

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

Ana Adeva Bustos^{a*}, Richard David Hedger^b, Hans-Petter Fjeldstad^c, Knut Alfredsen^a, Håkon Sundt^c, David Nicholas Barton^d.

^aDepartment of Civil and Environmental Engineering, NTNU, S. P. Andersens 5, Trondheim, Norway

^bNorwegian Institute for Nature Research (NINA), Høgskoleringen 9, Trondheim, 7043, Norway

^cSINTEF Energy Research, Sem Sælandsvei 11, Trondheim, 7048, Norway

^dNorwegian Institute for Nature Research (NINA), Gaustadalléen 21, Oslo,.0349, Norway

*Corresponding author, email: ana.adeva.bustos@ntnu.no

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

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 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

1 optimizing the balance between energy production and salmon smolt production. The
2 methodology was tested in the Mandalselva River (Norway), where a new minimum flow
3 regime has been proposed by the Norwegian Water Resources and Energy Directorate (NVE).
4 Because the proposed new minimum flow regime is not based on the natural pre-regulation
5 status in the river (which is not well known), this proposed regime has not been validated, and
6 may have limited potential for finding a successful solution for both ensuring energy
7 production and sustaining the fish population. In order to analyse the river in the context of
8 integrated watershed management and include the potential cost-effectiveness of mitigation
9 measures to offset impacts across projects, we conduct a cost-effectiveness trade-off analysis
10 of the application of scenario alternatives at two contrasting hydropower plants. We
11 investigate the scenarios that support a flow that generates energy in a profitable way, while
12 also maintaining or increasing the level of salmon production. We also investigate the
13 potential for habitat remediation to act as an ameliorating factor for flow regimes that would
14 maintain or increase salmon populations.
15
16

17 **2. MATERIALS AND METHOD**

18 **2.1 Study reach**

19
20
21
22
23 The Mandalselva River, located in southern Norway (58° N, 7° E), is 115 km long with a
24 catchment area of 1800 km² and a mean annual discharge of 88 m³s⁻¹ (Figure 1). The river is
25 regulated by 6 hydropower plants and 9 reservoirs. Nearly 90% of the storage capacity is
26 found in the Nāvann and Juvatnet reservoirs in the surrounding mountains. Atlantic salmon
27 can migrate 47 km upstream from the sea to a final migration barrier at the Kavfossen
28 waterfall. The two lowest hydropower plants, Bjelland and Laudal, constructed in a period
29 when Atlantic salmon were absent from the river due to acidification of the water [18], are
30 located within the part of the river where an introduced salmon population now resides. In
31 order to mitigate the aesthetic effects of the low minimum flow and maintain a continuous
32 water level in the bypasses of the hydropower plants, weirs have been constructed: two small
33 weirs at Bjelland bypass, and 8 stone weirs and one low concrete weir at Laudal bypass.
34
35
36

37
38 INSERT FIGURE 1 ABOUT HERE
39
40

41
42 Bjelland power plant has two Francis turbines in operation, a head of 87.5 m, an installed
43 capacity of 53 MW and an average annual production of 312 GWh. Laudal power plant has
44 two Francis turbines, a head of 36 m, an installed capacity of 26 MW and an average annual
45 production of 146 GWh. In 1997, after twenty years without a salmon stock, a liming program
46 and re-stocking strategy was initiated. This resulted in a rapid increase in the salmon
47 population abundance. Therefore, the procedure to revise the license was started by NVE in
48 2002. By 2015, the Laudal hydropower plant was in the second year of a five-year trial period
49 used to test the regulation flow specified by NVE, while in Bjelland no change in the
50 voluntary regime has been specified by NVE.
51
52

53 **2.2 Defining and running the discharge scenarios**

54
55
56 The methodology developed in this study was an integrated system that combined
57 hydrological, hydraulic and ecological modeling (Figure 2), building upon existing and well-
58 tested modeling tools, and linking to tools for statistical analysis and visualization of results.
59 A total of 8 scenarios were defined for each reach (Bjelland and Laudal), covering different
60
61
62
63
64
65

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 $6 \text{ m}^3 \text{ s}^{-1}$ in winter, a spring release of 50% of the inflow, and $8 - 25 \text{ m}^3 \text{ s}^{-1}$ in summer depending on inflow instead of the voluntary $1.5 \text{ m}^3 \text{ s}^{-1}$ winter and $3 \text{ m}^3 \text{ s}^{-1}$ 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 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.

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, $10 \text{ m}^3 \text{ s}^{-1}$ and $15 \text{ m}^3 \text{ s}^{-1}$ 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 ($\text{m}^3 \text{ s}^{-1}$)		Habitat modification?	Minimum discharge ($\text{m}^3 \text{ s}^{-1}$)		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

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 (Figure 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

1 hydropower operation and habitat modification. The ecological component involved using an
2 individual based model (IBM) to generate a salmon population, using outputs from the
3 hydrological and hydraulic modeling. The number of salmon smolts (individuals that have
4 reached adulthood) was obtained directly from the IBM, the energy cost was calculated using
5 the outputs from the flow regime hydropower simulations, the habitat modification cost was
6 calculated based on the estimated expenses for the works, and the benefit per scenario was
7 calculated using the outputs from the IBM and the smolt value from recreational fishing. A
8 net-cost analysis was carried out using the energy cost, the habitat cost and the benefit per
9 scenario. A cost-effectiveness analysis ranking was then carried out, comparing the scenarios.
10 In order to consider scenarios to achieve targets for smolt production, the cost per year of each
11 scenario was compared against total smolt production per year, and assessed in relation to the
12 reference scenario VOL. This was carried out by dividing the expected value of the annual
13 cost of power production and habitat modification (if applicable) by the estimated smolt
14 production per year, relative to the VOL scenario.
15
16

17
18 INSERT FIGURE 2 ABOUT HERE
19
20

21 2.2.1 Hydrological component

22
23
24 The hydrological component involved generating a time-series of 40 years of discharge data
25 to enable a multi-decadal simulation of smolt production. Available data for the hydropower
26 stations spanned a much shorter period than this, so data from gauges located some distance
27 from the study area were used as a proxy. Discharge at the hydropower stations were
28 estimated from gauge data using a relationship established for a four-year period when there
29 were both on-site and off-site observations of discharge (equation 1):
30
31

$$32 (1) Q_S = (F_S \cdot A_S) / (F_D \cdot A_D) \cdot Q_D$$

33
34
35 where Q_S is the discharge at a target location (hydropower station); Q_D is the discharge at the
36 gauging station; F_S is the specific runoff at the target location; A_S is the runoff area of the
37 target location; F_D is the specific runoff at the gauge; and A_D is the gauge area. The correlation
38 coefficient was 0.96, indicating that the scaling method was suitable for extending the data
39 series. This relationship was then used to predict discharges at the hydropower stations.
40
41

42 2.2.2 Hydraulic component

43
44
45 The hydraulic component determined how alterations in flow regime and habitat remediation
46 affected the channel wetted width, a key factor determining smolt production. The river
47 hydraulics were simulated with a 1D hydraulic model [19] for the sections where geometry
48 data were available. Where no geometry data were available, relationships between flow and
49 wetted width were determined using field surveys. The river channel was characterized into
50 three channel types – A, B, C (Figure 3) – and piecewise-defined functions were used to
51 describe how wetted width changed with discharge for each channel type [20]. For each of the
52 three channel types, a linear function was used from the lowest discharge until the first
53 observed discharge, a third degree polynomial was fitted using observed discharges and
54 wetted areas, and a linear function was used for the highest discharges. The Bjelland bypass
55 reach was defined as a combination of small lakes (type B) and narrow sections (type C).
56 Type A was used for the Laudal bypass reach.
57
58
59
60
61
62
63
64
65

INSERT FIGURE 3 ABOUT HERE

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 m² 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.

$$(2) P = \eta \cdot \rho \cdot g \cdot H \cdot Q$$

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 ($\text{m}^3 \text{ s}^{-1}$).

