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REMOVAL OF WEIRS AND THE INFLUENCE ON PHYSICAL HABITAT FOR SALMONIDS IN A NORWEGIAN RIVER

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ABSTRACT

In the late 1970s, the construction of weirs in Norwegian regulated river systems for aesthetic reasons was common. However, today, the focus of river restoration has shifted towards improving biological functionality and biodiversity. In the present study, two weirs, originally built to create a stable water level, were removed on a residual flow reach in a Norwegian regulated river as a measure to restore river connectivity and to re-establish the local population of Atlantic salmon. The removal design was based on hydraulic modelling, and biological monitoring was implemented before and after the weir removal to evaluate the biological response to weir removal. The results demonstrated that salmon spawning sites were recreated in the old bed substratum and were occupied immediately the first season after weir removal, when water velocities increased to more suitable levels for spawning. Accordingly, mortality of Atlantic salmon eggs was reduced and the densities of juveniles showed a marked increase after weir removal. Conversely, pike and cyprinids in the reach were found in the samples before weir removal but not after removal, indicating that the desired shift in fish community in response to habitat alteration was obtained. Furthermore, enumeration of migrating adult salmon at a fishway upstream of the study reach showed that the migration peak, on average, was 1 month earlier in the 3 years after removal as compared with the 5 years before removal. Finally, the use of hydraulic modelling represented a useful method for designing physical habitat adjustments and assessing their influence on fish biology. The model results also supported a rapid process in planning and execution of construction works.

KEY WORDS: dam removal; habitat modelling; habitat improvement; Atlantic salmon; river restoration; weir removal

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INTRODUCTION

Fragmentation of river systems and alteration of discharge are found in the majority of large rivers in the world (Nilsson *et al.*, 2005), and a consequence of this is loss of habitat and habitat connectivity. Construction of dams and weirs is a major threat to riverine fish populations (Petts 1984; Ward, 1989; Larinier, 2001) and is particularly harmful to diadromous fishes (Scruton *et al.*, 2008). This includes degradation of spawning sites and elimination of fast-flowing habitats for juvenile salmonids (Poff and Hart, 2002). Also, construction of dams and weirs can delay or block the migration routes of Atlantic salmon (*Salmo salar* L.) (Mills, 1989).

Physical, chemical and biological consequences of dam and weir construction, especially local effects, have been extensively studied over the past decades (Ward and Stanford, 1979; Ligon *et al.*, 1995; Pringle *et al.*, 2000). However, during the last two decades, removal of dams and weirs has become an important ecological issue, and the process is accelerating (Poff and Hart, 2002). As structures become older, their functional value often decreases, and this is especially common among smaller dams and weirs; consequently, increasing attention on dam removal is expected to evolve in the future (Hart *et al.*, 2002). Political agreements, such as the European Union's Water Framework Directive, support and even force ecological restoration of water courses. The positive impacts from dam removal on upstream migration seem obvious, and different studies have demonstrated these effects (American Rivers, 2002). At the same time social and economical aspects can make both construction and removal of dams controversial (Babbitt, 2002).

Acid deposition and acidification of Norwegian catchments peaked in the 1980s and resulted in both chronically and episodically acidified rivers (Hesthagen, 2011). The Atlantic salmon population in the river Nidelva was decimated during the first half of the 20th century, and during the 1970s, the population was extirpated (Hesthagen and Hansen, 1991). Consequently, little attention was paid to maintain the salmon habitat when the new Rygene powerplant was built in the 1970s. On a 3-km minimum flow reach, from the lowermost hydropower plant at Rygene to the estuary, three 50-m wide concrete weirs were constructed in

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the late 1970s. The purpose was to make the reach less barren and to improve conditions for different recreational activities. The weirs created 2.6 km of lake habitat, well suited for lake dwelling fish species but unsuited for migration, spawning and rearing of salmonids. Liming of lakes in the river Nidelva catchment started in 1997, and in 2005, full-scale liming of the river was in place. At present, water quality has reached sustainable levels for most native aquatic species, and a major objective is now to re-establish the Atlantic salmon stock. The new stock has gradually increased in size, based on planting of eggs, straying of spawners from nearby rivers and escaped farmed fish. The residual reach with weirs proved to be an obstacle for migration (Thorstad *et al.*, 2003, 2008), and habitat conditions were also unsuitable for spawning and rearing of juveniles. Adult salmon were delayed at the tunnel outlet of the power plant and between the weirs, even though the weirs were equipped with fish ladders (Thorstad *et al.*, 2003).

Hydraulic modelling has been increasingly used for analyses of aquatic biology, and 2D hydraulic models provide good representation of fish habitat and river hydraulics (Lacey and Millar, 2004). Higher order 2D and 3D models are not based on measured velocity data in the same fashion as in traditional one-dimensional modelling, which improve their predictive capacity. The application of 2D/3D models is well suited for analyses of impacts of changes in geometry on flow conditions such as habitat rehabilitation (Alfredsen *et al.*, 2004), and the ability to calculate lateral flow and flow curvature provides additional information for analysis of habitat changes (Ghanem *et al.*, 1996; Guay *et al.*, 2000). Surprisingly, predictions from hydraulic models as support for salmonid habitat restoration in rivers have only been documented in a few scientific papers, particularly because the predictive capability of the models could be very useful in such projects. Jalón and Gortázar (2007) used the two-dimensional model River2D (Steffler, 2000, University of Alberta, Canada) to simulate habitat adjustments for Atlantic salmon on the river Pas in Spain. Alfredsen *et al.* (2004) presented results from different rehabilitation studies in Norway by using different computer models; however, comparable biological responses were not verified. Generally, follow-up examination of biological results from model studies of physical habitat adjustments is lacking in many projects.

