

Article

An Assessment of Hydropeaking Metrics of a Large-Sized Hydropower Plant Operating in a Lowland River, Lithuania

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Abstract: This paper discusses rapid flow and stage fluctuations in a large lowland river downstream from a large hydropower plant (HPP) in Lithuania. The main problem arises when the HPP is operating in peak mode. Such operation of HPP causes rapid flow and stage fluctuations, which can have a certain impact on river ecosystems. The study analyzes general abiotic indicators such as upramping and downramping rates and stage fluctuations downstream of the HPP. The main idea was to assess recorded stage upramping and downramping rates along the river downstream of large HPP. To assess stage fluctuation statistics, COSH software was used. A maximum upramping rate of 1.04 m/h and maximum downramping rate of 0.88 m/h were identified using data from temporary and permanent gauging stations. Obtained results revealed that stage fluctuations exceed ecologically acceptable rates up to 20 km downstream of HPP. The effect of hydropeaking fades out only at a chainage of 45 km downstream of HPP. In mountainous regions, ecologically acceptable rates are reached at much smaller distances. The study shows that the traditional coefficient of variation of stage fluctuation data can be used to describe hydropeaking indicators. The main results of this study can be used for environmental impact assessment downstream from HPPs.

Keywords: large hydropower plant; lowland river; hydropeaking; hydrograph ramping; river channel water storage conditions

1. Introduction

Hydropower is the leader in the renewable energy sector, accounting for 71% of energy generated from renewable energy sources, and 16.4% of all electricity produced globally came from hydropower in 2016 [1]. Hydropower is largely developed and tapped most effectively in mountainous regions characterized by moderate to high gradient flowing rivers (channel slope > $0.02 \text{ m} \cdot \text{m}^{-1}$), though this is not always the case. Latvia is a small lowland country, situated near the Baltic Sea, and some 70% of its electricity is generated from hydropower [2]. On the other hand, its neighboring country Lithuania generates a significantly smaller amount of energy from hydropower, only 9%, even though the countries have very similar topographic and climatic conditions. Similar trends prevail in other Eastern European lowland regions such as Estonia, Belarus, and Poland. The contribution from hydropower to the power generation mix in these countries is rather low.

Although electricity generated by hydropower is often called green energy, there is the possibility that a hydropower plant (HPP) operating in peak mode could have a negative impact on downstream



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ecosystems. The biggest impact on ecosystems can be observed during the fast changes in operations of hydro turbines (when these turbines are rapidly stopped or started). This causes swift changes in water stage and discharge patterns, with hydrograph ramping taking place downstream from the HPPs. This process is called hydropeaking [3–5]. Hydropeaking has been studied in Europe since the 1930s [6] and in North America since the 1970s [7]. Large HPPs are usually prone to hydropeaking. Still, there are studies that have revealed intensive downstream hydrograph ramping in small HPPs which are not generating peak electricity at all [8].

Hydropeaking studies were mostly carried out in Europe's Alpine region (Italy, Austria, Switzerland), Pyrenees region (Spain, France) and boreal areas (Canada, Finland, Norway) [4]. There are a number of studies on the subject in the rest of Europe [9] and the USA as well [10]. According to [4] a review of global studies search, there are considerably fewer hydropeaking studies carried out in Asia (China, India, Russia) and South America (Brazil, Argentina, Chile), where the amount of electricity produced from hydropower is considerable.

A review showed a tendency that scientists were focusing on the impact of hydropeaking on biotic communities or habitats [5]. From over 300 studies reviewed, only 22 assessed possible mitigation measures. The most frequently listed hydropeaking indicators were as follows: Downramping rate, ratio of peak flow and baseflow, peak frequency, and time between peaks. Studies have shown that the impact of hydropeaking is highly dependent on the morphology of the river [11].

For a mountain river in Switzerland, two hydropeaking indicators were employed to statistically evaluate flow regime, impacted by hydropeaking: Sub-daily flow fluctuations and flow-ramping rate [12]. Although, these indicators give information on statistical values of altered flow regime, it is difficult to evaluate the severity of changes. Therefore, based on [12], to quantify the hydropeaking pressure, hydropeaking thresholds and hydropeaking pressure classes were identified [13]. Class 1, meaning that there is no or low pressure, to Class 3, meaning that there is high pressure and both hydropeaking indicators, are above thresholds corresponding to un-peaked flow regimes.

