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MODELLING THE IMPACT OF SMALL HYDROPOWER DAM ON SEDIMENT RETENTION IN THE RIVER VIRVYTE

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Abstract. The hydroelectric power plants (HPP) are a valuable source of renewable energy; however they negatively impact the environmental conditions in the river. The paper presents investigation of the ways to coordinate these problems. The mathematical-hydraulic modeling is used to investigate sedimentation process in the riverbed and in the flooded valley. The sedimentation and sediment retention in the valleys is more intensive, when the HPP dams are not high ($H \leq 4$ m) and their ponds do not overflow into floodplains. The great sediment retention was estimated during the 1 % probability flood of 1958 (8000t/year) in the investigated interval of the river Virvyte. Having arranged 3 ponds in this reach, sediment retention decreased by about 50 %, as the height of Kapėnai HPP dam was too big. The sedimentation during the years of various water heights in this river interval has been 500-2000 t/year, i.e. quite heavy. Grass in the flooded meadows entrap the sediments and decrease the water contamination below dam.

Keywords: hydraulic modeling, HPP ponds, sedimentation in grass.

1. Introduction

The hydroelectric power plants (HPP), which are built on the rivers, appear to be the source of renewable energy, and this makes them valuable. However, they worsen the water self-purification and change the living conditions of water flora and fauna (Bruno 2009; Lopardo and Seone 2004). Creation of new equilibrium mostly is time consuming or even impossible process. Therefore, the coordination of environmental and hydro energetical needs is necessary. The presented work aims to investigate the ways of this coordination.

The processes of the water quality development and sediment transport in ponds and in natural rivers are quite different. In this work mathematical-hydraulic modeling of sediment deposition in the valleys of small rivers overflowed during the floods is used to study these processes. The influence of ponds with different dam heights is also investigated. The investigations were conducted in the 12 km interval of the river Virvyte with 3 HPP: Skleipiai, Kapėnai and Kairiškiai (Fig.1). The selection of the interval was based on the availability of riverbed measurements necessary for modeling.

When the pond does not overflow into the valleys, the floodplain meadows are inundated only during the floods. Then the sediments washed from fields settle intensively in the grasses, and water quality is improved greatly, as the particles washed from agricultural land are deposited (Habersack *et al.* 2008; Jankowska-Huflejet 2006; Lukianas *et al.* 2006). When the dams are high, a part of floodplains is always flooded, and not grassed, and then the sediment deposition decreases. Consequently, high dams worsen the water quality in the rivers.

An especially developed mathematical model is employed for modeling of sediment deposition in flooded meadows (Rimkus *et al*. 2007). The already known models (MIKE 11 or MIKE 21) cannot be applied, as they calculate only movement of sandy particles and are not suitable for grass-covered areas, where the suspended sediment deposition is several times greater.

Deep ponds have unfavorable conditions for water quality due to intensive growing of algae and small vegetation. The decayed fine vegetation becomes water pollutants. The velocities increased during the daylong power regulation can lift the silt, which deposited on the bottom. The silt, washed by increased water discharges, passes down. Oxidation of this material reduces the amount of dissolved oxygen in a long strip of the river. This process in Lithuanian rivers has been already discussed (Vaidelienė *et al.* 2008; Ždankus 2008; Ždankus *et al*. 2000, 2005, 2008; Sabas 2005).

