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Mathematical Modeling of the Suspended Sediment Dynamics in the Riverbeds and Valleys of Lithuanian Rivers and Their Deltas

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1. Introduction

Flooded river valley meadows particularly in their deltas are very important for water quality and river ecology, as growing there grasses entrap the flow sediments and sediment bond chemical materials brought by river. Consequently the water of seas, gulfs and lagoons becomes much clearer. The river flow bring from the river-basin area the washed from agriculture fields ground, so called "wash load", which contain many fine clay particles with adsorbed organic and nutrient materials as nitrogen phosphorus or even heavy metals. The suspended sediment load in significant part is brought into the valleys, where its deposition is going on. So the water quality in the rivers and seas is improved.

It was estimated that in the Nemunas delta during the period 1950 – 1981 it got deposited about 250 t potassium, 950 t phosphorus, 38000 t of calcium, and 147000 t organic matter rich with nitrogen (Vaikasas et al. 1997). It did not get in the Curonian Lagoon and the Baltic Sea (Fig. 1). Nevertheless, the grass–covered floodplains and deltas are often separated from rivers by dikes for intensive agriculture or other purposes. When such systems are designed, it is necessary to model sediment deposition in these separated areas to estimate the future increase of water contamination of the rivers and their receivers: gulfs and seas. However, the calculation methods used in the known mathematical models are adapted for flow over the sandy river bottom only (Bixio & Defina, 2004). Calibration results of the mathematical model of the river Nemunas delta with common sediment deposition formulae for riverbed flows did not correspond to the data of measurements (Rimkus & Vaikasas, 1997). Sediment deposition in the grassed floodplains was several times greater than on the sandy beds, as in the meadows there are other boundary conditions much more favourable for sediment deposition. Therefore the calculated increase of water contamination would be much less than the possible real. Consequently, it was necessary to study the peculiarities of flow and sediment motion under these conditions as well as to work out the sediment deposition calculation formulae, suitable for calculations on the new created mathematical model.

Intensive sediment deposition in grassed floodplains was estimated and significant reduce of nutrients was found in many other rivers (Large & Petts, 1994; Fustec et al., 1991; Haycock & Burt, 1990, 1991; Middelkoep & Haselen, 1999). The decrease of sediment-bound phosphorus and nitrogen reached even 80-87% (Jankowska, 2006; Lamsodis & Vaikasas, 2005). It was also stated that accurate prediction of the movement and deposition calculation of muddy sediments is highly desirable, however knowledge of these complex objects is limited, and there is no generally accepted formula for accurate calculation of sediment transport rate (Soulsby et al., 2010).

The focus of our studies was processes of suspended sediment deposition in the flooded delta of the river Nemunas and in the grassed floodplain of the river Nevėžis and the small river Virvytė.

Investigations of sediment motion analysis in the Nemunas delta showed, that the suspended sediment deposition in flooded valley meadows was very intensive. It reaches about 80% of summary sediments bought to the delta by river flow. That is due to the favourable conditions for sediment deposition in the delta. The river flow of the Nemunas in its delta is divided in two parts: the part overflowing in the wide valley and the part remaining to flow further along the riverbed. During the floods, particularly the large ones, flow velocities in the riverbed below this overflow in the valley are hardly decreased; therefore the sandy sediments are intensively deposited here. They pond the water level higher and increase the overflow into the valley, where the deposition of fine sediments is hardly increased also.

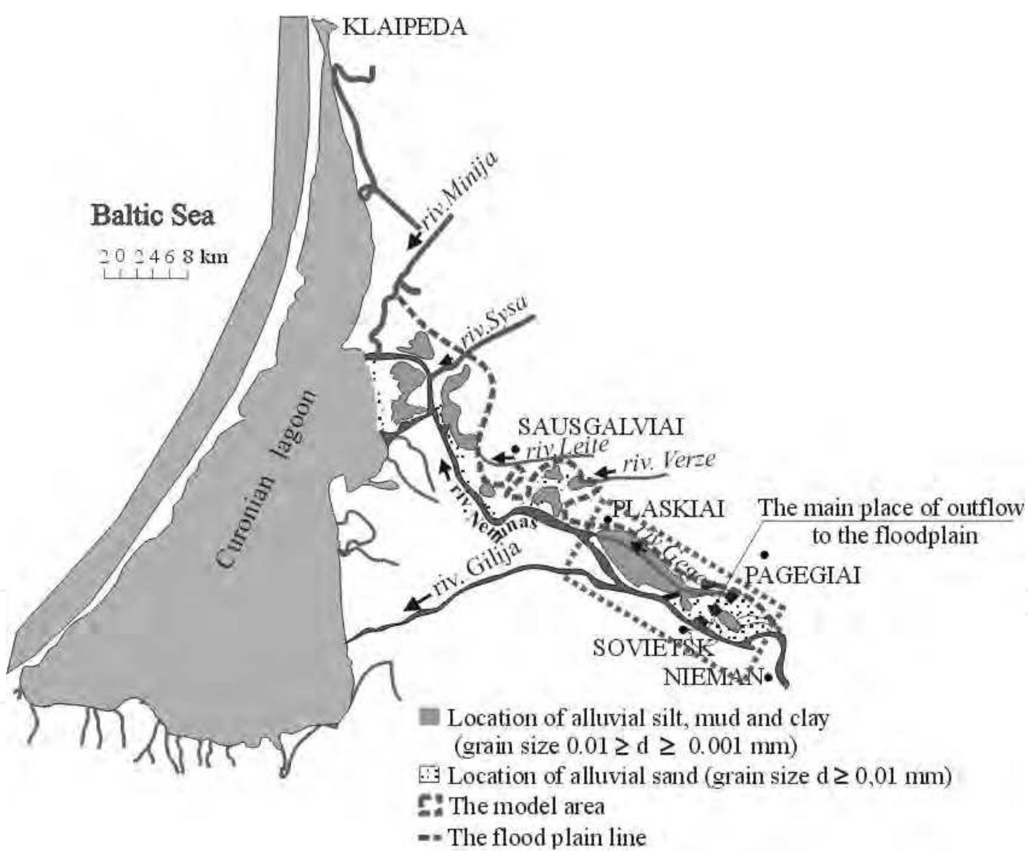

Fig. 1. Scheme of floodplain of the Nemunas delta and the Curonian Lagoon (The model area is indicated by a rectangle)

After the maximal water discharges of floods and between them, the deposited large amounts of sediments are washed off and leveled. This process has been modeled in the Nemunas delta for 50 years with various flood intensities. Consequently the dynamics of sediment motion in the riverbed and valley flows has been investigated.

In the flooded meadows of the river Nevėžis the suspended sediment deposition in grassed areas has been investigated (Vaikasas, 2010). The received data were employed for calibration of new formulae for the calculation of sediment deposition in grassed valleys of plane Lithuanian rivers.

In the small river Virvyte the sedimentation process in the riverbed and in flooded valley has been investigated under the conditions, when the cascade of hydropower plants along the whole river was build, which led to the modified conditions for water flora and fauna life. The hydro energetic plants worsened the ecological conditions of river, therefore the coordination ways of environmental and water energy employing needs were studied.

