A Method for Assessment of Sub-Daily Flow Alterations Using Wavelet Analysis for Regulated Rivers

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Abstract New tools are needed to evaluate the impacts of short-term hydropower regulation practices on downstream river systems and to progress towards sustainable river-flow management. As hydropower is increasingly being used to balance the energy load deficit caused by other less flexible sources, sub-daily flow conditions across many regulated river (RR) systems are changing. To address this, we used wavelet analyses to quantify the discharge variability in RRs and categorized the level of variability based on the conditions in natural free-flowing rivers. The presented framework used the definition of fluvial connectivity (Grill et al., 2019) to identify free-flowing rivers used in the study. We tested the developed framework in 12 different RR systems in Finland and found higher overall averaged subdail variation, with up to 20 times larger variability than natural conditions. A large, highly regulated Finnish river system was found to have the highest sub-daily variations in winter, while smaller RRs with lower levels of regulation had the highest variations in summer. The proposed framework offers a novel tool for sustainable river management and can be easily applied to various rivers and regions globally. It had flexibility to analyze sub-daily variations in desired seasonal or other ecologically sensitive periods.

1. Introduction

There is a global consensus around meeting the United Nations Sustainable Development Goals (SDGs), one of which is to "protect and restore water-related ecosystems" under SDGs (target 6.6). Rising energy demand has increased the number of dams being constructed worldwide for a seemingly flexible and low-carbon emitting power source. Hydropower provides the grid flexibility needed to achieve high penetration of wind and solar energy, compensating for the intermittency of these sources (Clack et al., 2017; Denholm & Hand, 2011). There are more than 3,700 hydropower dams (>1 MW) currently planned or under construction worldwide (Zarfl et al., 2015). According to the 2018 hydropower status report by the international hydropower association (International Hydropower Association, 2018), growth in hydroelectric generating capacity was fastest in East Asia and the Pacific, with 9.8 GW of capacity added in 2017. China, Brazil, and India together added around 16 GW of the installed capacity in 2017. Ecologically sensitive regions like Amazon and the Himalayas are also observing an increasing trend of significant hydropower construction (Winemiller et al., 2016), and currently, only 1/3rd of large global rivers as classified as free-flowing (Grill et al., 2019).

Streamflow regulation, intended for hydropower generation purposes, causes river flow alteration from the natural flow state by changing monthly, seasonal, and sub-daily flow patterns of RRs (Ashraf et al., 2018; 2016) and adversely affects the ecological state of rivers (Dynesius & Nilsson, 1994; Mustonen et al., 2016; Nilsson et al., 1993; Poff et al., 2007). High sub-daily flow variability is the result of higher electricity prices during peak demand periods, which induces more generation during peak demand periods, resulting in more water being released through turbines during peak hours of electricity/power demand and less to no water during low-demand hours.

Negative impacts of hydropicensing on downstream ecosystems are well documented. These include the direct impact on aquatic organisms (Casas-Mulet et al., 2016; Harnish et al., 2014), degradation of fish habitat (Garcia et al., 2011), alteration of the hyporheic habitat (Cristina Bruno et al., 2010), river thermal regime (Choi et al., 2018; Maheu et al., 2016; Zolezzi et al., 2011) and recreational value (Brown et al., 1999; Brunson & Shelby, 1993; Carolli et al., 2017; Rossel & de la Fuente, 2015; Teigland, 1999). Ecosystem services provided by rivers and lakes may also be affected by sudden changes in sub-daily river flows (Carolli et al., 2017). To manage
these challenges connected to hydropeaking and find optimal mitigation measures, it is first essential to assess sub-daily variation with robust methods.