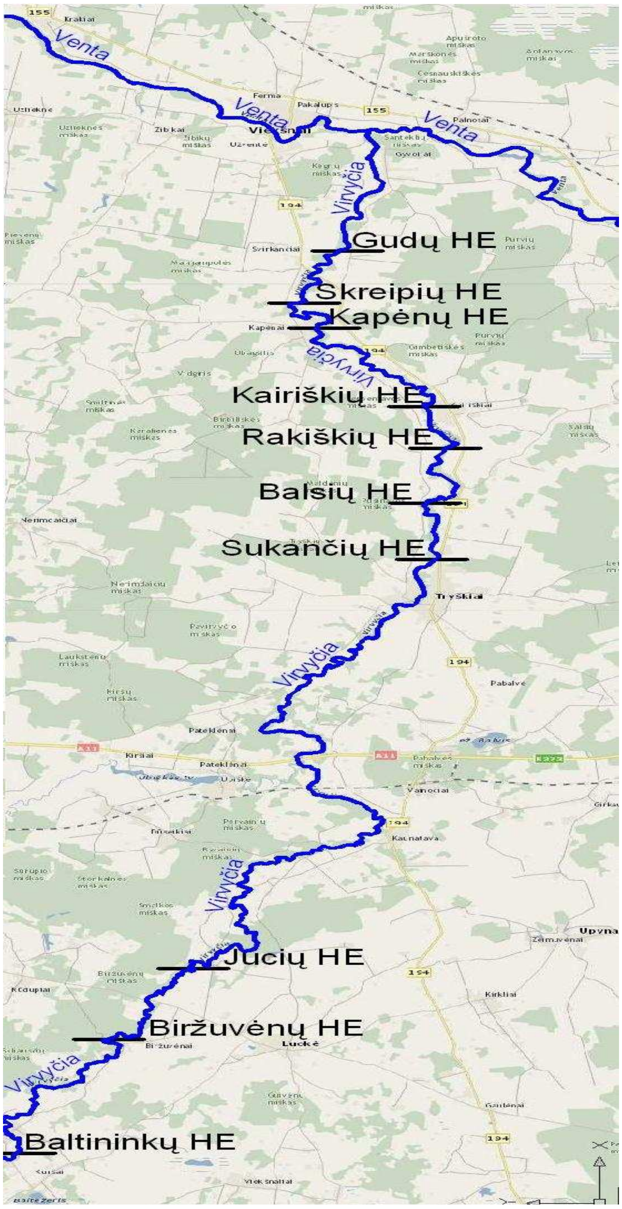

Fig 1. HPP cascade on the river Virvyte

Most ponds of the river Virvyte fill up the riverbed only; few of them overflow some into the valley. In the modeled interval, Kapėnai HPP pond occupies 30 ha of the floodplain. In the 50-year interval, the area of 60-70 ha has been flooded most frequently. Therefore, in this interval sedimentation naturally decreases in half. The average sediment deposition in the valley near the riverbed is found equal to 2-3 t/year. Investigations have established such quantity in the flooded valley of the river Nevėžis too.

The article discusses the results of the above mentioned mathematical-hydraulic modeling.

2. Method of investigations

The already made and verified mathematical-hydraulic model (Rimkus *et al*. 2007; Rimkus and Vaikasas, 1999a, b) is employed for investigation of sediment deposition in the river Virvyte. The other known commercial models are created for sandy river bottom, where the sediment deposition is several times lower than that in the grassed areas. That has been confirmed by natural sedimentation investigations in the Nemunas delta valley (Rimkus and Vaikasas 2010; Vaikasas and Dumbrauskas 2010). Therefore, the special investigations of sediment deposition have been performed during the floods in the Nemunas delta and in the flooded meadows of the river Nevėžis. Consequently, the following formula is created (Rimkus 2009; Rimkus *et al*, 2007):

$$D = k_{kor} w\overline{C} / F , \quad (1)$$

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

$$z = \frac{w}{\beta k u_*}, \quad (3)$$

where D - sediment deposition rate per unit of the bottom area, k_{cor}- correction coefficient estimating the state of grasses, w –velocity of sediment particles' fall, $\overline{C}$ - depth-average suspended sediment concentration, C_a - sediment concentration at the surface of grass layer, α = 3.3 h_{gr}, h_{gr}- thickness of grass layer, h - water depth, v_y- flow velocity at the distance y from the bottom, β = 0.6, k = 0.4 - Van Karman number.

Some difficulties occur in choosing the formula for sediment deposition calculations in the river Virvyte. Most of the known formulas have been created according to the laboratory investigations of sandy sediments. Therefore, they are not valid for clay and silt particles. The classical Zamarin's formula created for fine and coarse particles has been chosen:

$$C_{tr} = 0{,}022 \frac{v}{w_0} \sqrt{\frac{Riv}{w}} , \quad (4)$$

where C_{tr}- transportable sediment concentration, ν - average flow velocity, R - Hydraulic radius, i- kinetic energy gradient, w_0 = 0.002 when w < 0.002 m/s (for silt and clay) $w_0 = w$ when $w \geq 0.002$ m/s (for sand).

Calculation of suspended sediment deposition requires estimation of the distribution of stream velocities. The one-dimensional calculation methods are used for this purpose most often (MIKE 11). However, they estimate only average flow velocity and total sediment discharge. To estimate the sediment distribution across the valley, the river flow is divided into the strips with equal water discharges, for which the one-dimensional formulas are employed. Consequently, the model becomes quasi two-dimensional and, therefore, it can give more exact results. Employment of real 2D models is being very difficult, as for complicated valley relief, the necessary large number (several millions) of net points and time consuming calculations. The work with such models is not operative (particularly when the flow discharge is variable). Therefore, specially developed quasi two-dimensional model has been used in this work. This enables to calculate the sediment deposition in many-year period, and to estimate more thoroughly the influence of HES ponds on the river water quality.

