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# Evaluation of instream habitat enhancement options using fish habitat simulations: case-studies in the river Pas (Spain)

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## Abstract

In the northern coast of Spain there are rivers with Atlantic salmon populations. In the upper reaches of one of these streams, river Pas, the effectiveness of habitat enhancement measures was evaluated, under different instream flow conditions. By means of the Instream Flow Incremental Methodology and using a two dimensional hydraulic model (River2D, Steffler P (2000) *Software River2D. Two Dimensional Depth Averaged Finite Element Hydrodynamic Model*. University of Alberta, Canada), the potential value of stream habitat for different salmon development stages requirements was measured by Weighted Useable Area (WUA). This habitat evaluation was carried out for the unmodified stream reach, which represent the control or natural conditions. Habitat improvement measures (alternate deflectors and low dams) were simulated in the original riverbed topography. Over this modified base, habitat was estimated running River2D again. By comparing the salmon habitat evaluations in the control conditions with those obtained under those improvement conditions we have been able to assess the effectiveness of each one, and the instream flow environment at which maximum improvement is reached. The maximum habitat improvement was obtained around 10 $m^3/s$ for the adult salmon, and for the fry and parr it was around 6 $m^3/s$. However, the habitat simulation results show that with both improvement measures, under a natural flow regime the mean annual habitat increases around 1% of the WUA in relation to the control conditions, which is not a significant improvement. A similar small WUA increase was obtained when changing the bed topography, considering geomorphological adjustments due to the new erosion and sedimentation areas caused by the presence of these structures. Therefore, these types of habitat improvement measures are not recommended in these stream reaches.

## Introduction

Northern coastal rivers of Spain maintain Atlantic salmon (*Salmo salar* L.) populations, being the most southern localities along their world distribution range, although being on threatened status (García de Jalón 1997). Frequently, fish habitat in these rivers is quite degraded because of human activities. In this study, the effectiveness of some habitat improvement measures were investigated, to reveal if it is useful to implement these actions.

Fish stocks can be limited by food, refuge, spawning habitat, flow fluctuations and water-quality constraints but also by factors other than habitat such as biological interactions including competition, predation and parasitism. Previous to any Physical Habitat Improvement implantation one should check which of these factors is acting as a bottleneck for the fish population we want to enhance.

Improving physical habitat conditions for fisheries should take into account natural recovery processes (Cairns et al. 1977; Gore, 1985; Reice et al. 1990) and the biogenic capacity of the reach, in order to act along with nature (Heede and Rinne 1990) rather than against it, allowing nature to improve the stream by itself (White and Brynildson 1967).

In order to maintain habitat traits best adapted to target fish population needs, different non-structural and structural approaches have been proposed (García de Jalón 1995; Hey 1994). Structural measures often include different types of weirs and deflectors. The design and best implementation of some of these structures in alluvial rivers has been outlined by Rosgen (1996) from the geomorphological point of view. These structures change local hydraulic conditions and thus, their erosion and deposition dynamics. Consequently, its substrate and microtopography is modified and therefore their habitat characteristics.

Several types of structures are used to improve fish habitat in rivers: current deflectors, low dams, boulders, half-logs, bank overhangs and others are described in literature. (García de Jalón 1995). Shamloo et al. (2001) developed a study on the flow and erosion around some of these simple habitat structures, employed to provide feeding and resting areas for fish.

Deflectors are the most frequently used structures for habitat enhancement. They change the stream direction with the aim to protect the river margins, to dig pools, to concentrate water in summer or to create rapids (González del Tánago and García de Jalón 2001). For their construction, Wesche (1985) gives technical details. Usually, a series of alternate triangular deflectors is placed. Each deflector produces an accumulation of materials downstream, and it also changes the flow direction creating a pool near the other river margin. They are designed in a triangular shape with its longest side strongly fastened in the river border. According to White and Brynildson (1967), deflectors must not exceed the summer water level more than 25 cm in a year with normal rains.

Low dams are usually introduced in a riverbed to create or to deepen pools, and also to collect gravel, which will improve the natural redds in hard slope streams. These dams are built with a "spillway" to enable migratory fish to pass at a low water level. The dam considered in this study is not straight but in V-shape, to concentrate flow at the centre and to protect better the lateral anchorages (Reeves et al. 1991). This structure accelerates water when it passes over it, and this high speed of the water digs a pool downstream. It accumulates material upstream, as well.

Many enhancement projects have been recently implemented in Spain (Schmidt and Otaola-Urrutxi 2000). The aim of these projects was to improve the stream habitat by improving the stream bed complexity. Their goal was mainly to improve suitable habitat for stream salmonids and for the macrobenthic communities on which they feed. However, no previous analysis of their potential effectiveness was carried out, neither any surveillance studies of the effects after their implementation.

It is frequently assumed among fisheries manager practitioners that the implementation of instream habitat improvement measures, such as current deflectors, always benefit fish habitat. Since this statement is not true in every case, a theoretical study was developed in this work, to assess the effectiveness of habitat enhancement measures in a particular case. Therefore, the objective of this paper is to research and evaluate, by means of habitat simulation, if the introduction of some types of structures in the riverbed, will effectively improve the useable habitat for salmon, and to quantify its influence.

An upper reach of the river Pas was selected to develop this study, in the north of Iberian Peninsula, province of Cantabria, near the town of Puente Viesgo (Figure 1). River Pas is a chalky stream, which flows in north direction and discharges its water in the Cantabric Sea, open to the Atlantic Ocean. Atlantic salmons use to ascend this river for reproduction. Other fish species present in the river is brown trout (*Salmo trutta* L.) (García de Leániz and Verspoor 1989). Also

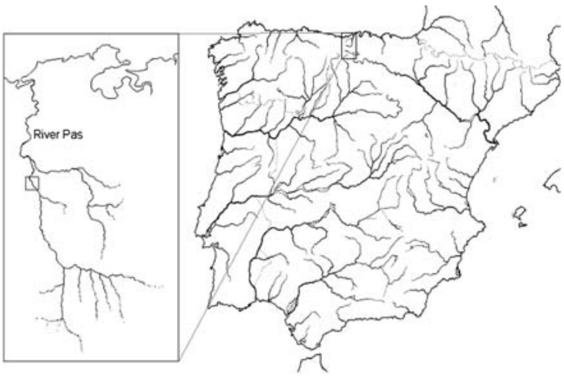


*Figure 1.* Location of river Pas and the studied reach.

