ARTICLE IN PRESS

Water Resources and Economics (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Water Resources and Economics

journal homepage: www.elsevier.com/locate/wre

Modeling the effects of alternative mitigation measures on Atlantic salmon production in a regulated river

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ARTICLE INFO

Keywords:
Energy production
Atlantic salmon production
Mitigation measures
Cost-effectiveness comparison
Fish benefit
Trade-offs analysis

ABSTRACT

As part of the investigation of a new and optimized environmental flow regime in a regulated river (Mandalselva, Norway), a modeling study was conducted on the trade-offs between the production of Atlantic salmon (Salmo salar) smolts and the production of hydropower. Impacts of alternative flow regimes on smolt production were examined under different physical mitigation scenarios using the minimum flow regime recently proposed by the Norwegian Water Resources and Energy Directorate (NVE) as a baseline. Different combinations of hydropower operational strategies and/or physical mitigation measures were examined together with changes in the minimum discharge using a series of linked simulation models with the objective of finding combinations that both increased smolt production and maintained power production. This methodology provided a toolbox for predicting both the potential tradeoffs between smolt production and power production and therefore the evaluation of the most cost-effective environmental flow regime. The main finding was that it was possible to achieve a similar smolt production with a lower hydropower plant flow release (with consequent lower power loss) than the flow regime proposed by the NVE. Introducing habitat modification measures further reduced the need for release of water in relation to the proposed minimum flow, while increasing the smolt production. In an economic cost-benefit analysis perspective, benefits per smolt from recreational fishing were small compared to hydropower costs per smolt, with hydropower losses determining optimal flow. This study concludes that the use of a modeling-based methodology to define a targeted environmental flow can be used to successfully balance the sometimes conflicting requirements of effective management of salmon populations while maintaining hydropower production.

1. Introduction

Norwegian hydropower development began more than a century ago [1]. Today, hydropower produces 97% of the country's electricity [2], and Norway is the largest hydropower producer in Europe. Approximately 70% of Norway's large rivers have been developed for hydropower, which includes ~30% of Norway's rivers which support Atlantic salmon (*Salmo salar*) populations. These rivers account for more than 40% of Norway's salmon fishery yields. There are altogether 452 Norwegian rivers, which have or have

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http://dx.doi.org/10.1016/j.wre.2017.02.003
Received 29 May 2015; Received in revised form 20 January 2017; Accepted 5 February 2017

Please cite this article as: Adeva Bustos, A., Water Resources and Economics (2017), http://dx.doi.org/10.1016/j.wre.2017.02.003

had self-reproducing salmon populations, making Norway a core area for conservation of the world's remaining salmon. However, out of 45 extirpated Norwegian salmon populations, 19 have been extirpated as a consequence of hydropower development [3]. Given this situation, Norway has a large challenge in harmonizing hydropower generation with salmon production.

The implementation of minimum flow regimes, which specify the minimum required discharge within a regulated river, is one of the available management methods used in salmon conservation. Although minimum flow regimes have been used in regulated Norwegian rivers since the 1970's, they often lack an ecological basis and are often arbitrarily defined as being a percentage of historical flow [4]. Most minimum flow regimes differ from the definition of environmental flows found in the Brisbane Declaration [5]: “[Environmental flow] describes the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems”. Presently, the concept for assessing minimum flow regimes is gradually shifting from rigid minimum flows to ecologically designed flow regimes in order to sustain certain ecological requirements [6,7]. This has also been driven in Norway by the implementation of the EU Water Framework Directive [8] (WFD) within the EEA-agreement. In order to reach Good Ecological Potential, which is the main requirement of the WFD in heavily modified water bodies, revision of some hydropower licences is required. For example, around 50 regulated watercourses have a high priority and 53 a low priority for hydropower license revision in the near future within Norway [9]. Therefore, it will be necessary to implement environmental flow regimes in many water courses. However, there is still no unified method to find an optimal minimum flow within such regimes.

Due to the wide ranging challenge of establishing environmental flows in hydropower operation, research has only just begun to address the difficulties of directly linking hydropower economics to operational adjustments conditioned by environmental requirements [10–13]. Jager et al. [14] found that decision analysis for the optimization of hydropower while sustaining the fish population either just prioritizes hydropower with simplified fish habitat objectives, or focuses on the relationship between reservoir release and fish, while ignoring hydropower objectives. The literature highlights the importance of calculating the hydropower revenue and the aggregate benefits to society from river ecosystems in order to find the optimal flow release [15]. Klauer et al. [16] stated that a cost-effectiveness analysis can be interpreted within the WFD as “reaching a good water status with least cost”, understanding cost-effectiveness analysis as the comparison of two or more alternatives by their costs (monetary units) and effects (non-monetary units). In order to attempt to include these non-monetary values into the cost-benefit analyses, some studies use an indicator of the ecological status. This indicator can be, for example, fish production and recreational fishing [17].

