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SIMULATING THE INFLUENCE OF THE HEIGHT OF HPP DAMS ON THE ENVIRONMENTAL CONDITIONS IN SMALL RIVER VIRVYTE

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Abstract. In natural floodplains, the grassed areas usually entrap fine suspended sediments (wash products rich in nutrients) of the floodwater, thus contributing to the process of self-purification. However, hydroelectric power plants (HPPs), built with the purpose of employing the renewable energy, can worsen this process, it occurs if they pond the floodplains and decrease these grassed areas. In the present paper, the sediment deposition in the floodplains with existing weir heights is investigated. The mathematical-hydraulic model is used for it. The 12 km length interval of the river Virvyte, having three ponds was investigated. The average volume of sedimentation in this region is 500–2000 t/year, i.e. quite large. In the investigated region of the river Virvyte, the sediment deposition decreased by about 50%, due to the impact of a too high dam (H = 5.5 m) of the Kapėnai HPP.

Keywords: hydraulic modelling, HPP ponds, water pollution, sediment deposition.

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Introduction

To utilize the renewable energy, hydroelectric power plants (HPPs) are built in rivers. However, their weirs and ponds affect the natural conditions of the rivers, thus deteriorating the life conditions of water fauna and flora. Ponds have major impact on the river hydrology (Wang *et al.* 2011; Marčiulionienė *et al.* 2011).Weirs also disrupt the natural flow of sediments and organic materials. The organic silt is mostly retained in reservoirs, instead of fertilizing the downstream floodplains. In the reservoirs, anaerobic processes and algal populations tend to dominate, and eutrophication may occur if there is an excess of nutrients in the water and sediments (Povilaitis 2008). Thus, ecosystems can be affected to a large extent when the exchange of water and sediments becomes difficult or impossible and the water quality may get worse (Fraley *et al.* 2007; Hohensinner *et al.* 2004; Vaikasas, Dumbrauskas 2010; Rimkus, Vaikasas 2010). Therefore, it is necessary to analyse these processes and reduce their negative influence by choosing optimal methods of hydro-energy employment. This was the main aim of the present investigation.

The arrangement of ponds impacts such important factors, as the quality of water and the dynamics of sediment transport (Olli 2008). These complex processes depend on a number of factors. This paper presents the results of mathematical-hydraulic modelling of the influence of HPP ponds with various dam heights on the sediment deposition in valleys overflowed during the floods. The present investigation is based on the model of a 12-km interval of the small river Virvytė, where a HPP cascade includes three HPPs: Skleipiai, Kapėnai and Kairiškiai (Fig. 1).

When the dams are not too high and the riverbed volume is sufficient for arrangement of ponds, the valleys are inundated only during the floods. In the flooded meadows, the sediments washed from the fields settle steadily (the process here is much more intensive than in the river beds). Consequently, the quality of river water is improving greatly because the settled particles, brought from the adjacent agricultural lands and deposited here, are rich in adsorbed nutrients (Bakel 2006; Rijn 2007). On the contrary, when the dams are too high, some part of the valley area is always dammed and thus not grassed. In this case, the valley area, useful for sedimentation, decreases. Consequently, the water self-purification process decreases also, as the more significant part of sediments, containing pollutant materials, returns from the valley to the river flow. Therefore, the exceedingly high dams

