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Rivers need floods: Management lessons learnt from the regulation of the Norwegian salmon river, Suldalslågen

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Abstract

The Norwegian river Suldalslågen, known for its population of large-sized Atlantic salmon (*Salmo salar*), has been regulated for hydropower in 1966–1967 and in 1980. The initial regulation increased winter flows and reduced summer flows and major floods. The second regulation, involving abstraction of water to a power station in an adjacent fjord, led to a strong reduction in flow. In addition to implementing different flow regimes, many remedial actions have been taken, often concurrently, making it almost impossible to detect the effect of single measures. In addition, the monitoring data have not always been consistent as regards methods and scope, and also, few data are available for preregulation conditions. This highlights major challenges in the long-term management of regulated rivers. The absence of major floods after regulation led to increased sedimentation and encouraged carpet mosses. This reduced interstitial spaces, creating a poor habitat for salmon fry and benthic invertebrates. The knowledge gained from the wide-ranging studies of the different flow regimes have enabled the environmental authorities to devise a final regulation regime from 2012. The final flow regime focused on biological values and functions to sustain the strain of wild, large adult salmon. The catch of wild salmon >7 kg has in fact increased since 2010 and stabilized between 1 and 2 metric tons, although the yield of large salmon prior to 1994 is unknown. In addition, the increase in the catch of large salmon is based on hatchery fish. Hatchery fish have also to a large extent contributed to the increase in the total salmon catch in recent years. Thus, that the catches in Suldalslågen are now at an all-time high is not due to improved conditions in the river but likely to hatchery fish.

KEYWORDS

Atlantic salmon, catch, flow, regulated river, river management, Suldalslågen

1 | INTRODUCTION

Rivers are complex physical, chemical, and biological systems, and dams and river regulation interrupt the natural patterns of downstream processes (Ward & Stanford, 1983). Thus, in remediating the effects of river regulation, it is necessary to adopt a holistic approach (Petts, 1986, 1996). Nevertheless, the flow regime has an overriding influence on ecosystem processes, witnessed by the development of the concept of environmental flows as the prime driver of river processes (Acreman & Ferguson, 2010; Poff & Zimmerman, 2010).

The period from 1961 to 1980 witnessed the completion of many larger hydropower projects. Storage is the most common type of hydropower development in Norway. The impacts of this kind are very complex, depending on the running of power stations, the release strategy of water from reservoirs, and the water quality in the different parts of the catchment. Among the crucial processes influenced by dams and altered flow regimes is the sediment regime (Petts, 1984; Yin, Yang, Petts, & Kondolf, 2014), as this will, for example, influence juvenile fish habitat directly both through the clogging of interstitial spaces and through encouraging the development of aquatic vegetation (Heggenes & Saltveit, 2002).

Atlantic salmon (*Salmo salar*) is the most economically important freshwater fish in Norway. There are more than 450 rivers that have or have had a self-reproducing population of Atlantic salmon (Hansen, Fiske, Holm, Jensen, & Sægrov, 2005). River regulation, migration barriers, acid precipitation, organic pollution, escapees from fish farming, and infections of the monogenean parasite *Gyrodactylus salaris* are among the threats in freshwater, whereas in the ocean, increased sea lice infections from sea farming, overfishing, and climate change are among the most important factors (Forseth et al., 2017). In some rivers, more than 30% of the spawning population consists of escapees, and successful spawning in rivers by escaped salmon has been observed (Forseth et al., 2017, Lura & Sægrov, 1993, Skaala et al., 2019).

River regulation is generally recognized as having a strong negative influence on the Atlantic salmon, through migration difficulties for both spawners and smolts, as well as degradation of spawning and juvenile habitats (Cowx & Gould, 1989; Johnsen et al., 2011; Jonsson & Jonsson, 2011; Petts, Imhof, Manny, Maher, & Weisberg, 1989). In ~80 Norwegian rivers (19%), hydropower development is a significant factor influencing the status of the salmon stock (Hansen, Fiske, Holm, Jensen, & Sægrov, 2008). Among the 45 Norwegian salmon populations that have been lost, 19 (42%) were lost due to hydropower development (Hansen et al., 2008). According to Hansen et al. (2008), the most common negative effects of hydropower development are the permanent or partial drying of the riverbed, frequent changes in water flow leading to the stranding of fish, and smolt mortality during downstream migration through turbines. Hydropower development has reduced the production of Atlantic salmon smolts in Norwegian rivers by 10–20% (Johnsen et al., 2011).

In Norway, systematic Atlantic salmon catches statistics began in 1876 (Hansen, 1986), resulting in >140 years of catch data for most large rivers. The Atlantic salmon catch has been more than halved since the 1980s, mainly because of reduced survival at sea but also from human activities (Anon, 2017). Fishing effort, both at sea and in rivers, has been restricted, and management plans for salmon rivers were implemented in 2008, comprising conservation limits and management targets (Forseth et al., 2013). At present, the spawning targets for most salmon population are achieved, but the surplus available for fishing is reduced and, in some rivers, entirely lacking (Anon, 2017).

The Suldalslågen, southwest Norway, is well known for its large salmon; the largest fish ever caught (1913) weighed 34 kg. The flow is now strongly influenced by the two hydropower developments in the catchment, and it is also one of Norway's most monitored regulated rivers. Various flow regimes have been tested to achieve a generally acceptable regime that could benefit both hydropower production and the Atlantic salmon population. Specific focus has been placed on maintaining biological values and functions in order to sustain the strain of wild, large adult salmon. In addition, the river has been limed to alleviate acidic episodes; salmon fry and smolt have been stocked to mitigate negative environmental impacts on recruitment. Escapees from fish farms also enter the river. The decline in salmon numbers has led to the introduction of catch and release angling for wild fish but not for stocked fish. This presents challenges when interpreting angler catch data. Further, to facilitate upstream migration of adult salmon and anadromous brown trout (*Salmo trutta*), two fish ladders have been constructed at the Sandsfossen, the lowermost waterfall in the river.

