FIELD EXPERIMENTS ON STRANDING IN JUVENILE ATLANTIC SALMON (SALMO SALAR) AND BROWN TROUT (SALMO TRUTTA) DURING RAPID FLOW DECREASES CAUSED BY HYDROPEAKING

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ABSTRACT

Field experiments showed that sudden reductions in river flow may cause high mortality of juvenile salmonids through stranding. A 75-m² enclosure in the drawdown zone of a regulated river was stocked with a known number of wild 0+ and/or 1+ wild Atlantic salmon (Salmo salar) and brown trout (Salmo trutta). The number stranded was estimated by counting the surviving fish collected in a bag as they left the enclosure.

In general, a far higher incidence of fish stranding was found during winter conditions (< 4.5°C) compared with the higher temperatures during late summer and early autumn. This is probably mainly because of lower fish activity during the cold season and a substrate seeking behaviour especially during daytime. Stranding was lower at night, probably because of a predominant night active behaviour. Hatchery salmon behaved oppositely to wild fish, and studies based on cultivated fish may give wrong conclusions as to the consequences of hydropeaking. Searching for fish in the substrate underestimated the consequences of sudden flow reductions, as fish were difficult to find. Stranding is not equal to mortality, as fish were found to survive for several hours in the substrate after dewatering. Long shut down procedures of the turbines during daytime, decreased stranding of Atlantic salmon (7–9 cm) drastically under spring conditions. Temperature, season and light conditions have the most pronounced effect on stranding of juvenile salmonids. It is possible to reduce stranding by taking into account these ecological considerations during hydropeaking operations. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: field experiments; hydropeaking; juvenile fish; salmonids; stranding

INTRODUCTION

The Norwegian electrical energy supply system is based on hydropower and the newly deregulated energy market will probably lead to increased use of hydropeaking. Differences in prices between day and night, and an increase in the import and export of electrical energy are the main reasons for changes in power production patterns to achieve maximum economic benefit. Therefore the Norwegian Research Council, several power producers and the water management agency established a research programme to focus on ecosystem impacts from hydropeaking.

Various effects of rapid changes in flow (‘hydropeaking’) on aquatic organisms have been documented, although only a few studies have documented direct effects on river organisms from stranding. Rapid reductions in flow will have a direct mortality effect on fish because of stranding (Hunter, 1992), or an indirect effect because of desiccation or drift of the benthos (Cushman, 1985; Lauters et al., 1996; Ceréghino and Lavandier, 1998). Hydropeaking may also reduce the quality of fish habitat and change fish community structures by changes in current speed (Valentin et al., 1994, 1996), but does not seem to affect fish stress levels when peaking is done frequently in rivers with high minimum flow (Flodmark

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et al., in press). However, energetic loss has been documented in Atlantic salmon juveniles in summer due to rapid habitat shift (Berg et al., unpublished data). Experimental studies have also shown that flow variations affect cover use by brown trout, especially in winter (Vehanen et al., 2000). The incidence of stranding has also been reported as being connected to other kinds of drawdown episodes (Adams et al., 1999). Although they may help the interpretation of field data, results from experimental laboratory studies in artificial channels, such as Bradford et al. (1995) and Bradford (1997), cannot fully simulate natural conditions, but may provide support for field studies. Using hatchery chinook and coho salmon fry Bradford (1997) found that temperature and not the rate of flow decrease was a significant factor for stranding, more fry stranding at 6 than at 12°C.

The effects of sudden and strong reductions in flow have been studied in several Norwegian rivers. During the first 5 years after the regulation of the River Suldalslågen, stranded fish were observed along the river bank after sudden reductions in flow. A far lower fish density was found in the upper and most vulnerable parts of the river, leading to an uneven distribution of fish (Saltveit, unpublished data, 1996). Lower densities of juvenile Atlantic salmon in the rivers Surna and Alta, below power stations, have also been assumed to be a consequence of sudden reductions in flow (Saltveit, 1990; Forseth et al., 1996).

The site in this study, the River Nidelva, was selected because earlier studies showed that rapid and frequent reductions in flow because of temporary shutting down of the power station caused stranding of fish (Arnekleiv et al., 1994). On one occasion the number of juvenile Atlantic salmon stranded was estimated to be 25.7/100 m² (Hvidsten, 1985). Young of year (YoY) Atlantic salmon were affected more severely than older juveniles. This was also the case in the River Suldalslågen, as areas containing habitat for YoY were more exposed than habitat suitable for older fish (Hvidsten, 1985; Saltveit, 1996). However, no studies have quantified mortality or effects on fish populations.

