FISH TELEMETRY

Efforts to aid downstream migrating brown trout (*Salmo trutta* L.) kelts and smolts passing a hydroelectric dam and a spillway

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Abstract The autumn and spring descent of 41 brown trout kelts (spent trout) (average total length L_t 75.9 cm) and the spring descent of 27 hatchery-reared smolts (average Lt 26.2 cm) were studied by radiotelemetry in 1993/1994 (kelts) and 1997/1998 (kelts and smolts) at the Hunderfossen dam and power plant, south-east Norway. In 1999 we studied spring descent of 48 untagged kelts by visual observations and video-monitoring at one spillway. In autumn 1993 and 1997, 62.4% and 44.0% of the tagged kelts migrated downstream to the dam at water temperatures between 0.1 and 0.8°C. During release of spillwater, the kelts gathered along the dam with limited movements. Neither smolts nor kelts used the 2 m submerged turbine shafts as a pathway to migrate downstream Hunderfossen dam. Nor did release of large amounts of deep water through spillways provide downstream migration possibilities for

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Norwegian Institute for Nature Research, 2624 Lillehammer, Norway kelts and possibly for smolts. The majority of both smolts and kelts migrated downstream at short periods of surface water release through the spillways, indicating high importance of surface water release. The threshold value of descend of kelts at surface release was between 1 and 4 m³ s⁻¹ which correspond to a water column between 12 and 36 cm. These findings are highly relevant regarding hydroelectric development in river systems containing iteroparous salmonid species.

Keywords Brown trout · Kelts · Downstream migration · Regulated river · Spillway · Water release

Introduction

On a worldwide scale probably thousands of hydropower dams, impoundments, tunnel outlets, reduced water flows in rivers, channelizations and other physical obstructions have interrupted the movements of fish and prevented natural reproduction and migration between separate habitats (Jungwirth, 1998; Northcote, 1998; Rivinoja et al., 2001; Carlsson et al., 2004). Construction of fish passages (fishways) is a common solution to this problem. Although many facilities, especially for upstream movements of salmonids, have been reported well functioning, the efficiency of many fishways have been questioned (Linløkken, 1993; Larinier, 1998) and even newly designed fish passages may have low efficiency (Aarestrup et al., 2003). However, facilities and guidance to secure downstream migration for post-spawners and their progeny have been given less attention. For example, the main focus in Scandinavian fisheries management is to safeguard only the upstream spawning migration of salmonids. However, recent studies have shown that intra- and instream migrations are common in landlocked brown trout (*Salmo trutta* L.) populations, and that the current regime with fish passages may have negative effects on the populations (Carlsson et al., 2004).

Lake Mjøsa, the largest lake in Norway, contains populations of fast-growing and piscivorous brown trout with considerable commercial and recreational interests (Aass & Kraabøl, 1999). The Hunder trout population is a migratory, fast-growing strain using the Gudbrandsdalslågen River for reproduction. This trout strain is known for particularly large individuals (maximum body mass of 15-18 kg). They migrate between their feeding areas in the lake where they feed on smelt (Osmerus eperlanus L.), vendace (Coregonus albula L.) and small whitefish (C. lavaretus L.) (Aass et al., 1989) and the spawning grounds in the Gudbrandsdalslågen River (Arnekleiv & Kraabøl, 1996). Much of the spawning migration stops at the Hunderfossen dam (Aass et al., 1989). The Hunderfossen power plant severely interferes with the upstream spawning migrations of adult brown trout as well as the lake-ward migrations of kelts (spent trout) and smolts (Aass et al., 1989; Arnekleiv & Kraabøl, 1996, 1999). To maintain the ecological connection eliminated by hydropower impoundment in 1964, a fishway was built contemporaneously with the power station. Each year, 75-600 brown trout pass the fish ladder, and the ascent has been studied in relation to water discharge and water temperature (Jensen & Aass, 1995). Brown trout that succeeded to pass the fish ladder migrated rapidly to their spawning sites 4-63 km above Hunderfossen dam (Arnekleiv & Kraabøl, 1996; Kraabøl & Arnekleiv, 1998). However, less attention has been given to the downstream migration of kelts and smolts. These fish normally spawn repeatedly during their life span, and they probably require access to feeding habitats in the lake Mjøsa below the hydropower dam after spawning since there is little fish food available in the river.

