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Contributions of short-term flow regulation patterns to trout habitats in a boreal river

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Physical habitat simulation modelling was used to evaluate the effects of flow regulation on the Siikajoki, a boreal river in Central Finland. In the modelling, the "natural flow" regime, the "implemented regulation" pattern and two alternative patterns of regulation were compared by using brown trout (*Salmo trutta*) as a test fish and by analysing example periods in winter and in summer. The availability of suitable habitats for brown trout (Weighted Usable Area, WUA) was clearly dependent on the flow rate. The fewest usable habitats were available for the size class "fry" (< 15 cm). We found only minor differences between the compared regulation patterns in terms of riverine habitats. A side channel in the test area proved to be good "buffer area" against flow changes, highlighting the importance of habitat diversity. In a sensitivity analysis of habitat modelling, modifications of the depth preference curve seemed to have a major influence on the WUA for young brown trout.

Introduction

Short-term regulation (hydropeaking) is used to adapt power production to the daily and weekly variation in consumption. The daily variation in electricity consumption has been increasing in the recent years. Hydropeaking is nowadays common in, for example, Finnish (Sinisalmi *et al*. 1997) and French (Liebig *et al*. 1996) rivers and is increasing in Norway (Alfredsen *et al*. 1999). Some kinds of discharge regulation exist in most river systems in Western Europe (Kristensen and Hansen 1994). The rapid and extensive changes of flow often have adverse effects on fish stocks (Liebig *et al*. 1996, Eie *et al*. 1997, Cowx and Welcomme 1998) and the benthic fauna (Gereghino and Lavadier 1996, Parasiewicz *et al*. 1996, Eie *et al*. 1997), resulting in

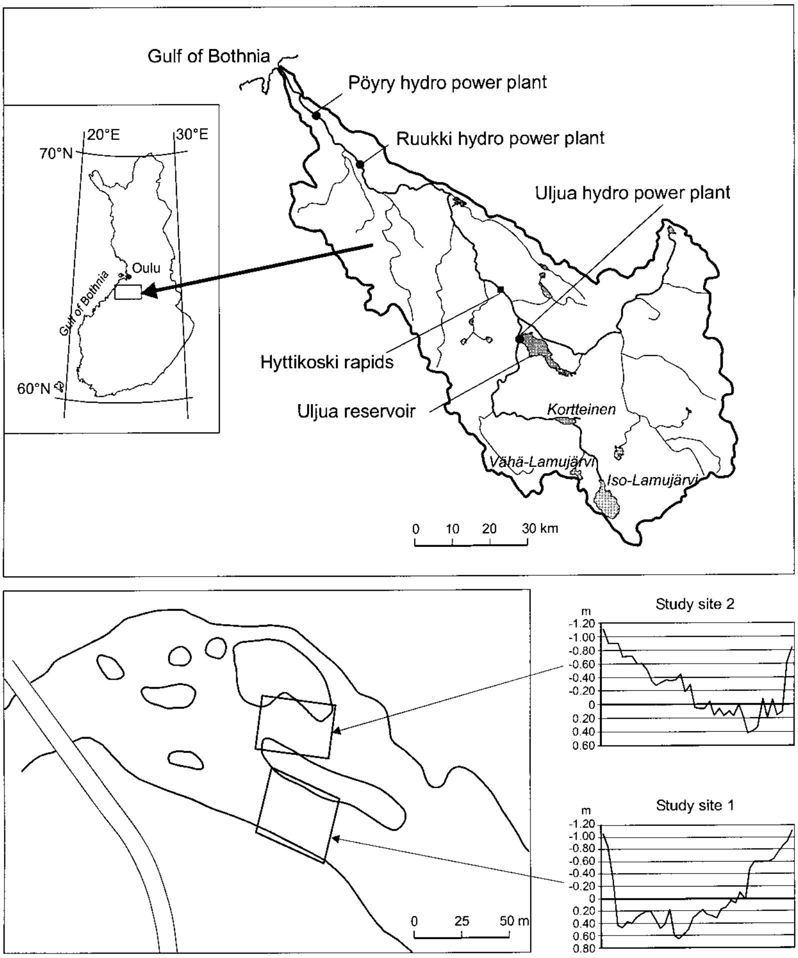

Fig. 1. Location of the Siikajoki and the Hyttikoski rapids section and cross-sections of the study sites 1 and 2.

habitat degradation, downstream displacement, habitat dewatering and stranding of juvenile fish (Liebig *et al.* 1996, Eie *et al.* 1997, Cowx and Welcomme 1998, Halleraker *et al.* 1999)

Because of the increasing appreciation and recreational use of aquatic environments, a great deal of pressure for change has been applied to develop more ecological regulation patterns for hydropower plants. In Finland, for example, an amendment of the water legislation enacted in 1994 (Finnish Water Act, chapter 8, 10 b §) allows revisions of legally valid regulation licenses if the regulation causes considerable adverse effects on the riverine environment and its use. The revision processes are often complicated and require extensive surveys and judicial procedures. In the Siikajoki, for example, the regulation license has been under revision since 1996 in accordance with the new water legislation (Northern Finland Environmental Permit Authority 31.X.2000, number 61/00/01).