Restoration projects and investigations of their influence on fish biology in Norway are rare, and no peer reviewed studies on dam removal in Norway have been published. In this study, a hydraulic model was used to describe the effects of weir removal on salmon habitat on two sections of the river Nidelva. The model was calibrated to the existing conditions and used to simulate the impacts of removing two weirs in the minimum flow reach. An objective was to utilize the model analyses to support the planning and execution of the weir removal. Consequently, collection of physical data and biological monitoring before and after removal was used to test the mitigating effects of dam removal, with a focus on spawning, migration and juvenile habitat.

MATERIALS AND METHODS

Study site

The study was carried out in the river Nidelva, in south-east Norway (58.4°N, 8.6°E) (Figure 1). The river is 210 km long with a catchment area of 4000 km² and a mean annual discharge of 110 $m^3 s^{-1}$. River Nidelva is extensively regulated by 16 hydropower plants. Atlantic salmon and brown trout (*Salmo trutta* L.) can migrate 18 km upstream from the Rygene power plant to the final migration barrier approximately 22 km from the sea. River Nidelva was known as a productive salmon river already as early as the 12th century, and fishery yields of 4–8 metric tons were reported yearly in the last part of the 19th century (Hesthagen, 2011). Other fish species indigenous to the river are European eel (*Anguilla anguilla*), European perch (*Perca fluviatilis*), three-spine stickleback (*Gasterosteus aculeatus*), European flounder (*Platichthys flesus*) and sea lamprey (*Petromyzon marinus*). In addition, brook trout (*Salvelinus fontinalis*), tench (*Tinca tinca*), common roach (*Rutilus rutilus*) and northern pike (*Esox lucius*) have been introduced to the river.

The study site was located downstream of the Rygene hydropower plant (Figure 1), the lowermost plant in the river, which has a 38-m head and a 170 $m^3 s^{-1}$ turbine capacity. The waterfall has been utilized for hydropower production for more than 100 years, but salmon and trout can ascend the waterfall through a fish ladder where all fish are enumerated. The tailrace outlet is located at Helle, 3 km downstream of the Rygene waterfall, leaving a minimum flow of 5 $m^3 s^{-1}$ in summer and 1 $m^3 s^{-1}$ in winter in the study reach. Through an agreement between the power company and stakeholders since 2007, a summer discharge of 3 $m^3 s^{-1}$ has been released during the weekdays, compensated by a 15 $m^3 s^{-1}$ attraction flow during the weekend. This regime was assumed to accelerate upstream migration through the reach.

The study site included the two lower weirs and the river reach influenced by them, altogether a 900-m-long section of the residual flow reach. The weirs were situated at natural sills in the river. Both weir crests were horizontal with a maximum height at the deepest part of approximately 2.5 m. One pool and weir fish ladder were constructed on the left side of each weir, and a 10-m-long, 30-cm-deep slot constricted the remaining residual flow in the middle of the crest of each weir. In 2007, the concrete constructions were completely removed with explosives and excavators, and the river course was restored to its natural shape to the extent

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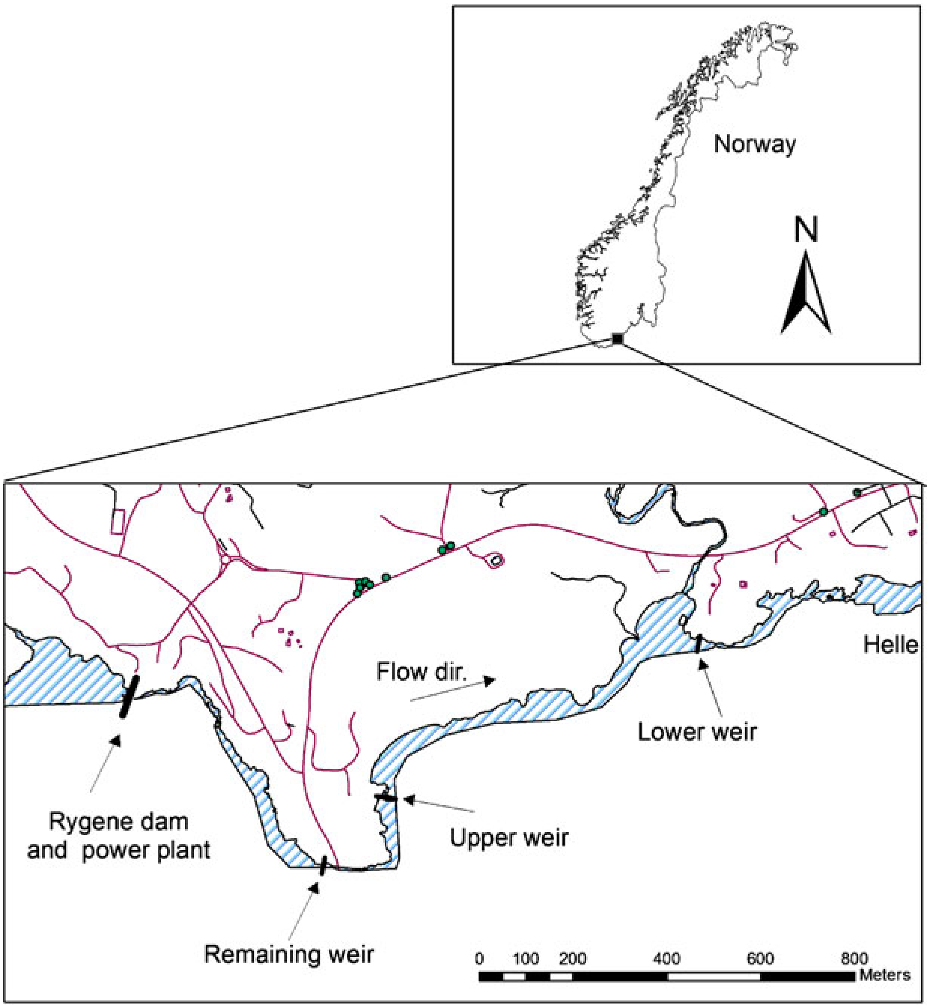