In this paper, we develop a new methodology that uses a sequence of models (hydrological, hydraulic, and ecological) to investigate different scenarios for hydropower operation for optimizing the balance between energy production and salmon smolt production. The methodology was tested in the Mandalselva River (Norway), where a new minimum flow regime has been proposed by the Norwegian Water Resources and Energy Directorate (NVE). Because the proposed new minimum flow regime is not based on the natural pre-regulation status in the river (which is not well known), this proposed regime has not been validated, and may have limited potential for finding a successful solution for both ensuring energy production and sustaining the fish population. In order to analyse the river in the context of integrated watershed management and include the potential cost-effectiveness of mitigation measures to offset impacts across projects, we conduct a cost-effectiveness trade-off analysis of the application of scenario alternatives at two contrasting hydropower plants. We investigate the scenarios that support a flow that generates energy in a profitable way, while also maintaining or increasing the level of salmon production. We also investigate the potential for habitat remediation to act as an ameliorating factor for flow regimes that would maintain or increase salmon populations.

2. Materials and method

2.1. Study reach

The Mandalselva River, located in southern Norway (58°N, 7°E), is 115 km long with a catchment area of 1800 km^2 and a mean annual discharge of 88 $m^3 s^{-1}$ (Fig. 1). The river is regulated by 6 hydropower plants and 9 reservoirs. Nearly 90% of the storage capacity is found in the Nåvann and Juvatnet reservoirs in the surrounding mountains. Atlantic salmon can migrate 47 km upstream from the sea to a final migration barrier at the Kavfossen waterfall. The two lowest hydropower plants, Bjelland and Laudal, constructed in a period when Atlantic salmon were absent from the river due to acidification of the water [18], are located within the part of the river where an introduced salmon population now resides. In order to mitigate the aesthetic effects of the low minimum flow and maintain a continuous water level in the bypasses of the hydropower plants, weirs have been constructed: two small weirs at Bjelland bypass, and 8 stone weirs and one low concrete weir at Laudal bypass.

Bjelland power plant has two Francis turbines in operation, a head of 87.5 m, an installed capacity of 53 MW and an average annual production of 312 GW h. Laudal power plant has two Francis turbines, a head of 36 m, an installed capacity of 26 MW and an average annual production of 146 GW h. In 1997, after twenty years without a salmon stock, a liming program and re-stocking strategy was initiated. This resulted in a rapid increase in the salmon population abundance. Therefore, the procedure to revise the license was started by NVE in 2002. By 2015, the Laudal hydropower plant was in the second year of a five-year trial period used to test the regulation flow specified by NVE, while in Bjelland no change in the voluntary regime has been specified by NVE.

2.2. Defining and running the discharge scenarios

The methodology developed in this study was an integrated system that combined hydrological, hydraulic and ecological modeling (Fig. 2), building upon existing and well-tested modeling tools, and linking to tools for statistical analysis and visualization

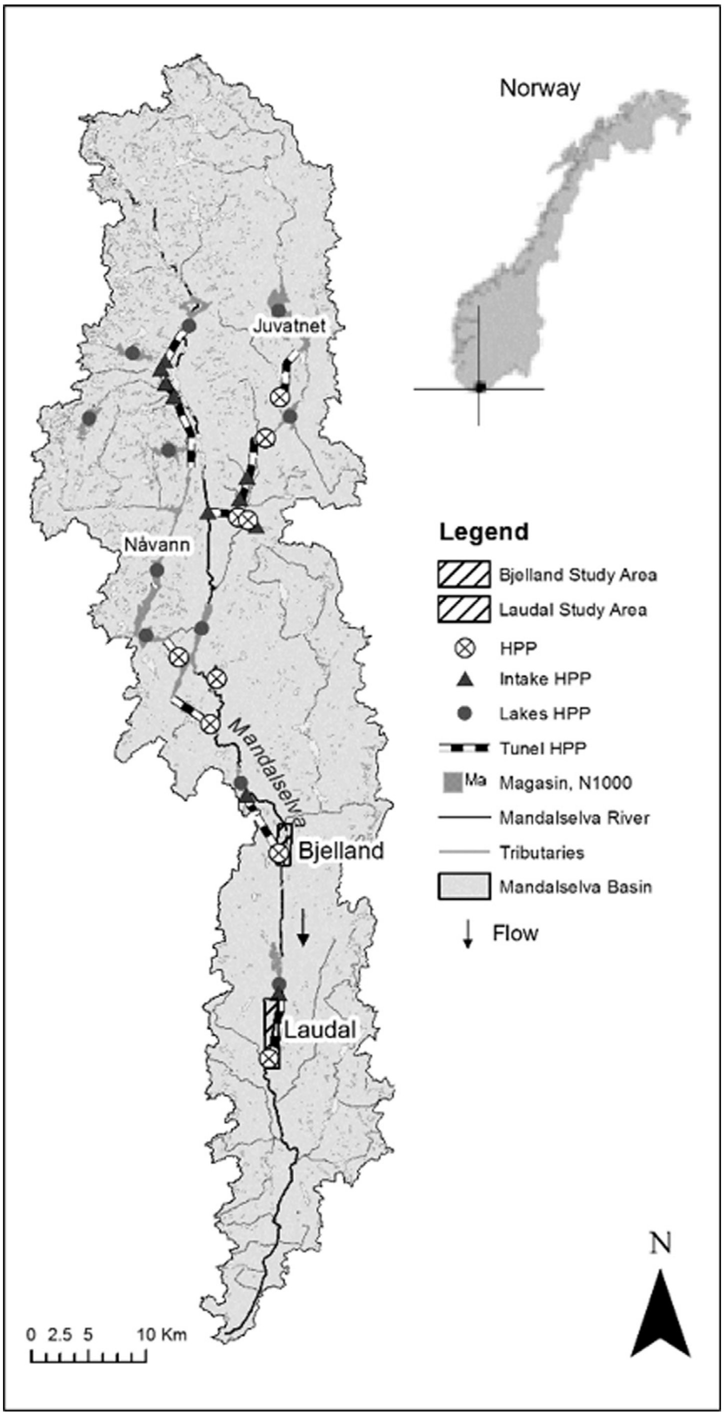

Fig. 1. Map of the Mandalselva River showing the hydropower system. The study area is marked with a rectangle in the basin for Bjelland and Laudal.

