JOURNAL OF ENVIRONMENTAL ENGINEERING
AND LANDSCAPE MANAGEMENT
2008
16(3): 128–134

IMPACT OF A HYDROPOWER PLANT ON THE DOWNSTREAM REACH OF A RIVER

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Submitted 9 Jul. 2007; accepted 6 Nov. 2007

Abstract. The impact of a hydropower plant (HPP) on the environment, first of all on the riverbed of downstream reach as well as on fish communities is analysed in the paper. Frequent switching on and off of turbines has been determined to be the reason of intensive and long-lasting riverbed scour, also significant reduction of fish communities. Each switching on and off of HPP turbines is found to cause a sudden change of water discharge and level in the downstream reach. Water level suddenly drops down after the turbine switches off. Uplift force of ground water flowing from a riverbed destructs a reinforcing layer of large ground particles formed during the self-lining process. Scour of small particles from the bottom sets in. The riverbed deepens significantly until a new reinforcing layer forms. Suggestions are given to slow down turbine switching within technical possibilities. This simple measure allows to increase the length of a reflux wave, to reduce the speed of water level drop and the length of river reach under the scour danger.

Keywords: river; hydropower plant; water level fluctuation; fish; riverbed; scour; self-lining.

1. Introduction

River flow regime is coherent with flora, fauna and the surrounding environment. Anthropogenic factors, first of all the hydropower development, may destabilize a complex river environment system and cause unpredictable consequences. Some of them are definitely harmful, the others are doubtful, and some are clearly useful. The analysis often shows changes in longitudinal substrate distribution, a significant increase in riparian vegetation, channel degradation, straightening of the river bed and a decrease of point bars locations and curves along the reach (Alfredsen *et al.* 2004). High head hydropower system will alter flow conditions in the downstream river reaches regarding both seasonal distribution and seasonal volume. A reduction in discharge and particularly reduced flooding can have several effects on variables controlling physical habitats. Loss of habitat due to channel degradation, increasing volume of fine material in the substrate, changes in velocity/depth composition, reduced migration due to very low flow, reduced holding areas for adult fish and effects on available spawning areas are experienced (Stanford and Ward 1996). Thus, it would be unreasonable to condemn the construction of hydropower plants (HPP) and to forbid the initiatives of the activity without careful consideration of all the pros and cons. To avoid the prevalence of harm over the use and profit, a deep analysis of all the consequences has to be carried out before commencing or approving the design and construction of HPP.

Analysis of factors causing harm to the environment due to the artificial change of the river flow regime was the aim of this work. Special attention was paid to the river flow discharge and level fluctuation. An assumption has been made that frequent and fast fluctuation of the level is harmful to both riverbed stability and fish population.

Intensive and long-lasting scour of the Nemunas riverbed within the downstream reach of Kaunas HPP (Fig. 1) after building it in 1959 was noticed long ago (Malinauskas and Zdankus 1988). The average bottom lowering within 14 km of the reach was about 1 m, and in some places it reached 2 m. The structures on the banks and communication lines in the riverbed were endangered in the area of Kaunas city.

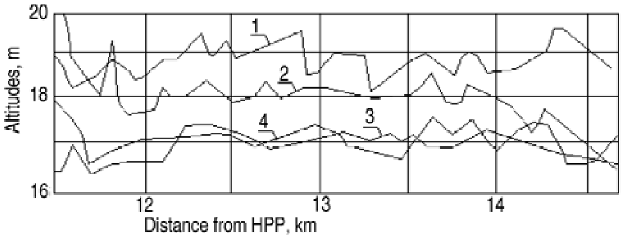

Fig. 1. Longitudinal profiles of the Nemunas riverbed downstream railway bridge in Kaunas: 1 – 1963; 2 – 1978; 3 – 1981; 4 – 1985

Each fast drop of the water level causes the loss of small fry staying in the hollows of drying banks. The flatter the banks and the faster the drop of water level, the greater the loss of small fry. The type of the fish and speed of the drop affect loss quantity as well.

European scientists (Lusk 1995a, b) have observed that the number of fish population in a river suddenly falls down after the erection of a dam and the construction of HPP. In such a river valuable fish communities change into worthless ones. After the erection of Kaunas HPP on the Nemunas river, the number of fish communities was reduced from 33 to 24 (Kesminas *et al.* 1994; Kesminas and Repecka 2005).

