Optimizing Atlantic salmon smolt survival by use of hydropower simulation modelling in a regulated river

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ABSTRACT

Downstream passage of hydroelectric dams remains a large challenge for Atlantic salmon juveniles. While mortality through turbines is often significant, bypass alternatives may involve complex technical solutions and expensive spill of water. Scientific studies on downstream passage of diadromous fishes in northern Europe are rare, and in Norway the problem is strongly linked to demands for efficient hydropower production. The current study explored mitigating measures by use of a hydropower simulation model and models for smolt migration. Migration pattern and route choice at a hydropower intake for 22 years was described for a river in southern Norway, based on simulated data for discharge and water temperature. Subsequently, the potential of controlling the migration pattern and smolt routing past the intake by altering release patterns from the reservoirs was tested. Initial simulations suggested that more than 50 % of the smolts went through the turbines all years. A general annual increase of bypass discharge from 3 to 15 m^3s^{-1} increased average bypass migration from 30 to 43 % at the cost of 18 US$ per fish. Individual release schedules from reservoirs for selected years indicated that bypass rates could be increased to 80 % at an average cost of approximately 5.8 US$ per fish and 2.8 US$ in the best years. The simulated improvements were exclusively based on discharge manipulations and further success is likely if hydrological adjustments are combined with physical measures, such as screening systems and light or sound facilities. Mitigating measures presumably depends on the specific site, but the methods developed in the present study represent a general technique for evaluating increased smolt survival past hydro power intakes. Employment of such simulation models can provide optimized smolt survival combined with cost effective power generation.

INTRODUCTION

During spring, Atlantic salmon (*Salmo salar*, L.) juveniles are subjected to physiological and behavioural changes to pre-adapt themselves to the marine life cycle phase. (Høgåsen 1998). The downstream migration will start after this smolting process and usually this requires one or more environmental triggers (McCormick 1998). Water temperature in the period before, and during, the smolt run is considered one of the controlling variables for the timing of the smolt migration (Jonsson and Ruud-Hansen 1985). Water discharge is the other main variable (Hvidsten et al. 1995), and each of these factors can stimulate in different responses in different population and be of varying importance (Davidsen et al. 2005, Antonsson and Gudjonsson 2005). The timing and synchronization of the smolt migration has an important role in determining smolt survival (McCormick 1998, Rikardsen and Dempson 2011**)**

Most of Norway's electricity is based on hydro power. Reservoirs provide water during winter, when runoff is small and the demand is large. Power production may also have a diurnal variation since less energy is consumed during the night hours. Hydro power is well suited for rapid load changes, as start-up and shut-down procedures are technically simple and do not involve considerable costs. However, hydropower infrastructure and discharge schemes have caused the reduction and even extinction of numerous Atlantic salmon populations in Europe and along the east coast of North America (Hindar et al. 2003). In Norway, approximately 30 % (n = 185) of the salmon rivers are negatively affected by hydropower development (Anon. 1999). Dams and hydropower intakes restrict fish migrations and the problem is particularly apparent for diadromous fishes. Upstream migration of adult Atlantic salmon can successfully be mitigated by construction of different designs of fish passes (Clay 1995, Scruton et al. 2008, Katopodis and Williams 2011). On the other hand, seaward migration of smolts remains a challenge in many regulated rivers as smolts appear to follow the main discharge (Rivinoja 2005, Svendsen et al. 2007). Accordingly, they enter hydropower intakes and eventually go through the turbines. Migration through turbines can cause significant mortality as a result of direct blade strike (Monten 1985) and delayed mortality due to various sub-lethal effects (Ferguson et al. 2006). Comprehensive studies on Pacific salmon have suggested that smolt survival through Kaplan turbines can be increased by fine tuning of turbine operation (Skalski et al. 2002). Migration into intakes can also be reduced with different screening systems, or by arranging a bypass system with a sufficient discharge. The latter solution will reduce the power production while screening systems are often expensive or physically unsuited for the site in question.

Regardless of the methods used to prevent downstream migration through hydropower turbines, predictions of timing of the smolt migration from upstream areas can optimize the choice of measures. In River Mandalselva in south Norway, Fjeldstad et al. (2012) developed a model to assess the timing of the downstream smolt run on a daily resolution. In the same study another model was fitted to explain the route choice when the smolts arrived at downstream intake area. Modelling smolt migration timing and route choice as outlined above depends on data on flow and temperature, data that in many cases do not exist for the intake area for long time periods. A way of overcoming this is to use hydropower models (e.g. Killingtveit and Sælthun 1995) to simulate flow conditions in the intake area as a basis for smolt migration analysis.

The objective of the present study was twofold. First, the variability of smolt migration patterns in River Mandalselva over 22 years (1988-2009) was investigated combining a hydropower production model and the smolt migration models from Fjeldstad et al. (2012).

Second, the potential of controlling the migration pattern and smolt routing past an intake by altering release patterns from the reservoirs was tested. Identification of variables and mitigating release procedures that could increase the smolt survival in the future was based on predictive simulation models. Hence, results from simulation models, not measurements, for both river discharge and water temperature in River Mandalselva were used as input for further modelling of smolt migration timing and eventually the route choice at the hydro power intake. This numeric approach made it possible to explore a variety of different release schedules from each reservoir in order to illustrate the possibilities for optimized smolt survival each year. Accordingly, the output from the hydropower simulation model directly calculated the economic consequences of any mitigating releases.

MATERIALS AND METHODS

Study site

The study was carried out in the River Mandalselva, southern Norway (58°N, 7°E, Figure 1). The catchment covers 1800 km^2 and is one of the largest in southern Norway. The river is 115 km long and has a mean annual discharge of 88 m^3s^{-1}. Six hydro power plants are situated in the river and natural and artificial lakes are utilized as reservoirs for the plants (Table 1). Nearly 90 % of the storage capacity in the system is found in the two mountainous lakes Nåvann and Juvatnet.

The Bjelland and Laudal power plants are situated on the anadromous part of the river. Bjelland is located just downstream the final migration barrier, Kavfossen waterfall (47 km from the sea). Further downstream, the Laudal power plant is supplied with water through a 6 km rock tunnel with its intake in Lake Mannflåvatn (Figure 1). Approximately 300 meters south of the intake, a concrete dam on the natural outlet of the lake controls the water level in

Lake Mannflåvatn. A sluice gate in the dam supplies the minimum residual discharge of 3 m^3s^{-1} to the bypassed river reach, which is also the upstream migration corridor for adult salmon. The gate has a flow capacity of 13 m^3s^{-1} and excess flood spill runs over the 50 meters wide concrete crest.

