Received: 15 April 2021 | Revised: 23 November 2021 | Accepted: 28 November 2021

DOI: 10.1002/rra.3917

SPECIAL ISSUE PAPER

WILEY

Classification of hydropeaking impacts on Atlantic salmon populations in regulated rivers

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Funding information
Norges Forskningsråd, Grant/Award Number: 193818; the Research Council of Norway

Abstract

This article proposes and demonstrates a new classification system of fish population level effects of hydropeaking operations in rivers. The classification of impacts is developed along two axes; first, the hydromorphological effect axis assesses the ecohydraulic alterations in rivers introduced by rapid and frequent variations in flow and water level, second the vulnerability axis assesses the site-specific vulnerability of the fish population. Finally, the population level impact is classified into four classes from small to very large by combining the two axes. The system was tested in four rivers in Norway exposed to hydropeaking, and they displayed a range of outcomes from small to very large impacts on the salmon populations. The river with a relatively high base flow and ramping restrictions scored better than rivers with the lower base flow or limited ramping restrictions, indicating that hydropeaking effects can be mitigated while maintaining high hydropower flexibility. Most effect factors could easily be calculated from timeseries of discharge and water level, whereas the use of hydraulic models to estimate potential stranding areas may require more work. The vulnerability factors are mainly qualitative and depend more heavily on expert judgments and are thus more uncertain. The system was deemed suitable for the purpose of supporting management decisions for rivers exposed to hydropeaking operations. It evaluates the severity of the additional pressures due to hydropeaking operations and proved useful to identify mitigating measures. While the system was developed for Atlantic salmon river systems, it could be adapted to other species or systems.

KEYWORDS

classification system, hydropeaking, hydropower, mitigating measure

1 | INTRODUCTION

Climate change calls for a transition of the energy system from fossil to renewable energy sources. Hydropower accounts for 15.5% of the global electricity production (International Hydropower Association, 2019). While solar and wind power are growing rapidly, these sources of electricity production are characterized by being intermittent, nondispatchable, and difficult to predict (International Energy Agency, 2018). In contrast to wind and solar power, hydropower with reservoirs can provide energy production and services in periods where the electricity production from solar and wind is insufficient. International Energy Agency (2016) predicts that the need for storage will increase rapidly, and hydropower with reservoirs is presently the only large-scale renewable storage available.

Hydropower can be used to regulate short- and medium-term variability in the electricity grid, often leading to frequent and rapid changes in flow downstream the power plant outlet, referred to as hydropeaking (Batalla et al., 2021; Harby & Noack, 2013; Moreira et al., 2019). Hydropeaking can also have an element of periodicity, that is, production during the daytime and stop in production during the nighttime, due to diurnal variation in electricity consumption. It is not a well-established, quantitative definition in the literature on how large or how rapid the changes must be in order to be categorized as hydropeaking operations. Carolli et al. (2015) and Bevelhimer, McManamay, and O'Connor (2015) have proposed procedures to characterize hydropeaking regimes based on the hydrological description of flow patterns, while Sauterleute and Charmasson (2014) and Greimel et al. (2016) developed calculation methods for such characterization.

Impacts from hydropeaking operations are generally restricted to river reaches downstream the outlet of the hydropower plant. Rapid (sub-daily) fluctuations in discharge, water level, and physio-chemical parameters (e.g., temperature, oxygen saturation) may cause negative impacts to the riverine ecosystems. Changes in hydrological and hydraulic conditions due to hydropeaking operations are well described (e.g., Harby & Noack, 2013; Saltveit, Halleraker, Arnekleiv, & Harby, 2001; Schneider et al., 2017), while associated rapid changes in water temperatures (thermopeaking, for example, Bakken, King, & Alfredsen, 2016; Bruno, Siviglia, Carolli, & Maiolini, 2013; Zolezzi, Siviglia, Toffolon, & Maiolini, 2011), gas saturation (saturopeaking, Pulg, Vollset, Velle, & Stranzl, 2016) and sound (soundpeaking, Lumsdon et al., 2018) are less investigated. Rapid and frequent changes in physical conditions lead to ecological impacts on aquatic plants (e.g., Bejarano, Jansson, & Nilsson, 2018), benthic invertebrates (e.g., Bruno, Maiolini, Carolli, & Silveri, 2010; Carolli, Bruno, Siviglia, & Maiolini, 2012; Gabbud, Bakker, Clémençon, & Lane, 2019), and fish species and communities (e.g., Auer, Zeiringer, Führer, Tonolla, & Schmutz, 2017; Melcher et al., 2017; Puffer, Berg, Einum, Saltveit, & Forseth, 2017; Schmutz et al., 2015), mainly due to flushing and stranding of organisms. Hydropeaking is assumed to represent an additional environmental pressure beyond traditional impacts from hydropower regulations (e.g., IPCC, 2011; World Commission on Dams, 2000), such as barriers and seasonal alterations of habitat conditions.

It is a trend toward an increased frequency in rapid sub-daily flow fluctuations since the early 1990 in Norwegian rivers (Wandurraga, 2019), and the challenges related to hydropeaking operations have received increased attention over the last decade. L'Abée-Lund and Otero (2018) presented the results from an assessment of sub-daily flow fluctuation in Norwegian small-scale hydropower plants and revealed that sub-daily flow variations are common in small-scale hydropower plants, while the study by Ashraf et al. (2018) covered the Nordic countries. Similar studies have been carried out in other countries with substantial hydropower production, such as Switzerland (Meile, Boillat, & Schleiss, 2011), Austria (Greimel et al., 2016), and USA (McManamay et al., 2016).

