k is kinetic energy as defined by

$$k \equiv \frac{1}{2} \overline{u_i u_j} \quad . \tag{5}$$

k is modelled as

$$\frac{\delta k}{\delta t} + U_j \left(\frac{\delta k}{\delta x_j} \right) = \frac{\delta}{\delta x_j} \left(\frac{v_T}{\sigma_k} \frac{\delta k}{\delta x_j} \right) + \mathrm{P_k} - \varepsilon \tag{6}$$

where P_k is given by

$$\mathrm{P_k} = \mathrm{v_T} \frac{\partial U_i}{\partial x_j} \left(\frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial x_j} \right) \tag{7}$$

and ε is modelled as

$$\frac{\partial \varepsilon}{\delta t} + U_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\frac{\mathrm{v_T}}{\sigma_\varepsilon} \frac{\delta \varepsilon}{\delta x_j} \right) + \mathrm{C}_{\varepsilon 1} \frac{\varepsilon}{k} \mathrm{P_k} \mathrm{C}_{\varepsilon 2} \frac{\varepsilon^2}{k} . \tag{8}$$

The influence of rough boundaries on fluid dynamics is modelled through the inclusion of the wall law

$$\frac{U}{u_*} = \frac{1}{\mathrm{K}} \ln \left[\frac{30z}{k_s} \right] , \tag{9}$$

as given by Schlicting (1979). The variable k_s equates to the roughness height.

The modelling approach used provides predictions of time-averaged flow variables and therefore does not seek to simulate the development and evolution of time-dependent flow structures (e.g. eddy shedding from cluster bedforms). The SSIIM model has been applied to several engineered and natural river flow situations. These include flow modelling for estimation of spillway capacity (Olsen and Kjellesvig, 1998b), simulation of water and sediment in a sand trap (Olsen and Skoglund, 1994), simulation of scour round a cylinder (Olsen and Kjellesvig, 1998a), simulation of flow dynamics in a river with large roughness elements (Olsen and Stokseth, 1995) and simulation of flow in natural pool-riffle sequences (Booker *et al.,* 2001).

Site description

Two reaches of the River Tame at Sandwell Valley Country Park, Birmingham, UK, were selected for this investigation. These two sites were located within 640m of each other and were chosen to represent different degrees of channel engineering. The close proximity of the sites to each other ensured that the water quality and flow regime of the sites could be considered as the same. The 'Highly Modified' reach was a 91m straightened reach with an average width of 11.9m and artificially strengthened banks contained within a larger two-stage channel. This reach had no distinct geomorphological features and a relatively uniform bed topography. In contrast, the 'Less Modified' reach, was 139m in length with an average width of 10.0m. This reach was also contained within a two-stage channel but had one bank consisting of natural material, a slightly sinuous path and an undulating bed profile. In-channel vegetation was not present at either site. Figure 1 shows maps of channel topography at both the sites.

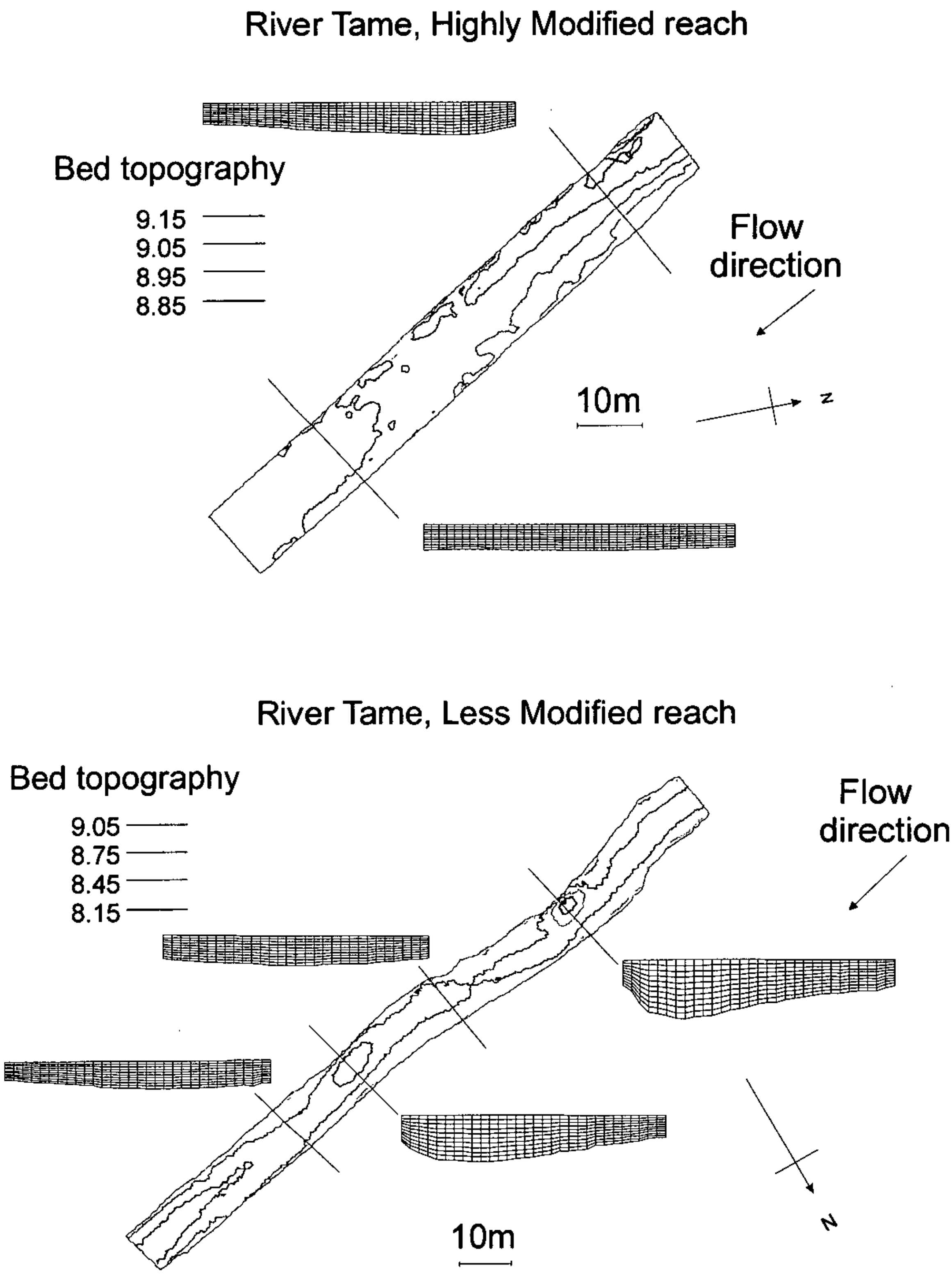

Figure 1. Numerical grids and topography for the Highly Modified and Less Modified.

Investigation of urban river classification has shown that the level of channel modification ranges widely for rivers in the Tame catchment (Davenport *et al.*, 2001). The sites investigated for this study where chosen to represent channels with differing levels of geomorpohological diversity as a result of channel modification. Both sites are broadly representative of the type of river channels found in urban catchments in that they have been modified in order to fulfil the function of flood conveyance. Neither site is at the extreme extent of the channel modification scale. For example, the Tame below the M6 Motorway is completely concreted, straight and uniform in cross-sectional shape, whereas in other reaches of the Tame active bank erosion/deposition and fully developed pool-riffle sequences exist. An extremely engineered river channel could have been chosen as a field site for this study, but the transferability of any conclusions drawn from analysis of the hydraulics at such a site would not be as applicable to the rest of the Tame catchment, or urban rivers in general. Although the two river reaches were relatively short in length (90 and 130m) there are long stretches of the River Tame which share the same characteristics. For example Davenport *et al.* (2001) showed that approximately 60% of the River Tame could be described as being modified to some extent, rather than being semi-natural. However, only 4% were categorised as being extremely modified.

Historical records show that salmon and trout have not been present in the River Tame for many years due to poor water quality. Water quality in the upper urbanised parts of the catchment remains generally poor above Lea Marston Purification Lakes, which is 25km downstream of the sites studied in this research, and consequently there are no long-term sustainable fish populations. Below the Purification Lakes and specifically downstream of the River Anker confluence, 36km downstream of the sites, the River Tame supports mixed populations of chub, dace and roach, these species are therefore investigated in this paper.

Model Boundary conditions

In order to create CFD simulations, boundary conditions must be supplied to the model in the form of the shape of the channel, the numerical grid, the inflow pattern at the upstream end of the channel, the downstream water surface elevation and the channel roughness. Topography at both sites was measured on a cross-sectional basis using a total station theodolite. In total 1206 points were measured at the Highly Modified site and 1726 at the Less Modified site. This equates to point densities of 1.1 and 1.2 measurements per m^2 at the Highly Modified and Less Modified sites respectively. All coordinates were measured relative to permanent survey markers. These topographic data were used to create the numerical grids illustrated in Figure 1. Guidelines for grid generation given by Bernard (1992) and Lane *et al.* (1999) were followed when generating numerical grid of 200×40 and 320×30 cells in the streamwise and cross-stream directions for the Highly Modified and Less Modified sites respectively. For simulation of flows less than $5m^3s^{-1}$ 10 cells were used in the vertical dimension in order to maintain orthogonality of the numerical grids and prevent the near-bed cell from being too small (Lane, 1998). These cells were distributed evenly throughout the depth. The number of cells in the vertical dimension was varied to conduct grid dependence experiments for simulations at higher flows. Results of which are given below.

At the upstream boundary of all simulations a uniform cross-stream velocity pattern was imposed, with vertically varying downstream velocity defined by the logarithmic profile, and zero cross-stream and vertical velocities. Lane et al. (1995) suggested that, where possible, velocity measurements should be used to impose boundary conditions across the upstream boundary. Measurements of velocity across the upstream boundaries were not possible in this study due to the flashy nature of the runoff regime on the River Tame. Booker (2000) addressed this issue by testing the difference in simulated hydraulics patterns that resulted from several hypothetical velocity distributions at the upstream boundary for a 3D-CFD of the Highland Water, Hampshire UK. In the River Tame the relatively straight regular channel morphologies of the upstream reaches at both sites reduced the importance of the upstream boundary condition.

Resistance to flow in the form of a roughness height is a model boundary condition that is particularly difficult to determine from field measurement (Lane *et al.*, 1999; Clifford *et al.*, 1992). Calibration of roughness was made possible by using independent data sets of water surface elevation and discharge obtained from measurement at the sites. The calibration method employed was to run simulations with the same boundary conditions, except roughness, for one monitored discharge and increase roughness systematically. The value of roughness that best replicated the field measurements of water surface elevation was then used to simulate water surface elevations at a different discharge to perform an independent test of the roughness parameter. This method of roughness calibration assumes that the topography of the channel is correctly represented in the model, that discharge values, which were obtained using a velocity-area method (British Standard 3680, 1980), are correct and that roughness is spatially uniform within the reach. Results from the roughness calibration procedure are shown in Table II**Error! Reference source not found.**. This procedure demonstrated that when roughness heights of 0.06 and 0.10m were used water surface elevations were well simulated across a range of flows at the Highly Modified and Less Modified sites respectively. Table II shows that the difference between calculated and observed water surface elevations were all similar to the expected measurement error in water surface elevation.

Table II. Results of roughness height (k_s) calibration for both sites.

Highly Modified							
Discharge (m^3s^{-1})	Q = 4.78	Q = 3.67	Q = 4.78	Q = 4.78	Q = 4.78	Q = 4.78	Q = 3.67
	Observed WSE (m)		Observed – Calculated				
Distance upstream (m)			k_s = 0.2 (m)	k_s = 0.15 (m)	k_s = 0.06 (m)	k_s = 0.05 (m)	k_s = 0.06 (m)
0.0	9.339	9.272	0.0028	0.0024	0.0012	0.0010	0.0011
38.4	9.430	9.369	0.0427	0.0346	0.0016	-0.0021	-0.0020
66.9	9.510	9.446	0.0442	0.0355	-0.0015	-0.0047	-0.0019
90.4	9.551	9.486	0.0508	0.0419	0.0021	-0.0011	-0.0021
		Average diff	0.0351	0.0286	0.0009	-0.0017	-0.0012
Less Modified							
Discharge (m^3s^{-1})	Q = 4.37	Q = 2.56	Q = 4.37	Q = 4.37	Q = 2.56		
	Observed WSE (m)		Observed – Calculated				
Distance upstream (m)			k_s = 0.06 (m)	k_s = 0.10 (m)	k_s = 0.10 (m)		
0.0	9.092	8.921	0.0006	0.0012	0.0020		
47.2	9.222	9.089	-0.0400	-0.0037	-0.0087		
64.0	9.231	9.092	-0.0487	-0.0063	-0.0094		
100.6	9.341	9.189	-0.0358	0.0149	0.0085		
137.7	9.382	9.218	-0.0431	0.0107	0.0136		
		Average diff	-0.0334	0.0034	0.0012		

The characterisation of bed roughness when applying CFD models to natural river situations is a difficult task (Nicholas, 2001). In addition to calibration methods substrate sediment sizes can be used to determine the roughness height for hydraulic simulations (e.g. Lawless and Robert, 2001a). Roughness height parameters may be imposed using a measure of sediment size and a roughness multiplier. This can range between $0.4D_{50}$ and $3.5D_{84}$ depending on substrate characteristics and whether grain roughness alone or the combined effect of grain and micro-topographical roughness are required. The latter was suggested by Hey (1986) and supported by Clifford *et al.* (1992). This method of roughness characterisation is one where grain sizes that are larger than the median are used to take account of the greater than proportional influence of larger particles (Leopold et al., 1964). One explanation of the use of roughness multipliers is to include the effects of pebble clusters and over-exposed grains, which increase roughness. Pebble clusters have been observed in streams with similar grain size distributions to those in the River Tame (Figure 2), such as Turkey Brook as shown by Hassan and Reid (1990). Buffin-Bélanger and Roy (1998) recorded measurements which showed that pebble clusters could have considerable effects on turbulent flow structures. Flume experiments reported by Lawless and Robert (2001b) show further evidence of the effects of pebble clusters on turbulent flow structures. A visual inspection of the sites showed that, although larger individual particles were present, pebble clusters as defined by Brayshaw (1984) and employed by Lawless and Robert (2001a) were not prevalent in the two reaches. This was supported by the relatively smooth angularity (93% were rounded or well rounded) and spherical shape (82% were either spherical, sub-prismoidal, or sub-discoidal), using Powers (1982) particles at the two sites (n = 300). Field inspection also showed that bed sediments at both sites were armoured with well-imbricated particles and that no micro-scale bed forms protruded as much as 0.06m (the dimensions of those used by Lawless and Robert (2001a; 2001b) in their experiments).

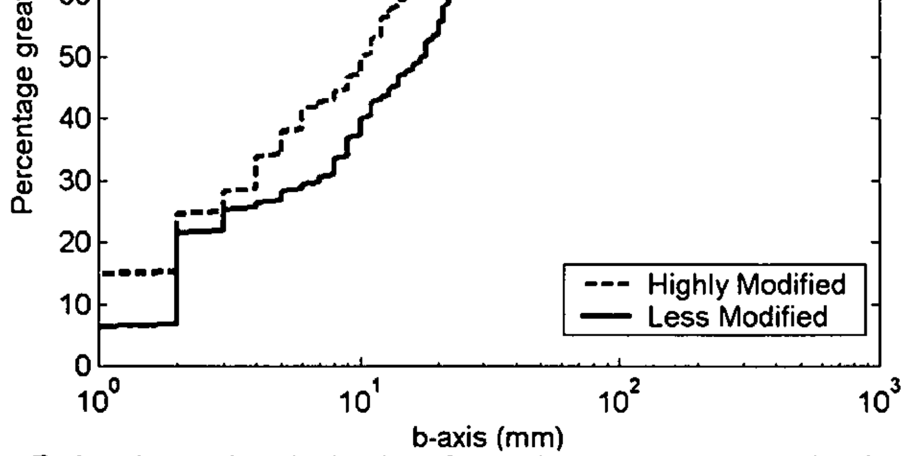

Figure 2. Bed sediment size distributions from grid-by-numbner sampling for the Highly Modified (n = 248) and Less Modified (n = 265)sites.

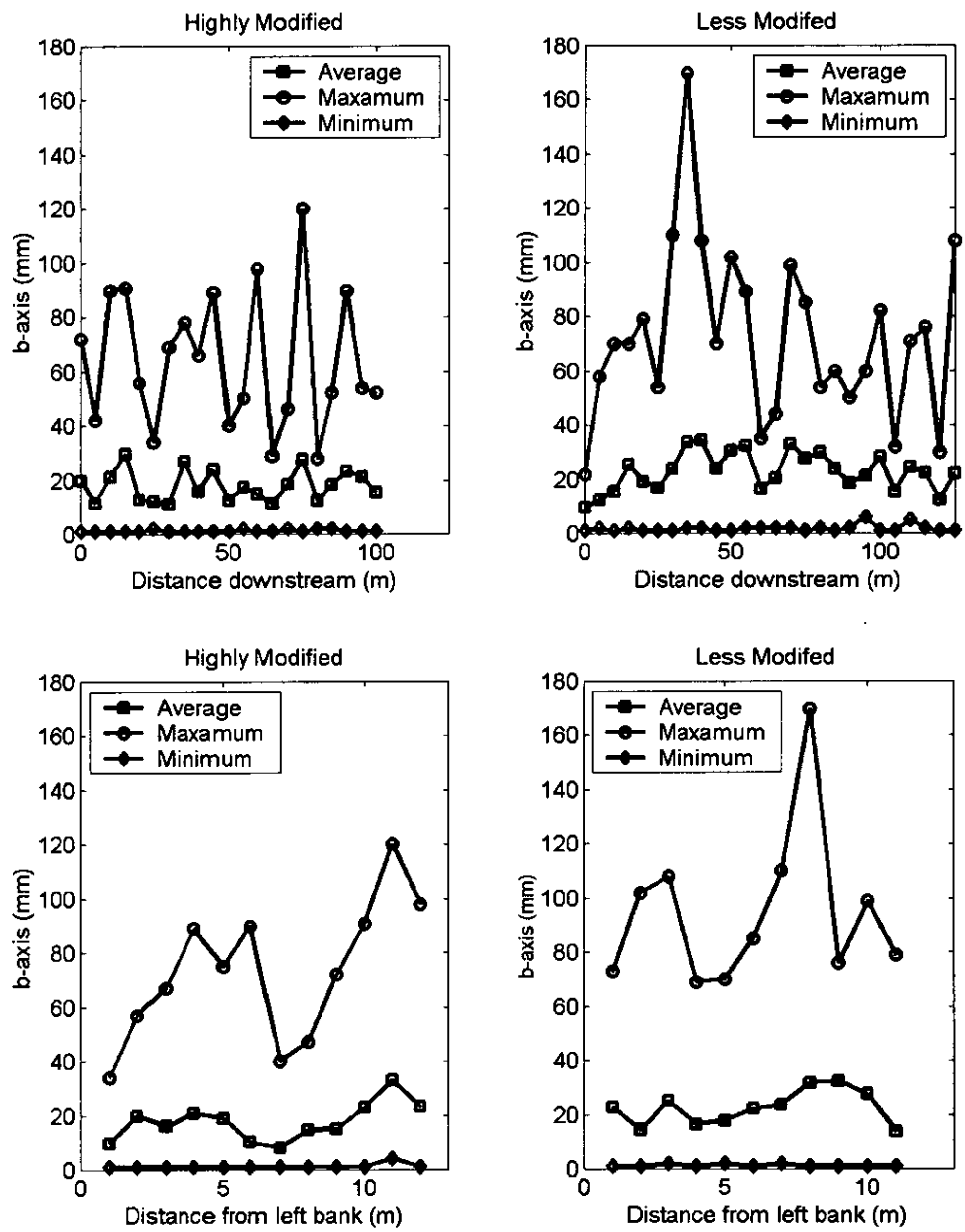

Figure 3. Downstream (top) and cross-stream (bottom) patterns average, maximum and minimum sediment size sampled at both sites.

Lawless and Robert (2001a) suggested that different roughness multipliers should be used for open plane-beds and those with pebble clusters. The b-axis particles were measured at the two sites site using the standard Wolman (1954) grid-by-number technique. Samples were measured every metre along cross-sections placed at 5m intervals within the two reaches. Results are shown in Figure 2. Overall the grain size distributions at the two sites were similar in structure. Particles at the Less Modified site were generally slightly larger than those at the Highly Modified. This agrees well with the roughness heights predicted by the calibration process. The D_{84} of bed sediment measured at the Highly Modified and Less Modified sites using this technique were 0.035 and 0.040m respectively. Assuming that the roughness calibration process is correct and that the D_{84} measurements are correctly represented by the grid-by-number sampling methodology this gives roughness multipliers of 1.7 and 2.5 for the Highly Modified and Less Modified sites respectively. Roughness multipliers less than 3.5 are further evidence showing that although larger individual particles were present, pebble clusters or mirco-form bed roughness were not a significant component of the channel resistance in these reaches.

The roughness calibration procedure described above assumes that roughness is spatially uniform within each reach. Several studies have reported sedimentological differences between bed forms such as the morphological units; pool, riffle and bar (O'Neil & Abrahams, 1984; Clifford, 1993; Sear, 1996). Therefore bed roughness cannot be assumed to be constant between the distinctive morphological units; pool, riffle and bar. Although the Less Modified site did have a gently undulating bed, there were no distinctive morphological units at either site (Figure 1). A visual inspection of both sites showed no distinctive sedimentological units were present. Spatial analysis of sediment size showed that there were no significant spatial patterns in either the downstream nor cross-stream directions at either site (Figure 3). This is evidence that supports the use of spatially uniform roughness heights for hydraulic simulations at the sites.

Model validation

Velocity profiles were measured at approximately equal distances across two cross-sections at both sites. At each location velocity was measured at 0.04m, 0.1m and every subsequent 0.1m in the vertical profile using an 802 Valeport electromagnetic current meter and a 30s measurement period. Biron *et al*, (1998) recommended that a longer time period for measuring velocities be employed. However, there is a trade-off between the measurement period and the number of measurements that can be taken. This is especially the case in urban rivers, such as the River Tame, that are characterised by very flashy runoff regimes. These measurements were recorded perpendicular to a tape measure that was stretched across the river between two fixed pegs. The position of each set of measurements was subsequently calculated using the positions of the pegs and the distances across the tape. Measurement locations are shown in Figure 4. Discharge for the two sets of velocity profiles were 4.0 and 3.8m^3s^{-1} at the Highly Modified and Less Modified sites respectively. This level of flow equates to flow only exceeded for approximately 14.1 and 15.2% of the time at the two sites. Figure 5 shows the measured and modelled velocity profiles. The figure shows that the form and magnitude of the calculated velocity profiles correspond with the observed profiles well. Near-bed measurements are particularly well replicated. A high degree of correspondence for calculated and observed velocity profiles, and in particular near-bed velocities, is an additional test of the realism of the roughness values produced by the roughness calibration procedure. The level of agreement between observed and calculated velocities corresponds well with published comparisons between CFD calculations and observed velocity when linear regressions were applied to the data (Nicholas and Sambrooke-Smith, 1999; Hodskinson and Ferguson, 1998; Lane *et al.*, 1999). Perfect correspondence between calculated and observed would produce a slope of one and a constant of zero using this technique. Figure 6 shows that a linear regression of calculated (U_{cal}) and observed (U_{obs}) velocities for the Tame sites gave

$$U_{obs} = 0.910\,U_{cal} - 0.007 \quad \text{and} \quad U_{obs} = 0.990\,U_{cal} - 0.071 \qquad \text{(10 and 11)}$$

with an r^2 values of 0.80 and 0.92 for the Highly Modified and Less Modified sites respectively. These results show that there was a good comparison between calculated and observed velocities at both sites. In comparison Nicholas and Sambrooke-Smith (1999) reported

$$M = 0.734\,P + 0.104 \qquad \text{and} \qquad M = 0.8\,P + 3.62 \qquad \text{(12 and 13)}$$

with r^2 values of 0.78 and 0.67 for P (calculated) and M (observed) velocity magnitude and direction respectively. Alternatively, Hodskinson and Ferguson (1998) reported a

$$U_{cal} = 0.89\,U_{obs} - 0.0533 \qquad (14)$$

relationship, where U_{cal} (downstream velocity component) had an r^2 value of 0.89 when correlated with field measurements. Similarly Lane *et al.* (1999) quoted regression slopes of 0.86 and 0.66 with r^2 values of 0.71 and 0.77 for downstream and cross-stream velocities respectively.

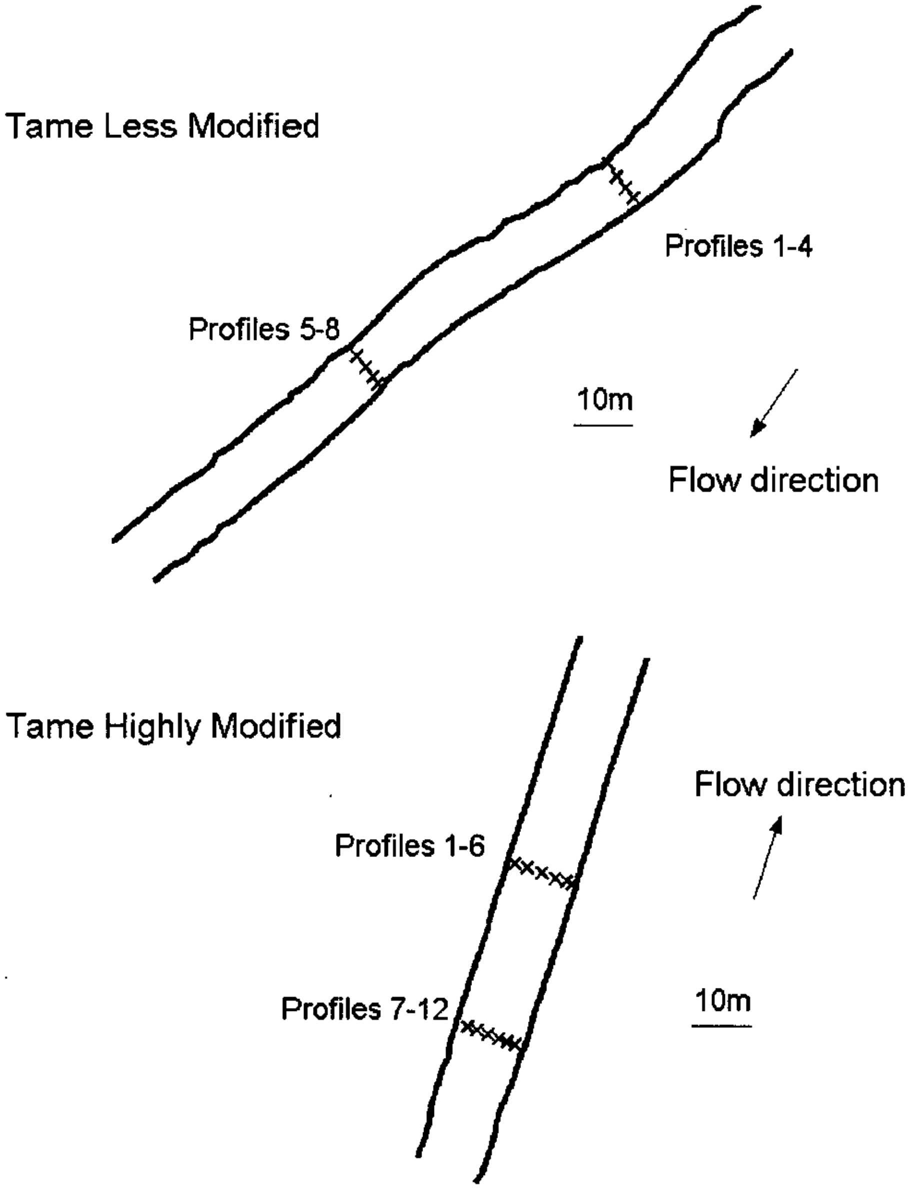

Figure 4. The locations of velocity measurements at each site.