To develop methods for the revision of regulation licences, a large research programme has been conducted in Finland, focussing on the impacts caused by hydropeaking on aquatic environments, recreational use, and power production optimisation in river systems. Especially, there has been a pressing need to develop efficient methods for the assessment of the effects of revised flow patterns (Sinisalmi *et al.* 1997). In this study, we focussed on the effects of long-term and short-term flow regulation patterns on the fish habitats in a regulated boreal river. The project had three objectives: (a) to assess the effects of flow regulation and power plants on the physical habitat of an experimental river section for the future development of regulation patterns; (b) to assess the applicability of a habitat simulation model to the assessment of the effects of long-term and short-term regulation on riverine habitats; and (c) to suggest methods for mitigating the adverse effects of short-term regulation

Study area

Siikajoki is a regulated river that discharges into the northern part of the Gulf of Bothnia (64°51´N, 25°43´E) in northern Finland (Fig. 1). Annual precipitation in the area is 450–500 mm and the mean temperature is +2 ± 3 °C. The catchment area of the Siikajoki is 4259 km^2, its length ca 160 km, and its total slope 0.06% (National Board of Waters 1978). At the end of the 1960s, a reservoir (Uljua) was constructed and flow regulation was also started in three natural lakes (Fig. 1). The area of the Uljua reservoir is 28 km^2 and its regulation capacity is 146 Mm^3. The combined regulation capacity of the three regulated natural lakes is 186 Mm^3.

There are three hydropower plants in the Siikajoki water course (Pöyry, Ruukki, Uljua). They were built in 1921–1970, and their combined capacity is 4.38 MW (Fig. 1). There is a free fish migration route from the sea up to the Uljua power plant through three fishways on the dams. Most rapids of the river have been dredged for timber floating or flood control.

After the construction of the Uljua reservoir in 1970, the winter and summer low flow rates in the Siikajoki have increased, while discharge during the spring flood has decreased remarkably (Table 1). Some exceptionally rainy years caused a higher mean flow value in the latter period. During the wintertime and the typical operation of the reservoirs and power plants, the daily discharge varies within 5–30 m^3 s^{-1} just below the Uljua dam and the water level fluctuates by 0.5–1.5 m. Ice volume has been larger by an average of 50% during the regulation period than before it in the middle parts of the Siikajoki. Numerical river ice model simulations indicate that frazil ice formation has increased by 300%–400% since the beginning of regulation because of the high wintertime flow rates and the increasing number of sections without a solid ice cover. The water in the Siikajoki is humic and slightly eutrophic. The oxygen content of the river downstream from the reservoir has occasionally been low during the wintertime (Northern Ostrobothnia Regional Environment Centre 1994).

According to the monitoring of fishery (Taskila and Kauppinen 1994), the most common fish species in the catches of local fishermen were bream (*Abramis brama*), pike (*Esox lucius*) and burbot (*Lota lota*). Roach (*Rutilus rutilus*), perch (*Perca fluviatilis*), bleak (*Alburnus alburnus*), ruff (*Gymnocephalus cernua*), brown trout, rainbow trout (*Oncorhynchus mykiss*) and grayling (*Thymallus thymallus*) were also caught. Lamprey (*Lampetra fluviatilis*) is an important fish for local fisherman at the river mouth. According to electrofishing experiments, the fish stock in the rapids sections of the river includes at least: minnow (*Phoxinus phoxinus*), stone loach (*Nemacheilus barbatulus*), bullhead (*Cottus gobio*), roach, perch, ruff, burbot, grayling, salmon (*Salmo salar*), brown trout, bleak, dace (*Leuciscus leuciscus*), pike, and three-spined stickleback (*Gasterosteus agileatus*) (Taskila and Kauppinen 1994, Taskila 2001).

Material and methods

The availability of habitats suitable for brown trout in terms of flow rate was calculated by

Table 1. Monthly (I–XII) mean flow rates (m^3 s^{-1}) in the Siikajoki before the beginning of effective regulation in 1936–1969 (A) and during regulation in 1970–1993 (B) (North Ostrobothnia Regional Environment Centre 1994).

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
A	10	4.8	4.5	82	145	29	18	18	23	32	24	36
B	26	24	23	82	118	38	21	24	28	46	52	41

using a PHABSIM-type physical habitat simulation model, EVHA (Souchon *et al.* 1989, Ginot and Souchon 1995, Ginot and Trocherie 1995). The variables included in the model were water depth, water velocity and particle size of bottom material. The habitat value (weighted usable area, WUA, m^2 $(100\ m)^{-1}$ river reach) for the multiplicative combination of the three habitat components was assessed using the standard procedures available in EVHA (Ginot and Trocherie 1995).

