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Survival of migrating sea trout (*Salmo trutta*) and Atlantic salmon (*Salmo salar*) smolts negotiating weirs in small Danish rivers

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Abstract – The survival of brown trout and Atlantic salmon smolts during passage over small weirs was estimated in two small Danish rivers during the spring of 1998. Parallel groups of smolts were released upstream and downstream of the weirs and recaptured in traps further downstream. The results showed a smolt loss varying from 18 to 71% for trout and 53% for salmon. Furthermore, the surviving smolts from the upstream groups were delayed for up to 9 days compared to downstream groups. The study demonstrated that an increased proportion of total river discharge allocated to fish passage increased the smolt survival. Losses may be because of fish penetrating grids erected at fish farm inlets, predation and delays, which may lead to desmoltification. The low survival may seriously threat both the long-term viability of wild populations of anadromous salmonids and the outcome of the intensive stocking programme in Denmark.

K. Aarestrup, A. Koed
Danish Institute for Fisheries Research, Vejlsøvej 39, DK-8600 Silkeborg, Denmark

Key words: *Salmo trutta*; *Salmo salar*; smolt; downstream migration; survival; flow

Kim Aarestrup, Danish Institute for Fisheries Research, Vejlsøvej 39, DK-8600 Silkeborg, Denmark; tel.: +45 89213100; e-mail: Kaa@dfu.min.dk

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Un resumen en español se incluye detrás del texto principal de este artículo.

Introduction

Recent studies of smolt survival and behaviour in Danish reservoirs have shown large mortalities of brown trout (*Salmo trutta* L.) and Atlantic salmon (*Salmo salar* L.) (Jepsen et al. 1998). This led to a speculation as to whether other obstacles, such as weirs, may also have negative effects on downstream-migrating smolts. Presently, there are over 1000 weirs in Denmark. Some 400 associated with fish farms. Legislative regulations of fish farms exist, which state that, generally, a 10-mm grid should be placed at the water intake, and that a minimum discharge of $10\,l \cdot s^{-1}$ circumventing the farm must be provided for the downstream passage of juvenile fish. These regulations have, in general, been assumed to be sufficient to ensure free passage of downstream-migrating smolts. However, there have been no studies or information available on how fish farm weirs may affect smolt migration or whether the regulations are sufficient to provide unopposed downstream passage of migrating fish. The potential effect of weirs on migrating salmonid stocks may be considerable, as smolts from the upper reaches and tributaries of many Danish watercourses may need to pass several weirs before reaching the sea.

New legislation regulating the operation of fish farms is currently being prepared for implementation in year 2005. The proportion of the total discharge to bypass the farms for passage of fauna is set to 50% of median minimum discharge in the proposed legislation. Median minimum discharge is used to characterise the water flow regimes of streams and is defined as the median of the minimum discharge ($l \cdot s^{-1}$) over several years (Iversen et al. 1989). However, whether this amount of water is sufficient to provide free downstream passage is currently unknown.

The present study was designed to examine the survival of smolts passing four weirs in two rivers in Denmark. One of the objectives of the study