It is clear that the ecological status of a natural river depends on the ramping rate. It was proposed that a ramping rate higher than 0.3 m/h is related to a bad ecological status and a rate lower than 0.15 m/h is related to a good ecological status [14].

An assessment of ramping rates in small HPPs operating in lowland rivers was carried out in Lithuania [15]. Significant ramping rates (up to 0.4 m/h) can be observed in some river stretches downstream of small HPPs, even though these HPPs are not generating peak electricity. In such cases, the impact of the HPP on the flow regime can be felt up to 10 km downstream of the power plant. To further evaluate impact of hydropeaking, hydropeaking indicators have to be to linked to biological responses, and therefore hydrobiological studies are performed. Fieldwork carried out by [16] revealed that if the downramping rate could be reduced from 0.6 m/h to 0.18 m/h, the stranding of brown trout fry in dewatered channel areas would decrease by 50%. A nature-like experimental channel was set up in Austria to enable hydropeaking simulations. The initial condition of an upramping rate of 2.22 m/h and downramping rate of 1.8 m/h was reduced to 0.3 m/h, and as a result, the risk of stranding of juvenile fish was significantly decreased [17].

There are various methods to assess the impact of hydropeaking on salmonid fish. For example, [18] suggested the following parameters: The rate of change in stage, the flow ratio, timing and frequency, dewatered area, and the duration of peaking events. Another method developed and successfully tested on rivers in Sweden by [3] characterizes the impact of HPP operations on within-day flow regimes across multiple dams and rivers. The approach is based on short-term metrics that provide a full representation of the flow regime at short time scales from free-flowing rivers to rivers exposed to hydropeaking.

It is difficult to examine the phenomenon of hydropeaking because it includes interactions between hydrology, hydraulics, and morphological changes [14,15]. Hydropeaking regimes can be classified into three phases according to a sequence of peak events and hydrological phases: (a) Low base discharge, when no electricity is generated; (b) rapid changes in discharge, when electricity

generation is increased or decreased; and (c) high peak discharge, during periods of maximal electricity generation [19]. To help to examine this phenomenon, various computational tools and numerical models are developed and commonly used.

COSH, a computational tool, was developed for hydropeaking time series analysis [20,21]. This tool accounts for the identification and quantification of rapid fluctuations in flow and stage in rivers. The tool recognizes rapid fluctuations in changes of stage and discharge and assesses hydropeaking parameters by dividing them into three groups based on magnitude, time, and frequency.

There is a common practice for assessing the impact of hydropeaking based on numerical 1D, 2D, 3D, and joint models. Longitudinal assessment of hydropeaking impacts using unsteady 1D and 2D depth-averaged modelling was conducted by [22,23]. The 3D hydrodynamic model was used to model flow characteristics during a hydropeaking event and compared with field measurements [24]. Reference [25] developed a model which detects fluctuation intensities out of multiple hydrographs along the affected river reaches. On the other hand, two-dimensional hydrodynamic models coupled with biological models for habitat assessment are widely used, e.g., CASiMir [26].

Some studies were carried out in Lithuania related to rapid stage and discharge fluctuations at a large hydropower plant, Kaunas HPP, downstream from the Nemunas River [27,28]. The Mike 21 2D hydrodynamic model was used to model river flow fluctuations for a 15 km stretch downstream from Kaunas HPP. The results showed that the flow wave velocity was 6–9 km/h, the range of stage change reached 1.2–1.5 m and the upramping rate was 0.45 m/h.

The impact of hydropower operations on rivers can cause stranding of fish or other water organisms during rapid drawdown, which can be characterized by so-called dewatered areas occurring in the varial zone of a stream channel [29]. To account for this negative phenomenon, hydrodynamic modelling was conducted in the Kaunas HPP [30]. Results showed that dewatered areas expanded with an increasing number of operating turbines. When this HPP released water from the base flow of 126 m³/s (one turbine) to 596 m³/s (four turbines), dewatered areas increased to 5.7 ha/km, or 33%, compared with the former case.