Energy production was calculated as follows:

$$(3) E = P \cdot t$$

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

3 For energy cost, the electricity price was fixed and used as a baseline for comparison ($\$0.04$
4 kWh^{-1} [28]). Volatile prices and potential up-ramping for peak demands may increase the
5 difference in cost per year between the reaches above this fixed price. However, the minimum
6 flow releases take precedence over production, so a peaking operation will not influence the
7 water released into the bypass.
8
9

10 2.4 Habitat modification and cost estimation

11 For the habitat modification it was assumed that the weir removal and the addition of the
12 spawning gravel would be planned and constructed in a single operation to minimize overall
13 costs. For Bjelland, both weirs were assumed to be removed in the model. For Laudal, the 8
14 low stone weirs were assumed to be removed and the concrete weir modified.
15
16
17
18

19 Estimated costs were based on experiences from other projects (Sven-Erik Gabrielsen (Uni
20 Miljø), Tor Kviljo (Terrateknikk) pers. Com. and NVE project prices). The estimated volumes
21 to be removed were 800 m^3 of concrete in Bjelland, and $\sim 200 \text{ m}^3$ of concrete and 4800 m^3 of
22 stones in Laudal. To the estimated cost of removal actions, a 40% additional cost was
23 considered for removal of concrete. In total, $\sim 500 \text{ m}^3$ of gravel was added in each reach in the
24 habitat modification scenarios. Costs of gravel were assumed to be $\$38$ - $\$43$ per m^3 and
25 additional costs of transport and cost of the removal of stones were estimates to be $\$43$ per
26 m^3 . In the Bjelland reach, the difficulty of access to the area was estimated as an additional
27 200% of the sum of weir removal and gravel addition costs. In the Laudal reach, a 10%
28 additional cost was added for accessibility.
29
30
31
32

33 2.5 Net-cost analysis

34 The benefit per scenario from important ecosystem services were assessed as a
35 complementary study to the cost-effectiveness analysis. We focused on recreational fishing
36 benefits which constitute the main commercial activity on the river besides hydropower
37 production. Would recreational fishing benefits of additional smolt be high enough to justify
38 foregone income from hydropower production and remediation costs? Three types of fishing
39 benefits that could be attributed to increased smolt productivity were included: marginal smolt
40 expenses, marginal smolt sale value and marginal willingness to pay (WTP). Given the
41 interannual variation in fishing activity, and the need to base calculations on value transfers
42 with a number of expert judgement we modelled benefits in Bayesian belief network (BBN).
43 BBNs are a modeling tool especially suited for documenting the joint uncertainty in
44 combining quantitative and qualitative modeling results. See supplementary material S1 for
45 documentation of the model. The BBN modeling estimated a mean total marginal value of
46 smolt for recreational fishing of $\$5.25$ per smolt (variance of $\$81.60$ per smolt). In the rest of
47 the analysis we use this figure as an estimate expected smolt benefit under different scenarios:
48
49
50
51
52
53

$$54 \quad (4) \quad RA = S_s \cdot SAR$$

55 where RA is the number of returning adults, S_s is the number of smolts, and SAR is the
56 percentage of smolts that return from the sea as adults considered as 6% [21].
57
58
59
60
61
62
63
64
65

$$(5) AF = RA \cdot RC$$

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.

$$(6) B_s = AF \cdot AV$$

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.

3. RESULTS

3.1 Smolt production versus energy production

Smolt production and energy production results were highly dependent on the scenario (Figure 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.

ISERT FIGURE 4 ABOUT HERE

3.2 Energy and habitat modification costs

There was a large difference between Bjelland and Laudal in terms of energy loss (Figure 4). NVE's regime was predicted to result in an energy production loss of $\sim 25 \text{ GWh a}^{-1}$ in Bjelland (Figure 4a) and $\sim 12.5 \text{ GWh a}^{-1}$ in Laudal (Figure 4b), compared with the voluntary release scenario (VOL). The annual loss of power of NVE versus VOL scenario was equivalent to $\sim \$995,486 \text{ a}^{-1}$ for Bjelland and $\sim \$479,227 \text{ a}^{-1}$ 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.

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

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) (Figure 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.

INSERT FIGURE 5 ABOUT HERE

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 (Figure 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.

INSERT FIGURE 6 ABOUT HERE

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

1 [24], who found that the extreme minimum flow in the hydropower bypass sections resulted
2 in a relatively small production compared with the historical situation before river regulation.

3 Results from the simulations also support that habitat modification and voluntarily release
4 (VOL) will increase smolt production to the same level as the NVE scenario without the
5 higher energy losses. The simulations also show that the most expensive mitigation measure
6 is not necessarily the most effective in terms of ecological response. Scenario SUM and NVE
7 generated equivalent smolt productions, but the latter scenario had highest cost, and the smolt
8 production per unit area was actually higher in SUM due to it having a smaller wetted (water
9 covered) area.
10
11

12 The relative merit of the scenarios, in terms of smolt production, was reach-specific.
13 Differences in smolt production among the scenarios without habitat modification were
14 smaller in the Bjelland reach than in the Laudal reach. This was because wetted area (the key
15 determinant of smolt production) was less sensitive to discharge in the Bjelland reach than in
16 the Laudal reach due to differences in river reach characteristics: Bjelland had a more ‘U’-
17 shaped channel profile, whereas Laudal was a straight reach impounded by several weirs with
18 a more ‘V’-shaped channel profile. Differences in smolt production among scenarios
19 involving habitat-modification was more variable because the watercourse characteristics had
20 been modified due to the removal of weirs, which affected the relationship between discharge
21 and wetted area, which is crucial for smolt production.
22
23
24
25

26 Predictions from the modeling approach in this study need to be considered within the context
27 of uncertainties in the data available. Data for model calibration were somewhat limited [22].
28 The hydropower operation simulations and the estimation of energy production is a first order
29 estimate, based on inflow and electricity price scenarios, using a long term operational
30 strategy tested against actual production from the Mandalselva power system. The short term
31 optimal operation of the energy system was not simulated in this project. This study has
32 focused on ‘first order’ habitat mitigation measures. However, it is important to also consider
33 how the removal of weirs will change the meso-habitat structure of the reach. After weir
34 removal, the natural course will no longer be adapted to prevailing flow conditions and
35 physical processes will be altered dramatically. Effects are context-specific: for example,
36 Gard [29] obtained a decreased amount of spawning habitat associated with high-flow
37 induced channel changes, whereas Harrison et al. [30] found an increase in the amount of
38 spawning habitat with time. This highlights the need for more detailed models that can more
39 accurately simulate changes in channel topography associated with high flow events which
40 could then be used to simulate habitat over time
41
42
43
44
45

46 The cost comparison between energy and habitat modification cost versus the benefits of
47 smolt for recreational fishing differed by several orders of magnitudes. Net costs of smolt
48 production would decrease if fishing intensity increased disproportionately due to more
49 favorable fishing conditions, while maintaining a catch-release policy. We did not identify
50 other ecosystem services from environmental flows. However, we think it unlikely that there
51 are other ecosystem services to equal the benefits from recreational fishing. From a river use
52 perspective recreational fishing is the largest. For this reason, we find it unlikely that
53 economic values of ecosystem services can be used as an argument for higher flows than the
54 voluntary release. Kennedy et al. [31] calculated a benefit of 20 Euros (~20 USD) per smolt,
55 but even when applying this value to our net-cost analyses, all scenarios would still have a
56 higher net costs in comparison to the voluntary release scenario. Our findings concur with
57 previous studies. For instance, it has been found that the implementation of increased flows in
58
59
60
61
62
63
64
65

1 a migratory fishway in the Ljusnan River (Sweden) generated a negative net present value
2 when taking into account the revenue loss from hydroelectricity and the local residents'
3 willingness to pay for increased flow, compensation for increased greenhouse gas emissions,
4 and changes to the demand for electricity and labor [32]. Håkansson [33] found that the
5 benefits from increasing the number of wild salmon that reach the spawning grounds in the
6 Vindel River (Sweden) based on the willingness-to-pay survey of both anglers and non-
7 anglers remains positive only when the valuation of salmon is high and the electricity price is
8 low.
9

10 According to our findings, the trial regime determined by the regulator NVE assumes that
11 unquantified benefits of non-recreational ecosystem services are orders of magnitude larger
12 than recreational benefits. Given that the Mandalselva River has recovered salmon due to
13 remediation measures and release program after a long period of acid rain it seems less likely
14 that regulation is justified based on a safe-minimum standards or precautionary principle.
15 Given the regulators implicit assumption about ecosystem services benefits and the
16 requirement to revise the concession terms, a cost-effectiveness analysis of smolt production
17 is a second-best approach to identifying preferred management scenarios. Firstly, it was
18 shown that scenarios with habitat modification were more cost-effective than scenarios
19 without habitat modification in both reaches. Secondly, producing additional smolt in the
20 Bjelland reach was less cost-effective than in the Laudal reach. The implementation of the
21 integrative method and the cost-effectiveness analyses show that for future analyses it is
22 highly recommended to start with identifying limiting factors on the specific study reach and
23 define different alternatives, their cost and their success with a quantitative indicator. Our
24 results comparing river reaches highlight the importance of choosing the correct place to carry
25 out river restoration project in a river network. The spatial targeting of measures across a river
26 scape is of particular interest in the context of biodiversity offsetting [34] between river
27 regulation stretches.
28
29
30
31
32
33

34 **5. CONCLUSIONS**

35
36
37 The scenario based modeling performed in this paper shows that, as an alternative to
38 increasing the minimum flow within a hydropower bypass (proposed by the NVE), habitat
39 modification can compensate for low flows and may be a cost-effective measure to achieve
40 higher smolt production. The modeling methodology allows for the testing of multiple flow
41 scenarios and provides the possibility of evaluating physical habitat modifications that would
42 be impractical to do by trial and error.
43
44
45