Based on a visual field survey, the Hyttikoski rapids (64°25´N, 25°47´E) was selected as the target of the model application, because it represented wide habitat diversity in an area exposed to extensive hydropeaking (Fig. 1). The typical daily range of flows in the Hyttikoski rapids was 20 to 30 $m^3\ s^{-1}$ in the summertime and 10 to 30 $m^3\ s^{-1}$ in the wintertime. Two study sites were selected in the braided river channel at the Hyttikoski rapids, representing typical running water habitats of the area (Fig. 1), where measurements for habitat modelling were carried out on a total of seven cross-sections in October 1994. Discharge regulation was interrupted for the time needed for the measurements. Site 1 was situated in the main channel of the braided river and site 2 in a side-channel. Each cross-section and each measurement point on a cross-section represented a homogeneous entity selected on the basis of the river morphology. The number of measurement points per cross-section totalled 69–140 (mean 95 points/cross-section). The length of the cross-sections varied from 26.1 m to 40.0 m. The topography of these cross-sections was measured by a level. Water velocity was measured at 0.2, 0.4 and 0.8 of the total depth at every measurement points, using a Schiltknecht Mini flowmeter with a propeller 2 cm in diameter. Substrate was classified on a modified Wentworth scale into 9 categories (< 4, 4.1–8, 8.1–16, 16.1–32, 32.1–64, 64.1–128,128.1–256, 256.1–512, and > 512 mm) out of the 13 categories presented by Heggenes (1988). The measured flow data and physical habitat data were used as input to the EVHA model (Ginot and Souchon 1995, Ginot and Trocherie 1995).

A test period for the summer (5–7.VII.1993) and the winter (29–31.I.1990) were chosen to illustrate the temporal variation in habitat availability. The periods were chosen on the basis of flow statistics to represent the typical hydrological conditions in the river. The flow statistics of 1990 was used to create flow and habitat time series during normal use of the reservoir. The discharges and water levels in the study area during the test periods and for the time series in 1990 were calculated with a numerical one-dimensional dynamic river flow model (IVO-FLOW, described by Wirkkala *et al.* (1997)) from the flow release data of the Uljua reservoir. The time step in the model calculations was 2 hours. The modelled flow scale was 3–225 $m^3\ s^{-1}$, and it covered all of the commonly presented flow events except the highest spring floods. The discharge in the main channel (site 1) and in the side-channels was measured at base flow and at peak flow. At both flows, 75% of the flow ran through the main channel and 10% through the branch where site 2 was located. This ratio was used for modelling habitat quality at the study sites at different flow rates.

Brown trout was selected as the test species because it is a native species of the Siikajoki rapids and because local fishermen's organisations are trying to restore a catchable brown trout stock in the river. The habitat suitability criteria used in the EVHA model were the standard criteria ("global curves") developed in North America and validated in France for mountain and pre-mountain rivers with a stony bottom (Souchon *et al.* 1989). It was not possible to define specific suitability criteria for the Siikajoki, because the brown trout stock was very sparse in the whole watercourse.

Four size categories of trout were distinguished: the "yolk sac stage", "fry" smaller than 15 cm, "young trout" (15 to 25 cm), and "adult" trout (25 to 40 cm) (Souchon *et al.* 1989). The size category "young trout" was used to assess seasonal changes in habitat availability and to compare the regulation patterns, because it represented the common stocking size of brown trout in the watercourse. The suitability criteria (Souchon *et al.* 1989) applied to the three smallest size classes in this study were quite similar to the criteria developed by Mäki-Petäys *et al.* (1997) in another river in northern Finland.

Of the modelled summer flow alternatives,

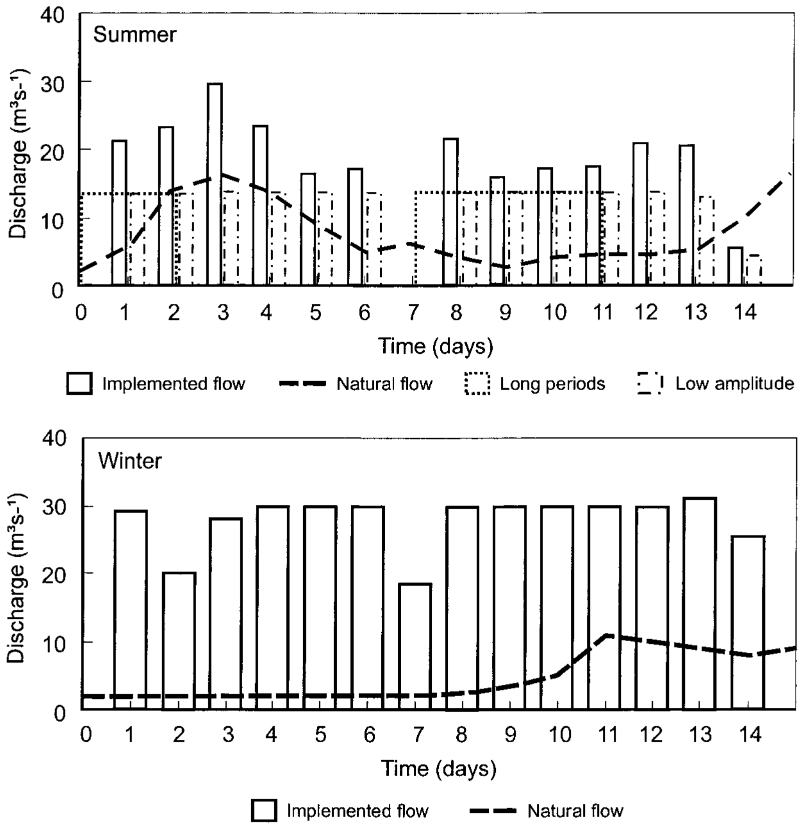

Fig. 2. Alternative flow regulation patterns of the Uljua reservoir during the experimental periods in summer and in winter used in habitat modelling at the Hyttikoski study sites.

one represented the natural flow regime ("natural flow") and another the implemented flow distribution ("implemented flow") during the test period (Fig. 2). The other summer flow alternatives, "long periods" and "low amplitude", were designed for searching more ecological release policies. During the experimental winter period, the alternatives "natural flow" and "implemented flow" (current regime) were compared (Fig. 2).