Figure 1. Site map. Hatched area represents the river. This figure is available in colour online at wileyonlinelibrary.com/journal/rra.

possible. Of the two weirs, the upper was characterized with a deep pool (17-m maximum depth) and an appendix-like widening of the river, which were not considered good salmon habitat. Nevertheless, the area adjacent to and upstream of the weir was a known historical spawning area. The lower weir was characterized by a 700-m river section including several pools and deeper reaches linked together with shallow areas. Sediment transport within the study site was regarded as small, because the Rygene dam, situated a short distance upriver from the site, trapped much of the bedload, whereas there were no significant tributaries into the river between the dam and the study site. Transport of sediments was therefore not included in the project. Large parts of the river bed in the study site consisted of gravel bars and cobbles and boulders (10–40 cm diameter). Some bed rock and sand were observed, mainly along the banks. Bed material in the deeper areas was not characterized.

Methods

Physical mapping. The topography ($n = 1156$), water levels and water edges ($n = 642$) in the two study reaches were mapped using a Leica System 500 Differential GPS-system (DGPS) (Leica Geosystems, St. Gallen, Switzerland) and AGA Model 400 Geodimeter (AGA, Arvada, CO, USA) in addition to depth sounding from a boat. Sounding was conducted using an Atlas Model 47 Echo Sounder (Atlas Hydrographic, Bremen, Germany) coupled with manual soundings, both positioned by the DGPS. A topographic map of the site is presented in Figure 2. Water level and water edges were measured at two discharges, 3 and 15 $m^3 s^{-1}$. Location and characteristics (position, height and width) of weirs and their fish ladders were also included in the survey. River bed substratum was mapped by visual interpretation from either a boat or from the river banks.

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Hydraulic modelling. The River2D hydraulic model (Steffler, 2000) was used for the hydraulic simulations. The model solves the depth-averaged shallow-water equations using a finite element method and has been used for a number of hydraulic-habitat projects (e.g. Crowder and Diplas, 2000; Jalón and Gortázar, 2007; Waddle, 2010).

The study area was divided into two sections, one above each of the weirs to be removed, hereafter referred to as upper and lower reaches, whereas the remaining weir is named the intact weir. The hydraulic models for each section were set up using measured topography and calibrated for observed water levels. A number of simulations for different alternative weir removal strategies were then conducted as follows: (i) for the upper reach, the current situation and reduction of water level by 0.7 m after weir removal were simulated; and (ii) for the lower reach, the current situation and reductions of water level by 0.5, 1.0 and 1.6 m were simulated, with the last scenario representing full removal of the weir. The two other reduction values (0.5 and 1.0 m) for the lower weir were considered to mimic alternative modifications of the weir to potentially reduce costs. All scenarios were modelled with discharges of 3 and 15 $m^3 s^{-1}$ as the future minimum flow alternatives. The main output variables, for example, water velocities, water depths and wetted area were analysed for each case. Velocity distribution plots were based exclusively on wetted grid cells.

A meso-scale approach was used to verify the model. Based on simulations, runs, riffles and pools were identified from the model results, and an on-site inspection after weir removal was conducted to verify the distribution of riffles, runs and pools as predicted by the model. Post-removal measurements of water levels were mapped with DGPS to verify the simulated hydraulic slopes and wetted area for the post-removal situations.

Colour images of the simulated hydraulics, in addition to an interpretation of probable biological consequences of the physical changes, were presented for the decision makers and local interest groups. This information contributed to a rapid decision of weir removal and was used to support the tender documents for the subsequent construction works.

Biological monitoring. In 2002, new spawning beds were created for Atlantic salmon through the addition of gravel in three areas (approximately 136, 210 and 110 m^2). One gravel addition was placed in association with running water found upstream of the upper weir, whereas the other additions were placed further upstream, that is, upstream of the intact weir. After the weirs were removed in 2007, gravel was added to an additional three spawning areas (approximately 52, 105 and 270 m^2) where typical lake habitat had changed into river habitat as a result of the restoration.