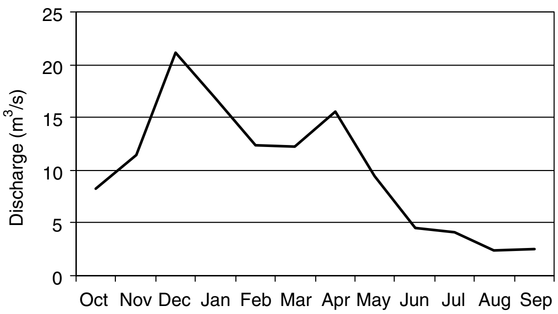


*Figure 2.* Natural regime. Calculated from daily flow data from the period 1965–1997 recorded at the gauging station no. 215, located in the town of Puente Viesgo (750 m downstream the study reach).

minnow (*Phoxinus phoxinus* L.) has been recorded in this reach.

Pas is a mountain river with high slopes and a great predominance of gravel and cobble in the substrate. The hydrological regime has its absolute maximum in December and a relative maximum in April, as shown in Figure 2. The river is prone to low flows at the end of summer, aggravated by water extractions for the supply of Santander city. Downstream the study site, there are several obstacles to salmon migration though they have fish passes. The nearby villages also discharge their water in the river. This impact is more serious in summer, when the stream flow is minimum.

## Materials and methods

The present study evaluates the habitat improvement reached by different stream habitat enhancement options, by means of the Instream Flow Incremental Methodology (IFIM), which has been developed by the U.S. Fish and Wildlife Service and amply described in Bovee (1982), Stalnaker et al. (1995) and Bovee et al. (1998). This methodology is based on habitat characterization with the aim of see, considering the habitat requirements of some species or development stages, and by means of a hydraulic simulation, how habitat use changes depending on the stream flow variations.

IFIM can be used for determination of ecologically acceptable discharges, in order to minimize ecological impacts caused by hydraulic structures. By means of IFIM it is possible to carry out hydrological analyses, prediction of several scenarios and determination of limits for water (Caletková and Komínková 2004). From the biological point of view, IFIM allows to compare useable habitat in different conditions, thus it is possible to predict the success of any particular physical habitat improvement measure.

For this work a two-dimensional hydraulic model was chosen, because these models are very useful in studies where the detailed local distribution of depths and velocities is important (Steffler et al. 2000). Two-dimensional approaches have been used in several stream habitat studies (Ghanem et al. 1996; Crowder and Diplas 2000, 2002; Vehanen et al. 2003 or Leclerc et al. 1995).

We have employed the software River2D (Steffler 2000), developed by Peter Steffler at the University of Alberta, in Canada. This program uses a two dimensional hydraulic model, which simulates the hydraulic conditions (average depth, water mean velocity and direction, water surface elevation, etc.) in the surface of the studied reach, and estimates the potential value of stream habitat for the requirements of different species and development stages by Weighted Useable Area (WUA).

The River2D model was developed specifically for use in natural streams and rivers. It is a Finite Element model, based on a conservative Petrov-Galerkin upwinding formulation. It features subcritical–supercritical and wet–dry area solution capabilities. A complete description of the formulation and implementation of the model is contained in Ghanem et al. (1995). The implementation of habitat requirements is done in a similar way as it is done in Phabsim one-dimensional model.

To carry out the simulation with this software it is necessary to have the riverbed topography, and to know the flow magnitude and the inflow and outflow water elevation. To estimate the Weighted Useable Area the program also need to know the preference of depth, current velocity and substrate type of all the development stages of the fish that are considered.

Using an Electronic Total Station PENTAX PCS-315 and an appropriate prism, the riverbed topography was measured at four reaches of around 100 meters long each in a one kilometer river segment. Among these reaches, the one which best represents the river segment was selected to carry out the habitat simulation. 395 topographical spots were surveyed within the river reach bed. The registered data were the *X* and *Y* coordinates and the bed elevation in meters, along with the composition of the substrate in the bed, according to the key showed in Table 1. It is important to take a good measurement of the river margins to know the water surface elevation when the fieldwork was done; this elevation, along with the stream flow at the same moment, will be the boundary conditions needed by the software to carry out the simulation.

The ''effective roughness height'' was chosen as the resistance parameter for the hydraulic model, because it tends to remain constant over a wider range of depth than roughness coefficients do. Compared to traditional one-dimensional models, where many two-dimensional effects are abstracted into the resistance factor, the two-dimensional resistance term accounts only for the direct bed shear. Observations of bed material and bedform size are usually sufficient to establish reasonable initial roughness estimates. For resistance due primarily to bed material roughness, a starting estimate of effective roughness height was taken as 2–3 times the largest grain diameter. The final values were obtained by calibrating the model results to measured water surface elevations and velocities.

*Table 1*. Types of substrate considered and their effective roughness height (in meters).

| Substrate type | Roughness (m) |
|---|---|
| 1. Silt and fine materials (< 0.6 mm) | 0.01 |
| 2. Sand (0.6–3 mm) | 0.05 |
| 3. Gravel (4–9 mm) | 0.03 |
| 4. Cobble (10–300 mm) | 0.07 |
| 5. Boulder and submersed logs (> 300 mm) | 0.7 |
| 6. Bed rock | 0.1 |

Instream flow magnitude was estimated in two transverse channel sections, one upstream and another downstream. Along each transverse section a series of points were located where a significant change in the slope, substrate type, water velocity, depth, etc. was found. In each point, its distance to the right margin was measured; depth was also noted down, employing a graduated stick; finally, water velocity at a distance from the riverbed of 0.6 times the depth was recorded, using an Electromagnetic Flow Meter VALEPORT 801. With these data flow magnitude in the reach was obtained.

The suitability of three hydraulic variables (current velocity, depth and substrate type) have been considered, and three Atlantic salmon development stages have been studied: adult, parr and fry. Their preference curves (Figures 3–5) are based in those developed by Heggenes (1990), but modified taking into account our field observations in river Pas.

These data allow to obtain the relation between discharge and potential habitat for each salmon development stage, by means of the hydraulic simulation. The boundary conditions required by the hydraulic model to execute the simulation are the stream flow at the upstream cross-section and the water surface elevation at the downstream and upstream cross-sections. With these data, the software is able to adjust the following expression:

$$q = a \cdot d^b$$

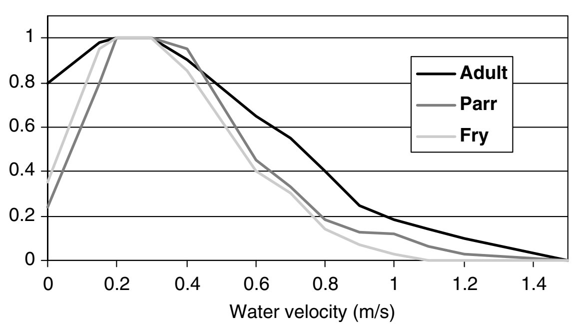


*Figure 3*. Average water velocity preference curve for Atlantic salmon.

