CLASSIFICATION AND COMPARISON OF HYDROLOGICAL IMPACTS OF HYDROPOWER TO SUPPORT THE CONCESION REVISION MANAGEMENT.

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In this study, an attempt to classify the flow regime alterations for 18 Norwegian rivers has been carried out. A recent report from the Norwegian authorities stated that around 50 regulated watercourses have high priority in the revision of their regulation permit before 2022 [1]. The report classifies rivers by scoring the impact of hydropower regulation on fish, biodiversity, and recreation. Then the report suggests changes in their revision according to their environmental and hydropower importance. In some cases, mitigation measures like implementation or revision of minimum flows are suggested. This paper provides a detailed study of the hydrological alterations produced by hydropower regulations on a national scale. The results will be compared with the classification carried out by Sørensen *et al.* [1] in terms of fish status as a result of hydropower impacts. The comparison will provide the hydrological indices that are most impacted, facilitating the selection of mitigation measures included in the regulation permit revision.

1 METHODS

The proposed methodology has been applied in 18 regulated rivers with a population of Atlantic salmon distributed geographically around Norway. The analyzed rivers belong to five water regions: Trøndelag, Vestfold, Hordaland, Nordland and Finmark.

1.1 Baseline streamflow data (unaltered flow)

Within the 18 Norwegian river systems, there is limited hydrological unaltered flow data. The aim was to acquire 20 years of daily mean flow data from each river gauge. An overlap period of 85% continuously unaltered flow data from all of the 18 gauges was considered appropriate. Kennard *et al.* [2] recommended at least a 50% overlap of gauge data to account for potential sources of uncertainties in such case studies. In order to compare the 20 years of unaltered flow (pre-impact) with 20 years of altered flow (post-impact), hydrologic modeling was used to simulate data where measurements were missing. To transfer data from gauged catchments, the regional regression model [3] and the drainage area ratio method were used [4].

1.1.1 Regional regression model

Regional regression models have been widely applied for prediction of hydrologic indices [5, 6]. In this study, a regional regression model, which was developed and tested by Hailegeorgis [3] for catchments in mid-Norway, was applied to predict streamflow percentiles. The regional regression model is based on a simple linear regression fitted between each stream flow percentile, and climatic and physical characteristics of unregulated catchments in a hydrologically homogeneous region:

$$Y = X\beta^* + \varepsilon \tag{1}$$

where Y is a vector of response variables, here stream flow percentiles in m^3s^{-1}, X is a matrix of independent variables for example drainage area, mean annual precipitation, lake area. and ε denotes error.

1.1.2 Drainage area model

The regional regression model performance is limited by the need of several unregulated data series. The drainage area model requires less unregulated data and is used in data scarce areas:

$$Q_{ut} = A_u / A_g\, Q_{gt} \tag{2}$$

Where Q_{ut} is the stream flow on day t at the ungauged catchment, Q_{gt} is the stream flow on day t at the reference stream flow, A_u is the ungauged catchment drainage area and A_g is the reference streamgauge drainage area.

1.2 Selection of flow metrics

Following the method of the Indicators of Hydrologic Alteration (IHA) by Richter *et al.* [7], 19 hydrologic indices has been used in the study. The selection of the indices combine indices already defined by Richter *et al.* [7] and new indices more adapted to Norwegian rivers and Atlantic salmon [8]. Hydrologic indices have considerable multicollinearity [9]. The 19 indices have been reduced to a set of non-redundant indices. A correlation matrix using the corrgram Package in R [10] has been carried out with a principal component analysis (PCA-based) re-ordering. 9 hydrological indices have been selected according to the pre-impact data analysis (Table 1).

Table1: Hydrological indices selected. Indices with * are defined by Hohl [8] and the rest by Richter *et al.* [7]

Hydrological index (units)	Description
Beginning of snowmelt* (day)	First day in year with a runoff over the 10% of the average of maximum runoff of the whole period and where the actual runoff is more than 20% higher than the day before and where the runoff the day before is more than 20% higher than two days before
No. of falls (number)	Number of periods with uninterrupted decrease in runoff over the defined limit for rises and falls
Date of 1 day max (day)	Date of the day with the maximum yearly daily runoff
Date of 1 day min (day)	Date of the day with the minimum yearly daily runoff
Max 24h fall* (m^3/s)	Maximal decrease in runoff compared with the day before
Mean value winter (m^3/s)	Percentage of December, January, February runoff compared to the total runoff
Winter/spring 1 day max* (m^3/s)	Maximum daily average runoff in the period from January 1st to June 30th (Spring: snowmelt period)
Mean value summer (m^3/s)	Percentage of June, July, August runoff compared to the total runoff
Low flow* (m^3/s)	Daily runoff is ordered from the highest to the smallest. Runoff no. 350 is sorted out and with the values from all the years a new series is built. From this series the average of the higher $^2/_3$ is built.

