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HYDRAULIC CRITERIA AND ESTIMATION OF THE HYDROPOWER PLANT (HPP) OPERATION IMPACT ON THE RIVER ENVIRONMENT

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Abstract. Interaction between a river and its environment is crucial, and negative impact of a HPP operation on the environment must be estimated. In order to be able to evaluate this impact, hydraulic parameters such as velocity, water depth, Froude Number (*Fr*) and fluctuation of flow regimes have been measured and hydro biological indices of water quality (HBI) have been calculated. Field experiment on the consequences of HPP turbines' operation in the rivers Virvyte and the Susve has been performed in natural, directly and indirectly impacted regimes in 10 cross-sections. To predict the influence of HPP, the meaning of *Fr* number criterion and the number of hydrophytes are compared. The results show that even small dams and reservoirs of HPP may impact the environmental change through facility operations over a sustained period, because in pounded reaches nearby/above HPP dams in the River Virvyte low *Fr* number in habitats ($0.04>Fr>0.0007$) has been established. In the River Susve, below the Angiriai HPP, a serious disturbance of hydraulic parameters is determined when a positive wave front resulting from an increase of initial sanitary flow rate $Q_s = 0.4 m^3/s$ to total flow rate $Q_{tot} = 10.4 m^3/s$ is moving downstream after the switching on the turbines. The maximal water level increase speed $\Delta h/\Delta t$(0.18 m/min=10.8 m/h) is recorded on the second minute from start of the turbine. Consequently, it creates additional pressure of about 200kPa at the instant and can be a strong stressor for biological community of the river. Over 1 km long propagation of the surge without loosing much potential energy (because it is perpetual) is the main reason to avoid rapid operation of HPP turbines in practice.

Keywords: hydraulics, hydropower plant, environment, *Fr* Number.

1. Introduction

The entire variety of hydraulic and hydrologic conditions affects living water organisms inevitably, and in turn, forms the diversity of species and their adaptation conditions, i.e. their resistance. The studies of fluvial structures (i.e. riffles and pools) show that glides, runs and riffles shelter the macroinvertebrates that are most demanding in terms of water quality. The fluvial forms are characterized by a wide variety of environmental conditions: submerged macro-phytes, well-oxygenated running water, a wide variety of flow velocities and depths. (Beauger, .*et al*.; 2004) Results from rivers the Dordogne and the Garonne in France confirm that growth of aquatic macrophytes is closely related to hydraulic conditions and flow chronicle. Flow rate variability (which results in variable depth and current velocities) constitute a determining factor for macrophytes' development. (Breugnot. *et al*.; 2004) The scientific research has also proved that the majority of insects are relatively tolerant to organic water pollution; therefore, they mostly like calm lowlands (water of ponds or lakes). However, the changes in algae and sediment and insect migration from the ponds dammed by hydropower plants (HPP) change their species composition dramatically below a dam (Lopardo, Seoane, 2004)

Thus, buildings across river sections like HPP weirs or dams have seriously affected the character of our rivers. Dams and reservoirs impart change in the environment with the magnitude of change unique to each facility. In the water storage area upside these dams the flow velocities reduce, this leads to an increased accumulation of sediments and afflicts the system of gravel vacancies. The rate of turbulence reduces combined with less substitution of gas and by organic strain of water results oxygen attrition .The impounded river develops typical characteristic of stagnant water and stream liking species are replaced by lenticliking ones. (Sabrowski, Hack .; 2004). In the downstream reaches the river flow remains in the initial bed and there are no evident changes, but dams and reservoirs may impart change in the environment though facility operations over a sustained period. Operational impacts develop through discontinuity in downstream gradients (eg. sediment supply, water quality) and modification of the natural flow regime. Chains of power plants increase this effect. These impacts lead to secondary changes in fluvial and floodplain processes, affecting the high spatial and temporal variability of available habitat characteristic of river – floodplain systems (e.g.