We are prone to believe that only the impact of Kaunas HPP on the Nemunas flow regime has caused changes of the riverbed and reduction of fish population.

2. Peculiarities of Lithuanian riverbeds

The majority of Lithuanian rivers are formed of alluvial grounds. They consist of particles of a different diameter varying within a broad range: from silt of 0.1 mm to gravel of 50 mm grain size. Due to non-uniformity of the grain size small particles are washed out from the riverbed surface and a protecting layer of larger particles is formed on the ground surface (Zdankus 2000). Gradually, the protecting layer becomes more and more resistant to scour. It acquires the ability to resist scour even at much higher than initial flow velocities. The pores between particles of the protecting layer are filled with smaller ones and also with organic matter. The layer becomes impermeable. While the water level in the river drops suddenly and ground water tends to move from the ground, the uplift force of hydrostatic pressure breaks the protecting layer and removes it. Intensive bottom scour originates and a new self-lining process starts again (Fig. 2). Each cycle of protecting layer construction – destruction lowers the riverbed and forms a large amount of scour products, which are moved by the flow downstream.

During a sudden lift of the flow depth water infiltrates into the river bottom. A downward force of hydrostatic pressure presses ground particles to the bottom and increases their stability. Riverbed resistance to scour increases (Zdankus 2000). Thus, sudden increment of the flow depth is not dangerous concerning the possibility of riverbed scour.

3. Natural alteration of river flow discharge and water level

The majority of Lithuanian rivers are formed in alluvial grounds. They tend to scour, therefore riverbeds are often eroded. Due to the scour, maximum intensity erosion is reached in the spring flood period, also during heavy showers when river discharge reaches the largest magnitude and the sudden flow depth fluctuation takes place.

The analysis of the long lasting hydrometric observation data (Dolgopoviene 2003; Lithuanian… 1990–2004) shows a comparatively slow change of natural river flow discharge and depth. Rain and snow melting in spring time cause rather slow changes of the river flow. Due to indicated reasons the water level fluctuation velocity usually does not exceed 20 cm/h. Formation and break of the ice cover cause much quicker changes of the flow. Much higher speed of water level changes may be observed during the ice debacle time. During the ice cover formation and breaking period, water level usually fluctuates at a speed of 15–30 cm/day (Alfredsen *et al.* 2004). Sometimes water level undergoes even greater changes due to the ice phenomena. On 23.12.1849 during the ice cover formation on the Nemunas at Smalininkai, water level rose at a speed of 97 cm/day. Ice blocks cause more sudden fluctuations in water level. During the debacle period of 12.03.1827, water level at Smalininkai rose up by 252 cm. The next day on the 13th March it dropped down to 272 cm. Thus, the drop speed was ≥ 272 cm/day = 11.33 cm/h.

The formation of an ice block leads to a sudden rise of the water level in the river upstream and drop down the block. After a collapse of the block water level suddenly drops upstream an ice block and rises downstream it. Here water moves with rather high velocities, the remainders of a self-lining layer are completely removed, the bottom of the river is being scoured very intensively. The data of flow velocities, discharge and level change during ice debacle are not available because observations and investigations of the phenomena cannot be performed due

