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Impact of Hydropower Plant Operation on Water Pollution ond Self-purification in the Virvyte River

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Abstract

In rural development areas small hydroelectric power plants (HPP) are a valuable source of renewable energy; but interaction between a river and its environment exist and negative impact of a HPP operation on the environment must be estimate. To evaluate this impact, hydraulic parameters such as velocity, water depth, Froude Number (*Fr*) and fluctuation of flow regimes were measured and hydro biological conditions of water were estimated in 10 HPP cascade in the Virvyte river. Field experiment on the consequences of HPP turbines' operation was performed in natural, directly and indirectly impacted regimes. To determine the concentrations of suspended solids (SS), total nitrogen (TN) and total phosphorus (TP), water samples were taken from each dam both upstream (reservoir) and downstream (river). To predict sedimentation and self-purification processes in the riverbed and in the flooded valley the mathematical-hydraulic modelling was used.

It was established that all the HPP, where water flowed via the reservoirs and downstream through the HPP turbines, changed the natural regimes of SS. All the reservoirs trapped most SS including the finest ones. As a result, in the reservoir bed substrates the percentage of the particles with diameters < 0.01 mm increased about threefold in comparison to that in the river bed. The direct correlation with the coefficients ranging from 0.35 to 0.94 was found between the reservoir capacities and the deposited amounts of these particles. The concentrations of SS were established to decrease due to water retention in the reservoirs. The TN and TP concentrations decreased some more than 10 % when the water stayed in the pond cascades. It was established, that even small dams and reservoirs of HPP may impact change in the environment through facility operations over a sustained period, because in pounded reaches nearby/above HPP dams in the Virvyte river low *Fr* number in habitats ($0.04 > Fr > 0.0007$) was determined. During the floods fine silt and clay particles rich in nutrients retention and self-purification of the rivers is more intensive when the HPP weirs are not high ($H \leq 4$ m) and their ponds do not decrease the floodplain area.

Key words: floodplains, hydropower plants, suspended sediments, dams and reservoirs, impact on environment

Introduction

Rivers and riversides, functioning both as pathways and buffer zones, (1) assist in migration and prevention of losses of chemical elements, nutrients, organic matter, and inorganic solids within/between/from landscapes; (2) provide the niche conditions for an array of plant and animals, herewith acting both as the migration corridors and sites for the successful bio-diversity; (3) supply people community with fresh water for drinking, irrigation, recreation, and potential to employ kinetic power of running water (Eiseltová 1995). Definitely, that is why river channels and valleys were being dammed for a long time (WMO/GWP 2006). For example, there were operating 52,649 dams with reservoir capacities more than 50 acre-feet at the end of last century in the Continental United States (Graf 1993), i.e. somewhere 0.6 dams/100 km^2. Approximately at the same time, there were 354 river dams (ab. 0.5 dams/100 km^2) in Lithuania (Gailiušis et al. 2001).

Dams, however, segment river channels into dammed and undammed reaches resulting in the changes in integrity of free-flow conditions and greatly disturbing the natural hydrological regime herewith the equilibrium of the above-mentioned ecological features of rivers and their riparian zones, coherent with the suspended sediment ant nutrients both transport and retention (Bustamante et al. 2004a; Bustamante et al. 2004b; Water 2007). Because of its tendency to sorb to fine sediment particles and organic matter, phosphorus is transported primarily in surface runoff with eroded sediments. Therefore, dams can impede phosphorus transport or hinder the passage of fish, invertebrates and certain terrestrial animals, thereby interrupting the longitudinal connectivity along the river corridor. The elimination or reduction of high flood events also changes the structure and functioning of the downstream floodplain ecosystems (WMO/GWP 2006). Thus, dams act as in-stream regulating structures within the main channel, resulting in inundations of river valleys both permanent upstream from the dams and only man-will-dependent downstream from the dams, thereby negating the normal ecological functions associated with flood events. Large areas along the river stream are submerged by the reservoirs created behind the dam. The organic silt is mostly retained in these reservoirs, instead of fertilizing the downstream flood plains and riparian ecosystems (Vaikasas 2002; Vaikasas et al. 2004). Meanwhile in reservoirs, anaerobic processes and algae populations tend to dominate if there is nutrient excess in the water and sediment (Jungwirth et al. 2005).