The river reach upstream Laudal power plant is important for the salmon population since approximately 35 % (around 30 000 smolts) of the potential smolt production in River Mandalselva takes place upstream the intake (Ugedal et al. 2006). Consequently, the intake to Laudal power plant is a main challenge for downstream migrating salmon smolts in the river. Fjeldstad et al. (2012) suggested that up to 90 % of all smolts enter the intake and subsequently the turbines in years with unfavourable discharge conditions. In this case that means a constant minimum residual discharge in the bypass and full capacity flow (110 m^3s^{-1}) through the two Francis turbines.

Typically, smolt migration in River Mandal takes place during the month of May, a period characterized by increasing water temperature and spring floods. In this time of the year, the hydro power plant at Laudal will normally utilize the plant capacity flow, except from the restriction of the minimum flow to the bypass section. Flood spill to the bypass is also common in this period as a result of snow melt and precipitation.

Data

Daily runoff data from a gauge in the catchment (22.16– Myglevatn) were obtained for the years 1988 -2009 from the Norwegian Water Resources and Energy Directorate. Air temperature data for the same period (1988-2009) were recorded by the Norwegian

Meteorological Institute at a weather station in the town of Mandal, at the outlet of the river. Water temperature data were recorded downstream of Bjelland power plant from 2003 to 2009 by use of a Heraeus model M310 sensor.

Discharge modelling

The nMag hydropower simulation software (Killingtveit and Sælthun 1995) was used to create a model of the River Mandalselva hydropower system. The model involved all reservoirs and the six power plants, including physical data for penstocks, turbines, tunnels and other relevant infrastructure (Figure 2). Release from each reservoir could be manipulated within the frames of available runoff and storage and turbine capacities. The model was calibrated with assistance from the power company, Agder Energi, based on the runoff data and historic production data. The calculated power production, which is a main output variable from the nMag model, was within a 5.4 % difference from the true production for all six power station in the period from 1988 and 2007 (Table 1). With the calibrated model, discharge series for the inflow to Lake Mannflåvatn were calculated for 1988-2009. The simulated discharge data represented an optimized power production regime, following the governing policy for that period.

Temperature modelling

Since the smolt timing model includes water temperature, data which were not available before 2003, water temperature had to be computed from available data. Therefore, a multivariable regression analysis was conducted with the “R” software package (R Development Core Team 2009) on the measurements from 2003 to 2009. Relations between water temperature, date, air temperature, discharge, discharge change from previous day, accumulated air temperature (from the 1st of March each year), and accumulated reservoir release volume (from the 1st of March each year) were tested for all seven years As a result, a linear regression between water temperature and accumulated air temperature and reservoir release was developed ($R^2 = 0.75$). This is a plausible relationship since accumulated temperature is a measure of energy input, and the released water a measure of cold temperature release from reservoirs. Accordingly, a complete water temperature data set for the years 1988-2009 was calculated and used in the subsequent modelling of smolt migration timing and route choice.

Smolt models

The smolt migration timing model, hereafter referred to as the timing model, (Fjeldstad et al. 2012) was developed based on smolt catch data from the site Hesså, between Bjelland and Lake Mannflåvatn (Figure 1). The model calculated the number of migrating smolts each day as a function of physical variables, such as river discharge and water temperature. The model was fitted to observations of approximately 2500 smolts caught in a smolt trap in the years 2003-2008. This model has a daily resolution and calculates the number of smolts to migrate each day with a general condition of no migration before 24 April. The migration time from Hesså to the Laudal intake was fixed to a value of three days as suggested by previous telemetry studies (Fjeldstad et al. 2012). Another regression model of the binomial family (Fjeldstad et al. 2012) was used to calculate the smolt route choice at the intake of Laudal power plant, hereafter called the route choice model. At the intake, the fish could enter the intake or chose a safe bypass. This model suggested that the route choice could be described as a function of the total discharge (bypass plus intake) and the proportion of the total discharge released into the bypass. Together with the hydropower simulation model, both smolt models were used to analyse the smolt migration from 1988 to 2009 and to explore possible mitigation scenarios for increased smolt survival

Analyses

The calculated discharge and water temperature data was first used as input to the timing model to describe the smolt migration from 1988 to 2009 under conditions where hydropower production was maximized in all six plants. The output from the timing model was subsequently used as input to the route choice model. The initial run of the route choice model was based on maximum power production through the Laudal hydropower plant and minimum bypass (3 m^3s^{-1}) except from periods with flood spill. The next step was to adapt mitigating release schedules for increased bypass migration by use of the route choice model exclusively. Inflow to Lake Mannflåvatn and smolt numbers from the migration model was on a daily resolution, and the route choice model included variables on hourly scale, a separate hydrological routing procedure was developed in Microsoft Excel, with the reservoir (Lake Mannflåvatn) serving as a source. The reservoir has a storage capacity of 2 mill. m^3, and analysis of hourly data illuminated the consequences for both power production and smolt route choice. Firstly, the route choice model was used to simulate the route choice with an increased constant minimum residual discharge (15 m^3s^{-1}) in the complete smolt run period for all 22 seasons, including calculations of economic costs. To focus on seasons with high proportions of fish entering turbines and periods with high smolt migration rates as predicted with the timing model, another simulation was conducted on the eight years with initial intake migration exceeding 73 % (the worst eight years). For these eight years the smolt route model was run with a bypass discharge of 50 m^3s^{-1} during the days when the timing model suggested more than 200 (of totally 10 000 in the model) smolts at the intake. The rest of the time, bypass flow was kept at 3 m^3s^{-1}. As 50 % of the smolts were assumed to migrate out of Lake Mannflåvatn during the 7 night hours, the simulations were also used to estimate the route choice and economic cost when 50 m^3s^{-1} was released only during night in the same period.

So far, the simulations of increased bypass flow were based on a smolt run determined by an upstream flow regime maximizing hydropower output, without a focus on synchronized smolt migration. The initial simulations from the smolt timing model suggested that the smolt migration was not well synchronized in most of the 22 years. Also, these simulations indicated that the migration peaks coincided with physical conditions causing large proportions of smolts entering the Laudal intake according to the route choice model. For instance, it was observed that a very early smolt run, mainly as a result of high water temperature, came in combination with the large spring discharge which attracted a large proportion to the intake. Consequently, the last modelling step was to manipulate the upstream reservoir release curves in the nMag model in order to find general procedures to plan a discharge regime that could contribute to a more favourable migration pattern in selected years. Two seasons, 2002 and 2007, were chosen as examples. Both seasons were characterized by early migration and high proportion of turbine migration according to initial conditions from the route choice model. The reservoir guide curve for one reservoir (Nåvann) in the nMag model was changed. Most importantly, the date for empty reservoir was postponed from April 1 to May 1, allowing a larger storage capacity in the start of the smolt run and thereby a reduced river discharge in that period. A new reservoir release schedule from Nåvann involved calculations of a new downstream water temperature data set, smolt migration data and route choice pattern and the route choice model was finally run with two different bypass discharges (3 and 15 m^3s^{-1}) for this case.