The main objective of this study was to quantify the effects of rapid flow changes on the survival of juvenile Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*), by obtaining quantitative data for survival and mortality. Furthermore, the aim was to clarify possible differences between salmon and trout, possible differences between substrate and river topography, and to obtain data on the speed of flow reduction and on diurnal and seasonal variations. This project is part of a larger research programme aimed at developing methods and models to evaluate the consequences of peaking discharges from power stations for river ecology. A secondary aim is to produce guidelines for hydropower companies to reduce fish stranding.

**MATERIAL AND METHODS**

**Study area**

The River Nidelva is 31 km long, has a mean natural flow of 102 m³/s, and has several hydropower stations. The lower part of the river is periodically strongly affected by hydropeaking. Flows may vary between 30 and >110 m³/s. The River Nidelva is regulated according to a moderate hydropeaking scheme and the flow has mainly been >70 m³/s during the last 3 years. The Nidelva produces anadromous fish over a 5 km long reach, up to the lowermost power station at Nedre Leirfoss (Bratsberg). The experimental area is situated ca. 1.3 km below the power station outlet. The dominant fish species are Atlantic salmon and brown trout.

The power station at Bratsberg in the Nidelva has two turbines. A normal procedure when closing the Bratsberg power station is an almost immediate shut down, which meant that our study site became dewatered in less than an hour or that the water level fell by >0.8 cm/min (Figure 1). We used a water level sensor (Aanderaa Instruments, Bergen) to measure the depth every 30 or 120 s in the minimum flow area. During November and December 1998, the effect of a slower reduction of flow when closing the power station was initially tested. When doing these experiments, the water level was reduced by on
average between 0.3 (slow) and 1.3 cm/min (rapid). Slow dewatering rates with similar lapse times were difficult to achieve because the turbines need the water for cooling and they tended to shut down when they gradually decrease their production to below 50% of their effect (Figure 1). This may also explain some of the bias found in our results on the effect of the speed of flow reduction.

**Enclosure**

One large enclosure was constructed in the drawdown zone of the River Nidelva (Figure 2). The enclosure consisted of iron piles drawn into the riverbed and iron stakes holding a netting fence of mesh size 4 mm. Under construction, the riverbed inside the enclosure was left as undisturbed as possible. It covered an area of 75 m² and the whole area was drained when flow was reduced to 30 m³/s. The maximum longitudinal distance within the enclosure was 21 m, and the maximum width 4.5 m. The height difference within the enclosure was ca. 50 cm. At the lowest end of the enclosure a net bag was located in the outlet, which was never dewatered. This represented the minimum flow. The entrance of the net bag was 0.7 x 0.7 m.

The substrate within the enclosure was mapped every 0.5 m along 44 transects. Other physical parameters within the enclosure were measured at 26 randomly selected spots at a stable flow of 110 m³/s (Table I). Current velocities were measured in four depth layers using an OTT propeller, while the direction of the current was related to the longitudinal mid-line.

The substrate in our enclosure was natural riverbed dominated by small cobbles with mean size of 85 mm. Gravel was the sub-dominant substrate (Table I), although larger cobbles also occurred. The embeddedness was rather high and therefore our enclosure offered a more suitable habitat for the smallest juveniles compared with fish exceeding 7 cm (two-summer-old fish) (Bohlin, 1977; Heggenes, 1988, 1990). When studying the effect of substrate and cover, artificial cover in the form of grey and black roof tiles (ca. 15 x 25 cm) were placed in the enclosure and arranged in groups. The mean depth was approximately 50 cm before dewatering.
Table I. Selected physical parameters within the enclosure

