Risk Assessment of Use of the Dnieper Cascade Hydropower Plants

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Abstract. In this article we wish to evaluate efficiency of use of Dnieper cascade hydropower plants on the basis of common approaches to environmental management. We evaluate the efficiency of use the flooded areas of the hydropower station in agriculture. Assessment of the man-made risks includes evaluation of static (regular maintenance of dams) and stochastic (probability of artificial tsunami) components. According to the world statistics of disasters caused by dam reservoirs, the probability of man-made tsunami is estimated around 0.01%. Using this rate of probability we can state that expected losses van be 5% of the confidence level. Dnieper reservoirs ranking on the degree of energy risk (the possibility of man-made tsunami generation) was made.

Keyword. risk assessment**,** hydropower plan**,** electricity, agriculture, environmental management.

Key Terms. MathematicalModel, Data, Environment, Infrastructure, Development.

1 Introduction

Before the era of nuclear power, contribution of hydropower in the energy balance of the former Soviet Union was considered indisputable. Thus the negative effects associated with the creation of reservoirs on the plains were not taken into account e.g. flooding of large areas, destruction of towns and historic monuments, increase of the risk of man-made disasters. But time passed and in 1970s in Ukraine were built several nuclear power plants and as a result appeared the need to develop solar, wind and bioenergy and it led to decrease of the share of electricity generation by hydropower plants to 5-7%. Over the past decade, the agricultural sector of the Ukrainian economy has become one of the major players in the global food market and agricultural export of the country has become one of the landmarks of the national economic development. That is why there is an urgent need to use territory of the cascade of Dnieper reservoirsfor agricultural purpose. However, beside inappropriate use of land resources [16] and deterioration of the quality of water resources there is a high risk of man-made disasters which can be caused by the functioning of the Dnieper cascade hydropower plants.

A. Pigou [11], P.Samuelson [15], R. Coase [12] presented classical approaches to exploration of the impact of externalities on economic performance (environmental management). The main idea of this approach is that the price of products (in this case electricity) does not respond the social price paid by people for violations of the environment [13] and therefore assessment of economic growth should be calculated taking into account the price of deterioration of the environment [1, 2] .

English researchers proposed classical approach to the exploration of the causes of destruction of dams, they assert the classical definition of the threats which are connected with creation of artificial reservoirs [16]. In Great Britain all the artificial reservoirs (more than 25 000 cubic meters of the size 100m * 100m * 2.5m) were under the control of local authorities and then the responsibility to control artificial reservoirs was transferred to National Environment Agency.

For comparison, Kyiv reservoir has a volume of 3.73 billion cubic meters and it is placed above the level of many districts of Kyiv [9]. Kurenevka tragedy which happened in 1961 showed that even not significant in volume reservoirs (600 000 cubic meters - 400m * 400m * 3,75m) can be extremely dangerous if they are placed above the level of the nearby territories and can lead to generation of artificial tsunami [9]. During World War II in parts of the Dnieper River below the Dnieper dam the retreating Soviet army tried to destroy the dam. The man-made disaster led to the flood victims among whom were citizens of Zaporozhe and coastal villages and soldiers of the Soviet Army (about 100 000 people) [6].

Researchers emphasize the negative effects of the creation and functioning of the Dniper reservoirs, besides flooding of large territories the negative effects concern a change of hydrological, hydro chemical and hydro biological regimes and slowing of water circulation [3, 6, 7]. In general, there is a great number of scientific papers on significant negative effects connected with creation of the Dnieper reservoirs for the environment of Dnieper, in particular, and for the economy of Ukraine in general. But the issue of quantitative estimation of possible losses caused by artificial tsunami has got little attention among researchers.

In this article we wish to explore a comprehensive risk assessment of further functioning of Dnieper hydroelectric cascade considering alternative options of usage of flooded areas and possible losses connected with future functioning of reservoirs and to develop the methodology of losses assessment connected with destruction of dams reservoirs.