There is a gap in knowledge concerning flow alterations during hydropeaking events at longitudinal and temporal scale during different amounts of discharge in river channels. On the one hand, it must be obvious that the severity of flow alterations has to decrease when one recedes further downstream from the source of hydropeaking. On the other hand, pre-existing (antecedent) flow storage volume in the river channel, such as high or low water flow in the river channel before the hydropeaking event, influences the rate of change of flow; i.e., the higher the river channel storage, the smaller the fluctuations of stage and flow. Another important aspect is that for hydropeaking assessment it is essential to take into account river morphometry and the shape of the river channel.

Therefore, it is important to quantify hydropeaking particularities during dry or wet years and different seasons and months and, more specifically, in much shorter periods; in other words, the status of the river channel in terms of its water flow storage degree before modifying flow conditions by the occurrence of a hydropeaking event. Moreover, an analysis of the literature shows that studies that quantify longitudinal assessment of hydropeaking are not so numerous.

The aim of this study was to assess the statistic indicators of the dynamics of hydropeaking at a large lowland river downstream from a large hydropower plant, taking into account temporal and longitudinal changes of the flow regime along the river. The objectives were to assess: (1) The changes of hydropeaking events along the river, and in particular to compare modified hydropeaking versus an unaltered river stretch; (2) the essential hydropeaking indicators with regard to the status of antecedent flow storage volume in the river channel before a hydropeaking event occurs.

In this paper, the impact of hydropeaking on ecosystems was not considered; nevertheless, the results of this study can serve as a background for further studies to propose mitigation measures. For the purposes of this paper, "ramping rate" refers to the rate of change of water stage (in meters per hour) and "hydropeaking" refers to the mode of operation of a facility where water is released in accordance with electricity demand.

2. Materials and Methods

2.1. Study Area

Lithuania is a low-lying country; about 90% of its area lies below 170 m elevation above sea level, with hills no higher than 290 m. The Nemunas is the largest lowland river in Lithuania, with a low channel slope averaging to 0.0002, flowing through Kaunas city to the Baltic Sea (Figure 1). The catchment area is approximately 100,000 km², with an average discharge of 632 m³/s.



Figure 1. Nemunas River, Kaunas hydropower plant (HPP) and permanent gauging station (GS) locations.

The study area is the Nemunas River stretch (some 50 km) downstream from the Kaunas HPP. It is the only hydropower plant on the Nemunas River in Lithuania, operating since 1959 (installed capacity P = 101 MW, head H = 20 m, reservoir area A = 63.5 km²). Based on the installed capacity classification, this power plant can be considered to be a large one [31].

According to the general classification of rivers based on discharge and drainage basin size [32], the Nemunas River is classified as large (basin size 10,000–100,000 km², river width 200–800 m, average discharge 100–1000 m³/s). Based on the classification of lowland and highland rivers [33], the Nemunas can be regarded as a purely lowland river (channel slope < $0.0004 \text{ m} \cdot \text{m}^{-1}$).

The Kaunas HPP, associated with a large reservoir (storage type with powerhouse incorporated into earth-filled embankment dam), operates in a restricted peaking mode. The operator in a normal operating regime is allowed to use water for electricity generation from the reservoir within a daily drawdown limit of ±0.4 m from the normal headwater level. Despite this, Nemunas River stretch is subjected to intensive hydropeaking downstream of the dam. Hydrographs clearly show the difference between natural free-flowing river flow just upstream of the Kaunas HPP reservoir (Nemajūnai gauging station) and altered river flow downstream at the Kaunas gauging station (Figure 2).



Figure 2. Natural flow (above) and altered (below) hydrographs; saw-toothed pattern hydrographs of the Nemunas River gauging stations upstream and downstream of the Kaunas HPP in December 2017.

Figure 3 shows the locations of permanent river stage and discharge gauging stations in the Nemunas River together with locations of temporary measurement sites that were made operational for the purpose of this study.



Figure 3. River stage recording sites at the Nemunas River with chainage showing permanent gauging stations (GS) and temporary measurement sites (operating in 2015 (**a**) and 2016 (**b**)).