2. Methods of investigation

The sediment deposition in the riverbeds and floodplains in investigated objects has been estimated by calculation of deposited sediment amounts for the period 1950 – 1991, for which the hydrometric data about the sediment concentrations was available. During this time of investigations the periods with high and low floods were observed, then on the bottom of riverbed the sediments were either accumulated from year to year or washed. Subsequently the river became either more shallow or deeper, also the water levels during the floods were changing accordingly. The discharge of water overflowing into the valley depends on these water levels. Consequently during these periods the sediment deposition in the valley was also changing. By calculations for long period the average data of sediment deposition have been received.

According to calculations, during the high floods the riverbed below the places of water overflow in the valley was filed with sediments almost fully, as the flow velocity decreased there significantly, and the flow was not able to bring the sediments further. Such were the floods in 1951, 1958 and 1979. The water overflow into the valley and sediment deposition was very increased then. During the sinking of flood and after it the accumulated sediment layer in this strip was quickly washed out and spread below. The water flow remains normal.

Sediment deposition calculations were performed for 4 sediment fractions found by investigations. Their particle diameters were 0.005, 0.01, 0.02 and 0.1 mm. These are the sediment particles from clay to fine sand. According to investigations of hydrometric stations the concentrations of these sediment fractions fluctuated in large diapason – from 3 to 100 mg/l. Their measured meanings were employed for calculations.

Sediment deposition intensity depends on the flood size. During low floods when small water discharge flows; all sediments brought into the valley get settled. With increasing floods the certain part of sediments is brought to the end of investigated valley interval and returned to the riverbed. Therefore for estimation of this process the investigations were necessary to be continued in long term period.

Sediment deposition in the Nemunas valley was calculated applying our own hydraulic-mathematical model "DELTA" created for the study of the Nemunas delta (Fig. 2) (Rimkus et al., 2004, 2007). The known mathematical models (MIKE 21 1995) were not applicable for our purpose because they are not adapted for sediment deposition calculations in the flooded meadows, for which the special formulae are to be applied.

For riverbed flows it is characteristic the bottom sediment load with high sediment concentration. The sediment deposition process begins when the flow in this bottom sediment layer is saturated, i.e. when the transportable sediment concentration or critical flow velocity is achieved. The concept of critical velocity or transportable concentration cannot be applied for sediment deposition calculations for flow with grass-covered bottoms, where neither the bed load of sediments nor high concentrations necessary for flow saturation are observed. The unique sediment deposition is constantly going on at the bottom in the flow over grass. Having measured the water turbidity, it was determined that at the grass level suspended sediment concentration exceeded the average concentration by only about 1.2 times, while the concentration near the sandy bottom of the river Minija (tributary of the Nemunas River in its delta) was eight times higher (Vaikasas & Rimkus, 1996). Consequently, the boundary conditions for sediment deposition in riverbed on grassed flood plains are quite different. Therefore the calculation equations, in both cases must be different as well.

The ability of grasses to entrap the sediment was already noticed earlier (Barfield et al., 1979, Thornton et al., 1997; Pasche & Rouve, 1984; Cristiansen & Wiberg, 1997; Carpena et al., 1999; Deletic, 2001). However the sedimentation process in grassed food plains was yet not investigated properly.

Method for calculation of sediment deposition in the grass-covered floodplain, proposed by Rimkus, was created with estimation of grass ability to entrap the sediments (Rimkus et al., 2007). Because of the low flow velocity between the grasses, the sediment deposition in them becomes similar to the deposition in still water. It is proportional to the fall velocity of sediment particles and on the sediment concentration between the grasses, which is formed by concentration in the flow at the grass layer. Therefore the sediment deposition into the unit of bottom area can be expressed as follows:

$$D = k_{cor} w C_b \tag{1}$$

where w – the fall velocity of sediment particles, C_b – sediment concentration at the flow bottom, i.e. at the surface of grass layer, k_{cor} – correction coefficient depending on the state of grasses; for the luxuriant grass it is greater.

The fall velocity of sediment particles depends mostly on their diameter. To estimate it, the composition of sediment particles must be known; therefore the water examples containing suspended sediments are taken during the floods. In natural water samples, fine sediments usually make the aggregates. During the laboratory experiments, the aggregates commonly are destroyed, and the physical sediment composition is received. However for cohesive sediment deposition calculations the deposition of aggregates must be estimated, therefore the experiments of sediment composition for this aim is to be performed of natural water samples with non-destroyed aggregates. Then the aggregates receive the equivalent diameter of sandy particles. It gives the real fall velocity of aggregates (Pukštas & Vaikasas, 2005).

Usually sediment concentration in the flow is expressed by average concentration $\overline{C}$; therefore it is necessary to estimate their ratio $F = \overline{C} / C_b$. Then formula (1) changes so:

$$D = k_{cor} w \overline{C} / F \tag{2}$$

For calculation of ratio F the next formula was derived:

$$F = \left(\frac{a}{h-a}\right)^z \left[\int_a^h \left(\frac{h-y}{y}\right)^z v_y dy\right] \cdot \frac{1}{\int_a^h v_y dy}, \quad z = \frac{w}{\beta k u_*}. \tag{3}$$

where h – water depth, y - distance of investigated point from the bottom, v_y – water velocity at the distance y from the bottom, $a=0.3h_{gr}$, h_{gr} – thickness of grass layer, k=0.4 – Van Karman number, z – Rouse number, β - ratio of the sediment and momentum diffusion coefficients, u_* - shear velocity.

For calculation of ratio F, the velocity distribution along the water depth is necessary. This distribution can be accepted, for example, as logarithmic. The vertical velocity distribution depends on the flow turbulence distribution, which depends on the boundary conditions. In the width valleys this conditions are simple and similar to the ones existing in wide enough experimental channels with grass-covered bottom, in which the logarithmic distribution of velocities is found (Kouwen & Unny, 1973; Christensen, 1985; Temple, 1986; Kouwen, 1987; Yurchuk, 1999). Such velocity distribution was used in our model. For fine clay sediments, it is received F=1.

This sediment deposition calculation method is described in detail in the published articles (Rimkus et al., 2007; Rimkus & Vaikasas, 1999). Sediment deposition calculations were performed according these formulae.

To calculate sediment motion in the Nemunas riverbed it was necessary to chose the formulae for calculation of discharges of bottom and suspended sediments. Difficulty was, that mostly they were derived and therefore are suitable for sediment particles coarser than 1 mm, while in the Nemunas Delta they are finer. The formulas of van Rijn (1993) was chosen, which are suitable and for particles with diameter equal to 0.2 mm. For bottom sediments they are as follows:

$$q_{dg} = 0.153(s-1)^{0.5} g^{0.5} d_{50}^{1.5} d_*^{-0.3} T^{2.1}, \text{ when } T = (\tau - \tau_{kr}) / \tau_{kr} < 3, \tag{4}$$

$$q_{dg} = 0.1(s-1)^{0.5} g^{0.5} d_{50}^{1.5} d_*^{-0.3} T^{1.5}, \text{ when } T \geq 3, \tag{5}$$

$$\tau = \rho g \left(\frac{v_{vid}}{18 \lg(4h / d_{90})} \right)^2 \tag{6}$$

$$\tau_{kr} = (\rho_s - \rho) g d_{50} \theta_{kr} \tag{7}$$

$$d_* = d_{50} \left((s-1) g / \nu^2 \right)^{1/3} \tag{8}$$

$$s = \rho_s / \rho \tag{9}$$

here q_{dg} – the bed load; d_{50} and ir d_{90} – diameters of sediment particles of probability 50 and 90 %; τ – the bed shear stresses; τ_{kr} – critical value for sediment deposition of bed sear stresses; v_{vid} – the average velocity of flow; h – water depth; d_* – non dimensional diameter of sediment particles; ρ_s and ir ρ – density of sediments and water; ν – viscosity of fluid.