The above-mentioned changes are even more complicated when the dams are completed with hydropower plants (HPP), particularly in the small rivers where lowhead dams with reservoirs of small capacities are arranged. The small reservoirs usually are not capable to ensure the permanent operation of HPP. Rather frequent interruption of operation of HPP leads to unnatural fluctuations of water levels both in either sides of the dams and in time. Their impact on the physical habitat and biological diversity are not understood well yet (Ren and Packman 2002). Therefore, more information and understanding about this is in need.

The aim of the studies was to learn more about and assess the measure of the influence of dams with HPP on the retention and the downstream transport of the suspended sediment and nutrients in small rivers of lowland environment in Lithuania.

Experimental site and methods. The investigations were carried out in Lithuania and involved 17 dams built on four rivers of the 3rd to 4th order. The height of the dams and the capacities of their reservoirs ranged from 2.25 to 14.50 m and from 28×10^3 to $15,500\times10^3$ m^3, respectively. All the dams were completed with HPP. To bring water to the HPP turbines, the power-channels there were equipped to all the dams lower than 5.5 m; whilst the higher ones were completed with the power-conduits, which submerged intakes were installed about three metres below the water levels in the reservoirs.

To determine, the concentrations of suspended solids (SS), total nitrogen (TN), and total phosphorus (TP), water samples were taken about 50 m from each dam, both upstream (reservoir) and downstream (river). The sampling depth was about 0.3–0.5 m below the water surface in either side of the dams and the turbines of the entire HES have been operating when sampling. Moreover, there were the bed substances both of the reservoirs and rivers (up- and downstream from the dams) sampled to determine their grain-size compositions as well as micro invertebrates. (Fig. 1).

The method of mathematical hydraulic modelling was used in this work to investigate the sedimentation process in the riverbeds and their valleys. The field investigations of sedimentation process as well as relationship with water quality are discussed in other manuscripts (Rimkus, Vaikasas 1999a,b; 2010, Rimkus et al., 2007). The known commercial models are not suitable for grass-covered valleys (Mike-21, 1995). 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 and Vaikasas, 1999a,b). This model was confirmed in investigations of natural sedimentation in the Nemunas delta and Nevežis floodplains. The 12 km interval of river Virvytė with 3 HPP: Skleipiai, Kapėnai and Kairiškiai was investigated (Fig. 2).

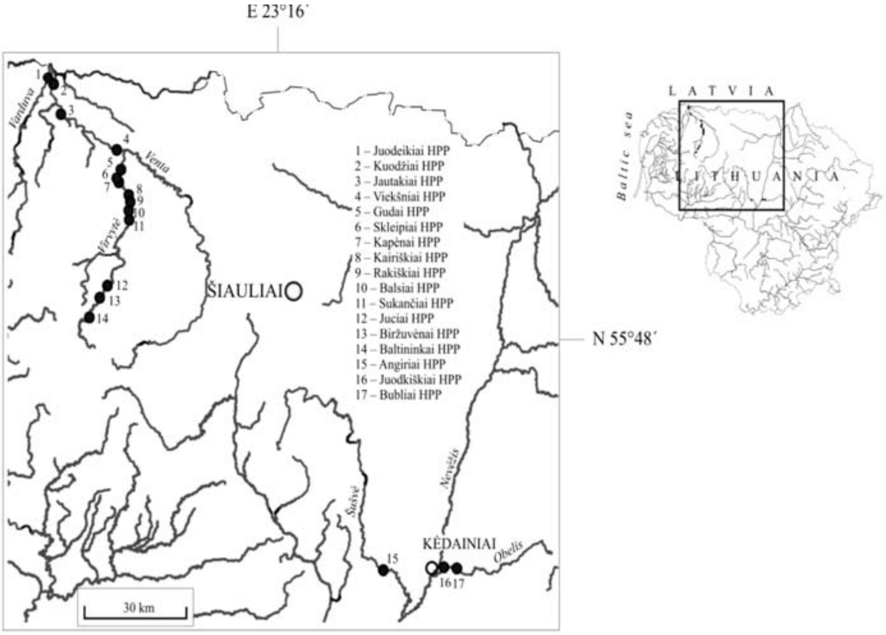

Figure 1. **Location map of studied dam**

It is clear that dams and reservoirs may impart change on 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 vorticity regimes fluctuation as well as by Froude number Fr, because it's value depend upon the form of flow boundaries. Thus, Fr number became a one of main tools for estimation of HPPinfluence. To predict this influence Fr number criterion and number of hydrophytes was compared.