46 The proposed methodology has a high potential for providing support in setting
47 environmental flows in heavily modified water bodies as designated by the Water Framework
48 Directive. This approach identifies hydropower production possibilities at varying levels of
49 environmental flows, and widens the definition of environmental flows to consider the
50 compensating effects of morphological habitat mitigation measures. Overall, it has been
51 shown that this approach can lead to more cost-effective definition of environmental flows
52 than approaches that only focus on river regulation. Despite the abundant data available on
53 many regulated rivers, Norwegian authorities do not currently compile modeling results in
54 hydropower regulations from different disciplines such as hydrology, hydraulics, ecology and
55 hydropower economics. The use of an integrated modeling approach for the assessment of
56 environmental flows has been demonstrated as a contribution to a better use of available
57 information. While the data are specific to the Mandalselva River, the modeling tools that
58
59
60
61
62
63
64
65

1 have been applied in this study are generic and the methodology could be applied to other
2 rivers regulated by hydropower. Continued methodology development should focus on
3 integrating other ecosystem services of rivers, such as landscape aesthetics and recreational
4 fishing interests, in a multi-criteria decision analysis framework.
5

6. ACKNOWLEDGEMENTS

8 This research received funding from the CEDREN project EcoManage (grant agreement from
9 Norwegian Research Council). We would like to thank Svein Haugland and Agder Energi for
10 providing access to data and discussion of model outcomes, and thank the editor and two
11 anonymous reviewers for comments that greatly improved the manuscript.
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

REFERENCES

1. Johnsen, B.O., J.V. Arnekleiv, L. Asplin, B.T. Barlaup, T.F. Næsje, B.O. Rossenland, S.J. Saltveit, and A. Tvede, *Hydropower Development- Ecological Eeffects*, in *Atlantic Salmon Ecology*, Ø. Aas, et al., Editors. 2011.
2. Sørensen, J., J.H. Halleraker, M. Bjørnhaug, R.M. Langåker, O.K. Selboe, E. Brodtkorb, I. Haug, and J. Fjellanger, *Vannkraftkonsesjoner som kan revideres innen 2022. Nasjonal gjennomgang og forslag til prioritering. Rapport nr. 49/2013*. 2013.
3. Hansen, L., P. Fiske, M. Holm, A. Jensen, and H. Sægrov, *Bestandsstatus for laks i Norge. Prognoser for 2008. Rapport fra arbeidsgruppe*. Utredning for DN 2008, 2008. **5**: p. 1-66.
4. Bakken, T.H., P. Zinke, A. Melcher, H. Sundt, T. Vehanen, K. Jorde, and M. Acreman, *Setting environmental flows in regulated rivers. TRA 4276*. 2012, SINTEF Energy Research: Trondheim.
5. Brisbane Declaration. *The Brisbane Declaration: Environmental flows are essential for freshwater ecosystem health and human well-being*. in *10th International River Symposium, Brisbane, Australia*. 2007.
6. Buchanan, C., H.L.N. Moltz, H.C. Haywood, J.B. Palmer, and A.N. Griggs, *A test of The Ecological Limits of Hydrologic Alteration (ELOHA) method for determining environmental flows in the Potomac River basin, U.S.A*. *Freshwater Biology*, 2013. **58**(12): p. 2632-2647.
7. Poff, N.L., B.D. Richter, A.H. Arthington, S.E. Bunn, R.J. Naiman, E. Kendy, M. Acreman, C. Apse, B.P. Bledsoe, M.C. Freeman, J. Henriksen, R.B. Jacobson, J.G. Kennen, D.M. Merritt, J.H. O'Keeffe, J.D. Olden, K. Rogers, R.E. Tharme, and A. Warner, *The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards*. *Freshwater Biology*, 2010. **55**(1): p. 147-170.
8. Water Framework Directive, *Water Framework Directive*. 2000.
9. Sørensen, J.N., *Vannkraftkonsesjoner som kan revideres innen 2022. Nasjonal gjennomgang og forslag til prioritering*. 2013, NVE: Oslo.
10. Charmasson, J. and P. Zinke, *Mitigation Measures Against Hydropeaking Effects*. 2011, SINTEF Energy Research.
11. Niu, S. and M. Insley, *On the economics of ramping rate restrictions at hydro power plants: Balancing profitability and environmental costs*. *Energy Economics*, 2013. **39**: p. 39-52.
12. Person, E., M. Bieri, A. Peter, and A.J. Schleiss, *Mitigation measures for fish habitat improvement in Alpine rivers affected by hydropower operations*. *Ecohydrology*, 2014. **7**(2): p. 580-599.
13. Barton, D.N., D. Berge, and R. Jansen, *Pressure-impact multi-criteria environmental flow analysis: application in the Øyeren delta, Glomma River Basin, Norway*. , in *Strategy and Methodology for Improved IWRM: An Integrated Interdisciplinary Assessment in Four Twinning River Basins in Europe and Asia*, A.R.-C.a.P.S. G.D. Gooch, Editor. 2010, IWA Publishing: London UK.
14. Jager, H.I. and B.T. Smith, *Sustainable reservoir operation: can we generate hydropower and preserve ecosystem values?* *River research and Applications*, 2008. **24**(3): p. 340-352.
15. Hanley, N., E.B. Barbier, and E. Barbier, *Pricing nature: cost-benefit analysis and environmental policy*. 2009: Edward Elgar Publishing.
16. Klauer, B., J. Schiller, and F. Bathe, *Concept for cost effective improvement of river morphology in the context of the European Water Framework Directive*. *Journal of Environmental Planning and Management*, 2014: p. 1-17.
17. Karjalainen, T.P., M. Marttunen, S. Sarkki, and A.M. Rytönen, *Integrating ecosystem services into environmental impact assessment: An analytic-deliberative approach*. *Environmental Impact Assessment Review*, 2013. **40**: p. 54-64.
18. Kroglund, F., B.O. Rosseland, H.-C. Teien, B. Salbu, T. Kristensen, and B. Finstad, *Water quality limits for Atlantic salmon (Salmo salar) exposed to short term reductions in pH and increased*

- aluminum simulating episodes. *Hydrology and Earth System Sciences Discussions*, 2007. **4**(5): p. 3317-3355.
19. HEC-RAS, *User manual. US Army Corps of Engineers, Hydrologic Engineering Center, Davis Version*. 2008.
 20. Sauterleute, J., *CEDREN EnviDORR: Correlations between flow and water covered area of four representative stretches of Mandal River*. 2011, SINTEF Energy.
 21. Hedger, R.D., L.E. Sundt-Hansen, T. Forseth, O. Diserud, O. Ugedal, and A.G. Finstad, *Modelling the complete life-cycle of Atlantic salmon (Salmo salar L.) using a spatially explicit individual-based approach*. *Ecological modelling*, 2013: p. 119-129.
 22. Hedger, R.D., L.E. Sundt-Hansen, T. Forseth, O. Ugedal, O. Diserud, and A.G. Finstad, *Predicting climate change effects on subarctic-Arctic populations of Atlantic salmon (Salmo salar)*. *Canadian Journal of Fisheries and Aquatic Sciences*, 2013: p. 159-168.
 23. Sauterleute, J.F., R.D. Hedger, C. Hauer, U. Pulg, H. Skoglund, L.E. Sundt-Hansen, T.H. Bakken, and O. Ugedal, *Modelling the effects of stranding on the Atlantic salmon population in the Dale River, Norway*. *Science of The Total Environment*, 2016. **573**: p. 574-584.
 24. Forseth, T., *Notat fra befarings strekning 2, mai 2009. Åseralprosjektene: konsekvensvurdering for fisk på lakseførende strekning*. 2012, NINA
 25. Forseth, T. and A. Harby, *Handbook for environmental design in regulated salmon rivers*. 2014, Trondheim: NINA.
 26. Barlaup, B.T., S.E. Gabrielsen, H. Skoglund, and T. Wiers, *Addition of spawning gravel—a means to restore spawning habitat of atlantic salmon (Salmo salar L.), and Anadromous and resident brown trout (Salmo trutta L.) in regulated rivers*. *River research and Applications*, 2008. **24**(5): p. 543-550.
 27. Thorstad, E., B. and T. Forseth, *Status for norske laksebestander i 2014. Rapport fra Vitenskapelig råd for lakseforvaltning nr 6*. 2014: Trondheim.
 28. Fjeldstad, H.P., K. Alfreidsen, and T. Boissy, *Optimizing Atlantic salmon smolt survival by use of hydropower simulation modelling in a regulated river*. *Fisheries Management and Ecology*, 2013: p. 22-31.
 29. Gard, M., *MODELLING CHANGES IN SALMON HABITAT ASSOCIATED WITH RIVER CHANNEL RESTORATION AND FLOW-INDUCED CHANNEL ALTERATIONS*. *River Research and Applications*, 2014. **30**(1): p. 40-44.
 30. Harrison, L.R., C.J. Legleiter, M.A. Wydzga, and T. Dunne, *Channel dynamics and habitat development in a meandering, gravel bed river*. *Water Resources Research*, 2011. **47**(4).
 31. Kennedy, G. and W. Crozier, *What is the value of a wild salmon smolt, Salmo salar L.?* *Fisheries Management and Ecology*, 1997. **4**(2): p. 103-110.
 32. Johansson, P.-O. and B. Kriström, *The economics of evaluating water projects: hydroelectricity versus other uses*. 2012: Springer Science & Business Media.
 33. Håkansson, C., *Costs and benefits of improving wild salmon passage in a regulated river*. *Journal of Environmental Planning and Management*, 2009. **52**(3): p. 345-363.
 34. BBOP, *Business, Biodiversity Offsets and BBOP: An Overview. Business and Biodiversity Offsets Programme (BBOP)*, Washington, D.C. 2009.