<table>
<thead>
<tr>
<th>Substrate (mm)</th>
<th>Depth (cm)</th>
<th>Current velocity (cm/s)</th>
<th>Flow direction (Degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant</td>
<td>n = 312</td>
<td>n = 26</td>
<td>5  10  15  40</td>
</tr>
<tr>
<td>Subdominant</td>
<td>n = 26</td>
<td>49</td>
<td>23  24  32  31  304</td>
</tr>
<tr>
<td>Average</td>
<td>85</td>
<td>8</td>
<td>23  24  32  31  304</td>
</tr>
<tr>
<td>Minimum</td>
<td>2</td>
<td>1</td>
<td>0   0   14  9  245</td>
</tr>
<tr>
<td>25% il</td>
<td>60</td>
<td>2</td>
<td>17  17  25  25  285</td>
</tr>
<tr>
<td>S.D.</td>
<td>38</td>
<td>12</td>
<td>10  11  9  10  27</td>
</tr>
<tr>
<td>Median</td>
<td>80</td>
<td>5</td>
<td>23  25  32  31  310</td>
</tr>
<tr>
<td>75% il</td>
<td>110</td>
<td>10</td>
<td>30  31  38  38  380</td>
</tr>
<tr>
<td>Maximum</td>
<td>250</td>
<td>150</td>
<td>46  50  51  52  350</td>
</tr>
</tbody>
</table>

Fish

Details about the various experiment series are summarized in Table II. The enclosure was stocked with a known number of wild fish in each experiment, normally varying between 50 and 100 individuals depending on size, corresponding to 1–2 fish/m². However, in series A, E2 and G-H the density varied more. The highest densities were used in the YoY experiments. After preliminary studies with hatchery fish, it was decided to use wild fish from the Nidelva collected by electrofishing. All the fish in each particular experiment were group marked to be able to identify in which experiment they were used, and acclimated for at least 24 h in large dark perforated plastic containers placed in the river. Based on cortisol values in the fish blood plasma, 24 h was found satisfactory for fish to return to unstressed cortisol levels (Arnekleiv et al., unpublished data). In total, 65 experiments were conducted with Atlantic salmon and/or brown trout (Table II).
Table II. Details of fish used and physical variability in each experimental series conducted in the enclosure. Median as bold and range in branches ( ) is shown for each parameter.

<table>
<thead>
<tr>
<th>Exp. series</th>
<th>Period</th>
<th>No. of exp. day/ night</th>
<th>Species</th>
<th>Year class</th>
<th>Fish length of each group (mm)</th>
<th>No. of juveniles introduced</th>
<th>Habitation time (h)</th>
<th>Dewatering speed total cm/min</th>
<th>Water temp. °C</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>18 Nov.–11 Dec. 1997</td>
<td>5/6</td>
<td>S. salar</td>
<td>YoY-hatch</td>
<td>61 (59–108)</td>
<td>50 (45–200)</td>
<td>22 (8–118)</td>
<td>1.3 (0.8–1.5)</td>
<td>3.1</td>
<td>Fish not tagged</td>
</tr>
<tr>
<td>B</td>
<td>15 Dec.–16 Dec. 1997</td>
<td>1/1</td>
<td>S. salar</td>
<td>YoY-wild</td>
<td>52 (50–53)</td>
<td>42, 95</td>
<td>22–30</td>
<td>1</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>17 Aug.–19 Aug. 1998</td>
<td>1/1</td>
<td>S. trutta</td>
<td>YoY-wild</td>
<td>50 (61–65)</td>
<td>6 (5–7)</td>
<td>100</td>
<td>8 (8–111)</td>
<td>0.6 (0.4–0.7)</td>
<td>9.2 (9.2–9.4)</td>
</tr>
<tr>
<td>D1</td>
<td>30 Sept.–6 Oct. 1998</td>
<td>3/2</td>
<td>S. salar</td>
<td>1+–wild</td>
<td>81 (79–87)</td>
<td>5 (4–6)</td>
<td>50</td>
<td>17 (7–69)</td>
<td>0.8 (0.5–1.0)</td>
<td>9.7 (9.2–10.3)</td>
</tr>
<tr>
<td>E1</td>
<td>25 Nov.–16 Dec. 1998</td>
<td>6/4</td>
<td>S. trutta</td>
<td>YoY-wild</td>
<td>61 (59–62)</td>
<td>7 (5–8)</td>
<td>50 or 100</td>
<td>19 (18–47)</td>
<td>0.6 (0.3–1.3)</td>
<td>3.6 (2.0–4.4)</td>
</tr>
<tr>
<td>E2</td>
<td>20 Nov.–16 Dec. 1998</td>
<td>7/5</td>
<td>S. salar</td>
<td>1+–wild</td>
<td>83 (80–84)</td>
<td>6 (5–8)</td>
<td>25 or 50</td>
<td>24 (20–73)</td>
<td>same as E1</td>
<td>3.4 (2.0–4.3)</td>
</tr>
<tr>
<td>F1</td>
<td>12 April–26 April 1999</td>
<td>6/0</td>
<td>S. salar</td>
<td>1+–wild</td>
<td>80 (78–88)</td>
<td>6 (4–7)</td>
<td>50</td>
<td>52 (43–68)</td>
<td>0.6 (0.2*–0.9)</td>
<td>2.2 (1.7–3.5)</td>
</tr>
<tr>
<td>F2</td>
<td>23 Aug.–26 Aug. 1999</td>
<td>7/0</td>
<td>S. salar</td>
<td>1+–wild</td>
<td>81 (80–88)</td>
<td>5 (4–6)</td>
<td>50</td>
<td>43 (43–69)</td>
<td>0.9 (0.2*–1.0)</td>
<td>3.0 (2.5–4.6)</td>
</tr>
<tr>
<td>G</td>
<td>26 April–12 May 1999</td>
<td>3/0</td>
<td>S. salar</td>
<td>1+–wild</td>
<td>84</td>
<td>10</td>
<td>50–33</td>
<td>7 (7–13)</td>
<td>10.3 (8.6–13.4)</td>
<td>additional cover</td>
</tr>
<tr>
<td>H</td>
<td>2 Sept.–21 Sept. 1999</td>
<td>3/0</td>
<td>S. salar</td>
<td>YoY/1+–wild</td>
<td>55/85</td>
<td>3/12</td>
<td>50–37</td>
<td>10 (10–32)</td>
<td>12.6 (10.6–15.3)</td>
<td>additional cover</td>
</tr>
</tbody>
</table>