2 Characteristics of Flooded Areas and Options of Alternative Exploitation

As we already mentioned, in twenty-first century the hydroelectric power generation ceased to be a decisive factor in the energy balance. The GDP growth in 2000-2007 was not connected with an increase in production of electricity. During this period was an increase in production of cereals for which the usage of electricity was minimal. It is difficult to estimate the total social costs of flooded areas, and overall benefits from the functioning of large reservoirs of water. In addition, it is difficult to assess losses connected with deterioration of water quality due to the lack of flow. There are a lot of other aspects that do not prove the necessity and efficiency of the functioning of reservoirs. However, we will focus on two main aspects: 1) alternative usage of reservoir areas in agricultural production; 2) level of risk connected with further exploitation of reservoirs (dams of the Dnieper reservoirs). Dnieper cascade hydroelectric station was built during the period of planned economy, the first dam was built on Dnieper in 1927 (Zaporozhe) and the last in 1976 (Kanev). General characteristics of reservoirs and power plants are presented in Table 1. The total area of Dnieper reservoirs is 6.9 thousand sq. km, 1.1% of the territory of Ukraine (Table 1). But if we take into account that the territory near rivers area was always the most fertile for agricultural sector, it is necessary to assess the share of reservoirs in the volume of agricultural land, which is 1,7%. Not all agricultural lands are fertile that is why the factual area which is used in agricultural sectoris about 27 million hectares (270 thousand sq. km) with a standard deviation 0.8 million hectares [4]. In this case, the share of the Dnieper reservoirs increases up to 2.6% of the area used for agriculture.

Table 1. Structure of Land Resources of Ukraine

The main types of land and economic activity	Total area	
	Thousand sq. km	% of total area
Agricultural land	415	68.8
Forests	106	17.6
Built-up areas	38	6.3
Territories covered by surface water (Dnieper reservoirs)	24(6.9)	4.0(1.1)
Unsuitable land for agricultural production	21	3.3
Total (territory of Ukraine)	604	100.0

Source:[4]

Compare the coast of total volume of products available through agricultural production from flooded areas after the creation reservoirs, and the cost of electricity generated by hydroelectric Dnieper cascade. General characteristics of reservoirs and their electricity generation capacity is presented in Table 2. From the total area of reservoirs we extracted the natural are of water surface using natural characteristics of the Dnieper and obtained the size of flooded areas which potentially could be used in agricultural sector.

The area of flooded territory is 6 thousand. sq. km. Dnieper cascade which consists of six hydroelectric power plant produce 10 billion kw * hr. per year, (40% are produced by Dnieper, 15% by Kremenchuk and15% by Kakhovska, 13% by Dniprodzerzhynsk, 10% by Kaniv, 7% by Kyiv. Dnieper hydropower station (HPS) has the best ratio of natural areas to the area of the reservoir - 38% and the worst ration has Kyiv HPS - 5%.

Table 2. Main Features of Reservoirs

	The average depth, m	The height of the dam, m	Volume, million cubic m	The potential energy of man-made tsunami, J $*10^{14}$	Area, square km	The natural area, square km	Flooded area, square km	Capacity, MW	Average annual production, mln kW • h
	1	2	3	4	5	6	7	8	9
Kyiv	4.0	11.5	3730	3.4	922	44	878	408.5	683
Kaniv	4.3	10.5	2500	2.04	581	110.7	470.3	444	972
Kremenchuk	6.0	17	13520	19.8	2252	166.5	2085.5	632.9	1506
Dniprodzerginsk	4.3	12.6	2460	2.5	567	102.6	464.4	352	1328
Dnipro	8.1	35.4	3320	10.2	410	154.8	255.2	1569	4008
Kakhovske	8.4	16	18180	21.04	2155	276	1879	351	1489
					6887		6032		9986

Source: [3;10]