Thus, as in many other regulated rivers, multiple mitigation measures are often implemented at the same time as the new hydrological regime. Therefore, it becomes increasingly difficult to disentangle the impacts of specific pressures on the salmon population or quantitatively demonstrate the effectiveness of targeted remedial measures. In addition, anadromous fish populations spend parts of the life cycle in the sea, and environmental changes here will affect stock structure and composition regardless of events in the river. That said, the Suldalslågen is considered typical of rivers in Norway and elsewhere and thus represents an invaluable long-term case study.

It is our aim in this review paper to highlight these challenges in river management by focusing on the population of Atlantic salmon and the difficulties in interpreting poorly controlled and multiple remedial actions. The data contained in the paper are collated from a large number of scientific papers and reports in Norwegian. There is unfortunately insufficient space to include all the methods, both field and statistical, and the reader is referred to the cited publications or to the authors for such information.

2 | THE RIVER SULDALSLÅGEN

The seventh order River Suldalslågen is 22 km long, running from the lake, Suldalsvatnet (69 m a.s.l., area 28.8 km^2) to the inner part of the Ryfylkefjord (59°N, 6°E) at Sand (L'Abée-Lund et al., 2009; Figure 1). The flow is strongly influenced by the two hydropower developments in the catchment (see below). Water temperatures in Suldalslågen range from 0°C to 4°C from December until late March, increasing to 10–14°C during summer. After the second regulation, the summer temperatures have been reduced (Magnell, Sandsbråten, & Kvambekk, 2004; Tvede, 1995), largely due to the discharge of cold water from mountain reservoirs.

Four fish species are present, but Atlantic salmon and brown trout, both anadromous and resident, dominate. Atlantic salmon spawn late compared to other Norwegian rivers, from mid-December with a peak

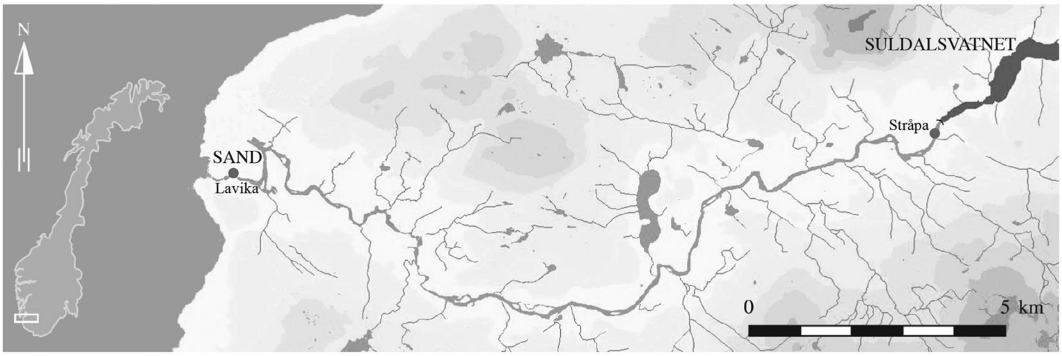

FIGURE 1 Map of the river Suldalslågen, Norway

in early January (Heggberget, 1988). Groundwater seepage has been shown to be crucial for salmon spawning, egg development, and the survival of eggs in the redds when dewatered (Casas-Mulet, Alfredsen, Brabrand, & Saltveit, 2015; Saltveit & Brabrand, 2013). Juvenile fish grow slowly, and Atlantic salmon juveniles spend, in general, 3–4 years in the river before smoltification.

The reduced flow and reduction in the size of the floods has reduced the sediment transport capacity and increased the likelihood of sedimentation of fine material. The sediment supply from the tributaries is expected to remain the same or even increase in the future due to more intensive human impacts in the catchment and larger and more frequent tributary high flows owing to climate change, causing more extreme flooding and thus increasing sediment supply (Bogen et al., 2004).

Filamentous benthic green algae dominate the phytobenthos, established on carpets of liverworts that can cover 100% of the riverbed surface. Chironomids, mayflies, stoneflies, caddisflies, and simuliids dominate the benthos (Saltveit & Bremnes, 2004, 2018).

3 | FLOW REGIME

The preregulation mean annual flow in Suldalslågen was ~90 m^3/s at the outlet of Suldalsvatnet but with very large seasonal variations: winter flows 3–20 m^3/s and a mean spring flood of ~400 m^3/s (Figure 2a). The first regulation, Røldal-Suldal, did not have any impact on the total mean flow into the river but increased winter flow and reduced flow in summer in relation to the unregulated conditions (Figure 2b).

The second regulation, Ulla-Førre, involving a dam at the outlet of Suldalsvatnet and water abstraction to a power station with an outlet in an adjacent fjord, led to a reduction in flow during both winter and summer, in relation to unregulated condition and the previous regulation. This latter regime was implemented in 1981 (Figure 2c). Until 1985, the location of the gauging station for the minimum flows was in the lowermost part of the river but released from the lake outlet. This gave rise to frequent and sudden reductions in flow when the residual catchment between the lake and the fjord provided the minimum instream flow. From 1986, the flow has been measured and released from the dam, and the variations in flow are largely controlled by inputs from the residual catchment below the dam (Figure 2c,d), and rapid reductions in water flow no longer occur.