Hydropeaking operations have to a variable extent been restricted in the licensing of the existing large-scale hydropower projects in Norway, as many licenses were formulated several decades back and before hydropeaking was an issue. In Norway, a large number of hydropower licenses are open for revision the coming years (NVE, 2013), aiming at improving ecological conditions in regulated rivers. Both minimum flow releases and hydropeaking operations are important topics in these revisions.

Moreira et al. (2019) reviewed legislation regimes and targets and thresholds of hydropeaking operations. They found that the systems developed by Bundesamt für Umwelt, Bern, Switzerland (BAFU, 2017) and Hayes et al. (2019) are the only publications that cover a wider set of parameters or life-stages with the ambition to propose a complete system for the management of hydropeaked rivers, while Bruder et al. (2016) presented a system for hydropeaking mitigation. These systems are, however, mainly based on hydrological and hydraulic descriptions of the impacts together with basic understanding and linkage to ecological effects from stranding experiments.

The aim of the article is to present a new classification system that provides information for better decision-making in Atlantic salmon rivers exposed to hydropeaking. This novelty of the work is that the system describes the ecological impacts at the population level, which goes beyond hydrological and hydraulic methods to describe hydropeaking operations. We do so by accounting for the vulnerability of the river populations exposed to hydropeaking operations and accumulative impacts from other pressures. The classification of the ecological impacts is developed along two different axes:

- The hydromorphological alteration axis; six different hydromorphological parameters describe the hydrological and hydraulic changes in the river introduced by rapid and frequent variations in flow and water level. The changes are classified in four classes, ranging from small, moderate, large, to very large alterations.
- The vulnerability axis; seven different vulnerability factors describe the site-specific vulnerability of the Atlantic salmon population in the specific river. These seven factors are classified in three classes, that is, low, moderate, and high vulnerability.

The hydromorphological alteration axis and the vulnerability axis are further combined into a total impact assessment, which are classified from small, moderate, large, and very large ecological impacts.

The development of the classification system focused on hydropeaking operations and was tested in four rivers exposed to hydropeaking operations. The proposed system was inspired by similar classification systems, such as those developed under the EU Water Framework Directive (WFD, 2000).

2 | FRAMEWORK, DATA, AND TOOLS

The section describes in detail the hydropeaking classification system as it is designed along two axes, the hydromorphological axis and the vulnerability axis, and how these axes are combined into a hydropeaking classification. The case studies in which the system has been tested are presented. The assessment can be carried out with a combination of use of computer-based tools, measurements, and expert judgments. In the testing described in this article, the expert assessments have been made by the authors of the article.

The system is developed to be applied on river reach scale. More specifically, the classification should be made on the entire reach of the river affected by hydropeaking operations, from the outlet of the hydropower plant, where the hydropeaking operations are generated, to the downstream location where the effect of the hydropeaking operations are diminished. This could be a downstream lake, reservoir or fjord, or in such a far distant from the outlet that the natural dampening of the river has smoothened out the effect of the hydropeaking operations.

2.1 | Framework of hydropeaking classification system assessed

2.1.1 | Hydromorphological effect factors

As part of the R&D project ENVIPEAK, a multidisciplinary team of researchers has worked out a set of abiotic and biotic indicators to capture the effects and population impacts on Atlantic salmon as a target species. We have identified in total six different effect factors (Table 1), we believe capture essential hydromorphological properties of hydropeaking related to impacts on salmon populations. These factors and their class borders are proposed based on previous research and literature search. Moreira et al. (2019) has reviewed mitigating measures (e.g., down-ramping thresholds) and suggested operational flow rules by a large number of studies, while Hayes et al. (2019) suggested life stage–adapted hydropeaking flow rule and sorted the findings with respect to types of hydropeaking impacts, species studied, and threshold values for the severity of the impacts, both being important sources of information. As it was not possible to find research specifically covering all elements the classification system should include, that is, hydromorphological assessment parameters were also selected and class borders defined based on the authors' long-term experiences working in regulated rivers in general and rivers exposed to hydropeaking operations in specific.

The selected parameters are primarily descriptors of stranding (down-ramping), as this is considered giving the severe short-term ecological impact. The parameters cover to a limited extent potential problems such as changes in energy consumption, rapid changes in habitat conditions, drift/flushing of biota (up-ramping), thermopeaking, or saturopeaking. All the class borders for the parameters (in Table 1) are set in such a way that rivers not exposed to hydropeaking operations shall end up in the class “small”.

The effect factors are applied for the section of the river exposed to hydropeaking operations. The parameters E1 and E3 must be calculated from representative locations within this section. Parameter E2 should be calculated based on assessment of the whole section exposed to hydropeaking, while the parameter values of E4-E6 are not sensitive to the location within the affected river data is taken from. The data series used for the calculation of parameters E1, and E3-E6 should be of one-hour resolution, which is normally what is available, or finer. The data series of flow and water level should be at least three years of typical production pattern.