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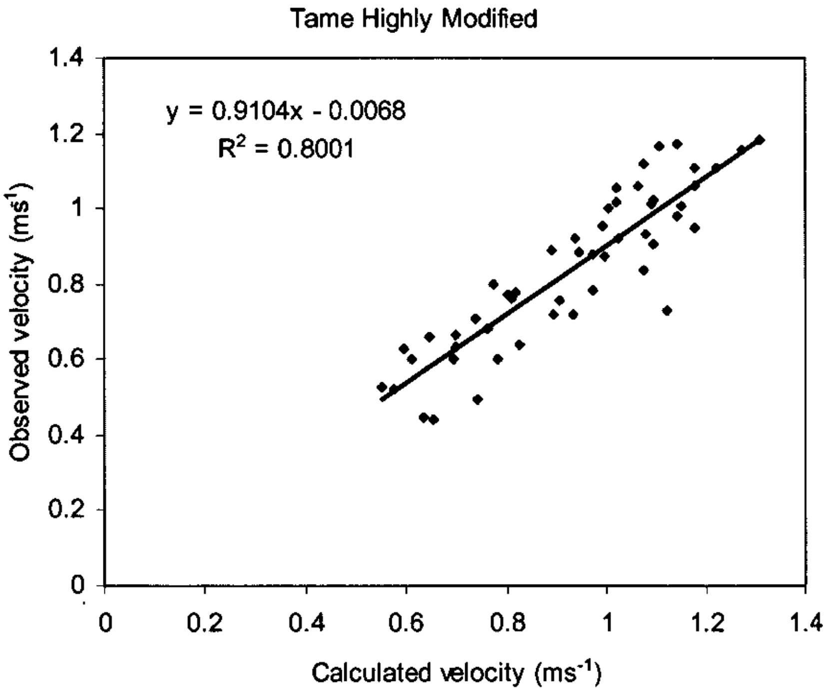
Figure 5. Calculated velocities profiles and field measurements (crosses) for cross-sections at the sites. Top two cross-sections are from the Highly Modified site. (These cross-sections were located 38 and 67m from the upstream boundary). The bottom two cross-sections are from the Less Modified site. (These cross-sections were located 47 and 100m from the upstream boundary).



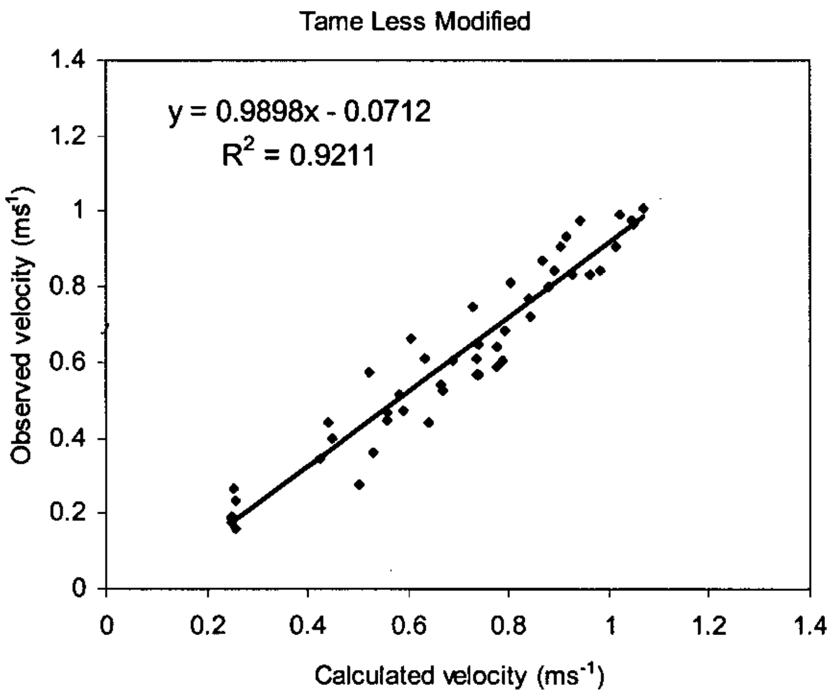


Figure 6. Comparisons of observed and calculated velocities for the Highly Modified site (top) and Less Modified (bottom) sites.

Simulation of high flow

Table III. Hydraulic conditions measurements at the two sites over a range of discharges.

		Discharge (m^3s^{-1})	Standard Deviation (of discharge measurements)	Average velocity (ms^{-1})	Average Depth (m)	Froude No	Reynolds No
Highly Modified	Flow 1	2.53	0.04	0.65	0.34	0.36	169.18
	Flow 2	3.67	0.07	0.80	0.42	0.39	253.25
	Flow 3	4.78	0.19	0.87	0.46	0.41	302.41
Less Modified	Flow 1	1.45	Na	0.31	0.38	0.16	91.18
	Flow 2	2.10	0.13	0.44	0.41	0.22	140.14
	Flow 3	2.56	0.16	0.53	0.44	0.25	178.20
	Flow 4	2.80	Na	0.47	0.46	0.22	165.43
	Flow 5	4.37	0.25	0.70	0.61	0.29	324.35

Table III shows measured hydraulic conditions at the two sites for a range of discharges. The velocity-area method (British Standard 3680, 1980) was used to make three estimates of discharges across four cross-sections in the Highly Modified site and five cross-sections in the Less Modified. Two additional discharge measurements were taken from the Less Modified site at one cross-section only. The discharges measured at each cross-section were then averaged to gain a value of discharge for each flow. Water surface elevations covering the length of each reach were also measured at the discharges shown in Table III. All water surface elevations were surveyed relative to fixed survey markers. Entering either channel at flows above $5m^3s^{-1}$ proved to be hazardous. Stage-discharge relationships were determined for the downstream cross-sections at both sites using these measured data and Equation 15.

$$Log(WSL - SZF) = Log(\mathrm{a}) + \mathrm{b}\ Log(Q) \qquad \textbf{(15)}$$

where *WSL* is stage, *SZF* is stage of zero flow, *Q* is discharge and a and b are constants determined using regressions performed on measured stage and discharge. The form of the stage-discharge relationship shown in Equation 15 corresponded well with that derived from spot gauging data supplied by the Environment Agency for the gauging structure, used to measure stage, but not discharge, on a continual basis, located between the two sites. This is further evidence in support of using stage-discharge relationships in the form given in Equation 15. Water surface predictions also corresponded well with positions of trash lines (lines of debris left after a flood marking the maximum water surface elevation) indicating water surface elevations at the sites. Vertical banks, symmetrical channel geometry, high gradients and a lack of channel vegetation all contribute to enhanced confidence in predicted water surface elevations for the first stage of the two-stage channels. Figure 7 shows the results for downstream cross-sections at both sites. The Figure shows that the main channel becomes bankfull when discharge rises above $18m^3s^{-1}$ at the Highly Modified site. This discharge corresponds approximately to the flow exceeded 0.8% of the time at the sites. CFD simulations were run for $18m^3s^{-1}$ flows at both sites using the downstream water surface elevations predictions shown in Figure 7 and the topography shown in Figure 1. Water surface levels throughout the remainder of the reach were free to adjust as described in Equation 2. Results showed that modelled water surface elevations were within 0.1m below the top of bank at the upstream cross-section for both sites. Results from these simulations were then used in an analysis of physical habitat at high flows.

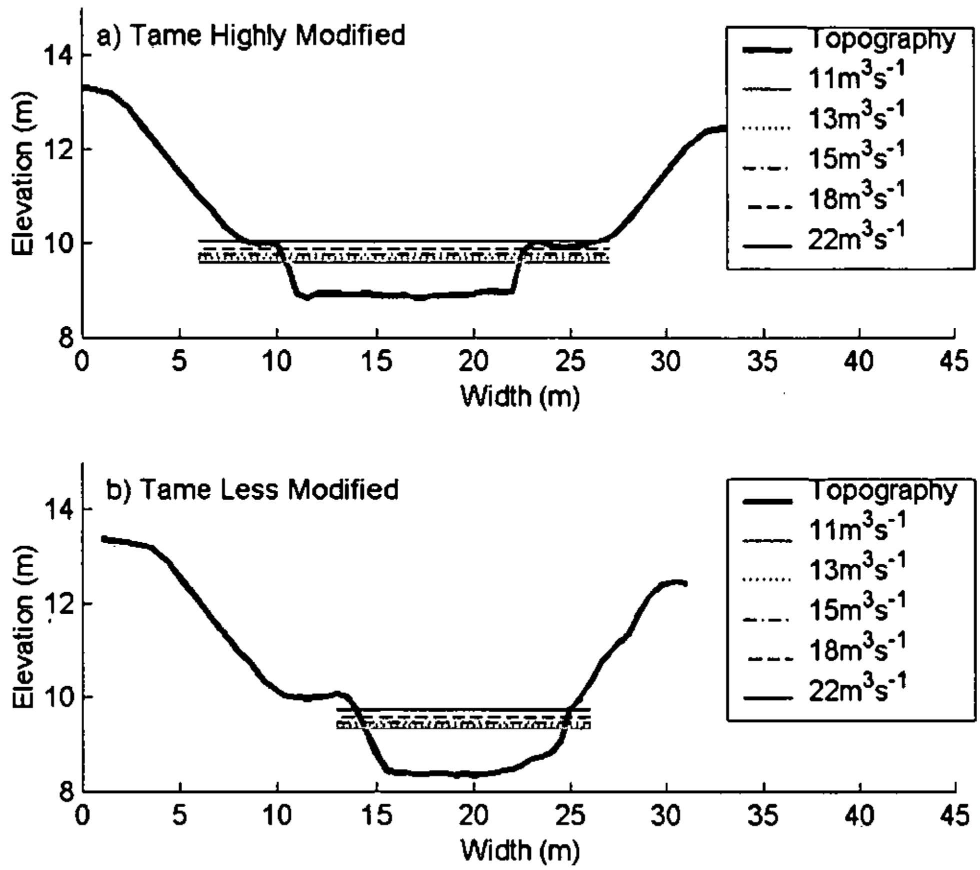


Figure 7. Stage-discharge relationships at the downstream cross-sections of each site.

Grid sensitivity

The resolution of the numerical grid in any CFD model will have an effect on the results produced. Nicholas (2001) stated that it may be necessary to accept that model sensitivity to horizontal and vertical mesh resolution is an inherent feature of CFD applications involving natural channels characterised by complex topography. For example, the number of cells is important where circulations are to be modelled, because at least four cells are required to resolve a circulation. Grid resolution is also important where near-bed hydraulic conditions are of interest, because this is where the greatest velocity and turbulent kinetic energy gradients exist. One test for the effects of changes in grid resolution on model results is that of grid dependence (e.g. Tzabiras, 1991; Peng and Davidson, 1999). In theory, when modelling the mean velocity characteristics of fluid dynamics (neglecting turbulent fluctuations) there is a spatial resolution beyond which the results produced are the same. In this situation the model is said to be grid independent. A trade-off exists between an attempt to achieve grid independence and the computing and time resources available.

When using CFD to investigate near-bed habitat, grid dependence and spatial resolution issues can be divided into two parts. The first is the dependence of the hydraulic calculations on grid resolution (e.g. to what extent do velocity patterns change shape as a result of changes in grid resolution). The second issue relates to the location within the hydraulic field that is analysed to assess habitat. How close to the river bed do fish swim during high flows, and therefore at what distance from the bed should velocities be used to compare with swimming speeds in an assessment of habitat at high flows? Answering the first of these issues is a relatively simple task of comparing results from simulations with different grid resolutions when interpolated onto the same positions. As near-bed velocity is the variable of interest in this study an experiment was conducted to assess changes in calculated near-bed velocity that occurred as a result of changes in the vertical grid resolution. Simulations of an $18m^3s^{-1}$ flow were calculated using the same boundary conditions, but with 10, 15 and 20 cells in the vertical dimension for both sites. All cells were evenly distributed throughout the water column for all runs and all other boundary conditions, including the numerical grid in the x-y plane, were held constant for each simulation.

A cubic interpolation scheme was applied to each calculated velocity profile to determine the calculated velocity at 0.02, 0.03 0.04 and 0.05m from the bed for these three simulations. These interpolated velocities were then used to perform linear regressions to assess the difference in velocity, at the same distance from the bed, for each combination of grid resolutions. Results are shown in Table IV. The results from all simulations correlated to a high degree, with 67% having r^2 values of over 0.98. The smallest r^2 was 0.92. This means that differences in calculated velocity caused by grid resolution were systematically distributed throughout the model domain.

Table IV. Results of linear regression of calculated velocity at the same distance above the bed, with different grid resolutions.

Height above bed (m)	No of cells used for x & y in regression	m	c	r^2
0.02	15 & 10	1.153	0.003	0.996
	20 & 10	1.239	0.005	0.988
	20 & 15	1.077	0.001	0.998
0.03	15 & 10	1.108	0.002	0.996
	20 & 10	1.146	0.003	0.986
	20 & 15	1.038	0.002	0.997
0.04	15 & 10	1.064	-0.001	0.995
	20 & 10	1.064	-0.004	0.983
	20 & 15	1.003	-0.007	0.997
0.05	15 & 10	1.025	-0.005	0.993
	20 & 10	0.995	-0.012	0.982
	20 & 15	0.975	-0.011	0.997

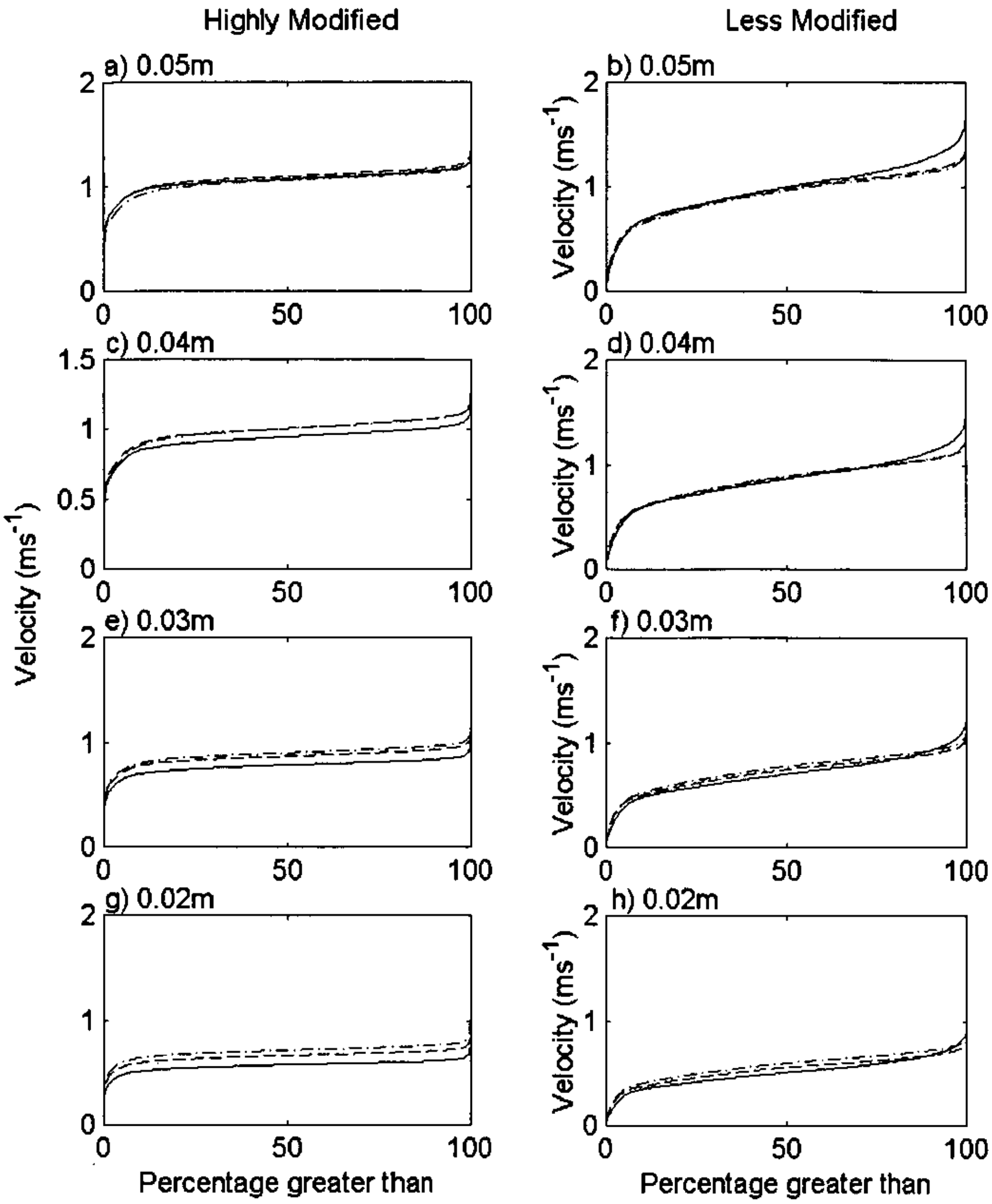


Figure 8. Cumulative frequency plots of velocity at 0.02, 0.03, 0.04 and 0.05 from the bed for the Highly Modified and Less Modified sites. Solid, dashed and dot-a-dashed lines correspond to 10, 15 and 20 cells in the vertical respectively.

Figure 8 shows cumulative frequency plots of modelled horizontal velocity at different heights from the bed derived from simulations with 10, 15 and 20 cells in the vertical. Results show that in all cases there is a greater difference between the 10 and 15 cell resolution grids in comparison to the difference between the 15 and 20. In general as height above the bed increases the difference in velocity calculated using the different resolution grids decreases. Specifically, the velocity field at or below 0.03m from the bed is more dependent on grid resolution than those above this height. In general, calculated velocity is faster for the finer resolution simulations. This is the case for all velocities that are 0.04m from the bed or less. There is one exception, in the Less Modified site, where velocities in the fastest 10-15 percent of the 10 in the vertical simulation are greater than those calculated using the finer resolution grids. The locations of these greatest discrepancies coincide with the areas of steepest bed slope in the Less Modified reach and as a result the locations are also those with the greater components of vertical and cross-stream velocity. This indicates that near-bed results are more dependent on grid resolution using the coarsest grid due to differences in simulation of the entire flow field rather than the way in which the model calculates near-bed velocities specifically.

Discrepancies in calculated velocity caused by differences in grid-resolution are comparable to those expected for measurement error in velocity measurements and less than errors associated with habitat suitability estimates derived by expert opinion (e.g. Johnson *et al.*, 1993). This is especially the case when comparing the 15 and 20 cells in the vertical resolutions. This suggests that, although there is uncertainty in the calculated results due to differences in grid resolution, these uncertainties may be viewed as being the similar in magnitude as errors associated with measurements recorded using current meters had this been possible.

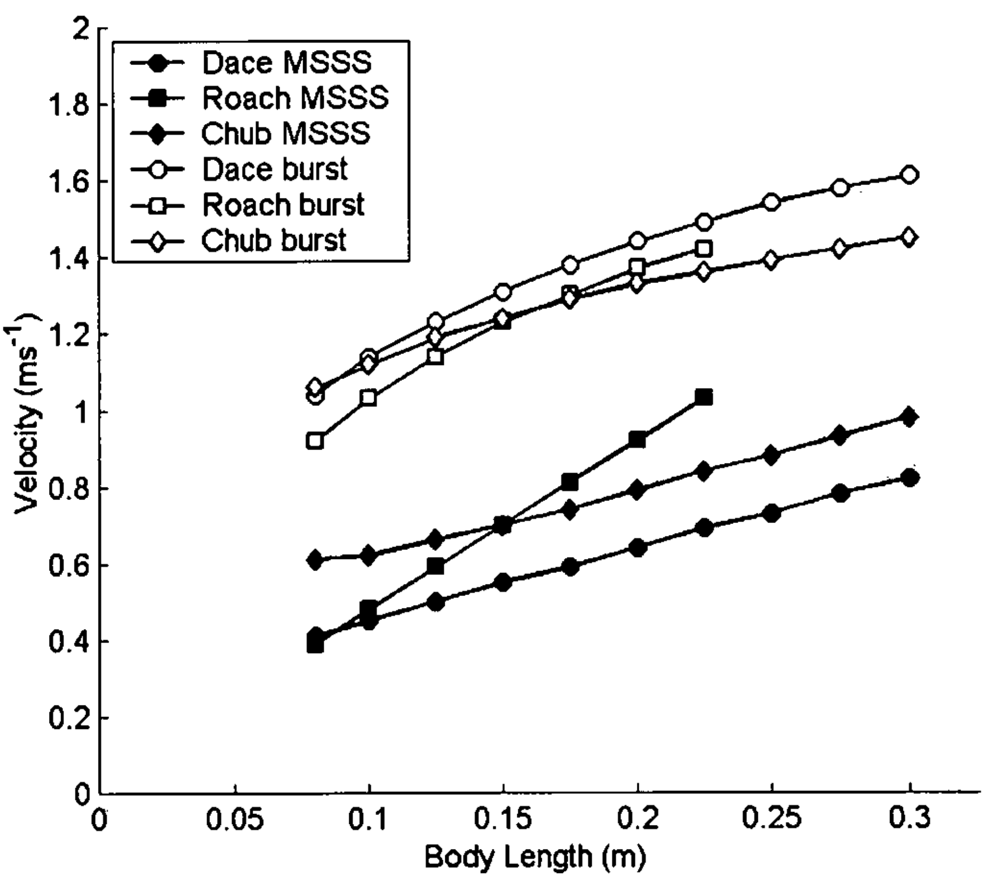


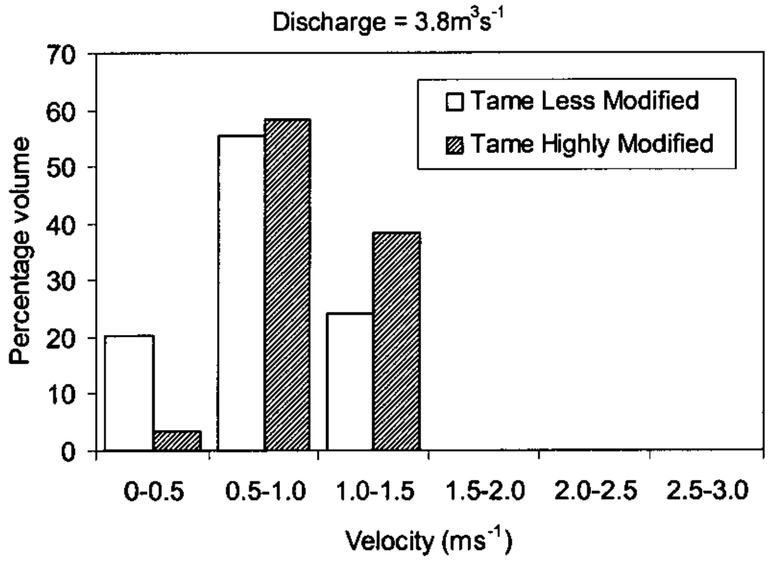
Figure 9. Mean "maximum sustainable swimming speed" and "burst swimming speed" for roach, dace and chub at 8°C (based on data from Clough & Turnpenny, 2001).

Fish Swimming speeds, migration and refuge use

Biologists have found that the swimming performance of fish is related to the health of the fish when exposed to sub-lethal toxic chemicals in the water (e.g. Alsop *et al.*, 1999). One frequently used measurement is critical swimming speed (Kolok *et al.*, 1998). Alternatively swimming speed capability may be split into three categories (Beamish, 1978). These are burst speed (can be maintained for ≤ 20s), prolonged speed (can be maintained for 20-200min) and sustained speed (can be maintained for > 200min) (Turnpenny *et al.,* 2001). The Maximum Sustained Swimming Speed (MSSS) is defined as the maximum velocity at which a fish can swim for a period of more than 200 minutes. Swimming speeds can vary with species (Hammer, 1995), body length (Wardle and He, 1988; Petrell and Jones, 2000), temperature (Clough & Turnpenny, 2001) and from individual to individual (Kolok *et al.,* 1998). Clough and Turnpenny (2001) conducted an extensive set of swimming speed experiments on groups of dace (*Leuciscus leuciscus L.*), roach (*Rutilus rutilus L.*) and chub (*Leuciscus cephalus L.*) of various body lengths in water of varying temperature. Figure 9 shows swimming speeds for these species. The figure shows that as the fish become larger their MSSS becomes greater. MSSS does vary with temperature. However, Clough and Turnpenny (2001) showed that MSSS changed by only $0.04ms^{-1}$ on average for dace, roach and chub for water of 12°C when compared to 8°C. Swimming speeds at 8°C are shown here as this was the coldest water temperature at which swimming speed experiments were conducted.

The availability of refuges is a crucial habitat factor for fish in river channels (Makinen et al., 2000). The importance of refugia to fish in lotic environments arises because they serve as protection from high current velocities (Langler and Smith, 2001). Investigation of fish behaviour during high flows is a logistically difficult task. Although some fish tracking has been carried out (e.g. Armstrong et al., 2001; Makinen et al., 2000) there is little information available relating to fish behaviour during high flows in rivers. Several studies have shown that some fish species use interstitial positions as refuges during lower flows (e.g. Valdimarsson and Metcalf, 1998). The function of this behaviour is unclear. The two possible explanations are a) that the fish are hiding from something and b) that the fish are seeking shelter from the water current. In fact, Valdimarsson and Metcalf (1998) showed that juvenile salmon clearly preferred refuges that allowed them to hide but offered little shelter from the current. Clearly fish populations as a whole are capable to seeking refuges. For example, Pinder (1997) showed that marinas and side channels are important components of the habitat system on the Great Ouse and acted as surrogates for natural floodplain features. However, it is not known to what degree individual fish are capable of seeking and finding refuges. Fish do not have perfect knowledge of the habitat available to them (Carr et al., 1997) but, Lucas and Batley (1996) showed that Barbel were capable of migrating over substantial distances, although in winter, mean daily activity was less than 20% of peak summer levels and fish were relatively dormant.