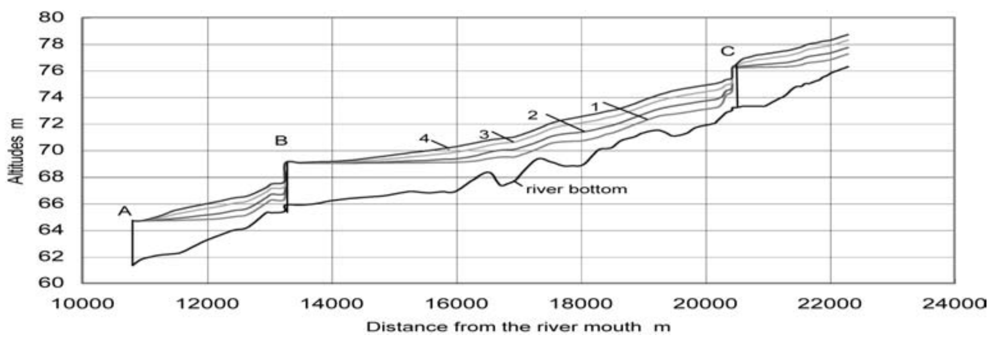

Figure 2. **Longitudinal profile of the investigated interval of the river Virvytė. Water levels of floods with water discharges:** 1 – 20 m^3/sec, 2 – 50 m^3/sec, 3 - 100 m^3/sec, 4 - 150 m^3/sec. HES dams: A - Skleipiai, B – Kapėnai, C – Kairiškiai

Results and discussion

It was established that natural regimes of SS was changed by all the dams when water was flowing via the reservoirs and downstream through the HES turbines. All the reservoirs have been trapping most SS including the finest of them (Fig. 3). As a result, the percentage of the particles with diameters < 0.01 mm in the reservoir bed substrates increased about threefold in proportion to the river bed ones. The direct correlation with the coefficients ranging from 0.35 to 0.94 was found between the reservoir capacities and the deposited amounts of these particles. It was also found the reduced concentrations of SS due to water delay in the reservoirs. However, these concentrations would increase appreciably in water downstream from the low dams always when HPP were operating, but would not be observed in cases of high (H>10) dams. Actually, the armouring of river channel beds was established being in progress downstream from the dams without reference to their heights.

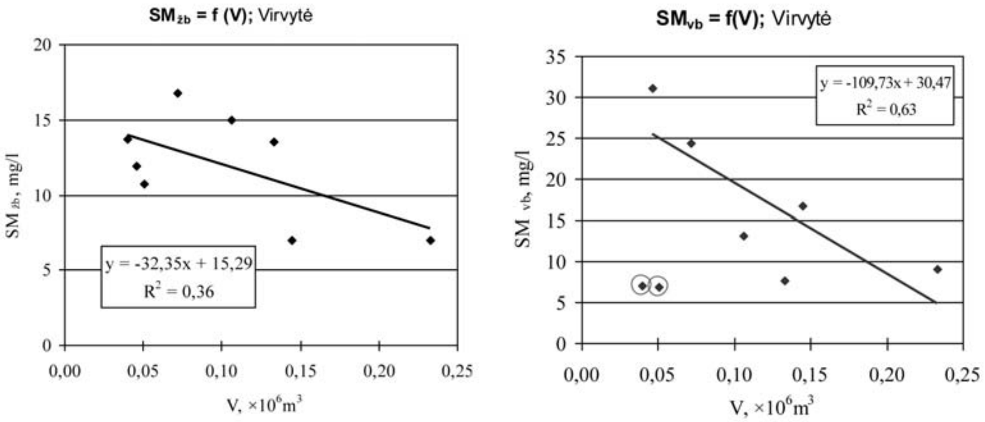

Figure 3. **Suspended sediment concentrations (SS) as function of HPP reservoirs volume V in the water below (a) and above (b) in river Virvytė**

