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Hydromorphological factors, stream power and fish habitat

Anders Foldvik, Line Sundt-Hansen, Peggy Zinke & Odd Terje Sandlund

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Hydromorphological factors, stream power and fish habitat

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SINTEF

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Summary

Foldvik, A., Sundt-Hansen, L., Zinke, P. & Sandlund, O.T. 2016. Hydromorphological factors, stream power and fish habitat. - NINA Kortrapport 2. 20 s. + annexes.

Here we report the first steps in an analysis of the potential correlation between specific stream power (SSP) and habitat quality in terms of shelter for juvenile salmonids in Norwegian rivers with anadromous salmonids. The background is that this possibly may be developed into a tool for the classification of ecological status under the EU Water Framework Directive in Norwegian salmon rivers, both rivers in a natural state and those impacted by hydropower regulation. It has previously been shown that the density of juvenile salmon is positively correlated with the amount and quality of shelter in the river substratum. The quality of shelter is influenced by the substratum particle size, which is shaped by erosion and sedimentation processes in the river on the background of, e.g., geology and topography in the catchment area. Based on field data from 12 Norwegian rivers with anadromous salmonids, we have analyzed the relationship between SSP and the measured amount of shelter for juvenile fish. In nine of the 12 rivers, there was, as expected, a weak positive correlation. A further development of this model requires more extensive data from a higher number of rivers, and improved quality of the topographic input data.

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Sammendrag

Foldvik, A., Sundt-Hansen, L., Zinke, P. & Sandlund, O.T. 2016. Hydromorfologiske factorer, strømningsenergi og fiskehabitat. - NINA Kortrapport 2. 20 s. + vedlegg

I denne rapporten har vi sett på sammenhengen mellom «specific stream power» (SSP, «strømningsenergi», svensk «flödesenergi») og skjul for laksefisk i norske elver. Utgangspunktet for denne tilnærmingen er at dette eventuelt kan utvikles til et verktøy som kan brukes i arbeidet med å gjennomføre vannforskriften for å klassifisere vannforekomster i rennende vann i både regulerte og uregulerte norske lakseelver. Det er dokumentert at tettheten av ungfisk av laks henger sammen med mengde og kvalitet på skjul i elvebunnen. Skjulmulighetene henger igjen sammen med partikkelstørrelsen i substratet, som formes av erosjons- og sedimentasjonsprosesser, gitt bl.a. de geologiske og topografiske forhold i nedbørfeltet. Basert på data for 12 norske lakseelver har vi gjennomført en analyse av SSP i forhold til målt mengde skjul for laksefisk. I ni av disse elvene var det som forventet en svak positiv sammenheng. En videre utvikling av denne modellen vil kreve tilgang på mer omfattende data fra flere elver og forbedret kvalitet på bl.a. topografiske data.

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Forord

I mars 2015 fikk NINA, i samarbeid med SINTEF Energi, tilskudd fra Miljødirektoratet til å fortsette arbeidet med å utvikle bedre metoder for klassifisering av vassdrag med hydromorfologiske endringer. I Norge har vi dokumentert en signifikant sammenheng mellom tettheten av ungfisk av laks og målt antall og mengde av hulrom (skjul) i elvesubstratet. I arbeidet med klassifisering av vannforekomster i elv har Sverige tatt i bruk det hydromorfologiske begrepet «flödesenergi» (stream power, eller strømningsenergi) som beskriver hvordan vannstrømmen i elva påvirker elveløpet. I denne rapporten beskriver vi hvordan forholdet mellom disse to parameterne arter seg i tolv norske elver der vi har skjulmålinger. Rapporten må betraktes som en framdriftsrapport i et langsiktig arbeid som nettopp har begynt. Rapporten er skrevet på engelsk med sikte på at dette arbeidet i det videre også vil skje i samarbeid med andre land som skal implementere EUs Vannrammedirektiv.

Trondheim, januar 2016
Odd Terje Sandlund
Prosjektleder

1 Introduction

Hydropower regulation of rivers normally changes the hydromorphological characteristics, which in turn affect the ecological conditions in the river. In most cases, this will change the amount or quality of available habitat for fish. Quantification of such ecological effects, where the impact of regulation may be gradual through changes in, e.g., the erosion-sedimentation processes, is data demanding. Adequate time series data on both the ecological and hydromorphological variables would normally be required.

Regulated rivers differ greatly in terms of the changes in annual discharge as well as the temporal discharge pattern. The extent to which this affects the hydromorphology, may vary in accordance with catchment properties such as; geological history, climate, anthropogenic impact, and river shape morphology such as gradient, sinuosity, catchment area, etc. (e.g. Vogel 2011). In relation to the Water Framework Directive (in Norway “vannforskriften”), the most important aspect is how, and to what extent the hydropower regulation has changed the ecological conditions as compared to the natural (or reference) condition. To our knowledge, there are no Norwegian time series of data recording changes in population parameters of fish in parallel with changes in hydromorphology resulting from hydropower regulation. Thus, some sort of a “space-for-time” approach seems necessary in order to analyse this issue.

In this report, we focus on a habitat measure that has previously been shown to be one of the most important habitat characteristics for juvenile Atlantic salmon, namely shelter availability (Finstad et al. 2007). The availability of shelter is an important aspect in the process to determine the spawning target (in Norwegian “gytebestandsmål”) of an anadromous river, and thereby also in the development of management goals, including the quality norm for wild salmon populations (Anon. 2013; 2014). Consequently, the structure of the riverbed (which determines shelter availability) is one of the most relevant hydromorphological parameters in relation to the ecological quality element fish.