Abbreviations used: S. salar = *Salmo salar*; S. trutta = *Salmo trutta*; hatch = hatchery fish; wild = wild fish caught by electrofishing. * Stepwise slow dewatering—see Figure 2.
The fish were carefully introduced into the upper part of the enclosure when watered, and kept here for 6–120 h for acclimatization before the enclosure was dewatered. The enclosure was left dry for at least 2 h before next experiment started.

Fish that survived (both found stranded and in the net bag) were reused in several experiments. Reusing wild fish in these experiments should cause no bias in our results, as fish in the river experience numerous dewatering episodes since the Nidelva is a hydropeaking river. Except for experiment series G and H all fish were introduced into the upper part of the enclosure, hence the fish was ‘forced’ to settle in the substrate 15–21.5 m away from the minimum flow area (the net bag). The net bag seemed to be an avoidable habitat (no substrate was available except for experiment series G and H). Before each dewatering the net bag was checked for fish, but fish were rarely observed.

The number stranded was estimated by counting the surviving fish leaving the enclosure and collected in a bag at its lower end. This bag was never dewatered. In addition, a search was made for fish in the substrate by two persons for 30–60 min. The experiments with wild fish were conducted with YoY and 1+ Atlantic salmon and with YoY brown trout, during day and night, at different temperatures and seasons (spring, late summer/autumn and winter), using different cover, drawdown speed and frequency. The experiments were designed both to be able to quantify mortality from stranding and to study the relative differences between the different stranding events.

Results with wild fish are presented as the proportion of fish found stranded based on fish found stranded after dewatering, or re-found dead or alive in the following experiments. In the experiment series A with hatchery fish the proportion of fish stranded was determined from fish not found in the net bag after dewatering.

RESULTS

The experimental studies are illustrated with results from one experiment with wild Atlantic salmon at low temperatures (Figure 3). In this experiment 97 YoY (length 52 mm ± 5.09) were stocked and acclimated in the enclosure for 21.5 h before the flow was reduced rapidly from 110 to 30 m³/s within 42 min (i.e. 1.5 cm/min). Altogether 40 fish were found alive in the bag, indicating that in this particular experiment 57 fish or ca. 60% became stranded. A search in the substrate gave ca. 20 fish, while a total of 37 fish or ca. 39% of those stranded were not found.