Hydroelectric dams, however, provide different migrating pathways such as turbines, sluiceways and fishways (Skalski et al., 2002; Scruton et al., 2003a, b; Rivinoja 2005) with various mortality depending on physical properties of the technical installations (Montèn, 1985; Jepsen et al., 1998; Coutant & Whitney, 2000; Muir et al., 2001). The sluiceways at Hunderfossen dam release water from both deep and surface layers of the reservoir. Both the turbines and the fishway release water from submerged gateways. The aims of this study was (1) to investigate which of these waterways were used by descending smolts and kelts, and (2) to analyze if the descend of smolt and kelts were dependent on surface water release, and (3) to identify threshold values for descending kelts.

Study site

River Gudbrandsdalslågen drains a 17,000 km² catchment area and mean water discharge in the lower parts of the river is $60-100 \text{ m}^3 \text{ s}^{-1}$ in winter and 350-500 m³ s⁻¹ in summer. Maximum water discharge during floods in spring and summer is 1000-2500 m³ s⁻¹. The Hunderfossen power station exploits a 46 m high waterfall, about 15 km upstream the outlet to Lake Mjøsa. The power generating water is abstracted from a river reservoir through two turbines and led back into the river through a tunnel about 4.4 km downstream from the dam (Fig. 1). The minimum discharge between the dam and the tunnel outlet is 1.8 m³ s⁻¹ in winter and spring (October-July), and varies between 5 and $20 \text{ m}^3 \text{ s}^{-1}$ the rest of the year. In late autumn and winter, the minimum water discharge is released in the fish ladder and this is normally the only water release passing the dam in this period. When the total river discharge exceeds the $300 \text{ m}^3 \text{ s}^{-1}$ capacity of the two Kaplan turbines, the surplus spillwater is released through seven spillways (Fig. 2). Normally, excess water is released through the



Fig. 1 Location of the Gudbrandsdalen River and the Hunderfossen power station, Norway

bottom of the six spillways (bottom water release). Each spillway has a capacity of 267 m³ s⁻¹ when fully opened and thus provide release of surface water similar to a natural fall. However, these spillways are seldom fully opened, and the water discharge is divided between the spillways providing bottom water release. Another spillway is draining floating ice and litter away from the turbine inlet (Fig. 2). This ice spillway is 6 m wide and has a capacity of surface water release of 1–40 m³ s⁻¹, which correspond to a water column between 12 and 198 cm.



Fig. 2 Schematic diagram of the Hunderfossen dam, showing the different spillways, fishway and turbine inlet

Materials and methods

Radio tracking and visual observations of kelts

The descent of brown trout kelts at the Hunderfossen dam and power station, was studied in two periods; 1993-1994 and 1997-1998, and visual observations were carried out in spring 1999. Forty one brown trout (BL range = 60-91 cm, BL mean = 75.9 cm) were caught in the fishway and radiotagged from July to late September in 1993 and 1997 (Table 1). They were released upstream of the dam. During tagging, the fish were placed in a partially covered cylindrical tank filled with well-oxygenated water. An ATS' radio transmitter (Models 16M, 7PN or 3PN Eiler activity, 142 MHz) (Eiler, 1990), was externally attached to each fish below the dorsal fin (Mellas & Haynes, 1985; Thorstad et al., 2000). The transmitter weighed between 16 and 27 g in air (0.5-1.5% of the mass of the fish). Fish were tracked manually each day, or one to two days a week in

Table 1 Number and length of resident brown troutstudied by radio tracking at the Hunderfossen dam in1993/1994 and 1997/1998

| Year | Sex | п | Average total body length (cm) | Range | Dates of capture (range) |
|------|---------|----|--------------------------------------|-------|--------------------------------|
| 1993 | Males | 5 | 70.6 | 65-80 | 09.07-24.09 |
| | Females | 11 | 71.1 | 63–79 | 09.07-24.09 |
| 1997 | Males | 11 | 77.2 | 61–91 | 29.07-09.10 |
| _ | Females | 14 | 74.8 | 60–89 | 29.07-09.10 |

winter and early spring. Due to a screen at the turbine inlet, adult brown trout could not pass through the turbines.

In spring 1998, telemetry experiments were undertaken to try to guide the downstream migration of kelts and smolts passing the dam, by using surface water release of $1-40 \text{ m}^3 \text{ s}^{-1}$ at the ice spillway. In 1999, descending kelts were visually observed from a bridge 5 m from the spillway during the first hours of spillwater release. Observing personell noted the number of kelts observed at the spillway entrance and number of kelts passing the spillway during trials of five different discharges of surface water release of 1, 4, 6, 15 and 25 m³ s⁻¹. In addition, a videocamera was used to inspect the detailed behaviour of descending kelts.

