Biodiversity Restoration and Renewable Energy from Hydropower: Conflict or Synergy?

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Abstract

Hydropower plants have a negative impact on biodiversity by transforming stream habitat and hydrology and thereby affecting aquatic organisms negatively. The negative effects can be mitigated by releasing water into the old river bed. This study investigates if the measure of releasing water creates costs and if ecological conditions at the old river bed contribute to such an impact. To this end, we used the cost-minimization framework in economics for deriving hypotheses. Tests were made with data from a survey to 76 hydropower plants in Sweden with questions on existence of a cost, size of the plant, type of water release from reservoirs, characteristics of the dried downstream old river bed, and official statistics on ecological status of the downstream dried segments. The results showed that 42% of the plants reported no cost, measured as impact on electricity production, from release of water into downstream old river bed. We applied logit and probit models to explain the probability of a cost. Significant results were obtained were the electricity produced and program for minimum water discharges increase the probability of loss in electricity production, but favorable ecological conditions in the old river bed decrease the probability of a cost.

Keywords: hydropower, biodiversity, streams and rivers, restoration, old river bed, cost, survey data, econometrics, Sweden

1. Introduction

Similar to many other countries, Sweden needs to comply with national and international targets on renewable energy and biodiversity provision. Hydropower is important for the provision of renewable electricity production and accounts for approximately 47% of the total electricity production in the country [1]. Nuclear power is the second largest source of electricity and accounts for 34% of total energy production. Not only is hydropower a large source of electricity, but also acts a powerful regulatory device for the large fluctuations in demand and supply of electricity. Further, it is among the least expensive sources of energy as measured in SEK/kWh [2].

Establishments of hydropower plants change the hydrological conditions in the riverine landscape which affects habitats for animals and plants. Streams can be totally or partially dried and thereby destroying the habitats for several species and migration pathways for fish species. Although there is no national evidence on the extinction of species because of the hydropower production, the effects imply a degradation of habitats for red listed species [3], which goes against the national target of preserving biodiversity.

In order to mitigate these effects water power plants may be run with a release of water from the reservoir(s) into the downstream dry channel (the old natural river channel). However, this may only be achieved at a cost in terms of less electricity production and hence fulfillment of the target on renewable energy. This study investigates whether such a cost exists, and which factors contribute to the probability of its occurrence. To this end, we use the cost-minimization framework to derive testable hypotheses. Test are made with data from a survey on 76 hydropower plants in Sweden with questions on the existence of a cost in terms of negative impact on electricity production, the type of water release from reservoirs, and characteristics of the dried downstream channel and the plant. This data set was completed with official statistics on ecological status in the downstream segments. We use econometric methods to examine the impact of water discharges from the reservoir and other explanatory variables on electricity production. The dependent variable is a binary variable which equals 1 when electricity production is affected and 0 otherwise. We, therefore, use a probit model for the regression analysis, where we estimate how the explanatory variables affect the probability of losing electricity production.

There is a large body of literature on ecological effects of biodiversity restoration in freshwaters, such as wetland restoration (see reviews in Refs. [4, 5]). Despite this, the literature on the determination of costs of measures mitigating biodiversity degradation from hydropower plants is scant (e.g., [6–8]). The cost of restoration objects depends on the investment and management of the restoration measure as such, and on the ecological conditions at the site affecting the need and quality of restoration [5]. In our view, the main contribution of this study is the estimation of the explanatory power of ecological conditions and water release from reservoirs on the probability of a restoration cost in terms of reduction in electricity production.

2. Theoretical framework

The theoretical framework rests on the assumption that each power plant minimizes costs for restoring biodiversity. This is a common assumption in economics where firms are assumed to use inputs, such as labor and capital, at given prices to minimize costs for producing certain outputs. By applying the so-called duality theory a cost function can be derived which shows the relation between the output and production cost (e.g., [9]). The cost is then expressed as a function of given input prices, and output level. In our case, biodiversity improvement constitutes the output Q^i where $i = 1,.., n$ sites of the hydropower plants. The level of the output, or success of restoration, which can be measured as number of fish species or as a quality index, depends on ecological conditions at the site, E^{il} where $l = 1,.., m$ conditions such as length of the channel and natural water flow, and on restoration measures at the plant, M^{ig} where $g = 1,.., h$ different restoration measures such as water discharges from the dam. The biodiversity at the site is then written as $Q^i = Q^i(M^{i1},..,M^{ih}; E^{i1},.., E^{im})$.