A value from 1 to 4 is assigned for each effect factor. Effect factors are combined by multiplying the values of the two factors considered most important (i.e., E1 Rate of change and E2 dewatered area), and then adding the values from the others (E3-E6). If restrictions are

TABLE 1 Factors and class borders to evaluate the direct effects from peaking on important parameters, adjacent to hydropower outlet in rivers

			Criteria for hydromorphological assessment			
Effect factors	Indicator	Unit	Small (value 1)	Moderate (value 2)	Large (value 3)	Very large (value 4)
E1: Rate of change	Water level change ratio	cm/h	<5	5–13	13–20	>20
E2: Dewatered area	Change in water-covered areas when flow is reduced from Qmax to Qmin	%	<5	5–10	10–20	>20
E3: Magnitude of flow changes	Flow ratio Qmax/Qmin	Ratio	<1.5	1.5–3	3–5	>5
E4: Frequency	Annual frequency—proportion of days per year	% (no of days)	<10 (<37)	10–25 (37–91)	25–40 (92–146)	>40 (>146)
E5: Distribution	Distribution of the hydropeaking throughout the year	Qualitative	Daily regulation in maximum two period	Daily regulation in several periods	Irregular in certain periods	Irregular throughout the year
E6: Timing	Flow reductions in critical periods	Qualitative	Spring and early summer	Summer and fall	In darkness in winter	In daylight in winter

Note: References providing the scientific basis for the selection of parameters and class borders are given below the table. Further description of the effect factors are given in the Data S1.

applied to make the first rate of change slow after a period without hydropeaking, the total score may be reduced with the value of 1 (down rating).

$$\text{Combined effect} = (\text{E1} \times \text{E2}) + \text{E3} + \text{E4} + \text{E5} + \text{E6}.$$

The lowest possible total score is 4 ([1 × 1] + 4–1) and the maximum score is 32 ([4 × 4] + 16). We have divided the total score of the effect factors into four classes. A combined score in the range 4 to 9 is "small," a score between 10 and 14 is "moderate," a score in the range from 15 to 20 gives a "large" effect, while a score between 21 and 32 is assigned the class "very large" combined effect (see details in Table I of the Data S1).

2.1.2 | Population vulnerability assessment

The vulnerability to peaking as well as other pressures on the salmon population must be taken into account because more vulnerable salmon populations will suffer more from hydropeaking operations than large and otherwise healthy populations. Table 2 presents the parameters that are accounted for in the assessment of the vulnerability of the salmon population in a regulated river, when exposed to hydropeaking as an additional pressure beyond more regular hydropower operations. They are based on the vast body of literature available on the ecology of Atlantic salmon (reviews in Aas, Einum, Klemetsen, & Skurdal, 2010) and more specifically classification systems in Forseth and Harby (2014), the rank of threats in Forseth et al., 2017), and the Norwegian quality norm for Atlantic salmon (https://lovdata.no/dokument/SF/forskrift/2013-09-20-1109). In contrast to the hydromorphological effect factors, the vulnerability factors are assessed on the whole anadromous salmon river stretch, not only the parts exposed to hydropeaking operations.

A value from 1 to 3 is assigned for each vulnerability factor. The total score is obtained by adding the score for each factor. Regulations sometimes have a positive effect on fish population size, especially when regulation leads to increased low flow reducing natural critical low-flow events that typically occur during dry periods in summer or winter. The total score may then be reduced by 3 if both winter and summer low flow is increased with 50%, with a score of 2 if the winter flow is increased and a score of 1 if the summer flow only is increased by 50% (see details in Table II of the Data S1).

The maximum total score for the vulnerability factor is 21 (7 × 3) and the lowest score is 4 ([7 × 1] – 3). High vulnerability is assigned to scores greater than 16, moderate vulnerability between 10 and 16, while a score equal to or lower than 10 gives a low vulnerability (see details in Table III of the Data S1).

TABLE 2 Factors used to evaluate the vulnerability of salmon populations exposed to hydropeaking, beyond impacts introduced by the regulation without hydropeaking operations

		Criteria for vulnerability characterization		
Vulnerability factor	**Indicator**	**Low (value 1)**	**Moderate (value 2)**	**High (value 3)**
V1: Effective population size (N_e)	Average no. of females last 5 years	>250 females	25–250 females	<25 females
V2: Degree of limitations in recruitment	Amount and spatial distribution of spawning grounds	Much and evenly distributed	Moderate	Low and patchy distributed
V3: Low flow periods as bottleneck for fish stock size	Change in lowest annual weekly flow in winter and summer combined	No or weak bottleneck	Moderate bottleneck	Strong bottleneck
V4: Habitat degradation	Change in magnitude and frequency of flood event, probability of degradation	Low probability	Moderate probability	High probability or documented
V5: Reduced water temperatures that lead to population effects	Reduction in summer water temperature and probability of population effects	Small (< 1°C), small population effect	Moderate (1–3°C), including probable population effect	Large (> 3°C), including probable or documented population effect
V6: Other factors	Acidification, water quality, habitat degradation due to other factors than regulations, diseases, parasites, etc.	No or small reduction in fish stock or carrying capacity	Moderately reduced fish stock or carrying capacity	Strongly reduced fish stock or carrying capacity
V7: Percentage of impacted river length compared to total length	Proportion of river reach with peaking compared to total anadromous length [%]	<10%	10–40%	>40%

Note: References providing the scientific basis for the selection of parameters and class borders are given above the table.

2.1.3 | Combined assessment of effect and vulnerability factors

In the overall assessment of the hydropeaking impacts, the hydromorphological effects are combined with the vulnerability. A vulnerable system only tolerates minor hydromorphological effects, while a system with low vulnerability may tolerate larger effects. At very large impacts (red), it is likely that hydropeaking will be a significant additional burden for the ecosystem and fish populations. The fish stocks will be reduced in the short term or over time, due to increased mortality or decreased production capacity. Combinations of small peaking effect and low or moderate vulnerability or moderate peaking effects and low vulnerability will both give a small impact. For these combinations, it is unlikely that the fish stocks will be considerably impacted. Figure 1 illustrates the concept of the combined assessment of the total impacts.