During the floods the suspended sediment concentration data is taken at the hydrometric post in Smalininkai. Investigations are performed with 4 sediment fractions with particle diameters of 0.001, 0.002, 0.005 and 0.01 mm.

3. Results and discussion

The sediment deposition in the flooded meadows of valleys reduces the water contamination, if the weir of HPP is not too high and the valleys are flooded only during the sufficiently high floods. For Skleipiai and Kairiškiai ponds the riverbed is sufficient, however, the pond of Kapėnai overflows some part of the valley meadows. Therefore, the calculations show considerable decrease of sediment deposition there, which is especially large, when the water discharge is low. It is shown in Fig.2.

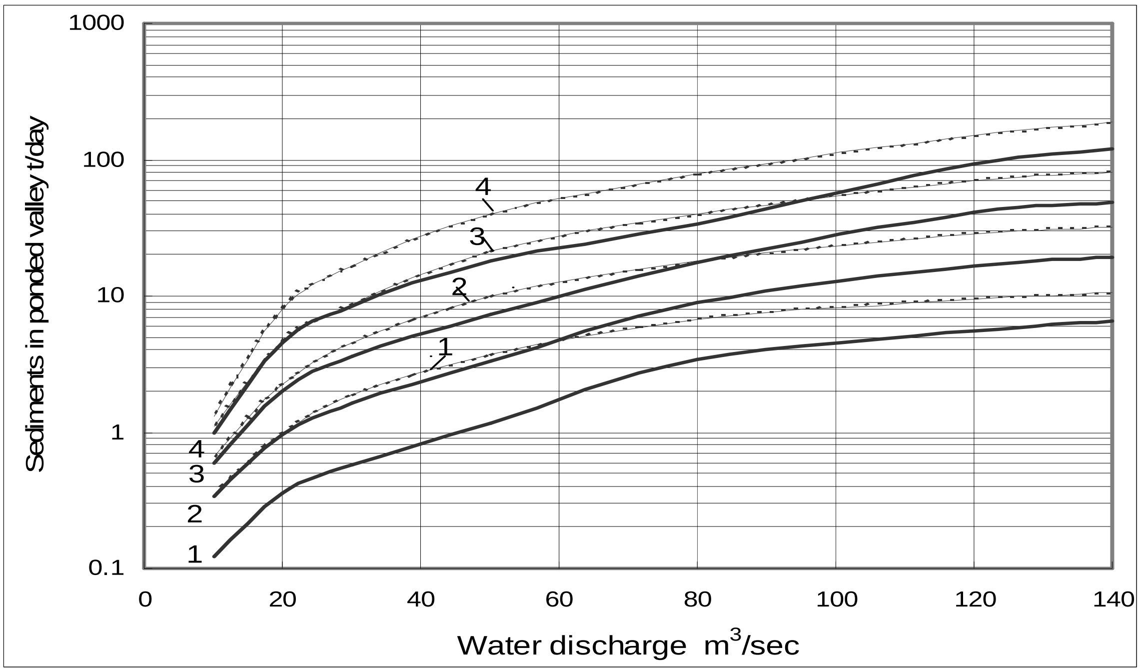

Fig 2. Dependences of the amount of deposited sediments in the investigated interval of the river Virvyte valley on the discharge of floods: thin lines – no dams, thick lines – with all 3 HES dams, dotted lines – only with dam of Kairiškiai HES. Diameters of sediment fraction particles: 1 – 0.001, 2 – 0.002, 3 – 0.005, 4 – 0.01 mm

Three investigated cases of the river ponds are presented in Fig.2. Thin lines show the sediment deposition in the case of pristine river, when there are no ponds. Thick lines indicate the variant with all three ponds, when the sediment deposition decreases intensively. During high floods sedimentation decreases almost to half, and during the small ones – even several times. The dotted lines indicate the variant, when only the Kairiškiai pond is constructed. In this case the sedimentation is practically the same or even a little greater than that in not ponded river, as even low dam ponds give some raise to the flood water level.

In the flooded meadows the sedimentation increases quickly with the growing water discharge, as the inundated area of valley increases also. Deposition of coarse particles is much more intensive than that of fine ones, as their falling velocity is also much higher.