FIGURE CAPTIONS

1
2 Figure 1. Map of the Mandalselva River showing the hydropower system. The study area is
3 marked with a rectangle in the basin for Bjelland and Laudal.
4

5
6 Figure 2. Flowchart of the methodology divided by steps (upper white rectangles),
7 components and results (grey blocks) and their interaction (arrows).
8

9
10 Figure 3. Discharge versus wetted width relationship for channel types (A, B, C).
11

12 Figure 4. Smolt and energy production graph for a) Bjelland reach and b) Laudal reach. Bars
13 represent the smolt production per 100 m² under each scenario. The black crosses represent
14 the energy produced under each scenario. Minimum flow – Q_{\min} (m³s⁻¹) – for summer and
15 winter and Q_{\min} average (m³s⁻¹) for summer is shown above each bar.
16

17
18 Figure 5. Net-cost graphs of each scenario relative to scenario VOL for a) Bjelland reach and
19 b) Laudal reach.
20

21
22 Figure 6. a) Cost-effectiveness rank from comparison of average marginal cost relative to
23 scenario VOL for a) Bjelland and b) Laudal. The horizontal line in the boxplot shows the
24 median. Boxes bound the 25 and 75 percentiles. Whiskers bound all values within 1.5 × the
25 inter-quartile range. Filled circles indicate observations outside the interquartile range.
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

S1 Supplementary Material: Economic valuation of benefits for recreational fishing of additional smolts in the Mandalselva River

1. METHOD

This supplementary material documents the first order assessment of marginal economic benefits of smolts. The assessment was carried out using Bayesian belief networks (BBN). BBNs make it possible to combine different quantitative and qualitative data sources and account for uncertainty, illustrating the model structure as an easily interpreted network diagram.

The valuation model includes three types of benefits that could be attributed to increased smolt production:

- *marginal smolt expenses* – the share of recreational fishing expenses attributable per smolt. Fishing expenditure data for 2013 were obtained from unpublished sources (Børre Dervo (NINA) pers. com.) combined with catch data for 2005-2014 from Scanatura.
- *marginal smolt sale value* – defined as the share of fishing licence sales value attributable per smolt
- *marginal willingness-to-pay (WTP)* – the share of fishers' stated willingness-to-pay in addition to fishing and licence expenses attributable per smolt. We calculated expected WTP/smolt based on survey results for the Nordic countries reported by Toivonen et al. [1] regarding consumer surplus as a percentage of fishing expenses.

The model assumes a smolt mortality variability of 90-98% (mean 94%, [2]) and catch as the % of returning adults taken from Järnegren et al. [3]. Migrating adults is a conservative estimate based on Järnegren et al. [3], where 35% of adults were assumed to be caught in 2009 (65% successful migration). This catch rate has been scaled according to 2009 permit numbers. We assume the catch rate is proportionally higher than 35% in years with more permits sold, and proportionally lower than 35% in years with fewer licences sold. Catch, C, (expressed as a % of adults) is estimated as follows:

$$C = 0.35 * \text{Annual permits sold} / \text{Permits sold in 2009}$$

The smolt-to-caught fish probability (equivalent to the percentage of smolts that are caught as grown fish), P, is estimated as follows

$$P = (1 - SM) * C$$

where SM is the smolt mortality (%). P is the proportion of value for caught fish that can be attributed to each smolt produced by measures, and is a multiplier applied to price (in Norwegian Krona, NOK)/fish caught (licence revenues, other expenses, willingness to pay)

Catch as a % of returning adults was scaled proportionally to the number of fishing licences sold, with 2009 used as a base year for scaling (4244 licences). Catch as a % of returning adults is probably more stochastic, as witnessed by the ratio of the number of fish caught over fishing permit days (catch-effectiveness). However, we have not pursued this question further

1 in these first order estimates. Based on these data sources we set up the BBN model below to
2 make a first order calculation of the total marginal value of smolts (Supplementary figure 1).

3 INSERT SUPPLEMENTARY FIGURE 1 ABOUT HERE
4
5
6

7 We tested the sensitivity of marginal benefit assessments to low and high resolution
8 discretization of benefits (green nodes at the bottom of Supplementary figure 1). We found
9 that results are somewhat sensitive to discretization of continuous variables [4]. However, the
10 sensitivity was not large enough to affect conclusions from comparisons with the cost-
11 effectiveness model.
12

13 14 15 2. RESULTS

16
17 INSERT SUPPLEMENTARY FIGURE 2 ABOUT HERE
18
19
20

21 Based on the Bayesian network model, the mean *total marginal value* of a smolt for
22 recreational fishing had a mean of \$5.25/smolt (33 NOK/smolt)¹ with a variance of \$81.60
23 /smolt (512.5 NOK/smolt) (green node, lower lhs Supplementary figure 2). A confidence
24 interval of roughly 90% predicted that benefits were <\$9.55/smolt (<60 NOK/smolt) (by
25 inspecting the probability distribution lhs Supplementary figure 2).
26
27

28 The node “Mandalselva River fishing statistics” is a submodel (Supplementary figure 3).
29
30

31 INSERT SUPPLEMENTARY FIGURE 3 ABOUT HERE
32
33
34

35 A value of information analysis of the model revealed which variables have the greatest
36 influence on total marginal value of smolts (Supplementary figure 4).
37

38 INSERT SUPPLEMENTARY FIGURE 4 ABOUT HERE
39
40
41

42 Fish licence sales was the largest type of benefit contributing to the total. The marginal
43 benefits were most sensitive to the assumptions about the smolt-to-caught fish probability
44 which was co-determined by the smolt mortality. For example, if smolt mortality dropped
45 from the expected 94% to 90%, the marginal value of smolt increased from \$5.25/smolt (33
46 NOK/smolt) to \$8.43/smolt (53 NOK/smolt).
47
48
49
50
51
52
53
54
55
56
57

58
59 ¹ The exchange rate used is the average rate corresponding to 2009, 1 USD= \$6.28. Source:
60 http://www.norges-bank.no/en/Statistics/exchange_rates/currency/USD/
61
62
63
64
65

References

1. Toivonen, A.L., E. Roth, S. Navrud, G. Gudbergsson, H. Appelblad, B. Bengtsson, and P. Tuunainen, *The economic value of recreational fisheries in Nordic countries*. Fisheries Management and Ecology, 2004. **11**(1): p. 1-14.
2. Hedger, R.D., L.E. Sundt-Hansen, T. Forseth, O. Diserud, O. Ugedal, and A.G. Finstad, *Modelling the complete life-cycle of Atlantic salmon (Salmo salar L.) using a spatially explicit individual-based approach*. Ecological modelling, 2013: p. 119-129.
3. Järnegren, J., H. Balk, I. Uglem, and T. Forseth, *Telling av oppvandrede fisk i Mandalselva ved bruk av DIDSON*. NINA Rapport 636: 22 pp. Norsk institutt for naturforskning, Trondheim., 2011. **636**.
4. Uusitalo, L., *Advantages and challenges of Bayesian networks in environmental modelling*. Ecological Modelling, 2007. **203**(3-4): p. 312-318.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

SUPPLEMENTARY FIGURE CAPTIONS

Supplementary figure 1. Valuation of benefits of additional smolts as a BBN model.

Supplementary figure 2. Economic valuation of additional smolts.

Supplementary figure 3. Sub-model of “Mandalselva River fisheries statistics” used in the BBN on benefits of smolts.

Supplementary figure 4. Value of information analysis of model variables.