2.2 | Case studies and data overview

The case studies for testing the system were selected based on the following criteria; (a) the rivers have been exposed to hydropeaking for several years and they host salmonid populations and (b) the rivers represent a gradient of pressure-impacts, climate, river-length exposed, and level of mitigation. They are presented in Figure 2 and Table 3.

The spawning target (or conservation limit, CL) defines the management target to secure the long-term sustainability of the salmon population (Anon, 2011), while population status is an assessment of the status with respect to the attainment of spawning targets, harvestable surplus, and genetic integrity according to the Norwegian quality norm for Atlantic salmon populations. The selected rivers vary regarding size, length of affected anadromous reach and salmon spawning targets, peaking pressure intensity, and climate.

In addition to data sources presented in Table 4, literature from prior investigations carried out in the case study rivers was compiled. This was in particular needed for the vulnerability assessment. As data did not exist for all factors to be assessed, or data collection was considered too extensive, and beyond the resources available for the assessment, expert judgment was used. The expert judgment was carried out as a round-table discussion with the authors of the article present until consensus was reached in the assessment.

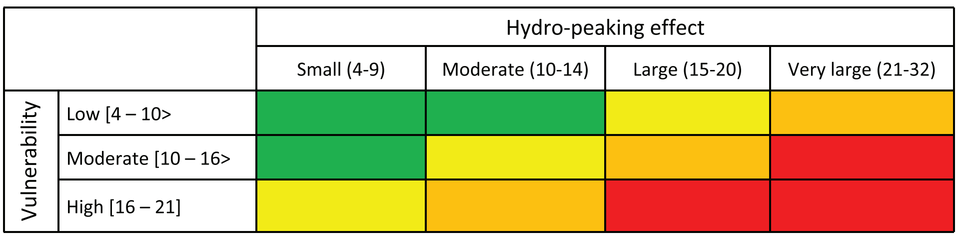

FIGURE 1 Combination of hydromorphological effect factors and vulnerability for total impact assessment. The color codes represent and small (green), moderate (yellow), large (orange), and very large (red) ecological impacts [Color figure can be viewed at wileyonlinelibrary.com]

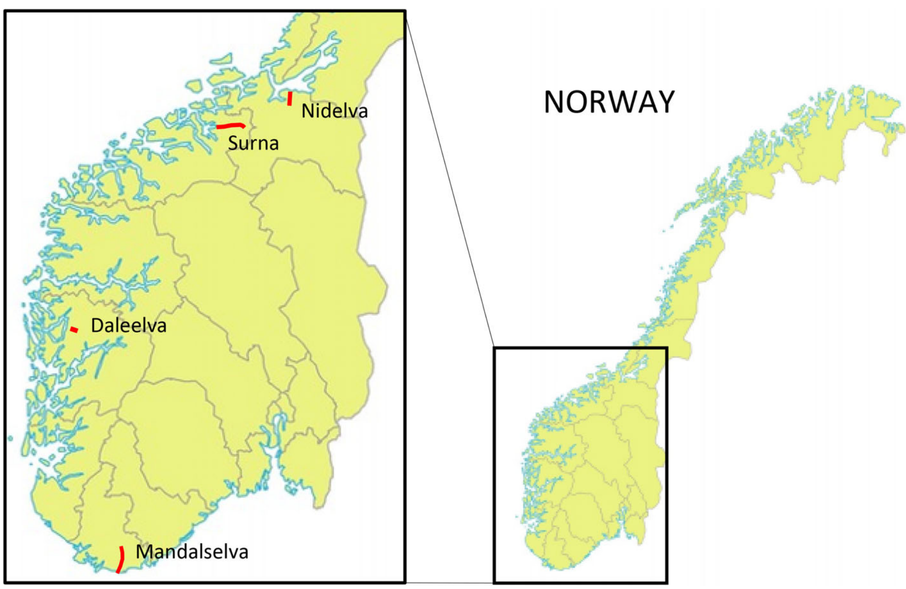

FIGURE 2 Location of the case study rivers in Norway [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Characteristics of the case study rivers

	Nidelva (Trondheim)	Surna	Daleelva (Vaksdal)	Mandalselva
Upstream catchment area [km^2]	3,060	920	171 (249)[a]	1,530
Mean annual flow [m^3/s]	93	41.2	103.0	48.9
Median (annual) flood [m^3/s]	478.8	319.7	124.5	486.3
Minimum flow [m^3/s]	30	15	5 (3)[b]	17
Peak flow through turbines [m^3/s]	150	38	44	110
River length impacted [km]	8.6	20	3.0	20
Anadromous reach length [km]	8.6	54 (71)[c]	4.7	38
Spawning target [kg], CL	2,730	4,836	195	5,155
Salmon status	High	Moderate	Good	Good
National salmon river	Yes	Yes	No	Yes

Note: The information on the upstream catchment area, mean annual flow, and median annual flood is taken from NVE Nevina (nevina.nve.no). Minimum flow from license agreements and peak flows through turbines are from NVE Atlas (atlas.nve.no), anadromous reach length and salmon status from Vann-Nett (www.vann-nett.no), and spawning target and national status from Lakseregisteret (www.lakseregisteret.no).
[a]The number in parenthesis (249 km^2) is the size of the neighbor catchment from where water is transferred into Daleelva.
[b]Minimum flow during winter in parenthesis.
[c]Number in parenthesis include tributaries.