Results: Assessment of habitat during high flows



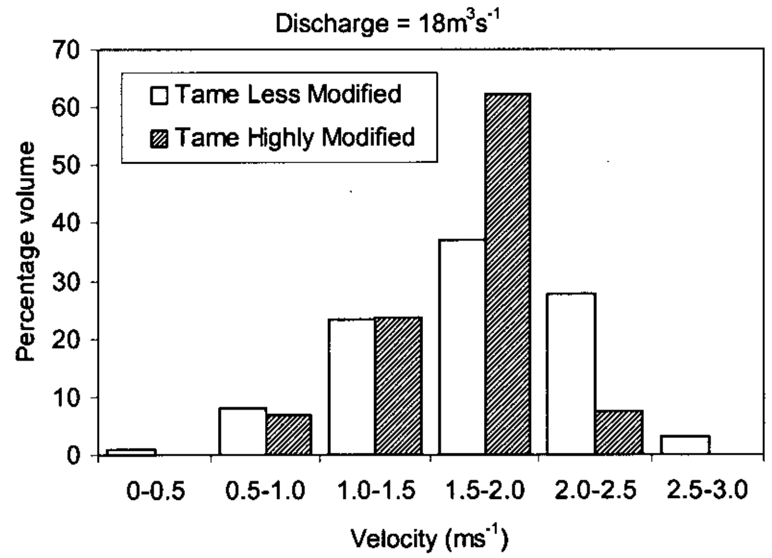


Figure 10. Histogram showing the distribution of modelled velocities at the two sites at discharges of 3.8 and $18m^3s^{-1}$.

Velocity patterns were simulated for flows of $18m^3s^{-1}$ at the Highly Modified and Less Modified sites. Figure 10 shows the distribution of velocities modelled for the two sites at a discharge of $18m^3s^{-1}$. Velocity distributions at a discharge of $3.8m^3s^{-1}$ (the discharge at which model calculations and field observations were compared for the Less Modified site) are also shown as a comparison. The figure shows that at both discharges the Highly Modified site has a narrower range of velocities in comparison with the Less Modified. In the Highly Modified site a lack of geomorphological diversity creates uniform hydraulic conditions which prevail throughout the reach. The diversity of flow conditions at the Less Modified site is most prominent at the 18 m^3s^{-1} flow. The undulating bed profile and slightly sinuous planform at this site create a broader range of velocities. In this reach faster velocities are predicted in the shallower, narrower parts of the channel. Slower velocities are present at deeper sections and downstream of the slight bends in the reach.

Simulated hydraulics were analysed in relation to MSSS to assess habitat suitability. The results of swimming speed investigations were combined with simulated velocity patterns to assess the percentage of in-stream habitat area that is less than the MSSS. This is the area of river, at a specified distance from the bed, in which fish of a certain size and species can sustain a position for at least 200 minutes. The area of the simulated flow field that is less than the mean MSSS for groups of chub, dace and roach will be called the "survivable area" here for purposes of discussion. Due to uncertainty as to the exact position of fish during high flows, and to simplify the three-dimensional nature of the analysis, different heights above the bed were considered separately. The percentage area less than a certain speed was calculated by relating the number of cells less than that speed to the total number of cells in the horizontal plane at different heights above the bed. Each cell represents a $0.14m^2$ area for both sites. It is assumed that this is a sufficiently large area for a fish to fit into.

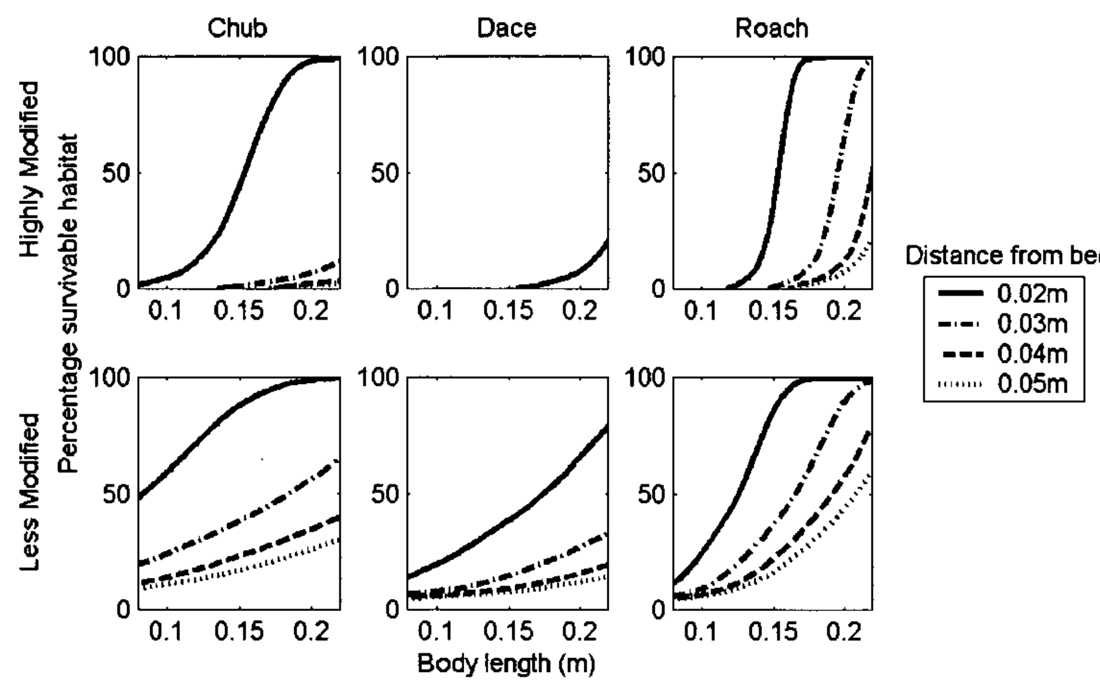


Figure 11. Percentage volume of habitat less than the mean "maximum sustainable swimming speed" at different distances from the bed in each reach at $18m^3s^{-1}$.

Figure 11 shows the percentage of survivable area for chub, dace and roach at 8°C at a discharge of $18m^3s^{-1}$ at both sites as derived from the 20 cells in the vertical simulations. Results are only shown for the range of fish sizes for which swimming speeds are given in Figure 9. The figure shows that as the body length increases there is an increase in the area of habitat in which a fish is likely to be able to sustain a stationary position. This is because bigger fish can sustain faster swimming speeds. Similarly, as distance from the bed increases the percentage of survivable habitat decreases due to faster velocities.

Results show that, at a discharge of $18m^3s^{-1}$, the Less Modified site has a greater volume of slower flowing water in comparison to the Highly Modified site regardless of height above bed. As a result there is more survivable habitat in the Less Modified reach for all sizes and all species at all distances from the bed. The deeper, slower flowing areas and rougher bed in this reach ensure that all sizes of all species have at least 5% survivable habitat at all distances from the bed. This is in contrast with the Highly Modified site where, at 0.03m from the bed, there is no survivable habitat for fish less than 0.13m in length of any species. There is only a small percentage of survivable habitat for fish smaller than 0.10m in the Highly Modified reach even at 0.02 above the bed. Smaller roach and dace, which have slowest MSSS, have no survivable habitat, even at only 0.02m from the bed. Dace have the slowest MSSS and as a result there is very little habitat in which dace of any size may be expected to survive in the Highly Modified reach during a sustained $18m^3s^{-1}$ event, even closer to the bed. Roach have the greatest rate of change of MSSS with body length. As a result the volume of survivable habitat for roach rises rapidly with increasing fish length in both reaches. This rise is particularly rapid in the Highly Modified site where, as body length increases, large rises in survivable habitat occur at different body lengths dependent on height above bed.

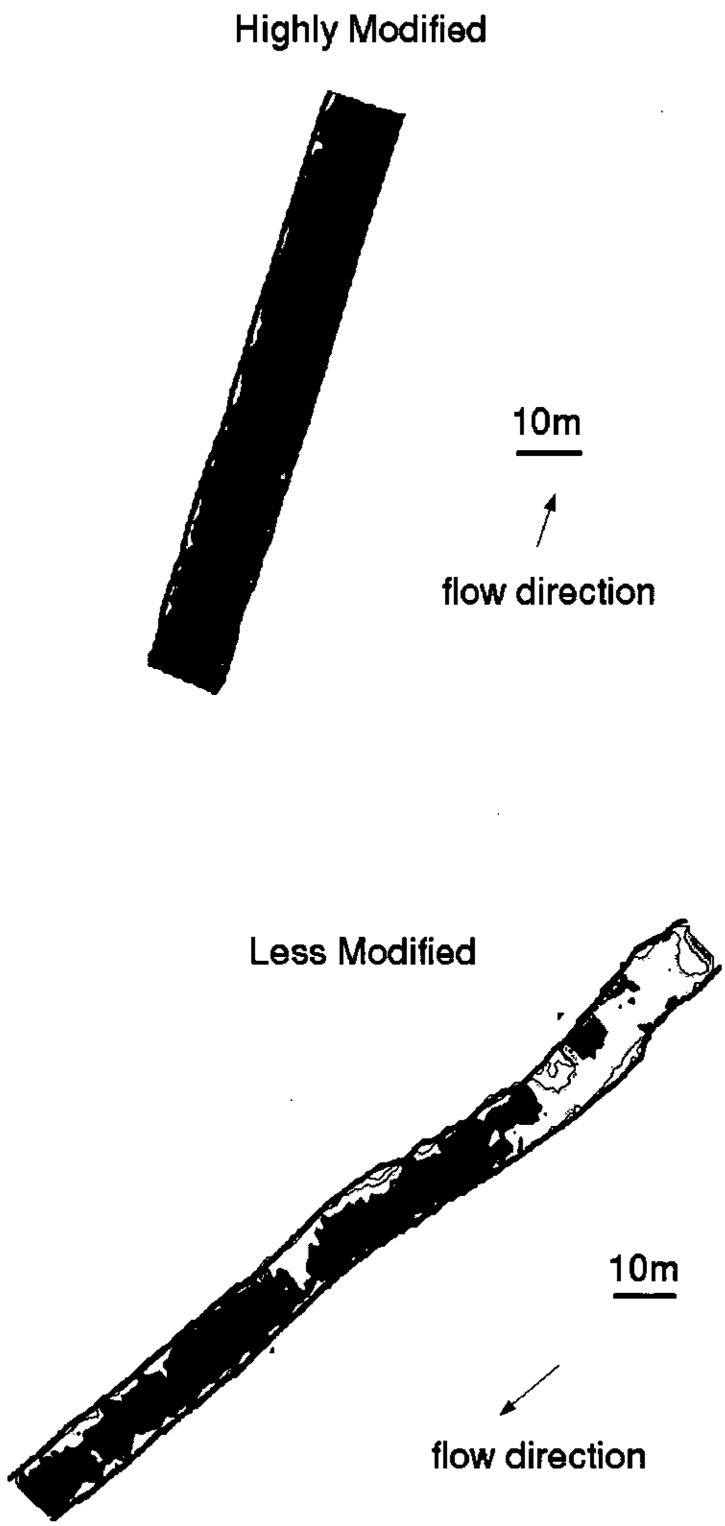


Figure 12. Velocity at 0.03m from the bed for the Highly Modified and Less Modified reaches at $18m^3s^{-1}$ ($0.25ms^{-1}$ contour intervals).

Figure 12 shows maps of near-bed velocity at the two sites. The figure shows simulated velocity at a height of 0.03m from the bed for the $18m^3s^{-1}$ simulations using 20 cells in the vertical. The figure shows that the majority of calculated near-bed velocity at both sites lies between 0.75 and $1.0ms^{-1}$. In the Highly Modified site the flatter channel bed and less sinuous channel planform mean that velocities are distributed more evenly. Slower velocities are concentrated into a narrow band along the left bank of the channel where depth is slightly shallower. The small area of velocity that is less than $0.75ms^{-1}$ is exclusively located adjacent to the banks. In contrast the Less Modified site has discrete zones of slower velocity. A deep pool approximately 40m from the upstream boundary provides a flow refuge which acts as a niche of suitable habitat in this reach. There is also a discrete area of velocity at the mid point of the reach, which is less than $0.5ms^{-1}$, created by the sheltering effect of a change in direction of the right bank planform. At the downstream end of the reach, where channel bed is less flat, wider areas of reduced near-bed velocity adjacent to the banks are also present.

Table V. Flow events exceeding $18m^3s^{-1}$ during 2000.

Event No	Duration (mins)	Month	Day
1	75	2	12
2	150	2	27
3	75	3	3
4	330	4	18
5	30	4	26
6	135	7	2
7	270	9	19
8	330	9	25
9	105	10	29
10	540	10	30
11	45	11	2
12	1110	11	5
13	240	12	5
14	480	12	7
15	225	12	11
16	75	12	12

There is a temporal aspect to using MSSS for the assessment of physical habitat as survival is dependent upon the duration over which velocities are exceeded. Analysis of flow records for the nearest gauging station to the sites shows that during the year 2000, a period of extreme rainfall events, discharge exceeded $18m^3s^{-1}$ a total of 16 times for periods varying between 45 minutes and 18.5 hours. Table V **Error! Reference source not found.**shows summary information for these events. There are eight events over $18m^3s^{-1}$ that lasted longer than the 200 minute time interval used to determine MSSS shown above. Assuming that habitat suitability does not improve above $18m^3s^{-1}$ and that the simulated hydraulic conditions shown in Figure 12 are correct, these eight events are potentially fatal for any fish which cannot find refuges.

There is possible improvement of habitat suitability for flows above $18m^3s^{-1}$ as flow overtops the banks of the first stage of the two-stage channel. However, the fish would be presented with the problem of re-entering the channel. This would be made difficult at the two sites investigated due to the presence of levees, which have built up with the deposition of fine sediment, as shown in Figure 7.

Discussion

Use of 3D-CFD models can provide hydro-ecologists with a powerful tool for assessing habitat quality. Specifically, 3D-CFD models allow analysis of spatially continuous hydraulic patterns. It is this aspect of the analysis which is crucial when investigating spatial phenomena such as flow refugia. A three-dimensional approach also allows simulation of near-bed hydraulic conditions that are more realistic than those provided by a two-dimensional model (e.g. Waddle *et al.,* 2000). The technique improves upon use of habitat suitability curves to assess physical habitat (e.g. Elliot *et al.*, 1999), which lack representation of vertical variations in velocity. However, the limitations of any scientific method should be considered when interpreting results. Intensive field data collection and computational resources are required to set model boundary conditions for any 3D-CFD modelling approach and application of 3D-CFD modelling to long river reaches is not practical. Therefore this type of approach needs to be used to develop a more rapid rule based method.

In this study a 3D-CFD model was used to make physically-based predictions of velocity patterns during high flows when entering the channel to take measurements was not possible. The model produced good results for lower flows. A grid dependence experiment was used to quantify the uncertainty in calculated velocities associated with using different grid resolutions. Results indicated that uncertainty caused by grid dependence is similar in magnitude to measurement errors for current meters, and is less than uncertainty surrounding quantification of habitat suitability indices or maximum sustainable swimming speeds.

The approach used assumes that flow at the upstream model boundary was relatively uniform, that the imposed downstream water surface elevation was correct, that the channel did not change shape, due to erosion and/or deposition, and that the numerical resolution was sufficiently fine to represent the smallest flow structure. In addition one of the most important assumptions of the model is that velocity patterns near the bed can be modelled using a wall law and a spatially uniform roughness. Nicolas (2001) compared simulated velocity profiles calculated using a wall law method with a random elevation model that simulated the effects of supra-grid-scale roughness elements. Results showed that, although the two methods produced differences in the turbulent kinetic energy profiles, differences in velocity profiles were not significant. The extent to which spatial variations in roughness create fish refuges is not clear and cannot be proved without fine resolution measurement of near-bed velocity covering a considerable area of the river during high flows.

A lack of knowledge of fish behaviour during high flows means that predictions of physical habitat during high flows cannot be easily verified. In a 3D model the boundary between the river bed and the water column has a definite position and an associated roughness height, whereas in reality the exact location of river bed is blurred by the texture of the sediments. This causes a particular problem in analysing fish habitat during high flows. There are few data available on the height of water roach, dace and chub of varying sizes require to swim in, and what velocity gradients acting over the height of fish are tolerable. Results from this study suggest that whatever height is used the Less Modified site provides better habitat at high flows than the Highly modified. There is also uncertainty as to the level of knowledge a fish may have regarding the habitat available to it. Although the results show that habitat in the Highly Modified reach is less suitable during high flows there is still uncertainty relating to migration of fish out of the reach in order to survive. Further research is required on how far fish can travel in order to find flow refugia during high flows.

Water quality and physical habitat quality are closely linked. The MSSS used in this study were derived using experiments on healthy fish. In the river Tame it is possible that high levels of pollution (e.g. Beamont *et al.*, 2000), low levels of dissolved oxygen and high levels of ammonia reduce swimming speeds of fish. For example swimming speeds of rainbow trout are significantly reduced when exposed to Cu (250 μgl^{-1}) in moderately hard water (McGeer *et al.*, 2000). It is also true that young-of-the-year fish, whose abundance is crucial in determining year-class strength (Hatcher *et al.*, 1991), will be more susceptible to the adverse effects of high flows than fish with body lengths greater than 0.08m. This is particularly the case during late summer (Gozlan *et al.*, 1999). This is important in urban rivers where high flow events can occur throughout the year due to impermeable surfaces and dense drainage networks.

The results do not prove that there is no habitat in which fish can survive during high flow events. However, comparison of simulated hydraulic patterns to fish swimming speeds has shown that poor physical habitat at high flows is a potential limiting factor for fish in these modified urban river channels. This is especially the case in more heavily modified reaches where low geomorphological diversity provides minimal flow refugia. Urban river regimes are particularly likely to provide poor physical habitat during high flows. This is because poor water quality reduces swimming speeds of fish, the engineered river channel reduces flow refuges and frequent high flows may occur at any time during the year. Therefore an integrated approach to habitat improvement that considers physical habitat as well as water quality issues is required to improve river health.

Creation of habitat refugia is one approach to increasing the quality of physical habitat and therefore maintain fish populations in urban river channels. Langer and Smith (2001) compared several different enhancement schemes on the Huntspill River. They showed that all schemes on this river successfully increased fish populations, and that the type and age of the enhancement scheme was relatively unimportant. This implies that as long as velocities are sufficiently decreased most designs of enhancement scheme will be beneficial. Creation of stable zones of slower velocity, such as re-circulating eddies located downstream of channel constrictions (Thompson *et al.*, 1996; Thompson *et al.*, 1999) or those associated with debris dams (Gippel, 1995), are potential schemes that could be employed on the River Tame. However, where flood conveyance is also a necessary function of the river channel careful design of such a scheme is necessary.

Conclusions

3D-CFD simulations have been used to assess physical habitat at high flows in two urban river reaches. Results suggest that the straighter, more heavily engineered channels provide very limited flow refugia for fish at high flows. Although MSSS of fish are surpassed in the majority of the less engineered reach, results show that a deeper pool and cross-sections that have less uniform depth provide increased flow refugia. This research indicates that physical habitat at high flows is an important factor for fish survival in urban rivers, where peak flow can be particularly high. This is particularly the case in rivers with poor water quality as laboratory tests show that swimming speeds decrease as water quality becomes poorer. This research therefore supports the hypothesis which states that "Cost effective rehabilitation of urban rivers depends not only upon scientifically sound improvements in water quality, but also on improvements in flow regime and physical habitat." As a result flood defence schemes should consider the incorporation of flow refugia into channel design when attempting to limit degradation of physical habitat. The challenge is how to incorporate refugia without compromising channel stability or flood defence requirements. CFD modelling provides one method for investigating how this may be achieved.

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Part III) Review of procedures to assess the risk to fish and invertebrates from sediment pollution in rivers

Carol Watts, November 2000

Introduction

PHABSIM is being extended for urban channels as part of the hydro-ecological modelling being carried out in the URGENT project. PHABSIM currently uses physical habitat variables to assess overall suitability of river channels for aquatic species, and it is hoped to incorporate water quality in assessment of river channels. Suspended sediment is of particular interest because high sediment concentrations in the water column and deposition to the river bed can cause detrimental effects on fish.

The aims of this report are to:
1) Determine whether an existing procedure to assess the risk of suspended sediment pollution in rivers can be applied to the River Tame, Birmingham, an urban catchment.
2) Conduct a literature search for suitability indexes which might be appropriate for species within the Tame catchment.

A regional procedure to assess the risk to fish from sediment pollution in rivers: the Lower Swale catchment, Yorkshire

Watts et. al (2001) describes how a regional model has been used to derive sediment concentrations for river reaches in the Lower Swale, Yorkshire, UK, and presents a procedure to assess the risk of sediment pollution in rivers to fish. Excerpts from the paper are given below.

> 'A distributed catchment delivery model (Cooper and Naden, 1998) was developed which simulates daily flows from rainfall and potential evaporation data using a two-layer hydrological model based on soil type and land use. This was applied on the basis of hydrological response units (HRUs), i.e. hydrologically independent areas which are derived automatically from a 50m digital elevation model and drain to an identified reach on the river network, at a spatial resolution of 5 to 8 km^2.
>
> A simple regression model which related in-stream suspended sediment concentration to flow and land use controls was also developed for small to medium sized catchments in Yorkshire (Naden & Cooper, 1999). The sediment model was applied within the catchment delivery model to HRUs in the Lower Swale to simulate time series of daily mean flow, sediment concentrations and loads between 1985 and 1992. For each reach, flows and sediment loads were calculated as the sum of all flows and loads over the HRUs draining to it, including all those draining to upstream reaches. Inputs from the catchment of the Upper Swale were calculated and fed into the most upstream reach on the Lower Swale. Daily sediment concentrations for each reach were then calculated by dividing the daily estimate of cumulative load by the daily cumulative flow. This makes the assumption that the gains and losses from in-stream processes are relatively small compared to the estimated sediment delivery.'

Peaks-over-threshold mean concentrations over 1 to 6-day durations were extracted to derive frequency curves which show the relationships between simulated sediment concentration and exceedance probability. The severity of such events on different fish types was illustrated using results from published literature (Newcombe and Jensen, 1996) which showed that the relationship between predicted severity of ill effect, sediment concentration and duration of exposure varied with fish species, life stage and particle size. A table of concentration ranges associated with different levels of ill effect for different fish types and durations of exposure is given. The risk of moderate habitat degradation for adult salmonids was calculated for all reaches, and maps of the risk of damage to such fish from 1, 2 and 6-day sediment events were presented. Similar maps can be derived for adult non-salmonids and other fish types. Maps of the risk of damage to fish from sediment concentrations exceeding 80mg/l can also be derived. Such maps can provide a useful tool for water managers in assessing the impact of sediment on fish, for setting achievable river water quality objectives, and for identifying problem reaches.

Applicability of this procedure to the Tame catchment

Description of Tame catchment

The Tame is a midland catchment, lying at a height of 66m at Lea Marston Lakes and 74m at Water Orton, and rising to 287m at the source of the Rea. The River Tame itself has a gravel bed. Prior to industrialisation it supported trout, but these declined rapidly in the 19th century, at a time when the Tame was being polluted by various industries including coal gas works, iron manufacturing, domestic sewage and paper mills. Water quality declined sufficiently that it was declared unsafe to drink in 1872 (Harkness, 1982). The river was considered to be devoid of fish in the early part of the 20th century, but the fish life is slowly recovering due to pollution control measures such as the building of more sewage treatment works and a general decline in heavy/manufacturing industry. However, the nature of the substrate differs from that found in a natural regime, in terms of the size and distribution of particles within the matrix. There is a greater percentage of fine sediment than larger particles, although there considered to be less substrate/bed sediment than expected (compared with the nearby River Blythe, a less urbanised, more natural river). Heavy metals tend to bind to fine sediment particles. Indeed, bed sediments of the Tame have been found to be up to 3000 times greater than background levels (Thoms, 1987). Such toxic sediments may contaminate the primary producers or lower orders of the food chain which are found in river gravels. This indicates that there has been a long-term water quality problem, which may affect the future water quality of the catchment depending on whether these sediments currently contaminate the local fauna, whether they are disturbed/entrained to re-enter the water column and whether desorption of contaminants from sediment particles occurs.

The Tame catchment lies in the urbanised environment of the Birmingham conurbation. The flow regime is highly modified in many places due to substantial imports from sewage treatment works, water reclamation works and other discharges, such as combined sewer overflows, storm tanks overflows and urban runoff and drainage. The flow regime is made more complex by the network of culverts, canals and urban drains. The river has been channelised in certain areas.

Applicability of the CDM and sediment model to the Tame catchment

A daily catchment delivery model already exists for the Tame catchment, upstream of the confluence with the Trent. The urbanised nature of the Tame catchment means that the HRUs are not necessarily hydrologically independent due to drains, canals, combined sewer overflows (CSO) etc. The CDM has been run for the Tame, producing cumulative simulated daily flows from all HRUs draining to the Tame at Lea Marston, from which a constant has been subtracted to account for sewage inputs. The model output has been input to Questor, an in-stream model, which adds sewage inputs back in, but it does not account for wet weather input of runoff, storm drainage or CSOs. Changes to the gauging stations over time and diversion of sewage effluents from upstream to Minworth Sewage Treatment Works 100m downstream of Water Orton may affect the observed flows for the Tame. Modelled flows for the Tame at Lea Marston are overestimated compared to observed data. This may be due to the urban component of the flow model which simulates quick flow or urban runoff, which was originally derived from largely agricultural catchments in Yorkshire. This could be recalibrated on the Tame catchment to give better flow estimates.

The sediment model could be derived from existing EA daily mean flow and suspended sediment data, and catchment characteristics. Data from representative catchments from across the whole of Yorkshire were used to derive a regional model. In this case, it is suggested that only representative, appropriately-sized catchments draining to the area above the Tame at Water Orton or the Tame at Lea Marston are used. The model is expected to show a strong relationship between sediment concentration, daily mean flow and percentage urban area characteristics, but may be related to other characteristics. Note, however, that the sediment concentration-flow relationship is often very scattered for urban catchments (see Figure 9, Naden and Cooper, 1999) and so a simple regression may not be the most appropriate model to describe the data. The suitability of the model largely depends on the quality of the data used. Note that the sampling of EA sediment data may be biased towards low flows. Any sediment model based on such data may therefore underestimate the sediment peaks which occur at high flows.

The CDM and sediment model currently operate at a daily time-step. A shorter time-step may be more appropriate to model the urbanised, responsive Tame catchment. The CDM could be amended to work at sub-daily level. However, this would require the addition of flow-routing within HRUs. Sub-daily rainfall could be used where available and/or daily inputs of rainfall and evaporation could be used to simulate sub-daily inputs. The sediment model could be derived from spot-sampled suspended sediment concentrations and the respective 15-minute flow. Ideally, a detailed model is required to model urban runoff, storm drains, and CSOs in wet weather conditions, when sediment is likely to increase rapidly. However, this is considered to require significant modelling effort which may not be justified in terms of the output of sediment concentrations. Therefore, it is suggested that any known significant CSO inputs could be fed into an in-stream model. Simple sewer models do exist however, such as SIMPOL (FWR, 1994), which estimates spill flows from CSOs.

For work on the Lower Swale flows and loads were simply cumulated down reaches in order to calculate concentrations. For the work on the Tame catchment, the HRU inputs to reaches have been used in conjunction with an in-stream model, Questor. This has simple flow-routing and allows for inputs from discharges and outputs (abstractions). Sediment is treated as conservative pollutant. Other in-stream models exist. CASCADE is similar to Questor but also includes concentration routing and in-stream processes of entrainment, deposition and erosion of the bed. An existing E-coli model has in-stream processes but no flow routing, and could be modified to model sediment. It is suggested that these models are applied to the sediment concentrations from the delivery model to compare results. Detailed flow and sediment monitoring would be required to determine which model is most appropriate.

The peaks-over-threshold techniques could be applied to the resulting frequency curves for different quantiles of high sediment concentrations. Newcombe and Jensen criteria could be applied in the first instance to derive maps of risk to fish species for the Tame. See below for more information on criteria for fish and invertebrates.