Telemetry studies of smolt migration

To study the downstream movements of smolts passing the dam, we used 27 smolts (BL range = 22-30 cm, BL mean = 26.2 cm) from the local hatchery. All smolts (2 years old and F1-generation of native, wild stock) were tagged with external attached radio-transmitters (Model TXP-1, Televilt AB, Sweden, 142 MHz). The transmitters weighed 2.6 g in the air (1.3%) of the mass of the smolt). The smolts were released in the reservoir above the dam on 14 May 1998 and tracked manually every 4 h each day and night during the experiments of surface water release (14-25 May, 1-6 June, 9-25 June). In the remaining periods between 25 May and 5 August, we manually tracked the fish every second day. Smolt had three possible routes to pass the dam: the turbines, the fishway or the spillways. By manual trackings, we assumed to determine which of the pathways used by descending smolts.

Statistical analyses

We used logistic regression models to analyse the relationship between the probability of observing descending kelts and smolts (separate tests), and the explanatory variables "water temperature", "total spillwater discharge", and "surface water discharge through the spillways". The test was carried out in Minitab (Release 13.0). To test whether the positions of kelts differed between periods before and during spillwater release (not normally distributed data), a non-parametric Wilcoxon Sign Ranks test was used.

Results

Descending kelts in 1993–1994

In November–December 1993 (period 1), 10 kelts descended from the spawning grounds and approached the dam. At water temperatures ranging between 0.1 and 0.8°C, they displayed a restless behaviour ranging up to 3.2 km upstream the dam. In early May 1994 (period 2), the additional 6 overwintering kelts migrated downstream to the dam and the restless behaviour continued until spillwater was released through the spillgates. During release of spillwater, the kelts assembled at the dam with limited movements (Fig. 3). The positions in period 1 were not significantly different from period 2 (Wilcoxon Signed Ranks test, Z = -0.391, P = 0.693) despite the higher water temperature range (5–6°C). The positions in period 1 were significantly different from period 3 (Wilcoxon Signed Ranks test, Z = -4.301, P < 0.001) and positions at period 2 were also significantly different from period 3 (Wilcoxon Signed Ranks test, Z = 0.344, P = 0.001).

Logistic regression model revealed no significant effect of total spillwater (Z = 0.43, P = 0.668), discharge in spillgate 1 (Z = 0.02, P = 0.983) or discharge in the ice spillway (Z = 1.18, P = 0.238) on the probability of observing descending kelts during spring 1994. However, all 16 kelts descended during three short periods of surface water release of 267 m³ s⁻¹ through spillgate 1. During these three periods, seven, six and three kelts descended, respectively. No kelts descended during intermediate periods with bottom water release up to 469 m³ s⁻¹ from the reservoir (Fig. 4).

Descending kelts in 1997–1998

In May 1998, 19 kelts descended through the spillgates. The logistic regression model revealed that there were a significant effect of water ice spillway discharge in the (Z = 4.13,P < 0.001) on the probability of observing descending kelts, and no significant effect of total spillwater discharge (Z = 0.980, P = 0.327) and temperature (Z = -1.15,P = 0.248) water (Fig. 5).

Visual observations of descending kelts in 1999

This 3.75 h observation study revealed that kelts passed the ice spillway at 4 m³ s⁻¹ but not at 1 m³ s⁻¹ (Table 2). In total, 48 kelts descended at water discharges between 4 and 25 m³ s⁻¹. However, the degree of hesitation observed (ex-

pressed as percent descending kelts compared to total number observed at the sluiceway) revealed that only 39% of the observed kelts at the sluiceway descended at 4 m³ s⁻¹, whilst 62% descended at 6 m 3 s $^{-1},\ 80\%$ at 15 m 3 s $^{-1}$ and 100% at 25 m³ s⁻¹ (Table 2). Despite this, the highest descending rate was observed at 4 $m^3 s^{-1}$. These results outpoint a descending threshold value between 1 and 4 $m^3 s^{-1}$, which correspond to a water column of 12 and 36 cm. Some hesitation occurred between 4 and 15 m³ s⁻¹, and at 25 m³ s⁻¹ kelts descended directly when approaching the sluiceway. The video recordings revealed that kelts descended the sluiceway with positive rheotaxi and propulsive flexations with their caudal fin, which provided them a slower falling velocity compared to the water column.