A crucial assumption in our analysis is that the plant manager minimizes total cost for achieving a minimum level of biodiversity, Q^{*i}. Each restoration measure is then associated with a cost, $C^{ig}(M^{ig})$, and a maximum capacity of implementation, $\overline{M}^{ig}$. For example, there is a maximum limit of water discharges into the channel. Plant size, K^i, may also affect costs; a large plant can have more expertise for implementing restoration measures than a small plant. On the other hand, a larger plant may give rise to more damages in the downstream waters, the mitigation of which requires costly restoration measures. The decision problem for the plant manager is then written as:

$$\begin{aligned} &\text{Min}C^i = \sum\nolimits_g C^{ig}(M^{ig}; K^i) \\ &M^{ig} \\ &\text{Subject}\, to\, Q^i(M^{i1}, .., M^{ih}; E^{i1}, \ldots, E^{im}) \geq Q*^i \text{ and } M^{ig} \leq \overline{M}^{ig} \end{aligned} \tag{1}$$

By applying the so-called duality theory to Eq. (1) we can express the cost of restoration at the plant as a function of the chosen restoration target Q^{*i}, ecological conditions at the site, E^{ig}, and the restoration measures, $\overline{M}^{ig}$, which is written as follows:

$$C^i = C^i(Q*^i, E^{i1}, \ldots, E^{im}, \overline{M}^{i1}, .., \overline{M}^{ih}, K^i) \tag{2}$$

Our main interest is to investigate the impact on costs of a marginal increase in the restoration ambition, Q^{*i}. The hypothesis is that the cost, C^i, increases since more of the restoration measures need to be implemented. In this case, there is a conflict between biodiversity restoration and electricity provision since resources that could be used for electricity production are used for biodiversity restoration. On the other hand, a non-positive effect would imply the opposite interpretation. As shown in Eqs. (1) and (2), a test of this hypothesis requires data, not only on C^i and Q^{*i}, but also on E^{il}, $\overline{M}^{ig}$, and K^i.

3. Description of data

Unfortunately, the necessary data presented in Section 2 is not available for a sufficient number of plants. Therefore, a survey was distributed to hydropower plants with dried channels. It turned out that the plant managers were not able to answer questions on our output variable, diversity at downstream sections of the reservoirs. The survey was therefore completed with official data on fish species.

The questionnaire was sent to the four largest hydropower companies in Sweden with any kind of restoration measures, where downstream dry or nearly dry river and stream channels had been identified and where electrofishing data were available for the dry or nearly dry channel downstream of the reservoir. The questionnaire was filled out and returned for 76 hydropower plants where fish data (see below) from downstream sections of the reservoirs were available. These plants are located in the entire Sweden, see **Figure A1**.

The survey included questions on the variables presented in Section 2: costs, measures for the release of water into the channel, ecological conditions of the dry river beds, and annual electricity production. The latter was used as a description of the characteristic of the plant. However, the respondents were not able to assess the costs of the measures, but on whether there had been a cost in terms of loss in electricity production. Therefore, our cost variable is binary, where $Cost = 1$ when there is a loss in electricity production and $Cost = 0$ otherwise.

With respect to the choice of measures, a common strategy is to implement a program with minimum water discharge from the reservoir to the old river bed, which ensures that there is a minimum flow of water in order to potentially sustain downstream stream and river organisms. A question was included on the existence of such a program (*Mindisch*) (by court order or voluntarily) where $Mindisch = 1$ when the measure is in place and $Mindisch = 0$ otherwise. The plants can also implement other strategies for improving biodiversity, such as an even flow of water to downstream water. A question was therefore included on the existence of other measures (*Othmeas*) where $Othmeas = 1$ if such measures exist and $Othmeas = 0$ otherwise.

Sufficient length of dry channels and natural water flow in the dry channels provide favorable ecological conditions for restoring biodiversity. Questions were included on the length of the dry channels (*Length*), and natural water flows in the dry channels in m/s (*Msec*) as continuous variables. The size of the plant was measured as the annual electricity production (*Elprod*).