Spawning activity was located by scuba diving and sampling of eggs from individual redds during winter or spring in the 2002–2009 period. Redds were categorized as belonging either to the restored areas or to the reference area. Eggs were identified to species level through genetic analysis

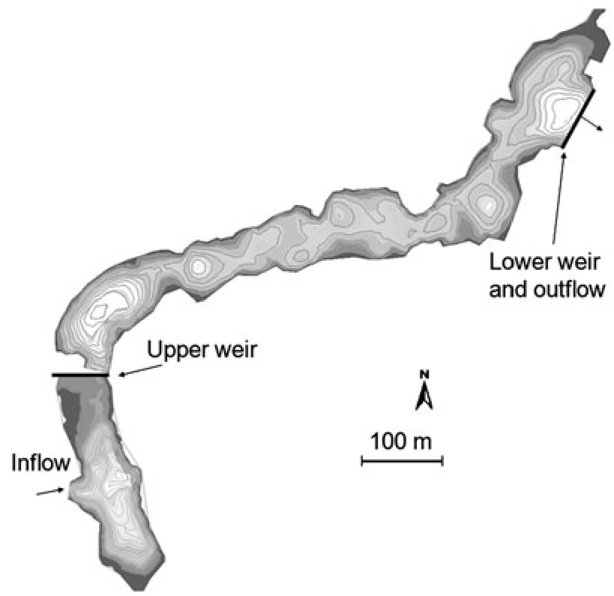

Figure 2. Bathymetric map with bed-level contours (interval = 1 m). The map covers wetted area at a discharge of 15 $m^3 s^{-1}$ before removal of the two weirs. The dam at Rygene hydropower station is situated around 400 m upstream from the inflow to the study site.

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(Mork and Heggberget, 1984; Vuorinen and Piironen, 1984). Because of the dominance of Atlantic salmon (99% of 340 redds was identified as Atlantic salmon), the additional 17 unidentified redds were also assumed to be used by Atlantic salmon. Three brown trout redds were removed from the analysis of redd characteristics.

For each sampled redd, the following data were recorded: egg survival (number of live to total eggs), water-depth (distance from gravel surface to water surface) and average velocity of the water column. Independent sample *t*-tests on arcsine transformed values were used to test each of these variables for differences before and after the restoration in both the restored and the reference areas.

Fish density estimates were obtained at 100-m^2 electrofishing stations (i.e. with three removals), following the method described by Bohlin *et al.* (1989). Electrofishing was conducted once a year, during the period from September to December. At each station, the total number of Atlantic salmon fry and fingerlings removed during electrofishing was used to record changes in fish density. In addition, the more sporadic appearance of other fish species such as pike or perch was recorded.

Between 2003 and 2007, electrofishing was conducted at two stations. One was located in the reference area just upstream of the intact weir and the other in the upper reach, just upstream of the upper weir. After the removal of the weirs in 2007, sampling continued at the two initial sites, and four additional stations were established in the restored area. The new stations were located in the restored area on the lower reach, where lake habitat had changed into riverine habitat as a result of weir removal.

Adult salmon and brown trout have been enumerated daily at the fish ladder at Rygene dam since 1992. Rygene is situated upstream of the study site and the enumeration is valuable for information regarding migration. Data for the seasons 2002–2009 were used in the migration analysis as the migrating fish stock was small until the beginning of this century. Only enumerated adult Atlantic salmon were used in this study as only a minor part of the migrating population was brown trout. Enumerated fish were grouped into 10-day intervals for the five seasons before weir removal (2002–2006). An equivalent dataset was compiled for the following three seasons (2007–2009) after the weir removal. The main focus of this analysis was to identify potential changes in the timing

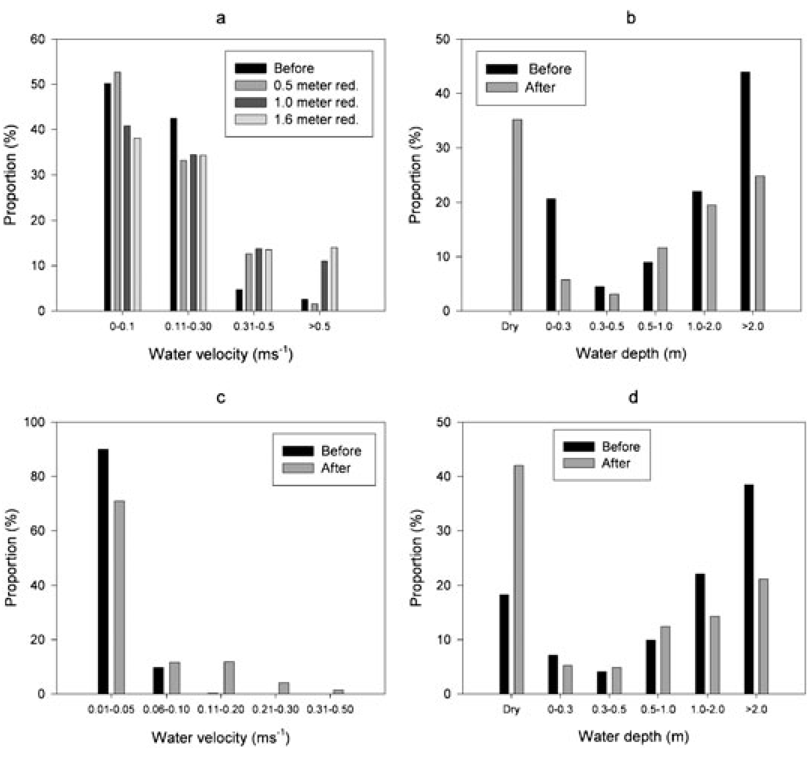

Figure 3. Calculated water velocities and depths before and after weir removal at 15 $m^3 s^{-1}$ (a and b) and 3 $m^3 s^{-1}$ (c and d) on the lower reach. Figure (a) also includes columns for partial weir removal (0.5 and 1.0 m water-level reduction). Dry cells are omitted in the velocity distribution figures.