of results. A total of 8 scenarios were defined for each reach (Bjelland and Laudal), covering different power plant operational strategies and/or the implementation of habitat modification. The motivation to define these scenarios was NVE's proposal for a new minimum residual flow regime. This more than doubles the previous spill regime at Laudal, released since 1995 as a voluntary act (NVE suggested to release 6 m^3 s^{-1} in winter, a spring release of 50% of the inflow, and 8–25 m^3 s^{-1} in summer depending on inflow instead of the voluntary 1.5 m^3 s^{-1} winter and 3 m^3 s^{-1} summer releases).

The 8 scenarios have been defined and named using two attributes: winter/summer discharge, and habitat modification (Table 1). VOL-type scenarios represent the voluntary act that was terminated in 2012; NVE-type scenarios represent the NVE proposed discharge regime. WINSUM- and SUM-type scenarios are intermediate scenarios between the VOL and NVE scenario, implemented to determine if an optimal solution, in terms of hydropower production while sustaining salmon smolt production, could be achieved between VOL and NVE scenarios. In addition to the proposed minimum discharges permitted in winter and summer, the NVE scenario and the intermediate scenarios (WINSUM and SUM) included a period of water release during spring, corresponding to the downstream migration of smolts (“smolt migration period”) from 20 May–3 June, where the specified water

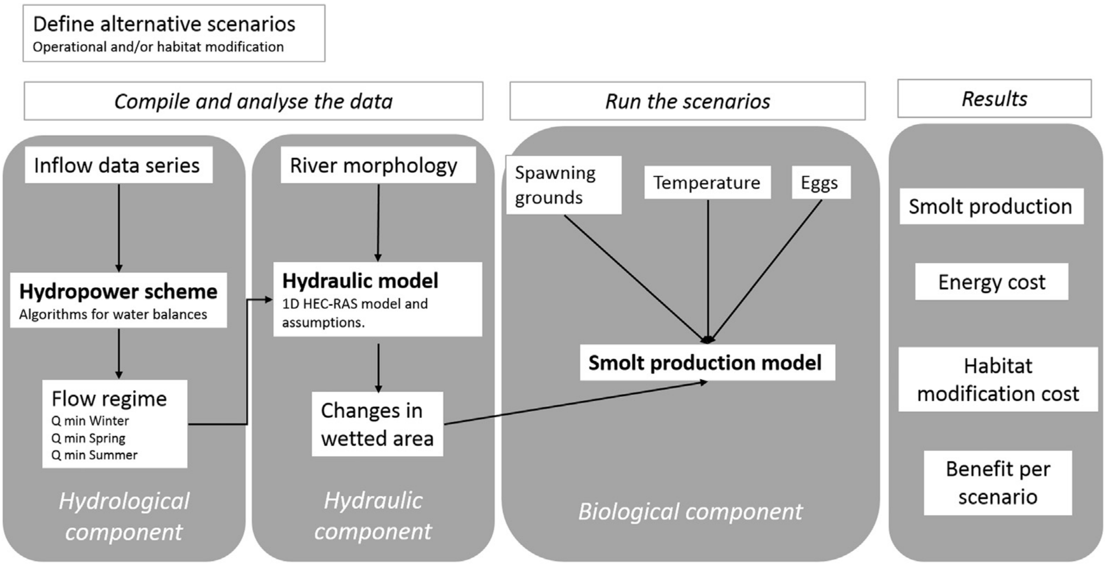

Fig. 2. Flowchart of the methodology divided by steps (upper white rectangles), components and results (grey blocks) and their interaction (arrows).

released was ~50% of the inflow to the hydropower plants. Habitat modification involved removal of weirs and addition of spawning grounds. These habitat adjustments were estimated as the maximum habitat improvement likely on the reach. These were established with the objective of investigating if habitat modification and less strict discharge regimes (intermediate scenarios: WINSUM or SUM) would give approximately the same salmon smolt production as NVE's proposed release without habitat modification.

In this study, both measured and simulated hydrological data were used as a basis for scenario analysis. Flow regimes was supplied through the hydrological component to the hydraulic component (Fig. 2). The hydraulic model was applied to determine the wetted area (total amount of the available river channel covered by water) produced by combinations of hydropower operation and habitat modification. The ecological component involved using an individual based model (IBM) to generate a salmon population, using outputs from the hydrological and hydraulic modeling. The number of salmon smolts (individuals that have reached adulthood) was obtained directly from the IBM, the energy cost was calculated using the outputs from the flow regime hydropower simulations, the habitat modification cost was calculated based on the estimated expenses for the works, and the benefit per scenario was calculated using the outputs from the IBM and the smolt value from recreational fishing. A net-cost analysis was carried out using the energy cost, the habitat cost and the benefit per scenario. A cost-effectiveness analysis ranking was then carried out, comparing the scenarios. In order to consider scenarios to achieve targets for smolt production, the cost per year of each scenario was compared against total smolt production per year, and assessed in relation to the reference scenario VOL. This was carried out by dividing the expected value of the annual cost of power production and habitat modification (if applicable) by the estimated smolt production per year, relative to the VOL scenario.