During the last two decades, river management policies and practices have typically accepted pre-dam or unregulated river flow regime as reference condition of river flow dynamics (Poff et al., 1997). A natural flow regime is increasingly proposed as a benchmark for ecologically sustainable flow releases from dams and has influenced conditions imposed on new dam licenses (Jager & Bevelhimer, 2007). But how to identify rivers with natural flow regimes? Prior definitions of ‘unimpounded’ or ‘unregulated’ rivers (Nilsson et al., 2005; Palmer et al., 2008) apply well to assess the changes from a purely hydrological perspective, but they may miss other aspects of natural river systems. In a recent study, Grill et al. (2019) defined FFRs as “rivers where ecosystem functions and services are largely unaffected by changes to the fluvial connectivity, allowing unobstructed movement and exchange of water, energy, material and species within the river system and with surrounding landscapes”, setting a more comprehensive benchmark for evaluating RRs. Such a benchmark helps in quantifying the temporal alteration introduced in river flow due to any anthropogenic activity, for example, hydropeaking induced alterations. However, it can also be also useful to check for cases where a time-varying water abstraction may be significant.

Numerous hydrologic indices have been developed to characterize natural and human-impacted flow regimes using daily or monthly average flow data (Poff & Zimmerman, 2010; Torabi Haghigi & Kløve, 2013; Vanzo et al., 2016). During the last decade, the analysis of river regime alteration at subdaily time step has also gained attention (Bejarano, Sordo-Ward, Alonso, Jansson, & Nilsson, 2020; Carolli et al., 2015). High-frequency, non-stationary temporal flow patterns are particularly prominent in rivers subjected to hydropeaking reservoir operations, where rapid fluctuations are typically present at sub-daily to daily scales (Bevelhimer et al., 2015; Meile et al., 2011; Zimmerman et al., 2010). The proposed hydrologic parameters and indices to quantify hydropeaking (Carolli et al., 2015; Meile et al., 2011) cover various hydrologic regime parameters but do not capture all scales representing hourly to yearly fluctuations in regulated flows. Moreover, these methodologies also neglect the differences between inter-seasonal sub-daily flow variations levels and, often choose an annual threshold to measure the hydropeaking against and not a seasonal one.

Continuous wavelet transform (CWT) is an effective tool to analyze non-stationary time series. Unlike Fourier transform (FT), which assumes stationarity when decomposing a signal into its inherent frequencies, CWT unfolds a time series not only in frequency but also in time (Percival & Walden, 2000). Continuous wavelet transform provides information on frequencies present in a signal while still maintaining a localisation in time and thus, offers a means to display intermittent temporal patterns in the time series. Wavelet analysis has been widely applied across many research areas since its introduction in the early 1980s (see, e.g., Percival & Walden, 2000). More recently, it has also been used to analyze variability at multiple temporal scales in both hydrologic time series (Shiau & Wu, 2013; Steel & Lange, 2007; Wu et al., 2015; Zolezzi et al., 2009) and in the chemical response due to variability in hydroclimatic forcing factors and chemical loading (Guan et al., 2011; Riml et al., 2019; Yan et al., 2017). The critical feature of wavelets (compared to other spectral methods) is that it provides localisation in time, that is, that non-stationary processes can be analyzed. This is useful when analyzing the effects of market-driven hydropower production. Several studies, for example, (Wu et al., 2015), (Shiau & Wu, 2013), and (Zolezzi et al., 2009) have utilized wavelet transforms for assessing flow regime alterations in different river systems. However, a common framework that evaluates the flow alterations against FFRs and thus categorizes the anthropogenic flow variations is still lacking, particularly in the context of sub-daily variation caused by hydropeaking.