Figure 3. Number of wild Atlantic salmon YoY stocked in the enclosure, number of fish found in the bag, estimated mortality and number and proportion stranded in one single experiment in the River Nidelva. The figure also shows the number and proportion of fish not found by searching in the substrate.
**Season, temperature and light**

In general, a far higher stranding frequency was found in both Atlantic salmon and brown trout at low temperatures (\(<4.5^\circ C\)) during winter compared with at higher temperatures (\(>9^\circ C\)) during summer and autumn (Figure 4).

For both brown trout YoY and two-summer-old Atlantic salmon (1+) a day and night variation during winter in their susceptibility to being stranded was found (Figure 4). The difference in brown trout was not as pronounced as in Atlantic salmon. Far fewer salmon became stranded during the night at low temperatures than during daytime (Figure 4). The possibility of being stranded during night in wintertime for salmon was not higher than during night in summer.

At higher temperatures (\(>9^\circ C\)) during summer the tendency is the opposite. Relatively more brown trout and Atlantic salmon stranded at night than during the day (Figure 4). Of the two species, Atlantic salmon had the most pronounced diurnal and seasonal variation in stranding susceptibility under rapid flow reductions (Figure 4). This is probably explained by the fact that the salmon used were larger than the trout, diurnal patterns probably being more typical of larger fish.

**Figure 4. Proportion of wild Atlantic salmon (1+) and brown trout (0+) stranded at different temperatures and light conditions (summer, winter and spring) in field experiments in the River Nidelva. Stranding is based on fish found stranded after dewatering or fish found in the ensuing experiments. The boxes represent the inner 50% of the data, while the vertical lines represents the median values. Whiskers are 10th and 90th percentiles while dots are individual outliers (for more details of the experiments, see Table II—experiment series C-F1)**

Drawdown speed, frequency and pattern

Replicates with similar slow dewatering rates were difficult to achieve (see ‘Study area’ and Figure 2), and this may explain some of the bias found in our results in Figures 5 and 6.

Figure 5. Proportion of wild Atlantic salmon (1+) stranded at different drawdown speeds during day and night in mid-winter in the River Nidelva (more information in Table II—experiment series E2)

![Graph showing proportion stranded vs. dewatering speed](image)

Figure 6. Proportion of wild Atlantic salmon (70–90 mm) stranded during spring in the River Nidelva during rapid and extremely slow drawdown speeds, and with natural and additional cover (more details in Table II—experiment series F1 and F2)

![Graph showing proportion stranded vs. dewatering time](image)
No clear tendency towards reduction in the susceptibility of being stranded was found within the range of the various tested dewatering speeds under mid-winter conditions (Figure 5). As earlier shown, stranding was less pronounced during night in wintertime. However, even though salmon are more active during night, no reduction in the incidence of stranding was found under slow reductions in flow, i.e. down to 0.3 cm/min or 120 min for dewatering of ca. 70 cm water column.

In May 1999, we did a series of trials in daytime at low water temperatures with a stepwise dewatering as illustrated in Figure 6. When the flow was reduced as slowly as an average 0.23–0.31 cm/min a positive effect in stranding reduction was achieved, almost eliminating the stranding of salmon on natural substrate. The time used to dewater the area was then 4–5 h (Figure 6). No significant correlation between dewatering frequency (habituation) and stranding has been found in the experiments with wild fish, although this has been shown in the hatchery fish (see below).

**Substrate and cover**

When the rate of drawdown was high, between 60 and 80 min dewatering time, no significant differences in stranding were found between the two substrate categories used (Figure 6). However, when reducing the dewatering speed, clear differences between the substrate types were seen. Increased cover gave increased susceptibility to becoming stranded. For natural substrate a positive statistically significant \((p < 0.05)\) relationship was found between stranding index and dewatering time (Figure 6).

**Daily hydropeaking**

In August–September 1999, the power company ran a real hydropeaking situation, and the flow varied as shown in Figure 7. Each dewatering was done in a normal rapid way at water temperatures \(> 9^\circ\)C. We conducted a series of experiments where the same group of fish was re-introduced in the net bag after counting. We placed large stones in the net bag to provide cover, and the fish were left in the net bag overnight, and the flow increased the next morning. In the experiments no fish were observed in the net bag before dewatering, so all fish migrated into the enclosure when the flow increased. All trials included stranding, so fish did not easily ‘learn’ to avoid stranding.