In the sensitivity analysis, the effects of changes in the habitat suitability criteria on the availability of habitat (WUA) for "young trout" at the Hyttikoski study site 1 were studied. The suitability criteria were included in the sensitivity analysis because there were no specific criteria for the study area. The suitability data, divided into 32 units by each variable, were altered by moving them towards zero or higher values at 1- or 2-unit increments or decrements, and the respective effect on the WUA was calculated (Fig. 3). Correspondingly, the sensitivity of the model to the measured water velocity and water depth values was also analysed by altering the values of these parameters by ±10%.

Results

When WUA was determined for the different developmental stages of fish, it turned out that there were clearly a fewer habitats available for "fry" under 15 cm in size compared with the other stages of development (Fig. 4 and 5). The availability of habitats suitable for the different size classes of brown trout was clearly dependent on the flow rate. WUA for all size classes decreased radically at the test site 1 of the main channel when the flow rate increased (Fig. 4). For this study site, the optimum flow range was 7–20 $m^3 s^{-1}$. In the side-channel (test site 2), the optimum range of flow rate was considerably wider (Fig. 5). The flow rate of the whole river may range from 10 to 60 $m^3 s^{-1}$ without any marked reduction in WUA in the test area 2. The

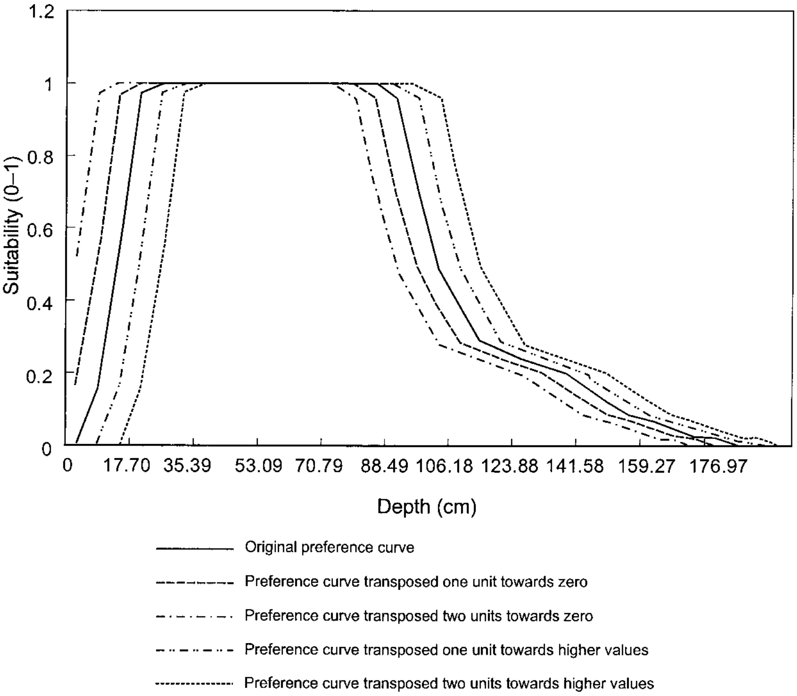

Fig. 3. Modification of the depth preference curve for "young" brown trout, length 15–25 cm, presented by Souchon *et al*. (1989) in the sensitivity analysis of habitat modelling of the Siikajoki. The preference data on water velocity and bottom substrate coarseness (Souchon *et al.* 1989) have been altered respectively.

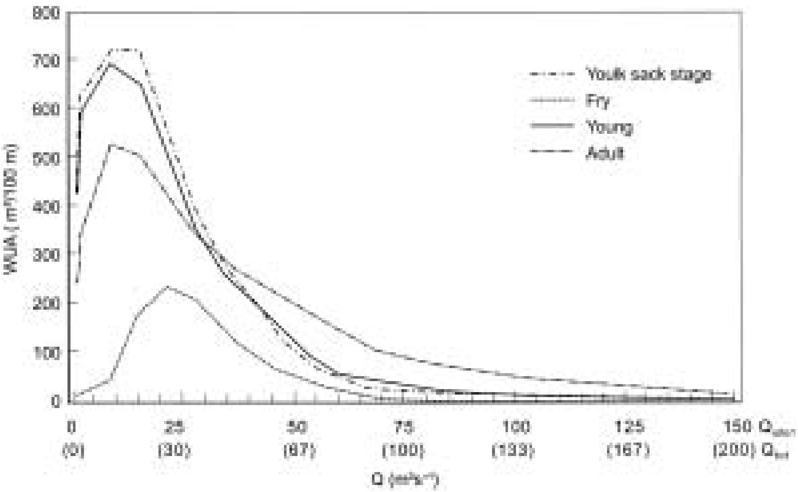

Fig. 4. The weighted usable area, WUA, (m^2 (100 m)$^{-1}$) for four brown trout size classes in proportion to discharge at the Hyttikoski main channel test site (site 1). Discharge values without brackets: flow in the main channel (Q_{site1}), in brackets: flow in the whole river (Q_{tot}).