The general objective of this study was to develop a framework to quantify and characterize sub-daily flow variation levels in RRs; hence the presented framework utilizes discharge data from FFRs as a reference to categorize sub-daily variation levels in RRs. This is, to our knowledge, the first methodology that, instead of just choosing an unregulated river for reference, utilizes FFRs based on the integrated connectivity status index (CSI) of Grill et al. (2019) to set a reference river flow condition to quantify and characterize hydropeaking in terms of sub-daily flow variation levels. The aims of the paper are to (a) estimate reference river flow dynamics in natural rivers using the CSI index, (b) to develop a framework to compare sub-daily flow variability in natural and RRs, and (c) to quantify annual and seasonal hydropeaking in a large number of case studies from Finland, a region that is relatively poorly represented in hydropeaking studies.
1.1. River Systems Selected for Analysis

For our analysis, we selected 12 RRs and 24 FFRs in Finland (Figure 1). We analyzed hourly discharge data from January 2010 to December 2020 from each river system. We selected regulated gauging stations to represent river system of varying sizes (ranging from mean annual flow of 515 m$^3$ s$^{-1}$ (Taivalkoski) down to 38 m$^3$ s$^{-1}$ (Skatila) (Table 1)) and represent high to low levels of regulation. The Taivalkoski gage on the Kemijoki river is downstream of 20 run-of-the-river hydropower stations, thus it represents a highly RR with high seasonal snowmelt pulses. The river system is heavily modified by 21 hydropower plants producing over 4.3 terawatt-hours (accounting for over a third of hydropower production in Finland). The Skatila River is a medium-size (mean 38 m$^3$ s$^{-1}$) low land river system in Finland in the west coast region at Bothnian bay. Naturally, the low land profile and small catchment storage of Skatila creates a flashy hydrograph that influence the regulation possibilities. The Lieksanjoki River represents the naturally regulated conditions of a river flowing between two large lakes (mean
107 m³ s⁻¹), which provide storage and a stable inflow year-round to the river system, typical for the lake district in southeast Finland and other lake-rich areas in the boreal region.

The geographical coverage of the chosen gauging stations representing FFRs comprises the entire country of Finland and are on river systems of varying size (mean annual flow ranging from 140 m³ s⁻¹ down to 4.6 m³ s⁻¹) for example, Ounasjoki at Marraskoski (mean flow 140 m³ s⁻¹), Kiiminjoki at Haukipudas (43 m³ s⁻¹), Nokisenkoski at Niinivesi (40 m³ s⁻¹) and Uskelanjoki at Kaukolankoski (4.6 m³ s⁻¹) covering reference-free flow conditions for different sizes, catchment geomorphology, and geographical locations.

### Table 1

| River system | Gauging station | Mean discharge (m³ s⁻¹) | Catchment area (km²) | Coordinates | Head (m) | Annual energy (GWh) | Gauging station location in catchment |
|--------------|-----------------|-------------------------|----------------------|-------------|-----------|---------------------|---------------------------------------|
| Inhanjoki    | Hankavesi, Inha | 8.6                     | 863                  | 6934635 N   | 352057 E  | 6.3                 | 3.1 MID                               |
| Kalajoki     | Hamari          | 7                       | 4,247                | 7107681 N   | 381936 E  | 6.4                 | 2.5 MID                               |
| Karvianjoki  | Vatakianskoski  | 10.8                    | 1,004                | 6875136 N   | 250212 E  | NA                  | 2.5 MID                               |
| Kemijoki     | Porttipahta     | 54                      | 4,867                | 7538730 N   | 489352 E  | 30                  | 100 UP                                |
| Kemijoki     | Taivalkoski     | 515                     | 51140                | 7302096 N   | 3387906 E | 15                  | 536 DOWN                              |
| Kymijoki     | Kannuskoski     | 6                       | 845                  | 6758924 N   | 513225 E  | 4.6                 | 1 DOWN                                |
| Kyröunjoki   | Skatila         | 38                      | 4,833                | 7009060 N   | 3241957 E | 42                  | 25 DOWN                               |
| Lapuanjoki   | Hirvikoski      | 4.7                     | 716                  | 6719831 N   | 480609 E  | 2.59                | 4.75 MID                              |
| Lestijoki    | Saarenpää       | 11.8                    | 1,371                | 7099504 N   | 341537 E  | 17.5                | 4.9 DOWN                              |
| Lieskansjoki | Lieskansjoki    | 74                      | 8,069                | 7026588 N   | 652025 E  | 10.8                | 76 MID                                |
| Ollkalanjoki | Ollkalanjoki    | 3                       | 268                  | 6703889 N   | 354349 E  | 1                   | NA UP                                 |
| Tohmajoki    | Kontturi        | 3                       | 402                  | 6876149 N   | 673968 E  | NA                  | NA DOWN                               |