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of migration as a result of the reduced number of physical obstacles (weirs).

RESULTS

Hydraulic modelling

The hydraulic conditions presented are based on the River2D model results. Flushing of added gravel was observed to some extent. However, erosion and sediment transport was regarded as insignificant in affecting the general distribution of the physical variables, such as water velocity and depth. Visual inspection of the post-removal conditions at the study site confirmed that the different meso-habitat characteristics, such as riffles and pools, were distributed as predicted in the model. Further statistical validation of the results was not considered to be within the scope of the project.

Lower reach. Simulated water velocities for the lower reach at a discharge of 15 $m^3\,s^{-1}$ showed a transition from low velocity to areas with more suitable water velocities for spawning (0.3–0.5 $m\,s^{-1}$) when the weir was removed. Modelling of full weir removal (1.6-m water-level reduction) determined that 22% of the area had calculated velocities greater than 0.3 $m\,s^{-1}$, as compared with before removal, where only 6% of the area had velocities larger than 0.3 $m\,s^{-1}$ (Figure 3). The simulation results of partial removal of the weir, for example, 0.5 and 1.0 m, indicated that water velocities increased proportionally with water-level reduction (Figure 3). Also, the areas with increased water velocities were found to be distributed throughout the reach after weir removal (Figure 4). At the same time, areas with calculated water velocities smaller than 0.1 $m\,s^{-1}$ were reduced from 50% to 38% when the weir was removed, reducing the habitat for competing, lake-dwelling fish species. Simulation and analysis of the three different scenarios for future water levels led to a management decision of complete removal of the lower weir. At a discharge of 3 $m^3\,s^{-1}$, only 0.2% of the wetted area had water velocities higher than 0.1 $m\,s^{-1}$ before removal of the weir (Figure 3), whereas 18% of the wetted area had water velocities between 0.1 and 0.5 $m\,s^{-1}$ after removal, which would improve both spawning and rearing habitat in the reach. Areas with very small velocities (0.01 to 0.05 $m\,s^{-1}$) were reduced from 90% to 71% after removal.

At the lower reach, the simulations demonstrated that the water level throughout the entire reach was influenced by the weir. At a 15 $m^3\,s^{-1}$ discharge, the area deeper than 2 m, habitats well suited for lake dwelling species, was reduced from 44% to 25% after weir removal and from 38% to 21% at 3 $m^3\,s^{-1}$ (Figure 3). Additionally, substrate mapping indicated that old gravel bars and cobbles were not silted or covered by organic material, which was favourable for a quick establishment of the restored habitat for salmon.

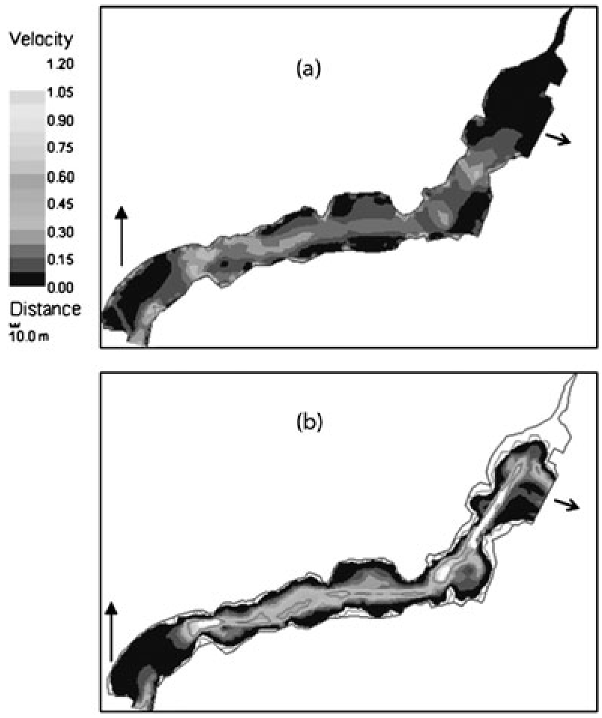

Figure 4. Calculated water velocities before (a) and after (b) complete weir removal at 15 $m^3\,s^{-1}$ discharge on the lower reach. Arrow indicates inflow and outflow directions.

Upper reach. Hydraulic simulations at both discharges (3 and 15 $m^3\,s^{-1}$) of the upper reach demonstrated that the main parts of the reach still appeared as a reservoir after the removal of the downstream weir. However, in areas with water velocities between 0.1 and 0.4 $m\,s^{-1}$, and especially in the interval between 0.1 and 0.2 $m\,s^{-1}$, the velocities generally increased to more than 0.4 $m\,s^{-1}$ after weir removal at a 15 $m^3\,s^{-1}$ discharge (Figure 5). Areas with water velocities larger than 0.3 $m\,s^{-1}$ were nearly doubled in area to 11% at higher discharge. Some areas with water velocities up to 0.1 $m\,s^{-1}$ became dry after weir removal, explaining, in part, why areas in the velocity interval 0–0.1 were reduced. The results indicated that standing water in the reach represented a large proportion of the wetted area. Areas with large water velocities were mainly located just upstream of the weir location, at a potential spawning area. Large cobbles and boulders at this location should also make this habitat suitable for juvenile salmonids. At a 3 $m^3\,s^{-1}$ discharge, there was an increase in areas with 0.1 and 0.2 $m\,s^{-1}$ from 0.3% to 10% of the wetted area.