RESULTS

Discharge, temperature and initial smolt migration

The calculated discharges from the nMag model illustrated that the smolt run period in River Mandalselva at Laudal was characterized by an average discharge between 50 and 100 m^3s^{-1} from 1988 to 2009 (Figure 3). These relatively similar discharge conditions from year to year shows that the river system is strongly controlled by the hydropower facilities. In only eight of the 22 years floods exceeded 110 m^3s^{-1} and thereby gave flood spill at the intake to Laudal power plant. In five of the years, the discharge peaked at over 200 m^3s^{-1} during short events. On the other hand, calculated water temperature for the same period demonstrated a larger difference among years (Figure 4). While average temperature in May 2009 was nearly 13 ˚C the average temperature was only 3 ˚C in 1988 in the same period. Water temperature simulations demonstrated that average water temperature in the month of May increased over the studied 22 year period (0.15 ˚C pr year with linear regression, $R^2 = 0.26$, $p = 0{,}015$). (Also, a linear trendline for the measured air temperature from 1988 to 2009 show an increase of 1˚C over the 22 year period).

Results from the initial smolt timing calculations (only 3 m^3s^{-1} bypass discharge as far a possible) demonstrated large variation in the migration patterns from year to year, both in peak timing and magnitude distribution pattern (Figure 5). It was assumed that increase in discharge would initiate the smolt run, but the analysis demonstrated that sudden discharge increase triggered smolt migration only to limited extent.

Smolt migration without mitigating measures

Simulations with the route choice model indicated large smolt mortality (large turbine proportion) with a minimum bypass flow of 3 m^3s^{-1} during the smolt run most of the 22 seasons (Figure 6). The proportion of smolt that chose the intake alternative was averagely 70 % (SD ± 10). In 2008, the simulations showed that more than 90 % of the smolts chose the intake and the proportion was larger than 50 % all years.

Effects of increased minimum residual discharge

When bypass discharge was increased to a fixed value of 15 m^3s^{-1} fewer fish went into the intake, as expected (average 57.5 %, SD ± 13.8, $p = 0.002$) (Figure 6). The simulations suggested that in seven out of 22 seasons more fish migrated through the bypass than into the intake tunnel and in 2001 and 2005 approximately 65 % of the fish chose the bypass. With a total of 30 000 migrating smolts upstream of the intake this increase represents almost 4000 smolts yearly. At the same time, a bypass increase from 3 to 15 m^3s^{-1} for 50 days involved an increased yearly cost of 1.4 million kWh, representing a cost of roughly 18 US$ per fish (market estimated Norwegian energy price is approximately 0.03 US$/kWh for May 2012 and May 2013.)

Effects of flood spill in target periods

The other strategy, instead of a constant increase in bypass discharge throughout the smolt run, was to look at selected years where high tunnel migration (low survival) was discovered in the initial simulations (3 m^3s^{-1} in bypass). In days when the smolt timing model predicted high numbers of migrating smolts, the bypass discharge was increased from 3 to 50 m^3s^{-1}. The route choice model was used to simulate increased bypass discharge 24 hours a day and a modified regime with increased discharge only at night (22:00- 05:00) (Table 3).

Averagely the proportion of smolts in the bypass increased from 21 to 51 % in the selected eight years, representing an increase of approximately 9000 smolts yearly and to an average cost of around 9 US$ pr fish, when the increased discharge of 50 m^3s^{-1} was spilled 24 hours a day. Increased bypass only during night would increase the number of smolts in the bypass by 4500 fish yearly and at the same time the energy cost was reduced from 9 to 5.1 € pr fish. As showed in table 3 this strategy is best suited for the seasons with a short migration period since the cost is linearly dependent on the period of flood spill. In 2007 this period was only 7 days, while in 1992 flood spill was needed for almost one month (25 days) according to this strategy

Effects of reservoir manipulations

One of the two large reservoirs, Nåvann, was manipulated to simulate the effect of a modified river discharge on the smolt migration in 2002 and 2007. These two seasons were also included in the eight seasons in the previous paragraph and were characterized with large smolt mortality. Additionally, the initial simulations showed that the smolt run came particularly synchronized and peaked very early these two years (Figure 5), a migration pattern observed during the recent years. A change of the reservoir guide curve for Nåvann reservoir changed the river discharge during the smolt run. The results of the calculation showed that river discharge was reduced both years between April 24 and June 1 but water temperature did not change significantly (Table 4).

Additionally, the smolt run duration did not change significantly in any of the two years. 90 % of the smolts migrated within 13 days in 2002 and 8 days in 2007 respectively, demonstrating synchronized smolt runs both years. The major difference was connected to the reduced river discharge during the smolt run (Figure 7). Since total discharge at the Laudal intake is negatively correlated with bypass migration in the route choice model, this change was reflected with higher bypass migration according to model. With a minimum residual discharge in the bypass of 3 m^3s^{-1} the bypass migration increased from 19 to 59 % in 2002 and from 26 to 53 % in 2007 with a new release guide curve at Nåvann. Hence, the increased number of smolts in the bypass was 12000 in 2002 and 8100 in 2007. Further, the number increased to 80 % in 2002 and 76 % in 2007 when simulated bypass discharge was increased from 3 to 15 m^3s^{-1} under the new release regime from Nåvann, representing another 6300 smolts in the bypass in 2002 and 6900 in 2007 respectively. Output from the nMag model suggested that the new release schedule did not involve increased costs, as flood spill was not increased. On the other hand increased bypass spill from 3 to 15 m^3s^{-1} involved an extra cost of 5.8 US$ per fish in 2002 and 6.3 US$ per fish in 2007. The last calculation involved extra bypass spill during 26 days in 2002 and 27 days in 2007, representing the total number of migration days(one fish or more) simulated by the timing model. Hence, savings per fish could be obtained by reducing the spill period, for instance to the main peak of 8 days in 2002 and 13 days in 2007 or by nightly release exclusively. According to such an analysis for the year 2007, an increase of altogether 15 000 smolts could be bypassed at the intake, at a cost of 2.8 US$ per fish.