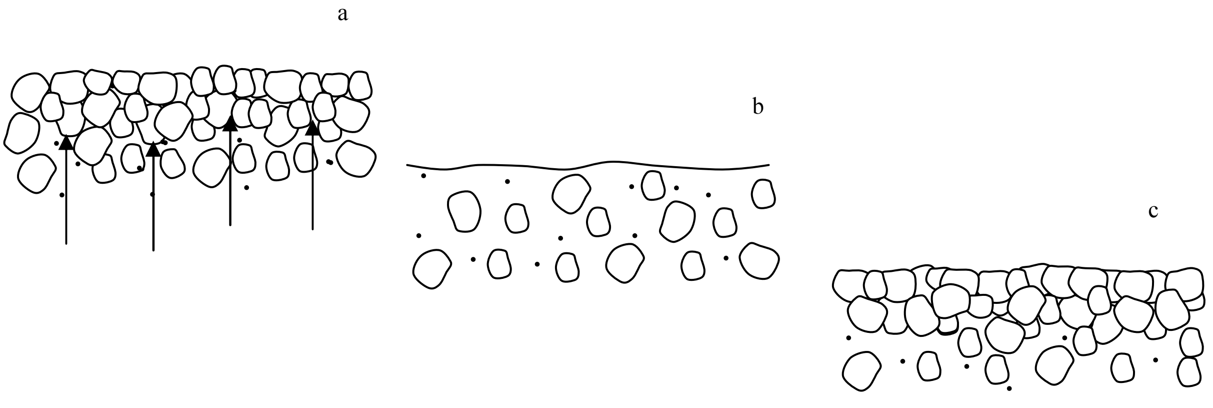

Fig. 2. Stages of riverbed self-lining: a – uplift forces destroy and remove protecting layer; b – scour of small ground particles continues; c – new protecting layer appears

to the unpredictable place and time of their occurrence. The old records (Kolupaila 1930) contain water levels measurements done once or twice per day only. An ice block forms and collapses within some hours. Thus, the above computed level drop 11.33 cm/h is much smaller than the actual one which should be computed dividing the level drop not by 24 h but by much shorter interval of time.

The self-lining layer of a riverbed may be damaged not only during the ice block formation and collapse. This may happen during an extremely intensive spring flood also, when flow scouring power exceeds the resistance of a self-lining layer. Fortunately, the layer usually restores after the flood, which lasts 2–5 weeks only (Gailiusis *et al.* 2001). Intensive scour of a riverbed damages severely fish spawning ground, makes their living conditions impossible to live. This is the main reason why the number of fish communities reduces downstream HPP. In addition, scour products increase load and sediment runoff as well.

4. HPP influence on the river flow level alteration

Each switching off and on of HPP turbines causes a sudden change of the flow discharge and depth. Due to the regular changes of flow parameters flux and reflux waves are generated regularly, the water level downstream HPP changes at a high speed periodically many times every day. Drop of the water level is much more dangerous than rise, therefore, in this investigation greater attention was paid to that stage of the water level fluctuation.

The speed of the level fluctuation depends on the turbine switching off time, distance from HPP, water flow discharges before and after the switching, and the width of a riverbed downstream the plant. The speed may never go up very highly even at a critical combination of the factors, but due to the turbine stop the level drop speed is many times higher compared to that caused by any natural reason, excluding ice jam formation and a case of collapse.

The turbines of any HPP are switched on and off rather often. Usually the regime of high-power HPP is adjusted according to the electric energy requirements and the river flow regime. One or some turbines are switched on in the morning and switched off in the evening, at the end of the working time. A small HPP usually works according to the available water, for some time it accumulates water in the pool, at the rest of time it utilizes its energy by turbines. In the spring flood period all HPP work in full power. In the summer dry season they work with minimal load passing minimal admissible water discharge through turbines. In both cases the turbines are switched on and off rather seldom. In the rest of the year HPP turbines are switched on and off several times a day. Thus, constant fluctuation of the water level in the downstream reach of HPP is an unavoidable phenomenon (Fig. 3). There was an interest to determine the speed of water level fluctuations and the intensity of fluctuation damping along the river. The comparison of level hydrographs for a distance from HPP gauging station to that for the downstream reach of Kaunas HPP shows great differences between them. The differences in the level change speed and recurrent frequency are evident. In the natural river flow the level drops at a speed < 10 cm/h, in the downstream reach of HPP – up to 500 cm/h. The sudden discharge (and level) fluctuation of the natural river flow happens up to 20 times per year, in the downstream reach of HPP – more than 300 times per year. Thus, the impact of HPP on the river flow regime is evident.

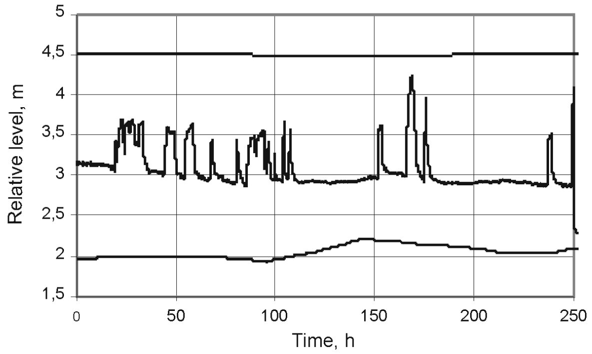

Fig. 3. Level hydrographs of the Nemunas river for cross-sections at Nemajunai (top), km upstream from Kaunas HPP, in downstream reach of the HPP (middle) and for cross-section at Smalininkai (bottom), km downstream the HPP. Zero time is 2004 09 20 12 00; actual absolute altitudes of top curve are larger by 46.20 m, middle – 17.10 m, bottom – 6.00 m

The length of a river reach at a high speed of level fluctuation is limited. Further from the HPP the changes of the discharge and level become smoother, the level drop speed decelerates and this reflux wave becomes less dangerous for riverbed stability. At a definite distance from the HPP the wave becomes harmless.