For the suspended sediments van Rijn (1993) proposed such formulas:

$$q_{sknd} = F v_{vid} h C_a \tag{10}$$

$$C_a = 0.15 \frac{d_{50}}{a} \frac{T^{1.5}}{d_*^{0.3}} \quad (11)$$

$$a = \Delta / 2, \quad (12)$$

here q_{sknd} – the discharge of suspended sediments; F – ratio of the sediment concentration, existing at the height *a,* and the average in the flow concentration, which can be estimated according the formula 2; Δ – the height of sandy waves at the bottom.

The calculation of suspended sediment deposition within the regions of investigated flow 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. (Fig. 2). Consequently, the model turns to a quasi two-dimensional one and, therefore, it can give more exact results. The application of real 2D models would be very difficult, since a large number (several millions) of net points must be chosen due to a complicated valley relief, 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 as well.

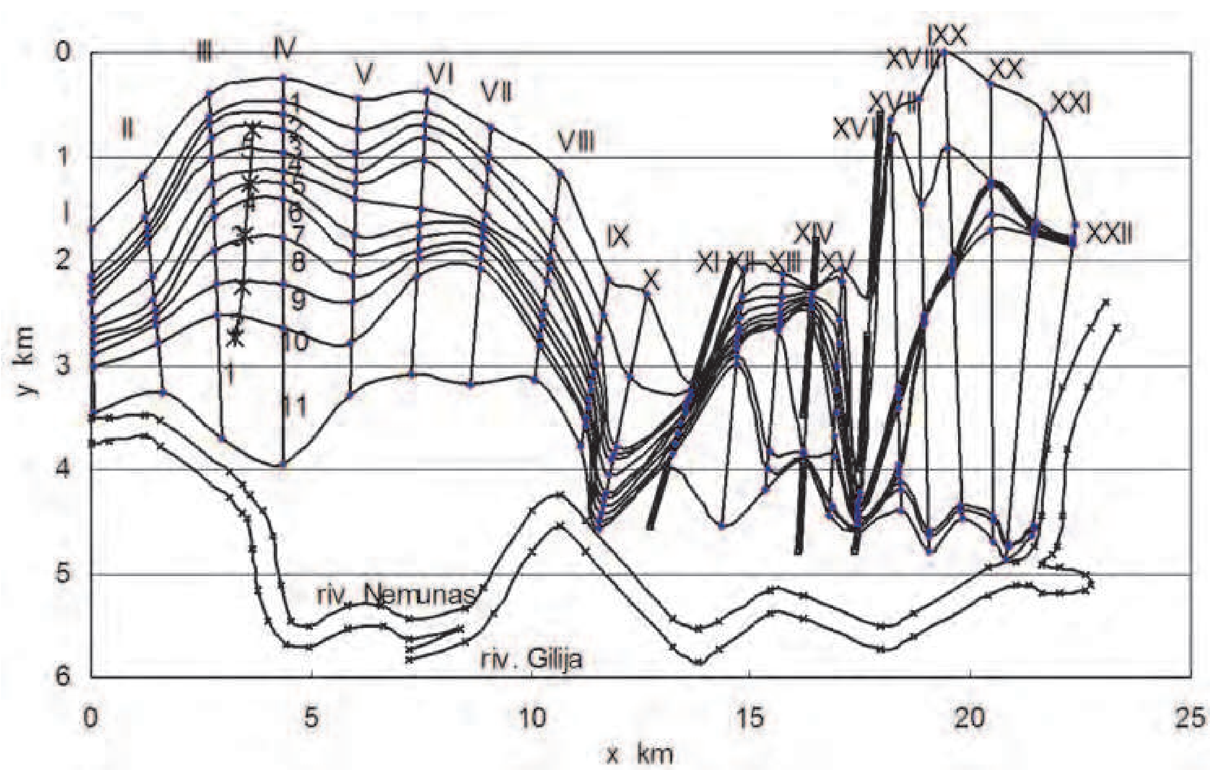

Fig. 2. Distribution of computerised stream strips at the investigated section of the Nemunas delta model (the flood of 1996): I-XXII – cross-section numbers; 1-5 – numbers of measurement posts; 1-11 – numbers of flow strips.

3. Modelling of the suspended sediment dynamics

3.1 Sediment motion dynamics in the river Nemunas delta

Amounts of sediments for four fractions deposited in upper and down strips of Nemunas delta calculated according the described calculation method are plotted in Fig. 3 and 4.

The change of sediment layer in the riverbed during 1950-1991 is represented in Fig. 5. There are plotted the thickness of sediment layer accumulated till this time. They were calculated for 4 segments. The first two are in down strip of valley and the third and fourth – in the upper one.

As the calculation results show, most of the sediments in the valley and also in the riverbed was deposited at the beginning of investigations, as the floods were large then (Rimkus &Vaikasas, 1999, 2010). Particularly intensive deposition was in 1958, when the flood was very large (probability 1%).

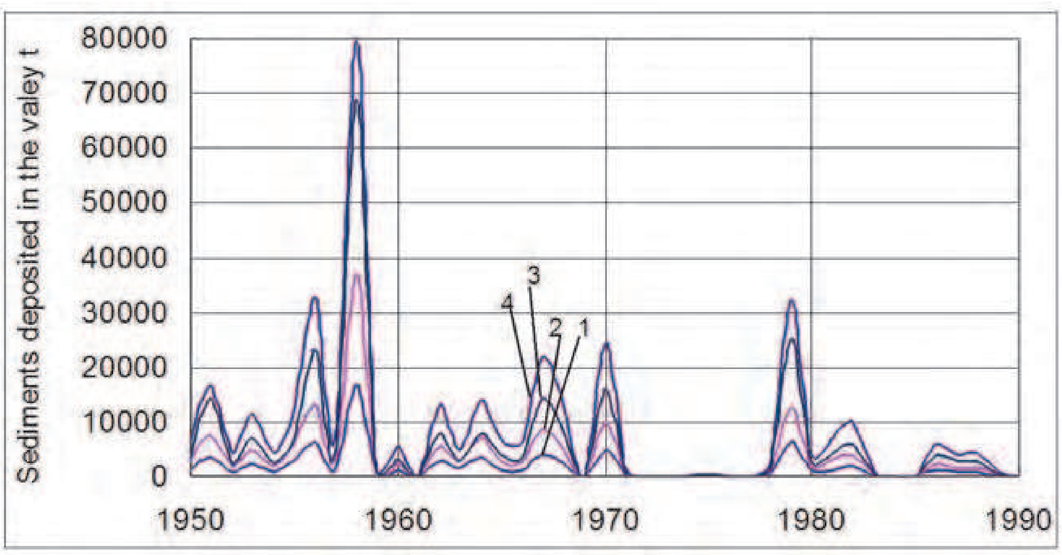

Fig. 3. Sediments deposited in down strip of valley: 1 – diameter of fraction particles 0.005 mm; 2 – diameter of fraction particles 0.01 mm; 3 – diameter of fraction particles 0.02 mm; 4 – diameter of fraction particles 0.1 mm. The summary amount of sediments settled during 1950–1991 time interval is equal to 739000 t.