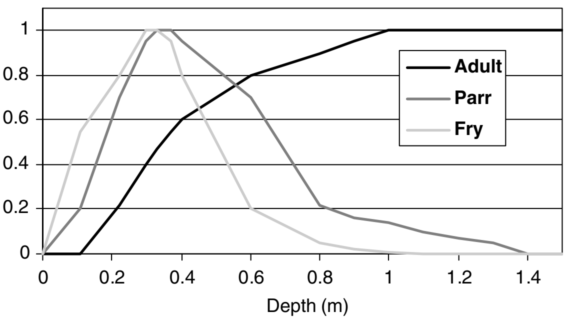


*Figure 4.* Water column depth preference curve for Atlantic salmon.

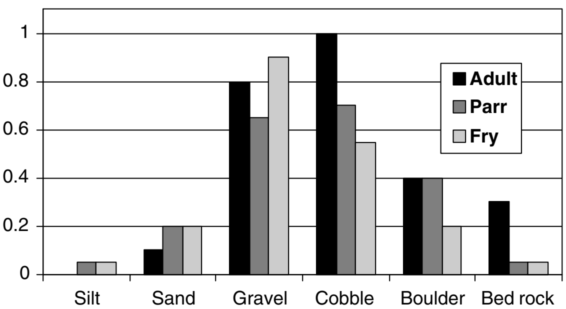


*Figure 5.* Substrate preference for Atlantic salmon.

where "$q$" is flow per unit of width ($m^2/s$), "$d$" is the water height in the downstream section and "$a$" and "$b$" are two constants which are adjusted according to stream flow and water height data measured in the field.

The Weighted Useable Area (WUA) is the surface ($m^2$) that can be potentially used, with a maximum preference, by the considered species or development stage. The study of Weighted Useable Area allows to know how a species can use the river habitat depending on the stream characteristics and flow variations.

Firstly, the habitat simulation was carried out for the stream reach under unmodified conditions. Next, three alternate triangular deflectors were supposed to be in the riverbed, and the simulation was done again, to see how the stream habitat changed. Another improvement measure was supposed: the introduction of a low dam in a narrowing of the studied reach. The simulation was carried out once again for the low dam case. By comparing habitat in the control conditions with habitat obtained with the deflectors and the low dam, the effectiveness of each improvement measure was assessed. This comparison also shows the instream flow environment at which maximum improvement is obtained.

Afterwards, the bed topography was changed considering the geomorphological adjustments due to the new erosion and sedimentation areas caused by the presence of the improvement structures. These adjustments on the erosion zones were estimated on the basis of an analysis of cells that had maximum shear stress values at high flows, while the sedimentation ones were evaluated at minimum shear stress cells. The quantification of these adjustments was estimated based on expert knowledge. These adjustments determined a modified riverbed topography that was introduced in River2D model. We have performed new simulations again for this topography in order to investigate their habitat changes and to quantify their potential habitat improvement.

With the aim to evaluate the habitat increase obtained with the improvement structures, one habitat value was calculated for each case, by adding all the WUAs weighed by the frequency of their corresponding discharges. This value was called "Frequency Weighted Habitat" (FWH). In this way, the most frequent flows have more influence in the final result. To carry out this analysis, we used daily flow data supplied by Spanish Water Authority ("Confederación Hidrográfica del Norte"). These data, ranging from October 1965 to September 1997, were recorded at the gauging station no. 215, located in the town of Puente Viesgo, 750 m downstream the study reach. For the calculation of fry and parr FWH, the whole data set were employed, while adult FWH was obtained considering only daily discharges from March to December, when adult salmons are in the river for reproduction. Frequency Weighted Habitat signifies the real habitat improvement under natural regime.

## Results

Discharge at the time of survey was 1.05 $m^3/s$ in the studied reach. Water heights were 67.39 m upstream and 66.92 m downstream. These water surface heights are relative elevations that have no absolute physical meaning. The adjusted values for "a" and "b" coefficients in each topographic case, from the expression $q = a \cdot d^b$, are shown in Table 2.

This coefficients were calculated from the boundary conditions at the initial calibration of the model, and are used to carry out the hydraulic simulation.

Figure 6 represents the ground plan of the reach selected to develop the study, as it was taken in the fieldwork. The shore line at the time of survey is also shown.

The software River2D divides the reach in a series of cells. After a simulation, it provides several outputs for each cell, such as depth, water surface elevation and velocity, Froude number and suitability indexes for the indicated development stage. Figure 7 is an example of these outputs where we can see depth (in grey scale) and water velocity (as vectors), for an instream flow of 1.05 $m^3/s$ (the one measured in the fieldwork). Figures 8–10 show the combined suitability index for the considered development stages: adult, parr and fry. Combined suitability index has been calculated as the geometric mean of depth, velocity and substrate suitability indexes, in order to be comparable with other simulations, even if they have used a different number of habitat variables.

*Table 2*. Coefficients from the expression $q = a{\cdot}d^b$, after calibration with discharge and water height data.

| Case | Coefficient "*a*" | Coefficient "*b*" |
|---|---|---|
| Current conditions | 1 | 2.096 |
| With three triangular deflectors | 1 | 2.243 |
| With a low dam | 1 | 2.097 |
| Geomorphological changes due to deflectors | 1 | 2.243 |
| Geomorphological changes due to low dam | 1 | 2.103 |

Figure 11 shows how Weighted Useable Area changes depending on the instream flow variations, in natural conditions, for each Atlantic salmon development stage. Adult habitat maximum is around 30 $m^3/s$, which only occurs during high flows. Though, parr and fry habitat reaches its maximum earlier, around 12 $m^3/s$.

*Simulation with three alternate triangular deflectors*

A series of three alternate triangular deflectors was placed over the previous unmodified riverbed (Figure 12). This new topography was introduced into the software River2D to carry out a new hydraulic simulation.

The simulation of this new surface, gave another Flow-WUA curves. Subtracting these curves from the ones achieved under unmodified conditions, the chart illustrated in Figure 13 was obtained, in which we can see the habitat improvement reached for each development stage within the flow range of 0–40 $m^3/s$. Positive values represent a habitat gain with the new structures.