2.2.1. Hydrological component

The hydrological component involved generating a time-series of 40 years of discharge data to enable a multi-decadal simulation of smolt production. Available data for the hydropower stations spanned a much shorter period than this, so data from gauges located some

Table 1
Scenarios, showing winter and summer minimum permitted discharges, and the presence or absence of habitat modification. In both reaches, summer rules were defined by a step function where the minimum discharge for SUM and NVE were equivalent but the observed average was different, 10 $m^3 s^{-1}$ and 15 $m^3 s^{-1}$ respectively. The discharge released during spring (~50% of inflow to the hydropower plants) was applied to all scenarios other than the VOL and VOL+H scenario.

Scenario	Bjelland bypass			Laudal bypass		
	Minimum discharge ($m^3 s^{-1}$)		Habitat modification?	Minimum discharge ($m^3 s^{-1}$)		Habitat modification?
	Winter	Summer		Winter	Summer	
VOL	1	2	No	1.5	3	No
VOL+H	1	2	Yes	1.5	3	Yes
WINSUM	4	6	No	4	6	No
WINSUM+H	4	6	Yes	4	6	Yes
SUM	6	8	No	6	8	No
SUM+H	6	8	Yes	6	8	Yes
NVE	6	8	No	6	8	No
NVE+H	6	8	Yes	6	8	Yes

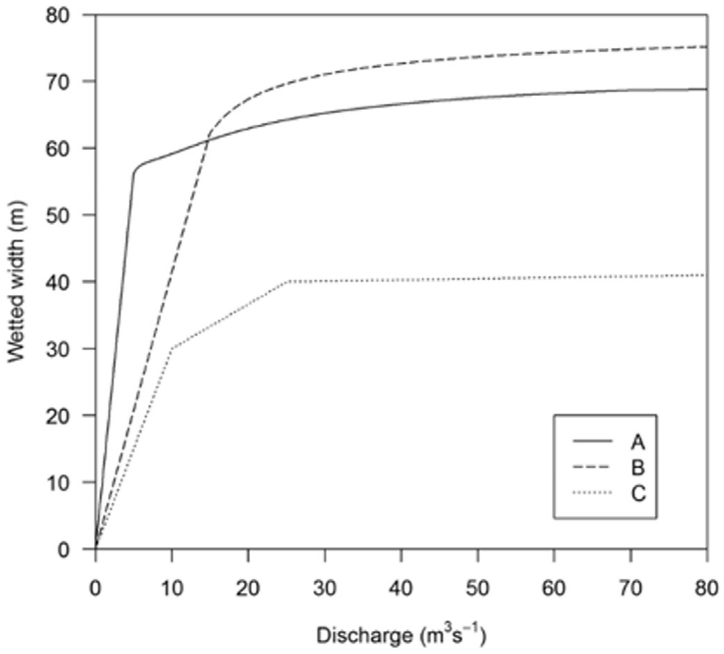

Fig. 3. Discharge versus wetted width relationship for channel types (A, B, C).

distance from the study area were used as a proxy. Discharge at the hydropower stations were estimated from gauge data using a relationship established for a four-year period when there were both on-site and off-site observations of discharge (Eq. (1)):

$$Q_S = (F_S \cdot A_S)/(F_D \cdot A_D) \cdot Q_D \tag{1}$$

where Q_S is the discharge at a target location (hydropower station); Q_D is the discharge at the gauging station; F_S is the specific runoff at the target location; A_S is the runoff area of the target location; F_D is the specific runoff at the gauge; and A_D is the gauge area. The correlation coefficient was 0.96, indicating that the scaling method was suitable for extending the data series. This relationship was then used to predict discharges at the hydropower stations.

2.2.2. Hydraulic component

The hydraulic component determined how alterations in flow regime and habitat remediation affected the channel wetted width, a key factor determining smolt production. The river hydraulics were simulated with a 1D hydraulic model [19] for the sections where geometry data were available. Where no geometry data were available, relationships between flow and wetted width were determined using field surveys. The river channel was characterized into three channel types – A, B, C (Fig. 3) – and piecewise-defined functions were used to describe how wetted width changed with discharge for each channel type [20]. For each of the three channel types, a linear function was used from the lowest discharge until the first observed discharge, a third degree polynomial was fitted using observed discharges and wetted areas, and a linear function was used for the highest discharges. The Bjelland bypass reach was defined as a combination of small lakes (type B) and narrow sections (type C). Type A was used for the Laudal bypass reach.