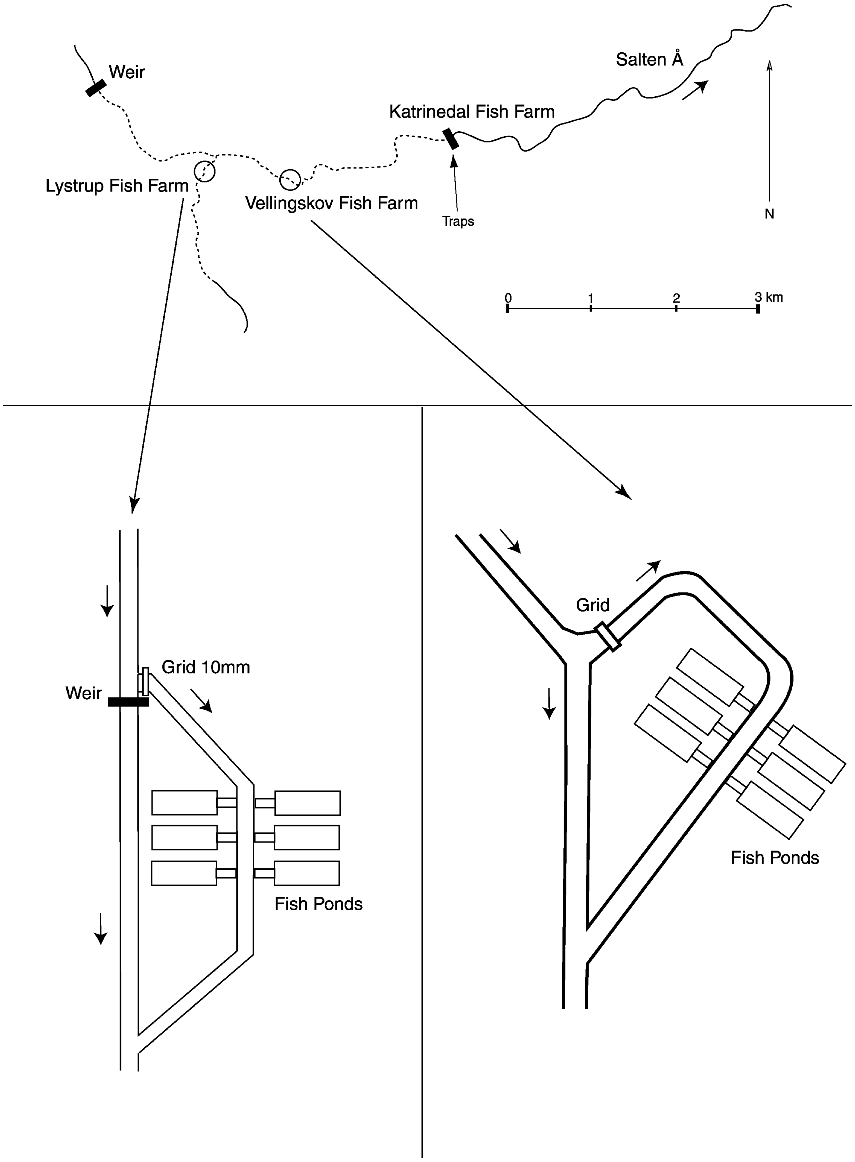

Fig. 1. Map of the study area in River Salten. Upper figure shows the river and location of weirs (circles) and traps. Dotted lines over the river indicate the stretches surveyed by electrofishery. Lower figure gives a schematic diagram of the weirs. Arrows indicate direction of flow.

was also to examine whether the proportion of total discharge allocated to fish passage could explain differences in mortality. Finally, it also aimed to give a preliminary assessment on whether 50% of median minimum discharge is sufficient to provide free downstream passage of smolts. Parallel groups of dye-marked smolts released upstream and downstream of the weirs provided the basis for the analysis. The smolts were recaptured in traps placed further downstream, and subsequently the entire study area was surveyed by electrofishing after the smolt run had terminated.

Study area

River Salten and River Mattrup are tributaries to the River Gudenaa situated in the central part of the Jutland peninsula. The River Salten is *c.* 20 km long, mainly spring fed and has a mean annual discharge of $1.5\,m^3 \cdot s^{-1}$ at the trapping site (Fig. 1). The River Mattrup is *c.* 15 km long and runs through two lakes at the upper end. It has a mean annual discharge of $0.9\,m^3 \cdot s^{-1}$ at the trapping site (Fig. 2).

In the River Salten, smolts were released at two weirs. The first, at Lystrup Fish Farm, is situated on the lowest part of Lystrup Stream, a tributary to River Salten *c.* 5 km upstream of the traps. The water intake to the fish farm was placed directly at the weir, and a 10-mm grid is permanently located at the upstream end of the intake channel (Fig. 1). All excess water ran directly over the weir, which had a height of 0.6 m. Median minimum discharge at the weir is $0.24\,m^3 \cdot s^{-1}$.