Flow and suspended sediment data availability

Available daily mean flow data

Table 1. Flow gauging stations in the Tame catchment

Station number	Station name	Period of record	BFI	Area (km^2)	Description
28003	Tame at Water Orton	1955 - 2000 (gaps 1982-93)	0.62	408	Fully urbanised, effluent baseflow, substantial regime disturbance from imports. Out of bank at high flows.
28081	Tame at Bescot	1982 – 2000	0.70	169	Fully urbanised, substantial imports from a Water Reclamation Works.
28039	Rea at Calthorpe Park	1967 – 2000	0.48	74	Almost fully urbanised, modified regime due to significant imports.
28066	Cole at Coleshill	1973 – 2000	0.44	130	Substantially urbanised, moderate modification to flows from effluent returns.
28080	Tame at Lea Marston	1957 – 2000	0.69	799	Substantially urbanised, substantial flow modification, large imports. Poor flow estimation at high flows.

Daily mean flows are available for the gauging stations above. Some changes to the gauging stations have occurred which may have affected the flows. There are likely to be 15-minute flows at the above sites. Level data only are available for other sites.

Available suspended sediment data

a) EA river monitoring stations

There are 184 river monitoring sites above the Tame at Lea Marston, not including those monitoring sites on canals, with data from 1989 to 1995. Excluding sites with fewer than ten samples, the mean and maximum suspended sediment concentration ranged from 5 to 196mg/l, and 14 to 5200mg/l respectively. The sampling frequency ranged from 2 to 53 samples per year. A detailed analysis has not been performed, but the preliminary work suggests that there are enough sites with suspended sediment data to perform a regression analysis of suspended sediment concentration and catchment characteristics in order to derive a sediment model for the Tame catchment. There are however, only five gauging stations still operating in the catchment.

The EA water quality samples may be biased towards low flow sampling so the full range of sediment may not be recorded, and not all high sediment events may be captured. Surface sampling techniques mean that EA sediment samples are biased towards fine sediments (e.g. < 63 um particles). Such small particles pose a risk to fish because the particles are sufficiently small to clog fish gills, and because such particles carry adsorbed organics and heavy metals, which contaminate bed sediment in which invertebrates feed or live.

b) Birmingham University suspended sediment monitoring

Birmingham University is monitoring suspended sediment during storm events at the Tame at Water Orton and the inlet and outlet (on the Tame) at Lea Marston Lakes. Storm events have been monitored since the start of 2000. At Water Orton, EA 'hobos' have been used to take suspended sediment samples every 10 minutes for 12 hour periods, and three 10-minute samples are collected into a bottle (as a composite sample) every half an hour. The maximum concentration is around 600mg/l for near-surface water, and 1300mg/l for near-bed measurements. The near-surface measurements will contain the fine sediment or smallest/lightest particles, those < 63um. These are most important for transport of organics and heavy metals. The bed-sediments of the Tame are said to be heavily polluted with heavy metals.

Whilst the Birmingham suspended sediment data is for year 2000 only and for storm events, the data will provide a useful indication of the range and rate of change of suspended sediment for the Tame at Water Orton and can be used to test the results of the sediment model. It may also be used to develop in-stream models which include simple flow and/or sediment routing.

Existing fish and invertebrate species in the Tame catchment

Table 2 shows the most popular fish and invertebrate species currently found in the Tame (upstream of Water Orton), the Rea and the Cole. In addition, small numbers of roach, perch and dace are believed to inhabit the Cole, Blythe and the Tame near Lea Marston. The Tame has the poorest water quality, followed by the Cole and the Rea. Fish survival is considered to be water quality limited due to chemical inputs/heavy metal pollution, rather than being limited by the habitat or flow conditions. Few coarse fish and no salmonid fish are found in the Tame today. The Tame was a trout river before industrialisation, which suggests that improvements to water quality and/or habitat and flow could lead to an increase in biodiversity in this river. Water quality has improved over the last 20 years.

Table 2. Most common fish and invertebrate species in the Tame catchment above Water Orton.

River catchment	Type	Species
Tame	Fish Invertibrates	Three-spined stickleback Tubificidae (oligochaete worm), Erpobdella octoculata (leech), Asellus aquaticus (hog louse), Cricotopus bicinctus (midge larvae)
Rea	Fish Invertibrates	Three-spined stickleback, stone loach, minnow, gudgeon Tubificidae, Gammarus pulex (shrimp), C.bicinctus, various snails, mayfly, caddisfly.
Cole	Fish Invertibrates	Three-spined stickleback, stone loach, minnow, gudgeon Tubificidae, E.octoculata, A.aquaticus, Gammarus pulex Lymnaea peregra (snail), Baetis rhodani (mayfly nymph), C.bicinctus, C.trifascia, Polypedilum spp., Micropsectra atrofasciata (all midge larvae)

Sediment suitability indices for fish and invertebrates in the Tame catchment (or elsewhere in UK)

The maximum allowable concentrations of total suspended solids for fisheries and aquatic life is 25mg/l in Europe and in Canada, 10mg/l above background concentration (if < 100mg/l) and 10% above background concentration (if > 100mg/l) (UNESCO et al., 1996).

Fish

Most of the work on the effects of different suspended sediment concentrations on fish has been carried out in Canada, America and New Zealand. However, there is very little literature on this topic in the UK. Alabaster and Lloyd (1980) suggested that below 25mg/l, no significant damage to fish would occur, but above 80mg/l, significant damage to fish would occur. The most comprehensive suitability index in the literature is by Newcombe and Jensen (1996), who related the effects on fish to different levels of suspended sediment concentration and duration of exposure, for different fish types and life stages. This was based on all available data, largely North-American based. The effects range between no effect, to avoidance techniques, physiological stress, habitat degradation, reduced growth rate and mortality. The critical concentrations for different durations of exposure for adult non-salmonids and other fish types are given in Newcombe and Jensen (1996) and Watts et al. (2001) – see Table 3 below. These are considered to be an excellent starting point to assess the risk to fish, but it is not known whether they are applicable to the suspended sediment conditions, flow regimes and fish species found in the UK, and in particular, urban catchments.

The Sediment Intrusion Dissolved Oxygen (SIDO) model uses time series of suspended sediment concentrations over different durations to model dissolved oxygen in the redd egg zone to quantify the effect of water quality on anadromous salmon species in gravel bed streams. It uses critical and lethal levels of dissolved oxygen, rather than suspended sediment, for certain fish species to assess effects. SIDO is currently being tested and calibrated for use in UK rivers.

Table 3. Suspended sediment concentration and the severity of ill effect for different fish, life stages, and durations of exposure (derived from Newcombe & Jensen, 1996). Results are quoted to three significant figures. *(taken from Watts et al, 2001).*
Severity of ill effect classes are defined as follows: 6 is moderate physiological stress; 7 is moderate habitat degradation and impaired homing; 8 is indications of major physiological stress (long-term reduction in feeding rate and feeding success, poor condition); 9 is reduced growth rate, delayed hatching, reduced fish density; and 10 is 0-20% mortality, increased predation, moderate to severe habitat degradation.

Fish type	Duration of exposure (days)	Predicted suspended sediment range (mg/l)				
		Severity of ill effect				
		6	7	8	9	1
Adult and juvenile freshwater salmonids	1	(33.1, 90.0)	(90.0, 665)	(665, 1810)	(1808.0, 4910)	(4910, 3630
	2	(12.2, 90.0)	(90.0, 245)	(245, 665)	(665.1, 4910)	(4910, 1340
	6	(4.5, 33.1)	(33.1, 90.0)	(90.0, 245)	(245, 1810)	(1810, 491
Adult freshwater salmonids	1	(33.1, 90.0)	(90.0, 245)	(245, 1810)	(1810, 4910)	(4910, 1340
	2	(12.2, 33.1)	(33.1, 245)	(245, 665)	(665, 1810)	(1810, 1340
	6	(4.5, 33.1)	(33.1, 90.0)	(90.0, 245)	(245, 1810)	(1810, 491
Juvenile freshwater salmonids	1	(33.1, 245)	(245, 665)	(665, 1810)	(1810, 13400)	(13400, 3630
	2	(12.2, 90.0)	(90.0, 245)	(245, 665)	(665, 4910)	(4910, 1340
	6	(4.5, 33.1)	(33.1, 90.0)	(90.0, 245)	(245, 1810)	(1810, 491
Adult freshwater non-salmonids	1	(0.61, 1.65)	(1.65, 90.0)	(90.0, 4910)	(4910, 98700)	> 9870
	2		(0.61, 12.2)	(12.2, 245)	(245, 13400)	> 1340
	6			(0.61, 33.1)	(33.1, 665)	(665, 3630
Eggs and larvae, salmonids and non-salmonids (freshwater and estuarine)	1		(0.61, 4.5)	(4.5, 90.0)	(90.0, 1810)	(1810, 9870
	2			(0.61, 4.5)	(4.5, 90.0)	(90.0, 181
	6				(0.61, 1.65)	(1.65, 90.

Invertebrates

There are a number of general indices which indicate the overall biological health of a river by looking at the presence and/or abundance of invertebrates at a site. The Biological Monitoring Working Party Score (BMWP) was originally developed from the Trent Biotic Index, established from sites on the River Trent, UK. RIVPACS (River and Invertibrate Prediction and Classification System) is used to assign biological grades to river reaches. Maitland (1977) developed a checklist of invertebrates, fish, and animals living in or closely associated with freshwater in the British Isles. This list has been updated and is available from the CEH Dorset Data Centre. Invertebrates can be sensitive to levels of contaminants attached to bed sediment, which is also dependent on species.

The tolerance of invertebrates to suspended sediment varies very widely depending on species. Work at the Centre for Intelligent Environmental Systems (CIES), Staffordshire University has recently classified the range of suspended sediment (and other water quality variables) at which specific species occur (http://www.soc.staffs.ac.uk/research/groups/cies2/). The work does not link levels of suspended sediment to specific effects on invertebrates. The website also contains recently revised BMWP scores for different species.

General techniques for assessing suitability

Suitability of suspended sediment concentrations for fish and invertebrates to survive over the long-term relies on conditions that are not too severe at any time to cause local extinction of the population. A suitability index could be developed which takes account of the effect of extreme events over time (Cooper, personal communication).

Future work

It is suggested that a regional procedure similar to that used to assess risk to fish from sediment pollution in the Lower Swale catchment can be applied to the River Tame, Birmingham. Observed and modelled flows and sediment loads must be compared to establish model performance and to test whether the complex urbanised flow regime is adequately represented. The catchment delivery model could be improved if necessary to model flows in urban catchments. An appropriate sediment model for the Tame which links concentrations to flow and dominant catchment characteristics can be derived using EA data from representative catchments from the Tame and its tributaries. The flow and sediment data from 1996 onwards need to be acquired in order to derive the best model.

At present flows and loads are cumulated down reaches in order to calculate concentrations. This could be improved upon by including in-stream processes such entrainment, deposition and erosion of the banks and/or bed, and to include flow and concentration routing. In-stream models exist which contain many of these elements. It is suggested that a selection of in-stream models (QUESTOR, CASCADE and an E-coli model) are applied to the sediment concentrations from the delivery model for comparison. Flow, suspended sediment and bed sediment monitoring is required to establish to determine which is most appropriate.

The suitability index of Newcombe and Jensen (1996) can be used to link sediment concentration and duration to effects on fish. However, this could perhaps be improved if research was carried out on the effects of sediment concentration on certain fish species that are present in the Tame catchment and other, cleaner urban catchments in the UK, and on those species which once existed in the Tame. Invertebrate presence/absence criteria exist for suspended sediment. However, no such sediment suitability index exists for invertebrates, and research is needed into determining what effects sediment has on invertebrates (those in the water column and those which live/feed in bed sediment) at sub-lethal concentrations.

Peaks over threshold techniques can be used to derive frequency curves for reach suspended sediment concentration at suitable quantiles, and converted to risk maps, either for specific concentration levels or for concentrations/durations which are linked to specific effects on fish.

The concentrations of suspended sediment in the River Tame suggest that there is likely to be a general risk to fish and invertebrates living there. However, the poor water quality in this catchment is likely to be the limiting factor on fish and invertibrate species.

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Part IV) Assessment of physical habitat in urban rivers

Booker, D.J.

Abstract

Rivers corridors provide areas of biodiversity that play important aesthetical and economical roles in urban environments. Many urban rivers in the UK have been influenced by flow regulation, river channel alteration, effluent disposal and pollution. Urban rivers are particularly impacted as impermeable surfaces cause flashy runoff, concrete straightened channels provide poor physical habitat and contaminated land or effluent disposal create poor water quality. These alterations combine to determine the health of river corridor ecosystems. There is an economical and social benefit of urban regeneration including rivers and river corridors. The NERC URGENT "Modelling River Corridors: the scientific basis for rehabilitation of urban rivers" program was designed to carry out the science necessary to underpin cost effective urban regeneration. The Physical Habitat Simulation (PHABSIM) model has been used to assess physical habitat of urban rivers at six sites in Birmingham. The PHABSIM model has been applied to pairs of reaches on the rivers Tame, Cole and Rea. Each pair of sites were selected on a space for time substitution basis with each pair representing different levels of habitat diversity in the particular river, but located within, at most, 0.75 km of each other. Field data have been collected to calibrate the hydraulic component of the PHABSIM model for all sites. Habitat suitability curves are then used to assess physical habitat quality and quantity within each of the modelled reaches for a range of flows. Physical habitat predictions are then used to calculate a Physical Habitat Assessment Score (PHAS). This score allows objective assessment of physical habitat predictions. The modelling process allows assessment of the extent to which restoration of channel morphology may improve physical habitat in comparison to changes in flow regime. Results suggest that the poorest physical habitat occur in the more engineered channels at the highest flows implying that reduction of peak flows may be equally as beneficial to ecology as local restoration of channel morphology. Scenarios of changes in flow regime, in the form of hourly time-series, were used to assess the impact that changes in flow may have on physical habitat. Results show that an increase in runoff would have detrimental effects in all cases, and that decreases in flow would benefit physical habitat. The less modified sites benefited marginally more than the more modified from decreases in flow. The benefit to physical habitat gained from three different scenarios, which all represented decreases in the flow regime, was assessed. Results showed that there was little difference in benefit received between these scenarios.

Key words: Physical habitat assessment, river rehabilitation, sustainable development, integrated catchment management, soft engineering.

1) Introduction

1.1) Background

River rehabilitation in urban rivers can be made possible through strategic action at different scales (Ellis, 1995). Source control of runoff and pollutants or in-line tanks and purification works can all lead to attenuated flood flows and create improvements to water quality. Localised improvements in physical habitat may also be possible through the implementation of river restoration or enhancement schemes, for example, re-introduction of pool-riffle sequences or a meandering planform. However, strategic decision-making is constrained by a lack of models to evaluate the ecological improvements of various management options. This reflects gaps in our knowledge relating to the interactions between the main boundary conditions controlling the ecology of river corridors, specifically flow regime, water quality and physical habitat (Figure 1).

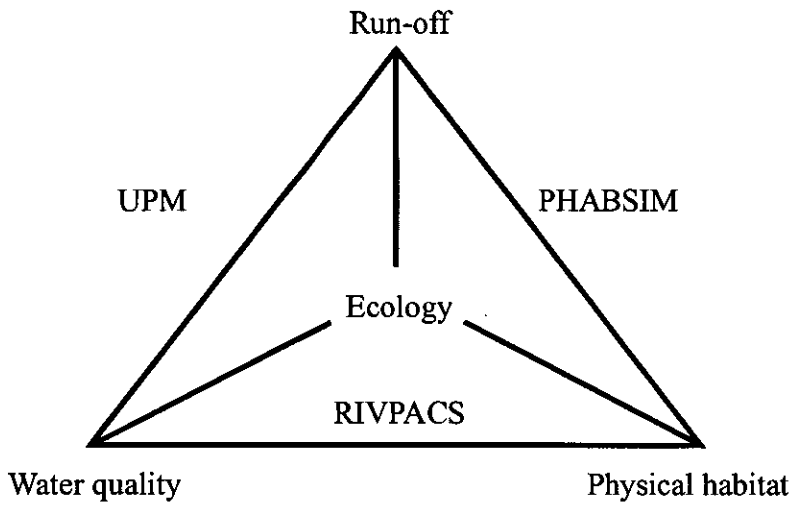


Figure 1. Boundary conditions controlling habitat quality in urban rivers

1.2) Aims and objectives

The URGENT: modelling river corridors project contained five Tasks. These were:

1) Development of rainfall run-off modelling methodology;
2) Development of coarse and fine scale modelling procedures for solute and sediment transport processes;
3) Development of a hydroecological classification of urban rivers;
4) Development of a bio-assessment method for urban rivers
5) Development of a hydroecological model to predict ecological effects of changes in (i) water quality (ii) flow regime and (iii) physical habitat within urban rivers in order to evaluate restoration strategies.

The specific objectives of the hydroecological modelling component of the Modelling River Corridors URGENT Project were:

1. to extend IFIM/PHABSIM to predominantly urban channels;

2. to develop a predictive tool capable of evaluating the role of physical habitat in the health of urban rivers for different water quality and flow scenarios and hence the effectiveness of river habitat rehabilitation and enhancement schemes and future environmental change.

This report outlines the modelling for assessment of physical habitat. Procedures for assessing physical habitat are described and results are given. Assessment of the ecological effects of changes in flow regime are then given using scenarios of changes in flows.

1.3) The instream flow incremental methodology

The Instream Flow Incremental Methodology (IFIM) was originally developed in the 1970's by the US Fish and Wildlife Service. IFIM is a water resources management tool that has been utilised by the Center for Ecology and Hydrology (formerly the Institute of Hydrology) since 1989. A core component of the IFIM methodology is the Physical Habitat Simulation PHABSIM model. This model has been applied to a wide variety of rivers in the UK, including groundwater dominated rivers (Elliot et al., 1999), rivers experiencing abstraction (Johnson et al., 1995) and upland rives (Dunbar, et al., 2001). In the past PHABSIM has been used to assess changes in physical habitat with changes in flow regime, for example, application to the Rivers Allen (Johnson *et al.*, 1995) and Piddle (Strevens, 1999). This type of study has often been undertaken to aid management decisions concerning future abstraction levels in groundwater dominated rivers. An example from the UK has been its use to support negotiation over the impacts of groundwater pumping on river flows, and thus the ecology of the River Kennet, an important Chalk stream (McPherson, 1997). PHABSIM has also been used to assess the impact of channel restoration on the River Wey (Acreman and Elliott, 1996).

1.4) PHABSIM Physical habitat modelling

The PHABSIM modelling software allows simulation of a unique site-specific physical habitat-discharge relationship for a range of flows. Subsequently physical habitat can be simulated for flow time-series or for flow scenarios. The modelling procedure requires calibration of the hydraulic components of PHABSIM using water surface and mean column velocities collected at cross-sections located in different habitat locations at the site of interest under different flow conditions. Velocity and depth of flow can then be simulated for a range of flows. This simulated output can be combined with biological data in the form of Habitat Suitability Indices (HSIs) to calculate the habitat area available for a particular species. This area is called Weighted Usable Area (WUA) and can be determined for individual life stages of target species. Further details of the PHABSIM modelling methodology can be found in Bovee (1986), Johnson et al. (1993) and Dunbar et al., (1997).

1.5) Project structure

To achieve the objectives set out in Section 1.2 the PHABSIM model was applied to pairs of reaches on the same river with very different habitat diversities but located within, at most, 0.75 km of each other. The geographical proximity of the sites ensured that the water quality and flow regimes at each pair of sites were similar. The proximity of each pair of sites was a control that allowed investigation of the effects of water quality. This was an important consideration for integration with Task 4 of the project. The methodology employed allowed comparison of the effect of different levels of engineering on the relationship between physical habitat. An additional benefit of the methodology is that it allows investigation of the effect of urban flow regimes on physical habitat. Employment of PHABSIM allows simulation of physical habitat over a range of flows. The PHABSIM modelling methodology also allows analysis of spatial hydraulic patterns or analysis of hypothetical changes in channel geometry (Elliott et al., 1996; Dunbar et al., 1997). However, this approach was not adopted here.

2) Physical habitat modelling methodology

2.1) Study site selection

The project specification called for 6 study reaches to be established. The original proposal specified one pair of these sites to be part of a pre- and post-rehabilitation scheme analysis. The other two pairs of sites were to be selected as a space for time substitution i.e. two sites in close proximity but one being highly modified and one being less modified or restored. As no suitable schemes were being carried out at an appropriate time, 3 pairs of sites, paired on a space-for-time substitution basis, were selected. The close proximity of each of the sites within a pair (less than 0.75km) ensured that the water quality of each pair of sites could be considered as the same.

In collaboration with Angela Davenport and Luke Bevan, 6 sites were chosen that met the requirements of this task and also those of Tasks 3 and 4. A description of each of the sites is given in Table I and photographs of the sites are shown in Figure 2.

Table I. Description of the six PHABSIM reaches.

River	Reach	Description	Grid Reference
Tame	Highly Modified	Highly straightened, highly channeliesd, two stage channel.	SP029927
	Less Modified	Straightened, two stage channel, some geomorphological diversity.	SP030925
Cole	Highly Modified	Straightened, highly channeliesd, two stage channel.	SP172879
	Restored	Meandering, pool-riffle gemorphology, natural active banks	SP175876
Rea	Concrete Lined	Straightened, highly channeliesd, with concrete banks, step weir in reach	SP063835
	Unlined	Straightened, channeliesd, with stone gabion banks	SP061829

Figure 2. Pictures of the sites. Clockwise from top left: Tame Less Modified, Tame Highly Modified, Cole Restored, Rea unlined, Rea Concrete Lined, Cole Modifed (at a high flow).

2.2) Study transects

At each of the sites listed in Table I, 4-5 transects were located with permanent survey markers and surveyed at 0.25 m or 0.5 m intervals, depending on channel width. Transects were placed across each distinct habitat unit that could be distinguished at low flow. For the more highly modified sites where there was little hydraulic variability no distinct habitat units were identifiable. In these situations transects were placed at semi-regular intervals over the reach length. In total 28 transects were established with 15-25 points surveyed within the flow at each transect. Table II summarises the transect survey data.

Table II. Summary of PHABSIM transect survey data.

Site	No. transects	Transect	No. survey points	Survey point spacing
Tame highly modified	4	1	28	0.5
		2	29	0.5
		3	29	0.5
		4	27	0.5
Tame less modified	5	1	30	0.5
		2	29	0.5
		3	31	0.5
		4	31	0.5
		5	38	0.5
Cole modified	4	1	41	0.25
		2	40	0.25
		3	37	0.25
		4	39	0.25
Cole restored	5	1	41	0.25
		2	40	0.25
		3	40	0.25
		4	40	0.25
		5	43	0.25
Rea lined	5	1	31	0.25
		2	32	0.25
		3	33	0.25
		4	22	0.5
		5	41	0.25
Rea unlined	5	1	36	0.25
		2	34	0.25
		3	35	0.25
		4	31	0.25
		5	34	0.25

2.3) PHABSIM Calibration data

Calibration of PHABSIM requires hydraulic input measured in the field at a range of flows. Data collection started in July 1999. All topographic site surveys and collection of at least two flows were collected during the summer of 1999. Data was collected for higher flows November and December 2000 for all six of the sites. Table III shows the details of all hydraulic data that has been collected from the six sites in Birmingham for input to PHABSIM. The minimum amount of data required to calibrate PHABSIM is three water surface elevation data sets and one set of velocity data. Table III shows all data collected to calibrate PHABSIM for all six sites.

Table III. Summary of flows at which field data collected for PHABSIM calibration.

	Summary of Discharges									
	Flow 1 (m^3/s)		Flow 2(m^3/s)		Flow 3(m^3/s)		Flow 4(m^3/s)		Flow 5(m^3/s)	
Site	WSE	Velocity	WSE	velocity	WSE	velocity	WSE	Velocity	WSE	Velocity
Tame highly modified	2.53	2.53	3.67	3.67	4.78	4.78				
Tame less modified	1.46		2.10	2.10	2.56	2.56	2.82		4.37	4.37
Cole modified	0.29	0.29	0.78	0.78	2.52	2.52				
Cole restored	0.29	0.29	0.94	0.94	14.02					
Rea lined	0.13	0.13	0.35	0.35	0.90	0.90	6.21			
Rea unlined	0.11	0.11	0.33	0.33	0.63	0.63	5.57			

Data from all flows was formatted on a database such that it could be input to PHABSIMwin. This data was used to calibrate the hydraulic component of PHABSIM for all sites. Elliot et al. (1996) recommend that a mean error in stage discharge relationship of 10% or below represents acceptable error. Mean error for the all sites was less than this recommended level. Mean errors for stage discharge comparisons at the two Tame sites were particularly low. The low level of errors in calibrated stage discharge relationship at these two sites can be attributed to the simplistic channel geometries, a lack of instream vegetation and the wide range of flows used in the calibration process at these sites.

2.4) How PHABSIM was calibrated

There are a variety of methods that can be used to calibrate the hydraulic component of PHABSIM. Specifically there are three different hydraulic simulation programs known as IFG4, MANSQ and WSP (Elliott et al., 1996). PHABSIM also requires sets of water surface elevation data for three different flows and at least one full set of velocity data set. The calibration procedure may also be undertaken using velocity data sets from one, two or three of the monitored flows.

PHABSIM models were calibrated to simulate a wide range of flows. Daily flow time-series of flows where obtained from the Environment Agency for the gauges located nearest to each site. Table IV shows the gauge locations and summary statistics of mean daily flows. Table V shows the range of flows during 2000 derived from 15minute temporal resolution data. PHABSIM was calibrated across a sufficiently wide range of flows to cover the range shown in Table V. This allowed simulations to be run using the daily-time step and 15minute derived flow data. Figure 3 shows diagrams depicting the models used to calibrate velocity and water surface elevation for all six reaches. In many cases the calibration procedure involved extrapolating the hydraulic models to simulate well beyond the range of the calibration data. In these situations the 'no velocity data' model was used. This method simulates velocity to be proportional to the depth. Analysis of the results showed that at high flows physical habitat predictions were not sensitive to the velocity model used because all velocities were unsuitably fast regardless of the method used to calculate them.

Table IV. Gauge locations and summary statistics for mean daily flows.

Gauging station	Start date	End date	Gaps (if any)	Q_{95}	Q_{50}	Q_5	Q_{max}
Cole at Coleshill	01-Nov-1973	04-Nov-1998	Continuous	0.194	0.556	2.993	16.08
Rea at Calthorpe park	14-Apr-1967	31-Dec-1998	Continuous	0.242	0.485	2.37	22.89
Tame at Bescot	09-Sept-1982	31-Dec-1998	Continuous	0.91	1.925	5.423	27.34

Table V. Range of flows based on 15minute flow data during 2000.