Fig 3 presents the calculation of the amount of sediment deposition as part of the sediments transported by the river. The deposited part is quite large. When the discharges are high, the sediment deposition increases less intensively, than that of the ones brought by the river, therefore, relative deposition decreases. The Kapėnai pond decreases the sediment deposition more intensively, when lower flood discharges flow, as this pond includes the part of valley, which would be grassed during the low floods.

In Fig.4 the longitudinal profile of the investigated interval during the floods with the discharges equal to 20, 50, 100 and 150 m^3/s is plotted. These floods pond the water level below the HES, and some decrease the power of the turbines. In the pond Kapėnai, this has the great area of cross-sections near the dam, the water level increases along the river less than in the other two ponds.

Therefore, the stream velocities in the ponds of Skleipiai and Kairiškiai are higher, and the water level increases along the flow more intensively. It leads to the increased inundated area of the valley, and the sediment deposition there. As a result, the meadows are more fertilized and the water quality is improved.

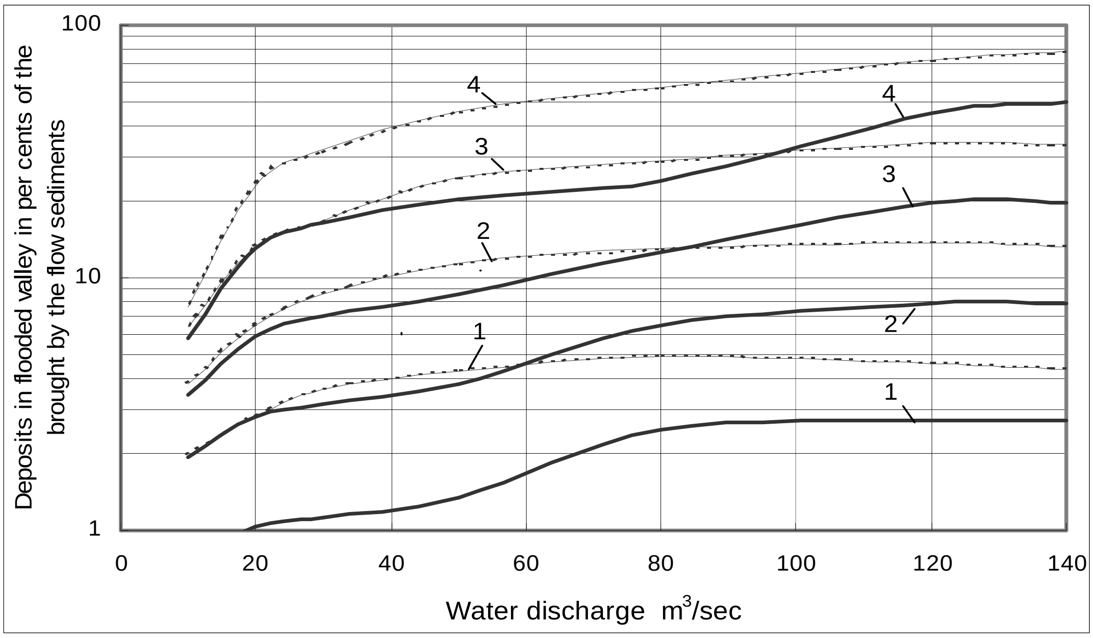

Fig 3. Intensity of sediment, brought by the river, deposition in the inundated valley (in percent): thin lines – no dams, thick lines – with all 3 HES dams, dotted lines – only with dam in Kairiškiai HES. Diameters of sediment fraction particles: 1 – 0.001, 2 – 0.002, 3 – 0.005, 4 – 0.01 mm.

During the high floods the sediment deposition in the meadows of the Virvyte is more intensive; however, such floods are rare. Lower flood discharges occur more frequently; therefore, the significant part of sediments is deposited then. For estimation of the influence of changing floods, the calculations have been performed for long-term period. The results are shown in figure 5. The sediment deposition during a flood depends on its size. The most intensive deposition was during the high and long-time flood with 1 % probability in 1958. In the years when the floods were low and did not overflow in the valley, there was no sediment deposition. The ponds, arranged in the investigated river interval, decrease the sediment deposition by about 50 % due to too high dam of Kapėnai HPP. The sediment deposition in the floodplains is quite large. Such amounts of sediments in the unit of valley area have also been found by field investigations. The grasses in flooded meadows really entrap the sediments and help the self-cleaning of rivers. Therefore, the decrease of grassed areas worsens this natural process.