The ecological impacts of the regulation are mainly due to the direct and indirect effects of the altered flow regime. However, a full restoration of the natural regime was considered unrealistic due to high costs, although it may be possible to mitigate the adverse effects of flow regulation by restoring critical parts of the flood regime. Various flow regimes were therefore tested between 1990 and 2003 to achieve a generally acceptable regime that could benefit both hydropower production and the Atlantic salmon population. This involved testing different flushing floods to reduce sedimentation and growth of phytobenthos and macrophytes, whereas variable flows were practiced during the angling season. A test of two different trial regimes, during the period 1998 to 2003, led to the final flow regime in 2012.

The main difference between these two test regimes was the size of flow in spring, early summer, and autumn. The first regime (1998–2000) had high flow for flushing and smolt migration (spring), increasing from 12 to 100 m^3/s and further to 150 m^3/s but no flushing flow in autumn. In the second test regime (2000–2003), the peaks in spring were smaller, 40 and 70 m^3/s, respectively, a lower flow to mid-July, but had a large flushing flow in the autumn. This second regime was practiced until a final regime was adopted in June 2012.

The final flow regime is a combination of the two test regimes, with two peaks in spring and autumn, but low flows during early summer. This means a winter water flow out of Suldalsvatnet of 12 m^3/s from December 1 until April 10, then a basic flow of 20 m^3/s until May 15, but with two peaks of 200 and 100 m^3/s in early May for smolt migration (Figure 2d). From July 1 to September 30, the average flow should be 60 m^3/s out of the lake but changing weekly between 40 and 80 m^3/s (for angling). From October 1, the flow is gradually reduced from 50 m^3/s to the winter flow but with two short-lasting flushing flows in the latter half of October, increasing twice from 35 to 200 m^3/s, for flushing of fine sediments and aquatic vegetation. All reductions in water flow from the dam must be made with a maximum of 6 cm/hr decrease. Flow variation is also provided by the residual catchment below the dam, and this may vary between years (Figure 2d; Lavika). It should be emphasized that flow changes have been substantial, both in volume and in variability.

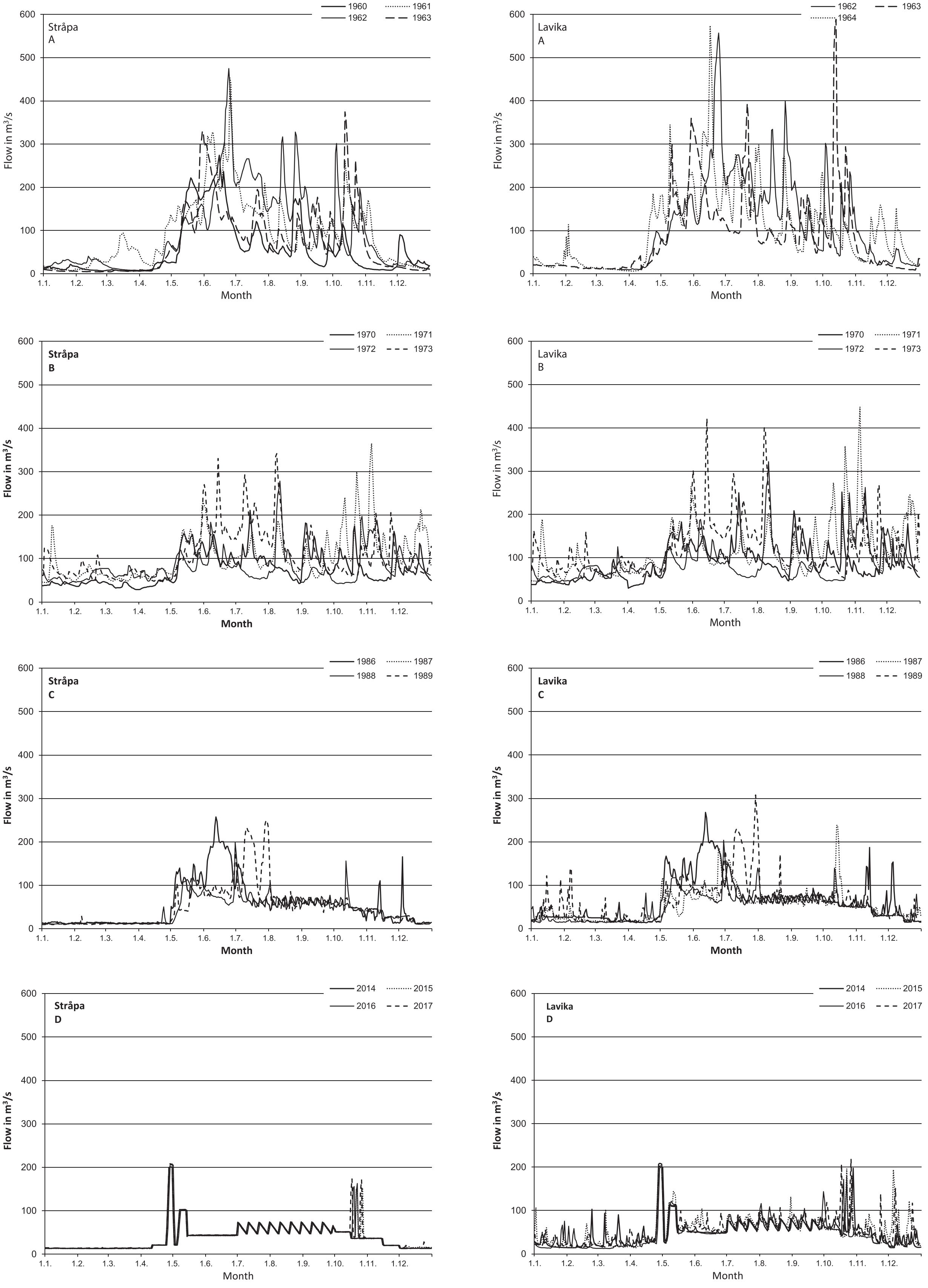

FIGURE 2 Mean daily flows in the river, Suldalslågen, at the outflow of the Lake Suldalsvatnet (Stråpa) and at the lowermost part (Lavika). (a) Unregulated flow; (b) Røldal-Suldal; (c) Ulla- Førre; (d) final regime