	Rea	Cole	Tame
Max	43.56	19.64	56.83
Min	0.18	0.16	0.16
Average	1.08	1.30	2.59

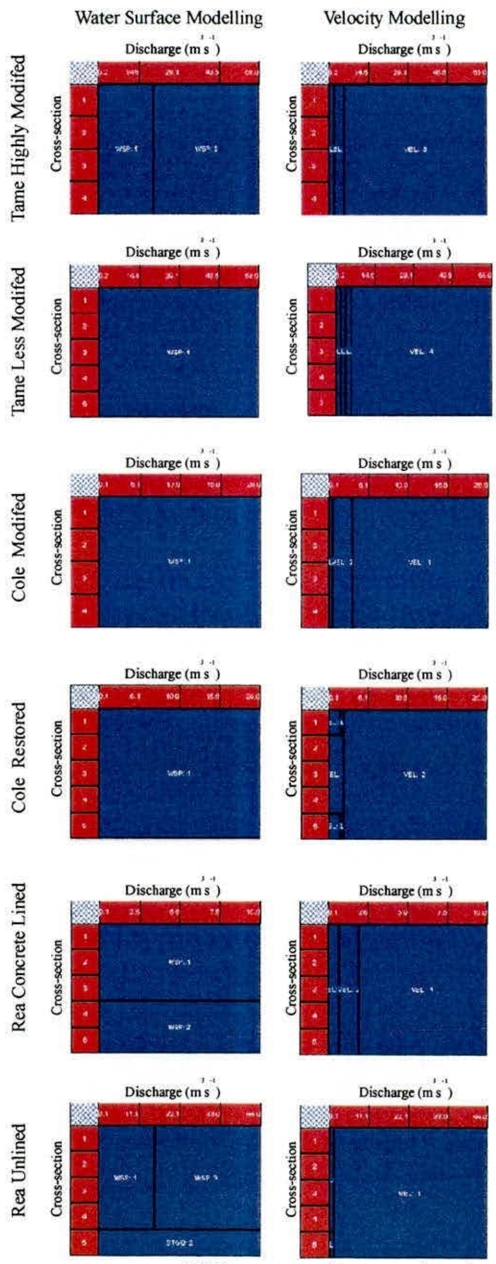


Figure 3. Diagram showing summary of Water surface and velocity models employed at each cross-section for a range of flows for all sites.

2.4.1) Tame Highly Modified

Table III shows that full sets of velocity and WSL were collected at this site for three relatively well spread discharges. The regular shape of the channel allowed simulation of water surface elevations using the step-backwater model WSP. This is the most physically based water surface elevation model available in PHABSIM. Two different WSP models were used, with slightly different roughness modifiers used at flows above $20m^3s^{-1}$.

PHABSIM was calibrated using all three velocity data sets for flows between 2.4 and 6.0 m^3s^{-1}. Only the lowest velocity data set was used below this and the proportional to depth method was used above 6 m^3s^{-1}.

2.4.2) Tame Less Modified

The Tame Less Modified site was calibrated using a similar method to that used for the Tame Highly Modified site. One WSP model was used for simulation of all water surface elevations at all flows. Four velocity models were used. The lowest velocity data set was used to calibrate the velocity model for flows less than $2.0m^3s^{-1}$. All three velocities were used between 2.0 and $3.9m^3s^{-1}$. The highest velocity data set only was used between 3.9 and 6.0 m^3s^{-1}. Figure 4 shows the differences between observed and simulated velocity distributions.

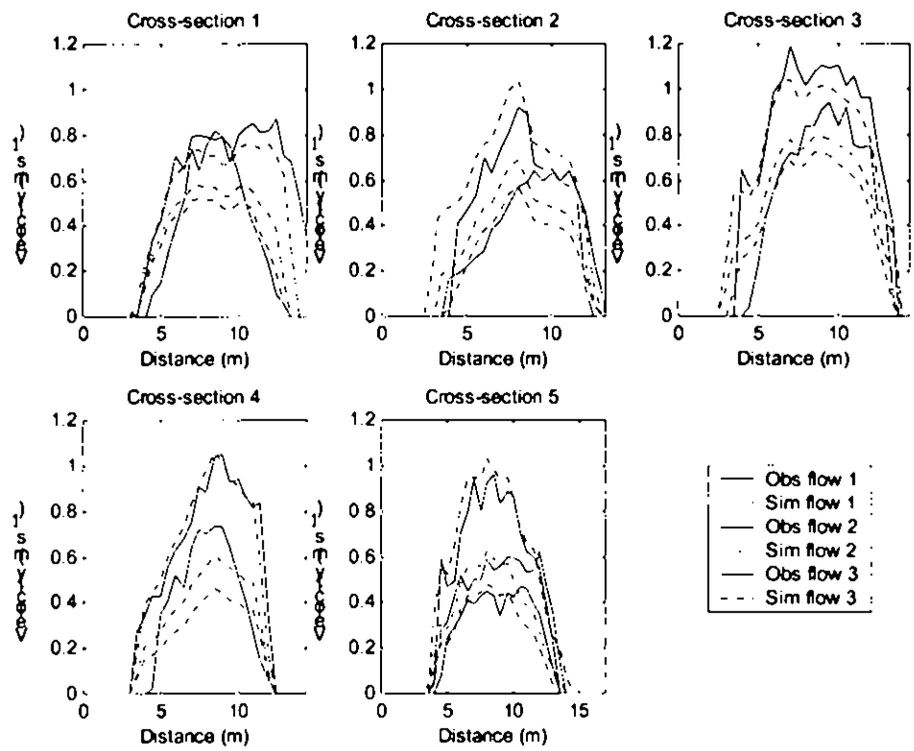


Figure 4. Comparison of observed and simulated velocities at the Tame less modified site. Flows 1,2 & 3 were of 1.46, 2.1 and 4.37 m^3s^{-1} respectively.

2.4.3) Cole restored

The Cole Restored site was an exceptional case with regard to water surface modelling as water surface elevation data were collected across a very wide range of flows, ranging from 0.29 to 14.02 m^3s^{-1}. This allowed a single WSP model to be used to simulated flow over the entire range of flows required. Figure 5 shows the measured and modelled stage-discharge relationships at the most upstream and downstream cross-sections at the site.

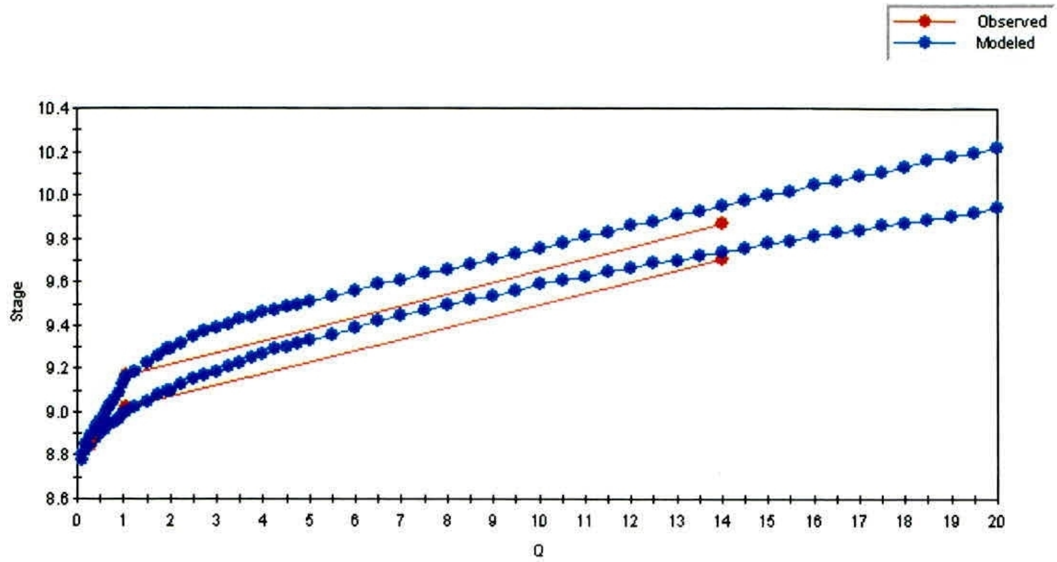


Figure 5. Stage discharge relationships for most upstream and downstream cross-sections at the Cole Restored site.

Velocity modelling for the Cole Resorted site was complicated as a result of the complex topography and the range of velocity data available. Two velocity data sets were available for flows of 0.29 and 1.07. Due to the lack of velocity data available for higher discharges the proportional to depth method was used for simulation of all velocities above 2.0 m^3s^{-1} and flows above 1.5 m^3s^{-1} at cross-sections 1 and 5. At cross-sections 2-4 both velocity data sets were used to simulate flows below 2.0 m^3s^{-1}. The same process was used for cross-sections 1 and 5 at flows less than 1.5 m^3s^{-1}. The coverage of the different models at different cross-sections was chosen such that where were smooth changes in the simulated distributions of velocities at different discharges.

2.4.4) Cole modified

Water surface elevations at the Cole Modified site were simulated using one WSP model for the entire flow range using all the available data. Velocities below 0.5m^3s^{-1} were simulated using the lowest calibration flow. Velocities between 0.5m^3s^{-1} and 3.0 m^3s^{-1} were simulated using two higher velocity calibration data sets. The proportional to depth method was used for simulation of velocities above 3.0m^3s^{-1}.

2.4.5) Rea Unlined

The Rea unlined site was also calibrated using two WSP models for cross-sections 1-4. These two models were used to simulate flows above and below 15m^3s^{-1}, and had slightly different roughness modifiers. WSP failed to adequately simulate water surface elevations at cross-section 5 and as a result a logarithmic stage-discharge relationship was employed at this cross-section. All velocities at all flows above $1.5 m^3 s^{-1}$ were simulated using the proportional to depth method. Below this all three calibration data sets were used for the first three cross-sections and the fourth cross-section between 0.4 and $1.5 m^3 s^{-1}$. At the fifth cross-section below $0.4\ m^3 s^{-1}$ only the lowest calibration data set was used to simulate velocities.

2.4.6) Rea lined

The Rea lined site contained a hydraulic step between cross-sections 3 and 4. For this reason two separate water surface models were employed to simulate flows upstream and downstream of this step. The same velocity modelling procedure was used for all cross-sections. The two lowest calibration data sets were used to simulate velocities below 0.8 $m^3 s^{-1}$. The highest calibration set was used to simulate flows between 0.8 and $2.0 m^3 s^{-1}$. The proportional to depth method was used to simulate velocities above $2.0\ m^3 s^{-1}$.

2.4.7) Summary for all sites

The following text describes some more details of modelling procedures for calibration of hydraulics at each site.

Site: Tame Highly Modified
PHABSIM file name: TamemodWSP+topo2 (with highflows)
Water Surface elevations: WSP used for all cross sections at all flows
WSP 1 (0.4-20) calibrated at: 3.7 (flow 2)
N values:
0.017
0.017
0.026
0.017
Roughness modifiers:
2.5=1.10
4.8=0.96
WSL Model: logstage- logQ
RMOD model: linear reg
WSP 2 (20-58) calibrated at: 3.7 (flow 2)
Is same as WSP1 except
Roughness modifiers:
2.5=1.05
4.8=0.96
Velocities models:
Model 1: all cross-sections, 0.1-2.4, flow 1
Model 2: all cross-sections, 2.4-6.0, flows 1,2 & 3
Model 3: all cross-sections, 6.0-11.0 no flows
Notes: WSL are extremely well modelled with 7 of the nine being showing 0 difference between modelled and measured, the other 2 have differences of 1cm.

Site: Tame nat
PHABSIM file name: Tamenat3+topo3
Water Surface elevations: WSP used for all cross sections at all flows
WSP calibrated at: 4.4 (highest flow)
N values:
0.039
0.039
0.009

0.035
0.020
Roughness modifiers:
1.5=1.65
2.1=1.40
2.6=not used
2.8=not used
WSL Model: logstage- logQ
RMOD model: linear reg
Velocities models:
Model 1: all cross-sections, 0.1-2.0, Q2.1
Model 2: all cross-sections, 2.0-4.5, Q's 2.1, 2.6 & 4.4
Model 3: all cross-sections, 4.5-6.0 Q's 4.4
Model 4: all cross-sections, 6.0-58.0 no flows
Notes: cannot get PHABSIM to read velocities in the 5th flow data set (but this flow is only $0.4 m^3 s^{-1}$ more than flow 1).

Site: Cole Modified
PHABSIM file name: ColeMod
Water Surface elevations: WSP used for all cross sections at all flows
WSP calibrated at: 1.92 (flow 3)
N values:
0.017
0.017
0.017
0.016
Roughness modifiers:
0.3=1.65
0.7=1.55
WSL Model: logstage- logQ
RMOD model: linear reg
Velocities models:
Model 1: all cross-sections, 0.1-0.5, flow 1
Model 2: all cross-sections, 0.5-3.0, flow 2 & 3
Model 3: all cross-sections, 3.0-16.0 no flows
Notes: all comparisons of WSE diff were 1cm or lower

Site: Cole Restored
PHABSIM file name: ColeNat
Water Surface elevations: WSP used for all cross sections at flows 0.1-10.1
WSP calibrated at: 1.07 (flow 2)
N values:
0.051
0.051
0.062
0.051
0.058
Roughness modifiers:
0.3=0.3
14.0=0.09
WSL Model: logstage- logQ
RMOD model: interpolation
Velocities models:
Model 1: Cross-sections 2-4 flows 0.1-2.0 flows 1 & 2.
Model 2: Cross-sections 1 & 5 flows 0.1-1.5 flows 1 & 2.
Model 3: Cross-sections 1 & 5 flows 1.5-2.0 no flows.
Model 4: all cross-sections, 2.0-16.0 no flows
Notes: Cross-sections 4 & 5 have smaller areas and therefore higher WSE at very high flows.

Site: Rea Concrete Lined

PHABSIM file name: ReaMod
Water Surface elevations: Separate WSP models used for cross-sections 1-3 and 4-5 at all flows
WSP calibrated at: both at 0.83
N values:
0.044
0.044
0.022

0.020
0.020
Roughness modifiers:
0.1=0.85
0.3=0.75
6.2=1.00

0.1=1.50
0.3=0.95
6.2=1.00
WSL Model: both logstage- logQ
RMOD model: both linear reg
Velocities models:
Model 1: all cross-sections, 0.1-0.8, flows 1 & 2
Model 2: all cross-sections, 0.8-2.0, flow 3
Model 3: all cross-sections, 2.0-10.0, no flows

Site: Rea Unlined
PHABSIM file name: ReaNat3
Water Surface elevations: two WSP models for 1-4 (one for very high flows). Have used stage-Q relationships for cross section 5
WSP calibrated at: both at 0.80
N values:
0.020
0.020
0.020
0.025
Roughness modifiers:
0.1=1.20
0.3=1.10
linear reg

N values:
0.020
0.020
0.020
0.024
Roughness modifiers:
0.1=1.20
0.3=1.30
linear interp
WSL Model: at CS 1 both logstage- logQ
Velocities models:
Model 1: all cross-sections, 1.5-12.0, no flows.
Model 2: cross-sections 1-4, 0.1-1.5, flows 1,2 & 3.
Model 3: cross-section 5, 0.1-0.4, flow 1.
Model 4: cross-section 5, 0.4-1.5, flow 2&3.
Notes: Had problems with WSP at cross section 5. Didn't use the highest flow from gauge as it was somewhat dubious.

3) Weighting

In a standard PHABSIM application cross-sections are chosen strategically to represent different habitats (e.g. riffle, pool or glide). Habitat mapping is undertaken and weights are assigned to each cross-section depending on the proportion of each habitat is present in the reach of interest. This approach was not adopted in this project. Observation of habitat diversity in urban showed that identification of specific habitat areas was not appropriate. Very similar habitat types were present for long stretches of river. As a result no weighting for individual cross-sections was used when simulating physical habitat. This means that each cross-section represented a section of river that started half way between that cross-section and the next upstream cross-section and finished half way between that cross-section and the next downstream cross-section.

4) Habitat Suitability Indices

4.1) Fish

Physical habitat modelling requires quantification of the relationship between usable habitat for different life-stages and the physical conditions such as depth, velocity and substrate. In PHABSIM applications these relationships are defined using Habitat Suitability Indices (HSIs) (Bovee, 1986). There has been a great deal of investigation into physical habitat use of Atlantic salmon (*Salmo salar L.*) and trout (*Salmo trutta L.*) (e.g. Kennedy and Strange, 1982; Belaud *et al.*, 1989; Heggenes and Saltveit, 1990; Milner *et al.*, 1998; Dunbar *et al.*, 2001). The physical habitat preferences of non-salmonids have been less well studied, but are receiving increasing attention (e.g. Garner, 1995; Winkler *et al.*, 1997). At one time the River Tame and its tributaries were highly valued fisheries (National Rivers Authority, 1996), supporting brown trout in the headwaters and a mixed cyprinid fishery in the lower reaches. Degradation of both water quality and physical habitat has lead to the current status of an impoverished and transient coarse fish population in most stretches (National Rivers Authority, 1996). Fish population data provided by the Environment Agency showed that coarse fish such as chub have been present in the Rivers Tame, Cole and Rea in recent years. HSIs are available for these species of coarse fish. For example, Johnson *et al.* (1993) provided HSIs for different life stages of roach and dace, while Armitage and Ladle (1991) illustrated indices for chub (see Figure 6). These indices were all derived from expert opinion, supported by previous literature on habitat use.

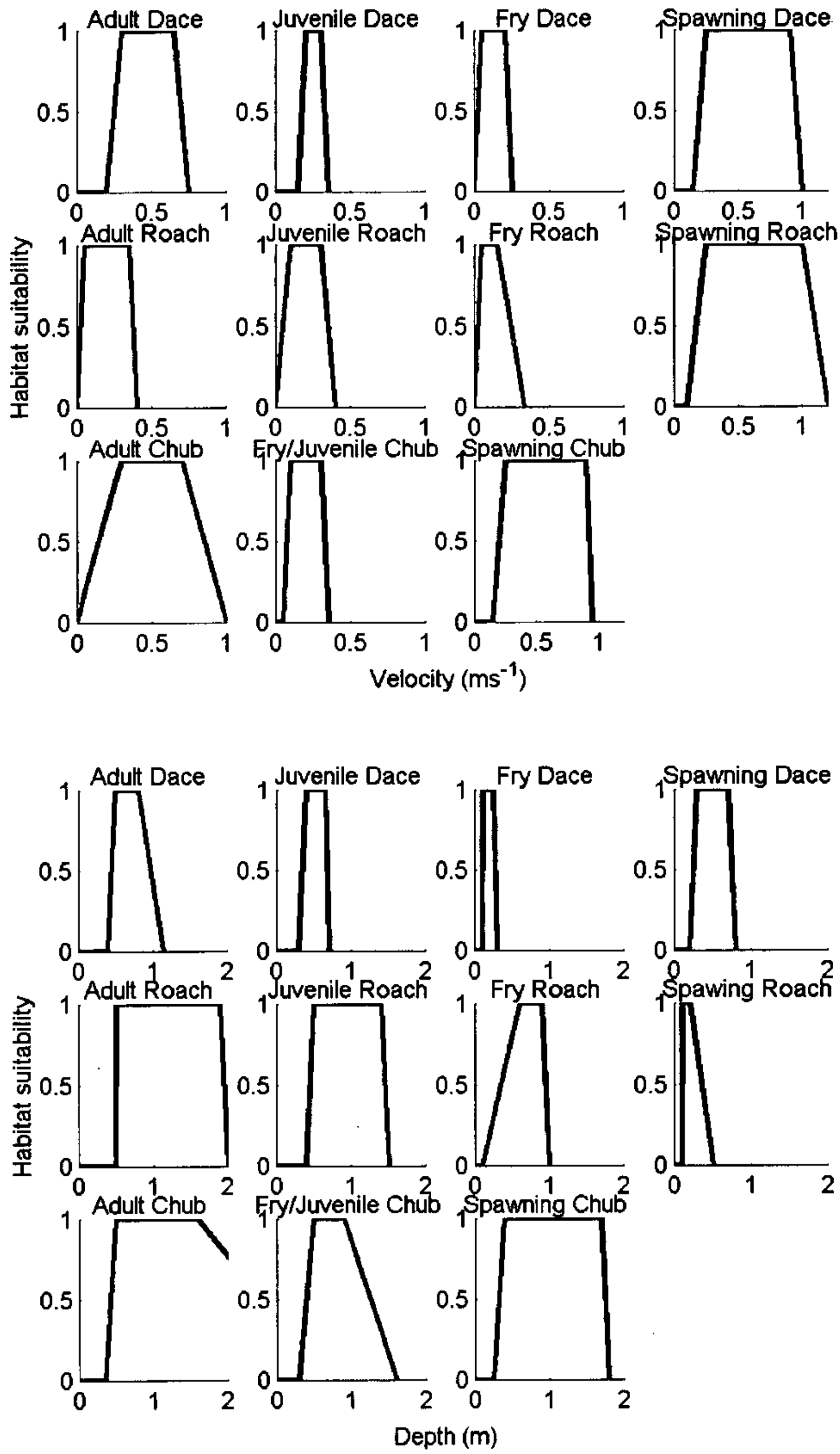


Figure 6. Habitat Suitability Indices for different life-stages of dace, roach and chub.

4.2) Invertebrates

Table VI. Data input to RIVPACS.

	Cole Coleshill Restored	Cole Coleshill Modified	Rea Calthrope Unlined	Rea Calthrope Lined	Tame Sandwell Less Mod	Tame sandwell Highly
Grid letters	SP	SP	SP	SP	SP	SP
Easting	172	175	061	063	030	029
Northing	879	876	829	835	925	927
Altitude	89	89	117	115	100	101
Slope	9.30	9.30	15.38	15.38	11.11	11.11
Discharge cat	3	3	3	3	4	4
Velocity category	-9	-9	-9	-9	-9	-9
Distance from source	7.5	7.5	3.3	3.3	3.5	3.5
Mean width	8.3	7.4	5.6	7.7	9.4	11.1
Mean depth	30	33	38	35	55	35
Alkalinity	-9	-9	-9	-9	-9	-9
Total hardness	285	285	250	250	352	352
Calcium	-9	-9	-9	-9	-9	-9
Conductivity	-9	-9	-9	-9	-9	-9
% boulders & cobbles	5	10	20	5	5	5
% pebbles & gravel	55	40	60	40	75	70
% sand	25	30	10	45	10	10
% silt & clay	15	20	10	10	10	15

PHABSIM can be used to assess physical habitat for plants and invertebrates as well as fish. For this project HSIs were gained for invertebrates using the RIVPACS database (Davy-Bowker, 2001) using the input information shown in Table VI. RIVPACS is a database of invertebrate taxa and physical conditions collected using standard sampling strategies at a wide range of sites known to have good water quality. This database allows predictions of expected taxa based on a sites physical characteristics. Water quality is not included in the database and is therefore not considered in this process. The predicted taxa therefore represent the taxa that might be expected given pristine water quality conditions at a site. Depth, velocity and substrate are all present in the database and can therefore be correlated with the presence/absence of a particular taxa in order to produce a HSI. The exact method used to derive the HSIs using this method is given in Armitage and Ladle (1989). Figure 7 shows the form of HSIs predicted to be present at the sites for animals that were not found during sampling at the sites (by Luke Bevan, as part of Task 4 of the Modelling river corridors project).

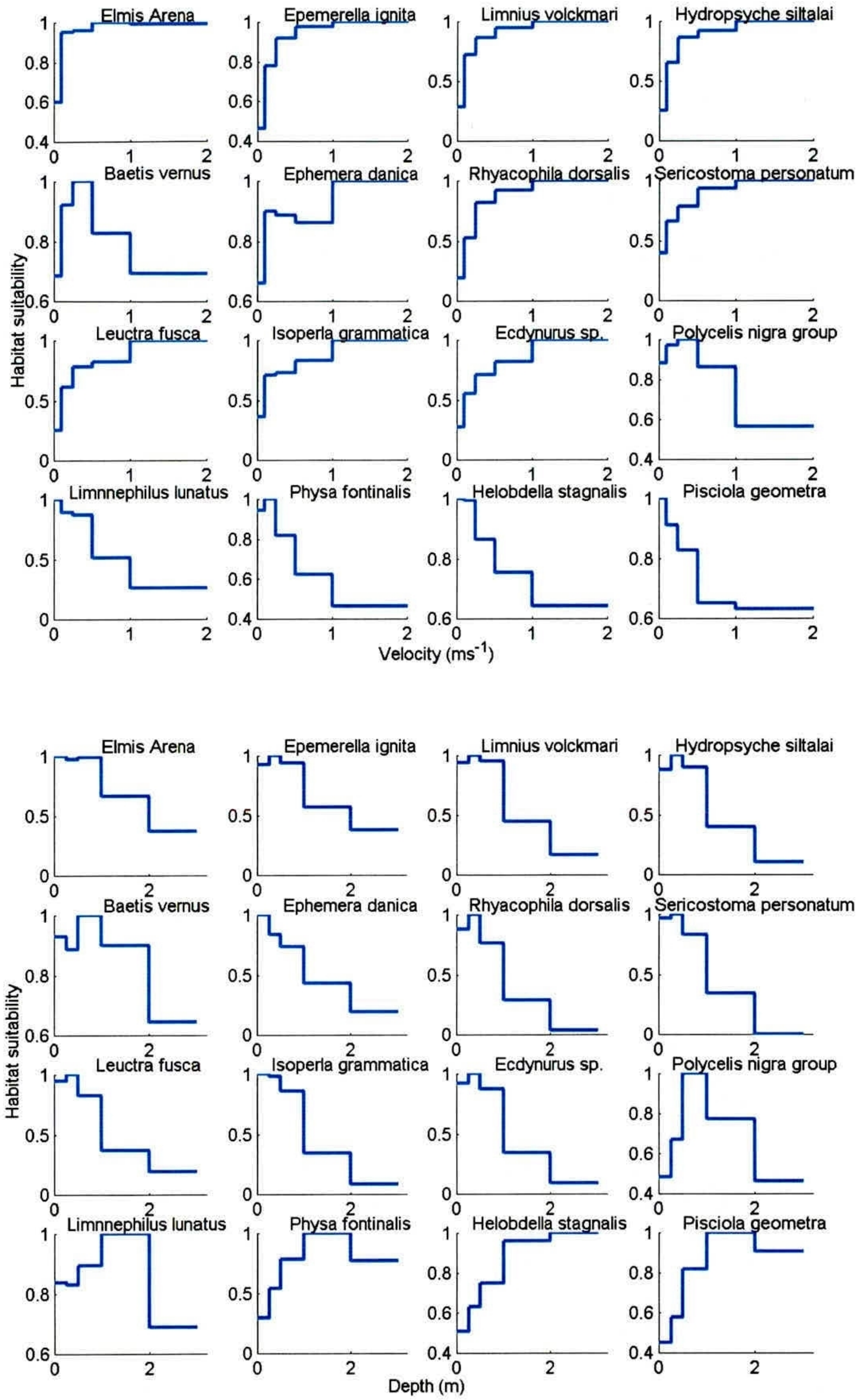


Figure 7. HIS curves predicted from the RIVPACS data base. Based on data supplied from Davy-Bowker (2001).