TABLE 4 Discharge timeseries used for the assessment of hydropeaking in four Norwegian case study rivers

River	Monitoring station no.	Monitoring station name	Period	Time resolution	Distance from outlet of HPP
Nidelva (Trondheim)	123.20	Rathe	1991–2014	1 hr	0.5 km
Surna	112.27	Skjermo	2000–2014	1 hr	1.3 km
Daleelva (Vaksdal)	—	—	16/22011–1/82014	1 hr	50 m
Mandalselva	20.23	Laudal	1991–2014	1 hr	0.2 km

Note: The data from Nidelva (Trondheim), Surna and Mandalselva were obtained from the Norwegian Water and Energy Directorate (NVE), while SINTEF collected data from Daleelva.

2.3 | Tools

The parameters describing the hydrological effect factors (E1, E3-E6) were calculated by use of the COSH-Tool (Sauterleute & Charmasson, 2014). COSH-Tool calculates hydropeaking characteristics based on timeseries of discharge and water level, such as number, magnitude, rate of change in the increase/decreases, and duration of the low and high flow periods and timing of the changes. The simulation model HEC-RAS (Brunner, 2010) was applied to compute the hydraulic effect factor (E2). HEC-RAS is a hydraulic numerical model that can calculate water levels and dewatered areas for a set of discharges, where bathymetric data of the river bottom are essential input and have proven feasible for studies as described in this article (Juárez, Adeva-Bustos, Alfredsen, & Dønnum, 2019). If aerial images for those discharges of relevance are available, these can be used instead of a hydraulic tool for the calculation of water-covered areas.

Various sources of information can be used for the assessment of the vulnerability factors, including available databases, reports from local studies, or by on-site visits. Habitat degradation due to changes in floods can be modeled with standard hydrological models, for example, HBV (Bergström, 1992), while temperature changes can be modeled (HEC-RAS). The percentage of the river affected by hydropeaking operations should be compared to the total river length and can be calculated from map-based sources. Some of the vulnerability factors can also be assessed by expert judgments.

For the purpose of the assessment of the four case study rivers, data were to a large extent taken from previous work, and the specific data references are given in each of the result tables.

3 | RESULTS FROM TESTING OF THE CLASSIFICATION SYSTEM

The first step in the assessment is to calculate the hydromorphological effect factors (Table 5).

For all test rivers, the hydromorphological effect parameters (E1, E3, E4, E5, and E6) given in Table 5 were calculated from the data series described in Table 7, with the use of COSH-Tool (Sauterleute & Charmasson, 2014). The dewatered areas (E2) for Nidelva originate from Arnekleiv, Koksvik, Davidsen, Sjursen, and Rønning (2013), that present numbers for water-covered areas for given discharges from 155 to 33 m^3/s, that is, full production to minimum flow. The

TABLE 5 Results from the assessment on the hydromorphological effect factors in the test cases, with the classified impact in parenthesis

	River			
Effect factors	**Nidelva**	**Surna**	**Daleelva**	**Mandalselva**
E1: Rate of change	29 cm/hr (very large)	12 cm/hr (moderate)	35 cm/hr (very large)	17 cm/hr (large)
E2: Dewatered area	18% (large)	9% (moderate)	24% (very large)	14% (large)
E3: Magnitude of flow changes	3.2 (large)	2 (moderate)	6.2 (large)	2.4 (moderate)
E4: Frequency	136 (large)	96 (large)	97 (large)	58 (moderate)
E5: Distribution	Diurnal regulation in several periods (moderate)	Diurnal regulation in several periods (moderate)	Diurnal regulation in several periods (moderate)	Diurnal regulation in 1–2 periods (small)
E6: Timing	Night-time during Winter (large)	Night-time during Winter (large)	Night-time during Winter (large)	Night-time during Winter (large)
COMBINED, without down rating	23 (very large)	14 (moderate)	27 (very large)	17 (large)
Down rating	0	−1	0	0
COMBINED, after down rating	23 (very large)	13 (moderate)	27 (very large)	17 (large)

TABLE 6 Division of the test rivers into sub-sections for the assessment of the vulnerability factors V2-V5

	River			
Section	**Nidelva**	**Surna (1)**	**Daleelva**	**Mandalselva (2)**
Upstream HPP and other sections not affected by regulation	—	Surna upstream Rinna: 22 (29)	—	Outlet Bjelland HPP—Mannflåvatn: 8
Bypass sections (permanently reduced flow)	—	Confluence Rinna—Outlet Trollheim HPP: 12 (22)	Storefoss—Outlet Dale HPP: 1.7	Kavfossen—Outlet Bjelland HPP: 4, and Mannflåvatn—Outlet Laudal HPP: 6
Downstream outlet of HPP (hydropeaked section)	Nedre Leirfoss—Elgeseter: 8.6	Outlet Trollheim HPP-fjord: 20	Outlet Dale HPP—fjord: 3.0	Outlet Laudal HPP—Krossen: 20
Total river assessed	8.6	Lomundsjø—fjord: 54 (71)	Storefoss—fjord: 4.7	Kavfossen—Krossen: 38

Note: The division is made according to the flow changes introduced by the regulations (Forseth & Harby, 2014). The numbers are given in km and are the basis for scaling (V7) the vulnerability to the entire river considered. HPP stands for hydropower plant. (1) River length with anadromous salmon is approximately 54 km, while the main tributaries account for around 17 km more of the river, where Tiåa is the most important. (2) These numbers exclude Mannflåvatn and Kosåna and other unregulated tributaries and small creeks.

dewatered areas for Daleelva and Mandalselva were estimated from a combination of hydro-dynamic modeling and aerial images during a reduction from 45 to 11 m^3/s and 50 to 20 m^3/s, respectively. For Surna, the dewatered areas were estimated for the discharge interval 42 to 19 m^3/s (Harby & Noack, 2013).