hydraulic – thermal regime here will be rather different from the initial one). (Ždankus, 2008) As a result, the lower reaches of HPP are influenced by hydro-peaking surges of a power plant. The switch between low flow and surge conditions causes rapid changes of the water-level (up to 2 cm/min), several times a day with varying timing and duration (Unfer *et al*.; 2004)

On the other hand, studies in artificially modified rivers demonstrate a relatively limited influence of small HPP on the use of the habitat. The little dams do not cause a negative effect, despite greater concentrations of bioorganic pollutants. The time of water presence in reservoirs is short and it diminishes the activity of cyanophytas.(Bustamante *et a*l.; 2004). But HPP hydro peaking is associated with artificial changes of environmental variables that may influence the reproductive behavior of different species. According to Gonzalez M.A. *et al.;* (2004), creation of an artificial barrier and impoundment of water causes a permanent discontinuity and inevitably results in mayor disturbance in the ecosystem. In fact, researchers have studied changes in macroinvertebrate communities in the reaches downstream of dams. But finding adequate methods of quantification of the damage is hard task, since it is difficult to consider both temporal and spatial natural variability of communities. Macrobenthic communities are exposed to seasonal fluctuations in the water level and current speed, and their life cycles are adapted to those changes. However, at the discharging point of turbines, communities are exposed to frequent and unpredictable fluctuations of the water flow, which represents a stressor factor they cannot cope with. Nevertheless, small hydraulic structures mostly do not receive the environmental consideration, probably they lack political significance and do not seem to affect the landscape and the geography (Lopardo & Seoane.; 2004).

So, mechanism of interaction between HPP and surrounding is complex and multiple with river flow being the most important its element. Any change of river flow hydraulic characteristic and regime leads to distortion of equilibrium and following long lasting adjustment of the regime to the system of environment. For example, periodically fluctuating velocities change sediment transport by deteriorating spawning grounds. Increase of mean flow velocity in 2 and more times in regulated rivers prevents fish fry movement against the stream that is uncomfortable and sometimes may prove fatal for juvenile. Increase of turbulence up to a certain limit may be favorable for benthos and fish juvenile, because turbulent oscillations of flow velocity are the only source of oxygen in the bottom layer. However, simultaneous increase of both fluctuations of velocity and pressure results in negative impact on habitat conditions (Dolgopolova, 2004, Vaideliene *et al*.; 2008).

Thus, interaction of river and environment is crucial, and link between biologically and hydraulically defined habitat units is need for estimation. But the target “good ecological status of river reaches” cannot be measured on a common scale and must therefore be broken down to a number of hydraulic parameters that affect the ecological status of the water. In the case of HPP it means that the impact on habitat quality changes must be estimated by the ecohydraulic parameters such as velocity, water depth, turbulence and sediment regimes’ fluctuation. In such context, the aim of the present paper is to show the likely impact of Lithuanian small HPP on river environment and possible criteria for its estimation.

2. Assessment of hydraulic criteria in HPP biotic environment. Fr Number

The study of different characteristics of the stream shows the importance of the set of conditions concerning flow velocity, turbulence intensity and pressure. Growing evidence suggests that flow complexity provides important habitat for aquatic organisms. Maddock (1999) observes that habitat metrics should not simply measure a physical attribute, but measure the physical attribute, which has biological significance. The link between “functional habitats” (biologically defined habitat units) and flow “biotopes” (hydraulically defined habitat units) has been found. [Kemp J L et al.; 2000] Kemp uses Froude Number to test the hydraulic habitats of three species of macroinvertebrates by recording flow velocity and depth and the finding is that their habitat occurrence is well described by Froude Number $Fr = v^2/g\,h$ (Fig.1).