2. Methodology

#### 2.1. Categorizing River Flow Status

Free flowing rivers for the study were selected based on an integrated CSI given by Grill et al. (2019) that quantifies the river connectivity ranging from 0% to 100% based on a set of weighted criteria. Grill et al. (2019) suggested that the CSI for a specific river reach is influenced by five major pressure factors that impact river connectivity: (a) river fragmentation, (b) flow regulation, (c) sediment trapping, (d) water consumption (surface or groundwater abstractions), and (e) infrastructure development in riparian and floodplain areas. The following six proxy indicators subsequently quantified these five pressure factors: (a) Degree of Fragmentation (DOF), (b) Degree of Regulation (DOR), (c) Sediment trapping index (SED), (d) Consumptive water use (USE), (e) Road density (RDD), and (f) Urban areas (URB). Following the work of Grill et al. (2019) we calculated the CSI for every river reach by producing a weighted average of the six individual pressure indicators, each defined within a range of 0%–100%, and to subtract it from the maximum of 100%:

\[
\text{CSI}_j = 100 - \frac{\sum_{i=1}^{n} x_{i,j} w_i}{\sum_{i=1}^{n} w_i}
\]

where CSIₗ is the CSI at river reach j, xᵢ,ₗ is the value of pressure indicator i at reach j, wᵢ is the weight applied to the pressure indicator i and n is the number of pressure indicators (in our case, (f)). They prescribed the sum of wᵢ to be 100%; hence the resulting CSI values can range from 0% (not connected) to 100% (fully connected). Rivers with CSI ≥ 95% over their entire length from source to river outlet were defined as FFRs. Readers are referred to Grill et al. (2019) for a more detailed explanation of CSI, FFRs, and sizes of globally mapped FFRs.
2.2. Wavelet Analysis of Hydrologic Time Series

As river flow data are typically noisy, irregular, and non-stationary, wavelet analysis can be used to characterize periodicities at different temporal scales and at different locations in time. The wavelet function is stretched by varying its scale to reveal how periodic components of the time series change over time (Daubechies, 1992). Following is a brief outline of the CWT procedure. For more in-depth description of the method, see Torrence and Compo (1998). We have used the Morlet wavelet as the wavelet base function since it is the preferred choice for streamflow data (Shiau & Wu, 2013; Steel & Lange, 2007; Wu et al., 2015; Zolezzi et al., 2009). The Morlet wavelet function, $\Psi_0(\eta)$, is mathematically expressed as:

$$\Psi_0(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2}$$

(2)

where $\eta = \left(\frac{t - \tau}{\delta t}\right)$ is a non-dimensional time parameter, $\omega_0 = 6$ is the non-dimensional frequency parameter (i.e., the number of oscillations within the wavelet which satisfies the admissibility condition) and provides a good balance between the time and frequency localisation (Farge, 1992; Wu et al., 2015; Zolezzi et al., 2009). In the former, $s$ is the wavelet scale (i.e., its duration), $n'$ denotes the time step, and $n$ is a localized time index. The CWT $W_s(n)$ of a discrete-time series $x_n$ for $n = 0 \ldots N - 1$, at a temporal scale $s$ with equal time spacing $\delta t$, will be the convolution of $x_n$ with a scaled and translated version of $\Psi_0(\eta)$.

$$W_s(n) = \sum_{n' = 0}^{N-1} x_{n'} \Psi^* \left( \frac{(n' - n)\delta t}{s} \right)$$

(3)

where $N = \text{length of time series}$ where, $\Psi^* =$ complex conjugate of $\Psi$, $\delta t = \text{data sampling interval}$. To approximate the CWT, convolutions are performed in the Fourier space using a discrete Fourier transform. The wavelet function $\Psi$ is obtained by normalizing with $\Psi_0(\eta)$. Finally, the wavelet power spectrum (WPS) can be defined as:

$$\text{WPS}_n(s) = |W_s(n)|^2$$

(4)

where, $|W_s(n)|^2$ is the wavelet power at time $n$ and scale $s$.