Temporary measurement sites with data loggers recorded the river stage at 10-min time spans from 24 to 30 November 2015 (9 sites up to 44.8 km downstream from the Kaunas HPP) and from 27 November to 11 December 2016 (5 sites up to 48.8 km downstream from the Kaunas HPP). The coordinates of each site were detected using a GPS receiver, additionally capturing the real-time water levels. Also, historical stage data (measurements at hourly intervals) at the Kaunas HPP gauging station were used from the hydrological-hydraulic study [34]. Additionally, gauged river stage data (at hourly intervals) of the same period (2015–2016) were gathered from the longstanding Kaunas HPP and Lampėdžiai gauging stations. A digital elevation model (resolution 1×1 m) was used to determine river channel cross-sections at each temporary stage measurement site.

There is one large tributary (Neris River, with an average discharge of 182 m³/s) at the studied area of the Nemunas River (downstream from Kaunas HPP) and a couple of smaller ones (Nevėžis River, with an average discharge of 33.2 m³/s, and Dubysa River, with an average discharge of 13.4 m³/s).

In this study, river stages were recorded before and after the confluence of the Neris River (14.6 km and 15.6 km downstream from Kaunas HPP).

To hypothesize one of the aim of this study, it was necessary to evaluate the capacity of the river channel to store stream flow inside it during different periods of the investigation. The simplest way to do so was to use the statistical occurrence of wet, average and dry years or a particular period in terms of river flow or stage [35,36]. Using long-term discharge measurements (1960–2016), it was determined that stage data from temporary stage measurement sites (2015–2016), gauging stations (2015–2016), and historical data (1988) corresponded to different kinds of hydrologic years. The year 2015 corresponded to a dry year (return period of 20 years with an average discharge of 129 m³/s), 2016 to an average year (average discharge of 293 m³/s) and 1988 to a wet year (return period 5 years, average discharge of 471 m³/s).

An alternative way to characterize the upper capacity of the river channel to store stream water is the bankfull discharge, which fills the channel to the tops of the riverbanks [37]. The bankfull discharge ($Qbf = 840 \text{ m}^3/\text{s}$) for the Nemunas River stretch under this study was determined with GIS analysis based on the water surface area of the river flow when its banks are full [38].



Three different flow (or stage) conditions resulting from particular river channel water storage levels are illustrated in Figure 4.

Figure 4. Three river channel situations showing range of stored water in terms of stage during investigated period (Kaunas HPP GS): (**a**) dry year (2015), low river channel water storage; (**b**) average year (2016), moderate river channel water storage; (**c**) wet year (1988), high river channel water storage (red line—bankfull water storage level, blue lines—maximum, average and minimum water storage levels).

To compare the altered Nemunas River stretch flow by hydropower production and the natural river stretch flow unaffected upstream by HPP impoundment in terms of the shape of natural flood hydrographs (rate of rising and falling limbs), the historical data of flash floods recorded at Nemajūnai GS for the period 1950 to 2010 years were analyzed.

An assessment of river stage fluctuation time series was carried out using software developed for the analysis of short-term variations of the stream during hydropeaking operations, the COSH tool [21].

2.2. Stage Data Validation

Data validation is a crucial issue. Therefore, the data acquired from temporary river stage measurement sites were collated with the data from the permanent gauging stations using the conventional correlation test. Additionally, the Nash–Sutcliffe model efficiency (NSE) coefficient was determined [39]. The relationships that can be considered as close enough are shown in Figure 5.



Figure 5. Correlation between river stage data from temporary stage measurement sites and permanent gauging stations. Left: Kaunas HPP gauging station and stage measurement site 0.8 km downstream from Kaunas HPP. Right: Lampėdžiai gauging station 19.2 km and temporary measurement site 18.4 km downstream from Kaunas HPP.

The coefficient of determination (R²) between the river stage data pertaining to Kaunas HPP gauging station (0.0 km) and temporary stage measurement site 0.8 km (results were shifted along the river slope at Kaunas HPP) is 0.925, and the NSE coefficient is 0.900. The stage data determination coefficient between Lampėdžiai gauging station (19.2 km) and temporary stage measurement site 18.4 km is 0.948, and the NSE coefficient is 0.917. The relationship between different sources of data is sufficiently high, therefore stage data from data loggers at temporary stage measurement sites were used in this study for further evaluation.

The main reasons for the small discrepancy in data values could be the different time intervals during measurements at temporary sites and gauging stations and changes in channel morphology.