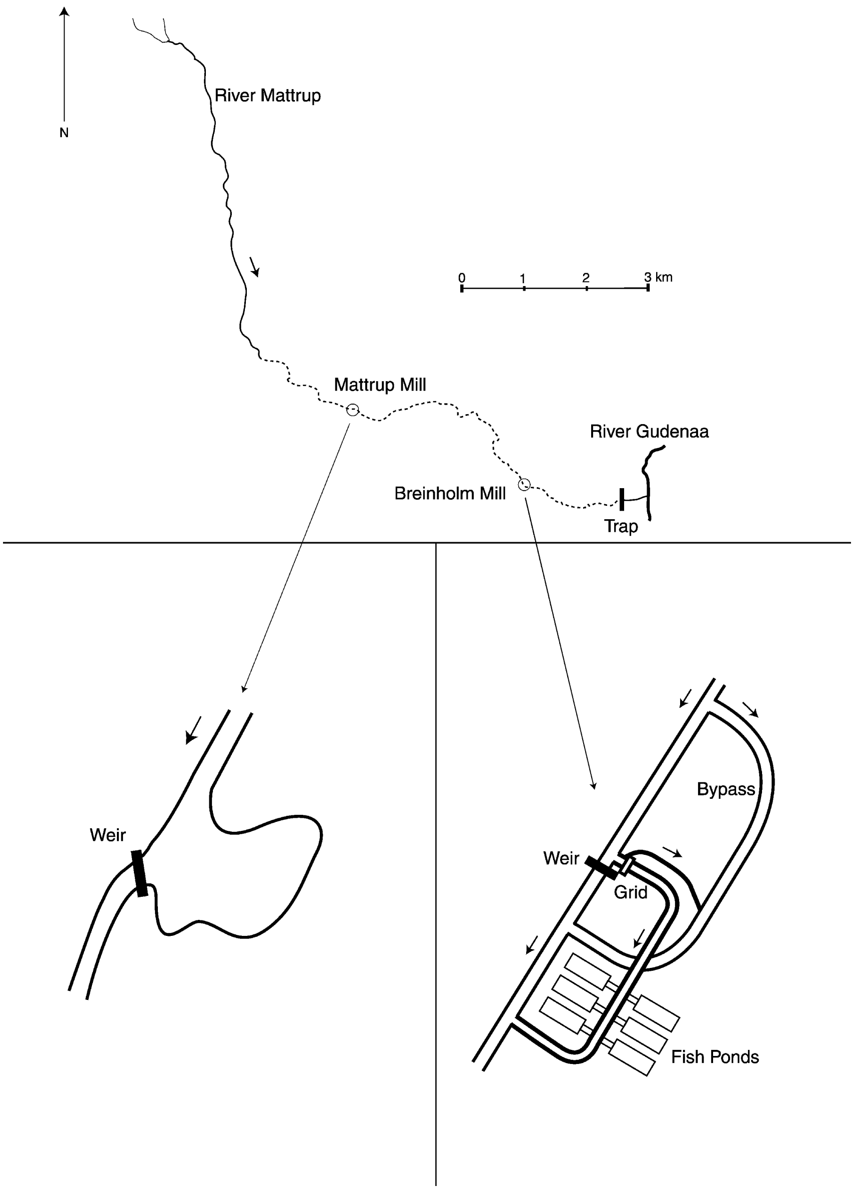

Fig. 2. Map of the study area in River Mattrup. Upper figure shows the river and location of weirs and traps. Dotted lines over the river indicate the stretches surveyed by electrofishery. Lower figure gives a schematic diagram of the weirs. Arrows indicate direction of flow.