The conditions for sediment deposition in the down and the upper parts of the delta are different, so the settled amounts of sediments are different too. The valley in the upper part is much wider; therefore the sediment deposition was more intensive there. However the floods overflow more rare in this part, because the altitudes of the overflow the places are rather high, therefore it decreased the overflow rates and sedimentation amount. In the upper strip the river did not overflow in 19 years of 42 years of the entire investigations. In the down strip area the river did not overflow only 11 times, as the overflow places are lower here. That increased the sedimentation here. However because of the less area of this strip, the sediment deposition was less intensive there.

The deposited amounts of sediments are quite large. In the upper part of delta it was deposited 35% of all sediments brought by river. Sedimentation in both strips reaches 60% of the brought by the river flow. Summary amount of sediments makes 2.3 mln t. The sediment deposition is going on also and in valley part near the Curonian Lagoon. Therefore the total deposition in the delta can reach about 80% of the brought by the river.

The not implemented project was made to protect these valley areas from the spring floods for intensive farming. It would increase the water contamination in the standing water of south part of the Curonian Lagoon, where and in this time the water is not quite clear. The similar project was realized in Denmark on the delta of the river Skjern. It caused the hard increase of water contamination in the Rinkgobing lagoon, and fishes began to die there. (Ministry…, 1999). Therefore it became necessary to restore the former floodwater flow through the valley. This example shows, how important is to perform the modeling of sediment motion in such cases. In the Nemunas delta only the protecting from summer floods was useful and had been performed. However, for example, in the valley of the river Minija the protection of some valley parts from the spring floods was suitable, as there are large enough not separated areas. In the river deltas such areas are absent mostly (Dolgopolova, 2004).

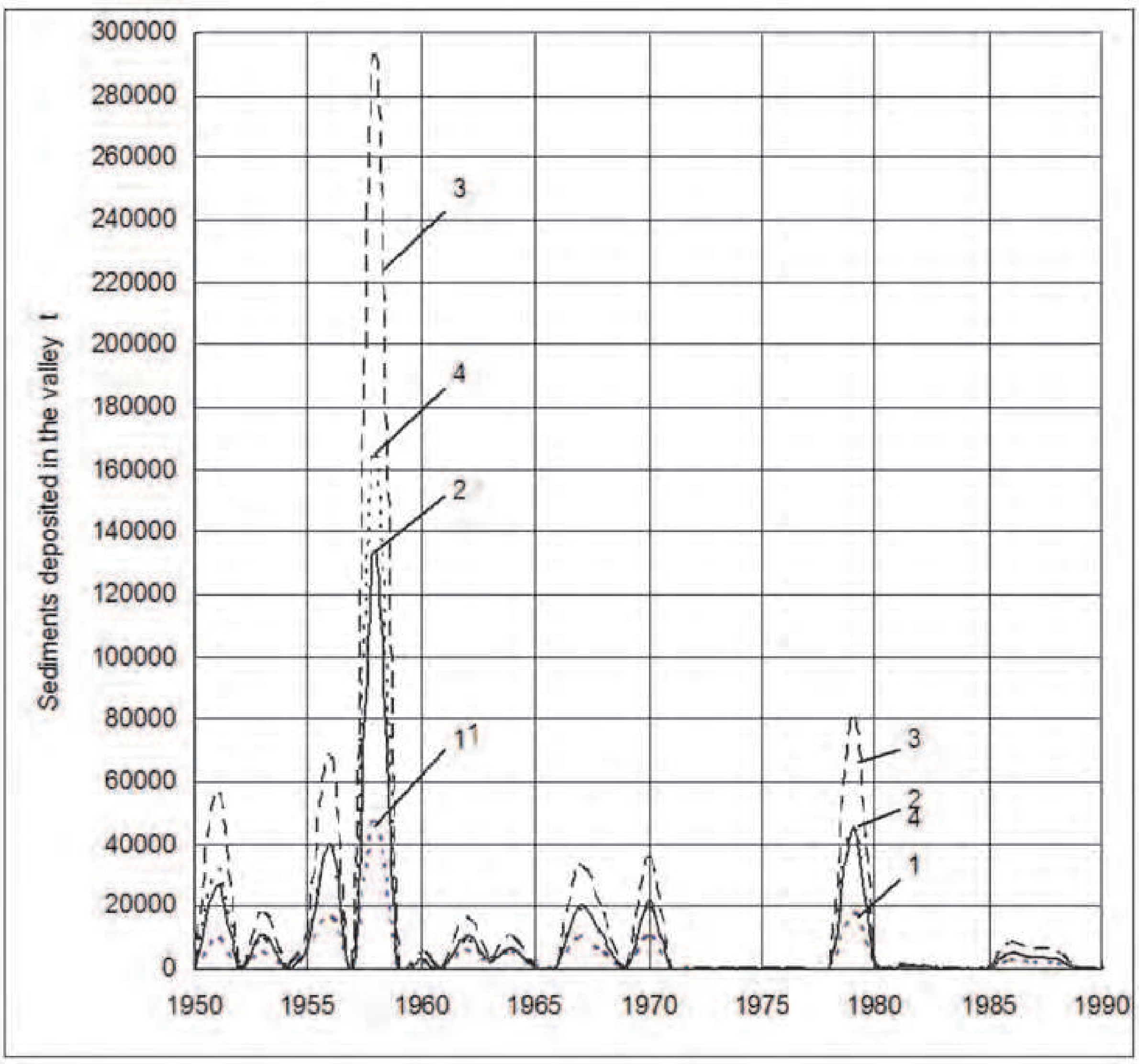

Fig. 4. Sediments deposited in upper strip of valley: 1 – diameter of fraction particles 0.005 mm; 2 – diameter of fraction particles 0.01 mm; 3 – diameter of fraction particles 0.02 mm; 4 – diameter of fraction particles 0.1 mm. The summary amount of sediments settled during 1950–1991 time interval is equal to 1670000 t