3. Results

3.1. Gauged Stage Data and River Morphology

Hydropeaking, which is caused by operating regimes of the HPP, is characterized as rapid changes in river flow at river channel cross-sections (Figure 6). So far, no ramping rate is currently legally prescribed for this plant, i.e., to limit the artificial changes in flow through the facility so that sudden, unexpected increases or decreases in river flow can be avoided.

For hydropeaking assessment, it is essential to take into account river morphometry and the shape of the river channel. Cross-sections of the Nemunas River channel at the temporary stage measurement sites and gauging stations are presented in Figure 7. This figure is based on the sites where measurements were carried out in 2015. As the sites where measurements were carried out in 2015 and 2016 until the chainage 26.5 km downstream from Kaunas HPP are overlapping, not all cross-sections are presented in Figure 7. Two additional sites further downstream, that are shown in Figure 7, were added in 2016, therefore Figure 7 shows the Nemunas River riverbed morphometry until chainage 48.8 km from Kaunas HPP. In this case it was assumed that riverbed is constant in time period of two years, or changes are insignificant.







Figure 7. Cross-sections of Nemunas River channel at temporary stage measurement sites and gauging stations in 2015. Two last cross-sections, 31.1 and 48.8 km distance from Kaunas HPP, were taken in 2016. Red lines show maximum river stage, blue lines, minimum stage.

As it can be seen from Figure 7, the Nemunas River channel width near the Kaunas HPP is approximately 500 m. Downstream from the Kaunas HPP (from 2.9 km to 15.6 km), channel width narrows to approximately 200 m; afterwards, from 15.6 km to 44.8 km, it expands again to 300–400 m.

These changes of river channel morphology have an effect on downramping and upramping rates at different Nemunas River channel cross-sections.

3.2. River Stage Dynamics

The river stage data from the temporary water measurement sites and Kaunas HPP and Lampėdžiai gauging stations are presented in Figure 8. As expected, the most intensive stage (as well as discharge) is observed at the tailwater of the Kaunas HPP. Going downstream from this hydropeaking source along the river channel, these fluctuations get progressively smoother. They almost disappear at a very far distance, some 45 km from the HPP. The demand for peak energy normally is between 08:00 and 18:00 during working days, which is clearly reflected in stage variations. During weekend days, the Kaunas HPP generates less electricity and consequently stage fluctuations are not so intense as on weekdays. Due to the open electricity market conditions, more hydropeaking events can be expected during weekend days [40].



Figure 8. Stage measurements along the Nemunas River downstream from Kaunas HPP: (**a**) Low flow period (return period 20 years), (**b**) mean flow period (return period 2 years).

It was noted that when the Nemunas River channel water storage is low, the generation of peak energy is also lower than when the channel contains a larger amount of flow water. This can be

justified by the fact that during low inflow periods, the Kaunas HPP tends to accumulate water in the reservoir and generate electricity by releasing only constant residual (environmental) flow through the turbines. Higher river stage fluctuations are observed during intense peak energy production, when the downstream river channel water storage conditions can be evaluated as moderate.

The upramping and downramping rates downstream from Kaunas HPP depending on the initial river channel flow conditions, low and average, are presented in Figures 9 and 10. Up to 15.6 km downstream from Kaunas HPP, the maximum, average and minimum downramping rates are 0.13–0.88 m/h, 0.06–0.31 m/h, and 0.04–0.14 m/h, respectively. However, the upramping rate reaches the limit of 0.1 m/h during the low water storage period only 26.4 km downstream from the HPP and during the average water storage period only 31.2 km downstream.



Figure 9. Dynamics of stage fluctuations downstream from Kaunas HPP during a low flow period: (a) upramping; (b) downramping. Red line: stage fluctuation limit assigned for natural flowing rivers (0.1 m/h).



Figure 10. Dynamics of stage fluctuations downstream from Kaunas HPP during average flow period: (a) upramping; (b) downramping. Red line: stage fluctuation limit assigned for natural flowing rivers (0.1 m/h).

The highest upramping rates were observed during the low channel water storage period. Near Kaunas HPP (0.0 km), maximum, average and minimum upramping rates were 0.67 m/h, 0.35 m/h, and 0.07 m/h, respectively. The highest upramping rates were measured 2.9 km downstream from Kaunas HPP. Here maximum, average and minimum upramping rates were recorded as 1.04 m/h, 0.42 m/h and 0.14 m/h, respectively. The same was observed for the downramping rates, only at the shorter distance—0.8 km downstream from Kaunas HPP. Maximum, average, and minimum downramping rates were 0.88 m/h, 0.42 m/h, and 0.11 m/h, respectively during the low channel water storage period.