The second release point at Vellingskov Fish Farm is situated at River Salten *c.* 2 km downstream of the outlet of Lystrup Stream and *c.* 3 km upstream of the traps. At the upstream end of the intake channel, a newly constructed bypass circumvents all excess water and therefore functions as a fish passage (Fig. 1). Five metres downstream in the intake channel, a 10-mm grid was permanently located. This grid did not meet the requirements of a general 10-mm distance between the bars because a few gaps between the bars were up to 30 mm. The height of the weir was 1.35 m. Median minimum flow was $0.94\,m^3 \cdot s^{-1}$.

In River Mattrup, smolts were also released at two weirs. The uppermost weir was at Mattrup Mill. The mill has not been operational for a long time, and the water is discharged across the weir. Directly upstream of the weir is a small millpond (Fig. 2). The height of the weir was 2 m. Median minimum flow was $0.46\,m^3 \cdot s^{-1}$.

Approximately 4 km downstream, Mattrup Mill is the weir at Breinholm Mill where Breinholm Fish Farm is located. A bypass channel circumvents the fish farm and has its entrance *c.* 200 m upstream of the weir and water intake channel to the farm. At the intake channel was located a 10-mm grid (Fig. 2). Directly at the grid is a smolt passage releasing $12\,l \cdot s^{-1}$. The water in the smolt passage discharges into the lower part of the bypass channel. Excess discharge is released over the weir. The bypass channel, the smolt passage and the water released over the weir all work as smolt passages. The height of the weir is 2.5 m. Median minimum flow is $0.55\,m^3 \cdot s^{-1}$. Distance from Breinholm Fish Farm to the trap is *c.* 1.5 km.

Materials and methods

Experimental fish

On 26 March 1998, 2900 brown trout (age 0+, mixed sex, mean length 17.8 ± 1.4 cm) from the Egebaek Hatchery (Denmark) were moved to outdoor tanks at the Institute of Freshwater Fisheries. The Egebaek trout is a domesticated stock, which has been used for smolt stockings in Denmark for more than 25 years (P. Ebbesen, Egebaek Hatchery, personal communication). The salmon smolts were first-generation offsprings (F1) from River Ätran strain kept at the FOS laks hatchery (mean length 15.1 ± 0.8 cm). In order to identify the different smolt groups upon recapture in the traps, the fish were dye-marked group-wise prior to release. Each group was assigned a unique code by giving one mark on the left or the right side below the adipose fin, dorsal fin or behind the gill, respectively. The dye-marking of both salmon and trout was performed on 27 March 1998. The fish were anaesthetised in a $20\,\mathrm{mg \cdot l^{-1}}$ solution of Benzocaine (Sigma Chemical Co., St Louis, USA) and dye-marked (Alcian blue) with a panjet-inoculator. The fish were kept in the tanks until release. The number of fish and the place of release are given in Table 1.

Field study

The water temperature in River Salten and River Mattrup was measured continuously with a Mylog data logger (Dansk Elektronik Design, Denmark). The Danish National Environmental Research Institute provided daily discharge data on both the total discharge and the amount of water discharged for fish passage at the weirs. The relative amount of water allocated for fish passage was measured as water allocated for fish passage in the period from release to last recaptured smolt in the traps divided by total discharge of the river in the same period.

The smolt groups were released on 31 March and 1 April 1998 above and below the two weirs in River Salten and River Mattrup, respectively (Table 1). On both occasions, the fish were transported to the release site in two 750-l tanks with oxygenated water. Total transportation time was *c.* 1 h.

The released fish were studied by recapture in the smolt-traps below the weirs. The traps in River Salten were of the fyke-net type placed at a fish farm in connection with a weir 3 km downstream of Vellingskov Fish Farm. These traps covered all potential downstream migration routes at the weir, except one. At this place (in front of a grid with 8-mm mesh size), it was impossible to place a trap. Therefore, in order to capture smolts aggregating in the area in front of the grid, this area was electrofished three times a week during the study period. At each session, the area was surveyed by electrofishing at least three times with *c.* 30 min apart until no further fish was captured.