The upper reach is basically a one large pool, and modelling of the weir removal confirmed that the entire area experienced a general water-level reduction of 0.7 m. Major areas in the reach remained deep (more than 2 m) after weir

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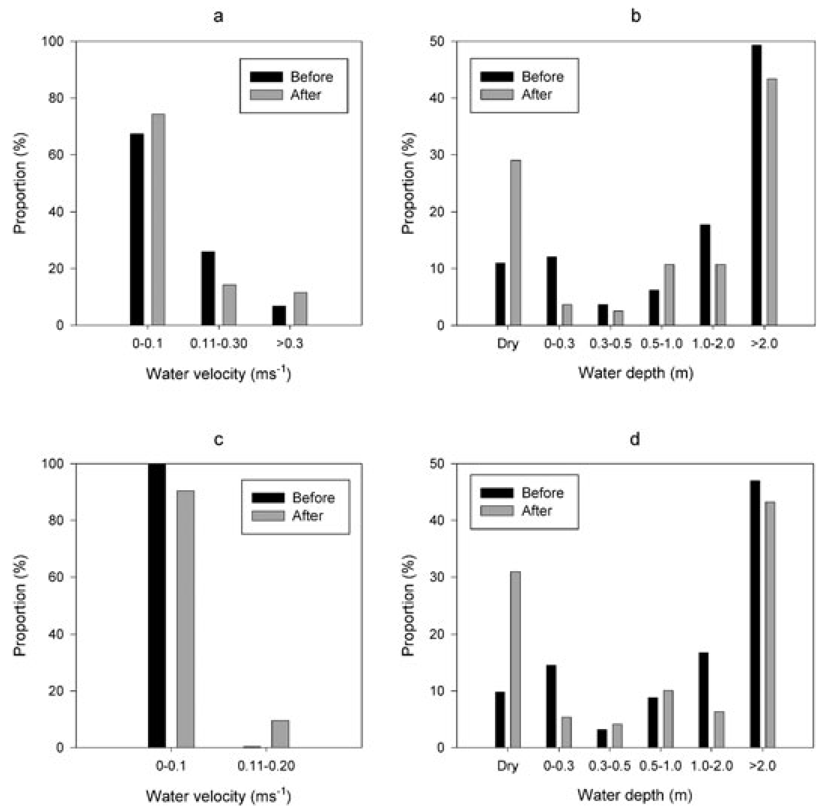

Figure 5. Calculated water velocities and depths before and after weir removal at 15 $m^3 s^{-1}$ (a and b) and 3 $m^3 s^{-1}$ (c and d) on the upper reach. Dry cells are omitted in the velocity distribution figures.

removal (Figure 4). Nevertheless, the amounts of deep area were reduced from 47% to 43% and from 49% to 43% of the wetted area at 3 and 15 $m^3 s^{-1}$, respectively.

Wetted area. Weir removal reduced the wetted area of the study site. At a discharge of 15 $m^3 s^{-1}$ on the lower reach, 35% of the original wetted area became dry after weir removal, which is one trade-off in such habitat adjustment projects (Figure 3). At 3 $m^3 s^{-1}$, the wetted area was reduced by 23% after weir removal. This came in addition to an 18% reduction when discharge was reduced from 15 to 3 $m^3 s^{-1}$. Hence, the total wetted area was 41% smaller without the weir at a discharge of 3 $m^3 s^{-1}$ compared with pre-conditions at 15 $m^3 s^{-1}$. For the upper reach, the calculated reduction in wetted area was 18% at 15 $m^3 s^{-1}$ and 21% at 3 $m^3 s^{-1}$ when the weir was removed (Figure 4). Post-removal measurements of water levels determined that the water-level reduction at the lower reach (1.6 m upstream of the weir) was very similar to that predicted by the model. On the upper reach, the measurements determined that the real reduction was 0.9 m upstream of the upper weir, compared with 0.7 m in the model. Owing to the large water depth and steep banks in the upper reach, this difference did not result in major changes in water velocities or wetted area. The post-removal visual inspections determined that the potential spawning area had been sufficiently predicted.

Biological conditions

Spawning habitat and egg survival. Spawning was recorded in areas of added gravel beds each year between 2003 and 2009, although only half of the new spawning areas were utilized in 2009. Of the areas established in 2002, one area was still in use in 2009, one was removed during the restoration in 2007 and the other was lost because of the flushing of the gravel during a flood. Of the three new gravel beds established after the restoration in 2007, active spawning was still recorded in two areas in 2008 and 2009, but the third site had also been lost because of flushing.