The amount of shelter, i.e. the interstitial space within the substratum of the riverbed, is clearly dependent on the erosion-sedimentation processes in the river. If fine materials are deposited, the interstitial spaces in the substratum will be filled, and the amount of available shelter will decrease. Opposite, if fine sediments are removed by erosion, shelter availability may increase. Shelter availability is also influenced by the type of river substratum and sediments that are “available” in the catchment area upstream. The geological characteristics constitute the material acted on by the erosion-sedimentation processes created by the water current. It has been shown that the amount of shelter can be linked to the river substrate, and that it is negatively correlated with the proportion of finer sediment particles (the 5 and 10 percentiles, D_5 and D_{10}) of the grain size distribution on the riverbed (for particle diameters of less than 256 mm; Jocham 2010, Szabo-Meszaros 2015). This means that shelter availability is high when the bed substrate contains a low amount of fine sediments. Moreover, shelter may often be related to the degree of embeddedness, i.e. the portion of fine sediments which surrounds the larger substrate particles of a stream bed (Sauterleute 2011). The main influencing factors of inner embeddedness are concentration of suspended matter, intensity of the infiltration flux (hydraulic gradient), grain size distribution, discharge (bed shear stress) and water temperature (Schälchli 2002). Hydropower regulation can change the flow regime of rivers, and hence the erosion-sedimentation processes.

A modelling study for the Norwegian rivers Lundesokna and Nidelva by Szabo-Meszaros (2015) supported the hypothesis that at river reaches where erosion occurs, the gradation parameters of the substrate (e.g. D_5, D_{10}, D_{50}, D_{90}) increased in most cases. However, although river bed substrate characteristics is one of the key parameters for river water bodies according to the WFD, there is still a lack of sufficient substrate data for many Norwegian rivers.

Recent studies have shown that stream power, a parameter that can be readily obtained from digital data, can been used as an integrated parameter to describe the driving forces acting on channel shape and substrate and to determine the river´s capacity to transport sediment and perform geomorphic work (Bizzi & Lerner 2015). Stream power (Swedish: "flödesenergi") is also one of the key parameters used for the Swedish classification of hydro-morphology (HaVa 2013). The concept of stream power as the unit rate of energy dissipation against the bed and banks of a river or stream was proposed by Bagnold (1966). Dimensionless stream power is best suited to considerations of reach-scale response to imposed changes in sediment supply or formative discharge, or engineered changes in stream channel gradient (Eaton and Church 2011). It has been shown that quantifying zones of high unit stream power can greatly help in determining how best to manage river channels (Biron et al. 2013).

A previous study (Zinke et al. 2015) included the rivers Mandalselva and Strynselva and suggested that application of the stream power concept could be a promising approach for classification and assessment of hydro-morphological changes and its consequences for fish in Norwegian rivers. For Mandalselva, the results suggested that it could be possible to characterize physical habitat classes (“mesohabitats”) by characteristic ranges of stream power. For Strynselva, there seemed to be a reasonable correlation between both substrate, shelter and stream power. The latter correlation is further investigated in the present pilot study. The coupling of stream power and fish shelter availability would be relevant not only for assessment of ecological status and classification in relation to the Water Framework Directive, but also to the specific management goals for Norwegian wild salmon stocks. In applying the principles of environmental design of hydropower (Forseth & Harby 2013), knowledge about the relationship between stream power and shelter availability would also be relevant. This is to our knowledge the first study to investigate the correlation between SSP and shelter availability for salmonids.

In this analysis, we use a space-for-time approach to investigate the links between measured shelter availability and the locally estimated stream power in 12 rivers. Our hypothesis was that the amount of shelter would increase with stream power, and that this relationship would be influenced by local factors such as geology.

2 Methods

The feasibility of using SSP as a predictor of substrate and shelter in Norwegian rivers was explored by combining geographical data (from Norwegian Mapping Authority) and hydrological data (from Norwegian Water Resources and Energy Directorate) with substrate and shelter data (from NINA).

2.1 Shelter availability

Data on shelter availability were obtained from 12 rivers (**table 1**) previously sampled in connection with establishing biological reference points for Atlantic salmon populations in Norway. The rivers are located in all regions of the country (**figure 1**), and while five have been regulated for hydropower production, seven are, in this respect, in a natural condition.

Shelters were measured in three 0.25 m^2 squares at cross-sections along the rivers according to Finstad et al. (2007, 2009). Intervals between cross-sections varied from 25 m for the shortest rivers, and up to 300-600 m for the longest rivers. For all rivers, except the Rivers Orkla and Stjørdalselva, the entire anadromous stretch of the rivers was sampled. Shelters are measured using a 13 mm wide plastic tube, and are grouped into three classes based on shelter depth (class 1: 20-50mm, class 2: 50-100 mm and class 3:> 100 mm (Finstad et al. 2007)). These data on shelter availability were analyzed against estimated stream power in the same 12 rivers.

We were not able to test how shelter measurements based on three sampling points reflect the actual shelter availability in the river cross section. Moreover, the measurement of shelter is restricted to wadeable depths and currents, thereby excluding deep and high velocity areas of the rivers. Hence, uncertainties regarding characterization of shelter availability may affect the correlation between SSP and the amount of shelter in our analyses.