The concentrations of total nitrogen and total phosphorus mostly demonstrated the antithetic correlation to the reservoir capacities (the coefficients ranged from -0.68 to -0.98), except the concentrations of TN in the category of low dam reservoirs. Moreover, the concentrations both of TN and TP showed alike behaviour when water would drain off via the turbines from the reservoirs despite the dam heights. The concentrations, though marginal, were found less downstream from the dams: for TN, by 3–15 %, and for TP, by 9 % on average in HPP of river Virvytė (Table 1).

Table 1. **Sediment and nutrient characteristic of HPP reservoirs and reaches in river Virvytė**

HPP reach	Weir head H, m	Reservoir volume V, 10^3 m^3	TN, mg/l	TP, mg/l	Turbidity SS, mg/l	Fine particles <0.01mm, %
Gudai HPP, reservoir	2.75	145	2.30	0.050	16.70	25.12
Below Gudai HPP, river			2.30	0.050	7.00	7.79
Skleipiai HPP, reservoir	3.50	50	2.37	0.067	31.05	18.02
Below Skleipiai HPP, river			2.34	0.056	11.90	8.68
Kapenai HPP, reservoir.	5.50	230	2.34	0.052	9.10	31.01
Below Kapenai HPP, river			2.21	0.048	7.00	2.52
Kairiskiai HPP, reservoir	4.80	70	2.20	0.054	24.40	12.06
Below Kairiskiai HPP, river			2.10	0.057	16.80	4.51
Rakiskiai HPP, reservoir	3.70	50	1.92	0.052	6.90	18.54
Below Rakiskiai HPP, river			2.10	0.051	10.70	8.30
Balsiai HPP, reservoir	2.95	110	2.04	0.050	13.20	8.27
Below Balsiu HPP, river			1.79	0.055	15.00	3.00
Sukončiai HPP, reservoir	3.25	130	1.94	0.051	7.70	22.00
Below Sukončiai HPP, river			2.07	0.052	13.50	0.93
Juciai HPP, reservoir	3.30	40	1.69	0.038	8.90	22.88
Below Juciai HPP, river			1.43	0.045	3.00	0.66
Biržuvėnai HPP, reservoir	3.50	40	1.36	0.041	7.10	20.80
Below Biržuvėnai HPP, river			1.47	0.035	13.70	5.04
Baltininkai HPP, reservoir	4.30	60	1.43	0.040	5.40	20.58
Below Baltininkai HPP, river			1.34	0.043	7.50	3.54

Although, it was established the concentrations of TP were higher by about 5 % downstream from the low dams when HPP did not operate in low water period. However, concentrations of TN and TP strongly depend from the suspended particles SS in all reservoirs of HPP.

In the deposits and water of large ponds and high dams (H>10m) distributions of TN and finest particles as well as SS strongly correlate with the distance from HPP weir (Fig. 5).