The trap in River Mattrup was constructed of two cages made of galvanised steel netting (10 mm × 10 mm) embedded in a 10-mm grating covering the entire width of the river. To facilitate the sampling of the traps, the cages were fitted with a 10 mm × 10 mm netting inside, which was hauled independently of the trap. The traps operated from 15 March to 2 June 1998. During this period, the traps were emptied once daily around 10 AM and on four occasions on a semi-daily basis.

In June, after the smolt run had finished, all study areas were surveyed by electrofishing, and the number of dye-marked fish remaining in the rivers was estimated by the depletion method (Bohlin et al. 1989). The surveyed stretch of River Salten constituted the river from the trap and 6 km upstream to an impassable weir (efficiency, $\hat{p} = 0.79$) (Fig. 1). Lystrup Stream was surveyed from the outlet in River Salten to *c.* 3 km upstream of the Lystrup Fish Farm ($\hat{p} = 0.95$). River Mattrup was surveyed on the river stretch from the traps to *c.* 2 km upstream of Mattrup Mill ($\hat{p} = 0.97$) (Fig. 2). All marked trout caught at the survey were assumed to be resident fish.

Table I. Number of released and recaptured dye-marked fish in River Salten and River Mattrup in the spring of 1998 (see text for further explanation).

Place of release and species (t = trout, s = salmon)	Number released upstream (*a*)	Number released downstream (*b*)	Number recaptured from upstream release (*c*)	Number recaptured from downstream release (*d*)	Corrected number of recaptured smolts released upstream of the weir ($f = c \cdot b \cdot a^{-1}$)	Corrected number of lost smolts released upstream of the weir ($g = b - f - [b - d] = d - f$)
Mattrup Mill (t)	500	400	48	45	38	7
Breinholm Fish Farm (t)	250	150	39	38	23	15
Lystrup Fish Farm (t)	500	400	34	41	27	14
Velllingskov Fish Farm (t)	400	300	36	76	27	49
Breinholm Fish Farm (s)	280	182	67	92	44	48

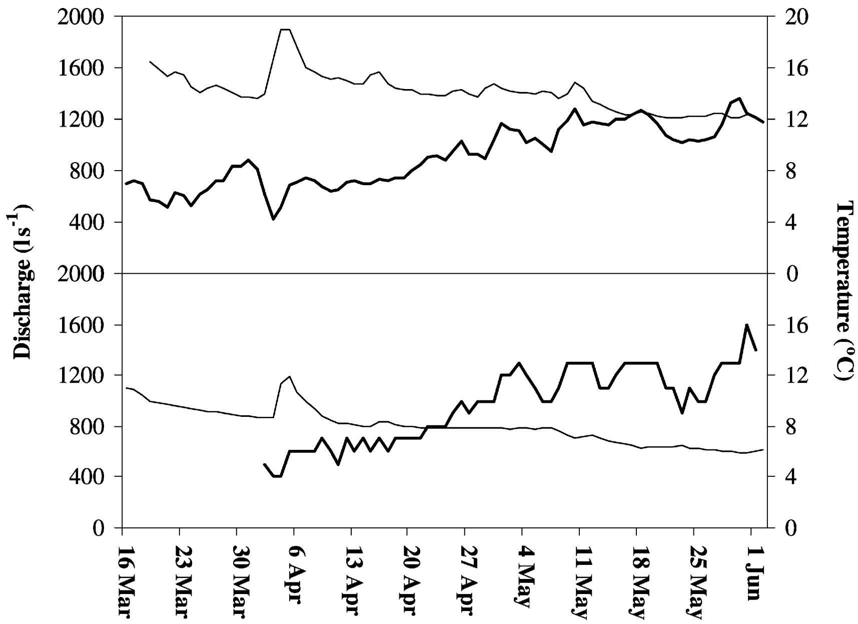

Fig. 3. Water temperature (thick line) and discharge (thin line) in the River Salten (upper figure) and River Mattrup (lower figure) during the study period in 1998.