Figure 1. *The position of the 12 investigated rivers.*

2.2 Stream power

Total stream power (TSP) in W/m is defined as

$$TSP = \rho \cdot g \cdot Q \cdot S \qquad (1)$$

and specific stream power (SSP) in W/m^2 is defined as

$$SSP = \frac{\rho \cdot g \cdot Q \cdot S}{b} = \frac{TSP}{b} \qquad (2)$$

where ρ is the density of water (1000 kg/m^3), g is the gravity constant (9.81 m/s^2), Q is the reference discharge (m^3/s), b is the mean width (m) of the surface water at reference discharge and S is an approximation of the channel slope.

TSP is a useful variable to predict channel dimension and pattern, and is a good indicator for channel pattern transitions and sediment budget analysis, i.e. to predict large scale channel classes (Eaton et al. 2010, Bizzi & Lerner 2015). SSP has been used for the quantification of stream channel stability assessment (Thorne et al. 2011) and as predictor of bedload transport (Eaton & Church 2011). It is an indicator of stability threshold (Bizzi & Lerner 2015).

In HaVa (2013), the mean discharge is used for Q, with the corresponding b. In geomorphological literature, however, the bank-full discharge corresponding to the median flood (index flood, approximately two-year return period) is usually preferred as reference discharge (with the corresponding bankfull width), because it is assumed to transport the largest proportion of the sediment load (e.g. Bizzi & Lerner 2015).

The following parameters were freely available as Geographical Information System (GIS)-files and were compiled for the entire river catchment:

- Digital elevation model (DEM), raster 10 x 10 m, from the Norwegian Mapping Authority (NMA)
- Catchment area information, vector data with attributes, from NVE
- Main river centerline, vector, from NVE
- River polygons, vector, from NMA
- Runoff information from NVE

The data were processed using GIS and overlaid with available habitat data (substrate, mesohabitat, shelter) from NINA. By creating points every 10 m along the main river centerline, elevation and habitat information were compiled along the river. At the same locations, lines crossing the river were created. By cutting these lines with the river polygon, the river width *b* was estimated, and this information was joined to the transect points. This river width represents approximately the bankfull width. Bankfull width corresponds often to the mean annual flood (MHQ) (Leopold et al. 1963), whereas the real wetted with for mean discharges (MQ) is expected to be lower. Therefore, we did not calculate SSP-values from the TSP-MQ-values.

The DEM-values for the rivers and lakes represent water surface elevations. The accuracy (standard deviation) of the DEM values ranges from 2-3 m to 4-6 m, depending on the quality of the database. The inaccuracies of the DEM may lead to a "noise" in the water surface elevations (which results in the impossible result of water appearing to run uphill) in longitudinal direction when the elevation values are extracted to the transect points.

The DEM allows the GIS-based derivation of second-order hydro-morphological information on the catchment scale, such as flow accumulation. The latter is the total number of cells draining to any given cell and can be transformed into the size of the catchment area (CAREA) belonging to a given point in the river. In order to deal with the imperfections of the DEM, a modified DEM with incised elevations along the river centerline was created (subtraction of 50 m). From this modified DEM, a flow direction raster and a flow accumulation raster was created using standard GIS procedures (D8 method). The slope (S) was found by using corrected elevation from the neighboring points and the known distance between them (10m).

Some issues and findings regarding the suitability of the existing NVE data were discussed in the previous project note (Zinke et al. 2015). The "main river" centre line of the NVE data set reflects the average course and does not follow the real flow direction for example in river reaches with two channels (**figure 2**). This leads to inconsistencies in the data of the water level elevations, with the need for corrections. In the present study, by working in a downstream direction, points showing an increase in elevation were set equal to the previous value upstream (resulting in gradient = 0).

Both the mean annual discharge MQ and a rough estimate of the mean annual flood MHQ (index flood, IF) were investigated as reference discharge Q for the calculation of stream power (Equations 1 and 2).

MHQ was estimated as function of the MQ using a regression function that was derived from the MQ and MHQ values of the available time series of the relevant rivers (**Figure 3, Table 1**).