1.3 Classification of flow regimes

A clustering method using an Euclidean distances dendrogram has been carried out with the gplot Package in R [11]. All the variables has been standardized in order to have scale-independent contribution. The classification analysis has been divided in ”pre-impact” period, ”post-impact” period and an Impact Ratio calculated as (“post-impact”-“pre-impact”)/”pre-impact”). Nine hydrological indices were obtained from the ”pre-impact” period as the discriminatory variables for river classification. It has been noted that there are other influential variables in the other two (“post-impact” and Impact Ratio). However, they have an 85% correlation with variables that are already used. Therefore, the same nine hydrologic indices are applied to the two other analyses.

2 RESULTS

2.1 Hydrological classification

Figure 1 shows the classification of the rivers before regulation (Pre Impact) and after (Post Impact). The Post impact classification contains only 2 classes equal to the Pre impact classification. The two classes have two rivers each, Mandalselva and Numedal and Drammen and Skienselva, respectively. The class composed of Drammen and Skienselva stands out from the rest of the rivers. They are characterized by higher values for variables like: mean value in winter, winter spring 1 day max, mean value in summer and annual low flow. This can be relate to their river system characteristics: big rivers with reservoirs far up on the catchments. The rest of the classes have been impacted differently, since rivers are grouped in different classes. Rivers classes in the Pre impact classification are more relate than river classes in Post impact classification.

Figure 2 shows the results from the impact ratio analysis. The dendogram on the left side of Figure 2 shows that the impact (regulation) has led to a completely different river classification. The dendogram classfication makes a differentiation between 2 major rivers classes. The Skibotndalen, Fortun, Aurland, Drammen and Orkla exhibit an increase in low flow, increase in the mean value in winter, reduction of max 24 h falls and reduction of falls after impact. The Nidelva makes a class by itself with an increase in number of falls, max 24 h falls, date of 1 day max and mean value in winter after impact, while the rest of the variables are reduced almost 100%.

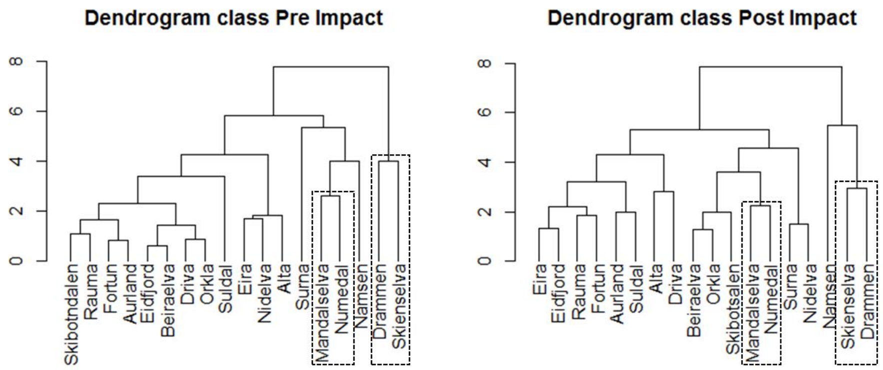

Figure 1. Dendrogram class Pre Impact (left) and Post Impact (right). Dotted squares indicated unchanged classes.

The Mandalselva, Numedal and Skienselva show a later beginning of snow melt and date of 1 day max, and a general decrease in the rest of variables.The Driva, Rauma and Beiarelva show an increase in winter spring 1 day max and increase or no change in mean value summer. They also show a moderate increase on date of 1 day min and decrease or no change in the rest of variables. These three rivers have low degree of regulation in common. The Namsem and Surna show an increase in mean value summer and low flow. Alta river is classified by itself and is characterized by no change in the beginning of snowmelt, a high increase on winter spring 1 day max and a reduction of the rest. The Eidfjord, Suldal and Eira are characterized by a general reduction in all the variables, they are rivers regulated by transfers to other systems.