A new riverbed topography was simulated considering geomorphological changes due to deflectors, and the chart in Figure 14 was obtained. It shows, similarly as Figure 13, the difference with WUA in natural conditions, so it

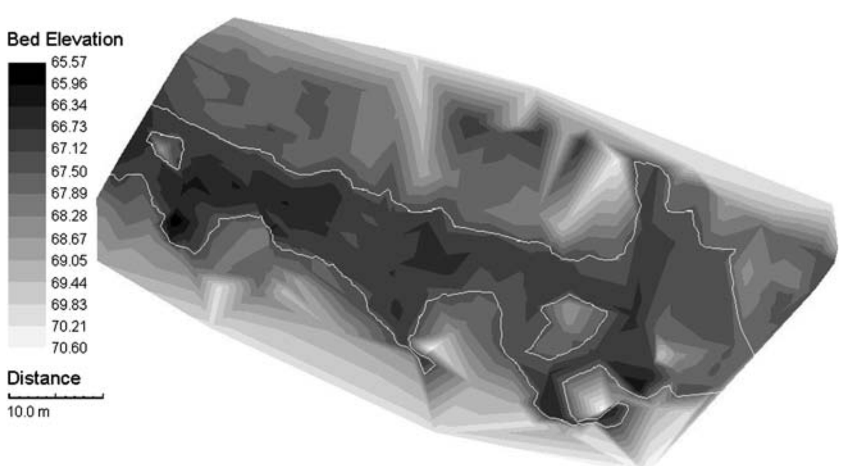


*Figure 6*. Topography of the studied reach, showing the shore line at the time of survey (white line).

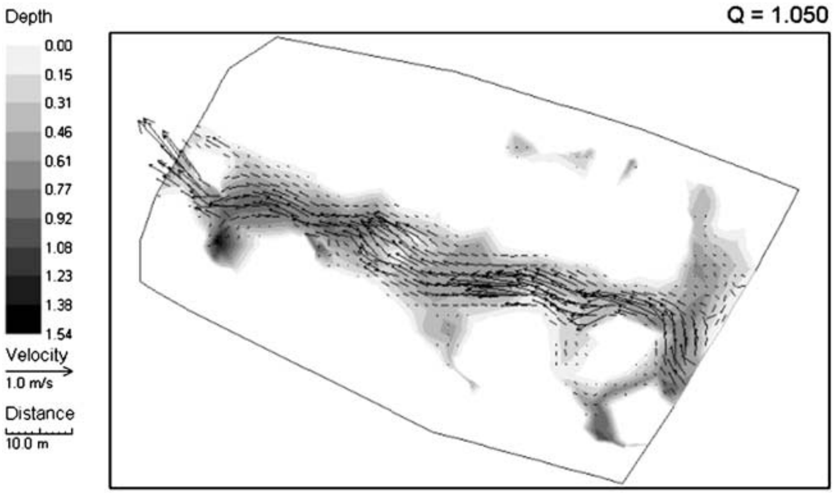


*Figure 7*. Depth and water velocity in the studied reach for the discharge measured in the fieldwork.

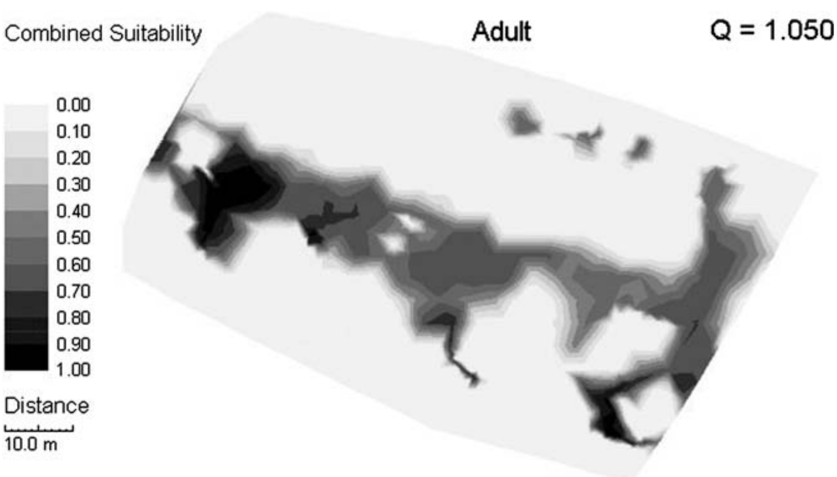


*Figure 8*. Combined suitability index for Atlantic salmon adult, for the discharge measured at the time of survey.

tells us about the habitat improvement for each discharge and development stage.

Adult habitat experiences an improvement within the flow range of 6–20 $m^3/s$, when introducing deflectors in the riverbed (Figure 13). For higher discharges it decreases. When the topography changes by geomorphological adjustments (Figure 14) this habitat gain is higher, and also the improvement range increases to 4–26 $m^3/s$.

Parr and fry curves behave similarly, except that parr habitat increases more between 10 and 20 $m^3/s$ than fry habitat. In the simulation with deflectors, both of them show an increment between 2 and 32 $m^3/s$, but it is only important until 18 $m^3/s$. For larger discharges they move around 0 $m^2$ of improvement. After topographic changes due to the new erosion and sedimentation, parr and fry habitat improves even more, but within the same interval.

With daily flow data from a 30 years period, Frequency Weighted Habitat (FWH) was calculated as it is explained in the methods. The FWH represents the real habitat improvement under natural flow regime, for each development stage in each case: unmodified conditions, alternate deflectors, low dam and after geomorphological adjustments due to the presence of each habitat improvement structure.

Figure 15 shows the evolution of the Frequency Weighted Habitat from natural conditions to the

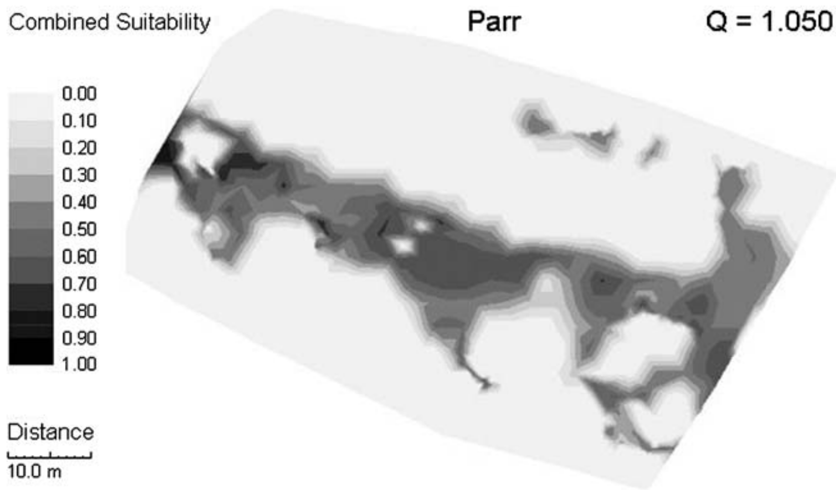


*Figure 9*. Combined suitability index for Atlantic salmon parr, for the discharge measured at the time of survey.