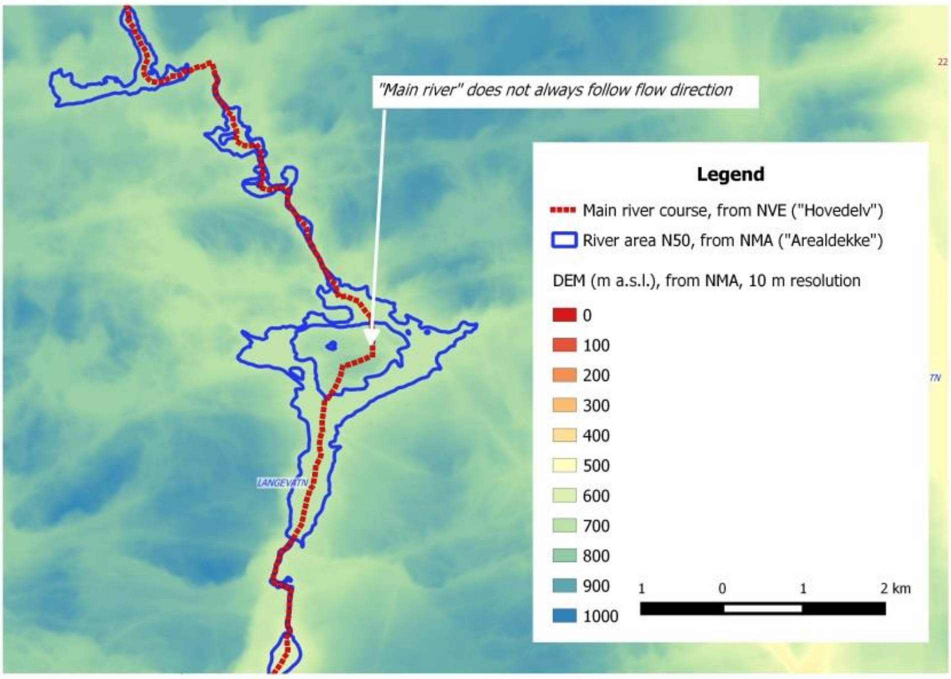

Figure 2. *Overlay of existing DEM, river area and main river course data, example detail for the Langevatn region at Mandalselva. From Zinke et al. (2015).*

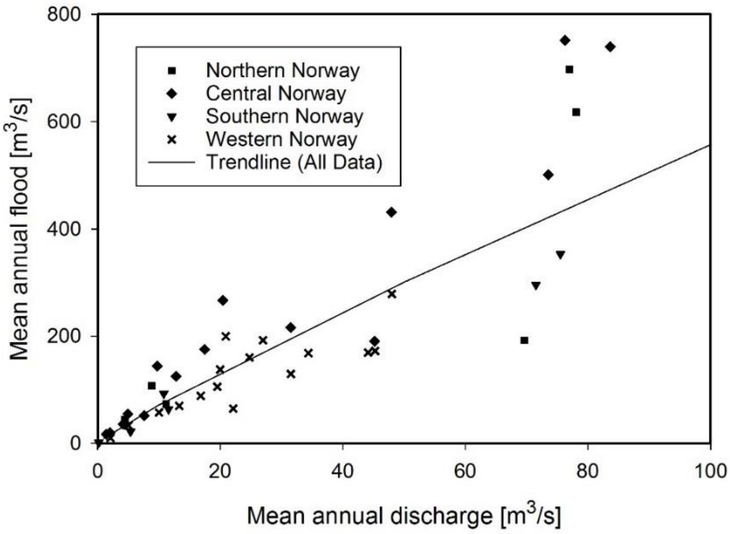

Figure 3*. Mean annual flood versus mean annual discharge for the measurement stations at the rivers of interest, based on time series from the NVE database.* $Y = 9{,}2586\,X^{0{,}8897}$ *(*$R^2 = 0{,}90$*)*

The distribution of the mean discharge MQ along the river (increase of Q depending on drainage area and tributaries) was calculated by multiplying the GIS-based catchment area of a river cross-section (CAREA) with a mean runoff value from the NVE REGINE database (1961-90). The calculated values represent unregulated conditions in the catchment area.

The plausibility of the results was assessed by comparing calculated discharges with measured discharges of the active NVE measurement stations along the rivers of interest (**figure 4**). The calculated mean discharge values represent the period 1961-90, while the mean measured values were calculated from the available time series (see Annex 1). There was a sufficient overall agreement for the mean flow values. Large discrepancies occurred only in regulated rivers, in particular Suldalslågen and Orkla (in minimum flow reaches). A similar comparison for the MHQ values shows relative large deviations (**figure 5**), indicating that the calculated TSP and SSP values for the index flood IF may be affected by relatively high uncertainties.

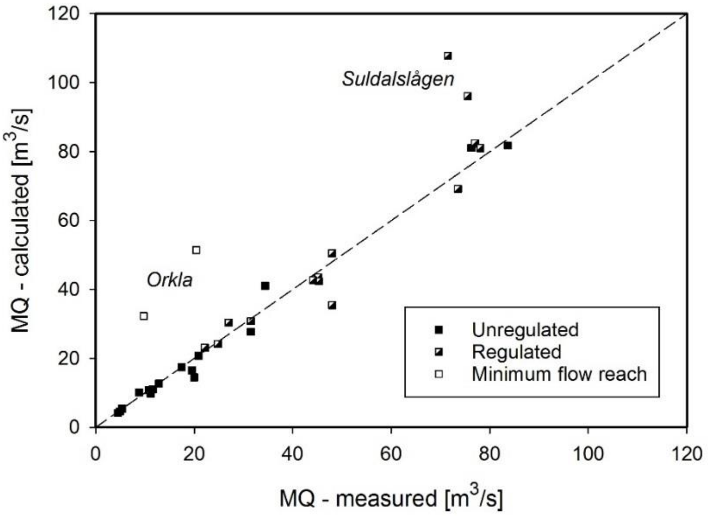

Figure 4. *Calculated versus measured mean annual discharge for the measurement stations at the rivers of interest, based on time series from the NVE database.*