The reported WPS values in this study are unitless because of data normalization, which helps to compare wavelet power between hydrographs from rivers of different sizes. The statistical package made for R programming language (WaveletComp) standardizes the time series

2.3. Formulation of the Threshold-Based Index to Categorize Sub-Daily Flow Variation Levels

The index is based on comparing averaged power spectrum between the RR and FFR groups. We used the wavelet power at a given period averaged across time to assess the spectral differences at sub-daily scales between regulated and free-flowing rivers. The sub-daily flow variations were characterized based on a temporally averaged WPS$_n(s)$ of flow referred to as the global wavelet power spectrum (GWPS) defined as:

$$\text{GWPS}(s) = \frac{1}{N} \sum_{n=0}^{N-1} \text{WPS}_n(s)$$

(5)

The averaged WPS at a given period can be used to quantify variations in a hydrograph (Figure 2). In this study, we have calculated the GWPS of sub-daily time scales based on observed discharge data from RRs and FFRs to estimate deviation in the flow variability of RRs from those at FFRs.

For the first part of the analysis, we categorized the sub-daily variations of the RRs by comparing them with sub-daily variations at FFRs. Average of GWPS (Equation 5) at each of the 24 FFRs was averaged for the entire study period (AGWPS). This collective AGWPS distribution of 24 FFRs was assessed statistically using Equation 6 (Tukey, 1977) to set the natural variability threshold. An index was then formed, which measures the level of sub-daily variation in multiples of the reference levels found in FFRs (Figure 3).

$$\text{NVL} = P_{75}(\text{AGWPS}) + 1.5(P_{75} - P_{25})(\text{AGWPS})$$

(6)
Here, NVL is the natural sub-daily variation level threshold shown in Figure 3 as panel b. AGWPS is the average GWPS for the entire period of the available free flowing data, $P_{25}$ and $P_{75}$ are the 25th and 75th percentiles of the AGWPS values. Other sections of the final scale (Figure 3c) are $1 \times$ NVL, $2 \times$ NVL $4 \times$ NVL...$>20 \times$ NVL. Hence, the ‘Natural variation levels’ section of the index (Figure 3c) comprises all of the AGWPS values equal to or less than the NVL threshold value calculated from all the unregulated gauging stations in Equation 6.

For the second part of the analysis, we did a more detailed seasonal assessment of the sub-daily flow variability. Here, we calculated each season’s seasonal sub-daily variation threshold from AGWPS of all FFRs (Equation 7).

$NVL_{S} = P_{25}(AGWPS)_{S} + 1.5(P_{75} - P_{25})(AGWPS)_{S}$

Here, $NVL_{S}$ is the natural sub-daily variation threshold of a particular season, $(AGWPS)_{S}$ is the average GWPS of that particular season for the entire period of the available free flowing data. Overall AGWPS values are attached as Supporting Information S1 and seasonal AGWPS values are presented in Table 2. NVL can be intuitively understood as a limit above which the subdaily flow fluctuations are unnaturally high and hence cannot be considered representative of free-flowing rivers. The source of these variations could be any non-damming

Figure 2. (a) Hydrograph from regulated rivers system and (b) its wavelet transform and (c) corresponding global wavelet power spectrum values at multiple temporal scales.
anthropogenic activity, for example, a high percentage of an urban area or even high frequency flow measurement errors. AGWPS can be understood as an average measure of sub daily fluctuation intensity for a specific period. The months of December, January, February and March constituted the Winter season, April and May as Spring, June, July and August as Summer and finally September, October and November as Autumn. These selected seasons represent seasons in the Northern European boreal region and should be changed if the methodology is further applied to other regions or climate zones. To set the threshold limit, we have to use as many free flowing samples as possible that roughly represent the flow dynamics of all types of rivers in the entire study area. In cases where a large data set of FFRs is not available, an ideal free flowing counterpart must be present to apply the method. A direct comparison can be made between AGWPS of a RR with its free flowing counterpart, which flows in the same area with comparable topographical, land use, meteorological and climatic conditions.