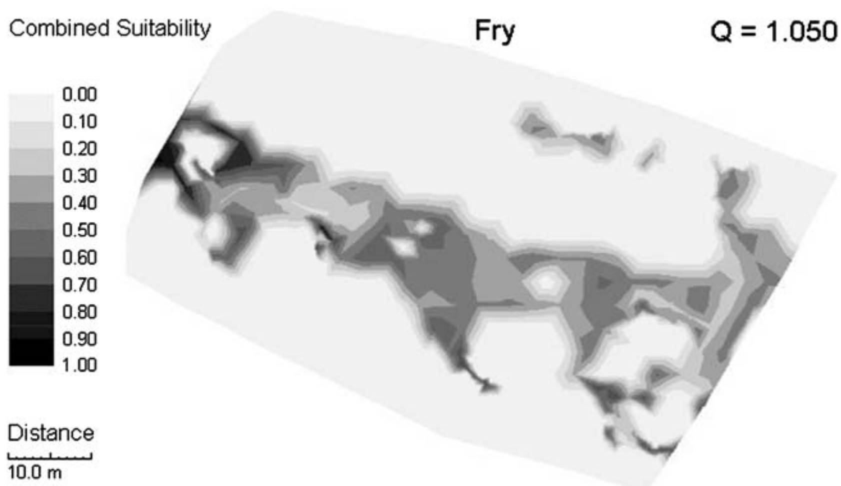


*Figure 10*. Combined suitability index for Atlantic salmon fry, for the discharge measured at the time of survey.

introduction of deflectors, and finally to the geomorphological adjustments case. Units in *Y*-axis are the percentage of improvement regarding to natural conditions habitat.

Chart in Figure 15 shows how habitat improvement fluctuates for each development stage and for both cases. There is no significant increase, because almost every point is between 1 and 1.4% of improvement, which is really small.

### *Simulation with a low dam*

The second improvement measure considered in this work was the introduction of a low dam in a narrow zone of the reach. The dam is low enough to allow water to pass over it, and it has also a slot to facilitate fish pass when little flows occur. As Figure 16 shows, we introduced the dam shape into the bed topography.

New Flow-WUA curves were obtained after simulation of the new surface with the dam. By comparing them with the ones obtained for the natural reach, we achieved the habitat improvement chart in Figure 17.

The supposed dam also produces changes in the geomorphology of the river. Hence, the bed topography was modified according to these adjustments and a simulation was carried out again. The results of this last simulation, after its

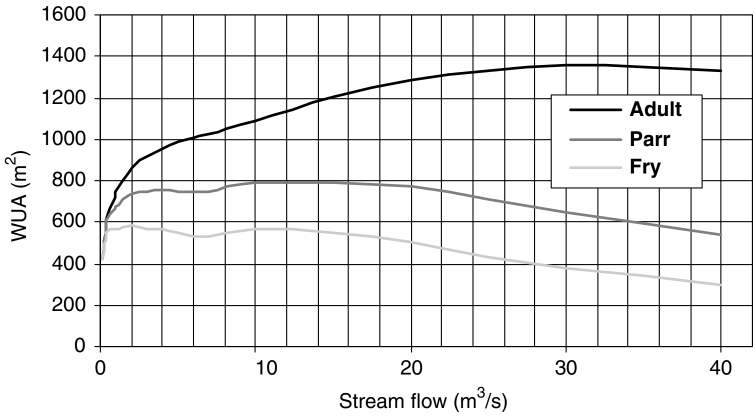


*Figure 11*. Relationship between WUA and stream flow under unmodified conditions.

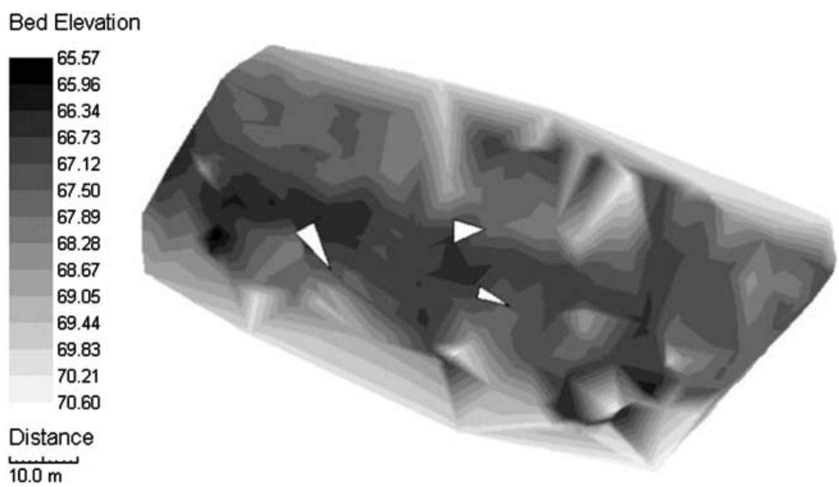


*Figure 12*. Location of the three triangular deflectors (drawn in white) in the studied reach.

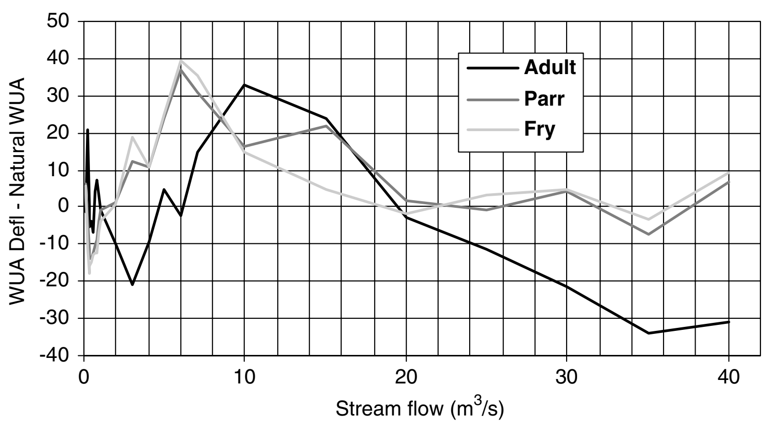


*Figure 13*. Habitat improvement reached for each flow value, when introducing a series of three alternate triangular deflectors in the riverbed.