upper limit of the optimum range is probably only exceeded during the spring and autumn floods. The restricting factor for the trout habitat in the main channel (study site 1) was substrate quality at low flow rates and water depth and velocity at higher flow rates. In the side-channel (study site 2), on the other hand, unsuitable particle size was the major factor limiting habitat suitability

On the seasonal scale, the minimum WUA values for "young" brown trout were obtained at the study sites during the spring and autumn floods (Fig. 6). During the summer test period, there were no remarkable differences between the regulation alternatives in the availability of usable area (WUA) for trout fry. At all calculated discharge alternatives and in all flow events (during the summer test period), the WUA for

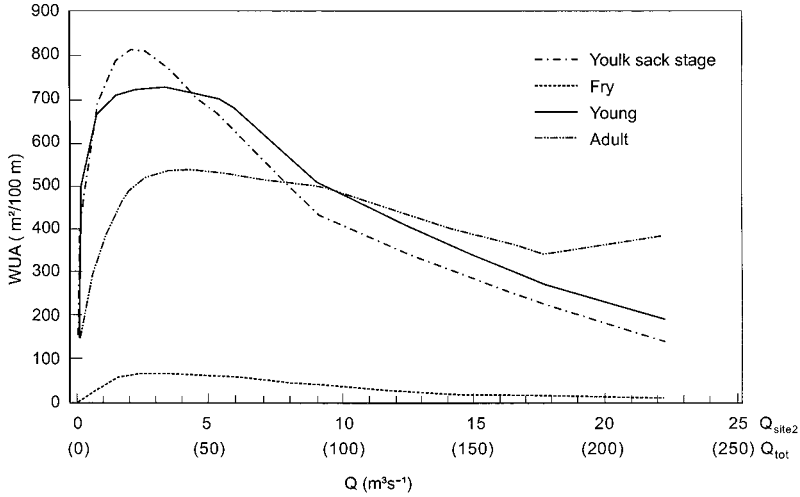

Fig. 5. The weighted usable area, WUA (m^2 (100 m)$^{-1}$), for four brown trout size classes in proportion to discharge at the Hyttikoski side channel test area (site 2). Discharge values without brackets: flow in the side channel (Q_{site2}), in brackets: flow in the whole river (Q_{tot})

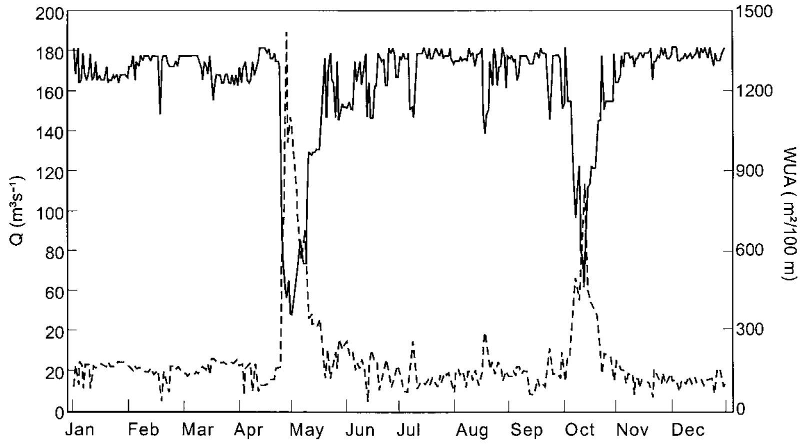

Fig. 6. The combined WUA (m^2 (100 m)$^{-1}$) of the study sites 1 and 2 at Hyttikoski rapids for "young" brown trout (15–25 cm) in proportion to the daily mean flow in 1990.

trout fry was 1100–1300 m^2 (100 m)$^{-1}$ (Fig. 7). During the winter test period, in the "natural flow" alternative, the extent of WUA for trout fry remained steadily within 1200–1300 m^2 (100 m)$^{-1}$ (Fig. 8). Instead, with the implemented flow distribution ("implemented flow"), the extent of the winter WUA was reduced to 1000 m^2 (100 m)$^{-1}$ at the peak flow rate.

In the sensitivity analysis, modifications of the depth suitability curve seemed to have a greater influence on the WUA for "young" brown trout than changes in the other suitability criteria (Fig. 9). An incremental change of 1 or 2 units in depth suitability decreases the corresponding WUA value, especially within or close to the optimal flow range. A corresponding change in the other direction has an opposite effect on the WUA. When the bottom substrate suitability curves were moved into the direction of coarser substrate or the water velocity suitability curves were moved towards higher velocity, the WUA values in the optimal flow range seemed to increase. The model was not found to be particularly sensitive to changes in the input of the two studied physical parameters, water depth and water velocity (Fig. 10).