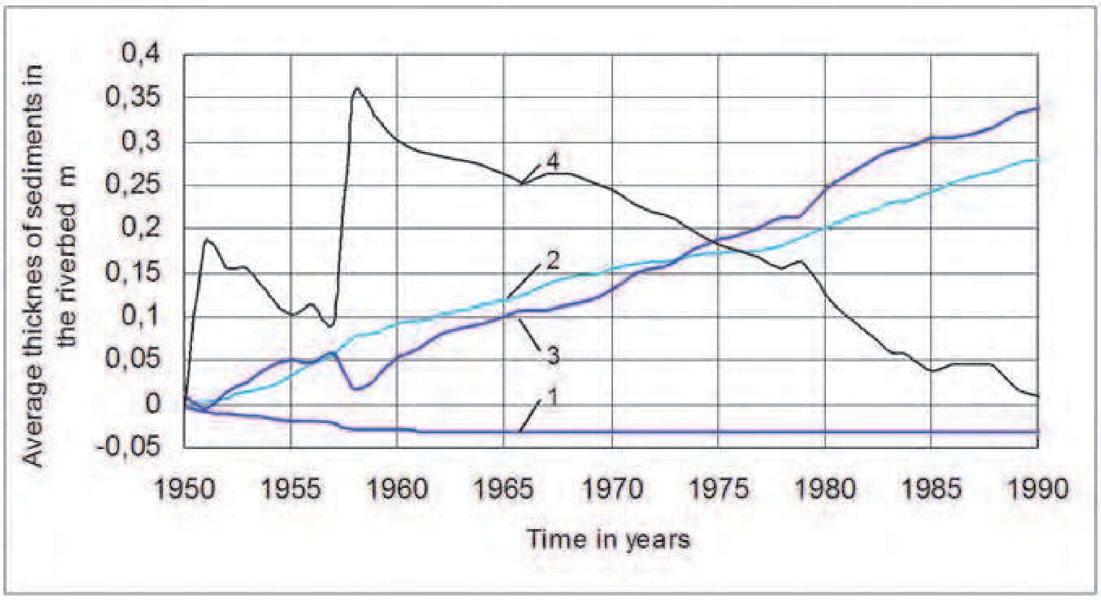

Fig. 5. The thickness of accumulated sediment layer: 1 – in the first segment of riverbed, in the first half of down strip; 2 – in the second segment, in the second half of down strip till the river Gege; 3 - in the third segment, in the first half of upper strip; 4 – in the forth segment, in the upper strip till its top.

3.2 The possibilities to increase the sediment deposition in the valleys

Naturally it would be desirable to find the means to increase the sediment deposition of muddy water still more. Therefore it was investigated the means and factors influencing the sediment deposition in the valleys. (Rimkus & Vaikasas, 2010). These factors are:

1. The increase of water discharge flowing through the valley by deepening and widening of places where the floodwater overflows from riverbed into the valley.
2. The forming before the floods of the best state of the grasses for sediment entrap in the floodplain meadows.
3. The building of way banks across the floodplain
4. The slowing of water stream in the valley by growing of bushes and wood.

For the increase of water discharge overflowing in the upper part of Nemunas delta it was widened and deepened the natural water overflow place existing at the settlement Panemunė (Fig.6). Increase of the conductivity of this overflow was successful, as the water flows further into the wide lake Užlenkė, from which it spreads into the whole valley. Attempt to increase the conductivity of other smaller overflows, for example of Malūnkalnis or Maržiogis, was not successful, as the overflowing water further flows through the narrow beds, which limits their conductivity. Widening only of the inflow from the riverbed is not effective.

The sediment deposition in the valley can be increased also by deepening of wide water overflow place below the railway bridge, however economically effective appeared only the deepening of the overflow at the Panemunė. On the possibility to dig here the channel the attention was turned during the investigations to select the optimal trace for the road round the town Sovietsk. The ground for the road banks could be taken from this channel. Thus it was found by these investigations not only the optimal trace of the road, excluding it's negative influence, it was detected also the possibility to increase and the conductivity of the valley. For the building of this road it would be necessary to dig the channel with the width 120 m and the depth – 2 m.

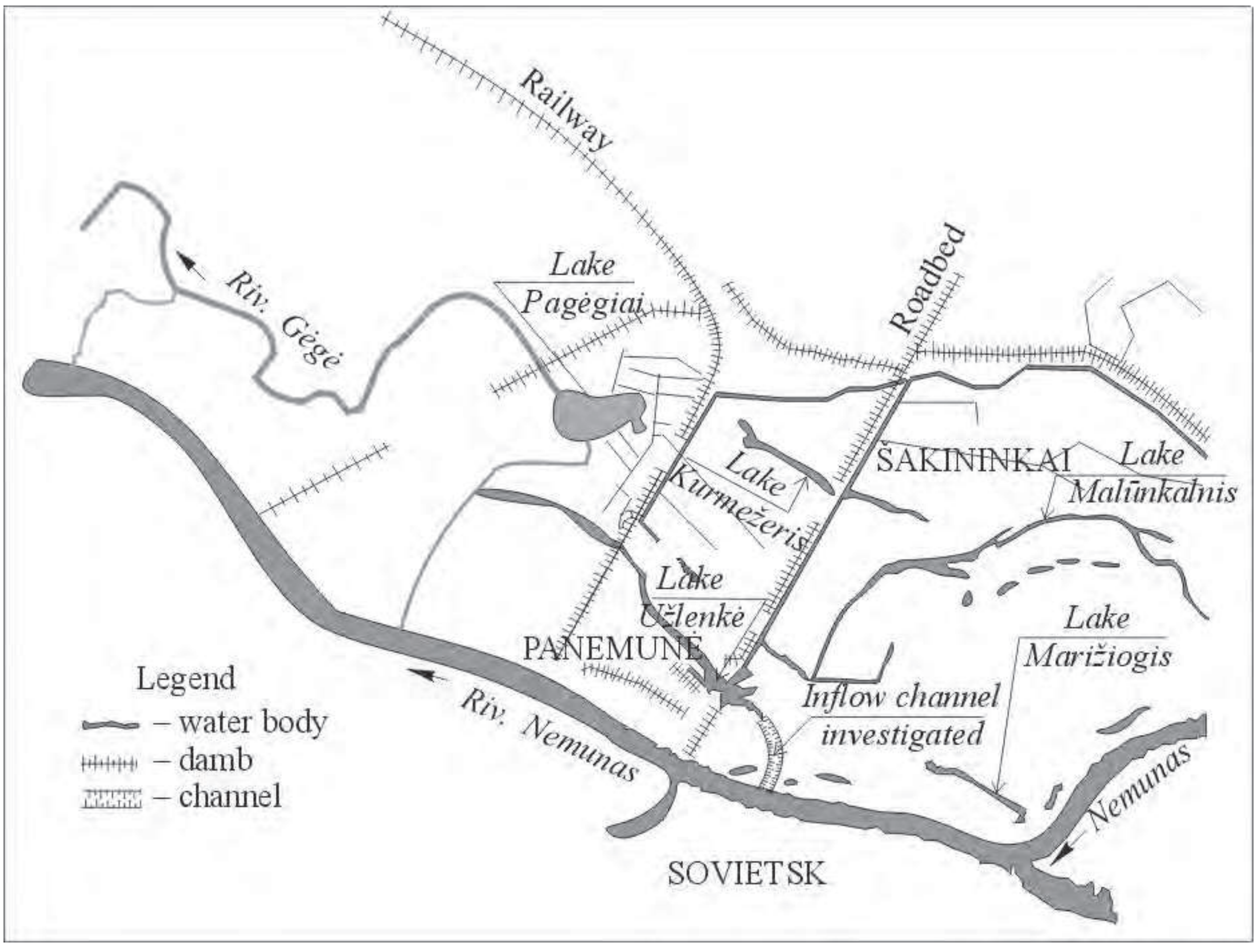

Fig. 6. The main canal and floodplains of the river Nemunas in Panemunė

The built across the Nemunas delta railway and highway decrease the sediment deposition about by 30%, as they are nearly to the main water overflow in valley. However the deepening of the water overflow into the valley at the Panemunė compensates this negative influence and still increases the water discharge flowing in the valley.