Before the 2007 restoration, spawning between the weirs was exclusively observed in gravel bed additions. However, during the first two years after the restoration, five new spawning sites were found within reaches that had changed from lake to river habitat (lower reach) (Figure 6). Redds in areas influenced by the restoration were found to have a significantly higher egg survival and were found to have significantly higher water velocity and lower water depth than redds in the 5-year period before the restoration

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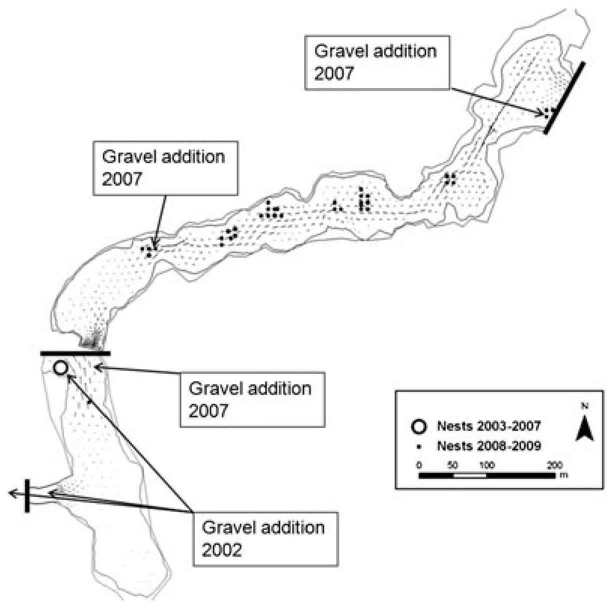

Figure 6. Observed Atlantic salmon spawning redds based on scuba diving. Vectors indicate calculated water velocity distribution. Vector values are calculated at a discharge of 15 $m^3 s^{-1}$ without weirs. Weir localities are indicated with solid bars. The intact weir is indicated down to the left.

(Table I). Redds in the reference area, which was unaffected by the restoration, demonstrated a smaller increase in egg survival and reduction in water depth but no changes in water velocity before and after the restoration (Table I).

Juvenile salmon. After the restoration, the numbers of Atlantic salmon fry and older juveniles in the restored area showed a marked increase compared with the numbers found in the reference area. In the 4-year period prior to the restoration, salmon were absent or caught at low densities (3/100 m^2 in 2004) in the upper reach. After the restoration, salmon appeared yearly at this station and at relatively high densities (26–28/100 m^2) (Figure 7). At the new electrofishing stations established in the restored area (i.e. lower reach), the densities showed a marked increase from the first year in 2007 to 2008 when peak abundance of 269 salmon/100 m^2 was recorded. The increase in 2008 was most likely caused by enhanced recruitment in the restored area as 95% of fish sampled in the lower reach in 2008 was young of the year and likely a result of spawning in the area during autumn, 2007. In 2009, the sampled fish were also dominated by young of the year, contributing 62% of the sample, whereas the remaining 38% of the sample were two summer-old juveniles. Considering species other than salmon, before the restoration, in 2003–2006, a total of 15 perch, 6 pike and 4 brown trout were caught at all stations. After the restoration, the only other species caught was brown trout (total of five at all stations), indicating that the

Table I. Characteristics of Atlantic salmon nests spawned in the study area of the river Nidelva

	Reference area				Influence area			
	Before restoration (2002–2007 period)		After restoration (2008–2009)		Before restoration (2002–2007 period)		After restoration (2008–2009)	
Nest characteristic	Mean (SD)	*N*	Mean (SD)	*N*	Mean (SD)	*N*	Mean (SD)	*N*
Egg survival (%)	66.2 (31.4)	153	77.7* (33.7)	24	69.4 (33.5)	70	93.3** (16.8)	109
Water depth (cm)	103.7 (28.0)	150	91.6* (19.6)	24	99.0 (13.8)	70	40.4** (17.4)	109
Water velocity (cm s^{-1})	10.2 (11.4)	36	13.6 (10.1)	23	10.9 (9.4)	10	30.3** (18.5)	109

Asterisks show significant differences within reference and influence area before and after restoration (*t*-test $*p < 0.05$, $**p < 0.001$). Analysis of egg survival is performed on arcsine transformed values, whereas the data are presented as untransformed values.

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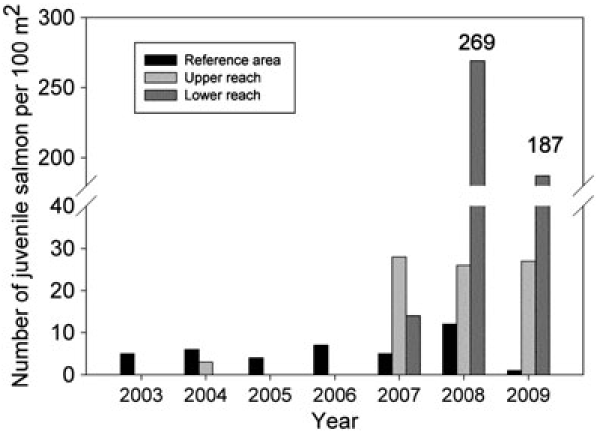

Figure 7. Juvenile Atlantic salmon densities on the study reach.

desired shift in fish community in response to habitat alteration was obtained.

Upstream migration. Removal of migration barriers was expected to increase migration speed through the study area. Data from the fish ladder at Rygene demonstrated that the migration peak before weir removal (2002–2006) was more than one month later than after the removal (2007–2009) (Figure 8). Fish passage peaked in the beginning of August during the last three years, post-restoration, whereas the average peak was in the middle of September during the five previous seasons. In 2006, more than 1600 fish passed the ladder, a large number compared with the 300–500 fish yearly from 2002 to 2005. This strongly increased the average migration numbers for the pre-restoration period but did not influence the timing of the peak in that period.