4 | JUVENILE FISH DENSITIES

The density of juvenile Atlantic salmon, year classes, 0+, 1+, and ≥2+, has been estimated during autumn at 16 stratified selected localities at the same flow between 1978 and 2003, using electrofishing and "successive-removal" estimates (Bohlin, Hamrin, Heggberget, Rasmussen, & og Saltveit, 1989; Zippin, 1958). No fish density data exist from unregulated condition, whereas from 2003 and onwards, data cannot be compared as there are fewer localities, and sampling is at a different time of the year, winter, and at lower flow (see Figure 2d).

During the first regulation, the density of yearlings was the same in 1978 and 1979, but in 1979, there was a statistically significant ($p < .05$, t test) lower density of 1+ (Figure 3). In the first years with the second regulation (from 1980), the highest densities of salmon yearlings (0+) occurred in 1981 and from 1986 to 1993, with the exception of 1989. From 1994 to 1999, there were very low densities of 0+ and 1+ juveniles (Figure 3). Even if the juvenile density in general increased from 2000, none of the 3-year classes had densities reaching the levels prior to 1995.

For the entire period from 1978 to 2003, there was a reduction over time in the density of both 1+ salmon ($r^2 = .225$; $p = .002$) and 2+ salmon ($r^2 = .529$; $p < .001$). After 1990, there is also statistically significant decrease over time for 2+ ($r^2 = .432$; $p = .01$; Saltveit, 2004; Saltveit & Bremnes, 2004). The ratio between the density of 0+ and 1+ in the following year is statistically significant ($p < .01$, $r^2 = .58$), so is the ratio of density of 1+ to 2+ ($p < .05$; $r^2 = .63$), indicating a degree of density-dependent regulation.

Density-independent factors also play a significant role in the number of juvenile salmon. The relationship between eggs and 0+ indicated that about half (54%) of the variations in 0+ is not explained by the variation in the number of eggs (Saltveit & Bremnes, 2004). For 1+, 42% of the variation in density was not explained by the density of 0+ the year before, whereas 37% of the variations in the density of 2+ cannot be explained by 1+ density. Theoretically, density-independent factors dominate population regulation below "carrying capacity" (Haldane, 1956). Habitat quality will be an important parameter defining "carrying capacity," and critical periods can be identified for the juveniles in Suldalslågen linked to factors independent of density, in particular, temperature and lack of suitable habitat for specific year classes.

There was a clear correlation between growth in salmon 0+ and river temperature ($p < .001$, Saltveit, 2004, Saltveit & Bremnes, 2004). Higher temperature in early summer gave increased growth, leading to earlier smoltification and reducing average smolt age from approximately 3.5 to 2.8 years (Saltveit & Bremnes, 2004), increasing the numbers of smolt produced in the river. It was postulated that in the long term, this would probably increase the number of adults returning, although this did not happen (Saltveit & Bremnes, 2004).

Some of the variation in juvenile density may be explained by events directly or indirectly linked to flow. Rapid short-term reductions in flow during the period 1980 to 1986 gave rise to increased mortality due to stranding (Figure 4). Dead fish were found after water level reductions especially in parts of the river that had extensive shallow areas. The rapid reductions were most prominent in the upper part of the watercourse and the effect on fish documented by a strong statistically significant increase ($p < .001$, Pearson correlation coefficient) in density downstream from the dam, leading to lower densities of 0+ in the river in the upper reaches near the dam compared to the lower reaches, compared with the period both before 1980 and also after 1985 (Saltveit, 2000). The low density in 1989 in all year classes was also related to a sudden reduction in flow from an accidental closure of the dam, causing stranding and mortality. Increased mortality due to stranding has been documented in several other regulated rivers or is highlighted as a possible cause of reduced juvenile fish densities and reduced yield of adult salmon (Hvidsten, 1985; Saltveit, 1990; Forseth et al., 1996). Since 1986, rapid reductions in water flow no longer occur, resulting in increased density of 0+ and more stable densities of older juveniles.