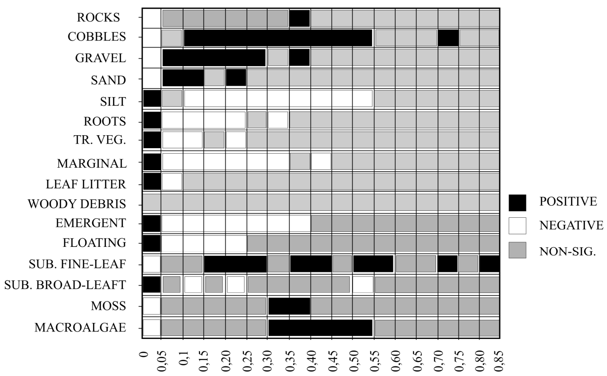

Fig 1. The association between occurrence of habitat and Froude number (according to Kemp *et al*.; 2000)

Studies of functional habitat distribution have established that various habitats have different optima in terms of depth h and velocity v. It is also suggested that water velocity affects river plants, with some species preferring slower and others - faster conditions. The physiological mechanisms behind this response have also been studied, with current velocity shown to affect photosynthetic rate. (Maddock.; 1999) Thus, Froude Number (the ratio of inertial to acceleration forces) is the most reliable complex hydraulic variable (complex hydraulic criterion) to describe river habitats in terms of hydraulics. It can better describe the preference of many species than flow velocity, depth or substrate type because complex criterion is combination of physical variables and is capable of explaining a greater proportion of the variation than a single variation alone. “Erosional” and “depositional” habitats are distinguished and Fr number is found to be the most influential environmental variable. Thus, the Froude number and the bed shear stress are found to be the main influencing hydraulic factors. (Shamloo *et al*.; 2001) The approach used is to examine the relationship between functional habitat occurrence and Fr number, with the aim of developing habitat preference curves. Fifteen of the 16 functional habitats in 32 sites encompassing 4 UK river catchments are found to be distributed with Froude number in a non-random fashion. The results provide the first evidence that Froude number and therefore flow biotopes are ecologically meaningful. This means that the impact of river flow regulation on habitat conditions of the lotic reaches of HPP impounded river can be estimated by this criterion.

The Fr plays a dominating role in hydraulics and is always of importance whenever the influence of gravity is important, as for instance in all flows with free surface (Kobus, 1980). Corresponding dimensional considerations for a fluid element with inertial reaction under the influence of gravity forces yield the force ratio:

$$Fr = \frac{v}{\sqrt{gh}} = \frac{inertia}{gravity} \tag{1}$$

The role of the Froude number Fr can be well illustrated by considering the flow in an open channel of depth *h* and of mean velocity *v*. The denominator $\sqrt{gh}$ represents in this case the propagation speed of a gravity wave in shallow water, and the Fr can be interpreted as the ratio of the mean flow velocity to this wave propagation speed. Accordingly, open channel flows can be classified into "sub-critical flows "(Fr<1), and "super-critical flows" (Fr >1), in which gravity waves can no longer be propagated in the upstream direction. Retaining the same Froude number is the most important similarity requirement in physical modeling open channel flows. But the Fr can be also important for the estimation of HPP produced hydraulic jump and its impact on the river flow energy alteration.(Ždankus 2001, Ždankus & Sabas, 2005, Ždankus 2008, Zdankus. *et a*l.; 2008). In the downstream and upstream reaches of HPP water level fluctuations and positive or negative surges (hydraulic jump) due the turbines operation can be produced. (Chanson H.; 2001). As small HPP usually works according to the available water, for some time it accumulates water in the pool, at the rest time it utilizes potential water energy by turbines. Thus, each switching off and on of HPP turbines causes a sudden change of the flow discharge, depth and energy, i.e.; Fr. A surge wave (mass transfer wave) results from the sudden change of flow and its parameters important for estimation of harmful impact on river flora and fauna can be evaluated by an unsteady non-uniform flow equations:

$$\frac{\partial Q}{\partial l} + \frac{\partial A}{\partial t} = 0 \tag{2}$$

$$i - \frac{\partial h}{\partial l} = \frac{v}{g}\frac{\partial v}{\partial l} + \left(\frac{Q}{K}\right)^2 + \frac{1}{g}\frac{\partial v}{\partial t} \tag{3}$$

where: Q – flow rate; *l* – distance traveled by the flow; A – cross-section area; *t* – time; *I* – river bottom slope; *V* – flow mean velocity*;K* – river bed conveyance coefficient; *g* – gravity constant.