To statistically characterize the gauged stage data series illustrated in Figure 8, conventional descriptive statistics was undertaken. The most important metric to determine the severity of river stage fluctuations along the river is the coefficient of variation (last column in Table 1).

Gauging Stations and Stationing	Datum. Masl	Range (m)	Min (m)	Max (m)	Data Sample	Mean (m)	Standard Error	Coefficient of Variation (Cv)
Low channel flow								
Kaunas HPP GS (0.0 km)	23.65	1.76	0.00	1.46	167	0.30	0.04	1.39
0.8 km	23.41	1.62	0.00	1.63	707	0.45	0.02	1.06
2.9 km	22.72	1.77	0.04	1.81	708	0.57	0.02	0.91
8.9 km	20.97	1.63	0.00	1.64	705	0.51	0.02	0.91
11.2 km	20.60	1.46	0.00	1.46	705	0.45	0.02	0.91
14.6 km	19.26	1.51	0.00	1.51	708	0.58	0.02	0.73
15.6 km	19.10	1.40	0.01	1.41	708	0.57	0.02	0.71
18.4 km	18.73	1.37	0.00	1.37	709	0.54	0.02	0.74
Lampėdžiai GS (19.2 km)	18.67	1.24	0.01	1.25	167	0.46	0.03	0.68
26.4 km	18.23	0.85	0.01	0.86	655	0.36	0.01	0.65
44.8 km	16.22	0.51	0.01	0.52	570	0.27	0.01	0.63
Average channel flow								
Kaunas HPP GS (0.0 km)	23.63	1.81	0.00	1.51	193	0.58	0.03	0.80
8.9 km	20.68	2.03	0.00	2.03	1345	0.79	0.01	0.61
11.2 km	19.77	1.85	0.00	1.85	1345	0.72	0.01	0.61
18.4 km	18.32	2.09	0.00	2.09	1345	0.83	0.01	0.50
Lampėdžiai GS (19.2 km)	19.34	1.53	0.00	1.53	193	0.76	0.02	0.44
31.1 km	16.28	1.32	0.00	1.32	1344	0.61	0.01	0.43
48.8 km	15.26	1.23	0.00	1.23	1344	0.57	0.01	0.42

Table 1. Key statistics of gauged stage data series along Nemunas River during low and average channel flow.

Ecologically acceptable up- and downramping stage rates were observed at quite a far distance from the hydropeaking source: 19.2 km station (Lampedžiai GS). The coefficient of variation of these stage data series can be regarded as a general alternative metric to their up- and downramping rates. This interchangeable and simple parameter at this station also means ecologically acceptable values at this station (Cv = 0.68 and 0.44 for low and average channel flow conditions, respectively).

The statistics of stage fluctuations based on the data from Kaunas HPP gauging station (0.0 km) during different channel water storage periods are presented in Table 2.

Table 2. Statistics of upramping and downramping rates based on data from Kaunas HPP gauging station (data sample: n = 840, 1440 and 830 for low, average and high river channel water storage, respectively).

	Maxim	um Upramping Rate	e (m/h)	Maximum Downramping Rate (m/h)			
Statistical Parameter	Low Channel Water Storage	Average/Moderate Channel Water Storage	High Channel Water Storage	Low Channel Water Storage	Average Channel Water Storage	High Channel Water Storage	
Mean	0.55	0.40	0.7	0.49	0.52	0.68	
Standard deviation	0.23	0.30	0.30	0.33	0.33	0.78	
Min	0.21	0.55	0.10	0.06	0.05	0.40	
10th percentile	0.32	0.02	0.30	0.14	0.10	0.50	
25th percentile	0.41	0.2	0.61	0.22	0.34	0.52	
Median	0.60	0.38	0.69	0.44	043	0.65	
75th percentile	0.62	0.65	0.89	0.72	0.82	0.80	
90th percentile	0.76	0.74	1.04	0.85	1.03	0.81	
Max	1.06	1.02	1.18	1.04	1.13	1.02	

The values of statistical parameters show that the maximum upramping rate is higher when the channel water storage is high. The maximum downramping rate is higher when channel water storage is average (1.13 m/h). Maximum upramping and downramping rates during the high channel water storage period were 1.18 m/h and 1.02 m/h, respectively, and during the low channel water storage period were 1.06 m/h and 1.04 m/h, respectively. During the average channel water storage

period, the maximum upramping rate was 1.02 m/h and downramping rate was 1.13 m/h. Upramping and downramping rates during the high channel water storage period were significantly higher than during the low channel water storage period. However, the highest downramping rate was observed during average river channel water storage conditions, 1.13 m/h.