We will explore the possibilities of obtaining agricultural production in flooded areas, we will start from evaluation of the efficiency of agricultural areas during last four years. Due to the high risk of the agricultural sector we use averaged indicator of efficiency during four last the years (Table 3).We obtained the indicator of efficiency of the usage of 1 thousand square kilometer of flooded areas which is equal o 0.89 billion UAH (prices of 2012), with a standard error of 0.03 billion. This means that we can get agricultural products at total value of 5.4 billion UAH (with a standard error of 0.2 billion) from flooded territories which are under Dnieper cascade

Table 3. General characteristics of the agricultural sector for the period 2010-2013

	2010	2011	2012	2013	$\bar{x}(\sigma(\bar{x}))$
Volume of production (billion UAH)*	194.9	233.7	223.2	252.9	226.2(10.3)
Area (sq. km)	246.4	247.1	261.3	262.0	254.2(3.7)
Agriculture return (%)	21.1	27.0	20.5	11.2	20.0(2.8)

* prices of 2012

Source: AgriculturalUkraine 2013 / Kyiv.-2014-p.187-200.

The value of electricity produced during a year and financial value of potential agricultural products are presented inTable 4.

We introduce the concept of efficiency of areas of separated reservoirs as the ratio of the value of the annual volume of electricity produced to the potential value of agricultural products that can be grown on flooded areas.

Table 4. The effeciency of the flooded areas in monetary terms

Name of reservoir	Flooded area, square km.	Output of agricultural products on the flooded areas, bln. USD.	Price of electricity produced, bln. USD. (VAT included)	The efficiency of the flooded areas, %
Kyiv	878	0.78	0.22	28.2
Kaniv	470.3	0.42	0.31	74.8
Kremenchuk	2085.5	1.86	0.49	26.1
Dniprodzerginsk	464.4	0.41	0.43	103.5
Dnipro	255.2	0.23	1.29	568.6
Kakhovske	1879	1.67	0.48	28.7
Total	6032	5.37	3.22	60

Source: own calculations

The total amount of the value of electricity produced is significantly less than the potential value of agricultural products that can be grown on the flooded areas, the value of electricity is only 60% of the potential value of grown agricultural products relative to the average indicator of Ukraine agricultural productivity. Graphical representation of efficiency for certain reservoirs is shown in Figure 1.

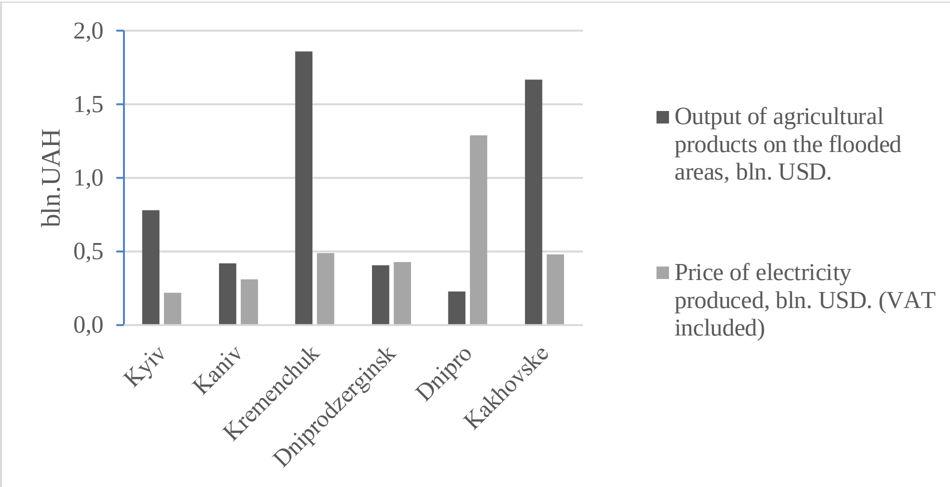

Fig.1. Comparison of possible income from agricultural production and power generation

Source: own calculations on base table 4

Data in Table 4 show that the efficiency of the flooded areas is significantly different for different reservoirs. The most effective reservoir is Dnieper HPS, because it was built in the place where the flow of Dnieper is rather fast (significant differences in levels). Further construction of power hydro stations led to the flooding of large areas that would have greater value if they were used in agricultural sector.