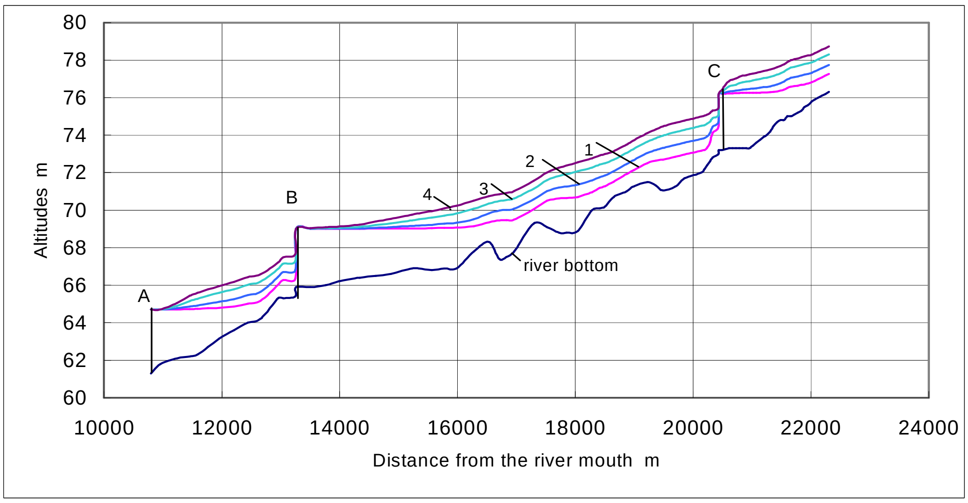

Fig 4. Longitudinal profile of the investigated interval of the river Virvyte. Water levels of floods with water discharges: 1 – 20 m^3/sec, 2 – 50 m^3/sec, 3 - 100 m^3/sec, 4 - 150 m^3/sec. HES dams: A - Skleipiai, B – Kapėnai, C – Kairiškiai

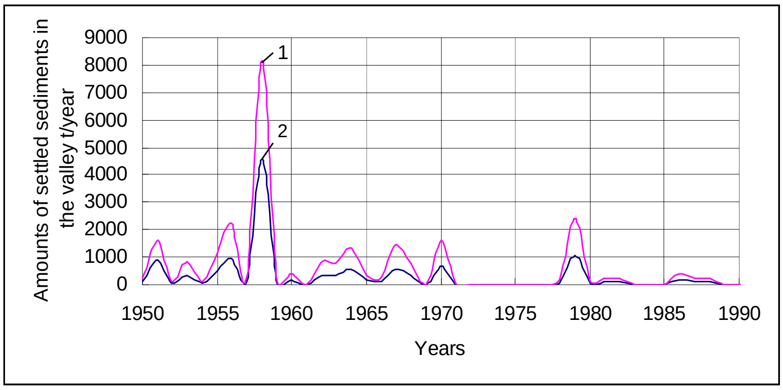

Fig 5. Amounts of settled sediments during the many-year period in the interval of the river Virvyte with the ponds of Skleipiai, Kapėnai and Kairiškiai: 1 – no ponds, 2 – there are all 3 ponds

The high dams in small rivers are not desirable in ecological aspect and can be necessary only for energetic needs, for example for the daylong regulation of power or for water energy accumulation. For this aim, the erection of one somewhat larger pond in the upper station of the cascade would be useful, which could regulate the water discharge for the lower existing plants. That would better meet the demand of local power exchange, and all the necessary pike energy could not be transported from the system. It would reduce the energy losses in the electrical network.

On the river Virvyte 10 HPP are built and grouped in two cascades. In the lower one, the upper station (Sukončiai) has the pond sufficient for daylong power regulation. However, at present it is impossible, as all stations of the cascade have only 1-2 propeller type turbines. They can operate only at their maximum power; otherwise, their efficiency coefficient would be too low. Having worked the pond down to the permissible level, the HPP is stopped, and the sanitary discharge is passed, until the pond is filled again. Such intensively fluctuating regime is very unfavorable for environment. The living fish decreases in amount.

It is necessary to change or install at least one Kaplan type turbine in the each station with optimally chosen power and real power regulation. When the power stations on the river Virvyte were designed, the necessity to install better turbines was not foreseen, as the summary power of all river stations was small in comparison with the power of the whole system. Therefore, the regulation of small HE power was not considered to be very important. Also, no attention was paid to the possible ecological damage.