Data analysis

A logistic regression with recaptured/lost smolt as the dependent factor and proportion of total discharge allocated to fish passage as the independent factor was performed. To isolate the effect of the weirs from other effects on the stretch from the weir to the traps, the counts (capture) of fish of each upstream release site were corrected by the counts at the corresponding downstream release site (Table 1). The counts of recaptured smolts (Table 1, *f*) and the counts of lost smolts (Table 1, *g*) were entered in the analysis as the dependent variable.

Results

In River Salten, the temperature ranged from 4.3 to 13.7°C, and the discharge from 1.2 to 1.9 $m^3 \cdot s^{-1}$ during the study period (Fig. 3). In River Mattrup, the temperature ranged from 4 to 16°C and the discharge from 0.6 to 1.2 $m^3 \cdot s^{-1}$ (Fig. 3).

Smolt delay

Based on the relative day of capture, the 50th percentile of capture was calculated for each release group (Table 3). The mean delay at the weirs varied from 0 to 9 days for trout smolt, and the mean delay for the salmon smolts was 7 days at Breinholm Fish Farm.

Smolt loss

The number of recaptured smolt in the traps and the number of estimated resident fish are given in Table 2. The trout smolt loss at the different weirs varied from 15 to 64% (Table 3). Correcting for the resident fish, electrofished in June after the smolt run terminated, only affected the calculated smolt loss slightly (Table 3).

Table 2. Relative number of recaptured smolt and estimated numbers (total and ratio) of resident fish of different release groups (see text for further explanation).

Group name	Species	Relative number (recaptured)	50% fractile	Estimated number (resident)	Relative number (resident)
UpMat	Trout	0.096	17 April	87	0.174
DownMat	Trout	0.113	8 April	84	0.210
UpBrein	Trout	0.156	7 April	33	0.132
DownBrein	Trout	0.253	7 April	5	0.033
UpLys	Trout	0.068	27 April	101	0.204
DownLys	Trout	0.103	24 April	64	0.162
UpVel	Trout	0.090	24 April	75	0.188
DownVel	Trout	0.253	20 April	101	0.339
UpBreinS	Salmon	0.239	15 April	0	–
DownBreinS	Salmon	0.505	8 April	0	–

Up = upstream, down = downstream, Mat = Mattrup Mill, Brein = Breinholm Fish Farm, Lys = Lystrup Fish Farm, Vel = Vellingskov Fish Farm.

Table 3. The delay (measured as the 50th percentile) and the relative loss of smolt both with and without correction for resident fish at the weirs together with the total and allocated discharge (absolute and ratio of the median minimum discharge; see text for further explanation).

Location	Delay (days)	Discharge (Q) $l \cdot s^{-1}$	Discharge in passage (% Q)	Median-minimum (Mm.) $l \cdot s^{-1}$	Discharge in passage (% Mm.)	Species	Smolt loss (%)	Smolt loss corrected (%)
Mattrup Mill	9	639	100	463	138	Trout	15	18
Breinholm Fish Farm	0	831	45	550	68	Trout	38	31
Lystrup Fish Farm	8	419	32	240	56	Trout	34	30
Vellingskov Fish Farm	4	1382	17	940	25	Trout	64	71
Breinholm Fish Farm	7	825	44	550	66	Salmon	53	53

Flow relation

The proportion of total discharge allocated to the fish passages at the weirs varied from 17% at Vellingskov Fish Farm to 100% at Mattrup Mill (Table 3). Given as percentages of the median minimum flow, the variation was from 25% at Vellingskov Fish Farm to 138% at Mattrup Mill. There was a negative correlation between the size of the smolt loss and the proportion of water released for fish passage (Fig. 4). Logistic regression demonstrated that there was a significant correlation between the loss/recapture ratio of smolts and discharge (logistic regression, $G = 246.23$, $P < 0.001$): the higher the proportion of total discharge allocated to the fish passage, the lower the loss/recapture ratio (constant $\exp(c) = 0.152$, $P < 0.001$; coefficient $\exp(b) = 1.027$, $P < 0.001$). Thus, the change of downstream recapture of a smolt released upstream of a weir increased, on average, by a factor of 1.027 per percent increased discharge of total discharge allocated to a fish pass. For example, an allocation increase from 15 to 30% of total discharge, on average, increases the chance of recapturing a smolt from 22.7 to 34.1%.