The second step was to assess the vulnerability. As the vulnerability of the salmon population was assessed in all parts of the river hosting anadromous salmon and not only those parts exposed to hydropeaking operations, the regulated system needed to be divided into different sections according to how the regulation changes the flow conditions (Table 6).

The vulnerability of the test rivers was assessed based on previous investigations, combined with the authors' experiences with these rivers. Expert judgment was in particular use when assessing the factors V2 (degree of limitations in recruitment) and V5 (reduced water temperatures). The detailed results for each of the vulnerability factors and the used sources of information are given in the "Supplementary material." The results of the vulnerability assessment are summarized in Table 7.

The third and last step are to combine the results from the calculation of the hydromorphological effect factors and the assessment of the vulnerability into an ecological classification of the hydropeaking impacts. The combined results are presented Figure 3 and as numbers in Table IV of the Data S1.

4 | DISCUSSION AND EVALUATION OF THE SYSTEM

4.1 | Suitability of the hydromorphological effect parameters

The system test showed that it was fairly straight-forward to calculate the hydromorphological effect factors with a tool such as COSH-Tool,

TABLE 7 Summarized results from the assessment of the vulnerability factors in the test cases, given for each river and the various types of sections (see Table 6)

Vulnerability factor	River			
	Nidelva	Surna	Daleelva	Mandalselva
V1: Effective population size—all sections	1	1	2	1
V2: Degree of limitations in recruitment—all sections combined	2	1	1.4	1.3
V2: Upstream HPP and other sections not affected by regulation	—	1	—	1
V2: Bypass sections (permanently reduced flow)	—	1	2	2
V2: Downstream outlet of HPP (hydropeaked section)	2	1	1	1
V3: Low flow periods as bottleneck for fish stock size – all sections combined	1	1.4	1.7	1.5
V3: Upstream HPP and other sections not affected by regulation	—	1	—	1
V3: Bypass sections (permanently reduced flow)	—	3	2	3
V3: Downstream outlet of HPP (hydropeaked section)	1	1	1	1
V4: Habitat degradation—all sections combined	2	1.7	1	1
V4: Upstream HPP and other sections not affected by regulation	—	1	—	1
V4: Bypass sections (permanently reduced flow)	—	1	1	1
V4: Downstream outlet of HPP (hydropeaked section)	2	3	1	1
V5: Reduced water temperatures that lead to population effects—all sections combined	1	2	1	1
V5: Upstream HPP and other sections not affected by regulation	—	1	—	1
V5: Bypass sections (permanently reduced flow)	—	1	1	1
V5: Downstream outlet of HPP (hydropeaked section)	1	2	1	1
V6: Other factors—all sections combined	1	1	1.4	1
V6: Upstream HPP and other sections not affected by regulation	—	1	—	1
V6: Bypass sections (permanently reduced flow)	—	1	2	1
V6: Downstream outlet of HPP (hydropeaked section)	1	1	1	1
V7: Percentage of impacted river length compared to total length	3	2	3	2
COMBINED vulnerability, without down rating	11.0 (moderate)	10.1 (moderate)	11.5 (moderate)	8.8 (low)
Down rating	0	−2	0	−3
COMBINED, after downrating	11.0 (moderate)	8.1 (low)	11.5 (moderate)	5.8 (low)

Note: Details about the assessment and the sources of information are provided in the "Data S1".

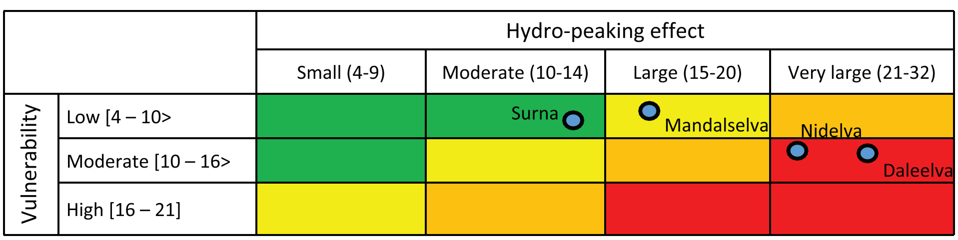

FIGURE 3 Resulting and combined class scores for each of the four test rivers. The color codes represent very large (red), large (orange), moderate (yellow), and small (green) ecological impacts. The blue dots represent the precise score values. See also Table IV in the Data S1 [Color figure can be viewed at wileyonlinelibrary.com]

given that timeseries of discharge and water level are available at an hourly time resolution, while the calculation and classification of hydraulic factors are more challenging. To obtain high precision for the entire river section, a hydrodynamic model of the river is necessary. Alternatively, aerial images covering the range of typical peaking and off-peaking flows can be used.

A hydrodynamic model allows estimates of the rate of change (E1) and water-covered/dewatered areas (E2) for all discharges of concern, and how these change for different discharge intervals. The use of aerial images is often limited by the range of flow values available. Given the rapid development of techniques to collect high-resolution images and topographic, such as LIDAR mounted to drones or airplanes, it is expected that the application of hydraulic modeling tools with high precision input data will become an efficient and precise way of calculating the hydromorphological parameters for larger areas.