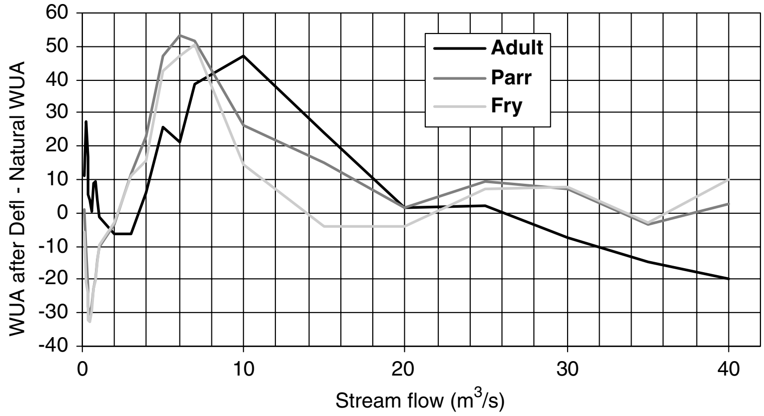


*Figure 14*. Habitat improvement reached for each flow value, considering the geomorphological adjustments caused by the presence of the series of three alternate triangular deflectors.

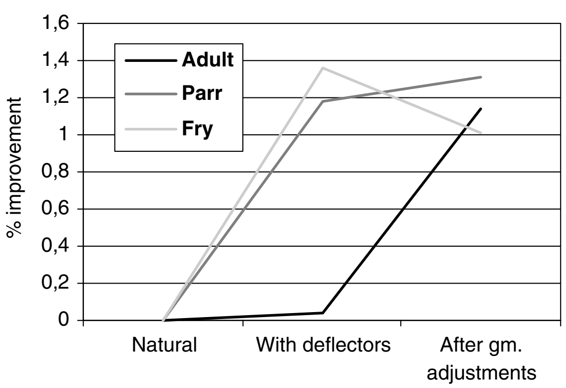


*Figure 15*. Habitat improvement as a percentage of WUA in control conditions, in deflectors case.

comparison with control curves, are shown in Figure 18.

The introduction of a low dam in the river causes an increment in the adult habitat within nearly the whole simulated range of discharges. When considering the geomorphological adjustments (Figure 18), the maximum increase (at 10 $m^3$/s), is smaller than when just the low dam is placed (Figure 17), but for higher flows the second case increases more adult habitat, having another maximum at 25 $m^3$/s.

Like in deflectors case, parr and fry curves have a similar behaviour. They contain at least two relative maximums: one around 5 $m^3$/s and the other at 30 $m^3$/s. They experience a habitat improvement only for small discharges, except

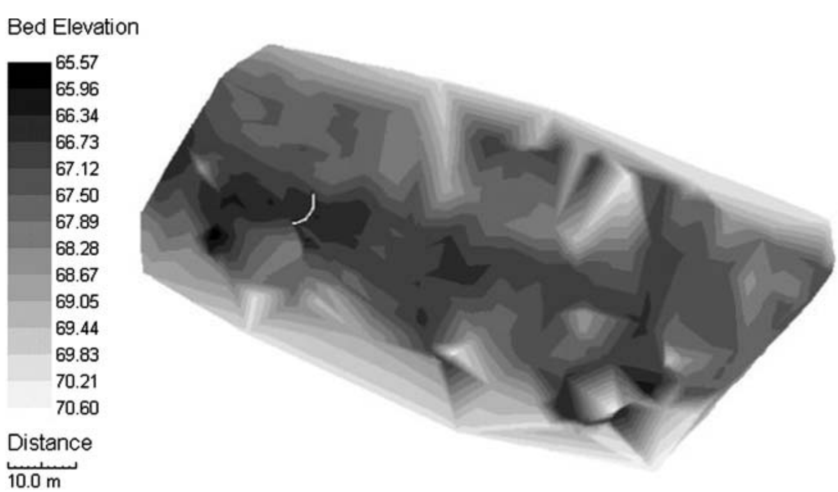


*Figure 16*. Location of the low dam (drawn in white) in the studied reach.

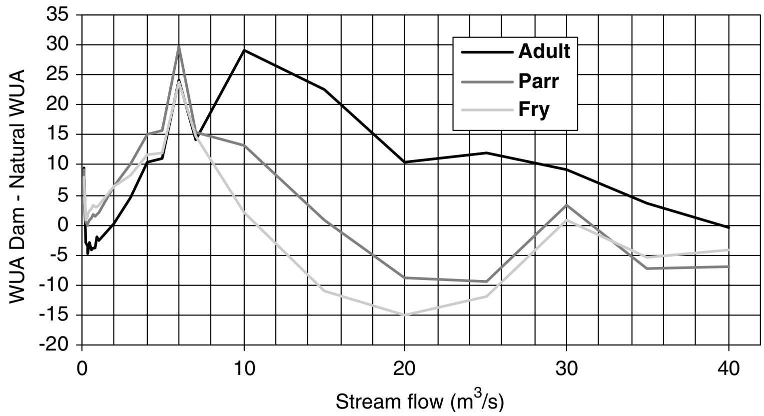


*Figure 17*. Habitat improvement reached for each flow value, when introducing a low dam in the riverbed.

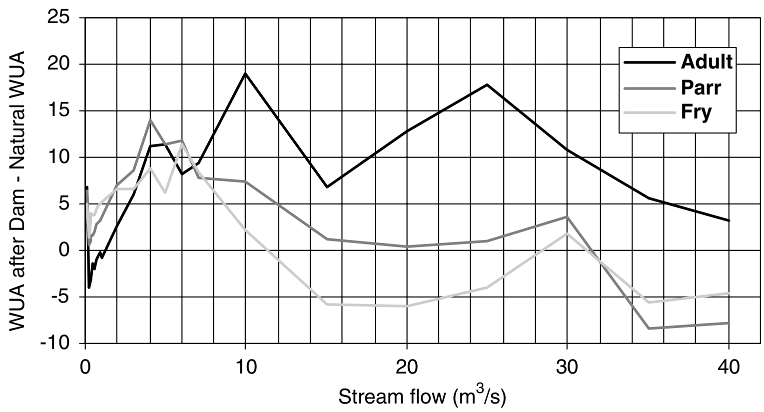


*Figure 18*. Habitat improvement reached for each flow value, considering the geomorphological adjustments caused by the presence of the low dam.

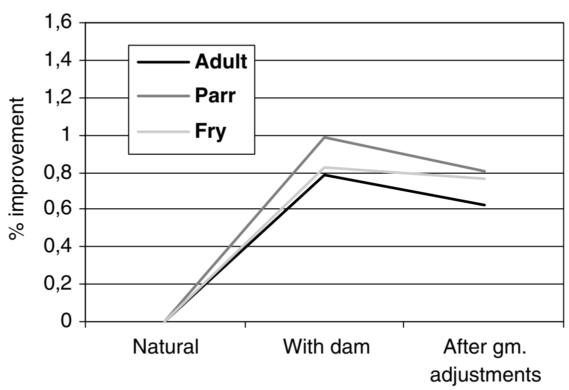


*Figure 19*. Habitat improvement as a percentage of WUA in natural conditions, in low dam case.

parr habitat in geomorphological adjustments case (Figure 18) but with a very little enhancement for high flows.