DISCUSSION

In the present study different bypass release strategies at a hydropower intake and from an upstream reservoir were explored by combining a hydropower simulation model and models for smolt timing and route choice for the Laudal power plant in River Mandalselva. Modelling of the smolt migration was conducted for 22 years, from 1988 to 2009. Firstly, the models were run with focus on optimized power production using the current release strategy. The results showed that more than 50 % of the smolts migrated through the turbines all years (averagely 70 %), and some years the proportion was 80-90 %. The first attempt to increase bypass migration was to simulate the impact of increased bypass discharge from 3 to 15 m^3s^{-1} during 50 days each spring. The results demonstrated that the proportion of fish that would choose to migrate the bypass increased from 30 to 43 % on average, at a yearly energy cost of 1.4 million kWh as a result of spilled water. The cost represented approximately 18 US$ per extra fish in the bypass, based on estimated market energy price for the 2012 and 2013 seasons. The next modelling step was to investigate a 50 m^3s^{-1} bypass flood in eight selected years in periods when smolt migration was simulated to be large. This analysis suggested that bypass migration increased on average from 21 to 51 % these eight seasons, resulting in an average flood spill cost of 9 US$ per fish. Finally, a modified release schedule from one of the large reservoirs was simulated for the smolt run in 2002 and 2007. The bypass migration was increased from 19 to 59 % in 2002 and from 26 to 53 % in 2007 respectively. An additional increase of bypass spill from 3 to 15 m^3s^{-1} during the smolt run increased the bypass to 80 % in 2002 and to 76 % in 2007, to an energy cost of 5.5- 6.3 € per fish.

Earlier studies have suggested that various configurations of physical measures can be used to guide smolt safely past hydro power turbines but the effect depend on site, species and physical conditions (Scruton et al. 2008, Calles et al. 2011). The findings of the present study are based on simulation models for river discharge, water temperature and smolt behavior. To the knowledge of the authors, smolt migration models accompanied with hydropower simulation models has not been used as a management tool to obtain favourable conditions for Atlantic salmon smolt migration. Modeling of hydropower variables, such as discharge and energy production, is founded on a market strategy within the frame of production capacity and available water, and the output represents an accurate estimate according to this strategy. A drawback with the model used in this study is that it uses a constant price function for all years and does not capture between years and short-term price variations. Issues related to short-term simulations were solved by using a separate diurnal price model implemented in a Microsoft Excel spreadsheet.

Fish behavior models are strongly dependent on the specific site. (Davidsen et al. 2005; Antonsson and Gudjonsson 2005) and must be based on detailed behavioural studies over time. The smolt timing model and the route choice model used in this study have been developed over several years in river Mandalselva, but adequate data for very high discharge was scarce. Fjeldstad et al. (2012) suggested that the smolt route model was calibrated for river discharges up to 110-120 m^3s^{-1} and that further telemetry studies were desirable for extension of this range. In the present study the model has been utilized for all discharges. Hence, in years with synchronized smolt migration at high floods this might give uncertain route choice results. (Floods exceeding 110 m^3s^{-1} were simulated in shorter periods in eight of the 22 studied seasons, but no further analysis has been conducted for these periods.) The smolt timing model has been developed and calibrated after each smolt run since 2003, based on smolt catches from a screw trap. Catching of smolts in a river is expensive and often challenging and reliable predictions are only achievable at an early date from a simulation model. Such predictions are necessary for long term hydro power planning, such as reservoir release strategies. The study shows that it is possible to manipulate smolt migration, particularly routing, by adapting reservoir releases in the cases when discharge is the forcing variable. The second key variable for smolt timing is water temperature, and it is far more difficult to modify river temperature by releasing or withholding water from the reservoirs, and this also has proved to be an expensive option. This is particularly the case in the warmer years with an early smolt run, releasing enough water to keep temperature down would be too costly to be feasible. Measured air temperatures and simulated water temperatures increased over the studied period. Whether this is a consequence of a climatic trend for the Mandal area has not been analysed as part of the study but it does correspond with the global observation of warming. Anyhow, such changes might influence the migration pattern in a river and consequently the strategies for management of the fish population and the hydropower production.

Smolt mortality rate through the Francis turbines at Laudal power plant has not been verified. In the present study the simulations suggest the route choice at Laudal and the mortality among smolts migrating into the intake is uncertain. A simplified calculation based on the turbine design has showed that the likelihood for direct blade strike can exceed 70 % and unpublished data from mark recapture studies of tagged smolt indicated 5 times higher return rate of adult fish that migrated through the bypass as smolts (Dagfinn Laudal, pers. comm.). A more accurate study of turbine mortality is desirable and will further clarify the consequences of the route choice for the salmon population, but routing of smolt through the bypass is regardless the preferred objective.

The work presented in this paper shows the applicability of combining hydropower simulation tools and smolt migration models to investigate the potential for reducing losses of out-migrating smolts at a hydropower intake. As shown in the paper, this is useful in understanding effects of operational regimes and in the planning of mitigation measures based on historical data. Since most Norwegian hydropower companies run inflow prognosis and production planning on a regular basis it could be possible to include smolt passage simulation in an operational context. Based on reservoir filling and snow storage data, a migration timing prediction could be made based on historical climate scenarios. Furthermore, migration timing and route choices could be simulated based on the day-to-day prognosis data and in situations with a potential for high migration measures could be taken. This could both secure migration survival and minimize the spill of water for the hydropower company, and would be a useful addition to existing management tools for Atlantic salmon.

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TABLES

Table 1. The six power stations in the River Mandalselva system with power capacities, flow capacity and yearly production figures. The column for calculated production comes from the nMag model while the next column shows production data from the power company. The last column shows the difference between calculated and observed production.

			Production (GWh)		
Power station	**Max. Power (MW)**	**Max. Q (m3s-1)**	**Calculated**	**Observed**	**Diff (%)**
Logna	19,60	14,9	107	105	2,3
Smeland	21,97	28,6	123	119	3,1
Skjerka	90,59	31,0	579	612	-5,4
Håverstad	41,59	60,0	270	282	-4,1
Bjelland	56,85	79,0	321	312	3,0
Laudal	29,13	110,0	151	146	3,6

Table 2. Eight selected years when bypass discharge was increased from 3 m^3s^{-1} to 50 m^3s^{-1} in days when smolt migration was estimated to be large. "Release days" indicate the number of such days. The two next columns shows the proportion of smolts that chose the two alternative routes. The two last columns gives the total calculated yearly energy cost when discharge was increased 24 hours a day (all day) and only during night (22:00- 05:00).