It is easy to determine the length of a river section, where riverbed erosion is quite possible, from the chart of the level drop speed versus the distance from the HPP graph (Fig. 4). From such a graph, constructed on field investigation data for Kaunas HPP downstream reach, the length of the likely eroded reach is about 19 km, if the admissible stage drop speed is accepted to be 20 cm/h.

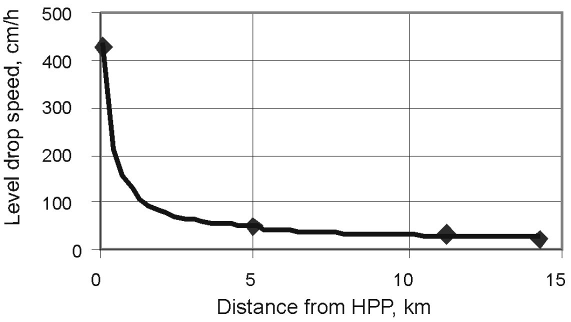

Fig. 4. Graph of stage drop speed versus distance from Kaunas HPP

The graph of the level drop speed versus the distance from the HPP should be used for the estimation of HPP impact on the environment and for the design of protection measures of the riverbed from scour. In this case the graph may be constructed only using analytical methods.

5. Estimation of reflux waves in downstream reach of HPP

One can conclude from the explanations above that a sudden drop of the water level may cause riverbed scour. The higher the speed of the level drop, the more probable the riverbed scour. In addition to the scour, the water level fluctuation endangers the river. It is considered that the maximum admissible drop speed is 20 cm/h. Such a speed is extremely rare in the natural river flow (Gailiusis *et al.* 2001) but it is quite frequent in the river flow downstream HPP. To estimate the danger of the level fluctuation, the actual speed should be compared to the maximum admissible one. The actual level drop speed may be measured under the natural conditions of the river flow computing by reflux wave parameters, which may be determined using analytical or empirical formulas.

To describe an unsteady non-uniform open channel flow, M. Chertousov (Чертоусов 1962) suggested and R. Chugaev (Хугаев 1975) improved the following differential equation set:

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

and (1)

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

where: Q is the flow discharge; l is the distance along the flow; A is the area of the flow cross-section; t is time; I_b is the river bottom longitudinal slope; h is the flow depth; v is the mean flow velocity; $K = CA\sqrt{R}$ is discharge modules, C is Chezy coefficient, R is hydraulic radius; g is free fall acceleration (Fig. 5).

Unfortunately, set (1) may be solved directly for the simplest case of a prismatic riverbed with its horizontal bed. Numerical solution of the set is possible on the basis of definite assumptions and with the help of triple iteration, which makes computations much time consuming.

To verify the results of our field investigations, we have analysed a possibility to apply the following model of the flow. The front of a reflux wave moves with the velocity v_1 (prior to the turbine switching off), its tail – with the velocity v_2 (after the turbine switching off). Due to the difference velocities ($v_1 - v_2$) the wave length l_w increases and the level drop velocity v_{ld} decreases along the river.

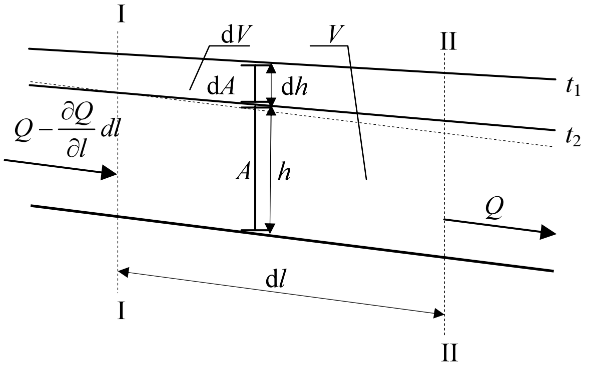

Fig. 5. Dimensions of water flow section for application of (8)