**Hatchery fish**

Shortly after stocking (10–20 h in the enclosure), hatchery fish were less vulnerable to stranding, especially in daytime (Figure 8). However, when the acclimation time increased, more hatchery fish stranded (Figure 8). The same was true at night and more hatchery Atlantic salmon stranded at night in wintertime, also shortly after stocking, which is opposite to the finding in wild Atlantic salmon (see Figure 5). Both relationships were statistically significant \((p < 0.05)\).

**DISCUSSION**

Our study was based on one enclosure, i.e. replicates were conducted in time. Environmental conditions, such as weather (rain, cloudy, sunny) and minor water temperature and quality, which we were unable to control, may have caused some bias in our results and may be a reason for some of the variations found. It was also very difficult to produce exactly a similar slow drawdown speed and pattern, and this may also explain some of the bias found in our results on the effect of the speed of flow reduction.

Our experiments do not only show that a large number of fish may become stranded, but they also show that it is almost impossible to find all fish, especially YoY, left behind, even within a limited area. Therefore, counting the fish found in the substrate after flow reduction incidents will underestimate fish mortality and the effects of hydropeaking.

Fish from previous experiments were sometimes found alive either in the bag or in the substrate in the following experiments. Notably during the winter period this regularly occurred and fish could appear after two or three experiments with flow reductions, indicating survival for several hours within the...
Figure 7. Number of Atlantic salmon found stranded, missing or in the net bag after repeated dewatering of the enclosure during a 3-day period of hydropeaking in August 1999 (more details in Table II—experiment series G)

substrate. However, also in autumn when the enclosure was dry overnight, several stranded fish survived in the substrate and were found in the following trial. However, in most of our experiments the enclosure was left dry for only a few hours. The proportion of fish surviving varied between season, on account of differences in temperature, but the substrate and topography of the river bottom were also probably of importance. In this context, inflow of groundwater might be important. Thus, these experiments do not necessary quantify mortality, unless the drawdown zone is dry for long periods. With rapid changes in flow, stranding is not equivalent to mortality. In similar experiments conducted on brown trout in the River Dale, western Norway (Saltveit et al., unpublished data), live fish from previous experiments could
be found even after three successive experiments, illustrating that death is not necessarily a consequence of stranding.

Observations of fish behaviour during the experiments clearly indicated that during flow reduction the fish arrived late to the lower part of the enclosure and entered the bag just before the enclosure dried up. This pattern of behaviour is similar to that observed by Bradford et al. (1995). They reported that juvenile salmonids often waited until their dorsal fin was dry before they migrated under dewatering. Similar findings were also seen in recent laboratory experiments with brown trout (Halleraker et al., unpublished data). Snorkeling observations (unpublished results) made in areas adjacent to the enclosure under dewatering in summer have also shown that juvenile salmonids follow the water edge both up and down under fluctuating flows. However, the same observations in mid-winter conditions demonstrated a low habitat use of the shallow areas. Hence, juvenile salmonids may seek deeper or other parts of the river during mid-winter conditions.

The far higher stranding frequency found in both Atlantic salmon and brown trout at low temperatures during winter, may be because of the far lower activity of the fish during winter, and to the fact that they hide within the substrate to a greater degree (Heggenes and Saltveit, 1990). Our results are in accordance to the findings of Bradford (1997) for chinook salmon \( \textit{Oncorhynchus tshwytshca} \). Based on the average proportion stranded, the stranding risk for salmon (70–90 mm) in mid-winter is about three times higher under dewatering during day versus night, three times higher during daytime in mid-winter compared with summer stranding, and about 1.8 times higher during dewatering in daylight in November–December versus April–May with comparable low temperatures (4–4.5°C).

Bradford (1997) found a sixfold greater stranding rate at 6°C compared to 12°C, and related this to the fact that juvenile salmonids reside closer to the substrate when temperature is low. Our experiments therefore underline the strong seasonal component in stranding (Bradford et al., 1995; Bradford, 1997). However, in our study stranding decreased significantly from November–December to April at the same dewatering speed, despite the fact that the water temperature was slightly (ca. 1.2°C) lower in spring. Hence, light and temperature cannot be separated as explanatory variables. The quantity of drift, light intensity (strong sun), time of year (increasing versus decreasing day length) and air temperature are probably also important. Such factors may make the salmon more active and thereby decrease stranding despite low water temperatures. These results are in contrast to the studies by Clarke and Scruton (1999), who stated that a temperature dependent shift in behaviour occurred gradually up to a temperature of 6°C.