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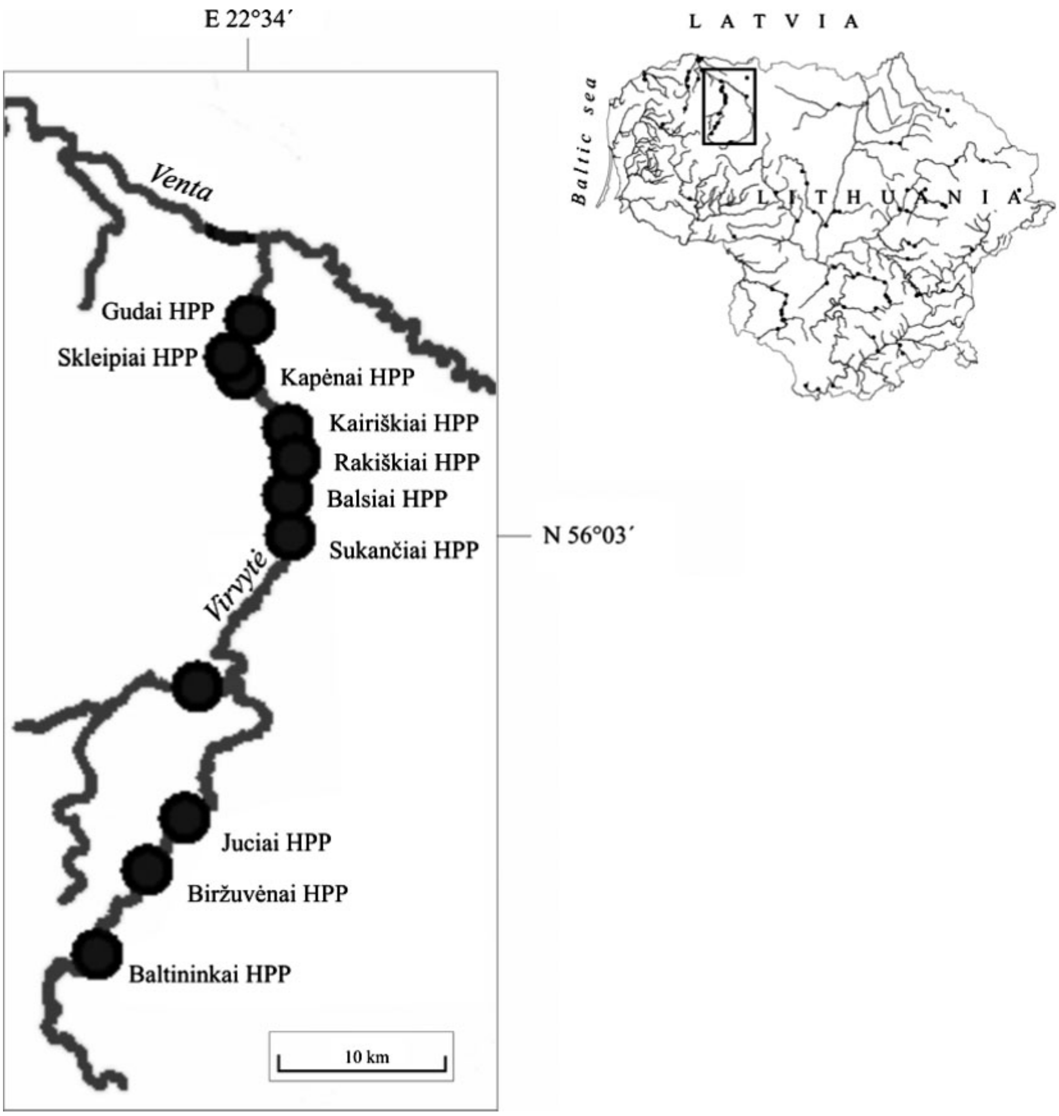

Fig. 1. HES cascades in the river Virvytė

worsen the water quality in the downward river reaches (Vastila *et al.* 2010).

We had to overcome some difficulties in modelling the sediment deposition in periodically flooded grass-covered valleys, since this process has not yet been sufficiently investigated. The necessary field investigations were performed during the floods in the river Nemunas delta and in flooded areas of the Nevėžis valley. A method for calculating sediment deposition in such areas was created (Rimkus *et al.* 2007).

In deep ponds, there are some factors that are unfavourable for the formation of water quality. The low stream velocities in large ponds create favourable conditions for algae and other small vegetation to grow. The decayed fine vegetation pollutes the water. Again, silt sinks to the bottom, although elevated flow velocities could lift it. The velocities increase during the daylong power regulation. With increased turbine discharge, the washed organic silt mixes with water and passes down. The oxidation of these organic materials decreases the amount of dissolved oxygen over a long interval of the river. This process in the Lithuanian rivers has already been discussed earlier (Vaidelienė, Michailov 2008; Zdankus *et al.* 2008).