5) Physical habitat results

5.1) Fish

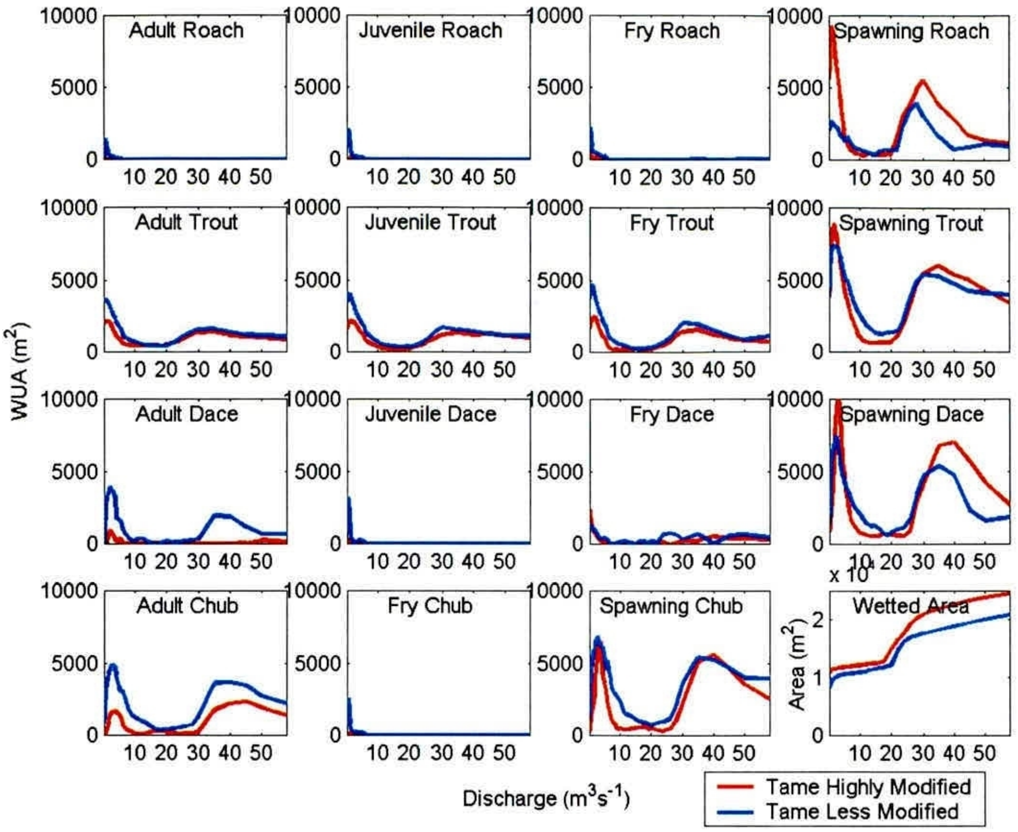


Figure 8. Weighted usable area against discharge for life stages of fish in the Tame Highly Modified and Less Modified sites.

Usable physical habitat is commonly expressed as Weighted Usable Area (WUA) in m^2 per 1000m of river channel. WUA is an aggregate measure of physical habitat quality and quantity and will be specific to a particular discharge and species / life stage. Further details are provided in Johnson *et al.* (1995). Figure 8 shows predicted WUA for different life stages of roach, dace, chub and brown trout for the two sites on the Tame. The main results are summarised below.

- The total area available is greatest in the Highly Modified site for all flows. This is because of the greater width of channel at this site.
- The total area available increases at approximately $18m^3s^{-1}$ for both sites as the flows overspill into the second stage of the two stage channels.
- There is greater WUA for all species and all flows at the Less Modified site for all life stages except spawning.
- There is greater WUA for spawning compared to the other life stages at both sites. This is caused by the relatively shallow fast flowing habitat that is available at low to medium flows at the sites.

- There is very little WUA for fry for the coarse fish species. This is because there are very narrow bands of velocity suitability for fry (Figure 6) and velocity quickly rises as discharge rises at both the Tame sites

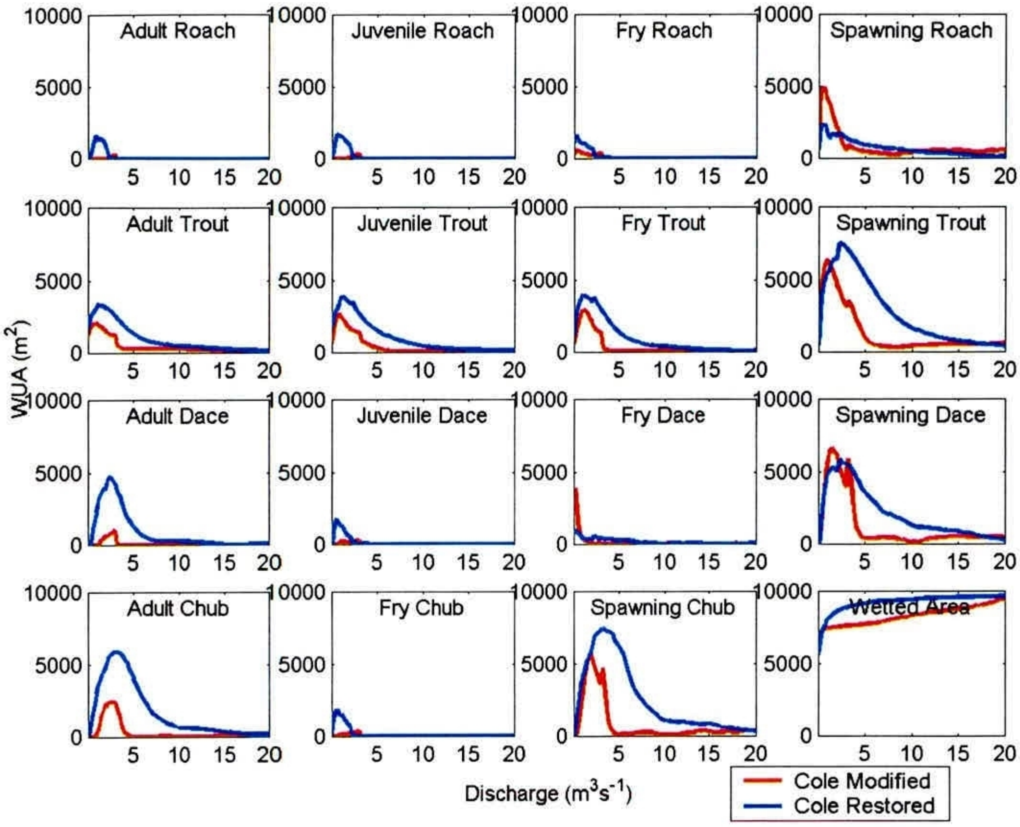


Figure 9. Weighted usable area against discharge for life stages of fish in the Cole Modified and Restored sites.

Figure 9 shows predicted WUA for different life stages of roach, dace, chub and brown trout for the two sites on the Cole. The main results are summarised below.

- The total area available is greatest in the Restored site for all flows. This is because of the greater width in this site.
- The total area available increases relatively steadily as discharge increase.
- There is greater WUA for all species and all life staged at nearly all flows at the Restored site with the exception of spawning Roach.
- There is greater WUA for spawning compared to the other life stages at both sites. However, the difference between the WUA for spawning and adults is less for the two Cole sites than in the two sites on the River Tame.
- The Cole Modified reach provides particularly low WUA for all stages of roach and dace except spawning. Although WUA is low for these species and life stages in the Restored site, some WUA is provided at lower flows.
- Greater morphological diversity in the Cole Restored reach provides greater WUA over a wider range of flows.

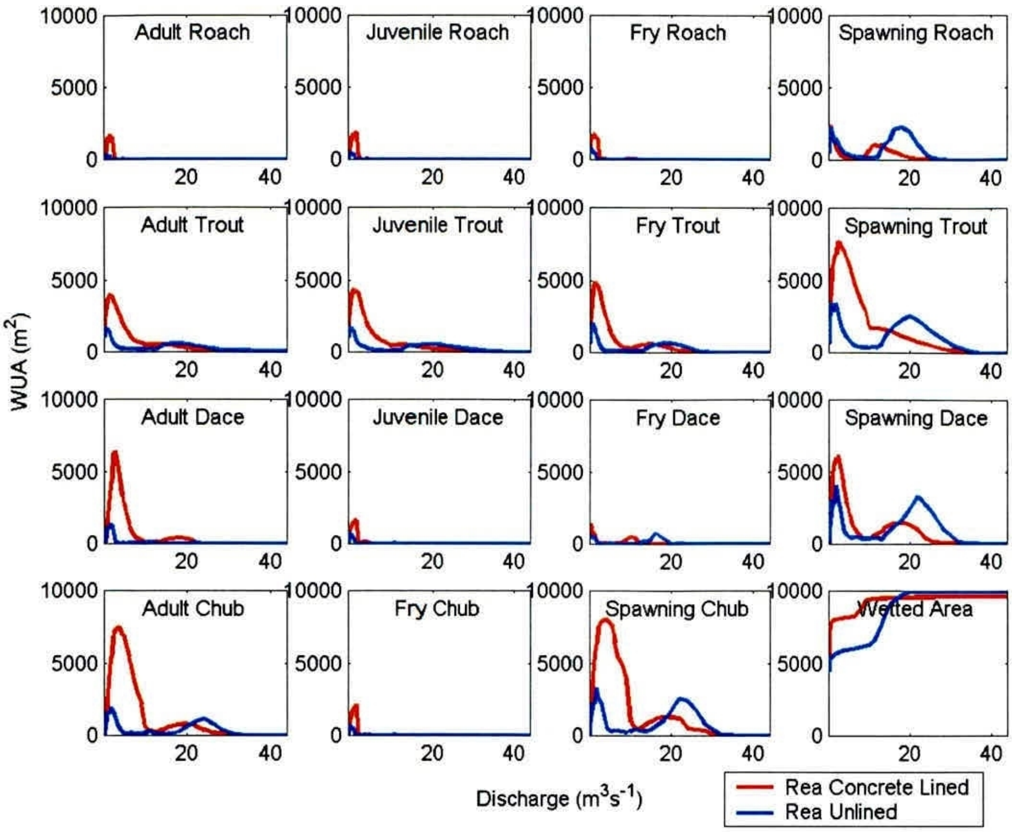


Figure 10. Weighted usable area against discharge for life stages of fish in the Rea Concrete Lined and Unlined.

Figure 10 shows predicted WUA for different life stages of roach, dace, chub and brown trout for the two sites on the Rea. The main results are summarised below.

- The total area available is greater for the Concrete lined site for lower flows. This is because this site has a wider channel at lower flows. As discharge increases to high flows the available area becomes similar for both sites.
- There is a rapid rise in wetted area in both sites when the channels become main channels become bankfull, as both channels are highly confined there is very little increase in wetted area above 20 m^3s^{-1}.
- There is greater WUA for all species and all life stages at nearly all flows at the Concrete Lined site with the exception of spawning Roach.
- There is very little WUA for juvenile or fry coarse fish at either site. This is especially the case over $4m^3s^{-1}$.
- There is a second peak in some of the WUA plots. This is caused at a point where overbank flows become suitable habitat. This is less pronounced in the Concrete lined site because the banks at that site are very high and never become overtopped. A small increase in physical habitat does occur when the path running parallel to the river becomes flooded.

5.2) Invertebrates

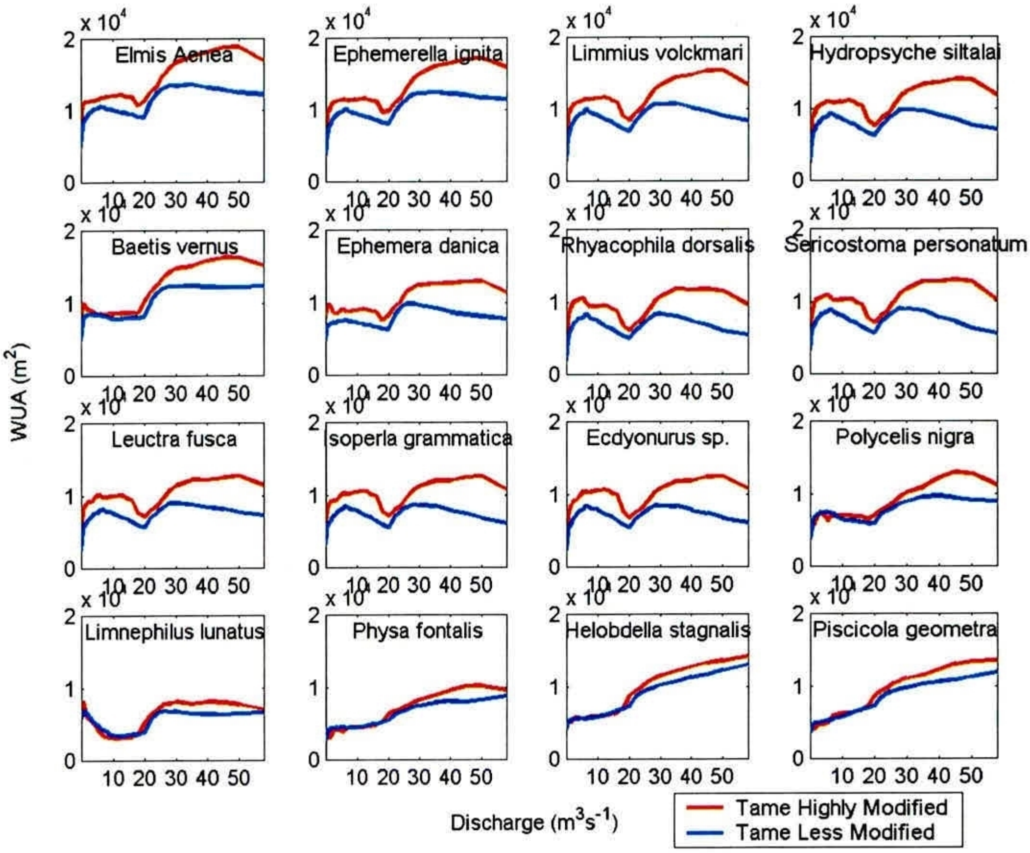


Figure 11. Weighted usable area against discharge for invertebrates in the Tame Highly Modified and Less Modified sites.

Figure 11 shows predicted WUA for different invertebrate taxa for the two sites on the Tame. The main results are summarised below.

- WUA for invertebrates is higher than for fish. This is caused by the less steep HSIs for invertebrates (Figure 7) in comparison to those for fish (Figure 6).
- WUA for invertebrates varies less with changes in discharge than is the case for fish. This is because the invertebrate HSIs dictate that invertebrates are able to tolerate a wider range of depth and velocity conditions than the different life stages of fish.
- Many of the predictions of WUA are very similar for different invertebrates taxa.
- Above 20m^{3}s^{-1} changes in WUA for invertebrates reflect changes in the available area at either site rather than any changes in the distributions of hydraulics conditions. This is because there are only very small changes in preference at velocities above 1ms^{-1} and depths greater than 2m.
- In general the Less Modified site provides greater WUA for invertebrates than the Highly Modified. This is a reflection of the difference in wetted area available rather than hydraulic conditions between the two sites.

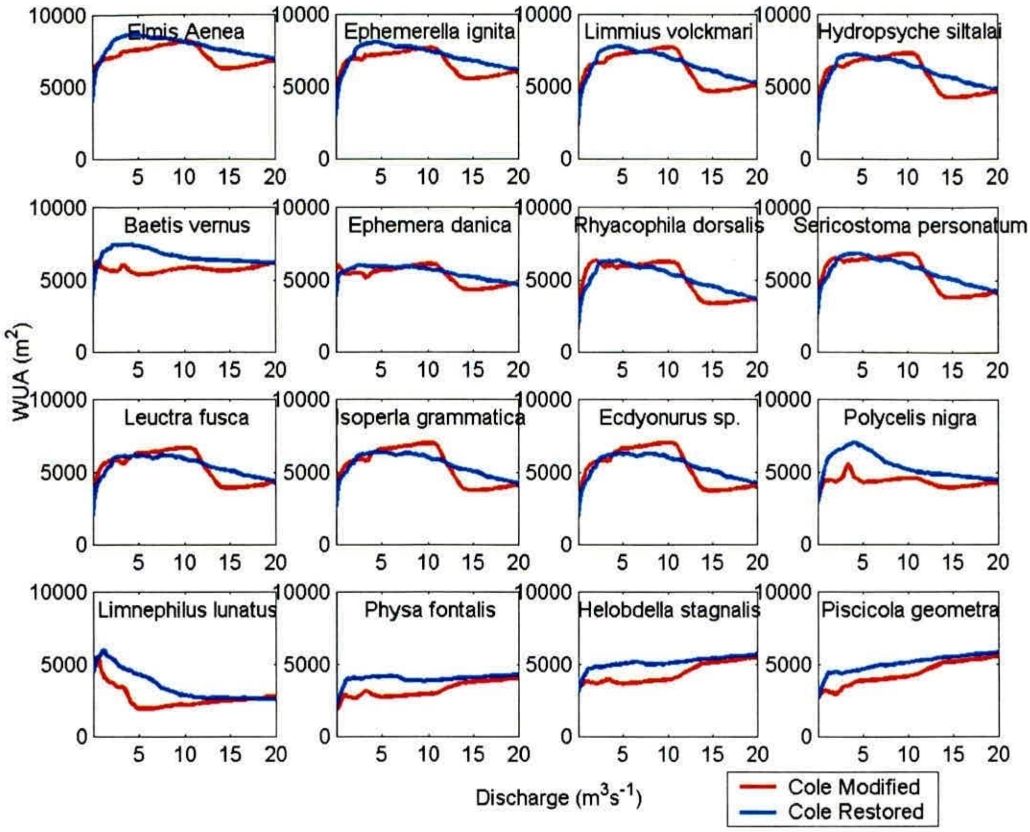


Figure 12. Weighted usable area against discharge for invertebrates in the Cole Modified and Restored sites.

Figure 12 shows predicted WUA for different invertebrate taxa for the two sites on the Cole. The main results are summarised below.

- Many of the predictions of WUA are very similar for different invertebrate taxa. This is particularly the case for predicted WUA for the Cole sites.
- In general the Less Restored site provides greater WUA for invertebrates than the Modified. This is a reflection of the area available rather than differences in hydraulics conditions. This suggests that there is very little difference in available physical habitat for invertebrates between the Cole Restored and Cole Modified sites. This contradicts the situation for fish.

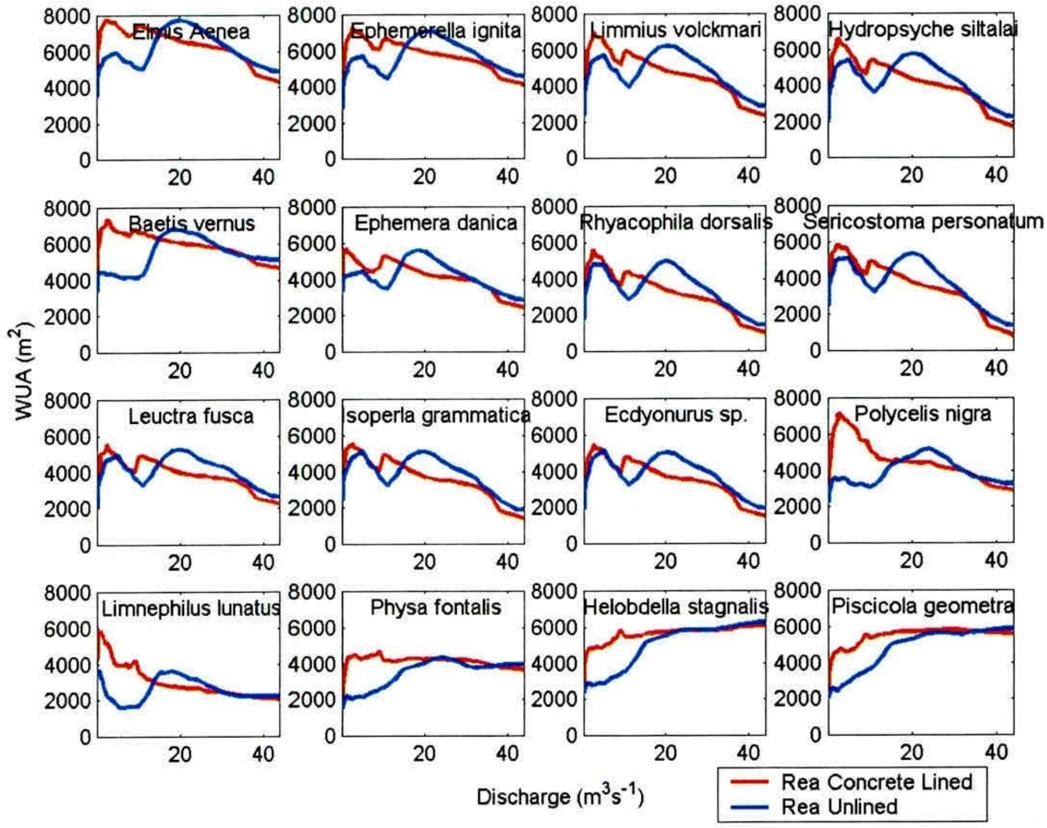


Figure 13. Weighted usable area against discharge for invertebrates in the Rea Concrete Lined and Unlined.

Figure 13 shows predicted WUA for different invertebrate taxa for the two sites on the Cole. The main results are summarised below.

- Many of the predictions of WUA are very similar for different invertebrates taxa.
- In general the Concrete Lined site provides greater WUA for invertebrates than the Unlined at lower flows. This is a reflection of the area available rather than differences in hydraulics conditions. This suggests that there is very little difference in available physical habitat for invertebrates between the Concrete Lined and Unlined sites.

6) Discussion of WUA results

Results show that, given the HSIs shown in Figure 6 and 7, and the hydraulic model calibrations, physical habitat for fish of all species and life stages was more sensitive to changes in hydraulic conditions than was the case for invertebrates. In many cases invertebrate WUA was a reflection of the available area in the river. This suggests that the invertebrates for which physical habitat was simulated here are relatively insensitive to the range of hydraulic conditions experienced in these rivers. This finding suggests that there would be minimal increases in the quality of physical habitat available to these invertebrates as a result of changes in the structure of the channel as would be the case in a river restoration/enhancement scheme. The results suggest that this would not be the case for fish. Available physical habitat was greater for the Less Modified site on the River

Tame and the Restored site on the River Cole. This reflects the broader range of hydraulic conditions available over a range of flows at these two sites. Results from the River Rea show that it is the Concrete Lined site that provides the greater physical habitat for fish over a wider range of flow. This result conflicts with the perception that the channel with the concrete lining would provide the poorer physical habitat. However, the results reflect the morphology of the channels. The narrow, relatively deep, channel at the Rea Unlined site provides relatively poor physical habitat because depth and velocity rise rapidly as discharge increases. The concrete lined channel is wider and therefore velocities and depths rise less rapidly with increases in flow in comparison with the unlined channel. Despite having concrete lined banks the concrete lined channel was relatively rough due to the presence of coarser bed sediments.

7) Scoring of physical habitat for fish

7.1) Background to assessments and scoring systems

GQA (biology)
In England and Wales, water quality is reported on a rolling five year programme, called the General Quality Assessment (GQA). The Agency's method for classifying the water quality of rivers and canals is known as the General Quality Assessment scheme (GQA). It is designed to provide an accurate and consistent assessment of the state of water quality and changes in this state over time. The scheme consists of separate windows on water quality. The Chemical GQA describes quality in terms of chemical measurements which detect the most common types of pollution. It allocates one of six grades (A to F) to each stretch of river, using the same, strictly defined procedures, throughout England and Wales. The process is set out below.

- Each sampling site is assigned the stretch of river that the site will characterise. In the main, these sites, and the monitoring, are the same as those used to take decisions on developments that may affect water quality - discharges, abstractions and changes in land use.
- Results from the routine pre-planned sampling programmes with samples analysed by accredited laboratories are used. To avoid bias all extra data collected for special surveys or in response to incidents or accidents are ignored. The routine programme involves monthly sampling at some 8,000 monitoring points on over 40,000 kilometres of rivers and canals.
- Sites are sampled a minimum of 12 times a year. The data collected over three years is used because this produces 36 samples per site, giving the required precision in making judgements about particular rivers, bearing in mind the cost of monitoring. All the results collected over the three years are included. No extreme data values are excluded.
- The percentiles are calculated from the samples using the method of moments, assuming a normal distribution for dissolved oxygen and lognormal for biochemical oxygen demand (BOD) and ammonia. The estimates of the percentiles are compared with the standards. A grade is assigned to each river length according to the worst determinand. This is the 'face-value' grade.
- All data and results for all rivers are made available to the public.

Physical habitat

One method of assessing environmental sensitivity is used in relation to water abstraction, and is called environmental weighting (EW). This method uses four separate parts for assessment. These are physical characterisation, fisheries classification, macrophyte scoring and macroinvertebrate scoring. Physical characterisation types are defined based on the following five categories.

1) Rivers with steep gradient and/or wide shallow cross-sections
2) Semi-natural, moderate gradient rivers and streams
3) Rivers with high baseflows or natural winterbournes. Baseflow index greater than 0.85.
4) Managed and low gradient rivers, streams and ditches.
5) Lowland river reaches.

This is a very basic method intended for use where there is very little information available on river status. No other assessment method for physical habitat are available.

7.2) Assessment of physical habitat using PHABSIM results

In cases where PHABSIM studies have been conducted an alternative method may be employed. Where PHABSIM studies have been carried out time-series of predicted WUA are available for a range of species and life stages. The aim of this section is to obtain a simple Physical Habitat Assessment Score (PHAS) for a site based no these PHABSIM predictions. The PHAS is a score that could be used to assess changes in physical habitat conditions created by changes to the flow regime or channel structure. The PHAS scoring system given here is designed to produce output as categories with values between one and five to be compatible with existing scoring systems for water quality.

Assessment of habitat refugia is one approach to quantifying the quality of physical habitat and therefore maintaining fish populations in urban river channels. Langer and Smith (2001) compared several different enhancement schemes on the Huntspill River. They showed that all schemes on this river successfully increased fish populations, and that the type and age of the enhancement scheme was relatively unimportant. This implies that as long as velocities in a certain proportion of the river are sufficiently decreased most designs of enhancement scheme will be beneficial. Young-of-the-year fish, whose abundance is crucial in determining year-class strength (Hatcher *et al.,* 1991), will be especially susceptible to the adverse effects of high flows in comparison to larger fish. This is particularly the case during late summer (Gozlan *et al.,* 1999). This is important in urban rivers where high flow events can occur throughout the year due to impermeable surfaces and dense drainage networks.

One method that can be used to gain a PHAS is to set a minimum habitat area. This will be called the minimum refuge area, or PRA here. The PRA is an estimate of the minimum percentage area that a life stage will need to survive. An assessment of physical habitat quality can then be made based on the amount of time for which that amount of habitat is available. Results presented in this sections are derived for the 15minute time-series of flows from the nearest Environment Agency gauging station to each of the sites for the year 2000.