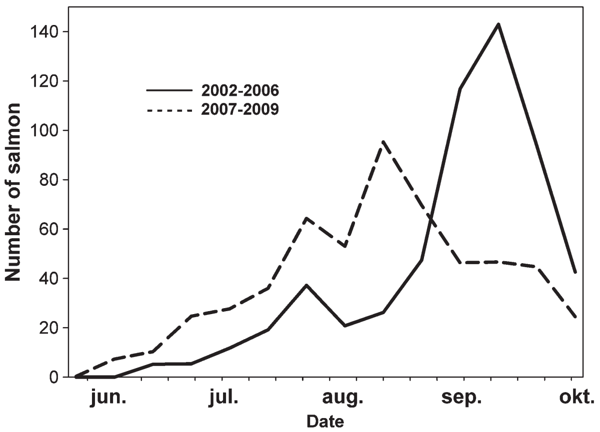

Figure 8. Averaged number of adult Atlantic salmon enumerated in the fish ladder at Rygene dam before (solid line) and after (dashed line) weir removal between 20 May and 1 October. Values on the *y*-axis represent yearly number of fish grouped in 10-day periods.

SUMMARY

Two concrete weirs in a 900-m residual flow river reach were removed in 2007. The two weirs had created a lake habitat on the reach at discharges of 3 and 15 $m^3 s^{-1}$ since 1979. Use of DGPS surveying, coupled with topographic-modelling and hydraulic-modelling applications, represented a comprehensive and useful toolbox for description of the physical habitat changes in the present project. Accordingly, graphic visualization of the model results informed and supported a rapid management process towards planning and executing removal of the weirs. Hydraulic modelling of the reach before weir removal in 2007, at the two different discharges, predicted that the physical habitat would change from a lake habitat to a riverine habitat more suited for Atlantic salmon. Calculated water velocities and depths indicated that potential spawning areas would be created in significant numbers and distributed throughout the reach. Some sediment transport/ erosion was observed in added gravel bars during the study. However, sediment transport and erosion were not regarded to affect the results from the hydraulic modelling on a meso-scale resolution significantly. This study and those in other Norwegian salmon rivers have demonstrated that spawning areas based on substrate additions can be susceptible to flushing during floods (Barlaup *et al.*, 2008). Monitoring of spawning redds in the reach after weir removal discovered large spawning activity immediately in the first season after removal. Fishermen recall that these old gravel beds constituted important natural spawning areas in the period from the 1940s and up to the building of the weirs in 1979 (Bjørn Jørgensen, river keeper, Arendal, pers. comm.). It is therefore expected that the reestablishment of these old spawning areas as a result of restoration will remain as permanent and stable spawning habitats.

The significant increase in egg survival recorded after the restoration strongly suggests improved incubation conditions within the gravel. This is further supported by the significant changes in water depth and water velocity, as predicted in the hydraulic model. The reuse of old gravel beds was found at five different sites, which resulted in a wide spatial distribution of the redds and which likely reduced intra-specific competition among emerging fry (cf. Einum *et al.*, 2008). The subsequent marked increase in juvenile densities was also likely a result of increased quantity and quality of both spawning habitat and juvenile habitat (the first year after weir removal, from 2007 to 2008, the recorded densities of juvenile salmon increased to a peak abundance of 269 salmon/100 m^2, mostly related to increases in salmon fry). Also, the reduced occurrence of predatory pike and perch likely contributed to the increased densities (survival) of juvenile salmon. Together, these results demonstrate that the restoration changed the habitat conditions to meet preferred criteria for spawning and rearing of Atlantic salmon.

In regulated rivers, wetted area is an important factor for fisheries and other interests (e.g. aesthetics), and riverine ecology depends strongly on this spatial parameter. A minimum residual flow is a common mitigation measure that is used to provide for a sufficient wetted area for maintenance of fish populations, which was also the case in minimum flows established for the Nidelva. In the present study, wetted area was purposely reduced as a trade-off between lake habitat conditions and riverine habitat conditions. Removal of the weirs in Nidelva reduced the wetted area up to 40%. Physical conditions before weir removal were insufficient for spawning of Atlantic salmon, and as a result, the reach was not occupied by juveniles to the full extent. In this case, a reduction of wetted area has increased the production of the target species. Additionally, the weirs and the standing water conditions represented potential migration barriers. Analyses of migration data from an upstream fish ladder determined that the migration peak was one month earlier after weir removal. Thorstad *et al.* (2003) reported migration delays in the residual flow reach, supporting the theory of weir removal as an influencing factor in improving migration speed. The complete mechanism for this trend was probably complex, as changes in flow regime and water quality during the same period were likely to influence migration. Thorstad *et al.* (2003) also observed that tagged fish were attracted to the tunnel outlet and remained inside the tunnel for a period. In 2006, a mechanical screen was constructed inside the tunnel outlet to prevent fish from entering, and this mitigation also likely reduced migration delay.

Scientific programmes and studies on ecological consequences related to hydropower development are numerous in Norwegian salmon rivers (Halleraker *et al.*, 2007; Ugedal *et al.*, 2008), but unfortunately, ecological data before and after physical habitat changes are often scarce. Predicting such impacts in a planning process is even more challenging as the pace and intensity of a development project exceed the means and ability of scientists to evaluate the biological effects (Poff *et al.*, 2010). In the present study, biological data were collected before and after weir removal, and consequently, hydraulic modelling results were used in planning of the weir removal, and the actual impacts on fish and their physical habitat could be verified.

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