The continuity equation (2) provides an estimation of the velocity of the surge V_{srg}:

$$V_{srg} = \frac{Q_2 - Q_1}{(h_2 - h_1)B} \tag{4}$$

where: Q_1 and Q_2 – flow rates before and after switch of turbines; h_2 and h_1 – average flow depths in cross-sections before and after change of flow rates; *B* - average free surface width of the main river channel

Considering critical conditions of wave front motion, the celerity C of small oscillatory waves can be estimated:

$$C = \sqrt{g\Delta h} \tag{5}$$

where $\Delta h = h_2 - h_1$ – free surface gravity wave height

An open channel flow contains definite mechanical energy *E* expressed by equation (3). If this energy is taken in cross-section of the river, the expression of energy obtains the following form:

$$E = h + \frac{\alpha v^2}{2g} \tag{6}$$

where *h* – water level from the lowest point of the bottom in cross-section (depth); *v* – average water velocity in cross- section; α - Coriolli coefficient (it takes into account peculiarities of kinetic energy distribution along cross-section in the flow); *g* – gravity acceleration.

In cross-section the part of flow potential energy h_c which is transferred to kinetic energy and used in HPP turbines, can be expressed as follows:

$$h_c = \frac{\alpha v^2}{gh} = Fr \tag{7}$$

The river-channel stability (Grishanin) criterion *M* also depends on *Fr* (Vaikasas *et al.;* 2004):

$$M = \frac{1}{\sqrt{Fr}}\sqrt[4]{\frac{h}{B}} \tag{8}$$

where *B* – width of the main channel.

If needed, the Froude number *Fr* may be written as a ratio of the flow velocity *V* and the celerity of a small waves *C* in the river*:*

$$Fr = \frac{V}{C} \tag{9}$$

Therefore, Fr number together with velocity, vortices, flow energy and circulation values distribution can be used to estimate HPP impact on river flow environment. Hydraulic waves (jumps) also are characterized by air entrainment. Thus, the rate of air entrainment into the water of the main channel may be calculated (Chanson H.; 2001)

$$\frac{Q_{air}}{Q} \approx 0.018(Fr_1 - 1) \qquad (10)$$

where Fr_1 – upstream Froude number.

It is clear that dams and reservoirs may impart change in *Fr* and the environment though facility operations of HPP over a sustained period. This impact on habitat quality changes as well as on *biota* can be estimated by the hydraulic parameters such as velocity, water depth, turbulence and fluctuation of vorticity regimes as well as by Froude number *Fr*, because its value depends upon the form of flow boundaries. Thus, *Fr* number has become one of the main tools for ecohydraulics in HPP.

3. Fr as criterion for estimation of **HPP impact on flow environment in the Virvyte River (case study)**

Table 1 shows the overall impact on flow characteristics and Fr number at10 places in natural, directly and indirectly impacted HPP cross-sections in the Virvyte River. To predict this influence Fr number criterion and number of hydrophytes are compared. The results of measurements and calculation, the association between functional habitat occurrence and Froude number (Kemp *et al.*;2000) indicate three distinct types of habitat response associated with HPP impact: negative, positive and non-signed or not impacted (see Fig 1). In pounded reaches nearby/ above HPP dam low Fr number habitats (0.04>Fr> 0.0007) are created and negative dam impact is observed. Only silt as bottom substrate and roots, marginal submerged plants and submerged, broad-leaved macrophytes are found in these river reaches (Table 1).