3. Results
3.1. Assessing and Characterizing Annual Hydropeaking in Terms of Free Flowing Rivers Sub-Daily Variations

Among the FFRs the highest AGWPS value was 0.023 at Kivijärvi and lowest 0.0002 at Oulankajoki (Figure 4). Sub-Daily AGWPS values from the selected regulated gauging stations varied between 0.89 and 0.00029 (Table S1 in the Supporting Information S1) having high variation power levels at different periods. Porttipahta showed the highest measure of sub-daily AGWPS followed by Taivalkoski and Lieksanjoki (Figure 5). Our RR sites contained different sizes of river systems and different regulation practices (Table 1), providing an opportunity to analyze a range of sub-daily variation patterns and providing a good testing ground for our method.

The use of wavelet analysis enabled simultaneous analysis of different flow variations in RR systems. Both Taivalkoski and Porttipahta displayed two high power variation patterns visible at a period of 0.5 and 1 day
Table 2
Seasonal Averaged for the Entire Study Period (AGWPS) Values From All the Studied Gauging Stations

| Station           | Spring 0.04 | Summer 0.05 | Autumn 0.02 | Winter 0.03 |
|-------------------|-------------|-------------|-------------|-------------|
| Alaköngäs        | 0.02        | 0.02        | 0.04        | 0.02        |
| Hamari           | 0.04        | 0.08        | 0.11        | 0.13        |
| Hankavesi        | 0.00        | 0.01        | 0.02        | 0.05        |
| Haukipudas       | 0.00        | 0.02        | 0.01        | 0.01        |
| Hirvikoski       | 0.01        | 0.01        | 0.01        | 0.01        |
| Inarijoki        | 0.01        | 0.02        | 0.01        | 0.01        |
| Ivalojoki        | 0.02        | 0.06        | 0.01        | 0.02        |
| Käenkoski        | 0.00        | 0.01        | 0.01        | 0.01        |
| Kannuskoski      | 0.07        | 0.30        | 0.19        | 0.18        |
| Kaukolanko       | 0.04        | 0.09        | 0.03        | 0.02        |
| Kivijärvi        | 0.04        | 0.06        | 0.02        | 0.22        |
| Konturi          | 0.01        | 0.02        | 0.01        | 0.00        |
| Lieksanjoki      | 0.59        | 0.06        | 0.07        | 0.14        |
| Lutto             | 0.01        | 0.02        | 0.02        | 0.03        |
| Muonionjoki      | 0.02        | 0.02        | 0.01        | 0.04        |
| Nuorittajoki     | 0.00        | 0.01        | 0.01        | 0.01        |
| Olkalanjoki      | 0.01        | 0.02        | 0.02        | 0.01        |
| Oulankajoki      | 0.00        | 0.05        | 0.02        | 0.08        |
| Ounasjoki        | 0.00        | 0.11        | 0.01        | 0.01        |
| Pello            | 0.03        | 0.02        | 0.01        | 0.02        |
| Porttipahta      | 0.59        | 1.40        | 1.39        | 1.36        |
| Rauanjoki        | 0.01        | 0.03        | 0.02        | 0.02        |
| Saarenpää        | 0.00        | 0.01        | 0.01        | 0.01        |
| Salmen silta     | 0.00        | 0.02        | 0.01        | 0.00        |
| Sägingjoki       | 0.00        | 0.01        | 0.01        | 0.01        |
| Simo             | 0.01        | 0.02        | 0.01        | 0.01        |
| Siuruanjoki      | 0.00        | 0.01        | 0.01        | 0.01        |
| Skatila          | 0.01        | 0.01        | 0.01        | 0.01        |
| Solojärvi        | 0.01        | 0.02        | 0.02        | 0.02        |
| Taasianjoki      | 0.01        | 0.02        | 0.01        | 0.01        |
| Taivaskoski      | 0.08        | 0.54        | 1.30        | 2.63        |
| Vakkola          | 0.01        | 0.01        | 0.01        | 0.01        |
| Varisvesi        | 0.02        | 0.03        | 0.01        | 0.01        |
| Vatajankoski     | 0.06        | 0.56        | 0.11        | 0.10        |
| Vekkoski         | 0.02        | 0.06        | 0.01        | 0.01        |
| Vuosijärvi       | 0.01        | 0.02        | 0.07        | 0.01        |