It should also be evaluated if the timeseries of discharge and water level are representative for the entire river section assessed. If the measurements are made close to the outlet of the hydropower plant, the changes in discharge and water level will be more rapid than further downstream as the propagation of water level changes is normally dampened going downstream the river. The dampening effect will vary on the hydromorphological properties of the rivers such as slope, the shape of the river channel, and roughness, and inflow of water from groundwater and downstream tributaries will gradually attenuate the hydropeaking wave. The timeseries should preferably be recorded at a representative location of the river exposed to hydropeaking, and the results should be evaluated with respect to the position of the measurement station compared to the river section assessed. In cases where discharge is not logged, a hydropower simulation model, using hydrological input, could be an alternative source for the hydromorphological data.

All the calculations were made based on timeseries with 1-hr resolution, which is the recommended time resolution of the data series to be applied for this classification. As hydropeaking often has a more rapid response than 60 min, timeseries of finer resolution would have been beneficial. As all the results have been calculated with the same time resolution, the comparison between the test rivers should be reliable, but comparison with other assessments should be made with caution. Further research would be desired in order to assess the effect of time resolution on the output from COSH-Tool calculations. The outcome of this must be reflected in the requirements of the monitoring programs given in the revision of old hydropower licenses or in new.

The selection of hydromorphological factors and the class limits was made based on a combination of literature values and expert knowledge. Our selection of parameters and limits have apparent similarities to BAFU (2017), which is the Swiss legislation system for hydropeaking operations The main parameter in BAFU (2017) describing stranding areas is "dry falling surface area in relation to wetted area," which is similar to our E2 dewatered areas. Furthermore, BAFU (2017) defines three parameters with threshold values for down-ramping rates for larval of grayling/brown trout at day-light (same class values both species), and for juveniles of the same species also at day-light (2 different class values). These three parameters for down-ramping rates relate to our parameter E1 rate of change. Our system differentiates the effect classification concerning the time of the day and year (E5 & E6) and the distribution and frequency of the hydropeaking operations (E4). For both dewatered areas and ramping rates, our class boundaries are more precautious, that is, smaller and slower changes lead to more severe impact classification than in BAFU (2017). It should also be underlined that our system is primarily developed for salmonids and demonstrated here for Atlantic salmon populations.

The defined hydromorphological effect factors are considered to be relevant also for other fish species and riverine biological quality elements (Bejarano et al., 2018; Hayes et al., 2019). Therefore, these hydromorphological factors are considered helpful for the assessment of the hydropeaking operations also without the biological vulnerability axis. A major value of the scoring system is in identification of the factors that are most strongly contributing to the overall score, as a guide for selecting the most effective mitigation strategy.

4.2 | Suitability of the vulnerability factors and the combined effects

Assessing the salmon population vulnerability is inherently somewhat more challenging than the hydromorphological effect factors, and some of the factors depend more strongly on expert judgments. Several of the factors are based on the methodology described in Forseth and Harby (2014), which still is a reasonably new methodology that requires more use to be verified. Moreover, without prior knowledge of the system, a full data-based assessment of vulnerability according to the present system would be time consuming and costly. However, this does not necessarily diminish the value of the combined system developed. Even with a high degree of expert judgment for the vulnerability factors, the combined classification is likely to be robust at identifying rivers where the additional pressure from hydropeaking would strongly affect the fish population.

The vulnerability factors are valid for Atlantic salmon and likely also anadromous brown trout but not for other relevant fish species. However, the central principles of the classification could relatively easily be adapted to other riverine fish species. The central point is that the vulnerability of the populations should be considered when assessing the effects of and mitigating hydropeaking.

The combination of hydromorphological effect factors and vulnerability factors into ecological impact classes, ranging from small (green cells), moderate (yellow), large (orange), and very large impacts (red cells), were based on expert judgments, as are indeed most other similar systems for ecological assessment (i.e., within WFD). Our results from the four test rivers showed an expected range in total impacts. Further applications will prove if the system facilitate the full range of hydropeaking operations in an appropriate way or if the rules for combination or impact class borders should be adjusted. The availability of biological data will hence be essential in the process of evaluation of the classification system.

Given the challenges mentioned, the system appears to be very useful to facilitate the assessment of the additional impact hydropeaking operations can introduce and help to identify where mitigation measures should be focused. The national authorities in Norway have clearly acknowledged the system and uses the effect factor and its class borders as the basis for issuing restrictions in new hydropower licenses and in the revision of old license terms (NVE, 2019).

4.3 | Discussion of the test results

The four test cases ended up covering the range of outcomes of the system from very large to low additional impacts. The system captured the fact that extensive mitigation measures have been introduced in Surna to reduce the impacts from hydropeaking operations, and this river ended up in the "green category," that is, small additional impact, however, with a small margin to the category "moderate." Daleelva and Nideelva (very large impacts) were in the other end of the scale, in particular caused by the rapid reductions in water level and large dewatered areas, which are the dominating factors as they are multiplied. Mandalselva was classified as having moderate additional impacts from hydropeaking operations, as the episodes of hydropeaking operations are relatively few, and the effect of regulation gives higher discharges in periods of low flows both during summer and winter, compared to the unregulated situation (high minimum flow requirements). It should be noted that only about 20 km of the anadromous section of the river is exposed to hydropeaking.