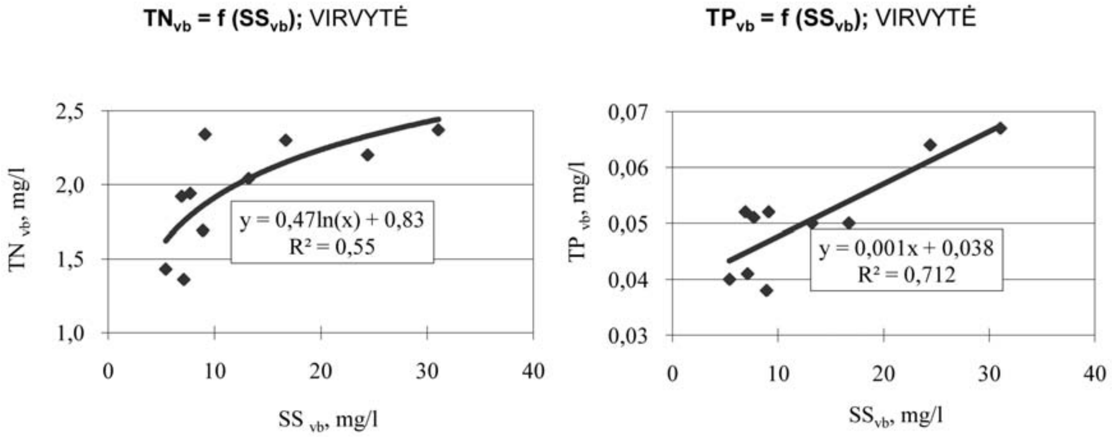

Figure 4. **Concentrations of TN (a) and TP (b) as functions of suspended particles (SS) concentration of pounded water in HPP dam cascades of river Virvyte in spring 2009-2011**.

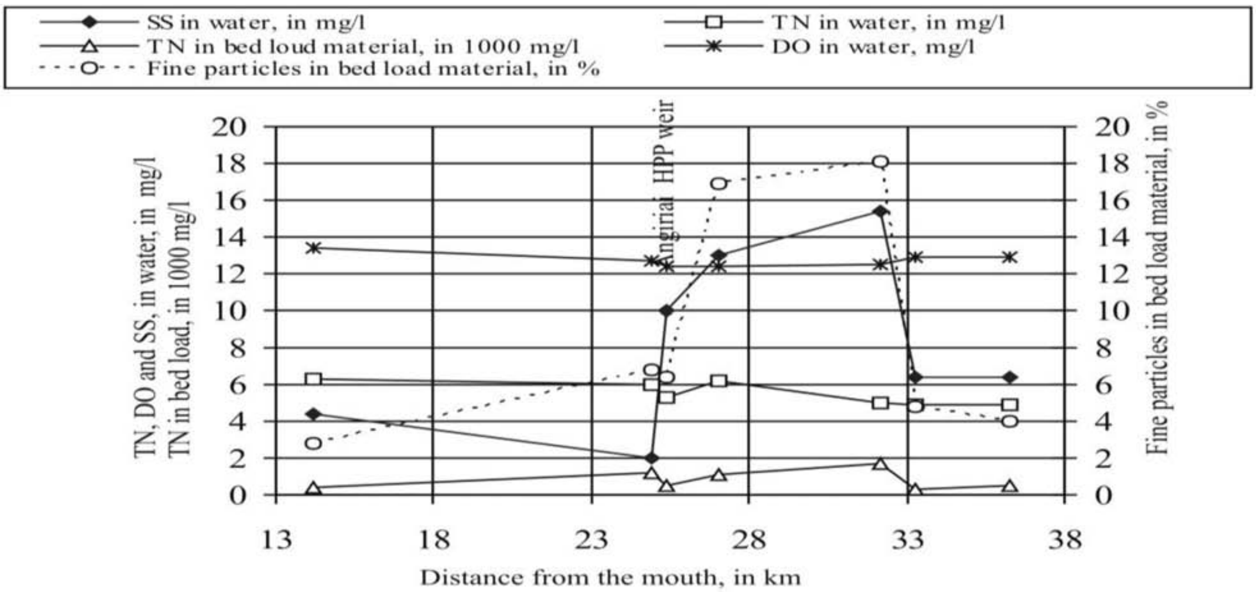

Figure 5. **The dynamics of TN, TP and SS in large reservoir Angiriai (W= 15.5 mil.m^3) of river Šušvė**

In the river – floodplain ecosystem, the river channel is the donor of water, sediment, and inorganic nutrients to the floodplain in the floods.(Eiseltova 1995) Thus, 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. 6 by the relations between the sediment deposition and water discharges.

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. 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.