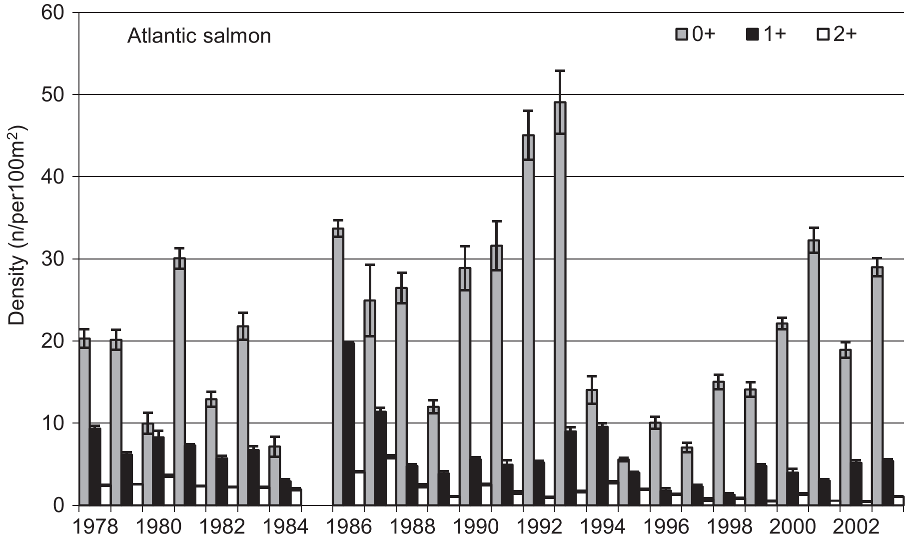

FIGURE 3 Estimated density (numbers per 100 m^2) of different year classes of Atlantic salmon juveniles in the river, Suldalslågen, during 1978 to 2003. Deviation from the mean is given as 95% C.L

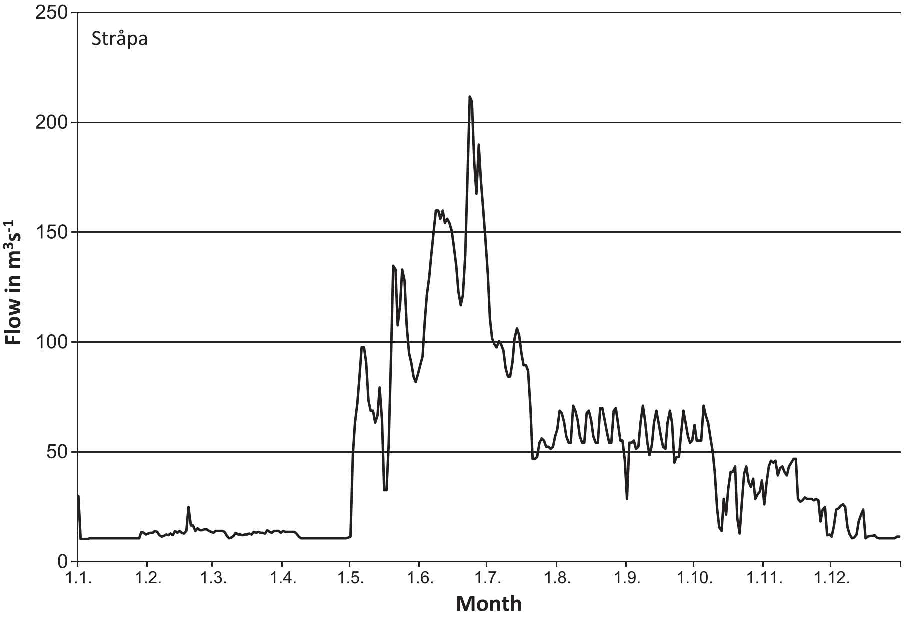

FIGURE 4 Mean daily flows in the river, Suldalslågen, in 1984 at the outflow of the lake, Suldalsvatnet (Stråpa)

Low 0+ density in 1981, 1985, and 1989 did not lead to lower density of that same year class in the two following years. There was also a general increase in the catch of Atlantic salmon from 1981 until 1990; thus, an impact from stranding on adults is not seen in the statistics. Surprisingly, the high juvenile densities from 1986 until 1993 did not have any positive effect on the catches from 1993 to 2005 (see Figure 7), as these years had the lowest catches ever reported from the river. Rather, the strong reduction in the juvenile density from 1994 relates to this dramatic decline in the spawning population of salmon (Sægrov, Hellen, & Kålås, 1997).

The catches of adult fish have varied considerably in Suldalslågen. This indicates that smolt survival at sea also varies widely from year to year and support the notion that the decline in spawning fish and juvenile density is at least in part caused by conditions outside the river, such as changes in sea temperature, salmon lice, and catches at sea (Sægrov & Hellen, 2004).

To mitigate the negative environmental impacts on recruitment, stocking in the Suldalslågen on a regular basis started in 1989 (Saltveit, 2006). The parental fish are wild salmon taken from the Suldalslågen. From 1992, mostly 0+ parr were stocked, but in 2003, this was changed from stocking both parr and smolt in the river to only stocking smolt into the fjord.

5 | CHANGES IN HABITATS AND HABITAT USE

Another and more possible cause of the low survival of juvenile salmon is limited suitable habitat due to increased sedimentation and subsequent growth of carpet moss. The specific demands for water velocity, water depth, substrate, and shelter in salmonids are well known (e.g., Armstrong, Kemp, Kennedy, Ladle, & Milne, 2003; Heggenes, Baglinière, & Cunjak, 1999). Winter can be a bottleneck for salmonids in rivers, in terms of both habitat and energy (Heggenes & Dokk, 1995, 2001; Heggenes, Krog, Lindås, Dokk, & Bremnes, 1993). The main limiting factor for the production of juvenile salmon in Suldalslågen is access to shelter and good habitat (Foldvik & Pettersen, 2017).

The proportion of fine particulate matter, both organic and inorganic, is relatively high (Bogen et al., 2003, 2004), and this can limit the production of juveniles due to high embeddedness. In such situations, juveniles must also use less favourable (suboptimal) areas, with silt and sand, as well as carpet moss. This involves greater energy loss and thus likely increased winter mortality (Cunjak, 1988). In winter, the water flow in the Suldalslågen is reduced, and large areas are dewatered. The remaining areas have a lot of sand and other fine material, which reduces hiding possibilities. The water-covered area is reduced from approximately 1.6 km^2 at 70 m^3/s to 1.1 km^2 at 12 m^3/s. Less wetted area during winter gives increased competition for the limited space and can thus increase mortality. This is supported by higher densities of 1+ salmon before 1980 (Saltveit & Bremnes, 2004), for a 3-year period when the Suldalslågen had higher winter flows (Røldal-Suldal regulation).