According to the statements above, the level drop velocity may be expressed as

$$v_{ld}=\frac{\Delta h}{t_w}, \tag{2}$$

where level drop is $\Delta h = h_1 - h_2$ and wave passage time is $t_w = l_w / v_w$ (Fig. 6). The wave length

$$l_w = (v_1 - v_2)\cdot t + v_1\cdot t_s, \tag{3}$$

where t_s is turbine stop time; t is time measured from the moment of the turbine stoppage start. Average wave motion velocity is $v_w = \frac{(v_1+v_2)}{2}$. Now the level drop velocity may be expressed as

$$v_{ld}=\frac{(h_1-h_2)(v_1+v_2)}{2((v_1-v_2)\cdot t+v_2 t_s)}. \tag{4}$$

Water level drop velocity magnitudes computed by formula (4) are given in Table. The influence of turbine stop time is evident: the shorter the time, the steeper the wave and the higher the level drop velocity. At the HPP drop speed is particularly high. It is evident from these data that further from the HPP the influence of the turbine stop time decreases.

6. HPP impact on river runoff

HPP may have quantitative and qualitative influence on water and sediment runoff of a river. The influence resulting from the magnitude of runoff parameters is considered as quantitative, the impact on the character of runoff distribution in time is qualitative.

Evaporation from the water body surface is more intensive than that from the land surface. It is reasonable to

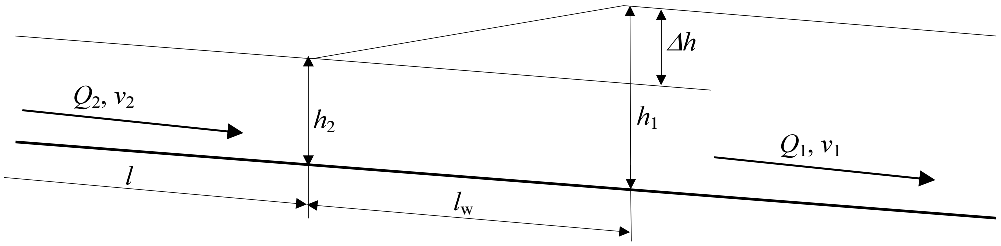

Fig. 6. Scheme of a reflux wave

Water level drop speed, cm/h

Time of stoppage, s	Distance from HPP to rated cross-section, km				
	0.12	4.94	11.26	14.26	20.00
According to computation by formula (4)					
30	2325	78.0	34.4	27.2	19.40
60	1813	77.2	34.2	27.1	19.35
150	1091	75.1	33.8	26.8	19.21
300	656	71.8	33.1	26.4	18.99
According to field measurement data					
	430	51.6	32.4	21.6	

The flow velocities before and after turbine stoppage were accepted to be $v_1 = 0.90$ m/s and $v_2 = 0.70$ m/s; flow depths $h_1 = 1.25$ m and $h_2 = 0.95$ m.

expect the river runoff reduction due to the increased evaporation loss from the HPP pool after its construction. The Sevan lake HPP in Armenia is an evident example of such a phenomenon. It is known that after the erection of the HPP and lift of the water level in the lake the production of electric energy was far away from the designed one. It was determined by the investigations that the evaporation loss was increased and the river runoff decreased significantly, due to the increment of the water surface area. The designed energy production was reached by lowering water level in the Sevan lake, reducing the water surface area and water evaporation loss.

Climatic conditions in Lithuania are rather different compared to those of Armenia. Due to higher annual humidity the difference between evaporation from land and water bodies is much smaller here. The areas of HPP pools are rather small compared to the river catchment areas. As an example, Kaunas HPP on the Nemunas river is taken. Catchment area of the river at cross-section of the HPP is A_c = 55764 km^2, area of HPP pool is A_p = 63.5 km^2. Annual evaporation from the land within limits of A_c is E_l = 550 mm/year and from pool water surface E_w = 660 mm/year (Lithuanian… 1990–2004). According to these data, the evaporation loss of runoff may be computed as follows:

$$\Delta R = 100 \cdot \frac{E_w - E_l}{E_l} \cdot \frac{A_p}{A_c} = \\ 100 \cdot \frac{660 - 550}{550} \cdot \frac{63.5}{45764} = 0.0278\%. \qquad (5)$$

The obtained magnitude of the loss is small enough to be neglected in hydrological computations, whose initial data are usually presented with a much larger admissible error. Thus, the impact of HPP on Lithuanian rivers annual runoff magnitude may be considered as negligibly small.