2.2.3. Ecological component

Outputs from the hydraulic model were used in an IBM to evaluate the effect of the differing scenarios on smolt production. An IBM approach was used for smolt production modeling because it enabled modeling the decadal effects of mitigation measures, something that is not possible using traditional physical habitat models. The IBM used – IB-salmon [21] – has been tested and applied to several cases in Norway [22,23]. Inputs to IB-salmon include abiotic factors (such as wetted area and river temperature) and biotic factors (such as egg deposition or spawning abundance). The model simulates population dynamics with a one-week temporal resolution over a domain where the river is compartmentalized into longitudinal section of 50 m in length.

Data on the distribution of spawning gravel habitat were obtained from Uni Miljø (unpublished) for the Bjelland bypass and Forseth [24] for the Laudal bypass. These data included both spawning habitat currently in use and potential spawning habitat that is currently unused due to low velocities or excessive depth. Scenarios involving habitat modification had increased spawning habitat from (1) the potential spawning habitat coming into use and (2) the artificial addition of spawning gravel. Gravel size was selected based on the size distribution of gravel already in use [25]. For Bjelland and Laudal ~2000 m^2 of new spawning area was assumed to be added to each bypass section in the scenarios involving habitat modeling. Based on findings by Barlaup et al. [26], who found that all artificial spawning grounds in five regulated Norwegian rivers were occupied by fish, it was assumed that all new spawning sites would be used by spawning salmon.

The intra-annual temperature pattern was kept consistent over all scenarios because the aim was to evaluate changes in smolt production solely from discharge and habitat modification. The number of eggs deposited was estimated from the body mass of returning females reported in Thorstad et al. [27]. The first 10 years of the data series were used as a burn-in to generate a realistic age-distribution of spawning adults, the first egg deposition occurred in year 11, and the analysis of smolt production and returning adults was done from year 12.

2.3. Power, energy production and cost estimation

The estimated power production was calculated as follows.

$$P = \eta \cdot \rho \cdot g \cdot H \cdot Q \tag{2}$$

where P is the potential power output in (W), η is the efficiency of the turbines (assumed efficiency of 0.9), ρ is the density of water (1000 kg m^{-3}), g is the acceleration due to gravity of 9.8 m s^{-2}, H is the net head of water (m) and Q is the average water flow (discharge) through the turbine (m^3 s^{-1}).

Energy production was calculated as follows:

$$E = P \cdot t \tag{3}$$

where E is the energy output in (kWh a^{-1}), P is the potential power output calculated in Eq. (2) (transformed to kW) and t is the time component as hours per year.

For energy cost, the electricity price was fixed and used as a baseline for comparison ($0.04 kW h^{-1} [28]). Volatile prices and potential up-ramping for peak demands may increase the difference in cost per year between the reaches above this fixed price. However, the minimum flow releases take precedence over production, so a peaking operation will not influence the water released into the bypass.

2.4. Habitat modification and cost estimation

For the habitat modification it was assumed that the weir removal and the addition of the spawning gravel would be planned and constructed in a single operation to minimize overall costs. For Bjelland, both weirs were assumed to be removed in the model. For Laudal, the 8 low stone weirs were assumed to be removed and the concrete weir modified.

Estimated costs were based on experiences from other projects (Sven-Erik Gabrielsen (Uni Miljø), Tor Kviljo (Terrateknikk) pers. Com. and NVE project prices). The estimated volumes to be removed were 800 m^3 of concrete in Bjelland, and ~200 m^3 of concrete and 4800 m^3 of stones in Laudal. To the estimated cost of removal actions, a 40% additional cost was considered for removal of concrete. In total, ~500 m^3 of gravel was added in each reach in the habitat modification scenarios. Costs of gravel were assumed to be $38-$43 per m^3 and additional costs of transport and cost of the removal of stones were estimates to be $43 per m^3. In the Bjelland reach, the difficulty of access to the area was estimated as an additional 200% of the sum of weir removal and gravel addition costs. In the Laudal reach, a 10% additional cost was added for accessibility.

2.5. Net-cost analysis

The benefit per scenario from important ecosystem services were assessed as a complementary study to the cost-effectiveness analysis. We focused on recreational fishing benefits which constitute the main commercial activity on the river besides hydropower production. Would recreational fishing benefits of additional smolt be high enough to justify foregone income from hydropower production and remediation costs? Three types of fishing benefits that could be attributed to increased smolt productivity were included: marginal smolt expenses, marginal smolt sale value and marginal willingness to pay (WTP). Given the interannual variation in fishing activity, and the need to base calculations on value transfers with a number of expert judgement we modelled benefits in Bayesian belief network (BBN). BBNs are a modeling tool especially suited for documenting the joint uncertainty in combining quantitative and qualitative modeling results. See Supplementary material S1 for documentation of the model. The BBN modeling estimated a mean total marginal value of smolt for recreational fishing of $5.25 per smolt (variance of $81.60 per smolt). In the rest of the analysis we use this figure as an estimate expected smolt benefit under different scenarios:

$$\mathrm{RA} = S_s \cdot SAR \tag{4}$$

where RA is the number of returning adults, S_s is the number of smolts, and SAR is the percentage of smolts that return from the sea as adults considered as 6% [21].

$$AF = RA \cdot RC \tag{5}$$

where AF is the number of adults captured in recreational fishing, and RC is the percentage of the recreational catch (35%) based on NINA Report 636–2011.

$$B_s = AF \cdot AV \tag{6}$$

where B_s is the benefit per scenario from recreational fishing and AV is the adult value.