Most ponds of the river Virvytė fill up only the riverbed, and only few of them overflow into the valley. In the modelled river interval, the pond of Kapėnai HES occupies 30 ha of a dammed valley. This decreases the sediment deposition in the valley. The main amount of sediments settled in the valley deposits during the frequent, although not large floods. In a modelled 50-year interval, an area of 60–70 ha was flooded most frequently. Therefore, it is natural that, in such a long period of time, the sedimentation decreased by half. The average sediment deposition in the valley strips near the riverbed makes 2–3 t/ha/year. The similar quantities were found during the field investigation in the flooded valley of the river Nevėžis (Vaikasas 2010).

This paper presents and discusses results of the above-mentioned mathematical hydraulic modelling of sediment retention in the floodplains and ponds with various weir heights.

1. Investigation method

The method of mathematical hydraulic modelling was used in this study to investigate the sedimentation process in the riverbeds and their valleys. The field investigations of sedimentation process and water quality are discussed in other papers (Rimkus, Vaikasas 1999, 2010; Rimkus *et al.* 2011). The known commercial models, for example, MIKE 21, were created to calculate the sediment movement on the sandy river bottoms; therefore, they are not suitable for grass-covered valleys. A numerical hydrodynamic model, elaborated and verified by the present authors, was employed for investigating the sediment deposition in the ponds and floodplains of the river Virvytė (Rimkus *et al.* 2007; Rimkus, Vaikasas 1999). This model was confirmed in investigations of natural sedimentation in the Nemunas delta valley. The actual sediment deposition in the meadows was found to be several times greater than the calculated one according the method used in commercial models. Therefore, special investigations of the sediment deposition were performed during floods in the Nemunas delta and in the flooded meadows of the river Nevėžis valley. Consequently, the following formulas for sedimentation were created (Rimkus, Vaikasas 2010; Rimkus *et al.* 2007):

$$D = \frac{k_{kor} w \bar{C}}{F}; \tag{1}$$

$$F = \frac{\bar{C}}{C_a} = \left(\frac{a}{h-a}\right)^z \left[\int_a^{h/2} \left(\frac{h-y}{y}\right)^z v_y dy + \int_{h/2}^{h} \exp(-4z(y/h-0.5)) v_y dy\right] \frac{1}{\int_0^h v_y dy}; \tag{2}$$

$$z = \frac{w}{\beta k u_*}, \tag{3}$$

where: D – sediment deposition rate per unit bottom area; k_{cor} – correction coefficient estimating the state of grasses; w – fall velocity of sediment particles in clear fluid; $\bar{C}$ – depth-averaged suspended sediment concentration; C_a – sediment concentration on the surface of grass layer; $a = 0.3h_{gr}$, – thickness of grass layer; h – water depth; v_y – flow velocity at a distance y from the bottom; $\beta = 0.6$, and $k = 0.4$ – von Karman number.

Some difficulties occurred also in choosing a formula for calculating the sediment deposition in the main canal of the river Virvytė. Most of the known formulas were constructed on the basis of laboratory investigations of sandy sediments. They are not valid for fine clay and silt particles (Rijn 2007). Therefore, we used the classical Zamarin formula, created for both fine and coarse particles:

$$C_{tr} = 0.022 \frac{v}{w_0} \sqrt{\frac{Riv}{w}}, \tag{4}$$

where: C_{tr} – transportable sediment concentration; v – average flow velocity; R – hydraulic radius; i – kinetic energy slope; $w_0 = 0.002$ if $w = <0.002$ m/s (for silt and clay) and $w_0 = w$ if $w \geq 0.002$ m/s (for sand).