Figure 1

[Click here to download high resolution image](#)

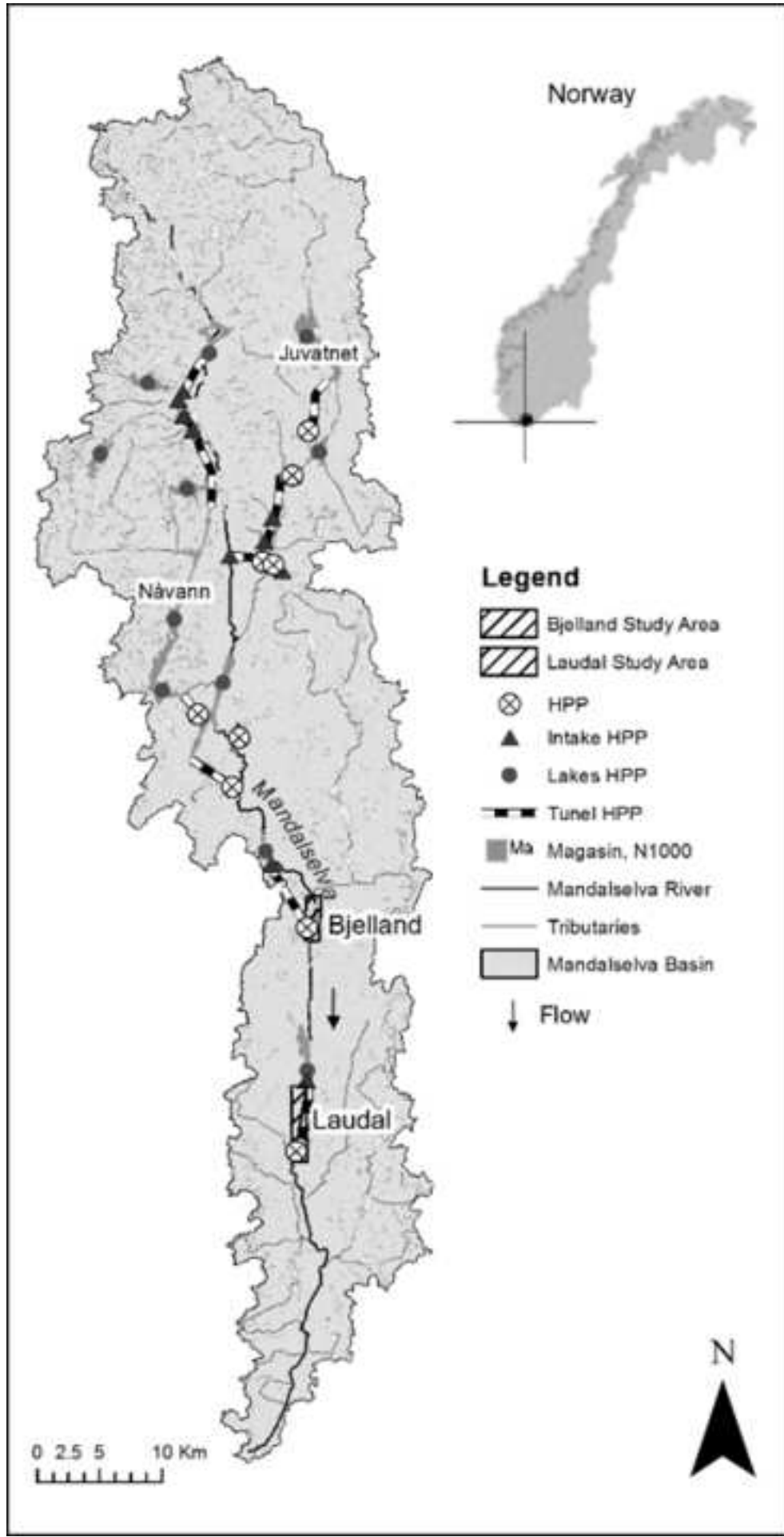


Figure 2
[Click here to download high resolution image](#)

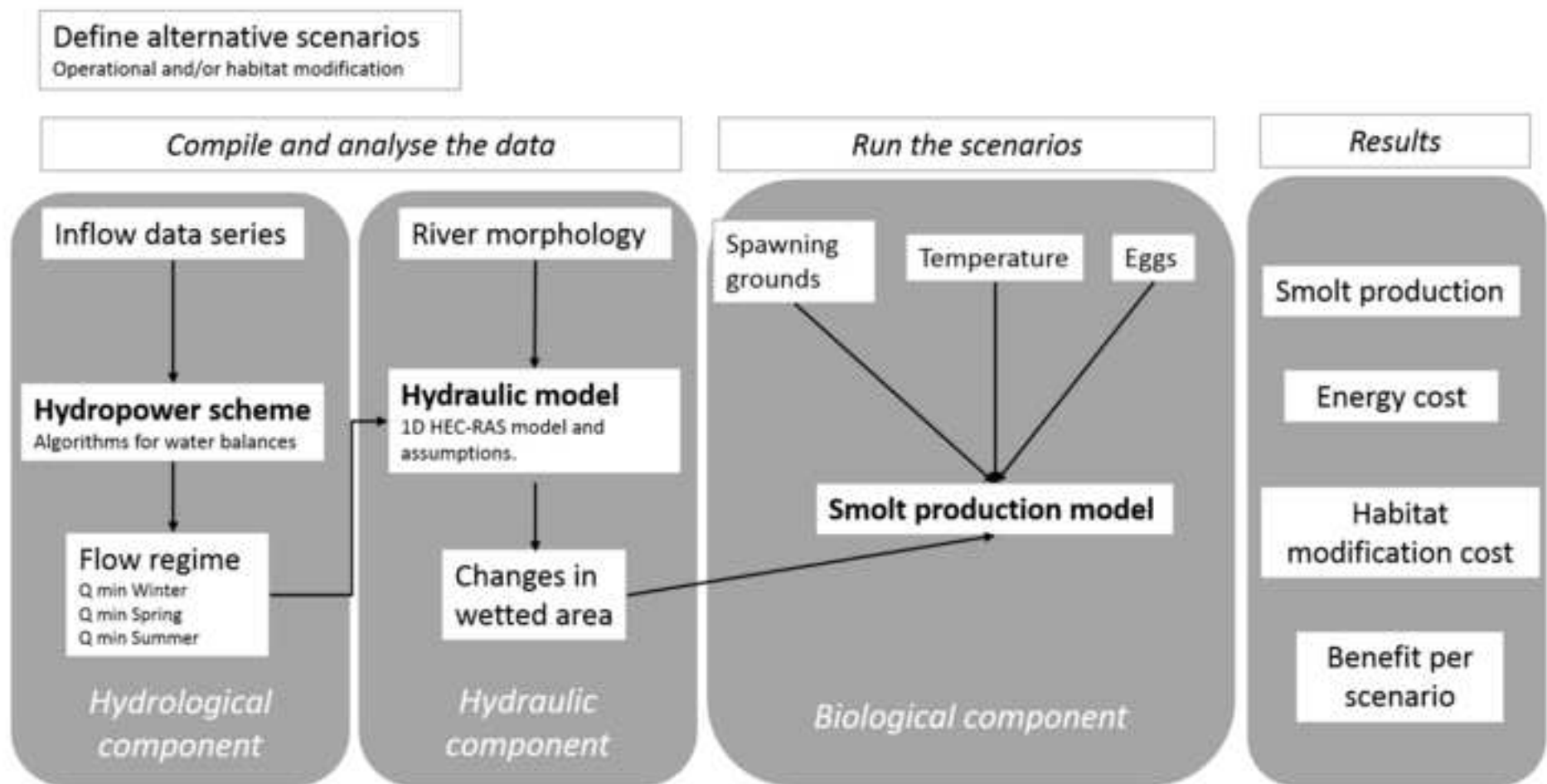


Figure 3
[Click here to download high resolution image](#)