Discussion

The loss and delay of the smolts at Mattrup Mill was surprising because all water was released for fish passage. *A priori*, we expected that there would be no delay and the survival would be close to 100%. However, this was not the case. The reason for the reduced survival might be the predators in the millpond. Pike and large brown trout have been caught in the millpond and might be responsible for the loss. The millpond may also explain the delay, if entering the less diffuse currents of the millpond confuses fish (as suggested by Jepsen et al. 1998).

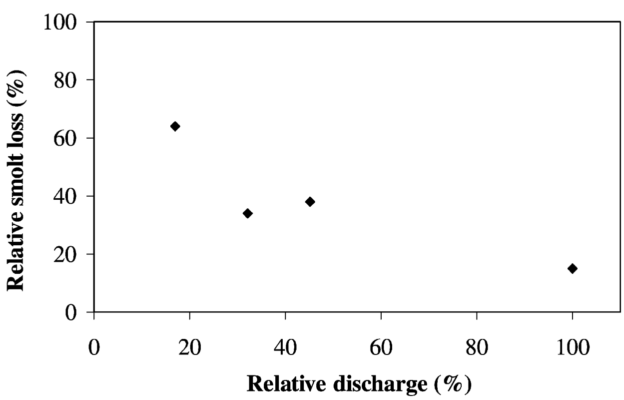

Fig. 4. Relation between the relative discharge (per cent of total discharge allocated to the fish pass) and the relative smolt loss.

The lowest situated weir in River Mattrup, Breinholm Fish Farm, allocated 45% of total discharge (65% of median minimum flow) in the fish passage and had a calculated smolt loss of 38% despite three possible routes a smolt can use for successful passage (bypass channel, youth fish pass and over the weir). The loss of salmon smolts was higher (53%), and salmon were delayed, on average, by 7 days. There is no apparent explanation why salmon performed poorer than trout. In a previous study of fish passage at weirs, salmon smolts also performed poorer than trout (personal observation). In the present study, a possible explanation could be the size difference between the released species, with salmon being smaller than trout. This may have increased the risk for salmon to penetrate the grids at the fish farm. However, there were no observations of fish penetrating the grid during the study period. As no electrofishing was performed behind the grid, it is not possible to conclude further on this matter. An alternative explanation may be the differences between the two species in their behaviour and orientation within the areas of maximum current. Adult brown trout were present both upstream and downstream of the weir at Breinholm Fish Farm and may have been predating on the released fish and thus contributed to the smolt loss.

At Lystrup Fish Farm, the loss of smolts was estimated to 34%. During the electrofishing, there was no concentration of predators immediately upstream of the weir. However, adult brown trout were captured further upstream. Predation may, therefore, explain some of the smolt loss. Dye-marked trout were recaptured behind the intake grid at the end of the study period. There were no holes or larger grid distances in the grid. This indicates that some fish are able to penetrate the 10-mm grid during the smolt run.

Vellingskov Fish Farm had the highest calculated loss in this study. It was also the fish farm, which released the lowest proportion of water for fish passage. Dye-marked fish were also found behind the intake grid, indicating penetration through the screen. Again, electrofishing demonstrated both pike and large brown trout upstream of the weir, which may explain some of the smolt loss.