The calculation of suspended sediment deposition within the regions investigated requires estimation of the stream velocities, which is most often done by using one-dimensional calculation methods. However, these methods determine only an average flow velocity and the sediment discharge in the floodplain as a whole. According to our model, created for estimating the sediment distribution across the valley, the river flow is divided into several strips with equal water discharges, and one-dimensional equations are employed in calculations. Consequently, the model turns to a quasi-two-dimensional one and, therefore, it can give more exact results. The application of real 2D models is very difficult, since, due to a complicated valley relief, a large number (several millions) of net points must be chosen, and the calculations take too much time. The work with such models is not efficient (particularly, when the flow and sediments discharges are variable). Therefore, our quasi-2D model was used. This enabled us to calculate the sediment deposition in a many-year period and to estimate thoroughly the influence of HPP ponds and weir heights on the quality of river water.

The data on suspended sediment concentrations during the floods were taken from the measurements at hydrometric posts (Vaikasas 2010). The investigations were performed with main four sediment fractions and particle diameters 0.001, 0.002, 0.005, and 0.01 mm.

2. Results and discussion

As mentioned above, the sedimentation in the inundated valley meadows reduces contamination of the river. When the weir of HPP dam is not too high, the valleys are overflowed only during sufficiently high floods. If a pond overflows in its lower part into the valley, the useful sediment retention area of the valley decreases, and thus the river self-cleaning capacity also reduces. For the ponds in Skleipiai and Kairiškiai, the riverbed is sufficient; however, in the Kapėnai pond, some part of the floodplain overflows in the valley. The calculation results show a considerable decrease of the sediment deposition in the valley in the lower region of this pond, as illustrated in Fig. 2 by the relations between the sediment deposition and water discharges.

Three groups of curves are plotted in Fig. 2. Thin lines depict the case where the HPP ponds are absent and the sediment deposition is great. Thick lines

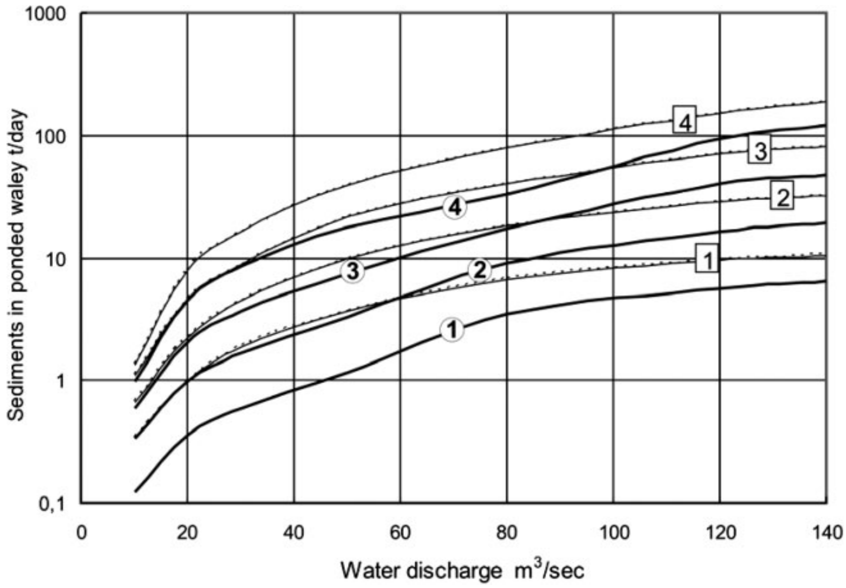

Fig. 2. Amount of deposited sediments in the investigated interval of the river Virvytė valley as a function of flood discharge: thin lines – dams are absent, thick lines – with all 3 HPP dams, dotted lines – only with a dam of Kairiškiai HPP. Particle diameters in the sediment fractions are 0.001 (1), 0.002 (2), 0.005 (3), and 0.01 (4) mm

indicate the case where all ponds are present in the investigated interval and the sediment deposition decreases intensively. During the high floods, the sediment deposition decreases almost by half and, during the small ones, even several times. The dotted lines show the case where only the Kairiškiai pond is equipped. Here, the sediment deposition is practically the same or even somewhat greater compared with the case without HPP dams. Thus, such a HPP has some positive influence, since even low dams slightly pond up the flood water levels.