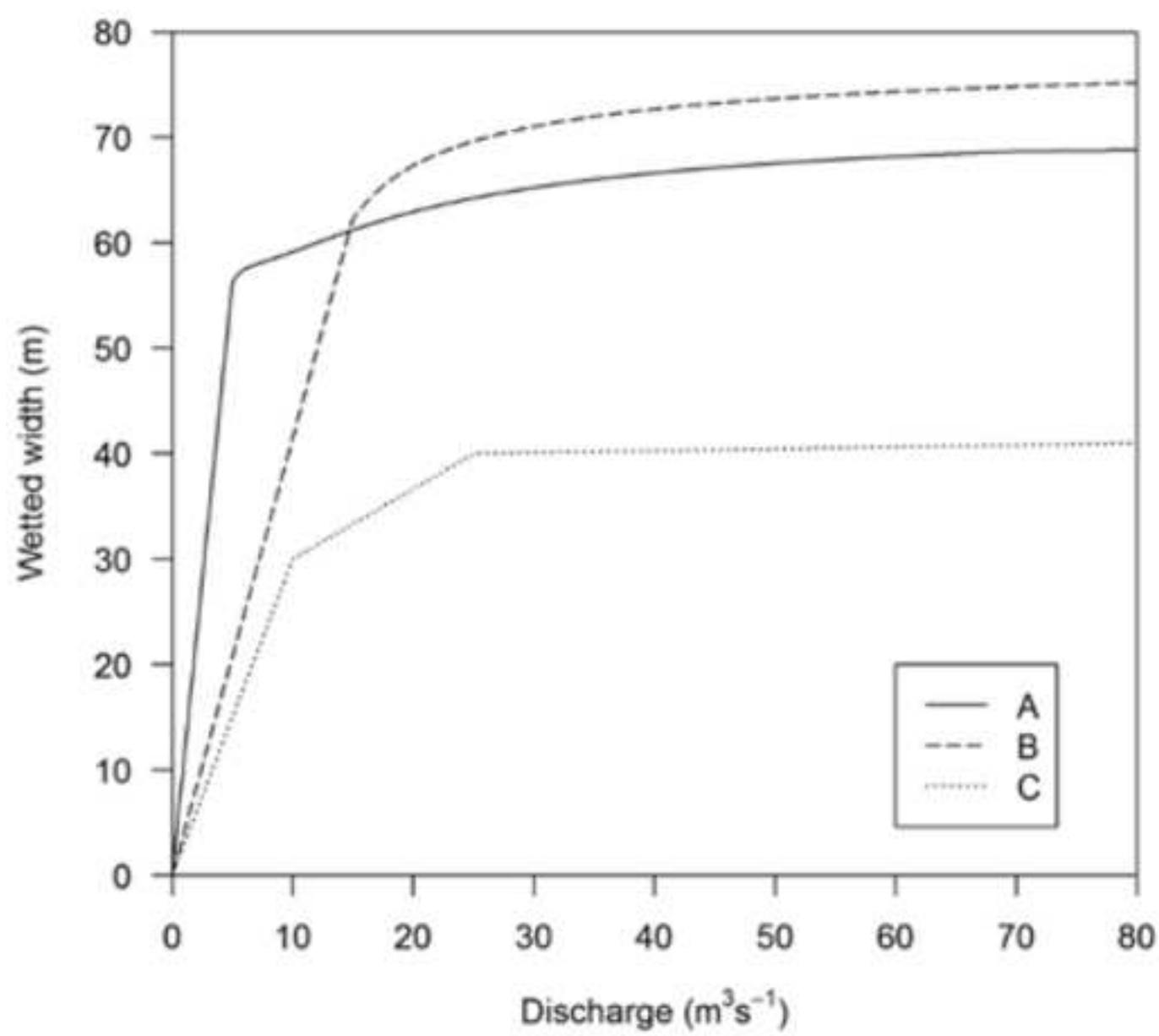


Figure 4
[Click here to download high resolution image](#)

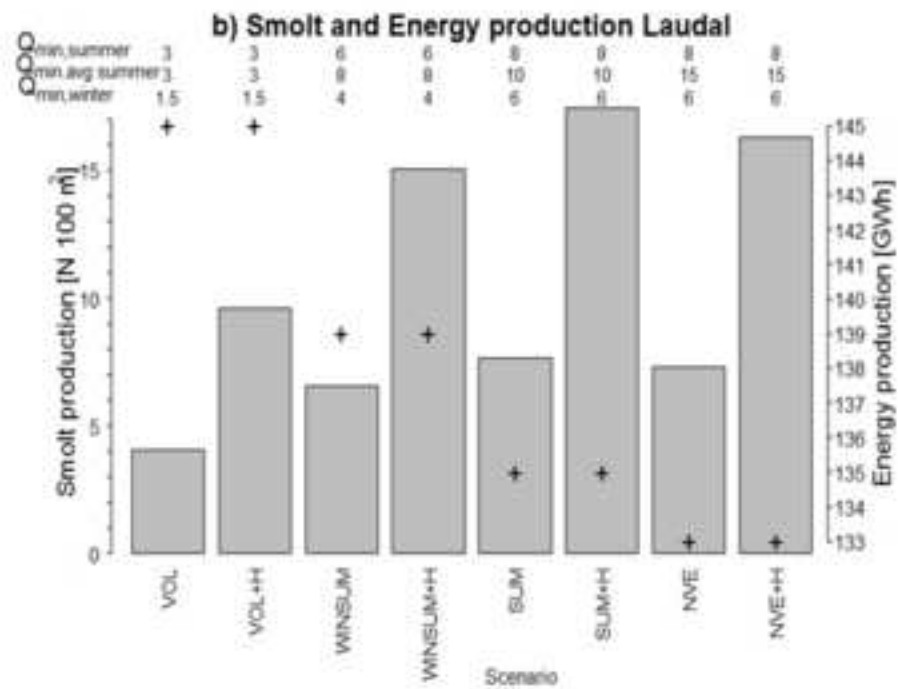
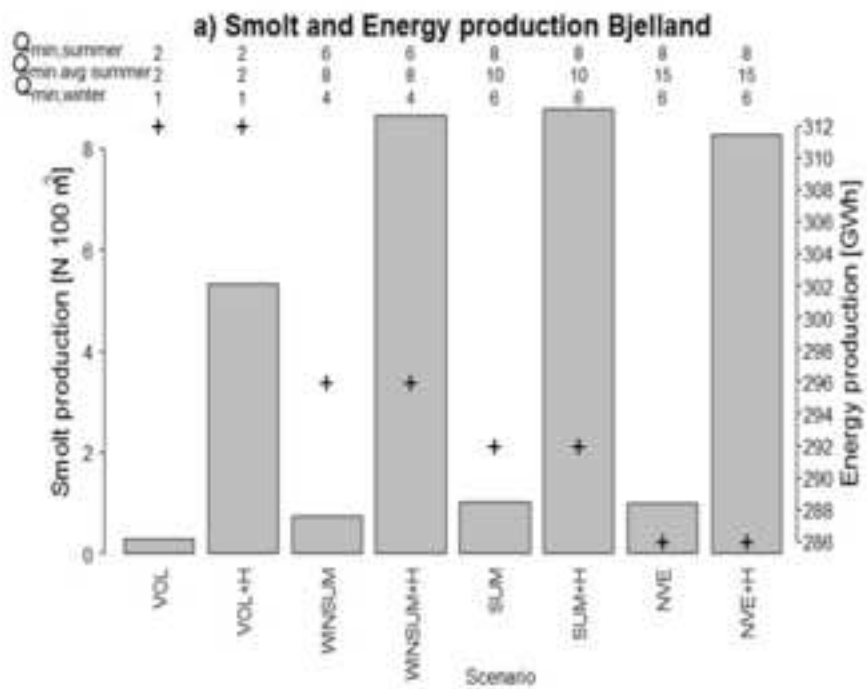


Figure 5
[Click here to download high resolution image](#)