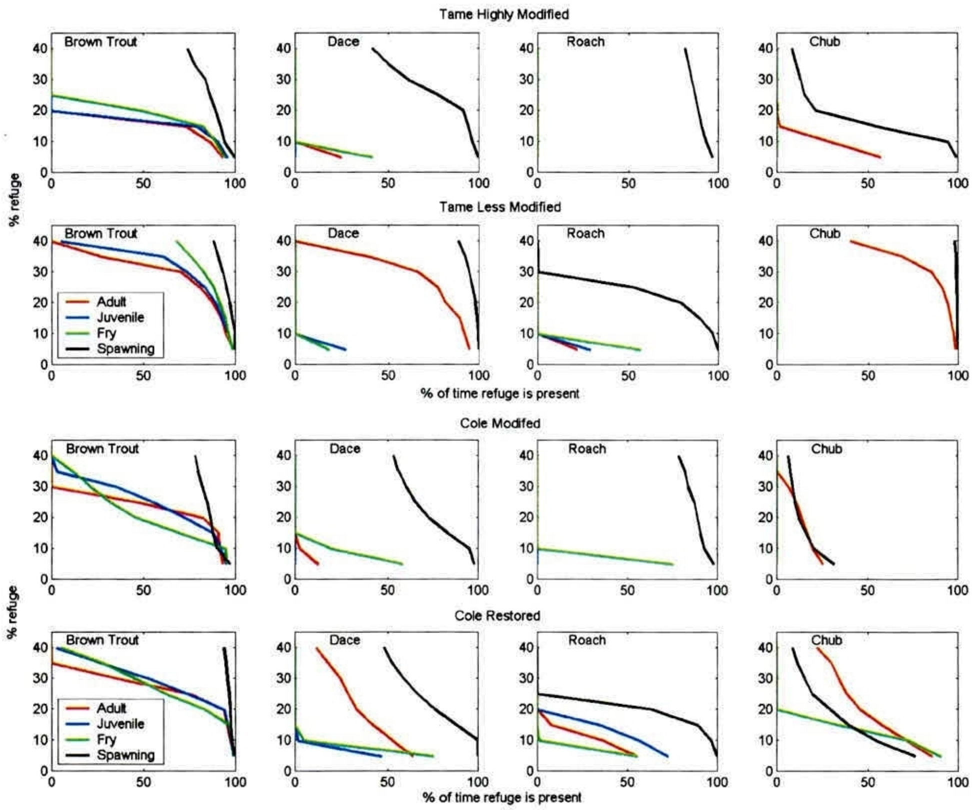
Simulation of physical habitat for different life stages should only be applied when that particular life stage is likely to be present in the river. For this reason results from the discrete times of the year were used for fry and spawning life stages (Table VII) based on Soriguer et al., (2000) and Encina and GranadoLorencio (1997).

Table VII. Times during which different life stages are likely to be present.

Species	Life stage	Time period (inclusive)
Brown trout	Spawning	November to December
Dace	Spawning	March to April
Roach	Spawning	April to June
Chub	Spawning	May to July
All species	Fry	April to September

There are essentially three steps that must be completed prior to gaining a PHAS. These are listed below.

1. The percentage of river required to maintain a refuge (PRA) must be defined.
2. The classes to be used to calculate a score between one and five for each life stage of each species must be defined.
3. The way in which the PHAS scores from each life stage of each species are to be combined to gain a final overall PHAS must be defined.



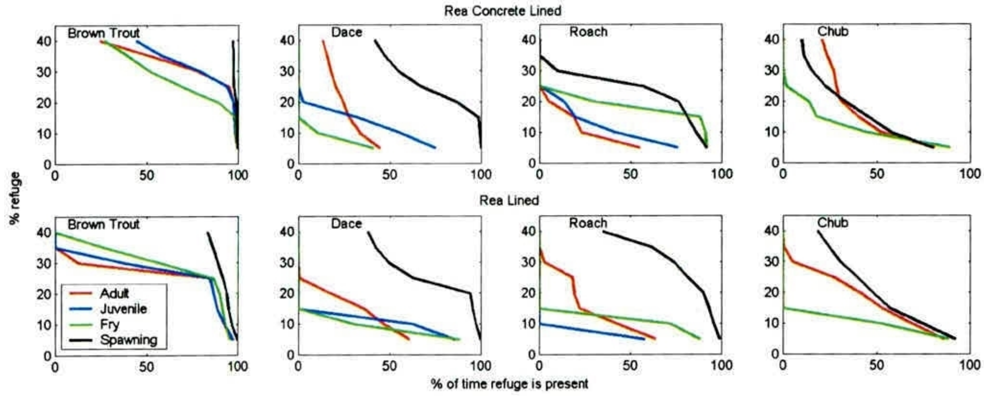


Figure 14. Percentage of time for which a given percentage of habitat is available at each sites. For chub the fry and juvenile life stages are lumped together.

Figure 14 shows the percentage of time during 2000 for which WUA was greater than a range of PRAs for each life stage of each species. In this figure WUA is expressed as a percentage of the average total river area available at each site throughout the year.

Results are summarised below:

- Where no line is drawn on the graph at no time does the WUA rise above that required for any PRA.
- The nearer to the top-right the line is the better the physical habitat.
- The nearer the bottom-left the line is the worse the physical habitat.
- More spawning habitat is available than any other life stage for all sites and all species.
- Straighter lines indicate linear relationships between the amount of habitat available and time for which habitat is available.
- For Brown trout when PRAs of less than 20% are set this quantity of suitable habitat is available for the vast majority of the time. As PRA rises above this the time for which greater areas of suitable habitat is present for decreases rapidly.

In order to derive a PHAS that realistically reflected the health of the river the following procedure was followed.

1. The percentage of river required to maintain a refuge (PRA) was defined as being 10% of the average total river area.
2. The percentage of time for which WUA was greater than 10% of the average river area was then calculated for each life stage of each species.
3. The percentages calculated for each life stage of each species was then averaged to gain the mean percentage for each species.
4. The mean percentage was then used to calculate the mean PHAS score using the categories 1= 100-80, 2 = 80-60, 3 = 60=40, 4 = 40-20, 5 = 20-0.
5. The same categories were also used to calculate PHAS scores for each individual life stage.
6. The minimum score for any life stage of a species was also found based on the PHAS scores calculated for each individual life stage.

Table VIII shows the percentage of time for which a PRA of 10% was present at each site. The HSIs for brown trout cover a much broader range of conditions than those for roach, dace and chub (see Figure 6). Therefore, when the procedure outlined above was employed, calculated PHAS scores for all brown trout life stages at all six sites were classified in the best habitat quality category (Category 1, >80%). This means that suitable habitat was present in at least 10% of the reaches for all life stages of brown trout for more than 80% of the time. As PRA reaches 20-30% the percentage of time for which this amount of habitat is available in the reaches falls rapidly for brown trout (Figure 14). This suggests that a more sensitive brown trout PHAS could be calculated by setting the PRA to a value greater than 10%. The following discussion focuses on PHAS scores for roach, dace and chub as these are considered target species for rehabilitation of urban rivers.

Table VIII. Percentage of time for which a PRA of 10% was present at each site.

Species	Life stages	Tame Highly Modified	Tame Less Modified	Cole Modified	Cole Restored	Rea Concrete Lined	Rea Unlined
Brown Trout	Adult	86.32	95.05	91.54	97.02	98.29	92.09
	Juvenile	90.88	96.12	92.30	97.53	98.47	92.44
	Fry	89.58	96.27	94.91	97.87	98.60	93.07
	Spawning	94.24	99.69	90.30	98.17	99.44	96.58
Dace	Adult	0.00	92.15	2.74	52.51	33.39	46.73
	Juvenile	0.00	0.00	0.00	1.47	55.11	62.74
	Fry	0.00	0.00	20.08	5.06	10.45	30.86
	Spawning	96.72	99.61	95.27	100.02	99.16	97.47
Roach	Adult	0.00	0.00	0.00	36.80	22.94	42.57
	Juvenile	0.00	0.00	0.00	56.66	41.27	0.00
	Fry	0.00	0.00	0.00	0.88	91.28	72.34
	Spawning	93.49	97.14	92.86	96.50	86.24	95.86
Chub	Adult	29.60	97.63	19.96	71.66	51.90	68.15
	Juvenile/fry	0.00	0.00	0.00	72.71	43.62	52.50
	Spawning	94.41	99.81	20.65	54.22	57.90	74.45

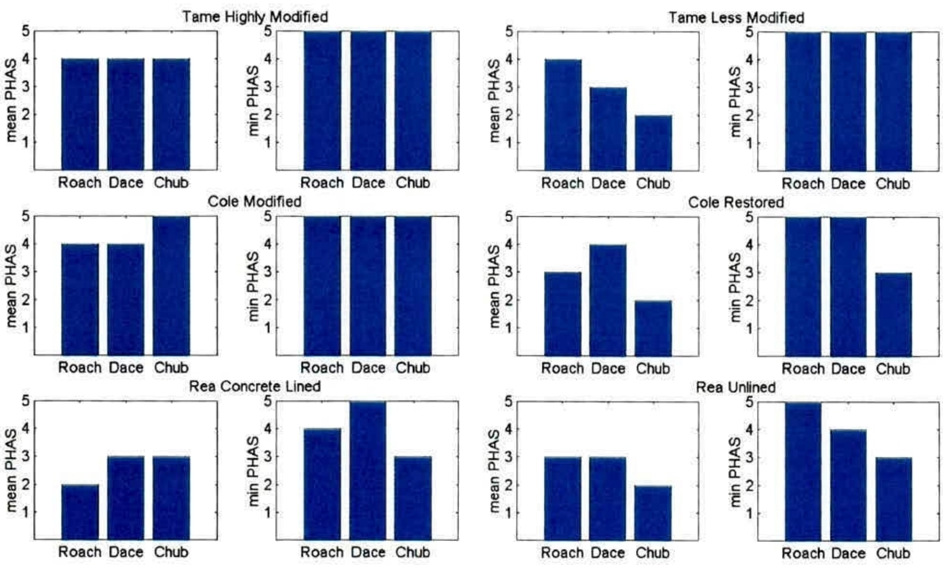


Figure 15. Predicted mean and minimum PHAS scores at the six sites (PRA = 10%).

7.3) Discussion of mean PHAS results

Figure 15 shows the results of the procedure outlined above for dace, roach and chub. The figure shows that mean PHAS scores for the six sites ranged between two and five. No mean PHAS was calculated to be in either the very worst of very best physical habitat category. For the River Tame the Highly Modified site scored a worse PHAS for dace and chub in comparison with the Less Modified site. The mean roach score is the same for both sites. The River Cole has the greatest difference between sites on the same river. Mean PHAS scores are less on the Restored section for roach and chub. The most within pair difference for chub scores were found on the River Cole, with the Restored section scoring a 2 and the Modified section only scoring a 5. On the River Rea the similarity in conditions at this pair of sites produced the least difference in PHAS scores between any pair of sites. In fact the relatively wide channels for the two sites on the Rea and the relatively reduced flows on the Rea resulted in these two sites having reasonably good PHAS scores, with all species scoring 2 or 3 at both sites. This is because velocities did not rise as rapidly with increases in discharge in comparison with the Tame sites and the Cole Modified.

Discussion of minimum PHAS results

The mean PHAS scores reflect the physical habitat quality averaged over the different life stages of each species. Where physical habitat is particularly bad for one life stage of a species there will be a knock-on effect on the following life stages. For example, where fry habitat is very poor it may be the case that no fry survive in order to utilise potentially good quality juvenile and adult habitat. For this reason the minimum PHAS scores for each species are also displayed in Figure 15. The figure shows that at the two Tame sites the minimum PHAS scores calculated for all three species was in the worse category for physical habitat. In every case the life stage with the minimum PHAS score was fry. This is a refection of the hydraulic situation present at these two sites. Results show that the combination of slow velocities and specific depth distributions that are required by fry only occur at the very lowest of flows at both sites. The flow regime on the Tame at the location of the sites dictates that these conditions did not occur for a sufficiently long period of time with respect to fry physical habitat.

The mean and minimum PHAS scores have been shown together here. This is because the two scores can be used in different contexts. Where the PHABSIM reach is one that represents long stretches of river the minimum PHAS score is the most appropriate measure of physical habitat quality. This is because refuges that are able to support fry life stages should be included in the reach and therefore the modelling process. However, where the PHABSIM reaches have been chosen to represent a specific section of the river that does not represent the river as a whole the mean PHAS score is a more appropriate measure of physical habitat. This is because fry refuges may exist outside of the modelled reach. In this case good quality juvenile and adult habitat may be utilised by fish migrating into the reach. Therefore the use of the mean PHAS scores would seem more applicable to the reaches used in this investigation. This is because the reaches were chosen to represent different levels of channel engineering, and in fact pairs of sites where chosen to be in close proximity to each other so that differences in water quality could be discounted. Clearly, fish are capable of migrating within any of the three pairs of sites as there are no physical barriers to migration between each pair of sites.

8) Applying PHAS scores to assess changes in physical habitat resulting from changes in flow

The PHAS scoring system can be used to assess changes in physical habitat that may occur with changes in flow regime in the same way as comparisons can be made between sites with the same flow regime. This approach can be used to assess the effects of proposed changes in flow that might result from changes in management practices. For example, in the 1970s, flood balancing areas and controlled washlands were created on the River Tame to further guard against long return period floods. Another proposed change in flow regime might occur by routing storm flow from Combined Sewer Overflows (CSOs) away from natural river channels. Further changes in flow regime might occur from future climate change.

8.1) PHAS scores resulting from different flow scenarios

In this report four flow scenarios are compared with observed flows to demonstrate the application of the PHAS assessment methodology. These flow scenarios were produced by Kate Durr as part of a PhD project at Birmingham University, Department of Civil Engineering. The scenarios have a temporal resolution of one hour and are based on data collected for 1999. The model used was SMAR (soil moisture accounting and routing model), which had been altered to include, an hourly time step, and the inverse Gaussian distribution for the routing function. The output includes baseflow. This model output was converted from the units mm hr^{-1} to m^3s^{-1}. These scenarios are used here to represent different flow regimes rather than the predicted effects of changes in a particular management practices.

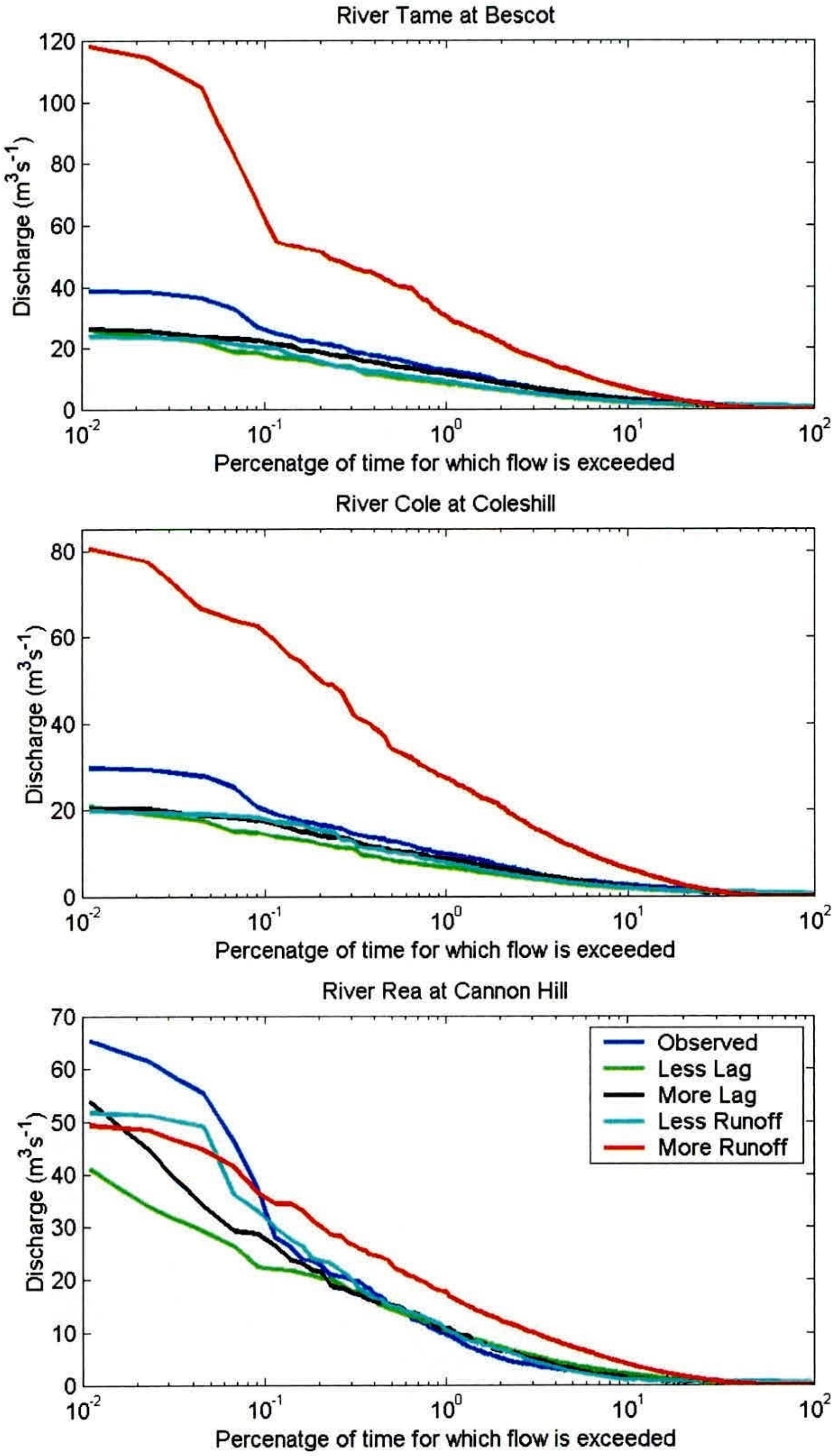


Figure 16. Flow duration curves for the scenarios and observed data.

Table IX. Summary statistics for flow scenarios and observed flows (Q5 and Q95 represent flows exceeded for 5% and 95% of the time).

	Observed	Less Lag	More Lag	Less Runoff	More Runoff
max	38.82	26.29	26.48	23.89	118.02
Min	0.19	0.00	0.00	0.00	0.00
mean	1.62	1.30	1.54	1.44	2.39
Q5	4.84	3.57	5.26	3.71	12.39
Q95	0.33	0.42	0.52	0.56	0.00

Flow duration curves (Figure 16) and summary statistics (Table IX) for the flow scenarios show that the More Runoff scenario is a substantial increase in discharge over the observed data for the Tame and the Cole, but not the Rea. The remaining three scenarios relate to differences in the timing of flows as well as the magnitude. Less Lag is a scenario where response times are reduced (see Figure 17). As a result the peak flows are similar to those for the observed data, however the rising limb of the storm hydrograph rises quicker and the receding limb falls more rapidly. This scenario represents the type of flows that might be expected with a decrease in the permeability of the catchment, as might be expected with an increase in buildings or roads. The More Lag scenario represents the opposite situation. This type of situation might arises if balancing ponds or more trees were introduced into the catchement. The Less Runoff and More Runoff scenarios represent the types of flow regime that might be expected with changes in the catchment climate.

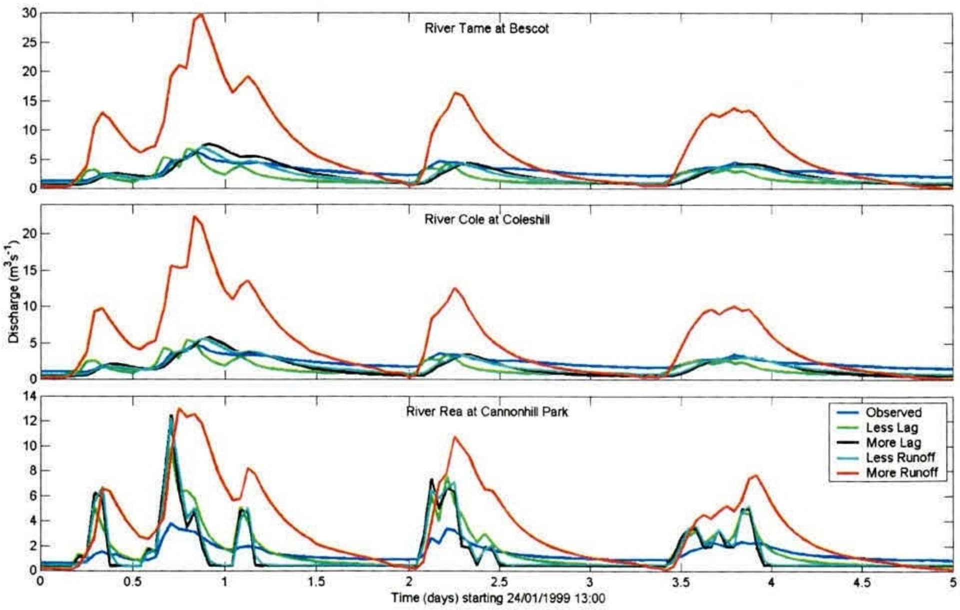


Figure 17. Hydrographs for the scenarios and observed data (top = River Tame, Bottom = River Cole).

In Figures 18-23 the life stages with the worst PHAS scores are identified on the graphs shown. Where two or more life stages are tied with the worst PHAS score the priority is given to adults, followed by juveniles, fry and spawning.

8.1.1) River Tame

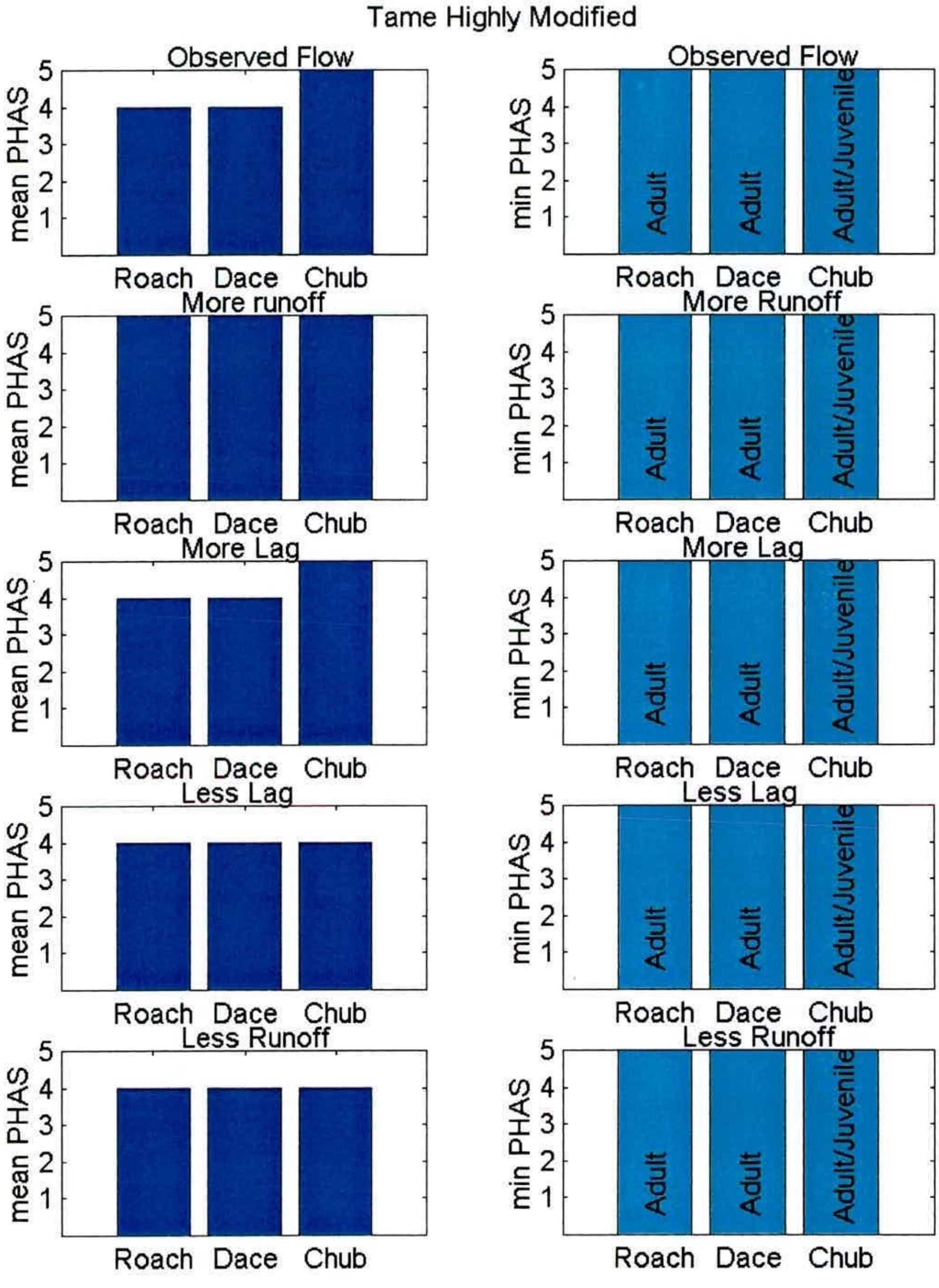


Figure 18. PHAS scores at the Tame Highly Modified site with different flow scenarios (calculated using hourly flows, observed data is from 1999).

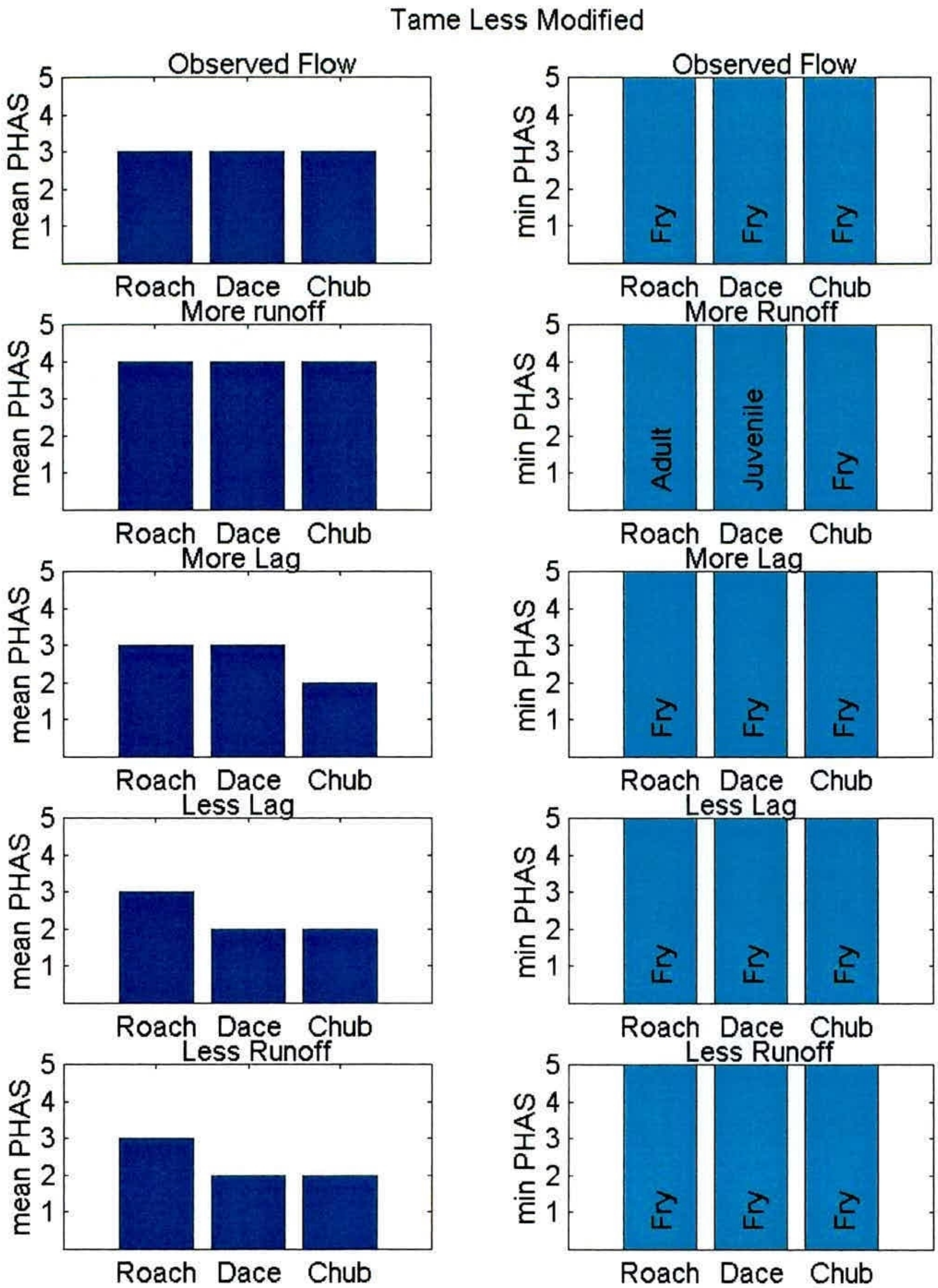


Figure 19. PHAS scores at the Tame Less Modified site with different flow scenarios (calculated using hourly flows, observed data is from 1999).