Table 1. Impact of HPP on flow environment in the Virvytė river

Location	Flow characteristics				$Fr = \frac{V^2}{gh}$	HPP impact on the habitat occurrence		
	With B, m	Depth h, m	Average velocity V, m/s	Bottom substrates		A number of hygrophyte species	Pond influence	HPP impact according to Fr
Above Baltininkai	13	1	1.5	Gravel	0.23	4	no	not impacted
Above Biržuvėnai	15	1	1.1	Gravel, cobles	0.12	8	no	not impacted
Above Sukončiai	20	1.5	0.4	Gravel, sand	0.04	8	no	negative
Pond of Baltininkai	300	1.5	0.1	Silt	0.0007	20	influenced	positive
Above Sukončiai	40	1.5	0.2	Silt	0.003	20	influenced	negative
Above Skleipiai	30	1.5	0.2	Silt	0.003	18	influenced	negative
Below Baltininkai	19	0.9	1.5	Gravel, sand	0.26	17	not directly influenced	positive
Below Juciai	9	1.2	1.1	Gravel	0.10	4	not directly influenced	positive
Pond of Sukončiai	25	0.9	0.3	Silt	0.01	6	influenced	non-signed
Below Kairiškiai	30	0.7	0.5	Sand gravel, cobbles	0.04	3	not directly influenced	negative
Below Gudai	30	1.2	0.4	Gravel	0.01	5	not directly influenced	negative

Habitats that tend to be associated to higher Froude Number (0.26>Fr>0.10) are sand and gravel or cobles. Some of them are natural reaches far above the pond not impacted by HPP, and below not directly influenced others. However, positive impact on environment below the dams is lessened by the number of hydrophytes only, and harmful impact of a surge wave is evident when turbines are operated.

4. A surge wave travel measurement in downstream reach of Angiriai HPP (case study)

Each switching of HPP turbines causes a sudden change of the flow discharge, depth and energy. A surge wave (mass transfer wave) results from the intensity of sudden change of the flow and produces sharp fluctuation of the water level and pressure as well as turbidity. The speed of water level fluctuation and the velocity of positive surge propagation are determined and the stress situation created by the surge on river flora and fauna downstream small Angiriai HPP is estimated. A large disturbance experiment, where a positive wave front resulting from an increase of initial sanitary flow rate Q_s $=0.4m^3$ /s to total flow rate Q_{tot} =10.4 m^3 /s moves downstream after the switch of turbines, is conducted (Fig 2).

Positive wave as an advancing wave front resulting from an increase of flow depth moving downstream the Angiriai HPP due to the switch on turbines is shown in Fig 2. The initial depth of water h_1 = 0.3m increases to h_2 = 1.13m and the Fr number changes from 0.03 to 0.113 after 53 min from the start of turbines nearly below the outflow of turbines in a stilling pool of the main canal**.** The maximum speed of water level increase $\Delta h / \Delta t$= 0.18 m/min=10.8 m/h is fixed on the second minute from the beginning. It creates additional pressure of about 200 kPa and can be a strong stressor factor for biological community of the river. At the distance of 0.47 km downstream the maximum water level increment decreases only to 0.16 m/ min and is fixed after 15 minutes. But when after 55 min the wave front reaches the third cross-section of the river (situated at 2.70 km downstream), the maximum of water level increment decreases to 0.03m/min = 1.80 m/h.