Descending smolts in 1998

In May-July 1998, all 27 smolts descended through the spillgates. The logistic regression model revealed that there were a significant effects of water discharge through the ice spillway (Z = 4.94, P < 0.001) and total spillwater discharge (Z = 2.79, P = 0.005) on the probability of observing descending smolts. Further, no significant effect of water temperature (Z = -1.66, P = 0.097) was found. These findings implies that





Fig. 4 (a) Water temperature, (b) water discharge passing the dam (total discharge minus the discharge at spillway 1 – stippled line, discharge at spillway 1 – solid line) and (c) downstream migration of radiotagged kelts (number of kelts shown) at Hunderfossen in 1993/ 1994



descending smolts use both the surface and bottom released spillwater as migratory pathways through the dam.

Discussion

This study demonstrated that neither smolts nor kelts used the 2 m deep submerged turbine shafts as a pathway to migrate downstream Hunderfossen dam. A few fish descended through the fishway entrance which is about 0.5 m submerged. Nor did release of large amounts of deep water through spillways provide downstream migration possibilities for kelts. We were not able to distinguish whether the smolts migrated by surface or bottom water release through the spillway. The majority of both smolts and kelts migrated downstream at short periods of surface water release through the spillways, indicating high importance of surface water release. The threshold value of descend of kelts at surface release was between 1 and 4 m³ s⁻¹ which correspond to a water column between 12 and 36 cm. These findings are highly relevant regarding hydroelectric Fig. 5 (a) Water temperature (solid line) and total discharge passing the dam (stippled line), (b) surface water discharge through the ice spillway, (c) number of descending radio-tagged kelts and (d) number of descending radio-tagged smolts at Hunderfossen dam and power station, May 14–August 4 in 1997



development in river systems containing iteroparous salmonid species. Paradoxically, discharges ranging from 300 to 500 m³ s⁻¹

released through submerged openings at the turbine intake or spillgates acted as a downstream migration barrier, whilst surface water

| Discharge at the ice spillway m ³ s ⁻¹ | Time | Minutes of observation | Number of kelts observed | Number of descending kelts | Descending kelts per minute | Percent descending kelts of number observed |
|--|-----------|------------------------|-----------------------------|----------------------------------|-----------------------------|---|
| 4 | 0830-1015 | 62 | 59 | 23 | 0.37 | 39 |
| 6 | 1015-1145 | 71 | 21 | 13 | 0.18 | 62 |
| 15 | 1145-1240 | 43 | 5 | 4 | 0.09 | 80 |
| 1 | 1240-1300 | 19 | 0 | 0 | 0 | 0 |
| 25 | 1300-1330 | 30 | 8 | 8 | 0.27 | 100 |
| Sum | | 225 | 93 | 48 | | |

 Table 2
 Summary of the observations of kelts at the ice spillway at different water discharge during the experiment 21 May 1999

release of $4 \text{ m}^3 \text{ s}^{-1}$ provide a highly effective pathway for kelts and probably smolts.

The turbine pathways seems to be a common rout for salmonid smolts passing hydroelectric facilities (Montèn, 1985; Hvidsten & Johnsen, 1997; Jepsen et al., 1998; Coutant & Whitney, 2000; Muir et al., 2001; Rivinoja, 2005). In our study, none of the smolts descended through the turbines. This may be explained by the large smolt size of Hunder trout (mean BL = 26.2 cm, range = 22-30 cm) compared to other salmonid smolts which are considerably smaller. Rivinoja (2005) and Kemp et al. (2005a) reported that the downstream movements of some larger smolt was altered in the vicinity of a power station similar to Hunderfossen Power Plant. These large smolts avoided turbine entrance and did not continue downstream migration. Kemp et al. (2005a, b) observed that downstream migrants hesitated to descend into dark spaces with accelerating water velocities. We suggests that there is some body size selectivity regarding turbine entrance of migrating smolts which may be explained by swimming performance positively correlated to BL.

Downstream migrating kelts possibly avoided the turbine entrance of the same reason. In addition, the grid in front of the turbine shaft may also act as an obstacle considering the rapid and accelerating water velocity at this intake area. Kelt may find it difficult to maneuver with precision under such conditions and may therefore neglect this pathways of several reasons. In 1994, none of the kelts used the ice spillway. The water discharge was 8 m³s⁻¹ during most of the time. However, the release of spillwater through spillgate 1 on the opposite end of the dam during the study period possibly attracted kelts away from the ice sluiceway and thereby prevented them from using this pathway. In 1998, surface water was released through the ice spillway and adjacent spillgates. These findings demonstrate the potential of guiding kelts by manipulating release points through the dam.