It is especially important to determine the occurrence or frequency of artificial river stage fluctuations within the 24 h period, as it can impact fish spawning or swim-up periods [23,41]. The frequency of hydropeaking events during the 24 h interval at the Nemunas River is presented in Table 3.

Table 3. Frequency of hydropeaking events during 24 h period depending on river channel flow conditions in Nemunas River at Kaunas HPP GS (0.0 km). Low, average and high river channel flow conditions in 2015, 2016, and 1988, respectively.

Upramping				Downramping				
Indicators	Low Flow	Average Flow	High Flow	Indicators	Low Flow	Average Flow	High Flow	
No. of peaks	12	22	11	No. of peaks	10	18	11	
Day	6	10	9	Day	3	8	10	
Sunrise/sunset	1	1	0	Sunrise/sunset	0	0	0	
Night	5	11	2	Night	7	10	1	

The figures given in Table 3 clearly point out that the most frequent hydropeaking events take place when the average flow is running in the river channel. During the average water flow upramping events occur 22 times, compared to 12 times during low flow and 11 times during high flow. The similar tendency can be noticed for downramping events. During the average water flow downramping events occur 18 times, compared to 10 times during low flow and 11 times during high flow. An uneven number of downramping and upramping events occur due to the manipulation of the Kaunas HPP operating regime: The number of operating turbines can be increased or decreased.

4. Discussion

Although hydropeaking phenomenon is relatively well known, the analysis of recent studies on hydropeaking revealed a lack of studies concerning large lowland rivers. The majority of hydropeaking studies are carried out in mountainous or steep topography regions, whereas the Nemunas River is a typical lowland river in which natural floods usually occur four to six times annually and last approximately two to five weeks, and the flood hydrograph limb rising speed is relatively slow (approximately 0.02 m/h).

Compared to the flow regime downstream of the Kaunas hydropower plant, the number of small artificial floods in the Nemunas River annually can be more than 300. In the river stretches affected by hydropeaking, flow dynamics change very rapidly. Minimum flow can be replaced by maximum flow in a couple of hours. Upramping and downramping rates induced by the operating regime of the Kaunas hydropower plant can be higher than 1 m/h. Such occurrence in the river flow affected by hydropeaking was also noticed by other authors [42]. In the previously study, upramping and downramping rates in the Nemunas River were assessed in the proximity of the bridge abutment [28], and that might have had an impact on the results. Comparing the two studies it is noticeable, that upramping and downramping rates are higher in this study.

This study revealed the importance of considering the flow conditions when assessing upramping and downramping rates as it was noticed that maximum rates of this parameters downstream from Kaunas HPP were observed at different chainage depending on flow conditions. During dry period maximum upramping rate was observed at chainage 2.9 km and downramping rate at chainage 0.8 km downstream from Kaunas HPP. However, during average flow period maximum upramping and downramping rates were observed at the tailwater of Kaunas HPP. It was the first study that assessed hydropeaking at Nemunas River in such extent and the results proved that the riverbed morphometry also is important factor that determines upramping and dowramping rates of the river flow. The ramping rates are more intense where riverbed is narrower than where riverbed is wider.

It is difficult to directly compare upramping and downramping rates in altered and free flowing rivers due to the extremely large differences (upramping and downramping rates approximately 16 times bigger for the latter).

At first, to assess the hydropeaking parameters, upramping and downramping rates in the Nemunas River, stage measurements were carried out during November–December 2015. It was a dry year which was important for us in this study, but also, during winter months, river is clear from vegetation, which has direct effect on roughness coefficient of the riverbed. The measurements were repeated in 2016 with similar conditions and similar results. Besides, the aim of this study was to assess hydropeaking "waves", that rise and fall very fast. The interval of stage or flow observations is very important for the assessment of hydropeaking. According to [20], for accurate assessment of hydropeaking, fine intervals (10 min, 15 min, 1 h) of stage or discharge measurements are needed. For this study, measurements were carried out at intervals of 10- and 15 min. Data obtained from gauging stations were recorded hourly. This enabled the maximum accuracy needed for precise assessment of the hydropeaking phenomenon.