The bush and wood growing in the valley decreases the flow velocities there. The decrease of flow velocities in the riverbeds can to increase deposition of suspended sediment. However in the meadows of the floodplains the sediment deposition does not increase with decreasing of flow velocities, as the velocities in flooded valleys are low and the grasses are not laid. Consequently they can to entrap the sediments independently on the little exchange of flow velocities, as their state does not change in these conditions.

In the cases when the thick bushes increase the water level too much, they can pond the water inflow in the valley and to decrease the sediment deposition there.

3.3 Sediment motion dynamics in the River Virvyte

To utilize the renewable energy, hydroelectric power plants (HPPs) are built in rivers. However, their weirs and made ponds affect the natural conditions of the rivers, thus deteriorating the life conditions of water fauna and flora. Ponds have major impact on river hydrology. It was found and in other rivers (Wang et al., 2003, Marčiulioniene et al., 2011). Weirs disrupt the natural motion of sediments and the organic materials accepted with them. The organic silt is mostly retained in the reservoirs, instead of fertilizing the downstream floodplains. In 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 (WFD, 2007; Povilaitis, 2008). Thus, ecosystems can be influenced to a large extent and the water quality may get worse (Vaikasas & Dumbrauskas, 2010; Rimkus & Vaikasas, 2010; Olli, 2008). Therefore, it is necessary to analyse these processes and reduce their negative influence by choosing optimal methods of hydro-energy employment. This was the second aim of the study.

Further in the chapter, there are presented the results of mathematical-hydraulic modelling of the influence of HPP ponds with various weir heights on the sediment deposition in valleys inundated during the floods. When the weirs are not too high and the riverbed volume is sufficient for arrangement of the ponds, the valleys are inundated only during the floods. In the flooded meadows, the sediments washed from the fields settle steadily. Consequently, the quality of river water is improved greatly because of the settled particles, brought from the adjacent agricultural lands and deposited there, are rich with adsorbed nutrient load (Bakel, 2006). On the contrary, when the weirs are too high, some part of the valley area is always inundated. In this case, the valley area, useful for sedimentation, decreases. Consequently, the water self purification process decreases also, as more significant part of sediments, containing pollutant materials, return from the valley to the river flow. Therefore the too high weirs can worsen the water quality in the downward river reaches.

In deep ponds, there are some other 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. The silt sinks on the bottom, although elevated flow velocities could lift it. These velocities increase during the daylong power regulation. With increased turbine discharge, the suspend 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, 2008; Ždankus, 2008; Ždankus & Sabas, 2005; Zdankus et al., 2008).

Most ponds of the river Virvytė fill up only the riverbed, and only few of them overflow into the valley. The present investigation is based on the modelling of a 12-km interval of the small river Virvytė, where a 11 HPP cascade includes three HPPs: Skleipiai, Kapėnai, and Kairiškiai (Fig.7). In the modelled river interval, the pond of Kapėnai HPP occupies 30 ha of a dammed valley. This decrease 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 at the Kapėnai pond 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).

For the ponds in Skleipiai and Kairiškiai, the riverbed is sufficient for their ponds; while in the Kapėnai pond, as it is mentioned above, some part of the pond 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. The results are plotted in Fig. 8.

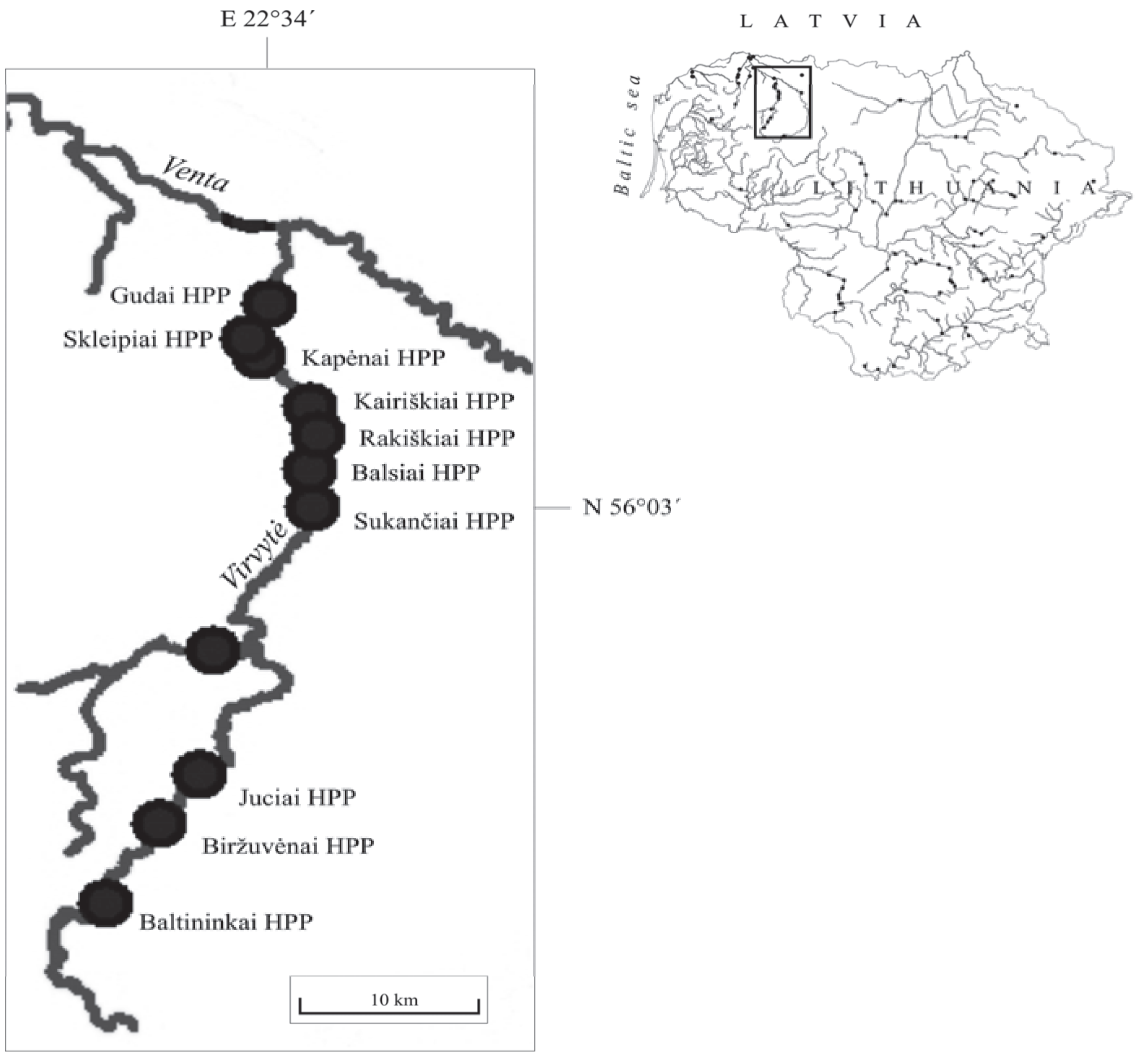

Fig. 7. The HPPs cascade in the river Virvyte

Three groups of curves are plotted in Fig. 8. Thin lines depict the case when the HPP ponds are absent and the sediment deposition is naturally great. Thick lines 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 weirs. Thus, such a HPP has some positive influence, since even low weirs slightly pond up the flood water levels.