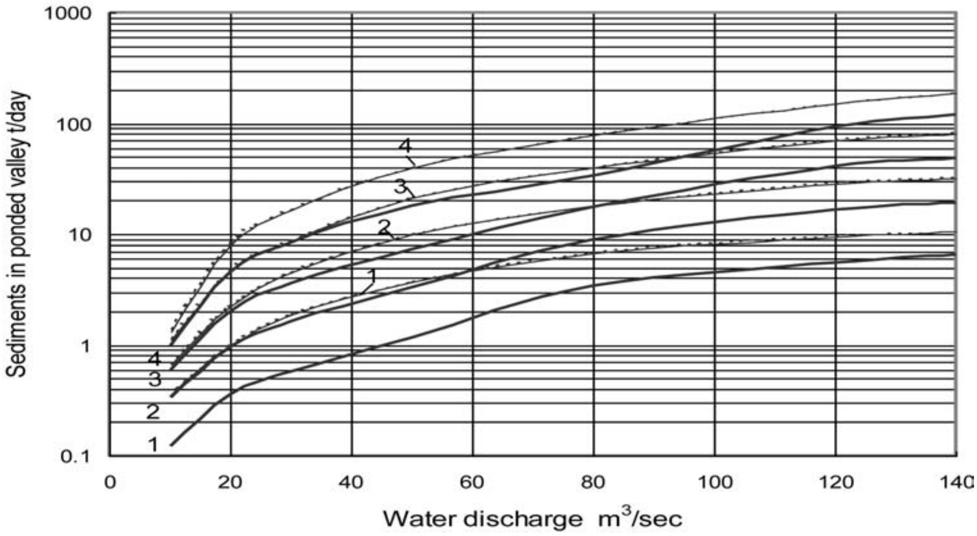

Figure 6. **Dependences of the amount of deposited sediments in the investigated interval of the river Virvytė valley on the discharge of floods:** thin lines – no dams, thick lines – with all 3 HES dams, dotted lines – only with dam of Kairiškiai HES. Diameters of sediment fraction particles: 1 – 0.001, 2 – 0.002, 3 – 0.005, 4 – 0.01 mm.

Table 2 shows the overall impact on flow characteristics and Fr number of 10 places in natural, directly and indirectly impacted HPP cross-sections in Virvytė River. The results of measurements and calculation the association between functional habitat occurrence and Froude number (Kemp et al. 2000) indicate that there were three distinct types of habitat response associated with HPP impact: negative, positive and non-signed or not impacted. In pounded reaches nearby above HPP dam low Fr number habitats (0.04>Fr> 0.0007) were created and negative dam impact was observed. Only silt as bottom substrate and roots, marginal submerged plants and submerged, broad-leaved macrophytes was find in this river reaches. Habitats that tended to be associated to higher Froude Number (0.26>Fr>0.10) were sand and gravel or cobles. Some of them was natural reaches far above the pond not impacted of HPP, and below not directly influenced others. However, positive impact on environment below the dams was lessened number of hydrophytes only, and a surge wave harmful impact when turbines are operated was evident.

Table 2. **Impact of HPP on flow environment in Virvytė river**

Location	Flow characteristics				$Fr = \frac{V^2}{gh}$	HPP impact onto habitat occurrence		
	With B, m	Depth h, m	Averaged velocity V, m/s	Bottom substrates		A number of hygrophyte species	Pond influence	HPP impact according 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

Conclusions

1. The HPP reservoirs created by low and average dams in small rivers of lowland environment impact on both natural flow regime and sediment and nutrient retention when water is flowing via the reservoirs and downstream through HPP turbines, given unfavourable hydrological, hydro-chemical and biogeochemical conditions in low water periods of winter and early spring.
2. In proportion to river bed substrate upstream, the reservoirs are capable to accumulate several times as larger amounts of both fine particles and TN and TP in their bed substrates. Measure of the accumulation depends on reservoir capacity.
3. It seems, there is the more chance for the suspended sediment to be transferred from a reservoir downstream into a river channel if the HPP is equipped with power-channel, not with the power-conduit.
4. Below the dams, water discharged through HPP turbines scours out river bed substrate resulting in the increase in TSS concentrations and encouragement of the progress of armouring. The increase in TSS concentrations in water below the dams by 10 mg/l induces the increase in TN and TP concentrations by 0.20 and 0.01 mg /l respectively.
5. Loss of both river continuum and fluvial dynamics due to erection of dams and elevation of water level, and natural gravel bars due to bed silting in reservoirs negatively impacts on fish living habitats and on the aquatic life in general.
6. 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 nutrient retention and self-cleaning of water.
7. In the pounded reaches nearby or above HPP dams of the Virvytė River low Fr number habitats ($0.04 > Fr > 0.0007$) are created and negative impact of the dam on the water clarity and biota is observed.

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