After these simulations with the low dam, the same flow frequency study as in deflectors case was done, to have a quantitative evaluation of this improvement measure in river Pas. These results are showed in Figure 19, where it is possible to observe how the habitat would improve, under natural regime, if the considered low dam was introduced.

As in deflectors case, Figure 19 shows non-significant habitat increases that are even smaller (less than 1%) than the ones obtained when introducing the series of deflectors.

*Instream habitat enhancement measures assessment*

In control conditions, the adult habitat increases with discharge until it reaches a maximum around

30 $m^3$/s, then it starts to decrease. Parr and fry habitat curves behave similarly, but they reach their maximum earlier, around 12 $m^3$/s (Figure 11). This is logical because depth and water velocity increase with flow, and adults prefer deeper areas and tolerate better high water velocities, as shown in the preference curves (Figures 3 and 4).

A series of deflectors in the stream improve adult habitat between 6 and 20 $m^3$/s, but not for greater discharges. After some time, when the riverbed has been adjusted due to the new erosion and sedimentation areas caused by the presence of these deflectors, the habitat gain is larger, and also the improvement range increases to 4–26 $m^3$/s. Parr and fry experience an increment of habitat within the range 2–32 $m^3$/s, but it is only important until 18 $m^3$/s. After geomorphological adjustments, their habitat increases a little more. Overall, the real habitat improvement under natural regime is really small and not significant at all. It fluctuates between 1 and 1.4% of improvement regarding to control conditions.

The introduction of a low dam in a narrow zone of the studied reach increases adult habitat within nearly the whole simulated range of discharges. After geomorphological changes the habitat increment is greater for higher flows. Parr and fry habitat improves nearly only for small discharges. The real habitat increase under natural regime is lesser when considering the new erosion and sedimentation areas generated by the dam. This increment is not significant (less than 1%), as it happened in deflectors case.

## Discussion

Instream Flow Incremental Methodology (IFIM) was originally developed as a specific tool to assess impacts caused by flow alteration, changes in channel morphology and in water quality (García de Jalón et al. 1993). The strength of IFIM in restoration programs planning lies on its capability for hydraulic simulation, which allows to evaluate the new available habitat, by comparing it with the original conditions or with other restoration scenarios.

In this work, the two-dimensional hydraulic model has described the detailed local distribution of depths and velocities, and the physical habitat complexity for several flows under different topographic scenarios. Since the analysis focus on the consequences of introducing some particular structures in the riverbed, which will change flow direction and create turbulence, the diversity of depths and water velocities and its detailed distribution acquires a great importance.

Two-dimensional hydraulic models have been employed by other authors to study fish habitat in several conditions. Vehanen et al. (2003) used a 2D model to assess the effectiveness of habitat enhancement measures for grayling (*Thymallus thymallus*) in a channelled river reach, which was restored by building small islands and reefs as well as cobble and boulder structures. A 2D model has been also employed by Leclerc et al. (1995) to study the habitat of juvenile Atlantic salmon of the Moisie River (Quebec) where a water diversion was planned. Ghanem et al. (1996) used one- and two-dimensional approaches to simulate the flow of water in a real fish habitat reach. They compared the computed velocity results with field velocity measurements. Results of the two-dimensional approach appeared to be significantly better than the one-dimensional ones.

Habitat simulation is employed in this work to estimate the effectiveness of different instream habitat improvement options (the inclusion in the riverbed of current deflectors and a low dam), prior to their construction. The simulation results allow to establish whether a concrete action will significantly enhance fish habitat, quantifying this enhancement and thus, whether it will be worth to be executed.

By comparing habitat evaluations in the control conditions with those obtained under the improvement conditions, their effectiveness can be assessed. The habitat simulation results show that with both improvement measures, under a natural flow regime the mean annual habitat increases around 1% of the WUA in relation to the control conditions, which is not a significant improvement. We obtained the same small WUA increase, when changing the bed topography, considering geomorphological adjustments due to the new erosion and sedimentation areas caused by the presence of these structures.

The very little habitat improvement attained (in some cases even a reduction) under these instream habitat enhancement options, shows that in this particular river reach it is not useful to implement the analysed measures. Deflectors and low dams contribute to water velocities and depths heterogeneity and therefore, to microhabitat diversity. However, this increase in habitat heterogeneity has not supposed a significant increase on salmon required habitat. Of course these results should not be generalized, as physical habitat improvement has been successfully applied in other cases. Hale (1965) has shown in two Minnesota streams that the carrying capacity for trout populations was increased after habitat restoration by means of similar enhancement measures.

The introduction of habitat improvement structures in the riverbed gives its best results in channelled streams, which are very homogeneous, because they increase the hydraulic heterogeneity. For this reason, we believe that the scarce habitat improvement is due to the characteristics of the studied reach, which is already quite heterogeneous. Atlantic salmon habitat does not increase in this reach with these habitat improvement options. Therefore, these types of habitat enhancement measures are not recommended in this case. Managers should look for the actual bottlenecks in order to minimize their effects.

Often, physical habitat improvement measures are undertaken without a previous diagnosis of the problem, which leads to a failure in the final objective, the enhancement of the target fish community. These actions are best carried out through a formally planned project, with multiple objectives (Gardiner 1991) and directed by multidisciplinary teams using a bioengineering assessment (Orsborn and Anderson 1986). Firstly, an evaluation of fish populations and their habitat should be done, taking into account the five main components of fish habitat, namely: spawning areas, food-production areas, refuge zones, flow regimes and water quality (García de Jalón 1995). With this knowledge it is now possible to realise which are the habitat problems and to find out if there are any population bottleneck. Only after this stage, we can consider the possibility of carrying out any physical habitat improvement measure, but before its implementation it is advisable to use habitat simulation as a tool for predicting and quantifying the final result of our actions. If finally some habitat improvement structure is placed, it will be essential to monitor its effectiveness and maintenance. Reeves et al. (1991) have suggested that the monitoring program must focus both on quantitative evaluations of habitat change and on fish population changes.

## References


Bovee K.D. 1982. A guide to stream habitat analysis using the instream flow incremental methodology. Instream Flow Information Paper 12. USDI Fish and Wildlife Service. Washington, 248 pp.