The total cost estimate was the sum of energy cost and habitat cost. The net cost was calculated as the total cost minus the total benefit for every scenario.

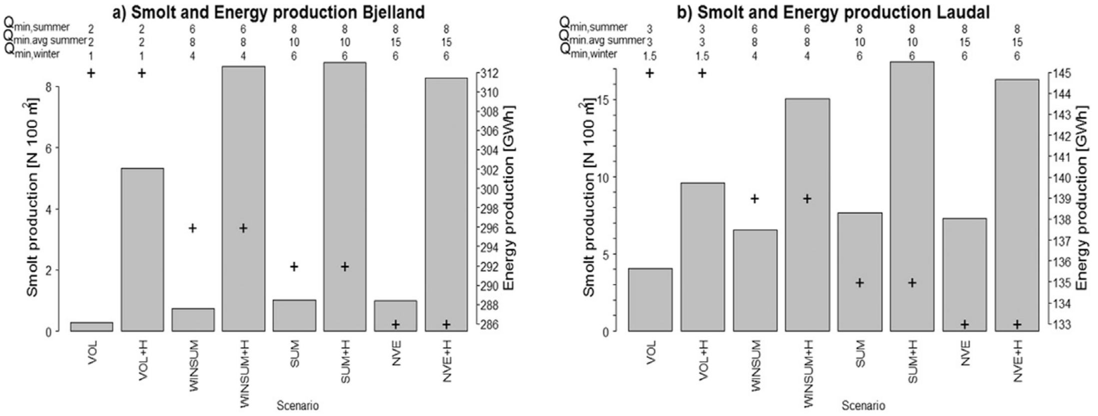

Fig. 4. Smolt and energy production graph for a) Bjelland reach and b) Laudal reach. Bars represent the smolt production per 100 m^2 under each scenario. The black crosses represent the energy produced under each scenario. Minimum flow – Q min ($m^3 s^{-1}$) – for summer and winter and Q min average ($m^3 s^{-1}$) for summer is shown above each bar.

3. Results

3.1. Smolt production versus energy production

Smolt production and energy production results were highly dependent on the scenario (Fig. 4). In both reaches, the voluntary release scenario (VOL) had the highest energy production but the lowest smolt production. The scenario involving voluntary release with habitat modification (VOL+H) had an equivalent energy production but much greater smolt production than the scenario for voluntary release without habitat modification (VOL). Scenario SUM+H showed the highest smolt production per unit area, Scenarios WINSUM, SUM and NVE showed similar level of smolt production per unit area, but scenario NVE has the lowest energy production. The same pattern applies with WINSUM+H, SUM+H and NVE+H.

3.2. Energy and habitat modification costs

There was a large difference between Bjelland and Laudal in terms of energy loss (Fig. 4). NVE's regime was predicted to result in an energy production loss of ~25 GW h a^{-1} in Bjelland (Fig. 4a) and ~12.5 GW h a^{-1} in Laudal (Fig. 4b), compared with the voluntary release scenario (VOL). The annual loss of power of NVE versus VOL scenario was equivalent to ~$995,486 a^{-1} for Bjelland and ~$479,227 a^{-1} for Laudal when using the fixed price as a low estimate baseline.

The habitat modification costs (a one-time expense for removal of weirs, and introduction of spawning gravel potentially with a three-year cycle) were estimated as investments of $217,713 and $261,433 for Bjelland and Laudal, respectively (Table 2). The annuity costs over 40 years at 5% p.a. amortization was $12,687 for Bjelland and $15,235 for Laudal.

The cost estimates for habitat modification were later validated with experience from actual removal of four of the weirs in Laudal stretch spring-summer 2016 with an average realized cost of $21,107/weir, comparing quite well with our *ex ante* estimate of $29.048/weir used in the modeling.

3.3. Net-cost of each scenario

The average benefit from recreational fishing in each scenario was an order of magnitude lower than the average cost from foregone hydropower production per smolt, particularly in Bjelland. All the scenarios had net costs compared to the voluntary release scenario (VOL) (Fig. 5), suggesting that recreational fishing benefits are far from justifying foregone hydropower on purely economic grounds. The scenarios with habitat modification were slightly less cost effective than scenarios without habitat modification. On these grounds the old voluntary regime would have been the optimal approach, with hydropower generating enough returns to potentially compensate foregone recreational fishing benefits.

Table 2
Estimated costs of habitat modification actions in Bjelland and Laudal.

Cause of expense	Cost (USD)	
	Bjelland	Laudal
Removal of weirs	144 473	239 933
Addition of gravel	21 500	21 500
Other	51 740	0
Total	217 713	261 433