		Proportion in bypass (%)		**Energy cost (kWh)**	
Year	**Release days**	**3 m^3s^{-1}**	**50 m^3s^{-1}**	**50 m^3s^{-1} all day**	**50 m^3s^{-1} during night**
1992	25	26	60	2 766 420	806 873
1995	19	26	60	2 102 479	613 223
1999	19	22	54	2 102 479	613 223
2002	10	19	44	1 106 568	322 749
2003	16	12	34	1 770 509	516 398
2007	7	26	68	774 598	225 924
2008	8	9	21	885 254	258 199
2009	11	25	66	1 217 225	355 024
Average	**14**	**21**	**51**	**1 590 692**	**463 952**

Table 3. Two years, 2002 and 2007 was simulated with two different release curves from the Nåvann reservoir, one simulation with optimized power production (original curve) and a second schedule with delayed release (modified curve) to delay the smolt migration. The table shows discharge and water temperature between April 24 and June 1 at the Laudal intake for both seasons and for both curves.

	Discharge (m^3s^{-1})				**Water temperature (˚C)**			
	Original curve		Modified curve		Original curve		Modified curve	
	Mean	Max	Mean	Max	Mean	Max	Mean	Max
2002	78	242	61	199	7.1	9.8	7.3	10.2
2007	51	82	29	55	8.5	11	8.8	11.5

FIGURE CAPTIONS

Figure 1. The River Mandalselva with the two lowermost power plants, Laudal and Bjelland, and the intake reservoir to Laudal power plant, Lake Mannflåvatn. The bypass reach between the intake to Laudal power plant and the power plant is indicated with a black rectangular. The smolt capture site, Hesså, is found between the lake and Bjelland power plant.

Figure 2. Representation of the River Mandalselva power system in the nMag model. White rectangulars indicate reservoirs and grey rectangulars represent the power station. Other elements and numbers are nodes in the model. “Project focus” indicates the Laudal power plant and the bypass.

Figure 3. Simulated river discharge at Laudal power plant from the nMag model in the month of May for the years 1988-2009.

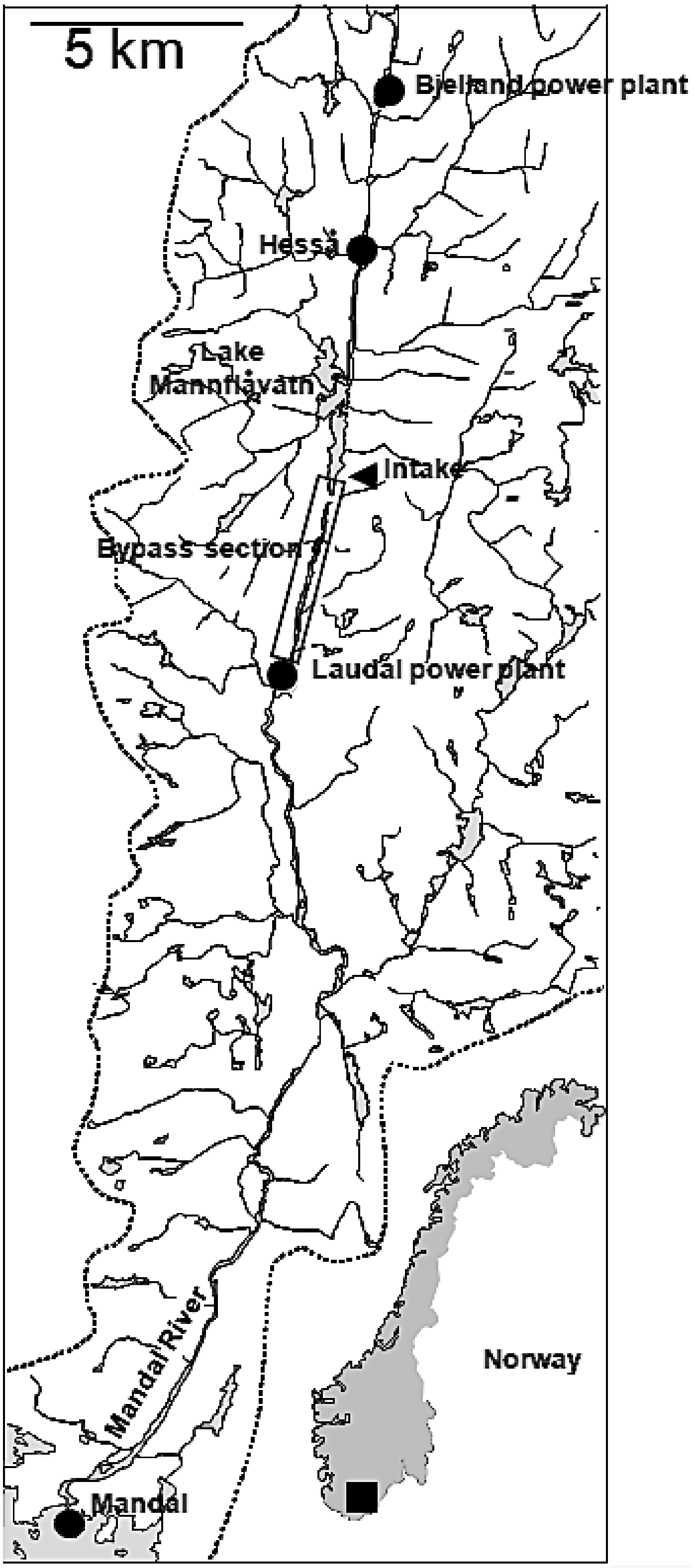
Figure 4. Calculated water temperatures at Laudal power plant in the month of May for the years 1988-2009.

Figure 5. Simulated smolt migration pattern for the years 1988-2009 with optimized power production (minimum bypass discharge at Laudal power plant of 3 m^3s^{-1}).

Figure 6. Number of years at different proportions of smolt in the intake route indicated with black bars (3 m^3s^{-1}) and grey bars (15 m^3s^{-1}). As an example: at the lowest discharge 70-80 % of the smolts chose the intake in eight out of 22 years. When bypass discharge was increased to 15 m^3s^{-1} the simulations suggested that this was the situation in only one of the 22 years.

Figure 7. River discharge at the Laudal intake in 2007 with original release curve (optimized power production) from the Nåvann reservoir and with delayed release (manipulated curve) from April 1 to May 30.