Discussion

On the basis of model simulations, there was a lack of habitat for the brown trout size class

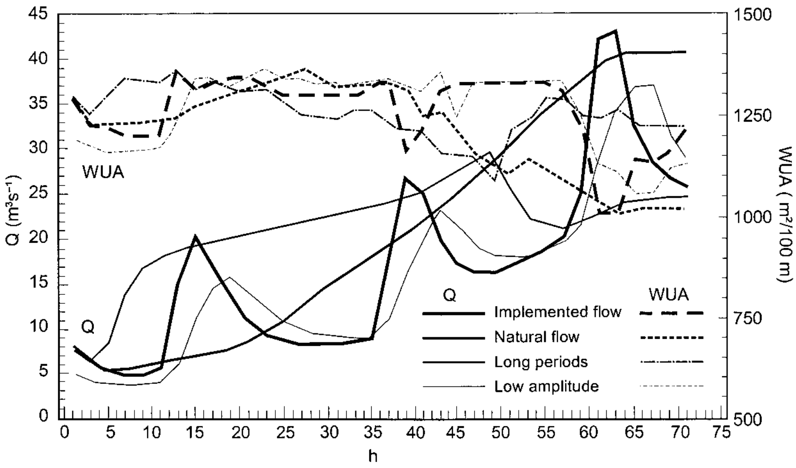

Fig. 7. The discharge Q (m^3 s^{-1}) and combined WUA (m^2 (100 m)$^{-1}$) of the study sites 1 and 2 for "young" brown trout (15–25 cm) at Hyttikoski rapids during a typical summer period, 5.7–7.7.1993, with alternative release policies.

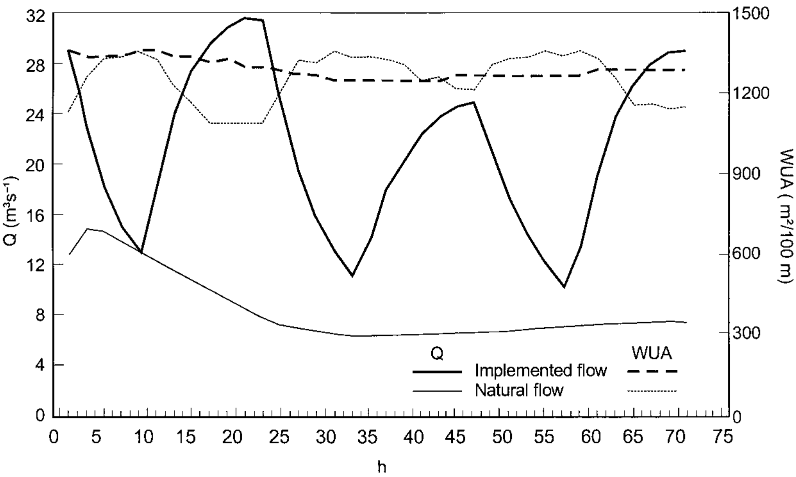

Fig. 8. The discharge Q (m^3 s^{-1}) and combined WUA (m^2 (100 m)$^{-1}$) of the study sites 1 and 2 for "young" brown trout (15–25 cm) at Hyttikoski rapids during a typical winter period, 29.1–31.1.1990, with alternative release policies.

"fry" at both Hyttikoski study sites. If this finding can be generalized to other rapids sections, there is limited potential for the natural reproduction of brown trout in the Siikajoki. Scaling up to the river is not possible, however, without the modelling of a large and representative scale of river sections stratified for different habitat types, as Bird (1996) has pointed out. Apart from physical habitat, the characteristics of water quality, including the low oxygen content in winter, may also limit the reproduction of salmonids. Anyway, in the electrofishing experiments made during a long period by Taskila and Kauppinen (1994) and Taskila (2001) brown trout have only been found at stocking sites in the downstream part of the river, the densities being low (0–2.7 individuals (100 m)$^{-2}$). On the basis of these fishery monitoring results of Taskila and Kauppinen (1994) and Taskila (2001) brown trout is unlikely to reproduce naturally in the Siikajoki.

The brown trout size class "young" is the common stocking size in the Siikajoki, because trout of this size are thought to be more tolerant of hard conditions. According to model simulations, some usable habitat for "young" brown trout could be found at all the common flow rates during the normal operation of power plants at the study sites of the Hyttikoski rapids section, which is exposed to extensive short-term regulation. The 20%–30% reduction of winter habitat in "implemented flow" compared