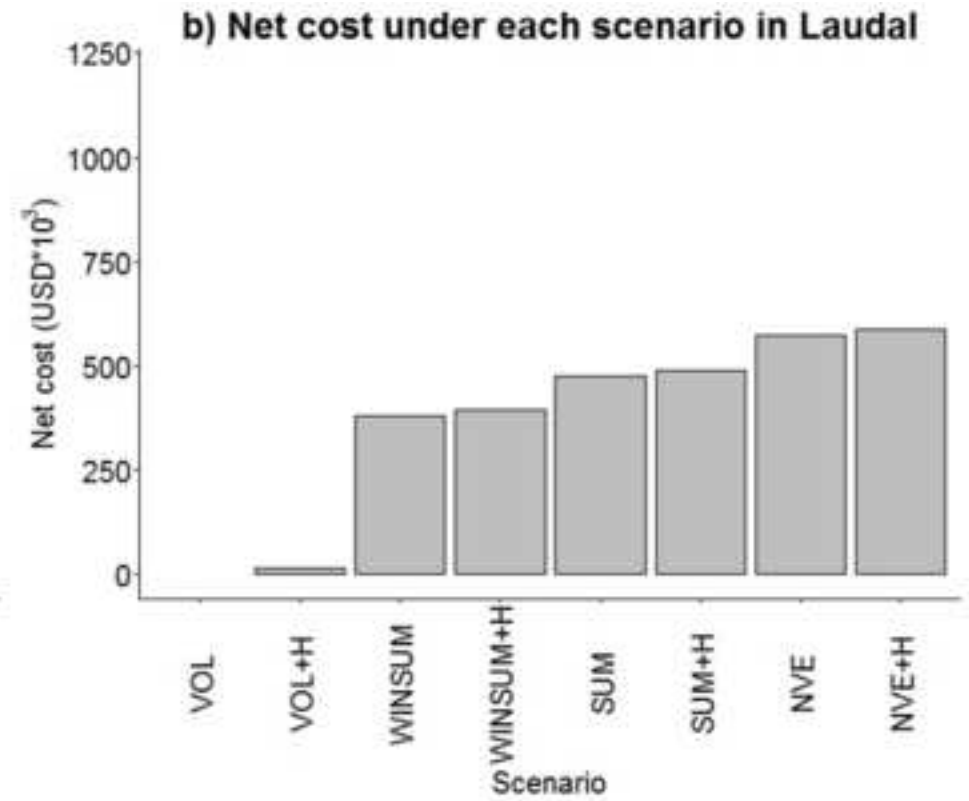
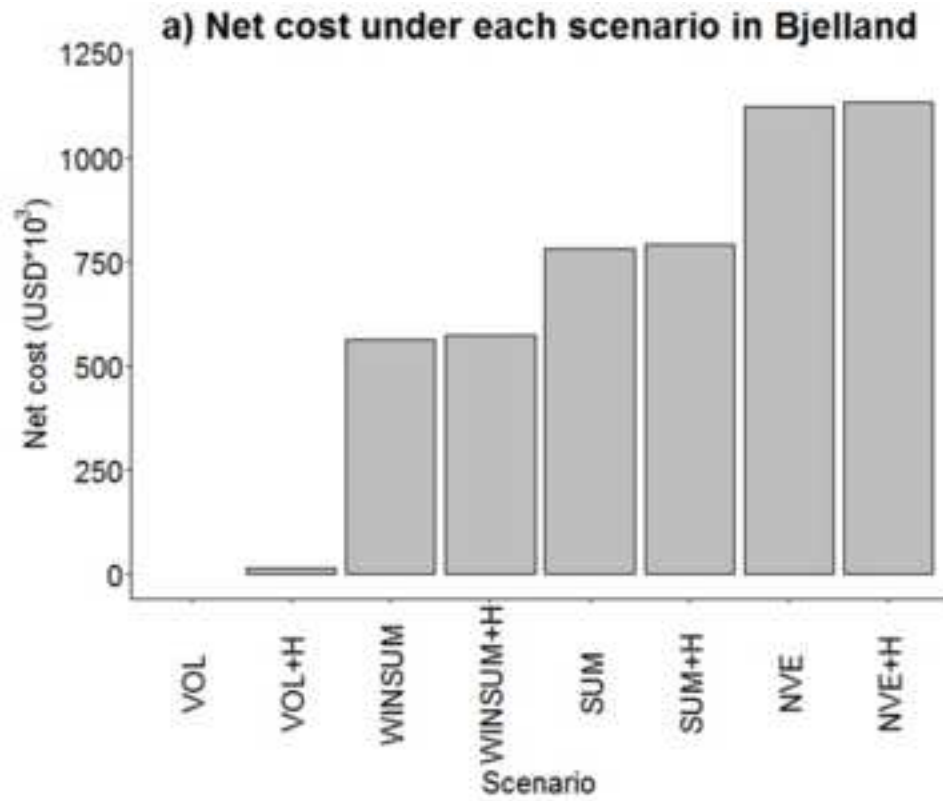
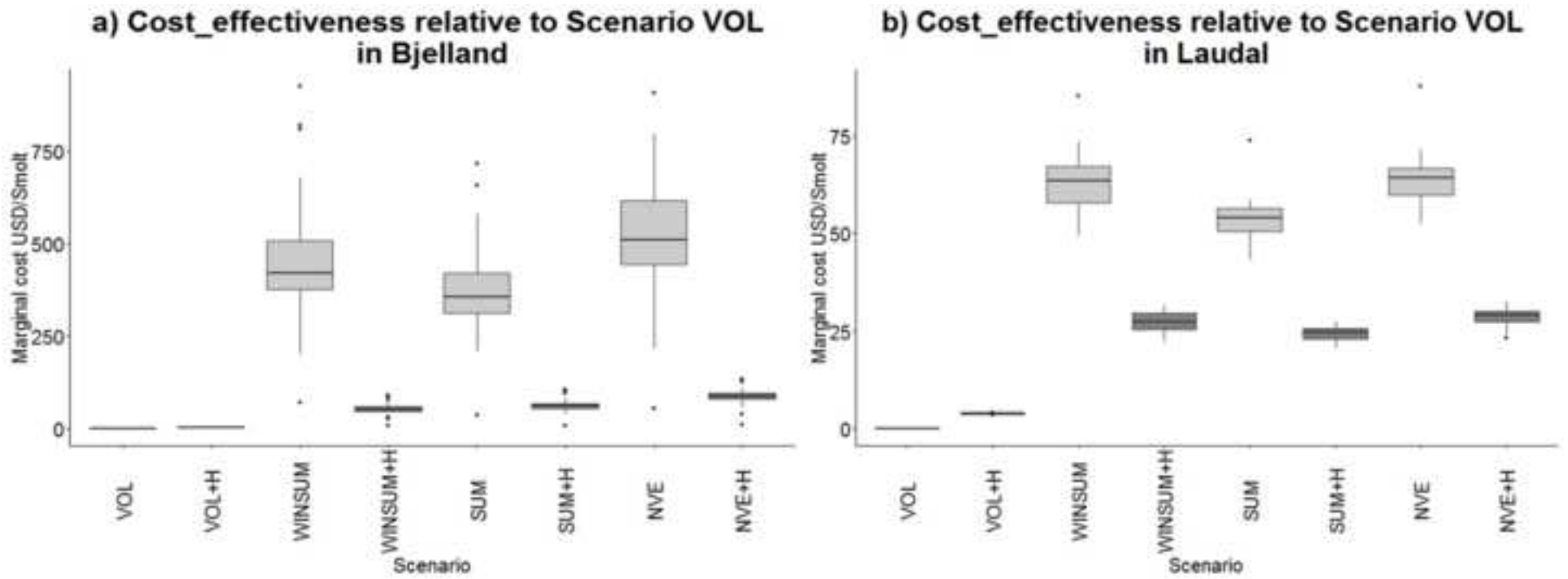
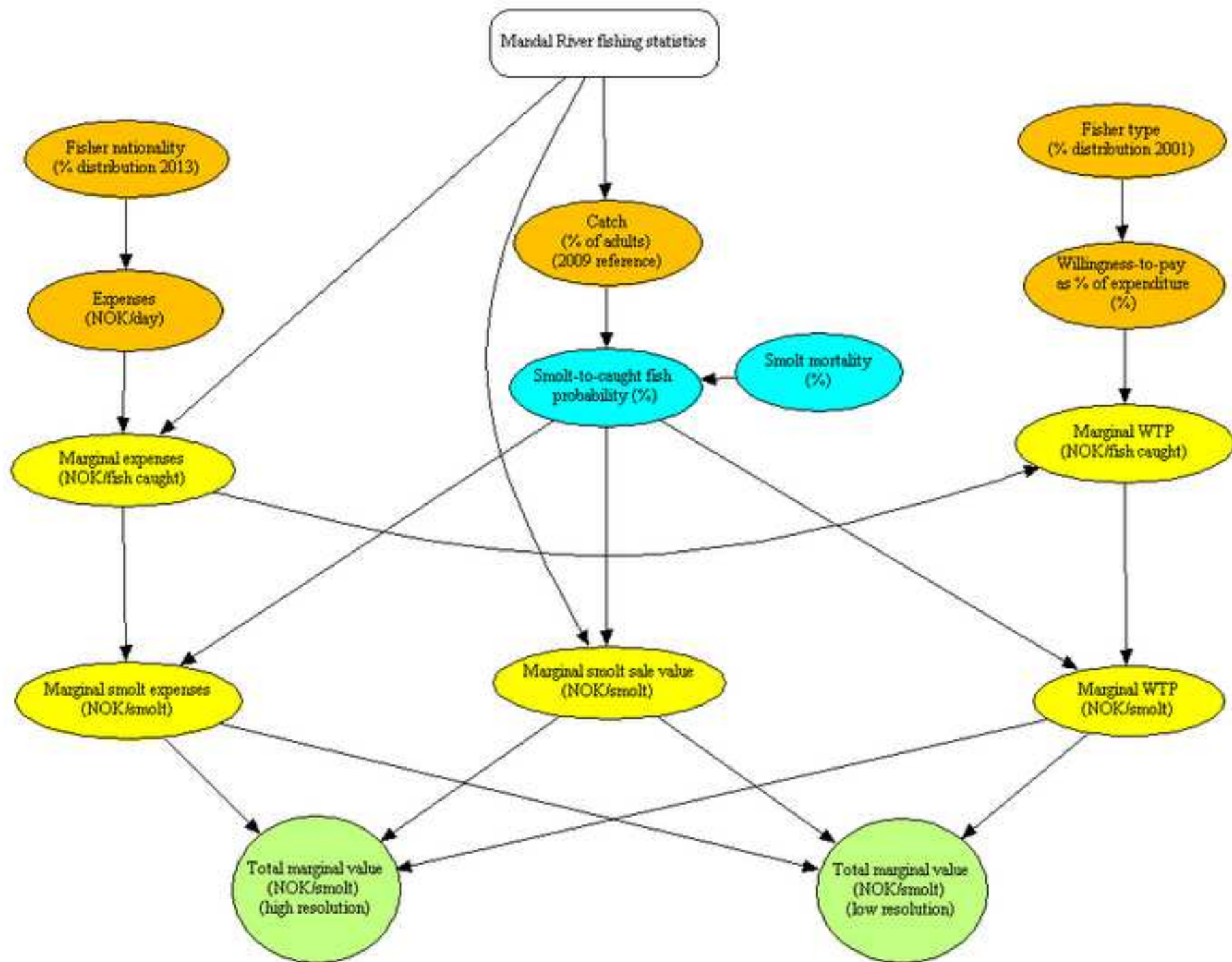