The sediment deposition and retention in the inundated valley increase quickly with rising water discharges, since in this case the sediment discharge also increases, and the decrease of sediment concentration because of their deposition is then compensated in the main channel. In addition, the area of inundated valley increases with the flood. The floodplain area in the region of these three ponds during the flood of a 1% probability covers 400 ha. The deposition of coarse particles increases with discharge growing much more intensively, because the fall velocity of the particles is also much higher.

In Fig. 3, the deposited sediments are expressed as part of the total amount of sediments brought to the river. The deposition is quite intensive. When the large discharge flows, the deposition of fine sediments increases less intensively than in the case of sediments brought by the river. Therefore, the relative deposition of these sediments starts decreasing a little.

The arrangement of the Kapėnai pond decreases the sediment deposition in the valley more intensively during the relatively low floods, since this pond overflows the part of the valley which would be flooded by the low, but more frequent floods.

Fig. 4 depicts the longitudinal profile of the investigated interval of the river Virvytė during the floods with a water discharge of 20, 50, 100, and 150 m^3/s. These floods pond the water level below the HES and somewhat decrease the power of the turbines. In the Kapėnai pond, there is a greater area of cross-sections near the dam, and thus the water level along the river increases less than in the other two ponds. Therefore, the stream velocities in the ponds of Skleipiai and Kairiškiai are higher, and their water levels increase along the flow more intensively. This leads to the increased inundated area of the valley and increased sediment deposition. As a result, the floodplain meadows are more fertilized and the water quality of the Virvyte River is improved.

During high floods, the sediment deposition in the meadows of Virvyte is more intensive; however, such floods are rare. The lower flood discharges occur more frequently, and the significant part of sediments is deposited then. To estimate the influence of different floods, the calculations were performed for a long-term period. The results are shown in Fig. 5.

The amount of sediments deposited in a one-year period depends on the size of the flood. The most intensive deposition was observed during the large flood with a 1% probability in 1958. Some years, the floods were low and did not overflow in the valley. In this case, the processes of sediment deposition and retention do not proceed. When all three ponds are involved, the sediment retention decreases by about 50% due to the exceedingly high dam of Kapėnai HES. Thus, the volume of sediments deposited in the

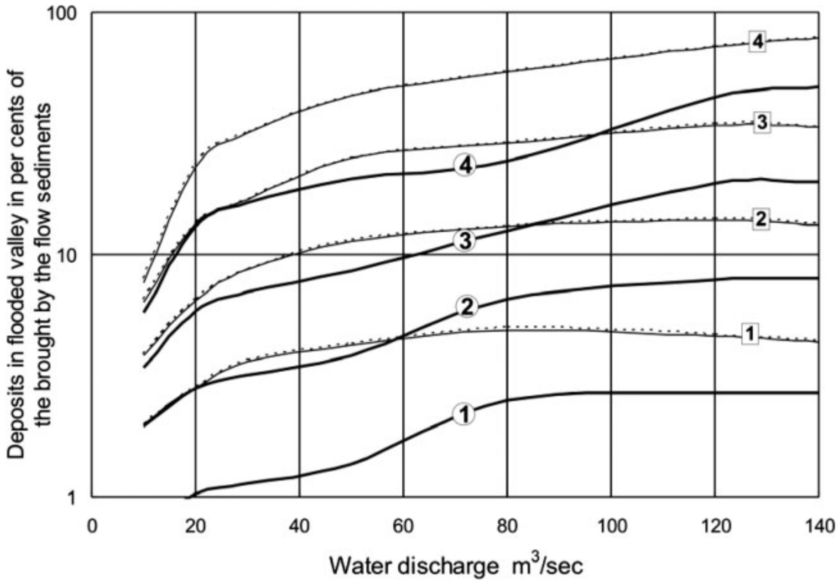

Fig. 3. Intensity of sediment deposition in the inundated valley as part of sediments brought by the river: thin lines – dams are absent, thick lines – with all 3 HPP dams, dotted lines – only with a dam in Kairiškiai HPP. Particle diameters in the sediment fractions were 0.001 (1), 0.002 (2), 0.005 (3), and 0.01 (4) mm