Habitat selection in brown trout and Atlantic salmon is very different between summer and winter, and may explain the differences in stranding between seasons for these two species. At low temperatures,
brown trout prefer more cover, lower flow and seek down into the substrate (Karlström, 1977; Cunjak and Power, 1986; Heggenes and Saltveit, 1990). Atlantic salmon fry will also hide in the substrate during winter (Rimmer et al., 1983; Cunjak, 1988; Heggenes and Saltveit, 1990), but for both species this passive hiding behaviour in winter is found only to be a daytime phenomenon, both species being active at night (Fraser et al., 1993, 1995; Heggenes et al., 1993). This explains the lower stranding tendency found in Atlantic salmon at night during winter. However, fewer differences were apparent in brown trout. Differences in diurnal winter activity occur in larger juvenile fish (op. cit.), i.e. mean sizes of 10 cm and above. Brown trout in our winter experiments were smaller than our salmon, and size differences and substrate may explain the discrepancy seen here. YoY brown trout are less aggressive, more willing to migrate in shoals and do not have such a strong cover seeking behaviour as the larger salmon used in the experiments. This is probably the reason that a relatively lower proportion of the brown trout stranded during daytime dewatering in mid-winter.

There was no tendency in the susceptibility of being stranded during mid-winter at gradually low dewatering speeds (down to 0.3 cm/min). Within the dewatering ranges used (0.3–1.3 cm/min), time of day therefore seemed to be more important than the dewatering speed in reducing stranding of Atlantic salmon mid-winter, unless the flow was reduced to slower than 0.3 cm/min or 20 cm/h. When the flow was reduced very slowly (stepwise by 0.2 cm/mm) in spring, a positive effect in stranding reduction was achieved, almost eliminating the stranding of salmon on natural substrate. To attain this, the time used to dewater the area was 4–5 h for a ca. 70 cm water column. An average dewatering speed, expressed as cm/h, seem to be too simple a measure for quantifying the dewatering, and create dewatering rules to avoid stranding.

Selection of preferred substrate in salmonids is dependent on fish size, with a preference for a coarser substrate with increasing fish size (Bohlin, 1977; Heggenes, 1988, 1990). The substrate in our enclosure was natural riverbed consisting of gravel and cobbles, with a rather low embededness. However, based on our studies with artificial substrate, the substrate or availability of suitable cover does not seem to be a controlling factor for stranding at high reduction rates, but is a determining factor when drawdown speed is reduced.

In general, far fewer hatchery fish stranded compared with wild fish. Having a schooling behaviour from hatcheries, they did not seem to seek shelter immediately after stocking. Hatchery fish have probably less well developed escape and cover searching mechanisms. They use more time to adapt to the natural river habitat and are therefore less vulnerable to stranding shortly after stocking. Bradford (1997) used hatchery fish in his experiment. They were only acclimated for 7 h before dewatering, which may cause a bias when applying the results to natural conditions. The diurnal difference between hatchery and wild fish could be linked to the fact that hatchery fish are used to being fed during daytime. These results clearly underline the importance of using wild fish when documenting possible effects in natural fish populations, but they also show that hatchery fish in due time may not be less affected by hydropoeaking.

CONCLUSIONS

From our field experiments in the River Nidelva, we can draw the conclusion that searching for juvenile fish in the substrate underestimates stranding and the consequences of sudden flow reductions. Stranding is not equivalent to mortality, as fish were found to survive for several hours in the substrate after dewatering. The most important factors affecting stranding rates in wild Atlantic salmon and brown trout were temperature, time of year and light conditions or time of day. The highest stranding rates were found at low water temperatures in daytime during mid-winter. Similar low temperatures during spring gave 1.8 times less stranding of 1+ salmon. Hatchery salmon behaved oppositely to wild fish, and conclusions based on reared fish may give incorrect conclusions. It is possible to reduce stranding by using more time when closing power stations, but a positive effect is not achieved unless proper cover is available. In experiments with stepwise slow flow reductions the stranding of salmon (1+) at low temperatures was almost eliminated during spring conditions. It should be possible to reduce stranding by ecologically
adjusted operational procedures and by taking into account both diurnal and seasonal considerations when dewatering rivers.

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