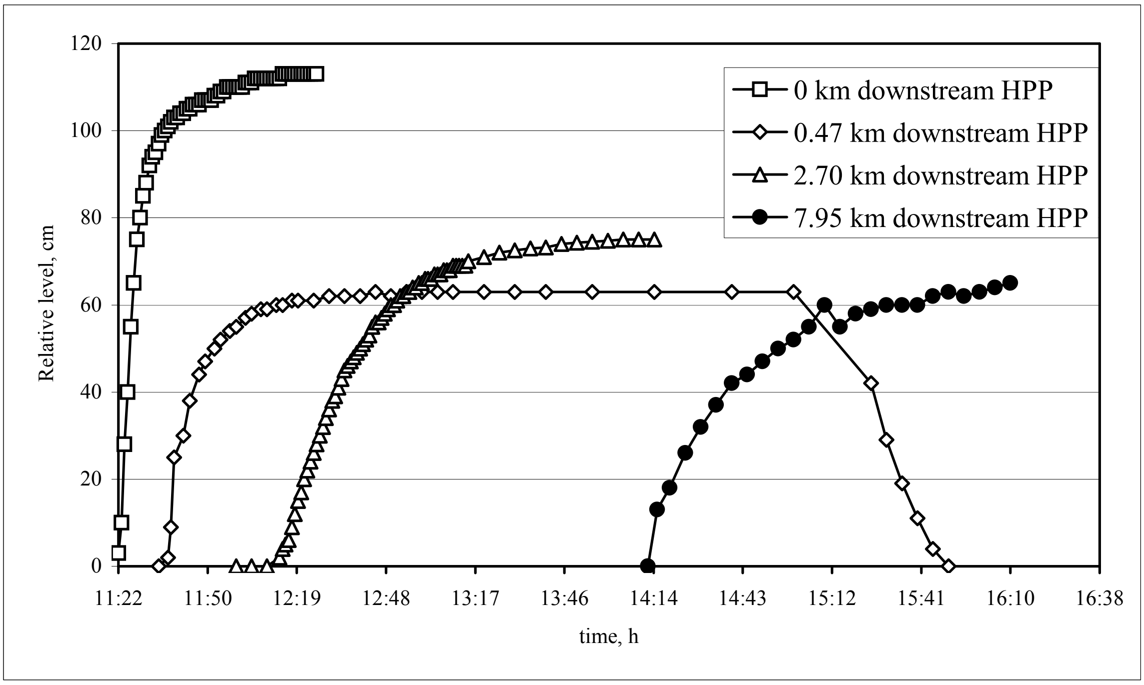

Fig 2. Positive wave propagation and water level fluctuation after the switch of turbines in downstream reaches of Angiriai HPP, 2009.08.13 (Q = 10.5 m^3/s; zero altitude 47.28 m)

In the last cross-section, situated at the distance of 7.95 km, the maximum increment of water level is fixed after 2 hours and it is 0.016 m/min or about 1m/h only. Thus, the water level fluctuation decelerates here about 10 times and wave impact becomes less dangerous for biological community. However, the amplitude of water level fluctuation depends on the cross-section area of the river canal and in this case is 0.60-1.13m. The surge velocity V_{srg} fluctuates over dozens of kilometers from 0.52 to 1.09 m/s depending on flow conditions in cross-sections and confirms the average value calculated by (4) formula. All these results confirm the law of stream energy conservation. According to this law, a positive surge can travel over very long distance without losing much energy because it is self – perpetuating (Chanson 2001). In natural and artificial channels wave front may travel damaging the downstream biota. It is evident that in practice rapid switch on HPP turbines operation must be avoided.

5. Conclusions

River flow in downstream reaches of HPP remains in initial bed and there are no evident changes, but dams and reservoirs may cause change in the environment though facility operations over a sustained period. The impact on habitat quality changes must be estimated by the hydraulic parameters such as velocity, water depth, turbulence and fluctuation of vortices regimes as well as by the Fr number, because its value depends upon the form of flow boundaries.

In the pounded reaches nearby or above HPP dams of the Virvyte River low Fr number habitats (0.04>Fr>

0.0007) are created and negative impact of the dam is observed.

A large disturbance experiment, where a positive wave front resulting from an increase of initial sanitary flow rate Q_s =0.4 m^3 /s to the total flow rate Q_{tot} = 10.4 m^3 /s moves downstream after the switch of turbines of Angiriai HPP on the Šušvė river, is conducted. The maximum speed of water level increase $\Delta h / \Delta t$ = 0.18 m/min=10.8 m/h is fixed on the second minute from the beginning. It creates additional pressure of about 200 kPa and can be a strong stressor factor for biological community of the river. It is evident that in practice rapid switch of HPP turbines operation must be avoided.

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