The electrofishing after the smolt run provided estimates of the number of resident fish. There were no salmon left in River Mattrup, indicating that all released salmon migrated or died. However, there were considerable numbers of the dye-marked trout left in both rivers. Generally, the difference between upstream and downstream groups was small and appeared random. The delay of the upstream released groups could lead to more fish desmoltifying and abandoning migratory behaviour, and we hypothesised that a higher number of fish would become resident upstream of the weirs than downstream. Alternatively, it may be argued that the usually more suitable habitat for trout downstream of the weirs might result in a higher number of resident fish in the groups released downstream of the weirs compared to the groups released upstream (Mills 1991; Elliott 1994). A complicating factor is, of course, the mortality of the fish during the study period, which may lead to misinterpretations of the number of remaining fish from the upstream and downstream releases after the study period. It is probably individual conditions at the weirs (e.g., physical conditions) that determine any difference in residency between upstream and downstream groups. Generally, the small differences in the number of resident fish also resulted only in minor difference in the estimated smolt loss. Thus, leaving out the estimated number of resident fish may not introduce any flaws in the interpretation of future studies on smolt loss at weirs.

The loss and delay of smolts that was observed in this study emphasises the importance of securing free passage for both upstream- and downstream-migrating fish. As the size of a smolt run has been shown to be directly correlated to the later spawning population (Crozier & Kennedy 1993; Jonsson et al. 1998), smolt losses of the magnitude observed here will seriously affect the later spawning population. The delay of the smolts may also affect the size of the population. Smolts are only optimally adjusted to saline condition during a period of few weeks in the spring (Hoar 1988). For anadromous salmon and trout, a delay may decrease the survival of postsmolts because the smolt may miss the optimal time of entry to the sea (Järvi 1989).

If a particular anadromous stock of fish (i.e., Atlantic salmon) have to pass several weirs of the types investigated here, it may threaten the survival of the species. Probably, it will also be futile attempting to reintroduce salmon in such rivers. In the case of partial migrants such as brown trout, it may not ultimately lead to extinction, but shift the fitness of the two life history alternatives into the direction of the resident form. Finally, it may seriously affect the outcome of the intensive stockings of juvenile trout and salmon in Danish rivers, whose main goal is to increase the potential stock of anadromous trout and salmon in Danish rivers (Rasmussen & Geertzh-Hansen 2001).

Despite different characteristics of the weirs, fish passages and river flow, we observed a general relation between allocated discharge to the fish pass and smolt loss. This was expected because the smolt migration, generally, is believed to be passive migration with the current (e.g., Hansen et al. 1984), although some studies have also suggested active movement (e.g., Fängstam 1993). This also indicates that survival may be subject to considerable variation between years because of flow regimes in spring. On the basis of the present study, it is evident that the present legislation in Denmark is insufficient to secure free passage of downstream-migrating smolts. Furthermore, it raises considerable doubt whether the specifications in the planned new legislation will be sufficient to ensure free downstream passage of smolts.

Resumen

1. La supervivencia de smolts de *Salmo trutta* y *S. salar* al cruzar pequeños azudes fué estimada en dos rios daneses durante la primavera de 1998. Grupos paralelos de smolts fueron soltados por encima y por debajo y, posteriormente, recapturados en trampas localizadas mucho mas abajo.
2. Los resultados mostraron una perdida de smolts de entre el 18% y el 71% para las truchas y del 53% para los salmones. Ademas, los smolts supervivientes de los grupos soltados por encima se retrasaron unos 9 dias respecto de los grupos aguas abajo. El estudio demuestra que una mayor proporción de caudal total del rio sobre los azudes incrementa la supervivencia de smolts.
3. Las perdidas pudieron ser debidas a que los peces penetran las rejas levantadas para la toma de agua de una granja, a la predación o a los propios retrasos que pueden provocar des-esmoltificación. Baja supervivencia puede amenazar seriamente tanto la viabilidad a largo plazo de la población natural de salmónidos anádromos, como los resultados del programa intensivo de re-poblaciones de Dinamarca.

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