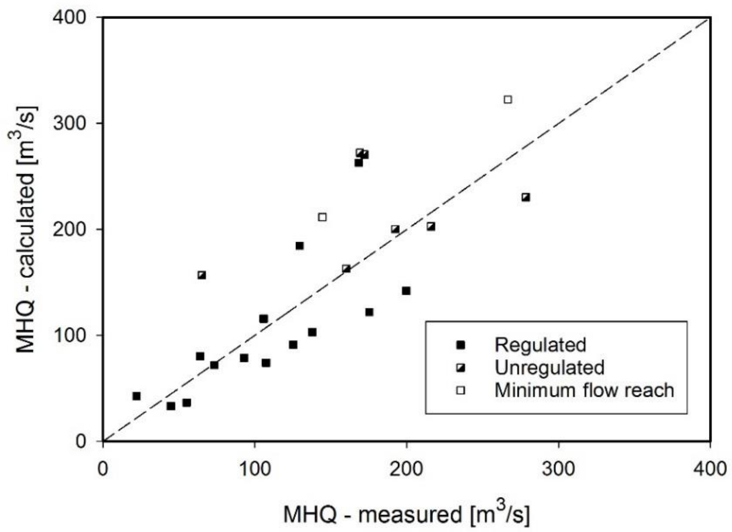

Figure 5. *Calculated versus measured mean annual flood for the measurement stations at the rivers of interest, based on time series from the NVE database.*

Total stream power TSP was calculated using the roughly estimated value of the index flood and a moving average of the channel gradient S of the modified DEM. The moving average was calculated over a reach scale distance D depending on the bankfull river width WF, with the following distances used for the assignment of TSP-WF values: i) WF < 10.01 m, D = 100 m; ii) WF = 10-25 m, D = 200 m; iii) WF = 25-75 m, D = 500m; iv) W > 75 m, D = 1000 m (cf. Bizzi and

Lerner 2015). Specific stream power SSP was obtained from the calculated TSP using equation 2 and is in the figures below indicated as SSPWF-IF.

2.3 Shelter vs. stream power

Shelter availability was modelled as a function of SSP and river using ANCOVA. Statistical analyses were conducted using the statistical software R, v. 2.14.2 (R Development Core Team 2012). The analyses give individual slopes and intercepts for all rivers. Both total number of shelters and a weighted sum of shelters were used in the analyses. Weighted sum of shelters is calculated as S1+S2*2+S3*3.

Values of SSP were appended to shelter measurements using QGIS (2.12.0-Lyon). SSP values ≤ 0 were omitted from the analysis, as these values in a majority of cases may have been due to the DEM inaccuracies (cf. **figure 2**) leaving a total of 572 shelter measurements.

3 Results

There was considerable variation in shelter availability and SSP both among and within rivers (table 1, figures 6 and 7). Average weighted shelter availability ranged from 2 for Stryn to 13 for Halselva, and the average unweighted shelter followed the same pattern as the weighted shelter. High SSP values were in general associated with small and steep rivers. The maximum SSP value in Stjørdalselva was lower than the average SSP values in Imsa, Halselva, Lærdalselva and Enningdalselva.

Table 1. *Values for weighted sum of shelters (WSH), number of shelters (NSH) and specific stream power (SSP) calculated for 12 Norwegian salmon rivers. Avg = mean value, min = minimum value, max = maximum value and sd = standard deviation.*

River*	WSH avg	WSH min	WSH max	WSH sd	NSH avg	NSH min	NSH max	NSH sd	SSP avg	SSP min	SSP max	SSP sd
ALT	8.6	0.0	27.0	6.6	5.1	0.0	14.3	3.5	125.9	6.8	656.6	118.1
ENN	3.4	0.0	10.0	3.7	1.7	0.0	5.0	1.7	423.0	22.6	2235.2	533.3
HAL	13.5	5.3	21.7	6.0	6.3	3.3	9.7	2.3	648.9	30.6	1159.1	371.0
IMS	6.0	0.0	18.7	6.8	2.8	0.0	8.0	2.9	733.7	129.5	1551.1	519.8
LAE	5.8	0.0	17.7	4.4	2.4	0.0	7.0	1.7	514.3	21.7	3115.8	614.8
LAU	3.9	0.0	14.7	3.7	2.0	0.0	7.0	1.8	121.2	0.9	444.5	120.9
NAU	2.8	0.0	16.7	3.5	1.2	0.0	5.7	1.3	121.0	3.8	950.6	162.9
ORK	4.3	0.0	14.3	3.7	2.1	0.0	6.0	1.5	192.0	5.7	1248.3	204.5
STJ	3.2	0.0	15.0	3.2	1.8	0.0	6.7	1.6	98.4	7.9	384.2	67.4
STO	8.6	1.3	16.7	3.6	4.1	1.0	7.0	1.5	309.3	22.1	868.1	173.0
STR	2.0	0.0	12.7	3.7	0.9	0.0	5.3	1.6	191.2	1.8	1093.9	280.6
SUL	5.4	0.0	18.3	5.1	3.0	0.0	9.0	2.6	360.5	7.8	2778.6	515.0
All	5.1	0.0	27.0	4.9	2.5	0.0	14.3	2.3	263.4	0.9	3115.8	381.6

*ALT: Alta; ENN: Enningdalselva; HAL: Halselva; IMS: Imsa; LAE: Lærdalselva; LAU: Laukhelle; NAU: Nausta; ORK: Orkla; STJ: Stjørdalselva; STO: Storåna, STR: Strynselva; SUL: Suldalslågen.

The results from the ANCOVA (R^2=0.27, F= 8.83, df=23 and 548, p= 2.2×10^{-16}) showed that for the majority of rivers there was a positive relationship between SSP and shelter availability, both as number of shelters (**figure 6**) and weighted shelter (**figure 7**).