Moss growth has also increased due to reduced floods and increased winter flows, and the river is now characterized by vigorous growth of two morphologically distinct moss communities: liver moss, with species forming a dense mat on the bottom, and river moss (*Fontinalis*) forming long tufts creating a more diverse spatial structure on and close to the bottom. Increased moss cover affects the bottom structure and intragravel and near-bottom hydraulics. Areas with dense mats of liver mosses held lower densities of 0+ and older salmon parr than areas where liver moss had been experimentally removed (Figure 5; Heggenes & Saltveit, 2002). No differences in densities of YoY salmon were found between areas with and without

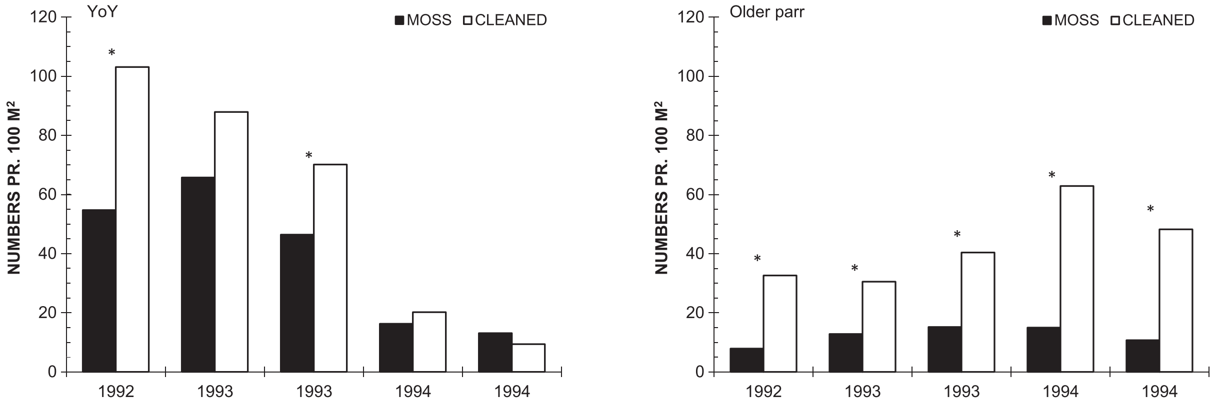

FIGURE 5 Estimated density of Atlantic salmon, YoY, and older juveniles (numbers per 100 m^2), in the river, Suldalslågen, in areas with liver moss and areas with moss removed. Statistically significant differences ($p < .05$) are indicated by asterisks (from Heggenes & Saltveit, 2002)

Fontinalis. For salmon parr, results were inconclusive. No major differences were found with regard to microhabitat selection between areas with and without river moss, suggesting that habitat quality in these areas was similar during summer, except with respect to substrate (Heggenes & Saltveit, 2002). The relative increase in liver mosses in the Suldalslågen had a negative impact on juvenile Atlantic salmon fish density (Heggenes & Saltveit, 2002).

Moss is also a refuge for the small early stages of benthic invertebrates. Several species of mayflies and caddisflies had higher densities in moss than outside. Chironomids, an important food especially for YoY, are the most important benthic taxon in moss, in terms of both species and individual numbers (Figure 6; Bremnes & Saltveit, 1997).

6 | RIVER CATCHES

Information on river catches of Atlantic salmon is from Statistics Norway (https://www.ssb.no/statbank/table/08991/) and the River Owner's Association, which also collects other data not given in Statistics Norway.

Data from Statistics Norway are difficult to interpret and use, as it only present the total catch of salmon, including fish from natural reproduction, stocked salmon, and escapees from fish farms. However, anglers in Suldalslågen are asked to note if the fish were stocked hatchery fish or had characteristics of escapees. All hatchery fish are marked by adipose fin removal, enabling separation from naturally reproduced fish. Therefore, the data from the River Owner's Association (https://statistikk.skynordic.no) were used to separate these three categories. In the evaluation, the escapees were excluded.

Furthermore, the evaluation was concentrated on catch of salmon larger than 7 kg, as the main official objectives for the final flow regime was to maintain a naturally reproducing stock of large wild salmon. This evaluation is possible because the catches have been separated into three size groups since 1994: salmon <3 kg, between 3 and 7 kg, and >7 kg. From 1979 to 1993, the catch was only divided into larger and smaller than 3 kg, and prior to 1979, there was no size separation. From 2009, a general catch and release strategy were introduced on a voluntary basis, although all female naturally