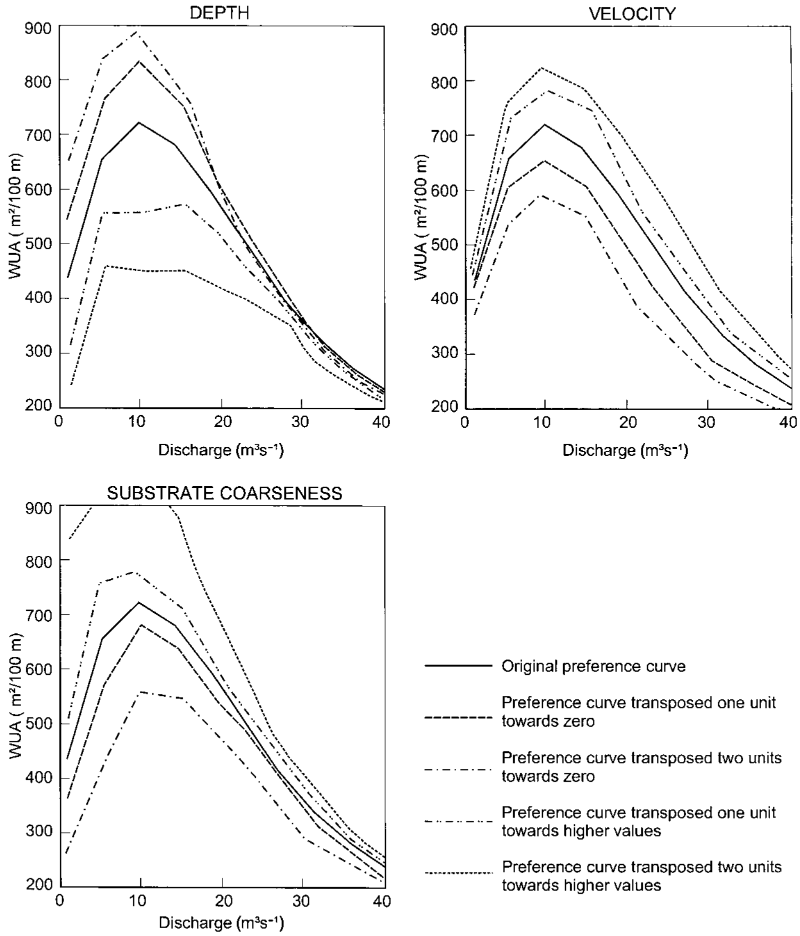

Fig. 9. The WUA for "young" trout (15–25 cm) at study site 1 with water depth, water velocity and bottom substrate coarseness preference curves transposed 1 or 2 units towards zero or higher values.

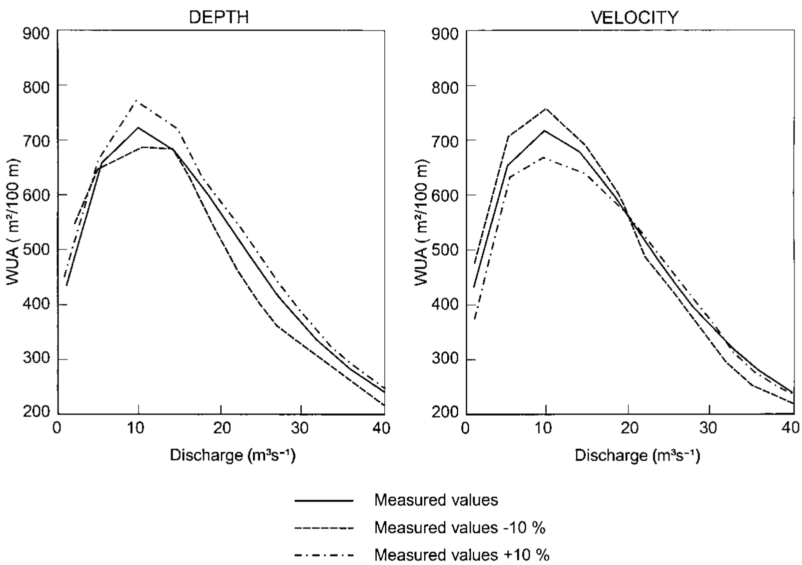

Fig. 10. The WUA for "young" trout (15–25 cm) at study site 1 at the measured depth and velocity values ± 10%.

with "natural flow" cannot alone explain the poor state of the stocked brown trout. In this study, we did not use any special habitat suitability criteria for the winter. In many studies made in cold regions, marked differences have been found between the winter and summer habitat use of brown trout (Heggenes 1994, Mäki-Petäys *et al.* 1997, 2000). For example, consideration of the preference of young brown trout for calm water conditions in winter (Heggenes 1994, Mäki-Petäys *et al.* 1997, 2000) would probably have led to more decreased WUA during the wintertime peak flow events.

On the basis of the sensitivity analysis, the most essential issue from the perspective of the reliability of PHABSIM-type modelling in the Siikajoki would be whether the brown trout's requirements for depth in northern rivers correspond to the "global" habitat criteria. Habitat suitability criteria should be determined in the field at least for critical periods and life stages (Bird 1996), but in a case like Siikajoki, this was impossible. There were, however, no substantial differences between the global mountain and pre-mountain suitability criteria of Souchon *et al.* (1989) used in the Siikajoki case, and the summer suitability criteria later compiled by Mäki-Petäys *et al.* (1997) in northern Finland.

The Hyttikoski study area was selected to represent optimal habitat diversity in the Siikajoki, with many other river sections being dredged and having quite monotonous habitat structure without refugee areas in the side channels or the sheltered channel margins. The side-channel in the study area with shallow, low-profile margins was better able to tolerate the changes in flow rate without remarkable habitat losses than the monotonous main channel. In the side-channel, which had diverse channel morphology, suitable habitats were located close to each other during the base flow and peak flow periods, which probably reduces the costs and stress on fishes caused by the need to search suitable conditions (Heggenes 1994) during hydropeaking operations.