The assumption was made that the ramping rate attenuates as a function of the distance downstream from a hydropower plant operating under peaking mode. This can be substantiated by open channel hydraulics and hydrological theory that any hydropeaking hydrograph (pulse) is modified as water waves flow down a river channel. This modification is similar to a flood routing problem ("hydrograph shape flattening") described in hydraulic and hydrology textbooks [41,43]. The finding of this study confirmed this assumption. The stage data revealed that the downramping rate during low and average channel water storage periods did not exceed the limit of 0.1 m/h only starting from the chainage 18 to 19 km downstream from Kaunas HPP as compared to 1.0 m/h in the tailwater of the power plant.

It is interesting to compare the changes in parameters of hydropeaking along the rivers in different geographic regions. Hydropower plant operating regimes along the river stretch downstream from an HPP in Alpine rivers were modelled by [22]. The modelling results, compared with similar case studies in the discussion, revealed that in the first 5 km downstream of the turbine outlet in the Alpine rivers there was a significant decrease in vertical ramping velocity (coarse riverbed slope in such cases is from 0.0014 to 0.0045 m·m⁻¹. Such an impressive decrease in the ramping rate a relatively short distance from the hydropower plant might be primarily explained by a much bigger bed slope of the mountain (or high gradient) river, at least 10 times compared with the bed gradient of a lowland river (0.0002 m·m⁻¹). In the latter, due to the alluvium bed channel, the ramping can be considerably dampened only 20 km and 10 km away from the HPP in a large and small river, respectively. Hence, this distance is two to four times larger than in mountain rivers.

Key statistics obtained from the stage data series along the Nemunas River during low and average river channel water storage periods show that the coefficient of variation of the stage series affected by hydropeaking tends to be lower downstream from the Kaunas HPP. At the chainage 19.2 km downstream from the hydropower plant, the coefficient of variation during low and average river channel water storage periods was 0.68 and 0.44, respectively. Previously obtained results showed that at this chainage, upramping and downramping rates did not exceed the ecologically acceptable rates, therefore these coefficients of variation can also be assumed to be ecologically acceptable. This means that if during the low channel water storage period the coefficient of variation reaches a value lower than 0.68 and during the average channel water storage period the coefficient of variation reaches a value lower than 0.44, it can be assumed that stage fluctuations along this river chainage are lower than or equal to ecologically acceptable rates. In conclusion, this very simple parameter of descriptive statistics can complement the known metrics of hydropeaking. In our search of the literature dealing with hydropeaking, we did not find any attempt to use such a simple metric to characterize the variation of stage data series along a river channel. Consequently, the comparison

with other independent results is limited. At this stage this study proposes to use the Cv parameter as an additional parameter for hydropeaking assessment. Further research is needed to evaluate the ecologically acceptable values of Cv in different conditions. To our best knowledge, there are no hydropeaking studies that utilize this parameter, therefore the future direction will be to identify minimum, maximum, and average ecologically acceptable Cv limits before using it as one the main parameter for hydropeaking assessment.

The literature review revealed that the intensity of water stage fluctuations (upramping or downramping rate) is very important for the survival of juvenile fish and other river organisms. According to [44] the air temperature and light conditions have effect on fish stranding. As at low temperatures and during the dark period fish tend to stay closer to the riverbed, upramping and downramping during the twilight are most dangerous [20,44]. Therefore, in this study frequency of hydropeaking events during a 24-h period was assessed during low, average and high river channel water storage periods. The obtained results revealed that during low and high periods, Kaunas HPP operating regime was smoother. This means that turbines were stopped and started fewer times than during average periods. From this the conclusion can be drawn that during average river channel water storage periods, stage fluctuations, and consequently the impact on the water ecosystems, are possibly higher than during low and high channel water storage periods. This is the first step to identify the hydropeaking impact on biotic organisms in Nemunas river, in collaboration with hydrobiology experts.

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