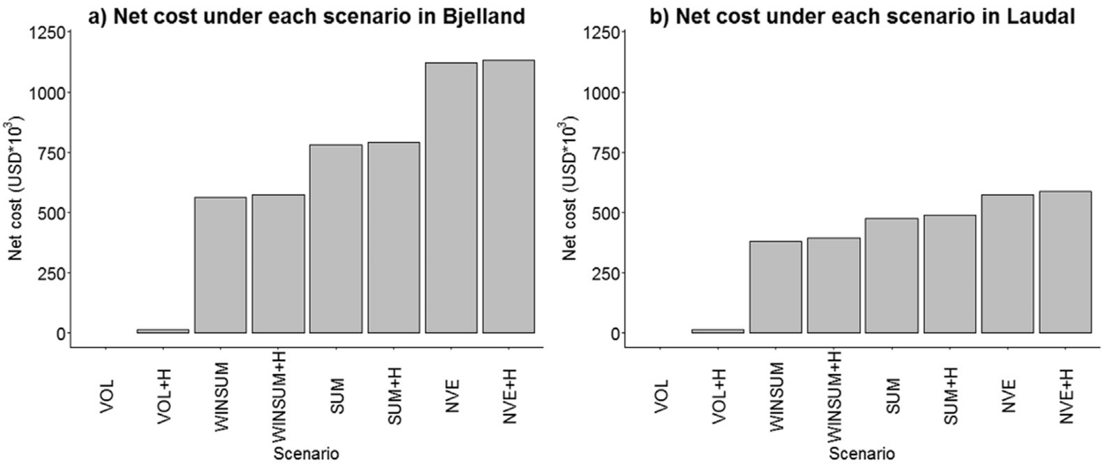

Fig. 5. Net-cost graphs of each scenario relative to scenario VOL for a) Bjelland reach and b) Laudal reach.

3.4. Cost-effectiveness of each scenario

Despite net costs across the main commercial uses of the river, the regulator NVE has required the hydropower company to test a flow regime that provides more smolt than the historic voluntary regime. Given this requirement, which regime provides more smolt per Dollar spent? All scenarios with habitat modification (+H) were more cost effective than scenarios without habitat modification for both reaches (Fig. 6). In both reaches, the most cost-effective scenario compared with the VOL scenario was VOL+H. Producing a smolt in the Bjelland reach was less cost-effective than producing it in the Laudal reach. Producing a smolt in the Bjelland reach under the WINSUM and WINSUM+H scenarios cost an average of $400 and $26.3 more than in the Laudal reach, respectively. In Bjelland, the next most cost effective scenario after VOL+H was WINSUM+H, whereas in the Laudal reach this was SUM+H.

4. Discussion

This study highlights the importance of minimum flow, rather than average flow, in regulating salmon smolt production. Total smolt production in the NVE scenario was not significantly different to that in the SUM scenario in either reach, despite the fact that the observed average discharges in the NVE scenario were higher during summer than in the SUM scenario. Specified minimum winter and summer discharges were equivalent for both scenarios, so this shows that the minimum flow (not the average flow) is the key factor for determining smolt production. This modeling work confirms the empirical work of Forseth [24], who found that the extreme minimum flow in the hydropower bypass sections resulted in a relatively small production compared with the historical situation before river regulation.

Results from the simulations also support that habitat modification and voluntarily release (VOL) will increase smolt production to the same level as the NVE scenario without the higher energy losses. The simulations also show that the most expensive mitigation measure is not necessarily the most effective in terms of ecological response. Scenario SUM and NVE generated equivalent smolt productions, but the latter scenario had highest cost, and the smolt production per unit area was actually higher in SUM due to it having a smaller wetted (water covered) area.

The relative merit of the scenarios, in terms of smolt production, was reach-specific. Differences in smolt production among the scenarios without habitat modification were smaller in the Bjelland reach than in the Laudal reach. This was because wetted area

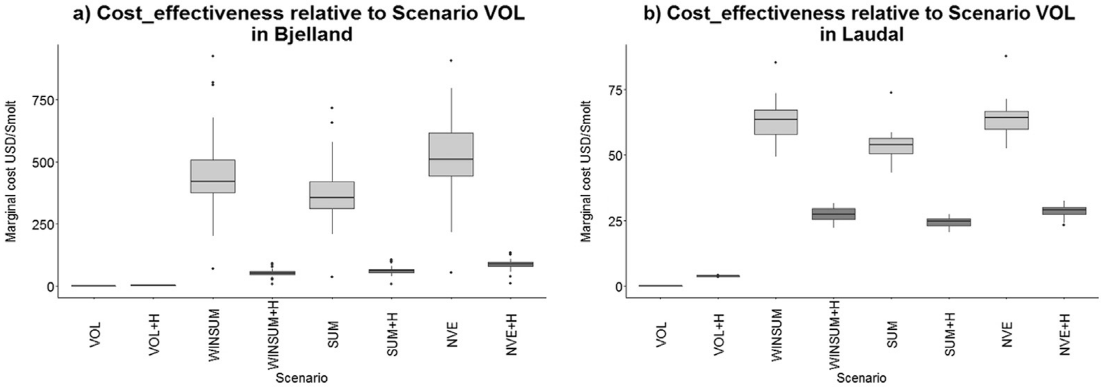

Fig. 6. a) Cost-effectiveness rank from comparison of average marginal cost relative to scenario VOL for a) Bjelland and b) Laudal. The horizontal line in the boxplot shows the median. Boxes bound the 25 and 75 percentiles. Whiskers bound all values within 1.5× the inter-quartile range. Filled circles indicate observations outside the interquartile range.

(the key determinant of smolt production) was less sensitive to discharge in the Bjelland reach than in the Laudal reach due to differences in river reach characteristics: Bjelland had a more 'U'-shaped channel profile, whereas Laudal was a straight reach impounded by several weirs with a more 'V'-shaped channel profile. Differences in smolt production among scenarios involving habitat-modification was more variable because the watercourse characteristics had been modified due to the removal of weirs, which affected the relationship between discharge and wetted area, which is crucial for smolt production.