A HPP of any power redistributes the river runoff due to the adjustment of the turbine-consumed water discharge according to the requirement for electric power. Water accumulates in the pool or is released from it, when passing turbines the discharge is smaller or larger than that of the river flow entering the pool (Fig. 7). The difference depends on the discharge units of time and volume of the pool. Momentary, hourly, diurnal, even weekly river discharges upstream and downstream HPP, as a rule, are different due to the accumulations in the pool. The annual discharge (runoff) does not depend on the HPP pool volume, if it is small, what is usual for flat relief conditions of Lithuania.

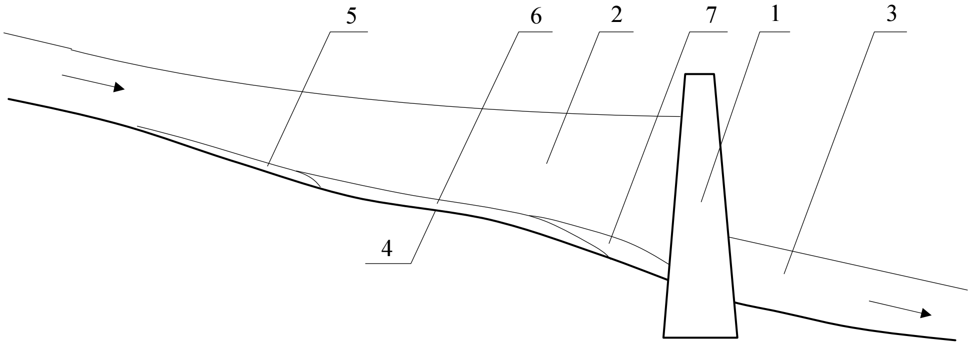

Fig. 7. Scheme of a river longitudinal section: 1 – dam; 2 – pool; 3 – downstream reach; 4 – riverbed profile; 5, 6 and 7 – coarse, mid-size and fine sediments

The erection of a dam on a river and increment of water depth in the pool cause decrement of water velocity and sedimentation of sand and silt there. It is commonly known that coarse sand transported by the river flow accumulates at the beginning of the pool, smaller particles move a definite distance of the pool, silt particles may reach the dam, the finest clay particles may pass the turbines and enter a downstream reach.

Silt carrying requires definite energy. Sedimentation of the load increases scouring capacity of the flow. Sudden and frequent fluctuation of flow depth downstream HPP strengthens scouring capacity again, therefore riverbed scour is unavoidable there. The riverbed scour restores former concentration of the flow load moving away from HPP, but immediately after this the scouring capacity of the flow remains increased forever, and erosion maintains long-lasting character (it is evident from Fig. 1).

To conclude with, the construction of HPP on a river impacts sediment distribution along the river and causes long-lasting scour in the riverbed resulting in increment of total runoff of sediments. As a result, the quantity and composition of sediments at the river delta are changed.

7. Other factors of HPP impact on the environment

In addition to the forms of HPP impact on the environment analysed above, there are many other important factors: flooding of the lands occupied by the pool, landscape changes, shipping and recreation conditions, macroclimate, cutting fish migration paths, etc. This paper is devoted to the HPP influence on the downstream reach of HPP, therefore briefly characterized forms of the impact are mentioned here only to compare them with the forms analysed above.

HPP pool usually occupies a significant area of land in the valley of a river. The flooded land is lost for agricultural and civil engineering needs, but may be used for fishery. Proper selection of the place for the erection of the pool may help to reduce the land loss.

The pool usually improves the landscape, especially when there are no water bodies around. The proper selection of HPP place may help to reduce the land loss and to improve the quality of the pool (Pašvenskas 2001).

In the case of dense network of lakes the HPP influence on the landscape may be insignificant or even negative. In all cases, society opposes the building of HPP. After some years of the construction of the HPP people become accustomed to the landscape change and their attitude to the pool presence becomes positive.