The installation of Kaplan type turbines buys off economically during some time, as it is not necessary to pass uselessly the sanitary discharge, when the utilized volume of pond is refilled. Possession of regulated power turbines allows to use the almost whole river water discharges except the surplus flowing during the floods. In addition, it is possible to produce higher value energy, adapted to the usage exchanges. In this way the ecologic and energetic demands can be coordinated.

As the dams on the river Virvytė are not high, the stream velocities in the ponds during the floods are sufficiently high. Therefore, they are not silted by deposition of silt and clay particles. Only the coarse particles brought from the fields settle there. That was established by taking ground samples from the bottom. Intensity of the deposition depends on the velocities developed during the floods. For investigation of this process, the sediment deposition during the time period from 1950 till 1992 was calculated. The results, i.e. the average sediment deposition in one year, are plotted in Fig 6.

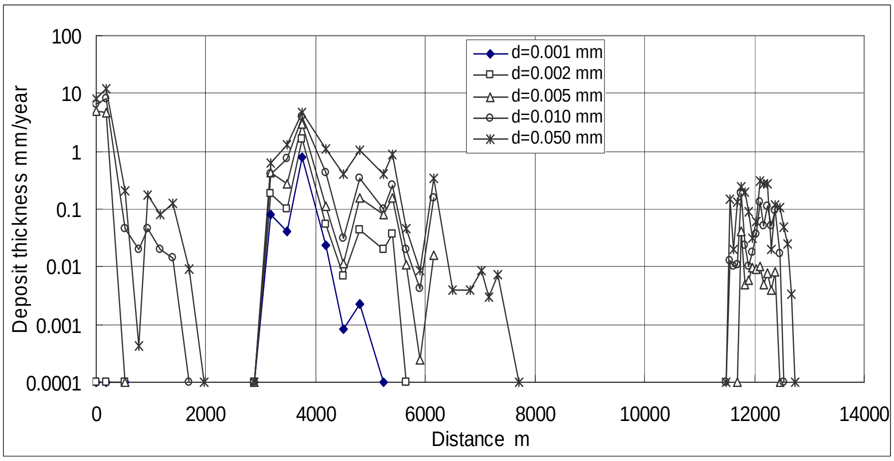

Fig 6. Deposition of 5 sediment fractions with different diameters in floodplain part of ponds in Skleipiai, Kapėnai and Kairiškiai

In the ponds, which do not overflow in the valley, the low velocities are higher; therefore, silt and clay particles are transported through entire pond. Only the sand particles with $d \geq 0.02$ mm are deposited near the dam, where the velocities are the lowest ones e.g. in Kairiškiai and Skleipiai ponds. In the pond Kapėnai, where the dam is higher, the velocities are lower. In this pond the silt and clay particles are also deposited near the dam. The deposition of sand particles begins at about 4500 m from the dam. In the river Virvyte there are two such larger ponds, other of them are similar to the Kairiškiai one, where the sand sediment deposition takes place only near the dam.

The examples of sediments have been taken from all ponds of the Virvyte. The particles with d=0.05 mm prevail. Consequently, ponds in the river Virvyte are not silted and decrease of water quality because of algae growing is impossible.

4. Conclusions and recommendations

Ecological conditions in small rivers used for hydro energy production are better, when the arranged ponds do not flood the valley. Then the area of periodically flooded meadows is not decreased. The suspended sediments, brought from fields, are intensively settled there. It is very important to self-cleaning of water. However, for energetic needs one larger pond is desirable in upper of HPP cascade for regulation of energy production.

In small rivers the propeller type turbines without power regulation are mostly used. They work at their maximum power periodically, what creates a large fluctuation of stream velocity and water depth that is very harmful for water flora and fauna. It is necessary to change or to install anew at least one Kaplan type turbine. It enables to use the river flow better. The increased energy production will buy off the expenses.

In the deep ponds, made by high dams, the favorable conditions for algae and small water vegetation growing are formed. It increases the water contamination with organic materials and the use of dissolved oxygen. Therefore, the high dams can be useful only in large rivers in the case of unavoidable energetic need (for the energy regulation and accumulation}. The example in Lithuania is the Kaunas HES and the hydro accumulation station located up the river. Accumulation of water energy is particularly useful, when the employment of unstable wind energy starts.

Coordination of the energetic and ecological needs is necessary. It is often a complex problem; therefore, the thorough scientific investigations and experimental projecting works are necessary in the future.

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