After spawning, 44-62% of the trout moved downstream to the reservoir above the dam in late autumn, and by early May, 100% of the surviving tagged kelts had moved downstream to the dam. A post-reproduction migration back to the lake in autumn or in early spring is also observed in other lake-migrating brown trout strains (Arnekleiv & Rønning, 2004; Rustadbakken et al., 2004). At the first release of bottom water at the spillways, kelts assembled at the dam, and tracking observation showed that they were swimming back and forth along the dam. We suggest that this behaviour was a searching behaviour to find their way downstream. The praxis to only open for bottom water release in spring and early summer obviously prevented kelts from passing the dam on their post-spawning migration in these periods. Because Hunder trout often spawn repeatedly, usually with an intermediate year in lake Mjøsa (Aass et al., 1989), it is vital that brown trout are given free passage on their downstream migration. During temperature increase in spring and early summer, large, piscivory brown trout probably have no prey fish to feed on in the river, and migration in salmonids may be triggered by the amount or the lack of available food (Northcote, 1992). Obstacles that are preventing, or delaying fish in reaching its main food source of smelt, vendace and small whitefish in the lake (Aass et al., 1989), probably

put considerable constraints and stresses on kelts and may cause increased mortality.

Fish often depend on special hydraulic conditions to pass physical obstacles. Cold water increases problems of passing obstacles for ascending fish (Jonsson, 1991) and a temperature of 7-9°C for brown trout to negotiate obstacles are found in several rivers (Ovidio & Phillipart, 2002; Rustadbakken et al., 2004). However, temperature requirements to swim downstream are less, and obstacles are obviously more easily cleared going downstream than upstream. At Hunderfossen, kelts were active during late autumn and winter at temperatures 0.1-0.8°C, and five kelts passed the fish ladder or spillway at 1.5°C in late autumn. This is in accordance with findings for descending anadromous brown trout in Imsa River (Jonsson & Jonsson, 2002). In autumn, the daily number of descending brown trout in Imsa River is positively correlated with discharge and negatively with water temperature, whereas in spring, high water temperature appeared to positively influence the descent (Jonsson & Jonsson, 2002). At Hunderfossen, the downstream migration of kelts occurred during increased water discharge and temperature. However, the maneuvering of the spill gates, giving either bottom water release or surface water release, probably overrode the effect of water temperature. The experiments with surface water release showed that kelts were concentrated in the upper water column and did not pass the dam (with one exception in autumn) at bottom water release or in the fishway. The upper entrance of the fishway is about 0.5 m below surface, and this is probably the reason for its low efficiency for downstream migration. Numbers of kelts were often observed in the surface water layer at the turbine inlet and spillways in April and early May, before any spillwater release occurred (O. Caspersen, pers. comm.). In 1998, 253 brown trout ascended the fish ladder at their spawning migration. In the visual observation study, with surface water release in May 1999, 48 kelts passed the dam in 3.75 h of $\ge 4 \text{ m}^3 \text{ s}^{-1}$ surface water release on their post-spawning downstream migration. This means that the entire spawning populations from previous season are able to descend this spillway within 20 h of ≥ 4

 $m^3 s^{-1}$ surface water release. At this particular site, a discharge of only 4–8 $m^3 s^{-1}$ (36–64 cm water depth, 1.3–2.7% of the total turbine discharge) may be enough to secure the descent of kelts.

Brown trout exhibit great variation in life history traits (Klemetsen et al., 2003). Ontogenetic habitat shifts occur in populations performing migrations between spawning and nursery areas in rivers and feeding areas in lakes or at sea. Correspondingly, smolt migration from nursery areas to feeding areas in lakes or at sea is common. Also in inland waters with migratory lake-run brown trout populations, a smolt migration similar to that of anadromous brown trout occurs. In anadromous brown trout, smolt is migrating in spring/early summer in the upper water layer at night in southern Norway (Jonsson, 1985, Hembre et al., 2001). The radio tagged smolt at Hunderfossen passed the dam through the water release in the spillway and not through the turbines. However, experiments were conducted with hatchery smolt and there is a possibility that wild smolt will behave in a different way and may pass through the turbines. Catches of adult trout from smolt stocked above and below the dam, gave greater catches of the stocked fish from below the dam, indicating a mortality of smolt passing the turbines or dam (P. Aass, pers. comm.).

This study revealed that neither kelts, nor smolts entered the turbine pathway during their downstream migration. Kelts almost exclusively used surface water released from two spillways as a migration route, whereas smolts probably also descended through deep water release from the spillways. The threshold value of downstream migrating kelts corresponds to a water column between 12 and 36 cm released as surface water. Further, these results demonstrate the importance of significant effort providing surface water releases at hydroelectric facilities which interrupt iteroparous and/or diadromous salmonid migratory systems.

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