Field investigations (Pašvenskas 2001) confirm the positive character of the HPP pool influence on the microclimate around it. The influence manifests itself in decrease in the temperature fluctuation amplitude during the hot summer season. This phenomenon is closely linked to the intensive evaporation from the pool water surface and increment of air humidity. Microclimate changes in a rather narrow zone around the pool. The width of the zone reaches $(0.15\div0.50)\cdot B_p$, where B_p is the width of the pool.

The construction of a dam on the river and creation of the pool definitely improve conditions for recreation, fishery, both professional and amateur. However, it cuts the ways for migrating fish and invertebrates. This may be mitigated by constructing fish passages, which are effective in the cases of their heads smaller than 10 m (Lithuanian… 2001). Fish-breeding plants are the most reasonable measure for the compensation of the pool harm for heads greater than 10 m.

8. Conclusions

1. Hydropower plant (HPP) influence on the environment is strong and multilateral. In the discussion of the idea to design HPP the issue of the impact should be estimated carefully.
2. The operation of HPP turbines causes frequent and sudden fluctuations of the river flow discharge and depth, what is harmful for riverbed stability and water fauna.
3. Long-lasting scour of the riverbed in downstream reach of HPP is one of the important factors of HPP impact on the environment.
4. To reduce the river flow scouring power in downstream reach of HPP, the turbine-switching off process should be as slow as possible.
5. HPP impact on the riverbed in downstream reach of HPP may be estimated by applying the method presented in this paper. The method offers to do computations of turbine stopping time from flow discharges before and after the stop and dimensions of the river cross-section.

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HIDROELEKTRINĖS POVEIKIS NEMUNO UPEI ŽEMUTINIAME BJEFE

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Santrauka

Nagrinėjamas hidroelektrinės (HE) poveikis aplinkai, pirmiausia upės vagai žemutiniame bjefe, taip pat ir žuvims. Buvo nustatyta, kad dažnas HE turbinų įjungimas ir išjungimas yra pagrindinė intensyvaus ir ilgai trunkančio vagos plovimo, taip pat žymaus žuvų skaičiaus sumažėjimo priežastis. Žinoma, kad kiekvienas HE turbinos įjungimas sukelia staigų vandens debito ir lygio kitimą žemutiniame bjefe. Išjungiant turbiną vandens lygis staiga mažėja. Iš upės dugno ištekančio gruntinio vandens slėgio jėga sulaužo iš didžiausių grunto dalelių susidedantį apsauginį sluoksnelį, susidariusį savigrindos proceso metu. Prasideda smulkių grunto dalelių plovimas iš dugno. Upės dugnas žemėja, kol susidaro naujas apsauginis sluoksnis. Siūloma turbinų stabdymo procesą lėtinti kiek įmanoma iki techniškai priimtino mažiausio greičio. Ši paprasta priemonė leidžia padidinti atoslūgio bangos ilgį, sumažinti vandens lygio kritimo greitį ir sutrumpinti upės ruožo, kuriam grėstų plovimas, ilgį.

Reikšminiai žodžiai: upė, hidroelektrinė, vandens lygio svyravimas, žuvys, vaga, plovimas, savigrinda.

ВОЗДЕЙСТВИЕ ГИДРОСТАНЦИИ НА РЕКУ НЯМУНАС В НИЖНЕМ БЬЕФЕ

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Резюме

Рассматривается воздействие гидростанции (ГС) на окружающую среду, в первую очередь на русло реки Нямунас в нижнем бьефе, а также на рыб. Было установлено, что частое включение и выключение турбин ГС является основной причиной интенсивного и длительного размыва русла реки, а также сокращения численности рыб. Известно, что каждое включение турбины ГС вызывает резкое колебание расхода и уровня реки в нижнем бьефе. После выключения турбины уровень воды резко понижается. Сила давления воды, вытекающей со дна реки, ломает защитный слой крупных частиц грунта, сформированный во время процесса самоотмостки. Начинается размыв мелких частиц грунта со дна. Дно реки понижается, пока не образуется новый защитный слой. Предлагается замедлить до технически возможной минимальную скорость остановки турбин. Этот простой способ позволяет увеличить длину волны отлива, уменьшить скорость падения уровня воды и сократить длину участка реки, которому грозит опасность размыва.

Ключевые слова: река, гидростанция, колебание уровня воды, рыбы, русло, размыв, самоотмостка.

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