Zalewski *et al.* (1994) pointed out that side-channels are essential for habitat and species diversity, especially in straightened rivers. Mäki-Petäys *et al.* (2000) noticed in flume experiments that the availability of flow refuges in the winter was a crucial habitat factor for juvenile brown trout and grayling. The complexity of habitat has also been found to increase the overwinter survival of juvenile salmonids (Quinn and Petterson 1996, Solazzi *et al.* 2000), while a simplification of habitat has been found to decrease the salmonid biomass (Fausch and Northcote 1991). Habitat complexity and sheltered patches must be particularly important in rivers where hydropeaking flows cause an additional stress on aquatic life.

Short-term regulation may have an impact on the living conditions of fish other than the reduction of habitat area in extreme flow conditions. One reason for the small size of the brown trout stock in the Siikajoki could be the difficult winter conditions, including the large daily fluctuations in flow rate following major changes in water level and water velocity and the consequent thickening of ice, all of which are factors that force fish to constantly seek new locations. The repeated need to change habitats exposes fish to predation and depletes their energy supplies (Heggenes 1994). In addition, Halleraker *et al.* (1999) reported notably more stranding of brown trout and salmon in a Norwegian hydropeaking river, because of the far greater sudden flow decrease at low water temperatures. Jakober *et al.* (1998) have pointed out that rivers which are partially ice covered and hence predisposed to large fluctuations in water temperature and ice conditions possess the most potentially adverse overwintering conditions for fishes. The accumulation of frazil ice and the formation of hanging ice dams may cause evacuation of brown trout (Brown *et al.* 2000). Because of these aspects, the harmful effects of cold winter temperature and ice formation may be severe in a regulated northern river, such as the Siikajoki, where the increased winter discharge and the increased flow fluctuations result in an ice cover that is often thick, but patchy.

According to the sensitivity analysis, small variation in the measured water depth and velocity values did not affect remarkably the results of habitat modelling. Bourgeois *et al.* (1996a) also found that the PHABSIM-type model in their application was not sensitive to random errors in water depth and velocity or substrate measurements, but the number and location of cross-sections were responsible for most of the variability in the predicted habitat. In the Siikajoki, the cross-sections were located by trained field biologists to represent longitudal segments with similar hydrological and morphological conditions. Effects of changing locations of cross-sections were not tested.

PHABSIM-type models have been criticized especially for the low correlation between WUA and the fish biomass (or density) (Mathur *et al.* 1985, Gore and Nestler 1988, Bourgeois *et al.* 1996b). A new method has also been developed for improving the ability of habitat models to illustrate local variations in fish density (Guay *et al.* 2000). Nevertheless, the limitations of the model caused the PHABSIM simulations to be best in the assessment of the direction and relative magnitude of the predicted changes rather than the absolute changes in usable habitat area. Gibbins *et al.* (2000) recently found PHABSIM to be useful for assessing the ecological implications of future changes in the regulation regime.

Conclusions

By using physical habitat simulation in representative experimental river sections, it is possible to define the effects of changes in the regulation regime on riverine habitats or at least the direction and order of magnitude of these effects with moderate resources. The model is also a good tool in evaluating the possibilities for in-stream habitat restoration in a river system. Anyhow, information from hydraulic models cannot be a substitute for biological understanding.

The brown trout size class "fry" was clearly found to have the fewest usable habitats in the studied river section. The side-channel of the branched river section was found to be a good "buffer area" against fluctuating flow. If short-term regulation is intensive, as in the upstream part of the Siikajoki, the habitat simulation procedure may miss the main biological effect of regulation, i.e. continuous alteration, because it only gives a static "picture" of each flow events.

It will be possible to predict the effects of hydropeaking better by using two- or three-dimensional hydraulic models in describing the hydraulic habitat features during different flow events and by using detailed time series of analysis to show the impacts of variable hydraulic conditions on the composition and distribution of fish populations (Alfredsen *et al.* 1999). Linking of bioenergetic and habitat modelling may give a tool for evaluating the costs of varying flow conditions for fishes in different habitat types. To improve the ability of the PHABSIM model to identify or predict the effects of rapidly changing flow, new research will also be needed, particularly in artificial flumes, where the other variables can be excluded, and especially in winter conditions, before the model can be applied to northern rivers

Temporal habitat variation is easy to illustrate during a static flow event by habitat suitability maps. Changes in flow cause changes in the location of available habitats, and the effect of the distance of refuges at different flow events should be studied. Another interesting topic would be the possibility to add a variable to the habitat model describing the intensity of flow variation (amplitude and frequency of flow peaks).

This habitat modelling experiment revealed only minor differences in riverine habitats between the alternative regulation patterns. The flow regulation patterns available in summer, i.e. the release of water for longer periods or with lower peaks, will probably not essentially improve the living conditions of young brown trout in the Siikajoki. In winter, none of the modelled flow events proved to be a clear bottleneck, but large and sudden flow fluctuations during low temperature may still cause stress to fishes. Restoration of dredged river sections may mitigate the harmful effects of flow regulation to some extent.

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