Predictions from the modeling approach in this study need to be considered within the context of uncertainties in the data available. Data for model calibration were somewhat limited [22]. The hydropower operation simulations and the estimation of energy production is a first order estimate, based on inflow and electricity price scenarios, using a long term operational strategy tested against actual production from the Mandalselva power system. The short term optimal operation of the energy system was not simulated in this project. This study has focused on 'first order' habitat mitigation measures. However, it is important to also consider how the removal of weirs will change the meso-habitat structure of the reach. After weir removal, the natural course will no longer be adapted to prevailing flow conditions and physical processes will be altered dramatically. Effects are context-specific: for example, Gard [29] obtained a decreased amount of spawning habitat associated with high-flow induced channel changes, whereas Harrison et al. [30] found an increase in the amount of spawning habitat with time. This highlights the need for more detailed models that can more accurately simulate changes in channel topography associated with high flow events which could then be used to simulate habitat over time.

The cost comparison between energy and habitat modification cost versus the benefits of smolt for recreational fishing differed by several orders of magnitudes. Net costs of smolt production would decrease if fishing intensity increased disproportionately due to more favorable fishing conditions, while maintaining a catch-release policy. We did not identify other ecosystem services from environmental flows. However, we think it unlikely that there are other ecosystem services to equal the benefits from recreational fishing. From a river use perspective recreational fishing is the largest. For this reason, we find it unlikely that economic values of ecosystem services can be used as an argument for higher flows than the voluntary release. Kennedy et al. [31] calculated a benefit of 20 Euros (~20 USD) per smolt, but even when applying this value to our net-cost analyses, all scenarios would still have a higher net costs in comparison to the voluntary release scenario. Our findings concur with previous studies. For instance, it has been found that the implementation of increased flows in a migratory fishway in the Ljusnan River (Sweden) generated a negative net present value when taking into account the revenue loss from hydroelectricity and the local residents' willingness to pay for increased flow, compensation for increased greenhouse gas emissions, and changes to the demand for electricity and labor [32]. Håkansson [33] found that the benefits from increasing the number of wild salmon that reach the spawning grounds in the Vindel River (Sweden) based on the willingness-to-pay survey of both anglers and non-anglers remains positive only when the valuation of salmon is high and the electricity price is low.

According to our findings, the trial regime determined by the regulator NVE assumes that unquantified benefits of non-recreational ecosystem services are orders of magnitude larger than recreational benefits. Given that the Mandalselva River has recovered salmon due to remediation measures and release program after a long period of acid rain it seems less likely that regulation is justified based on a safe-minimum standards or precautionary principle. Given the regulators implicit assumption about ecosystem services benefits and the requirement to revise the concession terms, a cost-effectiveness analysis of smolt production is a second-best approach to identifying preferred management scenarios. Firstly, it was shown that scenarios with habitat modification were more cost-effective than scenarios without habitat modification in both reaches. Secondly, producing additional smolt in the Bjelland reach was less cost-effective than in the Laudal reach. The implementation of the integrative method and the cost-effectiveness analyses show that for future analyses it is highly recommended to start with identifying limiting factors on the specific study reach and define different alternatives, their cost and their success with a quantitative indicator. Our results comparing river reaches highlight the importance of choosing the correct place to carry out river restoration project in a river network. The spatial targeting of measures across a river scape is of particular interest in the context of biodiversity offsetting [34] between river regulation stretches.

5. Conclusions

The scenario based modeling performed in this paper shows that, as an alternative to increasing the minimum flow within a hydropower bypass (proposed by the NVE), habitat modification can compensate for low flows and may be a cost-effective measure to achieve higher smolt production. The modeling methodology allows for the testing of multiple flow scenarios and provides the possibility of evaluating physical habitat modifications that would be impractical to do by trial and error.

The proposed methodology has a high potential for providing support in setting environmental flows in heavily modified water bodies as designated by the Water Framework Directive. This approach identifies hydropower production possibilities at varying levels of environmental flows, and widens the definition of environmental flows to consider the compensating effects of morphological habitat mitigation measures. Overall, it has been shown that this approach can lead to more cost-effective definition of environmental flows than approaches that only focus on river regulation. Despite the abundant data available on many regulated rivers, Norwegian authorities do not currently compile modeling results in hydropower regulations from different disciplines such as hydrology, hydraulics, ecology and hydropower economics. The use of an integrated modeling approach for the assessment of environmental flows has been demonstrated as a contribution to a better use of available information. While the data are specific to the Mandalselva River, the modeling tools that have been applied in this study are generic and the methodology could be applied to other rivers regulated by hydropower. Continued methodology development should focus on integrating other ecosystem services of rivers, such as landscape aesthetics and recreational fishing interests, in a multi-criteria decision analysis framework.

Acknowledgements

This research received funding from the CEDREN project EcoManage (Grant agreement from Norwegian Research Council, contract no. 215934/E20). We would like to thank Svein Haugland and Agder Energi for providing access to data and discussion of model outcomes, and thank the editor and two anonymous reviewers for comments that greatly improved the manuscript.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.wre.2017.02.003.

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