The sediment deposition in the inundated valley increases quickly with rising of water rates, since in this case the sediment discharge also increases, and the decrease of sediment concentration because of their deposition is then compensated. In addition, the area of inundated valley increases with the flood increase. 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 these particles is also much higher.

In Fig. 9 the deposited sediments are expressed as part of the total amount of sediments brought to the river. The deposition is quite intensive. When the water discharge is large, 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.

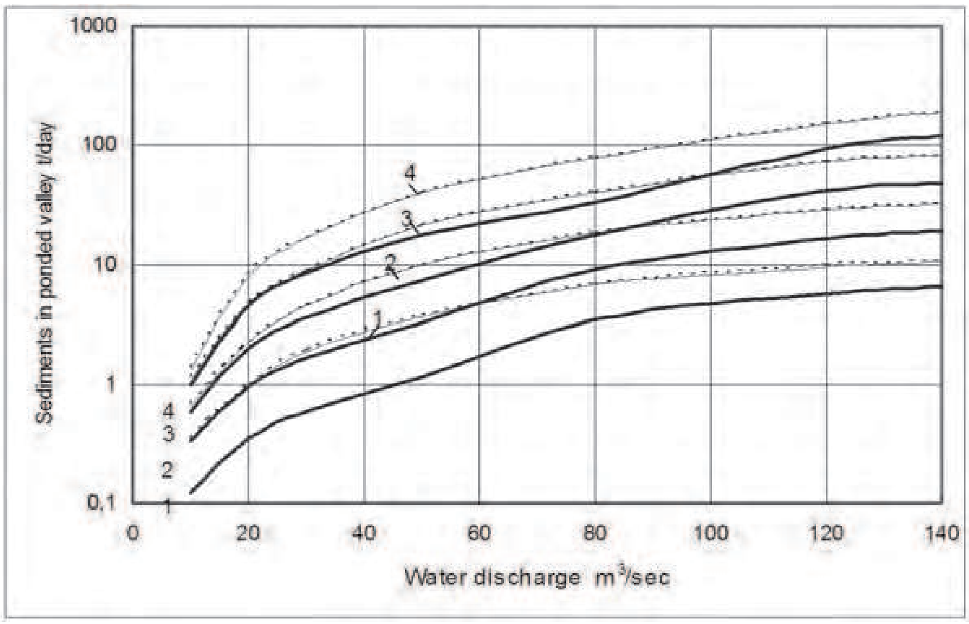

Fig. 8. Amount of deposited sediments in the investigated interval of the river Virvytė valley as a function of flood discharge: thin lines – weirs are absent, thick lines – with all 3 HPP weirs, dotted lines – only with a weir of Kairiškiai HPP. Particle diameters in the sediment fractions are 0.001 (1), 0.002 (2), 0.005 (3), and 0.01 (4) mm.

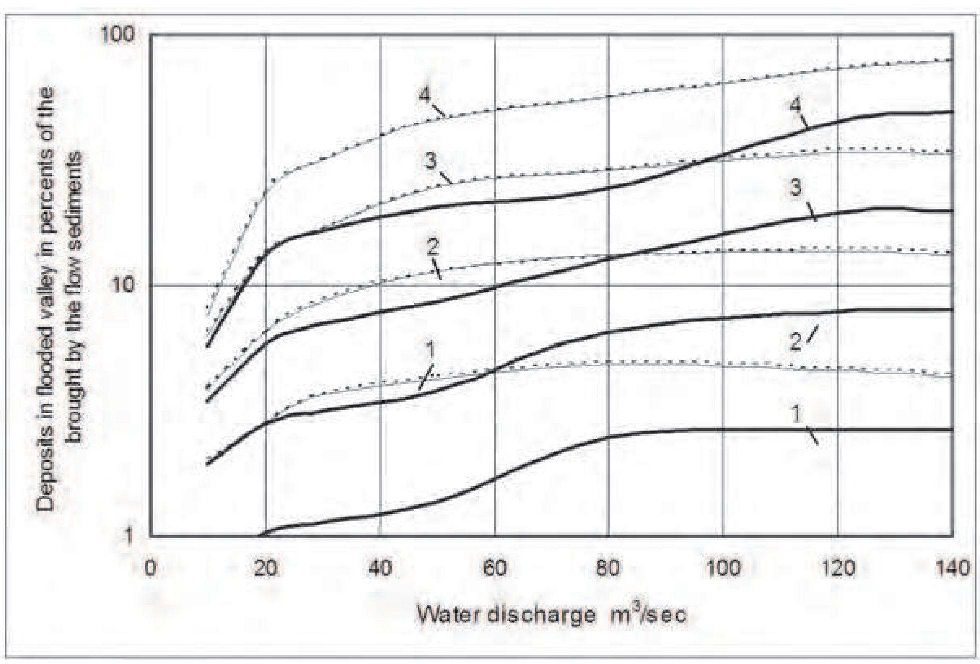

Fig. 9. Intensity of sediment deposition in the inundated valley as part of sediments brought by the river: thin lines – dams are absent, thick lines – with all 3 HPP dams, dotted lines – only with a dam in Kairiškiai HPP. Particle diameters in the sediment fractions were 0.001 (1), 0.002 (2), 0.005 (3), and 0.01 (4) mm.

The arrangement of the Kapėnai pond decreased the sediment deposition in the valley more intensively during the relatively low floods, since this pond took away some of floodplain parts important for the sediment retention, which would be flooded by the low, but more frequent floods.
Fig. 10 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 HPP 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 increase of inundated area of the valley and to increase of 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 the 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 Figure 11.
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 too high weir of Kapėnai HPP.