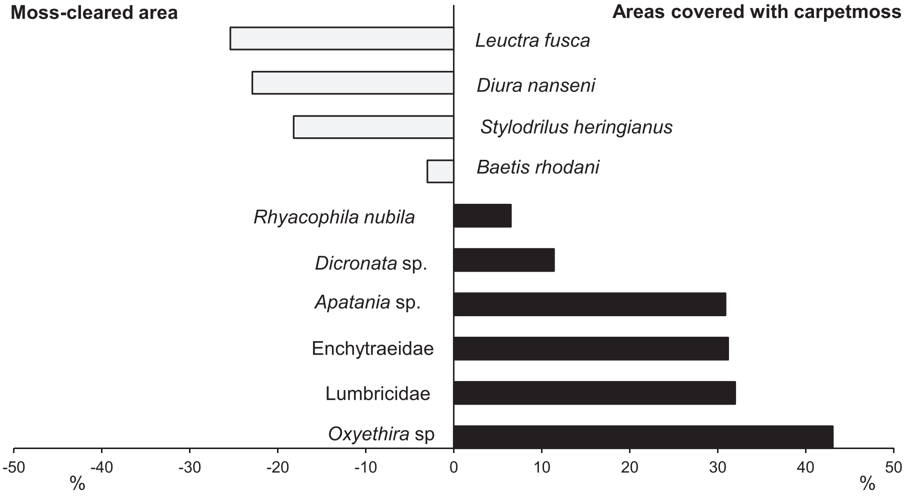

FIGURE 6 Percentage deviation from an equal distribution for species of benthic invertebrate on substrate of carpet moss and on substrate without moss in Suldalslågen (redrawn from Bremnes & Saltveit, 1997)

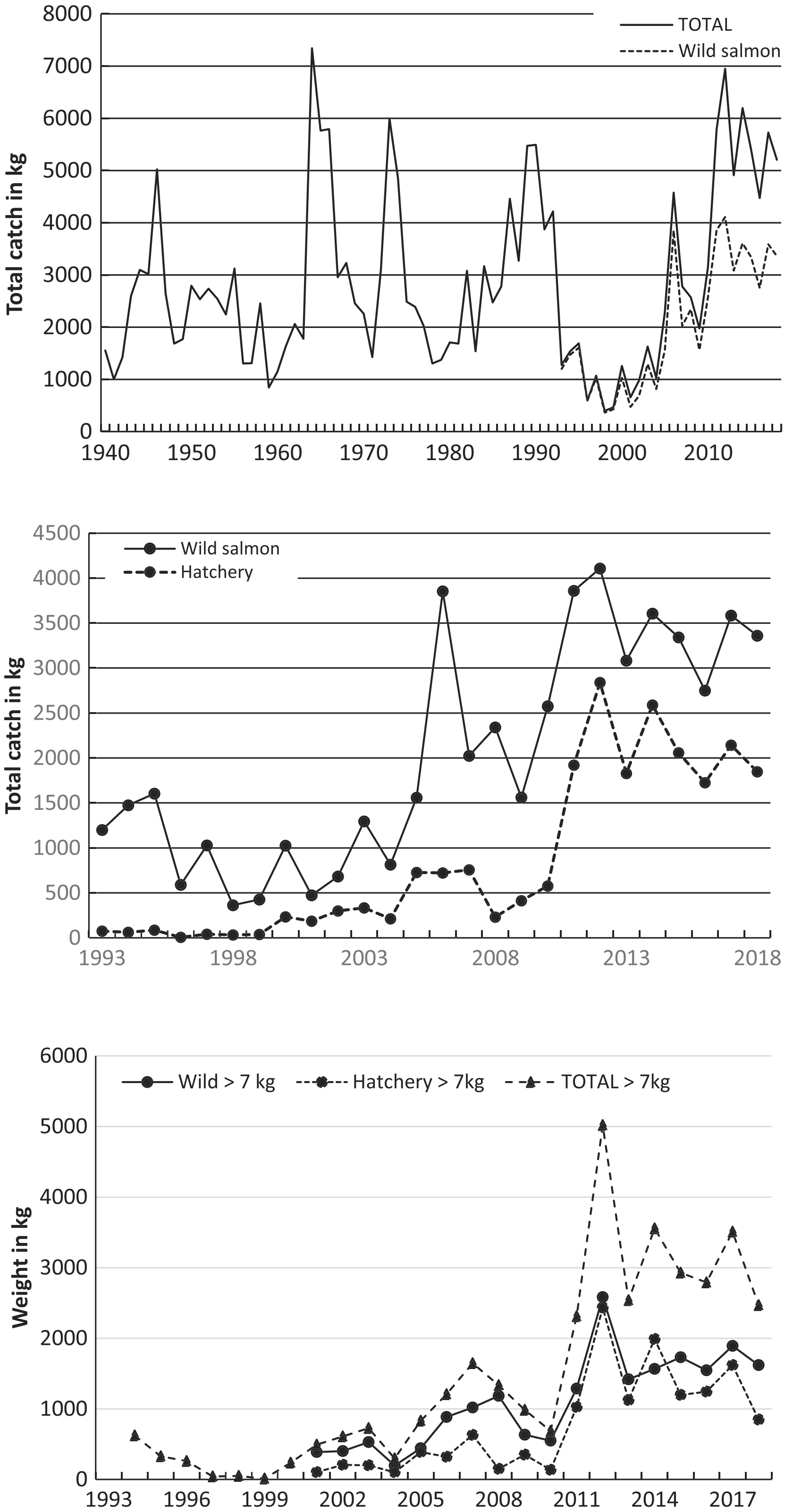

FIGURE 7 Annual rod catches of Atlantic salmon in different years and periods in the river, Suldalslågen. (a) Total catch from 1940 to 2018 with contributions from naturally reproduced salmon (wild) from 1994 to 2018. (b) Total catch of naturally reproduced salmon (wild) and from stocking (hatchery) from 1994 to 2018. (c) Catch of salmon larger than 7 kg; total, naturally reproduced (wild) and from stocking (hatchery)

reproduced salmon larger than 75 cm had to be released. This rule for females did not apply to catches of hatchery fish, resulting in less hatchery fish released. This may cause a bias in the statistics if released fish are recaptured, meaning that the wild salmon catch may be overestimated in relation to hatchery fish.