floodplain is quite large. Such amounts of sediments per unit floodplain area were found in field investigations (Rimkus, Vaikasas 2010; Rimkus *et al*. 2007). In periodically flooded meadows, the grasses actually entrap the sediments and favour self-cleaning of the rivers. Therefore, a decrease in the grassed areas worsens this natural process. This fact was also confirmed by other researchers (Jankowska-Huflejet 2006; Deng *et al*. 2007; Vaikasas, Dumbrauskas 2010; Lukianas *et al.* 2006). As one can see, in small rivers, high dams are not desirable from the ecological point of view; they can be important only for energetic purposes, for example, for the daylong regulation of power or for water energy accumulation. One rather large pond at the upper station of a cascade would be enough to successfully regulate the water discharge for the plants in the lower region of the river. Such a pond would better supply the local exchange of power demands, and all the necessary pike energy could not be transported from the system. This would reduce the energy losses in the electricity supply network.

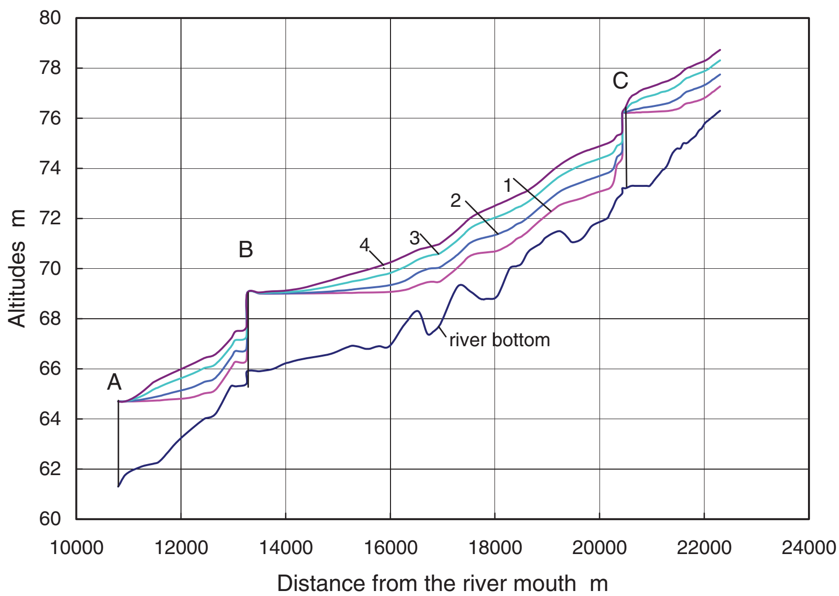

Fig. 4. Longitudinal profile of the investigated interval of the river Virvytė. Water levels of floods with water discharges of 20 (1), 50 (2), 100 (3), and 150 (4) m^3/sec. HES dams: A – Skleipiai, B – Kapėnai, and C – Kairiškiai

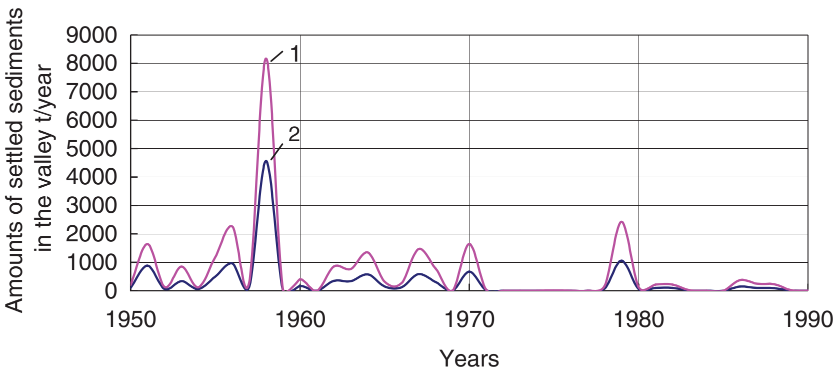

Fig. 5. Amounts of the sediments settled during a many-year period in the interval of Virvytė with the HPP ponds of Skleipiai, Kapėnai, and Kairiškiai: 1 – ponds are absent and 2 – all three ponds are involved