Figures 18 and 19 show PHAS scores calculated for the Tame Highly Modified and Less Modified sites. The results show the mean and minimum PHAS scores calculated using the hourly observed flow record from 1999 and the modelled scenarios. Results are summarised below.

Tame Highly Modified

- The More Runoff scenario decreases the PHAS scores to such an extent that all life stages of all species have PHAS scores of 5. This is the worst possible situation for physical habitat and means that there is less than 10% river area of suitable habitat for less than 20% of the time for all life stages of all three species.
- The PHAS scores are the same for observed flows and the More Lag scenario. This result is not surprising as these two sets of flows are similar in magnitude, the only differences being in the timing of flows. Since PHABSIM results and therefore PHAS scores are time independent this difference in timing causes the PHAS scores to be the same.
- The Less Lag and Less Runoff scenarios result in improvements in the mean chub PHAS score from 5 to 4.

Tame Less Modified

- The More Runoff scenario increases the mean PHAS scores for all species. In the case of roach this is a decrease in habitat quality over 2 categories from 3 to 5.
- The PHAS scores for the More Lag, Less Lag and Less Runoff scenarios are all the same. These scenarios all result in improvements to the mean PHAS scores for dace and chub, but not roach when compared to the observed flows.
- Despite improvements to the mean PHAS scores the minimum PHAS scores remain in the worst category. This is because there is very little fry habitat for any of the species at any flow in either site (see Figure 8).

<u>8.1.2) River Cole</u>

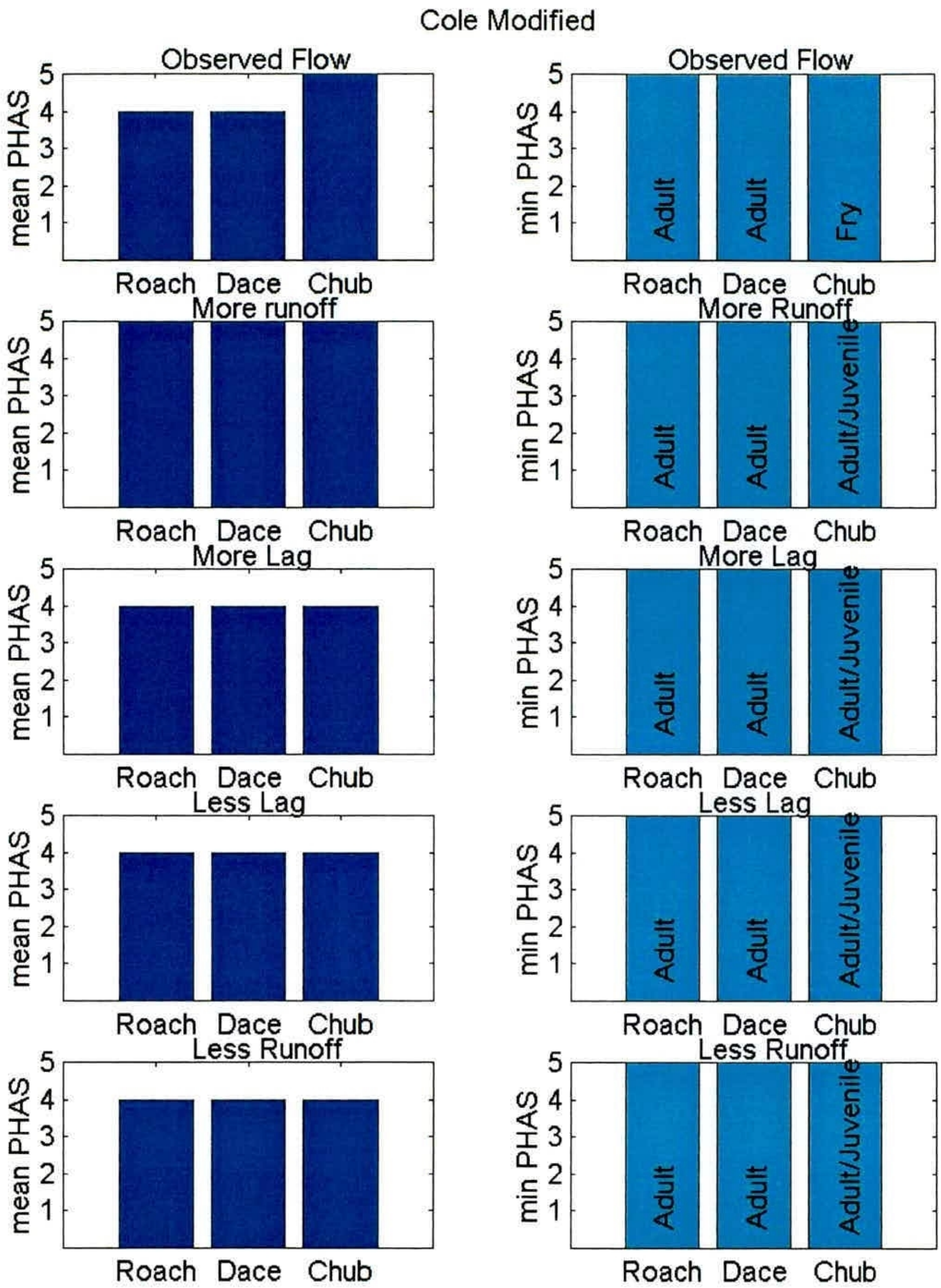


Figure 20. PHAS scores at the Cole Modified site with different flow scenarios (calculated using hourly flows, observed data is from 1999).

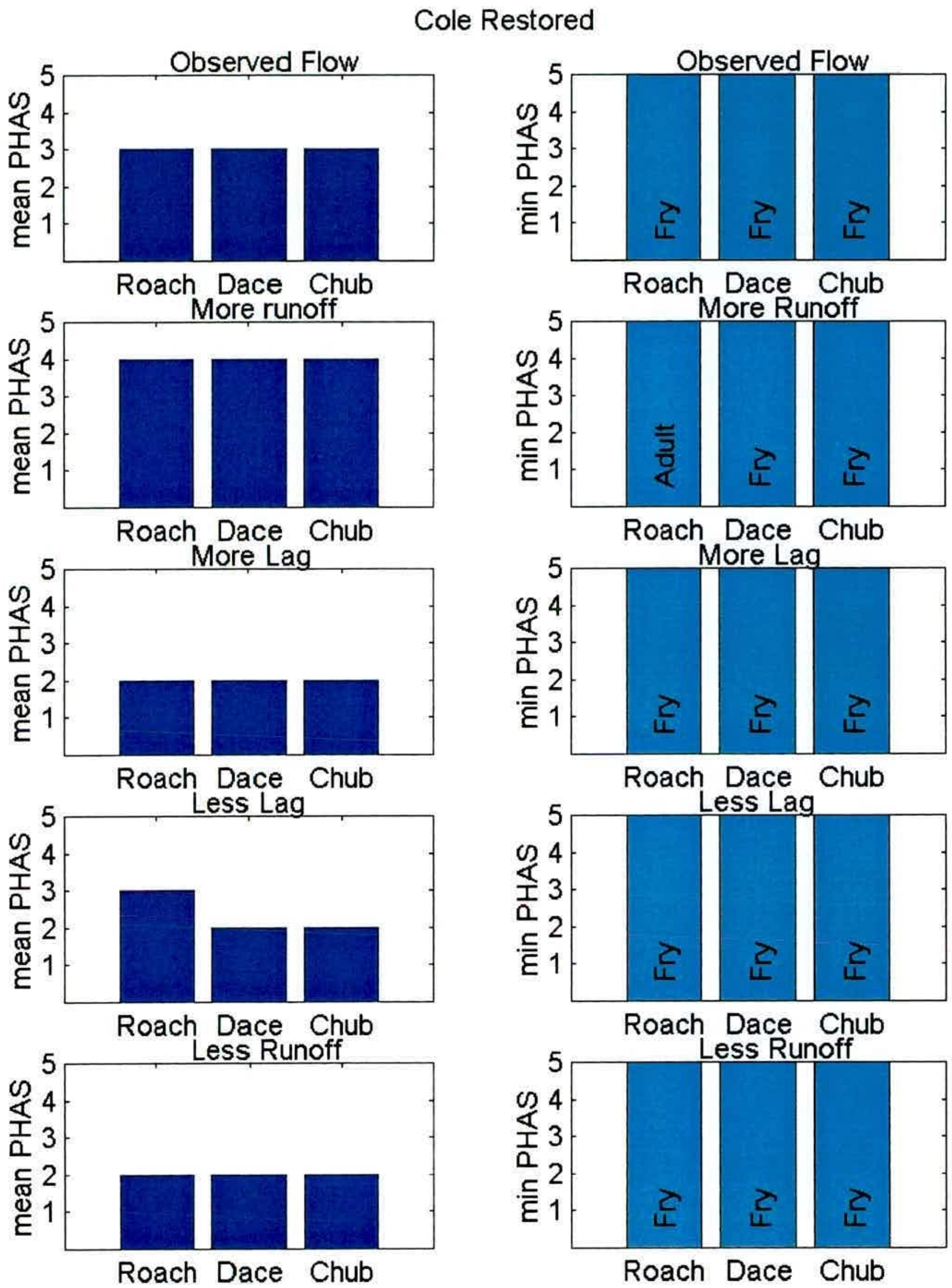


Figure 21. PHAS scores at the Cole Resotred site with different flow scenarios (calculated using hourly flows, observed data is from 1999).

Figures 20 and 21 show PHAS scores calculated for the Cole Modified and Restored sites. The results show the mean and minimum PHAS scores calculated using the hourly observed flow record from 1999 and the modelled scenarios. Results are summarised below.

Cole Modified

- The More Runoff scenario increases the PHAS scores to such an extent that all life stages of all species have PHAS scores of 5. This is the worst possible situation for physical habitat and means that there is less than 10% river area of suitable habitat for less than 20% of the time for all life stages of all three species. This reflects the large increase discharge that this scenario represents (see Figure 17).
- The PHAS scores for Chub improved for all scenarios except the More Runoff scenario when compared with the observed flows. This result reflect the similarity in flow duration curves for these scenarios. The flow duration of these sets of flows are similar in magnitude, the only differences being in the timing of flows. Since PHABSIM results and therefore PHAS scores are time independent this difference in timing causes the PHAS scores to be the same.
- Predicted fry habitat at the Cole modified site is in the worst PHAS category for all three species given all flow scenarios and the observed flow data. This reflects the poor habitat at the site for fry (see Figure 9). In fact the WUA-discharge relationship suggests that there is never more than 10% suitable fry habitat at the site for any species. As a result changes in the at the site do not cause any change in the PHAS scores for fry and have little effect on the overall species PHAS score.

Cole Restored

- The More Runoff scenario increases the mean PHAS scores for all species by one class. For all species this is a decrease in habitat quality over one category from 3 to 4.
- The PHAS scores for the More Lag and Less Runoff scenarios are the same. These scenarios all result in improvements to the mean PHAS scores for all three species. The Less Lag scenario results the same improvement for dace and chub, but not roach.
- Despite improvements to the mean PHAS scores the minimum PHAS scores remain in the worst category. This is because there is very little fry habitat for any of the species at any flow above $4m^3s^{-1}$ (see Figure 9).

8.1.3) River Rea

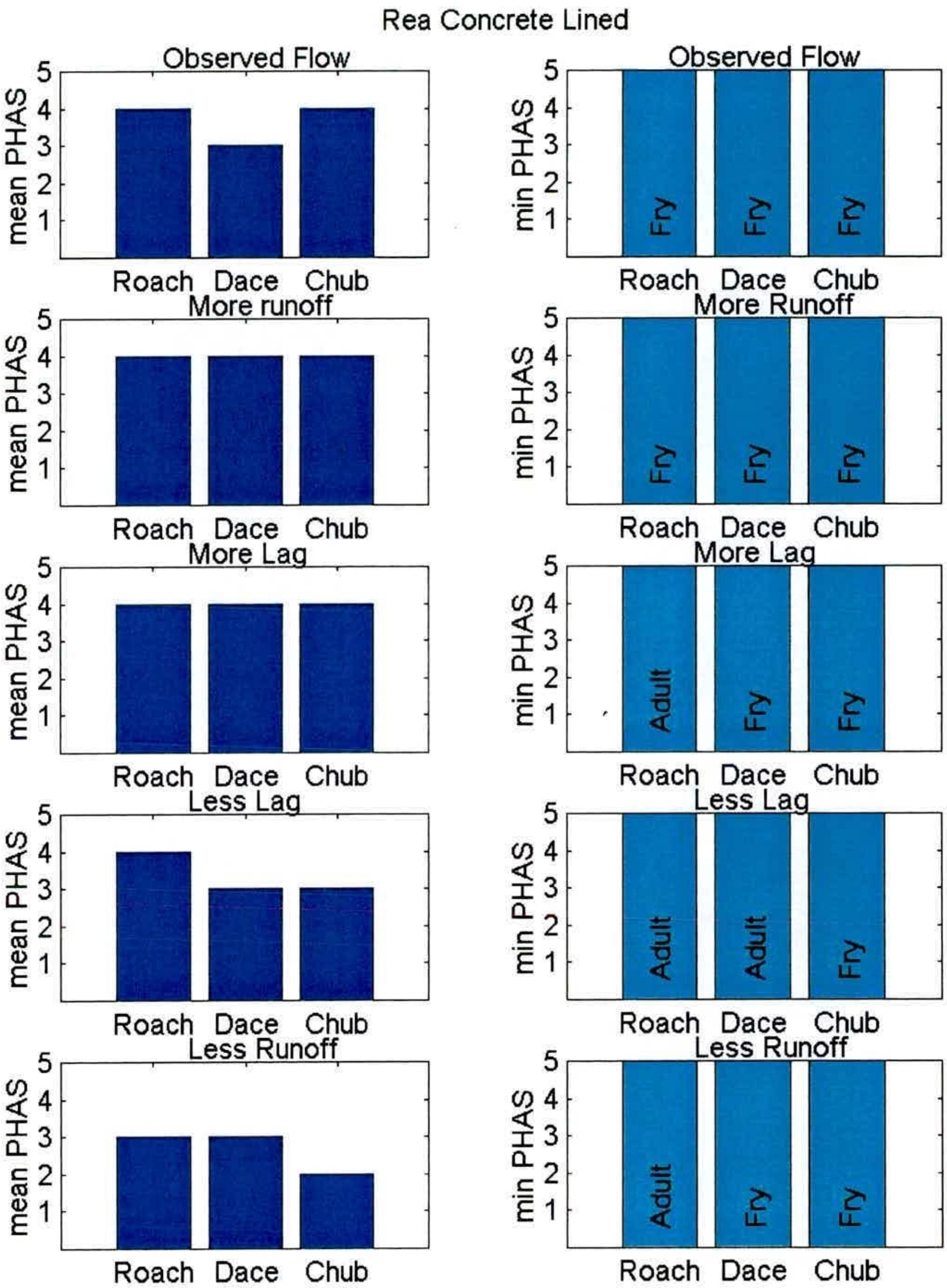


Figure 22. PHAS scores at the Rea Concrete Lined site with different flow scenarios (calculated using hourly flows, observed data is from 1999).

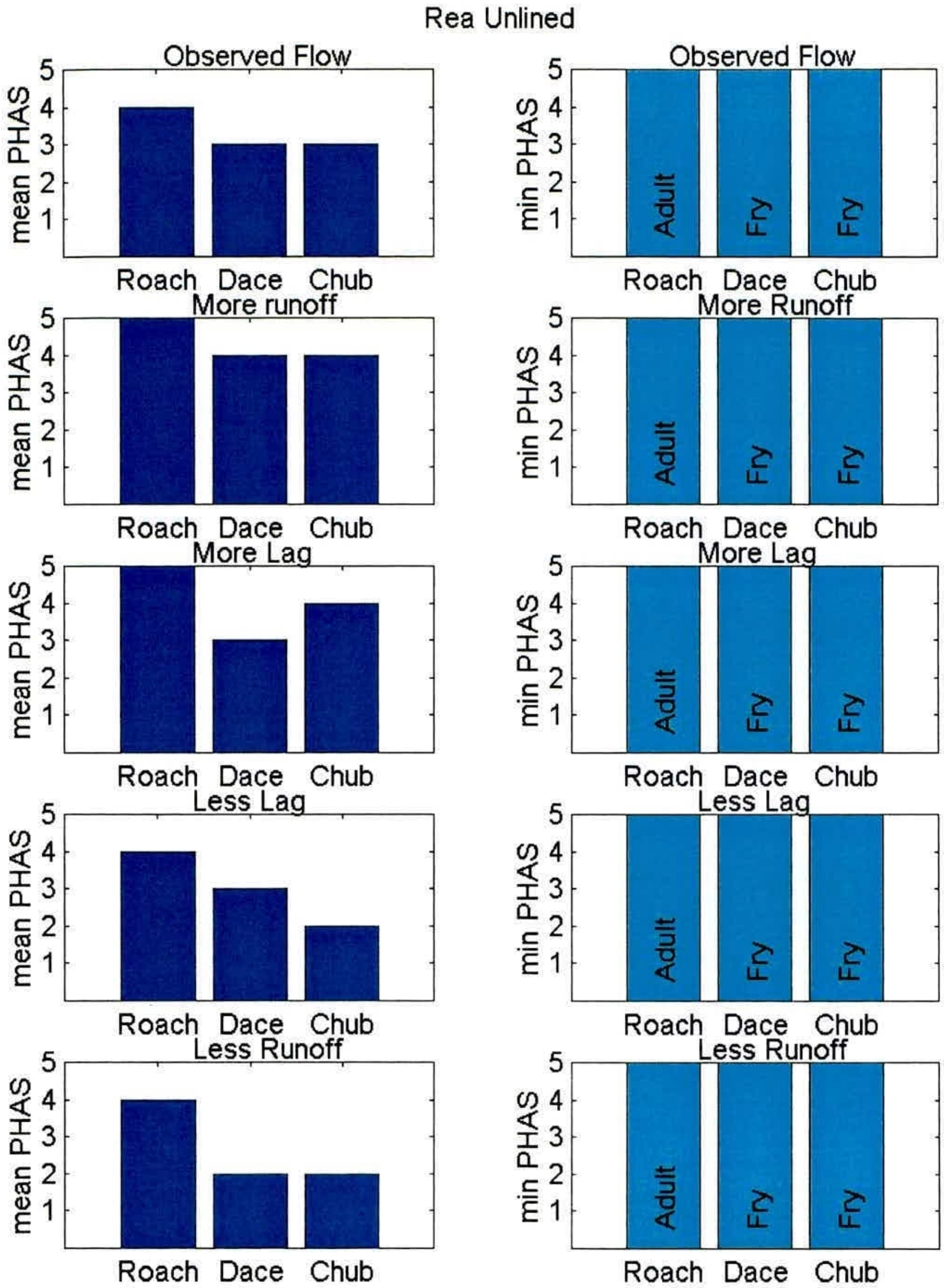


Figure 23. PHAS scores at the Rea Unlined site with different flow scenarios (calculated using hourly flows, observed data is from 1999).

Figures 22 and 23 show PHAS scores calculated for the Rea Concrete Lined and Unlined sites. The results show the mean and minimum PHAS scores calculated using the hourly observed flow record from 1999 and the modelled scenarios. Flow scenarios for the River Rea contrast those for the Cole and Tame. For this reason the patterns of PHAS scores for the Rea do differ from those calculated for the Tame and the Cole sites. Results are summarised below.

Rea Concrete Lined

- The More Runoff scenario increases the mean PHAS score of Dace by one so that all species have the same mean scores.
- PHAS scores calculated for the More Lag scenario produced the same result as the More Runoff scenario.
- The PHAS scores for Chub improved for the Less Lag scenario by one class and the Less Runoff scenario by two classes with the observed flows.
- Roach mean PHAS score is only improved for the Less Runoff scenario.
- Predicted fry habitat at the Rea Concrete Lined site is in the worst PHAS category for all three species given all flow scenarios and the observed flow data. This reflects the poor habitat at the site for fry (see Figure 10). In fact the WUA-discharge relationship suggests that there is never more than 10% suitable fry habitat at the site for any species. As a result changes in the at the site do not cause any change in the PHAS scores for fry and have little effect on the overall species PHAS score.

Rea Unlined

- The More Runoff scenario increases the mean PHAS scores for all species by one class.
- Roach mean PHAS scores do not improve for any of the scenarios in comparison to the observed data.
- The results for the More Lag scenario are the same as for the More Runoff scenario with the exception of dace, which remains the same rather than decreasing.
- The Less Runoff scenario produces the best scores with dace and chub both improving to score 2.
- Despite improvements to the mean PHAS scores the minimum PHAS scores remain in the worst category. This is because there is very little fry habitat for any of the species at any flow above $4m^3s^{-1}$ (see Figure 10).

9) Discussion of the PHAS method

As with any scientific methodology there are advantages and disadvantages which should be considered when applying the method. There are listed below.

Advantages

- The method is designed to complement the GQA method employed by the Environment Agency. As a result scores from one to five are used.
- PHAS scores provided an objective method for assessing physical habitat quality.
- No subjectivity or expert opinion is used in the analysis. The method is therefore replicable and consistent.
- The method employed is relatively simple to carry out once the PHABSIM predictions have been made.
- The method allows comparison of sites and comparison of different flow regimes at the same site.
- The approach is appropriate for assessing sites with poor physical habitat where river rehabilitation schemes may be appropriate.

Disadvantages

- A PHABSIM study is required prior to calculation of PHAS scores.
- The PRA was set at an arbitrary level of 10% of the river. Changes in this variable will affect the results (see Figure 14).
- Equal divisions for the percentage of time were arbitrarily used for determining the PHAS score.
- The assumption that the provision of at least 10% area of suitable habitat for more than 80% of the time does not necessarily mean that the physical habitat in a reach is of a very high standard. Improvements in physical habitat could still be made given these conditions.
- Use of a percentage of the average total area in the river, rather than a finite area, to set the minimum area required as a refuge may be considered to be a disadvantage. In a very small river 10% of the total river area may be too small an area to provide sufficient habitat for a life stage of a certain species to survive.
- Changes in flow regime may create changes sediment budget and therefore changes in the morphology of a site. This means that the relationship between discharge and physical habitat, on which the PHAS method is based, may also be altered. This may not be a problem in urban rivers where channel engineering means that large increases in transport energy are required in order to create changes in morphology. However, this may be an issue that requires consideration when applying the method to more natural systems.
- The approach may not be suitable for assessment of rivers with narrower flow ranges or higher quality physical habitat. This is because there will be no distinction between rivers where at least 10% of the river area is suitable at all flows or rivers where detrimental flows only occur for less than 20% of the time. However the PHAS system could be adapted for application in these circumstances.

10) Conclusions

The aim of Task 5 of the modelling river corridors URGENT project was to develop a hydroecological model to predict the ecological effects of changes in (i) water quality (ii) flow regime and (iii) physical habitat within urban rivers in order to evaluate restoration strategies. The specific objectives of the hydroecological modelling component of the Modelling River Corridors URGENT Project were to extend IFIM/PHABSIM to predominantly urban river channels and to develop a predictive tool capable of evaluating the role of physical habitat in the health of urban rivers for different water quality and flow scenarios and hence the effectiveness of river habitat rehabilitation and enhancement schemes and future environmental change.

PHABSIM results are complex in nature and often difficult to interpret. The PHAS scoring system provides an objectively derived predictive tool capable of evaluating the ecological effects of changes in channel characteristics and/or flow regime. The PHAS scoring systems requires a predefined relationship between discharge and physical habitat availability. The system is based on a five-classed scoring system in line with the GQA system for the assessment of water quality. In this respect the system is designed to be simple to operate and easy to interpret. PHAS provides an objective assessment of PHABSIM results, which are often complex in nature and difficult to interpret. Although the PHAS system does not fully integrate the effects of physical habitat and water quality on habitat quality it does provide an integrated framework for assessment of both of these factors together. For example comparison of GQA and PHAS scores allows priority to be given to improvements in either water quality or physical habitat, or both, when attempting to conduct river rehabilitation.

The system used here employed a value of 10% for the Percentage Refuge Area (PRA). This variable is analogous to the minimum area of habitat in which a species or life stage would require for survival. Equal bands of 20% width are used to distinguish between classes. The setting of PRA and the band widths could be changed. Sensitivity analysis showed that the results would be sensitive to changes in the PRA variable (Figure 14). However, this sensitivity may only be in terms of the overall scores that are calculated and not in the differences between scores that are produced when a pair of sites, or a set of scenarios, are compared. Further research is required to analysis the sensitivity of results to changes in the band widths. This is especially the case with regard to a broader range of sites that may include higher quality physical habitat and steadier flow regimes.

Results show that there are distinct increases in the availability of suitable physical habitat for coarse fish in the Tame Less Modified and Cole Restored sites in comparison with their Highly Modified and Modified pairs respectively. This suggests that channel modification does limit physical habitat given similar flow regimes. Specifically, more engineered channels are less sinuous and have flatter beds. This results in a lack of hydraulic diversity and faster flowing water. In general, as discharge increases velocities surpass those required for suitable habitat in the more heavily engineered channels sooner than in less engineered channels. In some cases the combination of depth and velocity required for specific life stages of coarse fish only coincided for a very narrow range of flows in the more heavily engineered channels. However, there was not a clear difference in physical habitat within the pair of sites on the River Rea. At this site the Concrete Lined reach may have been expected to be worse in terms of physical habitat availability based on an aesthetical judgement alone. This did not prove to be case. The results suggested that there was little difference in the quality of available physical habitat between this pair of sites. This was because the channel geometry at the Unlined site was dictated by the presence of fixed rip rap bank protection and was in fact deeper and narrower that the Concrete Lined reach. The consequence of this was that as discharge increased the quality of physical habitat in the Unlined reach was restricted by fast velocities.

Scenarios of changes in flow regime, in the form of hourly time-series, were used to assess the impact that changes in flow may have on physical habitat. Results show that an increase in runoff would have detrimental effects in all cases, and that decreases in flow would benefit physical habitat. The less modified sites benefited marginally more than the more modified from decreases in flow. The benefit to physical habitat gained from three different scenarios, which represented various changes in flow regime, was assessed. Results showed that there was little difference in benefit received between these scenarios.

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