As shown in Section 2, the variable measuring biological conditions of the downstream dry or partly dry stream or river section should reflect the effects of restoration measures and ecological conditions in the channel. This would require data and analysis of biological conditions before and after the implementation of the measures. Such data is not available. Instead, we use data on measurements of biological conditions in the downstream river section, which is available as electrofishing data at the Swedish Electrofishing Register [10]. The Swedish stream and river fish index *VIX* was used to assess the ecological status of the downstream sections [11]. The *VIX* index ranges from 0 to 1, where high values denote high ecological status and low values denote bad ecological status according to the EU Water Framework Directive [12].

Descriptive statistics of the dependent variable *Cost* and the independent variables are displayed in **Table 1**.

The results from the survey showed that 58% of all plants report a cost in terms of a reduction in electricity production and 47% have implemented minimum flow discharges into the old

Variable	Observations	Mean	Standard deviation	Minimum	Maximum
Cost	66	0.576	0.498	0	1
Elprod, electricity production in kWh	66	90,400,000	202,000,000	900	1,120,000,000
Length in m	75	2113	2612	62	16,308
Msec, water flow in m^3/s	67	48	83	0	377
Mindisch	75	0.47	0.50	0	1
Othmeas	75	0.69	0.46	0	1
VIX	20	0.43	0.23	0	1

Table 1. Descriptive statistics.

natural downstream channel as a biodiversity restoration measure. It might be argued that mainly those dams with discharges of water from the reservoirs to the dry channel face a cost. However, the plants reporting a loss in electricity production is evenly distributed between plants with and without minimum discharges to the dried channels.

The range in dam size as measured by electricity production is large within the dataset, ranging from 900 to 1,120,000,000 kWh/year (**Table 1**). The continuous variables *Elprod*, *Length*, and *Msec* are highly skewed, and we, therefore, transformed them into the logarithms *Logelprod*, *Loglength*, and *Logmsec.*

4. Econometric model

We have employed the standard logit and probit models to estimate the explanatory power of the independent variables listed in **Table 1** on the probability of a cost. The difference between the logit and probit model is the distributions of the error terms. The former follows a cumulative standard logistic distribution, whereas the later follows a cumulative standard normal distribution (see e.g., [13, 14]). The probability functions in both the models are symmetric around zero and tend to give similar parameter estimate. Therefore, we have estimated parameters of interest applying both estimators. We know that our dependent variable *Cost*, can take only two values, i.e., 1 if there is a cost and 0 if there is no cost. The probability of $Cost = 1$ is p and the probability of $Cost = 0$ is $(1-p)$. Hence, the expectation of *Cost*, *E[Cost],* is given as follows:

$$E[Cost] = 1 * p + 0 * (1 - p) \Rightarrow p \tag{3}$$

Considering the probability that $Cost = 1$ is a function of different covariates presented in **Table 1**, denoted by vector X, and parameters of interest β, we can write the standard binary choice model as follows:

$$P(Cost = 1|X) = f(\beta X) \tag{4}$$

Consequently, the logit and probit models corresponding to Eq. (4) are given by Eqs. (5) and (6), respectively, as:

$$f\left(\beta' X\right) = \frac{e^{\beta' X}}{1 + e^{\beta' X}} \tag{5}$$

$$f\left(\beta' X\right) = \Pi\left(\beta' X\right) = \int_{-\infty}^{\beta' X} \frac{1}{\sqrt{2\pi}} e^{-\frac{u^2}{2}} du \tag{6}$$

Since probit and logit models are nonlinear in both parameter and variables, the usual ordinary least square (OLS) and weighted least square (WLS) estimators could not be plausible. For that reason, identification of parameters given by a vector β preferably should be obtained by applying the maximum likelihood (MLE) estimator. Generally, binary choice models can be derived from the latent variable model as it provides a link with standard linear regression models which makes interpretation of the parameters straightforward. Besides, the model illustrates the difference between logit and probit models. Suppose the binary outcome variable *Cost* and the corresponding latent variable *Cost** satisfies the single infix model as:

$$Cost* = \beta X + \varepsilon \tag{7}$$

Given that *Cost* is observable, it can be expressed as:

$$Cost = \begin{cases} 1 \ \ if \ \ Cost* > 0 \\ 0 \ \ if \ \ Cost* \leq 0 \end{cases} \tag{8}$$

Combining Eqs. (7) and (8), we can have the following response probabilities:

$$P(Cost = 1) = P(\beta X + \varepsilon > 0) = P(-\varepsilon < \beta X) = f(\beta X) \tag{9}$$

where, $f\left(\beta' X\right)$ is the cumulative density functions (CDF). In the case of probit model, the error term follows the standard normal distribution whereas it follows the logistic distribution in the case of a logit model.