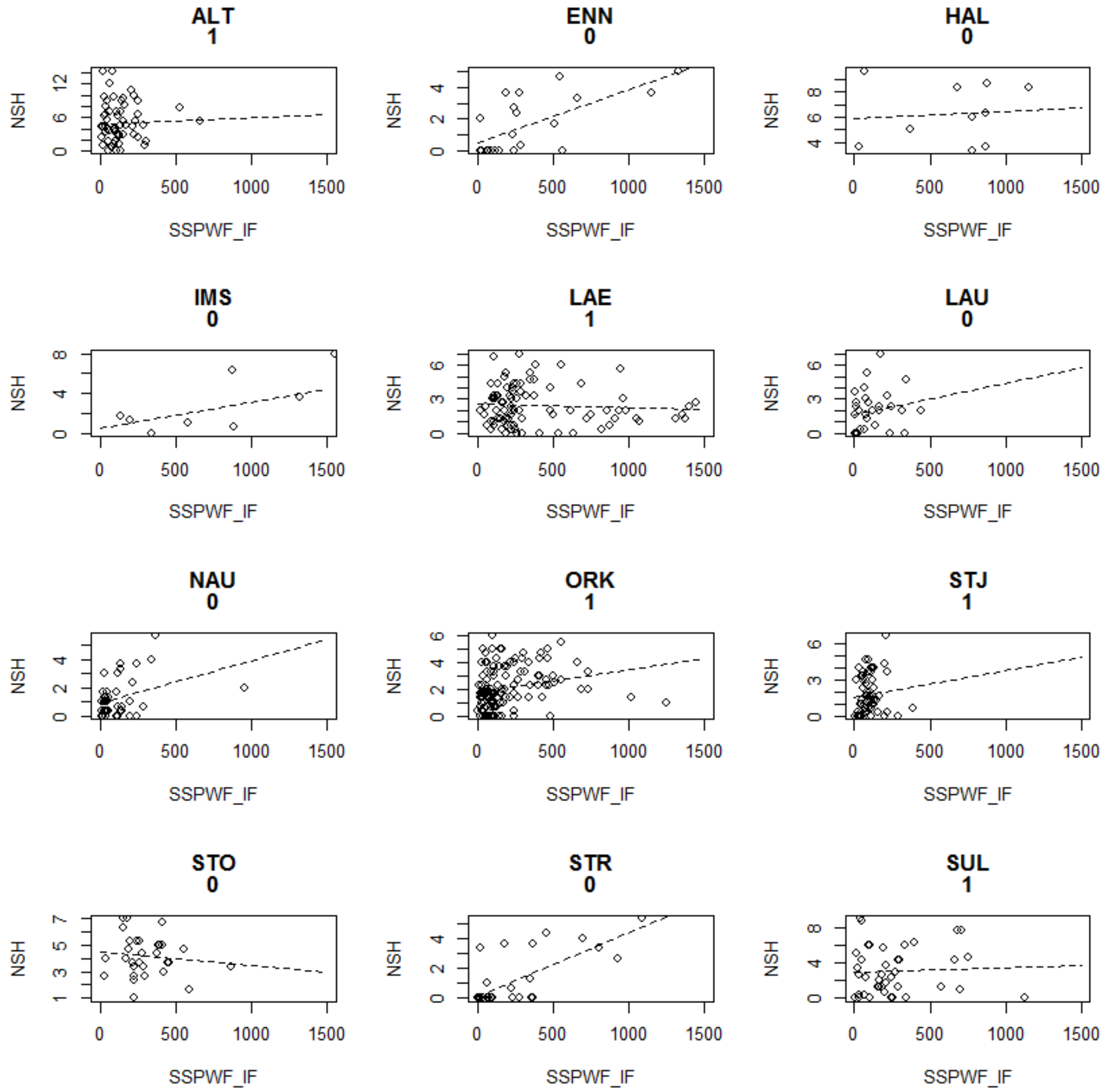

Figure 6. *Specific stream power (SSPWF_IF, in W/m^2) vs. number of shelters in 12 Norwegian rivers with anadromous salmonids.*