Bovee K.D., Lamb B.L., Bartholow J.M., Stalnaker C.B., Taylor J. and Henriksen J. 1998. Stream habitat analysis using the Instream Flow Incremental Methodology. US Geological Survey, Biological Resources Division Information and Technology Report, US Department of the Interior, USGS/BRD-1998–0004, viii + 131 pp.

Cairns J. Jr., Dickson K.L. and Herricks E.E. (eds), 1977. Recovery and Restoration of Damaged Ecosystems. University of Virginia Press, Charlottesville Virginia, p. 531.

Caletková J. and Komínková D. 2004. PHABSIM as an instrument for identification a range of the ecological discharges for bentic community. In: Garcíade Jalón D. and Vizcaíno P. (eds), Proceedings of Fifth International Symposium on Ecohydraulics Aquatic Habitats: Analysis & Restoration, IAHR, Madrid, pp. 449–455.

Crowder D.W. and Diplas P. 2000. Using two-dimensional hydrodynamic models at scales of ecological importance. J Hydrol. 230: 172–191.

Crowder D.W. and Diplas P. 2002. Assessing changes in watershed flow regimes with spatially explicit hydraulic models. J. Amer. Water Res. Assoc. 38(2): 397–408.

García de Jalón D. 1995. Management of physical habitat for fish stocks. In: Harper D.M. and Ferguson A.J.D. (eds), The Ecological Basis for River Management, John Wiley & Sons, Chichester, pp. 363–374.

García de Jalón D. 1997. Estado de conservación de los salmónidos españoles. In: Granado-Lorencio C. (ed.), Conservación, recuperación y gestión de la ictiofauna continental ibérica, Publicaciones de la Estación de Ecología Acuática, Sevilla, pp. 77–100.

García de Jalón D., Mayo M., Hervella F., Barcelo E. and Fernandez T. 1993. Principios y técnicas de gestión de la pesca en aguas continentales. Ediciones Mundi-Prensa-Madrid, p. 247.

García de Leániz C. and Verspoor E. 1989. Natural hybridization between Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*) in northern Spain. J. Fish Biol. 34: 41–46.

Gardiner R.W. 1991. Scottish grayling: history and biology of the populations. Proc. Inst. Fish. Manag. Annu. Study Cour. 22: 171–178.

Ghanem A., Steffler P.M., Hicks F.E. and Katopodis C. 1995. Two dimensional finite element model for aquatic habitats. Water Resources Engineering Report 95-S1. Department of Civil Engineering. University of Alberta, 189 pp.

Ghanem A., Steffler P., Hicks F. and Katopodis C. 1996. Two-dimensional hydraulic simulation of physical habitat conditions in flowing streams. Regul. Rivers-Res. Manag. 12(2–3): 185–200.

González del Tánago M. and Garcíade Jalón D. 2001. Restauración de Ríos y Riberas. Fundación Conde del Valle de Salazar. Mundi-Prensa, Madrid, p. 319.

Gore J.A. (ed.), 1985. The Restoration of Rivers and Streams: Theories and Experience. Butterworth Publishers, Boston, p. 280.

Hale J.G. 1965. An evaluation of trout stream habitat improvement in a North Shore tributary of Lake Superior. Minnesota Fish. Invest. 5: 37–50.

Heede B.H. and Rinne J.N. 1990. Hydrodynamic and fluvial morphologic processes: implications for fisheries management and research. N Amer. J. Fish. Manag. 10: 249–268.

Heggenes J. 1990. Habitat utilization and preferences in brown trout (Salmo trutta) and juvenile Atlantic salmon (Salmo salar) in streams. Ph.D. Thesis. Department of Nature Conservation, Agricultural University of Norway, AS and Freshwater Ecology and Inland Fisheries Laboratory, Zoological Museum, University of Oslo. pp. 291–319.

Hey R.D. 1994. Environmentally sensitive river engineering. In: Callow P. and Petts G.E. (eds), The Rivers Handbook, Vol. Vol. 2. Blackwell Scientific, Oxford, pp. 337–362.

Leclerc M., Boudreault A., Bechara J.A. and Corfa G. 1995. 2-Dimensional hydrodynamic modeling – a neglected tool in the Instream Flow Incremental Methodology. Trans. Amer. Fish Soc. 124(5): 645–662.

Orsborn J.F. and Anderson J.W. 1986. Stream improvements and fish response. A bio-engineering assessmentfs. Water Resour. Bull. 22: 381–388.

Reeves G.H., Hall J.D., Roelofs T.D., Hickman T.L. and Baker C.O. 1991. Rehabilitation and modifying stream habitats. In: Meehan W.R. (ed.), Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats, American Fisheries Society Special Publication No. 19, Bethesda, pp. 519–557.

Reice S.R., Wissmar R.C. and Naiman R.J. 1990. Disturbance regimes, resilience and recovery of animal communities and habitats in lotic ecosystems. Environ. Manag. 14(5): 647–659.

Rosgen D. 1996. Applied River Morphology, Wildland Hydrology. Pagosa Springs, Colorado, p. 380.

Schmidt G. and Otaola-Urrutxi M. 2000. Manual práctico para la aplicación de técnicas de bioingeniería en la restauración de ríos y riberas. CEDEX, Madrid, p. 79.

Shamloo H., Rajaratnam N. and Katopodis C. 2001. Hydraulics of simple habitat structures. J. Hydr. Res. 39(4): 351–366.

Stalnaker C., Lamb B.L., Henriksen J., Bovee K.D. and Bartholow J.M. (1995) The instream flow incremental methodology: a primer for IFIM, Biological Report 29, National Biological Service, US Department of the Interior, 45 pp.

Steffler P. 2000. Software River2D. Two Dimensional Depth Averaged Finite Element Hydrodynamic Model. University of Alberta, Canada.

Steffler P., Waddle T., Ghanem A., Katopodis C. and Locke A. 2000. Comparison of one and two-dimensional open channel flow models for a small habitat stream. Rivers 7(3): 205–220.

Vehanen T., Huusko A., Yrjänä T., Lathi M. and Mäki-Petäys A. 2003. Habitat preference by grayling (*Thymallus thymallus*) in an artificially modified, hydropeaking riverbed: a contribution to understand the effectiveness of habitat enhancement measures. J. Appl. Ichthyol. 19: 15–20.

Wesche T.A. 1985. Stream channel modifications and reclamation structures to enhance fish habitat. In: Gore J.A. (ed.), The Restoration of Rivers and Streams, Butterworth Publishers, London, pp. 103–163.

White R.I. and Brynildson O.M. 1967. Guidelines for Management of Trout Stream Habitat in Wisconsin, Technical Bulletin No. 39. Department of Natural Resources, Madison, Wisconsin, p. 63.