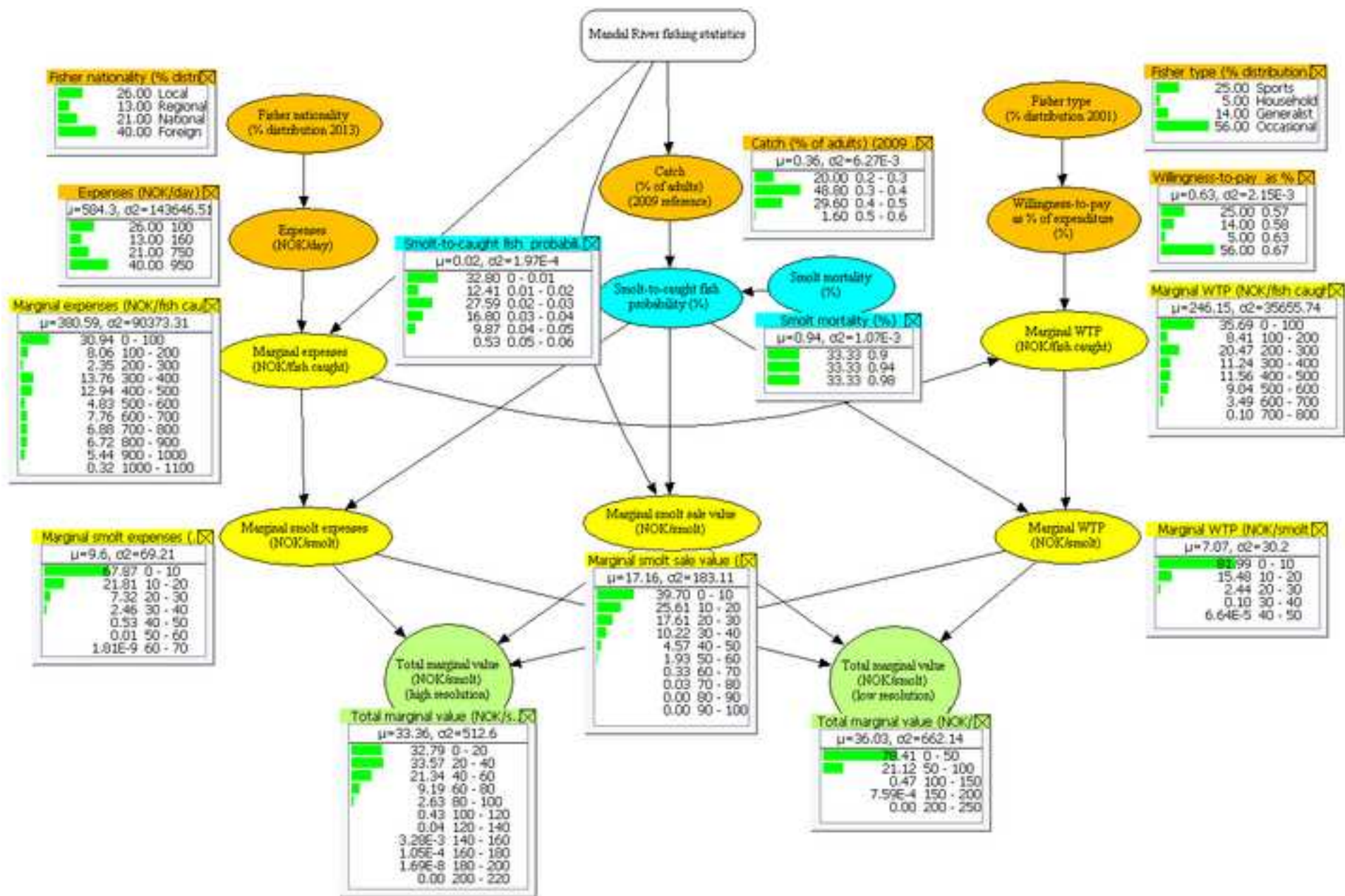
Figure 6
[Click here to download high resolution image](#)



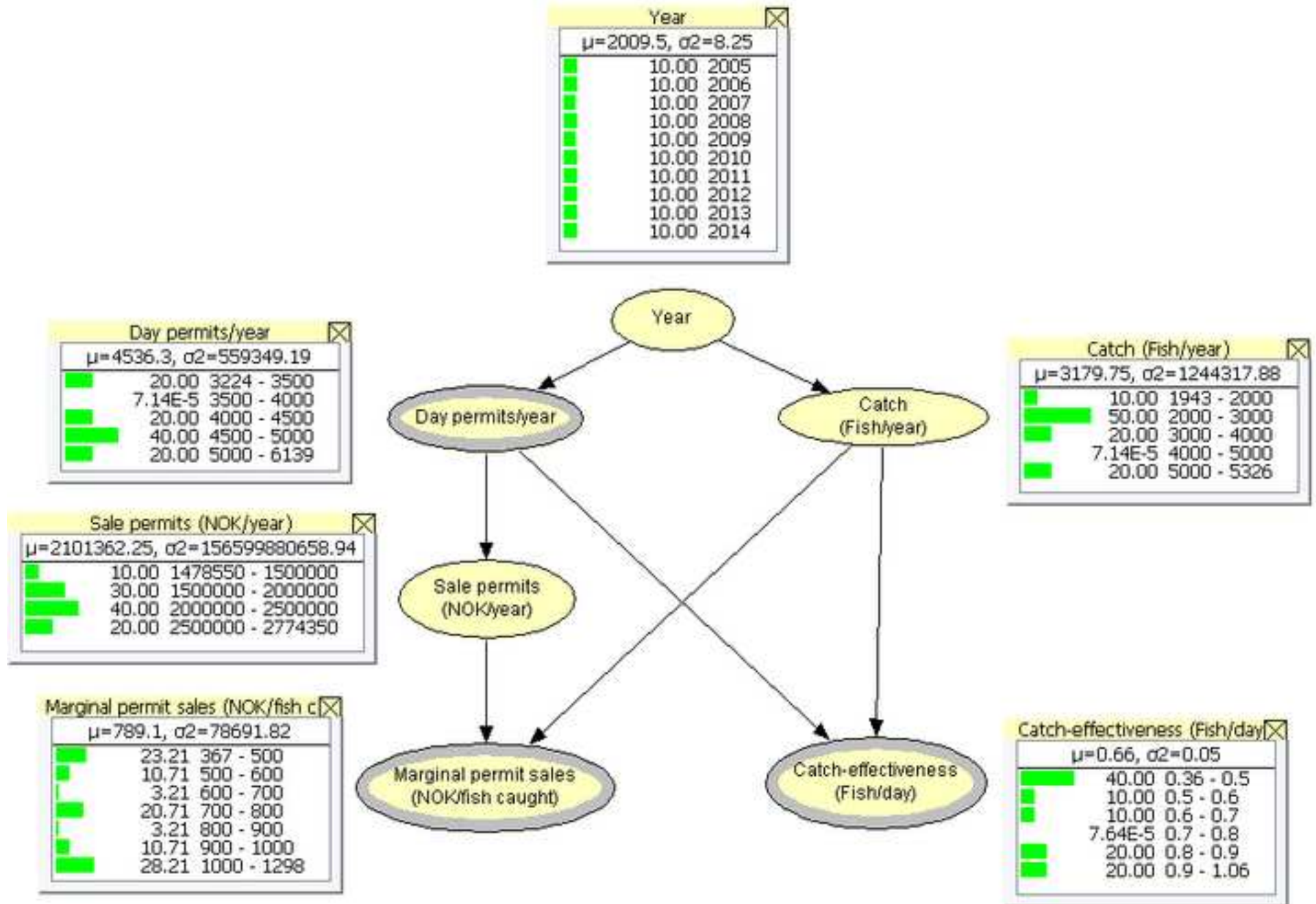
SM Figure 1
[Click here to download high resolution image](#)



SM Figure 2
[Click here to download high resolution image](#)



SM Figure 3
[Click here to download high resolution image](#)



SM Figure 4

[Click here to download high resolution image](#)