The signs of parameters β are directly interpretable in both logit and probit models, but not the magnitudes. For that reason, deriving the marginal effects and discrete changes in the estimates is crucial in order to obtain the magnitudes of parameters. The marginal effect of the continuous covariate is given by partial derivative with respect to that variable, whereas the discrete changes of dummy covariate are given by the difference in predicted probabilities of the variable at 0 and 1, setting other covariates constant at their reference points. Mathematical notion of marginal effects and discrete changes in binary outcome models can be found in Ref. [13].

Recall from Section 3 that the availability of data is limited for the *VIX* variable with only 20 observations. We, therefore, estimated regression equations with and without this variable. The regression equation without *VIX* is specified as:

Model 1:

$$Cost = \beta_o + \beta_1 \text{Logelprod} + \beta_2 \text{Loglength} + \beta_3 \text{Logmsec} + \beta_4 \text{Mindisch} + \beta_5 \text{Othmeas} + \varepsilon \tag{10}$$

The estimates give information on the probability of a cost from introducing restoration measures *Mindisch* and *Othmeas*, and the impacts of *Logelprod, Loglength*, and *Logmsec*. The regression equation with *VIX* includes all variables and is specified as:

Model 2:

$$\begin{aligned} Cost \; = \; & \beta_6 + \beta_7 \text{Logelprod} + \beta_8 \text{Loglength} + \beta_9 \text{Logmsec} \\ & + \beta_{10} \text{Mindisch} + \beta_{11} \text{Othmeas} + \beta_{12} \text{VIX} + \varepsilon \end{aligned} \tag{11}$$

5. Results

The results showed that the independent variable *Othmeas* was never significant, and we therefore excluded this variable. Another result was that the inclusion of all explanatory variables in Model 2 gave poor statistical fit because of the low number of observations. We, therefore, excluded *Loglength* and *Logmse* in Model 2.

There might also be statistical problems associated with endogeneity in the included explanatory variables. Since the purpose of minimum discharge (*Mindisch)* is to sustain ecological conditions in the dry channels, this variable might be dependent on the ecological status in the stream channels, *Loglength*, and *Logmsec* in Model 1 and *VIX* in Model 2. If so, the ordinary least square (OLS) estimates will not give consistent estimates (e.g., [15]). Therefore, we tested for endogeneity in *Mindisch* by using *Loglength* and *Logmsec* as instruments in Model 1 and *VIX* as an instrument in Model 2. Wald tests of both models showed that exogeneity in *Mindisch* could not be rejected at the 10% level (see, e.g., [15] for a description of the test). This means that we can treat *Mindisch* as an independent variable.

We also tested for the existence of heteroscedasticity, which was not present in any model according to the results from Breach-Pagan tests (e.g., [16]). However, Pearson test of correlation among all explanatory variables showed significant associations at the 1% level between *Logelprod* and several other explanatory variables (**Table A1**). Despite these association, variance inflation factor (*VIF*) tests did not reveal problems of multicollinearity (mean $VIF = 1.29$ for Model 1 and mean $VIF = 1.36$ for Model 2).

The binary dependent variable denotes the likelihood of a cost of changes in any of the explanatory variables. We would expect *Mindisch* to increase the probability of a cost since this measure discharges water into the dry channel which could be used for electricity production. On the other hand, natural conditions in the dry channels, measured as channel length and natural water discharge, are likely to reduce the likelihood of a cost because there is less need for mitigation measures. As a measure of the size of the dam, *Logelprod* can increase the probability of a loss in electricity production. The regression results of Model 1 are presented in **Table 2**.