Atlantic salmon catches from the River Suldalslågen from 1940 onwards exhibit large annual variations (Figure 7). After the second regulation, there was a gradual increase in river catches from 1981 to 1992, followed by a dramatic decline in 1993. This year, only 1,275 kg were caught, the lowest river catch since 1978/1979.

Angling catches remained low and even declined further in the following years. Yield remains low until 2004, followed by a general increase in the catch in recent years.

Before 2010, stocked Atlantic salmon constituted a rather small part of the anglers catches, varying from 6.8 kg in 1996 to 750 kg in 2007 (Figure 7), but from 2010, the catch of hatchery fish increased dramatically, with a peak in 2012 of 2,840 kg. Before 2000, the share of hatchery fish was less than 10% based on weight. In the following years, the share of hatchery fish in the catch was only less than 15% in 2006, 2008, and 2010. In all other years, it was higher than 20% and, from 2011, never lower than 30% of the total catch of salmon in the river.

From 1994 to 2001, the catch for salmon >7 kg could not be separated into wild or hatchery fish. The catch of salmon >7 kg was very low, declining from 622 kg in 1994 to only 11 kg in 1999 (Figure 7). Thereafter, there was a general and slight increase until 2007. From the low number in 2010, the catch increased dramatically to a total of 5,000 kg in 2012. From then on, the catch varied between 3,550 kg (2014) and 2,470 kg (2018). Before 2011, the catch of salmon larger than 7 kg was dominated by salmon from natural reproduction (Figure 7). However, thereafter, the two categories had similar shares of the catch and were not significantly different (*t* test, n.s.). This also accounts for the mean size of the fish being the same. Bearing in mind that wild salmon may be overrepresented in the catches, this means that at least half of the catches of large salmon is now based on hatchery fish and that the total catch based on naturally reproduced fish is now far lower than can be apparent from Statistics Norway (Figure 7).

For both categories, there was a decline in mean size from 2001, though not significant. However, since 1979, there has been a statistically significant decline in the mean size of the total catch ($p < .05$), and since 1994, there has been a decline in the mean size of fish larger than 7 kg, although not statistically significant ($p = .09$).

7 | DISCUSSION

There is uncertainty about the factors that produce large-sized salmon (Jonsson et al., 1991). The main factor seems to be water flow and gradient, a direct size selective factor. Large salmon are more dependent than small salmon on high water flow during migration (Bergan et al., 2003). Selection towards larger salmon in the Suldalslågen has probably taken place through several processes, of which water flow during migration and spawning is important. The average water flow in the Suldalslågen has in natural condition been high during many of the stages in the salmon's life cycle. The various regulation regimes have over time led to reduced water flow, and it is likely that this has weakened selection for large salmon. In the River Eira, known for its large salmon, a clear relationship has been detected between reduced flow and the occurrence of smaller salmon (Jensen et al., 2003). Fish ladders can also be selective for fish size, as it is likely that the smallest salmon choose fish ladders, rather than waterfalls. There is little information on this, but there are indications from some rivers with fish ladders, such as Vefsna, Namsen, and Lærdalselva (Anon, 1990; Saltveit, 1993). Thus, it cannot be assumed with reasonable certainty that the strain of large-sized salmon in Suldalslågen will be maintained despite the introduction of an environmental flow regime to take account of the salmon population and riverine processes. Moreover, temporal genetic changes suggest that the salmon population in Suldalslågen has received immigrants from other populations, and at the same time, the stock enhancement programme has likely reduced the genetic variation (Karlsson, 2015).

The main objectives of the new flow regime were to maintain natural functions and processes in the river to sustain the strain of naturally reproducing wild large adult salmon at the same time as safeguarding the power company's requirements for power production. As a generally accepted indicator for determining whether the objective has been achieved or not, the catches of salmon larger than 7 kg naturally produced in the river were used. Due to stocking and the different implementation of the catch and release between wild and hatchery salmon, the evaluation is based on both released (catch and release) and killed fish, but bearing in mind the bias this may cause, as wild fish can be recaptured repeatedly.

The conditions for the new regime are not verifiable because the preregulation catches of salmon larger than 7 kg are not known. It is therefore not possible to conclude whether the objective of the new flow regime have been achieved or not. The catch of wild salmon >7 kg has certainly increased since 2010 and stabilized between 1 and 2 metric tons, although the yield of large salmon prior to 1994 is not known. However, the substantial increase in the catch of large salmon is based on hatchery fish. In addition, hatchery fish contribute to a large extent to the increase in the total catch of salmon the recent years, bearing in mind the bias from catch and release, favouring the catch of wild fish (Figure 7). Thus, the all-time high in catches in the Suldalslågen is not due to improved conditions in the river but to stocking.

8 | CONCLUSIONS

Managing a large river with many conflicting pressures and patchy data is difficult. Even honest and genuine attempts to improve matters, such as catch and release angling, present challenges by rendering long-term datasets incomparable. In addition, despite remediation efforts locally, external processes, both spatially and regulatory, such as fish farm escapees, acid rain, overfishing at sea, and climate change, only complicate matters further. Nevertheless, it is important to ensure consistent methods and only implement and evaluate single measures at a time along with sufficient controls, although economic and temporal limitations usually impose severe limitations. Despite these almost unsurmountable challenges in the management of regulated rivers, it is crucial to be aware of these aspects when implementing new and potentially improved remedial measures to counteract the impact of river regulation on their biota and ecosystem processes.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable; no new data is generated. Our paper is a review, and all the data involved are cited in published papers and reports. No new data is included.

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