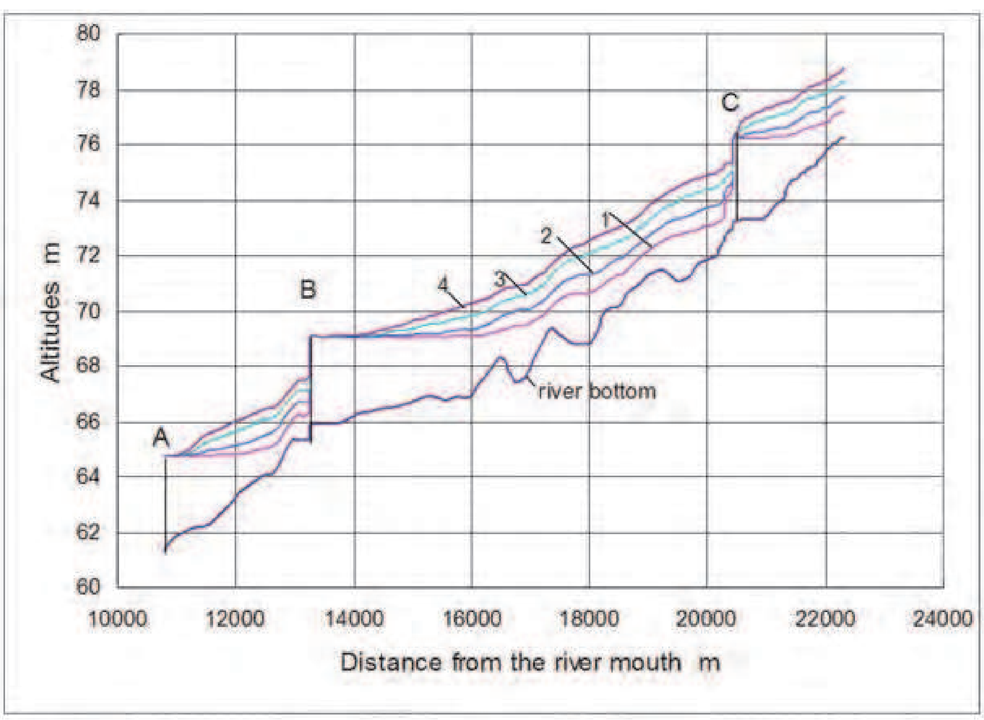

Fig. 10. Longitudinal profile of the investigated interval of the river Virvytė. Water levels of floods with water discharges of 20 (1), 50 (2), 100 (3), and 150 (4) m^3/sec. HES dams: A – Skleipiai, B – Kapėnai, and C – Kairiškiai.

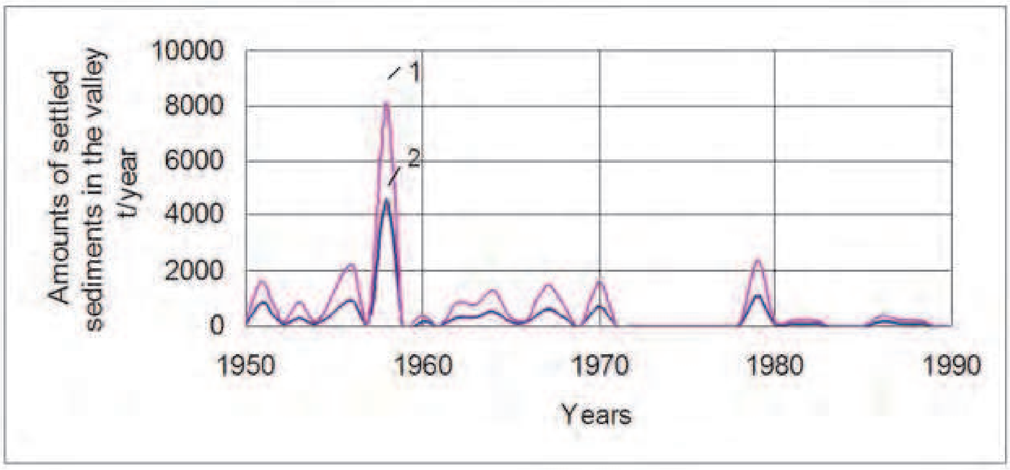

Fig. 11. Amounts of the sediments settled during a many-year period in the interval of Virvyte with the HPP ponds of Skleipiai, Kapėnai, and Kairiškiai: 1 – ponds are absent and 2 – all three ponds are involved.

Thus, the volume of sediments deposited in the floodplain is quite large. Such amounts of sediments per unit floodplain area have been found in our field investigations (Rimkus & Vaikasas, 2010; Rimkus et al., 2007; Lamsodis & Vaikasas, 2005; Vaikasas & Rimkus, 2003). 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; Habersack et al., 2008; Vaikasas & Dumbrauskas, 2010; Lukianas et al., 2006; Ždankus & Sabas 2005; Zdankus et al., 2008). 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. It would not worsen the ecological conditions significantly, however such a pond would better supply the local exchange of electricity 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.

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 Ždankus and Krakauskas (2000), 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 (Lopardo & Seone, 2004).

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 possibility of ecological damage.
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. 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 utilizing almost the whole water discharges 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 (Bruno, 2009). However, a certain large enough amount of rivers in each region must be left untouched, for preservation of natural environment.
Since the most 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 in all ponds of HPPs.

4. Conclusions

The flooded meadows in river valleys especially in their deltas are very important for ecology conditions, as the grasses in these valleys entrap the brought by water flow sediments with adsorbed contaminations.
When the protection of river valleys from the spring floods is designing, it is necessary to model the sediment deposition, and to estimate the possible increase of water contamination. In such cases it is necessary the large enough areas not separated by dikes for sediment deposition, which usually are absent in the deltas.
The calculation methods for sediment deposition in flooded grassed valleys have not been performed yet, therefore the new formulae for these calculations are proposed.
When in the rivers the hydro energetic power plants are constructed, the environmental and energetic needs are to be coordinated. When designing power plants on the river Virvyte, this coordination was no performed. Therefore the ecological conditions were heavily worsened.
Water self cleaning in small rivers with HPPs is better, when the weirs are not too high, and the ponds do not inundate in the valleys.
Mostly in small rivers HPP turbines are of cheaper propeller type, which cannot regulate their power, and therefore work periodically with the maximal power. That is very harmful for water flora and fauna. To improve this situation the Kaplan type turbines with power regulation must be installed.

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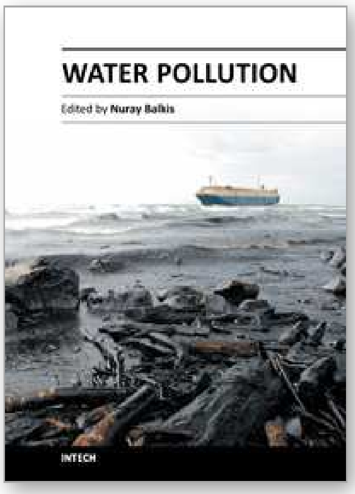

Water Pollution
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Water pollution is a major global problem that requires ongoing evaluation and revision of water resource policy at all levels (from international down to individual aquifers and wells). It has been suggested that it is the leading worldwide cause of deaths and diseases, and that it accounts for the deaths of more than 14,000 people daily. In addition to the acute problems of water pollution in developing countries, industrialized countries continue to struggle with pollution problems as well. Water is typically referred to as polluted when it is impaired by anthropogenic contaminants and either does not support a human use, such as drinking water, and/or undergoes a marked shift in its ability to support its constituent biotic communities, such as fish. Natural phenomena such as volcanoes, algae blooms, storms, and earthquakes also cause major changes in water quality and the ecological status of water. Most water pollutants are eventually carried by rivers into the oceans.

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