aFree Flowing Rivers (FFR). bSeasonal AGWPS Threshold Value.
scales using FFRs mapped by Grill et al. (2019) as reference river flow conditions. The methodology provides a clear procedure to assess subdaily flow alterations and opens hydropower regulation practices to analyze river flow variability at hourly to daily scales.

We have also incorporated the significant seasonal variations in hydropeaking levels by formulating separate threshold values for each season. In this application, we analyzed seasonal differences, but the method itself can be applied at any time period to be assessed. Even though the proposed methodology was tested in Northern European conditions in Finland, with gauging stations selected to represent a wide range of rivers across the country, the method can be easily applied to river systems globally. Also, by increasing the number of FFRs, a better representation of the range of natural variation can be included, thus providing a more accurate categorization of hydropeaking in a specific region. Another convenient characteristic of this approach is that the proposed index can also assess sub-daily flow variability (i.e., hydropeaking) at multiple time scales, for example, annual and seasonal, as demonstrated in Sections 3.1 and 3.2, allowing analysis of critical periods for ecosystems and services.

Three out of the 12 regulated stations displayed annual subdaily variation levels exceeding eight times the FFR threshold value. Due to the nature of runoff generation in the studied rivers (primarily snowmelt dominated) and small reservoir size, flow regulation is significantly constrained during the spring flood period. Hence, there were smaller subdaily variations (closer to natural levels) at all RRs in spring. Our analysis pointed out large hydropeaking levels, especially in the Kemijoki river system of Finland, used for load balancing in the Nordic energy markets. However, clear and visible sub-daily variation was seen in most of our selected RR sites. This

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**Figure 4.** (a) Wavelet transform with wavelet power levels (WPL) and Averaged for the entire study period (AGWPS) of Kivijärvi and (b) Oulankajoki. The graphs in right panels show the average wavelet power at specific time periods.
result is important because many of the examined river reaches (e.g., Taivalkoski, Kannuskoski and Kontturi) are accessible for salmon and trout. It has been shown that high sub-daily flow variability leads to sediment and macroinvertebrate scouring, unfavorable juvenile fish-rearing habitats and fish stranding (Fette et al., 2007; Halleraker et al., 2003; Korman & Campana, 2009; Scruton et al., 2008). Assessing seasonal hydropeaking is especially important during periods of ecological importance, such as salmonid egg incubation. Thus, elevated levels of sub-daily flow variability, for example, during pre-Summer to Summer (May–June) when many salmon species migrate to river channel or during Autumn (September-November) when salmons spawn, indicate possibilities for external stress factors on ecosystems or species during these ecologically critical periods. At Taivalkoski and Porttipahta, the levels of sub-daily variability were 10 times or greater than FFR threshold value for the winter season. Fish eggs that remain in the gravel on riverbeds throughout the winter are vulnerable to scour during sudden, unnatural flow variations due to hydropeaking.