3 Risks Evaluation of Further Dnieper Cascade Functioning

All possible losses connected with functioning of reservoirs are not limited to the wastage of flooded areas. The general scheme of the risks evaluation of further functioning of reservoirs is presented in Figure 2. They can be divided into three groups: economic, technological and environmental.

We made an attempt to assess the expected total annual losses $\overline{L}$ which consist of economical - L_{ek}; ecological - L_{ekol}; and technological - L_t:

$$\overline{L} = L_{ek} + L_{ekol} + L_t \tag{1}$$

In the first approximation economic losses are equal to the difference between the price of potential agricultural products V_{ap} and the value of producing electric energy V_e:

$$L_{ek} = V_{ap} - V_e \tag{2}$$

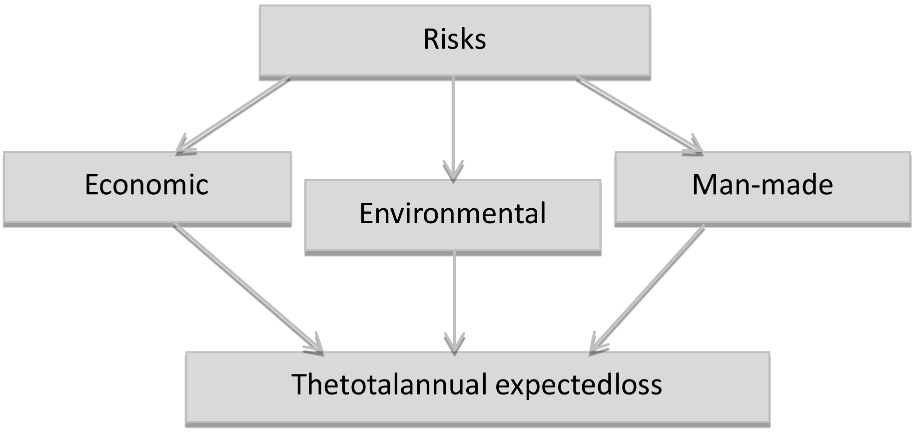

Fig. 2. Model of possible risks of functioning of Dnieper reservoirs

Environmental risk in a first approximation must be evaluated on the basis of cost of measures aimed to bring the mass of water in the reservoir (with absence of flow) to state of the river water.

The most difficult to evaluate are technological (man-made) risks, which present both static (regular repair of dams, measures aimed to support state reservoirs) and stochastic components. The latter is relevant to the possibility of artificial tsunami due to partial or complete destruction of the dam. Taking into account the global statistics the probability of the destruction of the dam is evaluated around 0.01% [14]. At first glance it is a small probability and it seems that is can be ignored, but the evaluation of the probability of depressurization of the reactor of Chernobyl type was considered lower for two orders of magnitude (0.0001%), which did not prevent this to happen. We evaluate the risk of man-made reservoir functioning for each reservoir. The potential energy that depends of the height of the dam and of the volume of reservoir after the destruction of the dam creates an artificial tsunami (Table 2). We wish to explore the least effective case (Table 4) and the most dangerous in terms of potential losses– Kyiv reservoir.

The approximate evaluation of the power of the artificial tsunami in case of destruction of the dam of Kyiv HPS can be calculated on the basis of the potential energy of water masses and sludge. The volume of the Kyiv reservoir is 3730 million ton. (Table 2) to which we add 90 million tons of radioactive sludge [8]. The average depth of reservoir is 4m and the average height of dam is 11.5m, dam reservoir center of gravity is situated at a height of 9.5 m according to the water level of the Dnieper River after the dam. That is why the potential energy of artificial tsunami that threatens Kyiv is:

$$E_{ц} = m \cdot \Delta h \cdot g \approx 3730 \cdot 10^{9} \cdot 9.81 \cdot 11.5 \approx 4.2 \cdot 10^{14} J$$
$$m = (3.73 + 0.09) \cdot 10^{12} kg;$$
$$\Delta h = 11.5м - 2м = 9.5m; \quad (3)$$
$$g = 9.81 m / s^{2}$$