According to **Table 2**, the results from the logit and probit models are quite similar. All explanatory variables are significant and have the expected sign. The models are significant at the 0.01 level according to the model Chi-square statistic, and the predicted "$Cost = 1$" corresponds to 87% of the observed "$Cost = 1$." The statistical performance of the probit model is slightly better

Variable name	**Logit**		**Probit**	
	Coeff.	**Prob.**	**Coeff.**	**Prob.**
Constant	−3.891	0.331	−2.396	0.215
Logelprod	0.841^{***}	0.000	0.496^{***}	0.000
Loglength	-0.777^{*}	0.061	-0.443^{**}	0.041
Logmsec	-1.334^{***}	0.001	-0.785^{***}	0.000
Mindisch	1.826^{*}	0.086	1.062^{*}	0.053
Model significance^{a} Pseudo R^2	$p = 0.000$		$p = 0.000$	
	0.440		0.444	
Predicted *Cost* = 1/observed *Cost* = 1	33/38		33/38	
AIC, BIC	54.177, 64.565		53.851, 64.238	

Notes: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$; ^{a}Chi-square(4).

Table 2. Regression results of Model 1 with different estimators, $N = 59$.

than the logit model as measured by pseudo R^2, Aikaike Information Criterion (*AIC*), and Bayesian Information Criterion (*BIC*) tests.

The results for the two estimators are similar when replacing *Loglength* and *Logmsec* with *VIX*, see **Table 3**.

The statistical performance of Model 2 as measured by the significance of explanatory variables, overall model significance pseudo R^2, *AIC*, and *BIC* was lower than for Model 1, which may be explained by the lower number of observations. A common result for Model 1 and Model 2 was the positive and significant effect of *Logelprod*. Although *Mindisch* has the expected negative sign in Model 2, it was not significant. The estimate of *VIX* has an unexpected negative sign. Since *VIX*

Variable name	**Logit**		**Probit**	
	Coeff.	**Prob.**	**Coeff.**	**Prob.**
Constant	−9.811	0.013	−5.825	0.004
Logelprod	0.731	0.013	0.430	0.002
VIX	−2.644	0.655	−1.597	0.496
Mindisch	0.750	0.754	0.464	0.659
Model significance^{a} Pseudo R^2	$p = 0.004$		$p = 0.004$	
	0.408		0.407	
Predicted yes/observed yes	10/13		10/13	
AIC, BIC	23.339, 27.322		23.338, 27.321	

Notes: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$; ^{a}Chi-square(3).

Table 3. Regression results of Model 2 with different estimators, $N = 20$.

Variable	**Logit**				**Probit**			
	Model 1		**Model 2**		**Model 1**		**Model 2**	
	dy/dx	**p-value**	**dy/dx**	**p-value**	**dy/dx**	**p-value**	**dy/dx**	**p-value**
Logelprod	0.176^{***}	0.000	0.152^{***}	0.001	0.175^{***}	0.000	0.154^{***}	0.000
Loglength	-0.164^{*}	0.053			-0.156^{**}	0.035		
Logmsek	-0.280^{***}	0.000			-0.277^{**}	0.000		
VIX			-0.553	0.646			-0.572	0.486
Mindisch[a]	0.384^{***}	0.065	0.157	0.750	0.375^{**}	0.042	0.166	0.655

Notes: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$; [a]dy/dx is for discrete change of dummy variable from 0 to 1.

Table 4. Estimates of marginal effects of each of the explanatory variable at the mean value of all variables.

shows the fish habitat conditions at a downstream segment, a higher level of *VIX* should be associated with a higher probability of a cost according to the simple economic theory presented in Section 2. On the other hand, a negative sign indicates that there is no conflict in the achievement of biodiversity targets and energy production. However, the estimate is not significant and we cannot make conclusions about the effects of *VIX* on the probability of a cost.

Generally, coefficients of binary outcome models are in log-units and cannot directly be interpreted as marginal effects. This is due to the fact that the logit or probit transformation of the outcome variable has a linear relationship with the predictor variables. However, it is possible to derive the individual marginal effects or elasticities of covariates at their mean values (**Table 4**).

The probit and logit models give similar marginal effects of *Logelprod* for both Model 1 and Model 2 (**Table 4**). The probability of a loss in electricity production increases by 0.18 (Model 1) or 0.15 (Model 2). An increase in *Mindisch* has the largest impact on the probability, an increase by one unit raises the probability by 0.38 (Model 1). On the other hand, an increase in the natural conditions in the dry channel reduces the risk by 0.16 and 0.26 for *Loglength* and *Logmsek*, respectively.