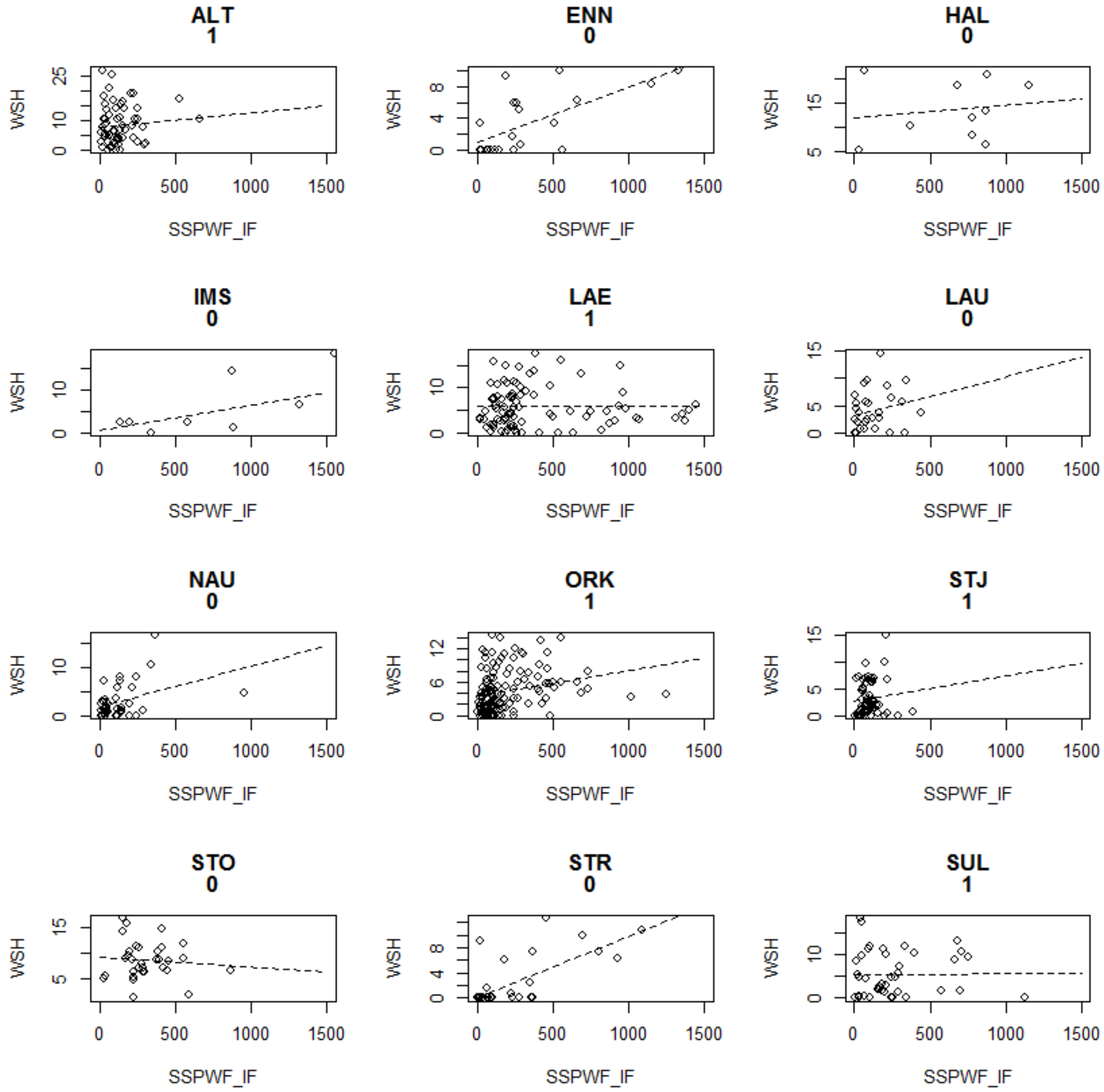

Figure 7. *Specific stream power (SSPWF_IF) vs. weighted quantity of shelters (WSH) in 12 Norwegian rivers with anadromous salmonids.*

4 Discussion

For most of the investigated rivers, the present study revealed a rather weak correlation between specific stream power and shelter. Among the rivers with the best positive correlations was Strynselva, which was analyzed in the previous study (Zinke et al. 2015).

There was a weak positive relationship between specific stream power (SSP) and density and weighted quantity of shelters for nine out of the twelve rivers. One unregulated river, Storåna, exhibited a negative relationship, whereas Lærdalselva and Suldalslågen, which are both regulated rivers, showed no trend in the amount of shelter versus stream power.

The correlations may be affected by the area of shelter measurements being relatively small compared to the area of the individual river section. The shelter data were collected for other purposes than the current study. A specific sampling design for this project would probably improve the suitability of the data in this analysis. In most cases, the number of measurements per section of estimated SSP is three or less. Thus, in some cases, the recorded shelter values may not be representative for the river sections. This could be tested by extending the number of measurements in one or two selected rivers, in order to investigate how many data points would be required to establish a reliable shelter index.

The reason why Storåna river showed a negative relationship between SSP and shelter availability, is likely a consequence of the available substrate in the river being extremely coarse (cf. annex 2). In Lærdalselva numerous weirs have been constructed, which may have influenced the substrate dynamics. Equally important in this context is that weirs would also create many abrupt changes in elevation precluding correct calculation of SSP. Suldalslågen is characterized by extensive aquatic vegetation, i.e. a relatively dense layer of aquatic mosses (cf. annex 2). The development of moss cover on the substratum reflects reduced erosion, as the mosses require stability to be able to develop and grow. The moss cover subsequently cause an increasing sedimentation rate, enhancing the clogging of interstitial space in the substratum (i.e. reduced shelter).

In this study, we have used only digital data that was readily available and could be processed within the scope of the project and the budget. The accuracy of the SSP calculation could be highly improved if a better digital elevation model and a corrected data set for the main river course (following the thalweg or center lines of the river branches instead of the main river course) would be available. Further, the relationship between MQ and MHQ which was used in this study is a very rough estimate. More accurate estimates of the index flood and the respective TSP and SSP values can be produced when a number of catchment characteristics are included, such as lake percentage, snow mountain percentage, mean annual rainfall etc., by using available regional regression functions (Wilson et al. 2011). The approach could likely be further refined by including the relative difference between the river area of interest and the river area upstream. This type of spatial ΔSSP would likely predict sedimentation-erosion processes better than SSP alone (Gartner et al. 2015).

The observed weak correlations between shelter and SSP for most of the investigated rivers indicate that one has to look more deeply into the complex relationships between stream power, river morphology and substrate (since the latter can be directly correlated to shelter). International literature suggests that SSP and TSP are useful parameters to predict channel dimension and patterns (Eaton et al. 2010, Bizzi & Lerner 2015). The respective river types could be related to the physical habitat requirements of fish, and possibly also to the amount of fine sediments in the substrate. It is known that highly dynamic streams and rivers with a variety of morphological structures (pools, runs, riffles, boulders, gravel banks, etc.) and varying current conditions show less inner embeddedness or have reaches without embedded substrate (Schälchli 2002).