The highest measure of sub-daily AGWPS was at Porttipahta (0.89) gauging station, located at an upstream reservoir of the same name on the Kemijoki river system. Taivalkoski, which is located in the same river system, had the second-highest value for sub-daily AGWPS (0.34). Taivalkoski has a height of only 15 meters, reservoir capacity of only 50 million m$^3$ (average annual discharge of 550 m$^3$ s$^{-1}$), and thus restricted possibilities for high-frequency regulation, high levels of overall annual sub-daily flow variations were observed. At other studied stations with small reservoir capacities, sub-daily AGWPS values were generally lower than 0.1. However, values at bigger RR sites were higher than natural FFR rivers.
Natural FFR river mainly showed minor sub-daily variation in flow conditions. The exception was Kaukolankoski, which showed considerably higher sub-daily variation levels than the other unregulated stations in the region. It could be because Kaukolankoski’s catchment consists of 41% agricultural area with a rapid runoff response compared to the other investigated FFRs (with <5% agricultural area). This highlights that the sub-daily period value of AGWPS in unregulated rivers also varies due to varying land use, water diversion, and consumption, etc. Hence omitting values above the upper quartile (Equations 6 and 7) helped us to set a more accurate reference value.

It is important to assess impacts of hydropneaking because hydropneaking can affect the ecological and recreational values of river systems by worsening the water quality (Rossel & de la Fuente, 2015) and biophysical environment (Brown et al., 1991; Brunson & Shelby, 1993; Teigland, 1999). River recreation has economic, psychological, physiological, social, and cultural, and ecological benefits. Many existing dams were built when environmental and recreational issues were not considered as seriously as now, and the generation of electricity was seen as an overriding national interest (Robbins & Lewis, 2008). However, the demand for recreational use of watercourses has been growing due to increased leisure time and urbanization and increased environmental awareness. This trend places new challenges for the management of RR systems. For example, there are concurrent policy initiatives such as the EU Water Framework Directive (WFD, Directive 2000/60/EC) to restore the
multi-functionality of riverine ecosystems. Hence there is a need for developing robust multi-objective hydro-power optimisation operation models.

The time-averaging of GWPS (i.e., the AGWPS) means that the distribution of variability at various periodicities was specifically accounted for in the proposed method. Also, the low power of non-peaked sub-daily flow was overridden by high power sub-daily hydropneaking events, thus masking some additional information. One should also be careful in using this methodology to assess time series from multipurpose reservoirs used primarily for flood control and which have smaller impoundments downstream for re-regulation. Sub-daily variation levels on these types of RRs can be smaller than that in the free-flowing rivers.

However, the methodology is a reasonable classification tool of hydropneaking levels at river stations using variation levels in the unregulated river as a reference condition. Even though not part of the study, this method can potentially also be used to investigate any shift in diurnal pattern change of river flow due to increasing share of variable energy sources in our energy systems. It should be clear that the proposed framework is based on hydrological changes. It provides input for assessing ecological impacts of hydropneaking, but does not in itself analyze ecological impacts. Defining hydropneaking thresholds can be useful in river or fish habitat restoration projects or to address other ecological concerns connected to water management by minimizing the anthropogenic impact caused by hydropneaking.

Figure 7. Comparison of the index for reaches in the two groups by box and whisker plot (with overlayed data points) for average seasonal global wavelet power spectrum values of regulated rivers and free flowing rivers.
Data Availability Statement

The streamflow data sets analysed during the study are available upon request, which could be placed to the appropriate person at the Finnish environmental institute's website (https://www.syke.fi/en-US/Services). The global CSI data set by Grill et al., 2019 is made available, at https://doi.org/10.6084/m9.figshare.7688801 under a CC-BY-4.0 license.

Acknowledgments

This study was funded by Maj- and Tor Nessling Foundation (grant no. 201800109). The BioWater project supported the writing, Nordic Center of Excellence, funded by NordForsk (Project Number 82263) and Ecoriver and HYDRO RDI projects funded by the Academy of Finland (grant numbers 323810 and 337523) and Quantum Institute spearhead project. We utilised the ‘WaveletComp’ package available for the R programming language to do the wavelet transform.

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