According to the energetic characteristics the potential tsunami that threatens Kyiv is equal to five nuclear charges dropped during the Second World War on Hiroshima (15-20 kt. TNT) [15]. Of course, the shock effect of nuclear explosion and artificial tsunamis is difficult to compare because the shock wave in the first case expands at speed exceeding the speed of sound and artificial tsunami speed is determined by the depth of the Dnieper, and taking into consideration the depth of Dniper the speed will not exceed 30 km / h.).

The situation is complicated by the presence of 90 million tons of radioactive sludge at the bottom of the reservoir, the presence of which can contribute significantly to strengthening of the effects of artificial tsunami and the risk of radioactive contamination of the Dnieper and coastal areas to Kanev reservoir. In the case of this scenario, 10% of Kyiv may be contaminated [9].

Similar characteristics are calculated for each of the reservoirs (Table 2). Kremenchuk and Kakhovka reservoirs have the highest level of risk connected with emergance of artificial tsunami, it can be explained by volume of the accumulated water.

Losses caused by artificial tsunami in certain time *t* due to the violation of the integrity of the dam are proportional to the product of the tsunami energy (E_{ts}) and cost values (urban infrastructure) located in the area of artificial tsunami(S_{ots}):

$$L_t = k \cdot E_{ts} \cdot S_{ots} \quad (4)$$

where, k – coefficient of dimension J^{-1}, which can be determined only empirically.

The expected losses:
$$\bar{L}_t = p \cdot L_t \quad (5)$$
Variance:
$$\sigma^2 = p \cdot L_t^2 \cdot (1-p) \approx p \cdot L_t^2 \Rightarrow \sigma = L_t \sqrt{p} \quad (6)$$

Losses in confidence level α - $L_\alpha(p(L \geq L_\alpha) = \alpha)$ [13]:
$$L_\alpha = \bar{L}_t + x_\alpha \cdot L_t \sqrt{p} = L_t(p + x_\alpha \sqrt{p}), \quad (7)$$

where x_α –quantile of the normal distribution.

We make an assessment of potential losses of Kyiv which can be caused by the potential of artificial tsunami concentrated in the Kiev reservoir.

Up to 10% of the houses located in Kyiv according to the evaluation of hydrologists are under the tsunami risk. The volume of living area in houses in Kyiv is 62.2 million square meters [5]. The cost of 10% of Kiev buildings, at an average price of 0.5 thousand dollars per sq. m, is 3.1 billion USD. Hence, the expected losses for a given probability of violating the integrity of the dam is $3\cdot 10^5$ dollars. Losses in confidence level α:

$$\begin{aligned} L_\alpha &= \overline{L}_t + x_\alpha \cdot L_t \sqrt{p} = L_t (p + x_\alpha \sqrt{p}) = \\ &= 3.1\cdot 10^9 (10^{-4} + 1.65 \cdot \sqrt{10^{-4}}) = \\ &= 3.1\cdot 10^9 \cdot 0.0166 = 5.1\cdot 10^7 \end{aligned} \tag{8}$$

This means that the annual potential losses from the use of the Kiev reservoir taking into account the risk of man-made tsunami are near 51 million USD.

After analyzing potential threats and possible damage, which can be caused by artificial tsunami in Kyiv we cannot propose the immediate dismantling of all the dams on the river Dnieper. The data in Table 2 on artificial potential energy of the tsunami should be supplemented by information connected with potential losses according expression (8). There must be made a forecast of losses caused by the destruction of the reservoirs. After all the calculations, we can evaluate the hazard rank of every reservoir and thus offer the procedure of their disassembling in order to restore the natural state of the Dnieper.