This study admittedly includes too few rivers to establish a model for SSP vs. shelter, which could be applied as a tool of general value. Thus, recording of shelter conditions in more rivers would be useful. This approach could also be developed further by estimating SSP based on historic pre-regulation discharges in regulated rivers. By establishing a reference condition for

SSP for each river, we may be able to assess the impact of reduced water discharge on habitat quality for fish.

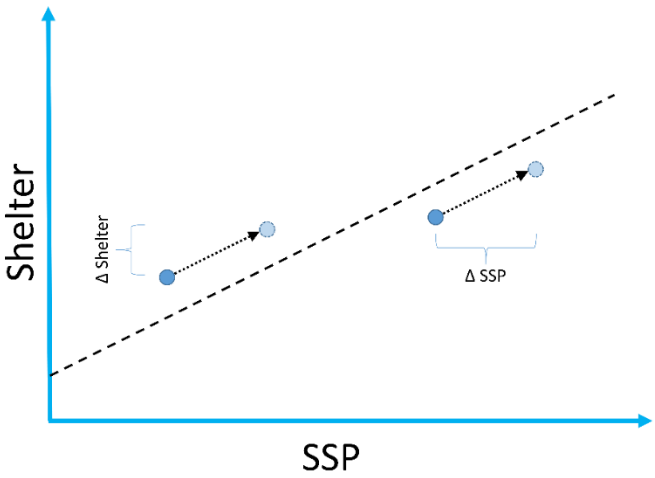

Figure 8. *Illustration showing a simple conceptual model for how an established relationship between SSP and shelter could be used to predict the change in shelter (Δ Shelter) for a given change in SSP (Δ SSP).*

Figure 8 illustrates the simple conceptual model laying behind the hypothesis of this pilot study. The results show that several factors affect the correlation between shelter and SSP, modifying the simple conceptual model presented in **figure 8**. For instance, it seems likely that the amount of shelter will increase with increasing stream power only to a certain level. Under some conditions, extremely high SSP may be reflected in a riverbed consisting only of boulders and bedrock, which provide poor shelter for juvenile salmonids. Moreover, regulated rivers differ greatly in terms of the changes in annual discharge as well as the temporal discharge pattern. The extent to which this affects the hydromorphology, including the river substratum, may vary according to catchment properties such as geological history, climate, anthropogenic impact, and river characteristics such as gradient, sinuosity, catchment area, etc. (e.g. Vogel 2011). These catchment characteristics influence sediment supply, which is essential in shaping fish shelter in the substratum.

Hydropower regulation can also affect formation of ice cover in rivers. Events where ice cover breaks up and move downstream can be dramatic events in terms of scouring of the riverbed and erosion-deposition processes.

The effect of the predicted change in shelter from pre to post regulation could be assessed using the existing classification system devised for Atlantic salmon. This may assist in the classification of ecological status in regulated rivers, and ultimately provide a basis for deciding on compensation measures in cases where the discrepancy from the reference conditions is too large.

By way of conclusion, we believe that SSP is a useful parameter in analyzing the status of rivers as habitat for fish, and consequently for the classification of ecological status according to the WFD. However, this concept needs further development, by inclusion of better input data and the investigation of possible links between hydromorphological river types and shelter, as described above.

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Annex 1 NVE hydrological stations

NVE measurement stations and time series

River	Station	Time series
Altaelva	212.11	1971-2015
Altaelva	212.9	1991-2014
Eibyelva	212.27	2007-2015
Halselva	212.49	1920-2015
Laukhelle	194.4	1925-2014
Stjørdalselva	124.12	1963-2014
Stjørdalselva	124.16	1994-2014
Gaula	122.2	1908-2014
Gaula	122.9	1958-2014
Gaula	122.11	1941-2014
Bua	122.14	1963-2014
Sokna	122.17	1972-2014
Orkla	121.22	1912-2014
Orkla	121.23	1990-2014
Orkla	121.39	2007-2014
Surna	112.27	1986-2014
Storåna	27.16	1984-2014
Imsa	29.60	1975-1998
Suldalslågen	36.6	1962-2014
Suldalslågen	36.11	1904-2014
Strynsvassdraget	88.11	1902-2014
Hornindalsvassdraget	89.1	1900-2014
Nausta	84.11	1963-2014
Jølstra	84.21	1993-2014
Jølstra	84.32	1999-2014
Gaularvassdraget	83.2	1902-2014
Lærdalselvi	73.2	1987-2014
Lærdalselvi	73.4	1961-2014
Flåmselvi	72.5	1944-2014
Aurlandsvassdraget	72.7	1908-1980
Nærøydalselvi	71.1	1908-2014
Enningdalselva	1046.3075	1980-2008

Annex 2 Photos of some of the investigated rivers

(Source, except when otherwise stated: www.Norgeibilder.no, accessed January 2016)

Enningdalselva

Suldalslågen substrat

Photo: Randi Saksgård, NINA

Suldalslågen øvre

Suldalslågen nedre

Stjørdalselva øvre

Stjørdalselva nedre

Laukhella øvre

Laukhella nedre

Nausta øvre

Nausta nedre

Strynselva øvre

Strynselva nedre

Orkla nedre

Alta nedre

Halselva øvre

Storåna

Imsa

Lærdalselva

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