2.2 Salmon status classificaiton

The salmon register database (Laksregisteret) classification has been grouped in four categories: Extinct, Very Poor, Poor, Very good. Among the 18 rivers analysed, Drammen, Orkla, Mandalselva and Namsen have the flow regulation as a secondary cause of their status, and they fall in Poor and Very good categories. Driva has parasites as the main and only cause of falls in Poor category. The rest of the rivers all have flow regulation at least as one of the main cause of their status. Skibotndalen falls in extinct, with flow regulation, parasites and other cause as main reasons. Aurland, Nidelva, Numedal, Skienselva, Beiarelva, Surna, Alta and Eira fall into Very Poor category. Among them, Eira has hydrological regulation as the only cause. Aurland, Nidelva and Numedal have the main cause as flow regulation and then secondary causes as acidification, contamination, physical interventions and agricultural contamination. Beiarelva, Surna and Alta have various main causes such as flow regulation, acidification and Beiarelva also has a defective fish pass. Fortun, Driva, Rauma, Eidfjord and Suldal fall into Poor category where Fortun and Suldal have as main cause flow regulation and secondary cause acidification and physical interventions. Rauma and Eidfjord have as main causes, flow regulation and parasites.

3 DISCUSSION

The classification of the river according the Impact Ratio results has been compared with the classification of the rivers according to the Atlantic salmon (A. salmon) status. Among the 18 rivers studied in general those that fall in the same class for Atlantic salmon status due to mainly flow regulation, are also classified closer for the Impact Ratio classification. Orkla and Namsen both are classified as Very good for Atlantic salmon but they are far from each other in the Impact Ratio classification, this can be link to the fact that they have flow regulation as a secondary cause of their status. Eira, which falls into Very Poor for salmon and with the only and main reason as the flow regulation shows a high decrease in almost all the hydrological indices. Fortun and Suldal fall into Poor class for salmon but they are far from each other in the Impact Ratio classification, both have flow regulation as main cause but also other factors as secondary causes. This could indicate that other factors rather than flow regulation may have highest impact. Skibotndalen has extinct salmon status with various reasons as main cause, but also in the Impact Ratio classification fall into a single class. Finally, some rivers do not show any relation with the Impact Ratio classification.

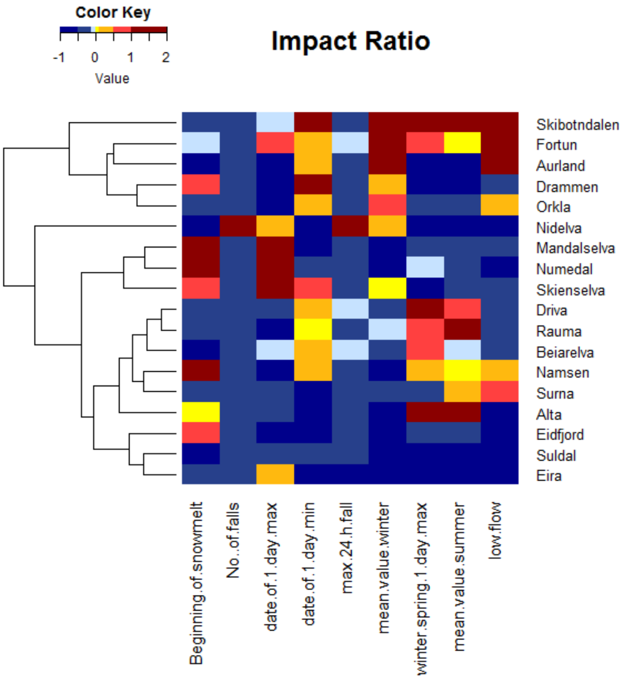

Figure 2: Heat map showing the percentage change in flow metrics between Pre Impact and Post Impact flow regimes. Color Key shows the changes from decrement -100% to increment represent as 200%.

4 CONCLUSIONS

Figure 2 reveals some interesting patterns, classification results can be relate according to their operational systems and/or catchment characteristics. Despite the difficulties in relating the river classification to changes in flow metrics, some interesting results are presented. Future work and the addition of more rivers could provide a better understanding of metrics included in flow regulation factor in Sørensen et al. [1] classification and if these are appropriate considered in relation to salmon. Being able to detect which are the most relevant flow metrics affecting the salmon population from the work in progress could help to define and manage future mitigation and compensatory measures for the revision of the concession expected for 2022.

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