All rivers may have undergone long-term degradation in morphology during the period of hydropeaking, and our assessment was assumed to represent "a typical situation" for the period the dataseries cover (Table 7). Surna is the only river where explicit restrictions on salmon friendly hydropeaking operations have been defined voluntary by the hydropower company. The first restriction was introduced in 2005, while further restrictions were established in 2009, which now include restrictions on down-ramping rates for all relevant discharge intervals. At the same time, Surna has experienced a trend of more frequent hydropeaking (Ugedal, Larsen, Torbjørn, Bjørn, & Johnsen, 2006) and severe up-ramping are therefore a potentially increasing ecological challenge (Wandurraga, 2019). The environmental license of the Trollheim regulation (which directly affects Surna) is now under revision, and the national authorities have proposed to formalize and limit the down-ramping rates to (usually) not exceeding 5 cm/hour during all periods of the year. In our assessment, we have used the voluntary restrictions on down-ramping as the basis for the impact factor E1, while we used the whole dataseries for the other hydromorphological effect factors. In Mandalselva, the following clause is stated in the legislation defining the operation of Laudal hydropower plant; "in order to avoid stranding of fish, the discharges should be reduced gently. Changes in the power production should be made with cautions" (translated from Norwegian). There are no specific ramping values to comply with, but general statements about careful operation of the power plant should be made.

Flow ramping ratio (FRR) is a standard indicator used to assess the severity of hydropeaking operations, while there is no clear quantitative value used for legislative purposes. VAW and LCH (2006) reported flow ratio values from Swiss and Austrian rivers between 2 and 50. Bain (2007) documented extreme flow ratios up to 510 in rivers in the United States, Canada, Finland, and France. Bakken, Forseth, and Harby (2016) reported flow ratio from three Canadian rivers where the median values range from 1.2 to close to 80. It should be noted as flow ratio is defined as the Qmax divided on Qmin and when Qmin is very low, the flow ratio goes toward infinity if, for example, no environmental flow requirements are defined throughout the year. If the minimum flow restrictions are low, hydropeaking operations can quickly end up in the worst class in our system. In our selected case studies, all rivers have a relatively high minimum flow requirement (<7 in FRR, except Daleelva 15), as three of four also are national salmon rivers (where mitigation measures are expected to be ambitious).

It is impossible to separate the additional impacts from hydropeaking from other factors influencing the fish population. One approach to further investigate and diversify the various impacts and the ecological effect of hydropeaking operations could be to parameterize and simulate a set of scenarios hydropeaking operations in a salmon population model, which was done in Daleelva (Sauterleute et al., 2016) and Mandalselva (Hedger et al., 2018). Sauterleute et al. (2016) modeled the largest negative effect on the population abundance for hydropeaking during winter in daylight, and they also found that smolt production had the highest sensitivity to the stranding mortality of older juvenile fish. Hedger et al. (2018) did a more systematic sensitivity analysis of the importance of stranding on the population dynamics and concluded that population abundance was highly sensitive to density-dependent mortality. These were both pioneer works in the assessment of population effects due to hydropeaking, and it is not easy to evaluate if the outcome of our test of the classification system is correct or not. We believe, however, that further research and development of population-based models will give us valuable results that can be used to adjust the present version of the classification system.

The assessment was made for the entire river reaches handled as homogenous units. There are several challenges related to this, which include the fact that the calculated results are given as uniform from just downstream the outlet of the power plant and to the very far end of the river section. This is usually not the case as a rising or falling limb would be dampened with distance from the outlet, affecting particularly factors E1 rate of change and E3 magnitude of flow changes.

5 | CONCLUSION

We have proposed and tested a new system to classify ecological impacts with the aim to provide information for better decisions in Atlantic salmon rivers exposed to hydropeaking operations. While the system is currently species-specific, it can be adapted to other fish species or riverine ecosystem components. The test of the system clearly illustrated its value, both in terms of classification of the additional effects of hydropeaking in regulated rivers and as a foundation for mitigation measures. While classifications of some of the factors depend on expert judgments, the combined system appears robust in terms of identifying rivers where the additional pressures from hydropeaking would strongly affect the fish populations. Moreover, setting up the primary and combined classifications is a tool to systematically assess the importance and severity of the different effect and vulnerability factors, the total ecological impacts, and different ways of mitigating the effects. Hydropeaking results from a critical adjustment in hydropower electricity production to balance the grid and support the varying electricity demands. There is a trade-off between maintaining flexibility of the hydropower system and protecting the river environment. In our judgment, the developed system is valuable both in terms of identifying rivers where hydropeaking operations have high (and should be avoided) and low ecological costs, and how to reduce such costs when hydropower flexibility is important, and hydropeaking is implemented. It can also form a basis for further investigations. Mitigation can be attained both by measures to reduce the severity of the hydromorphological effect factors and the population vulnerability. In the current system, the different factors can be changed, and new ecological scores can be calculated in an iterative approach to obtain an optimal trade-off of hydropower flexibility and environmental protection. Further research should be directed toward more operational testing of the system (e.g., in the implementation of the WFD), to improve the system's ability to define river-specific mitigating measures, and to enable better support for comparison between rivers.

ACKNOWLEDGMENT

This work was carried out under the project EnviPEAK within the research centre CEDREN (Centre for Environmental Design of Renewable Energy, http://www.cedren.no, grant no. 193818). Funding was provided by the Research Council of Norway, private and public partners in the environmental and energy sector and the research organizations of the authors.

DATA AVAILABILITY STATEMENT

The data used in this study are available from the sources referred to directly in the text, or available on request from the corresponding author (data collected by SINTEF).

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SUPPORTING INFORMATION

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How to cite this article: Bakken, T. H., Harby, A., Forseth, T., Ugedal, O., Sauterleute, J. F., Halleraker, J. H., & Alfredsen, K. (2021). Classification of hydropeaking impacts on Atlantic salmon populations in regulated rivers. *River Research and Applications*, 1–13. https://doi.org/10.1002/rra.3917