FIGURES



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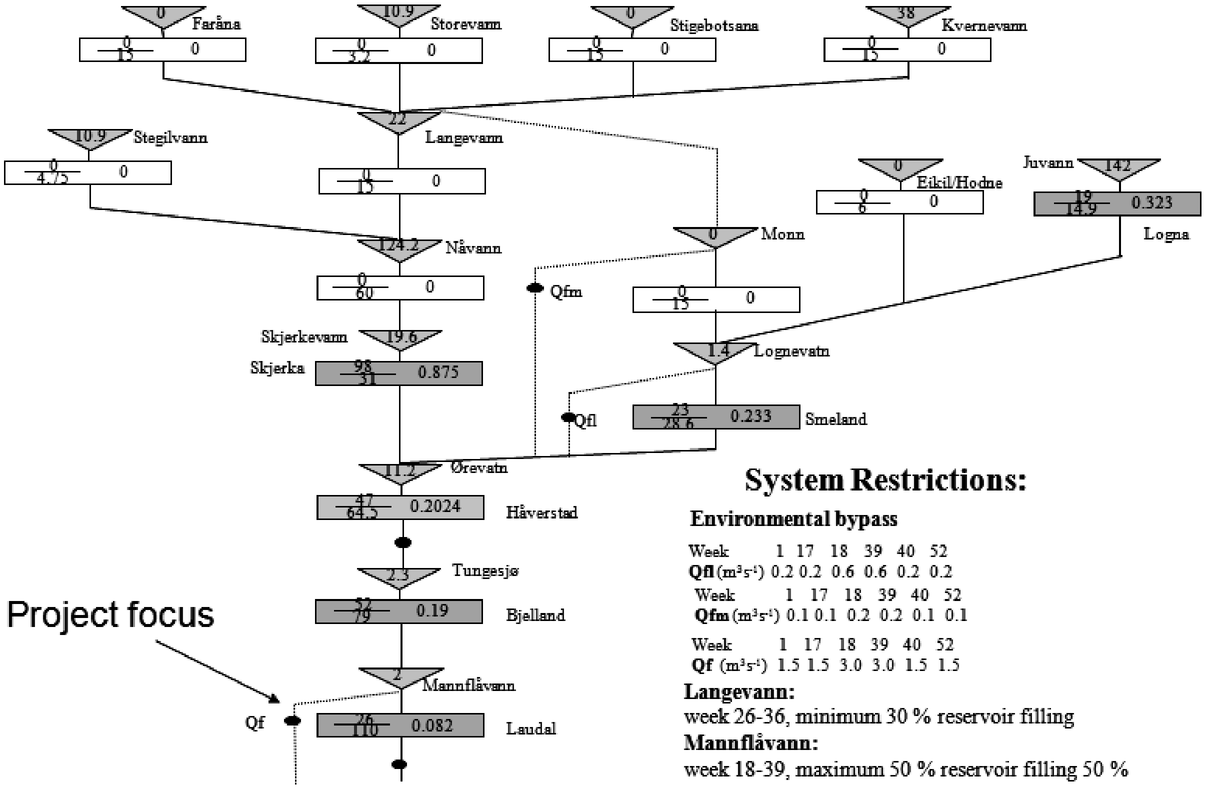

System Restrictions:

Environmental bypass

Week	1	17	18	39	40	52
Qfl (m^3s^{-1})	0.2	0.2	0.6	0.6	0.2	0.2

Week	1	17	18	39	40	52
Qfm (m^3s^{-1})	0.1	0.1	0.2	0.2	0.1	0.1

Week	1	17	18	39	40	52
Qf (m^3s^{-1})	1.5	1.5	3.0	3.0	1.5	1.5

Langevann:
week 26-36, minimum 30 % reservoir filling
Mannflåvann:
week 18-39, maximum 50 % reservoir filling 50 %

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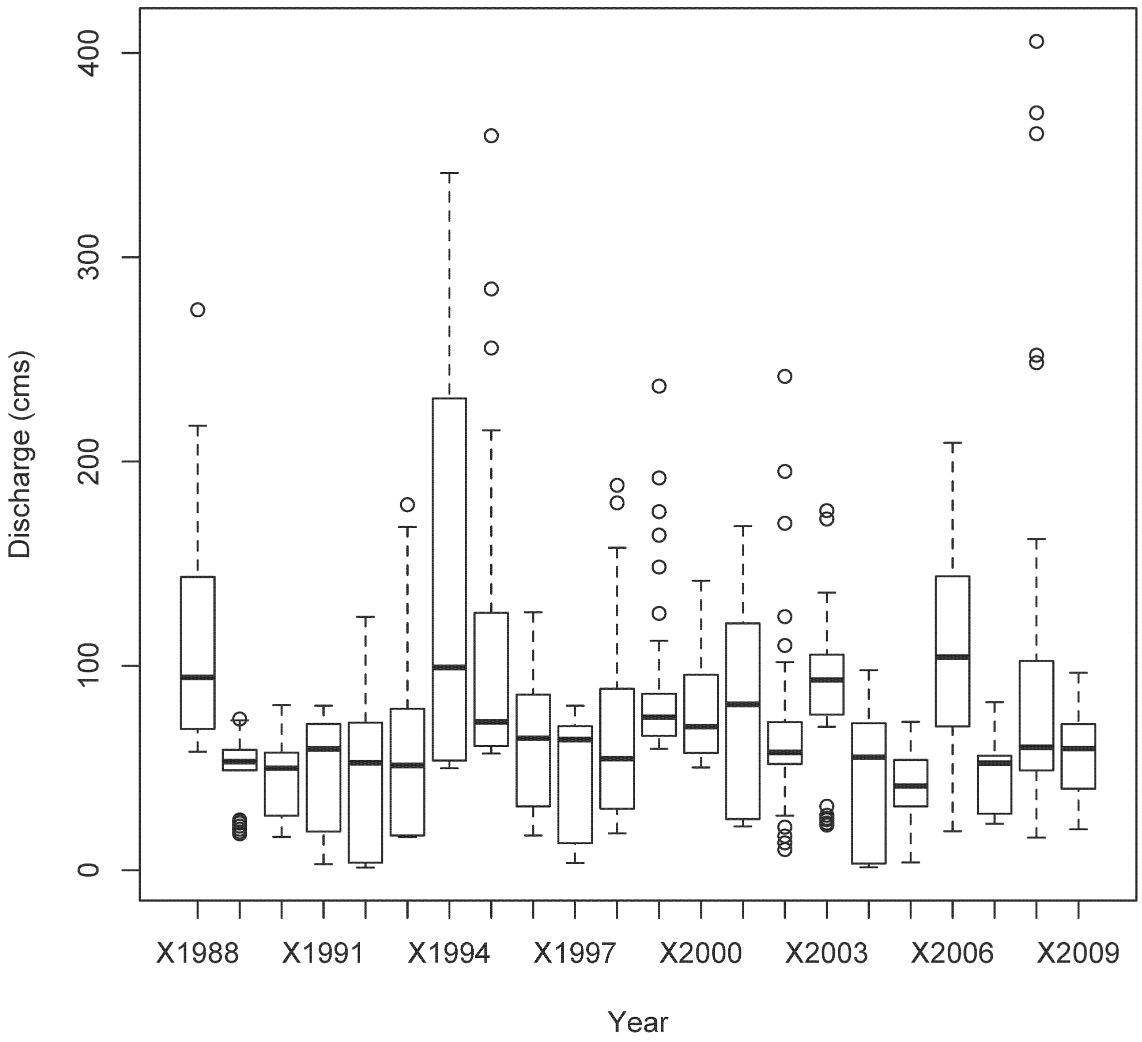