6. Discussion and conclusions

The purpose of this study was to determine if restoration of biodiversity in dry channels at hydropower plants in Sweden can be costly for the plants and how the probability of a cost is affected by the size of the plant, site-specific factors in the dry channels, and ecological status in downstream regions of the river. The measure considered for restoration is the existence of a program for minimum releases of water from the reservoirs to the dry channel, and the cost is defined as a decrease in electricity production. The study rests on data from a survey of the largest hydropower plants in Sweden, which resulted in data for 76 plants with dry channels.

According to the responses in the survey, 58% of the plants with a program for minimum water discharges report a cost. The reasons for not reporting such a loss can be that it is considered as negligible or that the respondent has insufficient information. We cannot distinguish between these reasons, but it can be argued that impacts of releases of water from the reservoirs to the dry channels on electricity production would be shown in the continuous monitoring of electricity production. Nevertheless, we should be careful in interpreting the lack of reporting of a loss as the nonexistence of decreases in electricity production from programs on minimum discharges to dry channels.

The main results from our analysis of the different variables in explaining the probability of a reported cost are that the existence of a program for minimum water releases and a larger size of the plant as measured by kWh electricity production increase the probability. On the other hand, site characteristics as measured by the flow of natural water into the dry channel and length of the dry channels reduce the probability. These results point out potential cost savings for improving biodiversity in dry channels at hydropower plants by targeting water releases from reservoirs.

A cost-effective restoration policy requires that restoration measures are directed toward locations with high biodiversity impacts (e.g., [17]). Admittedly, due to lack of data on the impact of restoration measures on biodiversity, our results can give only partial guidance on the cost-effective restoration of biodiversity loss by means of water releases from reservoirs. Despite this limitation, the results can be useful when considering that current Swedish policy is to a large extent based on uniform regulations for all hydropower plants, such a maximum loss of 2.3% in the annual production of electricity [18]. Our results show that the probability of costs in terms of losses in electricity production is low for relatively small-sized plants, and where the natural flow of waters to the dry channels is high and the length of the channels is large. Thus, a comparison of costs and effects of current uniform policy with a policy targeting restoration measures toward plant sites with these characteristics can be of interest for economic analysis.

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Appendix: Table A1 and Figure A1.

	Logelprod	Loglength	Logmsec	Mindisch	VIX
Logelprod	1				
Loglength	0.056	1			
Logmsec	0.279	−0.021	1		
Mindisch	−0.605	−0.013	−0.399	1	
VIX	−0.069	−0.031	−0.181	0.294	1

Table A1. Correlation matrix.

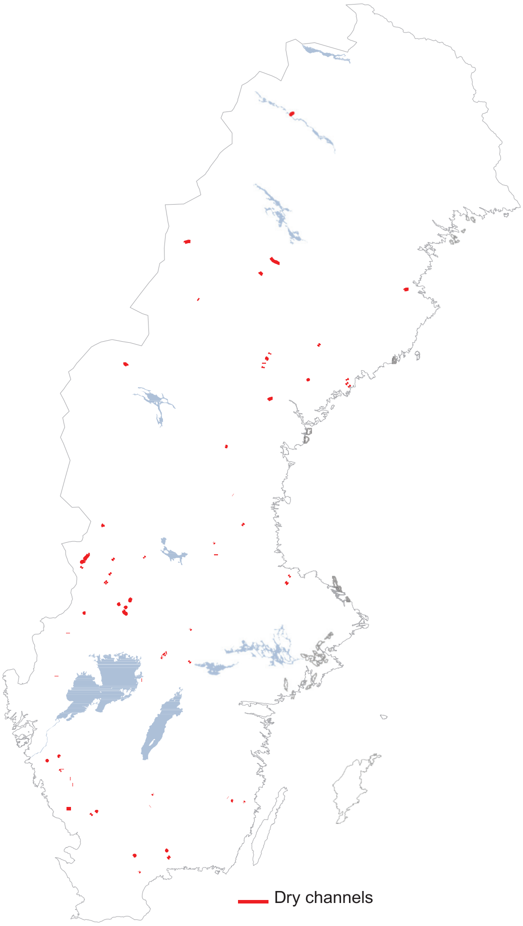

Figure A1. Locations of hydropower plants and dry channels included in the survey.

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