Ten hydropower stations built on the river Virvytė are grouped in two cascades. In the lower one, the upper station (Sukančiai) has a pond sufficient for a daylong power regulation. However, such a regulation and optimal energy production are impossible now, since these stations are equipped with only one or two large propeller-type turbines (for economic reasons). Usually, they operate at their maximum power, which is much higher than the one ensured by the river; otherwise, their efficiency coefficient would be too low. Having worked down the water level in the pond to a permissible limit, the power units are stopped, and only a sanitary discharge is allowed to pass until the pond is filled again. This situation was discussed by Zdankus *et al.* (2008), too. According to the investigations performed in the river Virvytė, such an intensive fluctuation regime is very unfavourable for the environment. The living fish is decreasing in number. Such unfavourable conditions were also found in other rivers (Fraley *et al.* 2007).

To improve this situation, at least one Kaplan-type turbine with a wide power regulation should be installed anew or replace the old one at each station. When designing the power stations on the river Virvytė, the necessity to install better turbines has not been considered, because the total power of all river stations was small compared with the power of the whole system. Therefore, the regulation of small HE power stations was not considered to be of significant importance. Moreover, no attention was paid to the ever-increasing hazard of ecological damage.

The installation of Kaplan-type turbines would be compensated economically in some period of time, since it would be not necessary to pass a sanitary discharge uselessly, when the utilized volume of pond is refilled. The turbines with a power regulation allow one to utilize almost the whole water discharge of the river, except the surplus flowing during the floods. In addition, this makes it possible to produce higher-value energy adapted to the usage exchange. In this way, the ecological and energetic demands will be coordinated. Therefore, it is even supposed that the erection of HPPs in small rivers can be also possible and useful (Hohensinner *et al.* 2004). However, a certain amount of rivers in each region must be left untouched, for preservation of natural environment.

Since the dams of the river Virvytė are not high, the stream velocities in its ponds during the floods are sufficient for transportation of fine sediments. Therefore, they are not silted by the deposition of silt and clay particles. Only coarse particles brought from the fields settle there. This fact has been proved by analysing the ground samples taken from the bottom of all ponds of HPPs.

Conclusions and recommendations

1. The ecological conditions in small rivers with the arranged HPPs are better, when their dams are not too high. Then the water in the ponds does not flood the valley permanently, and the periodically flooded grassed areas, which are of importance for self-cleaning of the river, do not decrease. The suspended sediments, brought by the water and containing the pollutant materials, are intensively settled there. However, from the energetic point of view, the existence of at least one rather large pond in the upper region of a HPP cascade is reasonable for regulating the energy production.

2. Concerning the HPPs in small rivers, the majority of propeller-type turbines without power regulation have been installed earlier. They operate periodically at their maximum power, which is the reason for large fluctuations of stream velocities and water depth. It is very harmful for the water fauna; therefore, it is necessary to modify them or to install additionally at least one Kaplan-type turbine. More perfect small turbines enable one to improve the employment of the river water flow. They recoup themselves due to the increased production of energy.

3. In deep ponds formed by high dams, the unfavourable conditions for algae and small water

vegetation are created. Therefore, high dams can be useful only in large rivers in the case of an unavoidable energetic need (for the flow energy regulation and accumulation). As an example of such an approach, the Kaunas HPP and the high-power hydro-accumulation station built in Lithuania can be considered. The accumulation of water energy will be particularly useful at a wider employment of unstable wind energy. However, the energetic and ecological needs should be coordinated. In most cases, a complex of problems has to be solved, which requires thorough scientific investigations and experimental projecting work in the future.

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