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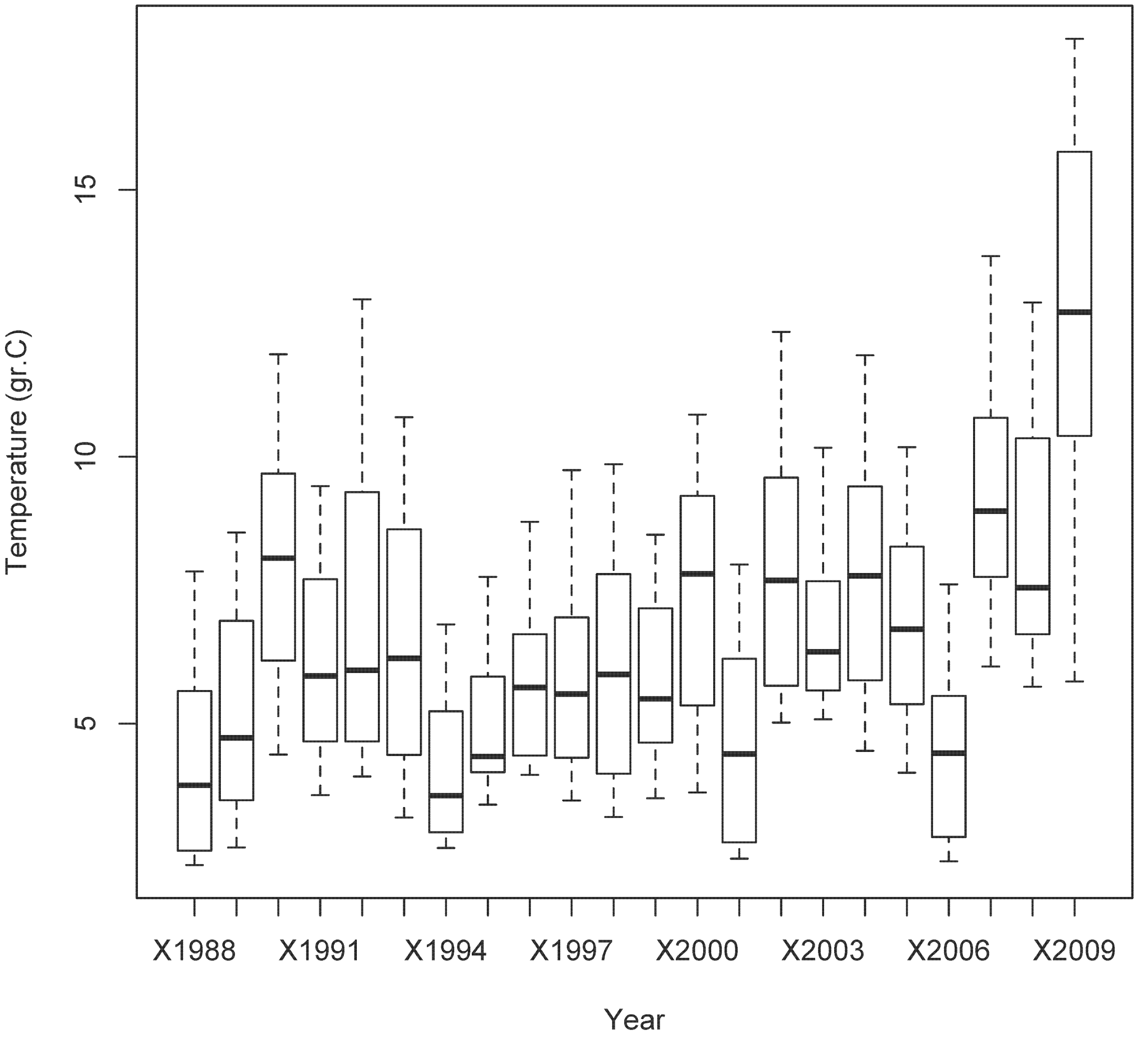

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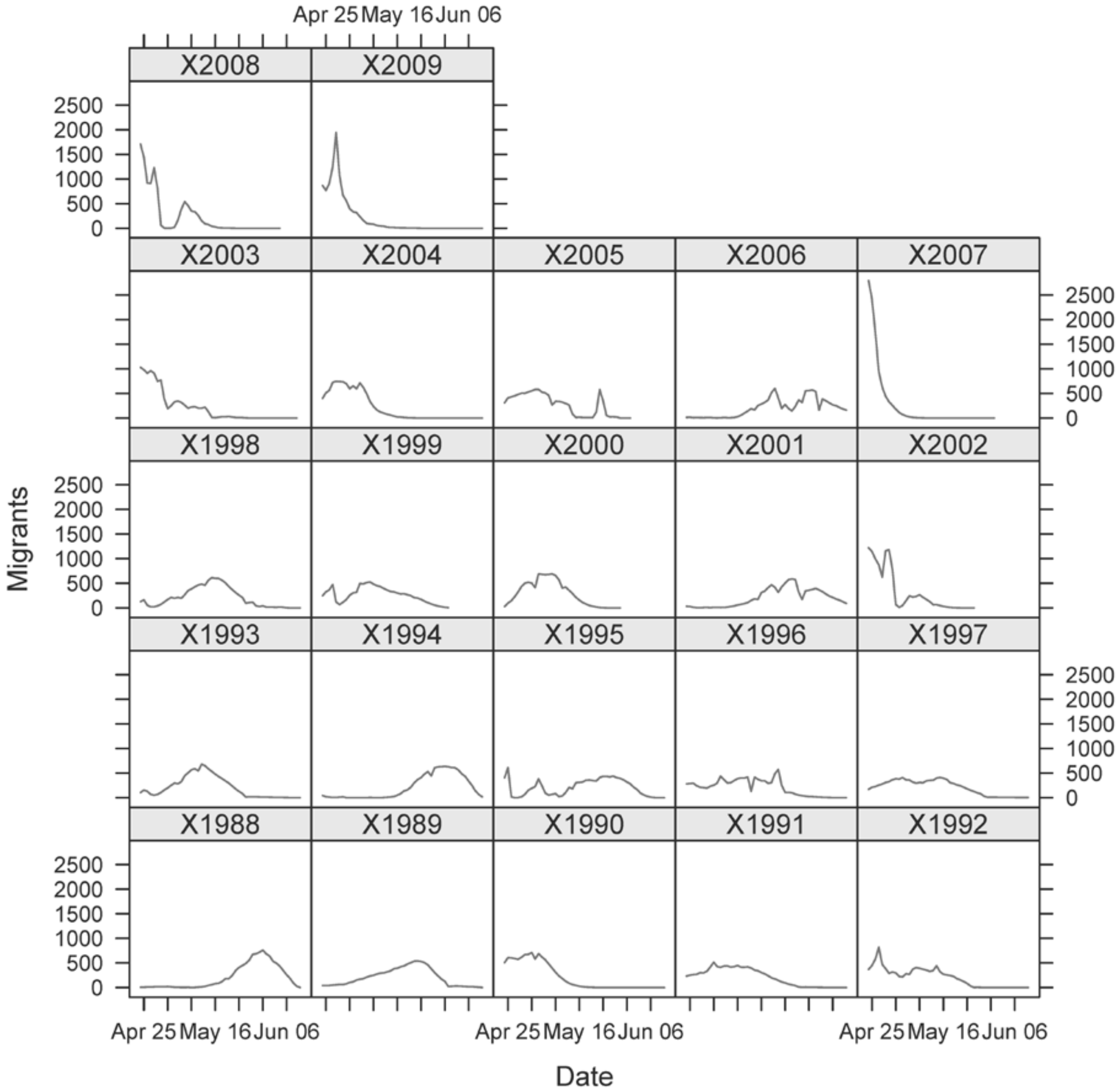

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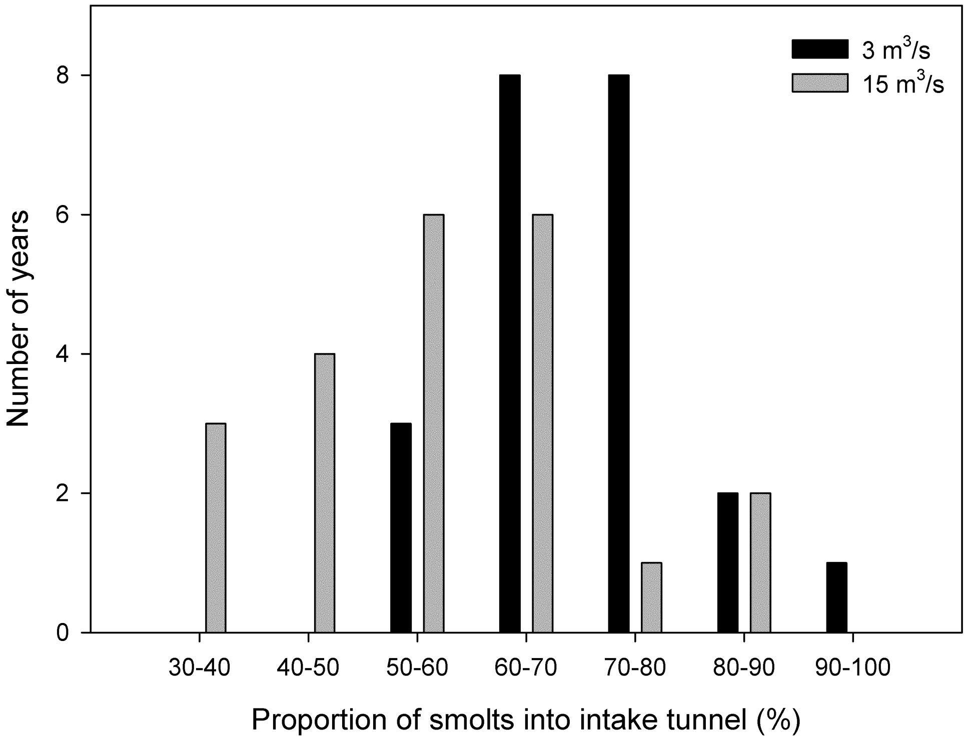

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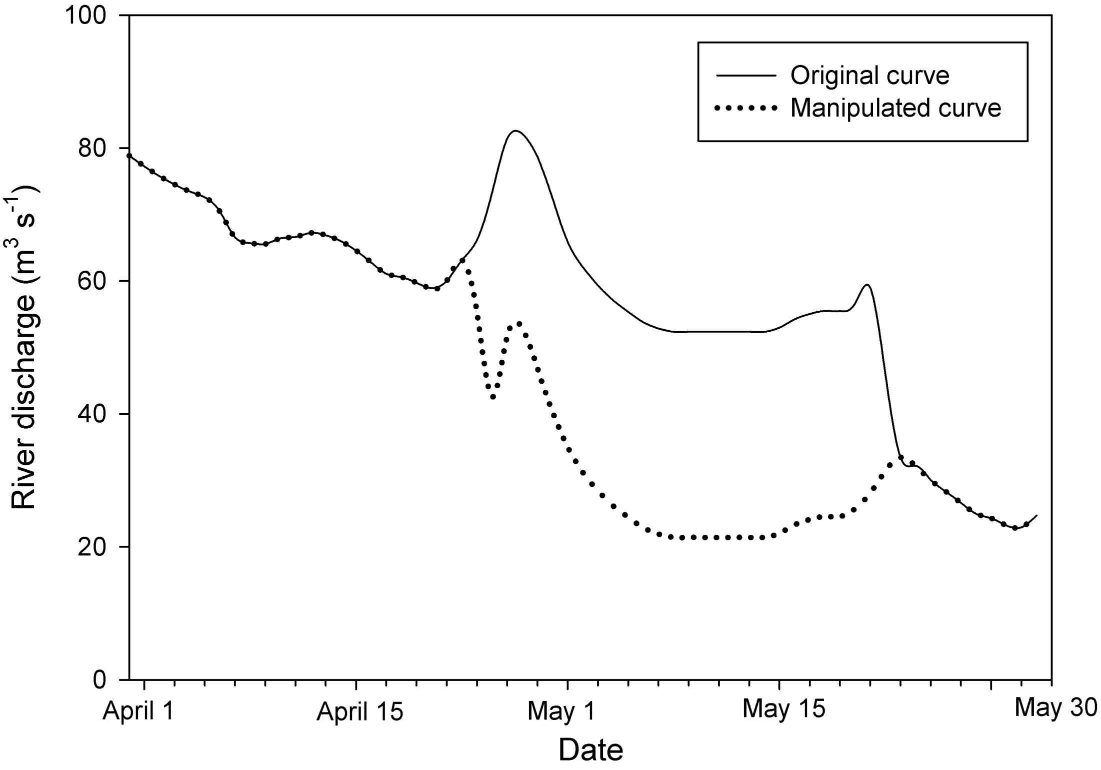

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