4 Conclusions

New information technologies and development of the theory of environmental management leads to a revision of the main concepts of the planned economy. Thus it leads to the change of our view on necessity and efficiency of functioning of hydropower stations. We analyzed the energetic efficiency of certain reservoirs on the basis of an alternative use of the flooded territory in agriculture. Energy efficiency of different reservoirs is rather different. A significant share of electricity is produced by Dnieper hydropower station, thus there is an opportunity of gradual transition to use of updating energy sources that do not threaten energy security. Therefore, the final decision about dismantling of hydropower stations should be made on the basis of comprehensive assessment of economic-ecological efficiency and evaluation of losses which can be caused by man-made tsunami.

We propose a complex approach to risk assessment of use of the Dnieper cascade hydropower station. We use a stochastic method of assessment of potential losses connected with the use of Dnieper reservoirs in order to assess the losses, which can be caused by violation of the integrity of the dam. We evaluated the potential losses of man-made tsunami for Kyiv reservoir. In the research was made evaluation of the potential hazards of each of the Dnieper reservoirs which can be caused by man-made tsunami. On the basis of the achieved results we ranked the reservoirs according to the degree of economic insecurity.

Transformation of the of the key symbol of the Ukrainian state of rapid flow into the system of stagnated reservoirs has no economic reasons taking into account that hydropower stations produce only 5% of the electricity of the total amount and the flooded areas can be used more efficiently. are more effectively use the flooded areas.

References

1. Veklych O. Ekologichna cina ekonomichnogo zrostannya Ukrainy. Ekonomika Ukrainy. 2012. 1. 51—60. (in Ukrainian)
2. Danylyshyn B. M., Dorogunczov S. I., Mishhenko V. S., Koval Ya. V., Novorotov O. S., Palamarchuk M. M. Pryrodno-resursnyj potencial stalogo rozvytku Ukrayiny. Kyiv: RVPS Ukrainy. 1999. (in Ukrainian)
3. Electronic resource Dnipro: http: uk.wikipedia.org (in Ukrainian)
4. Electronic resource of Derzhavnyj komitet statystyky: http://www.ukrstat.gov.ua/ (in Ukrainian)
5. Statystychnyj byuleten «Zhytlovyj fond Ukrayiny u 2013 roci» - Kyiv: Derzhavna sluzhba statystyky, 2014. S.8 (in Ukrainian)
6. Dnipro siogodni: tilky stogne, ale vzhe ne reve. Electronic resource Dzerkalo tyzhnia: http://gazeta.dt.ua (in Ukrainian)
7. Electronic resource Ystoryya Dneprogesa. Vzryv I vosstanovlenye: http://lifeglobe.net/ (in Ukrainian)
8. Electronic resource Kaskad Dniprovskyh vodosxovyshch: buty chy ne buty?: http://undiwep.com.ua/ (in Ukrainian)
9. Myxajlenko L.E., Lapshyn Yu. S., Vashhenko V.N. K voprosu o sostoyanya plotyn Kyevskoj GES. Derzhavna ekologichna akademiya pislyadyplomnoyi osvity ta upravlinnya. Naukovo-praktychnyj zhurnal «Ekologichni nauky» 2013, 2, 42-50. (in Ukrainian)
10. Electronic resource Ocinka zagroz gidrodynamichnoyi nebezpeky v Ukraini: http://ohranatrud-ua.ru/stati-po-gz/927-gidrodinamichnoji-nebezpeki-v-ukrajini.html (in Ukrainian)
11. PigouA. Ekonomycheskaya teoriya blagosostoyaniya, Russia: English translation.-Moscow: Progress, 1985. (in Russian)
12. Coase Ronald The Problem of Social Cost, Journal of Law and Economics, 1960, 3(1), 1–44.
13. Maidment D.R. Handbook of Hidrology. NewYork.-1992.-Grow-Fill Inc.
14. Muller, Richard A. "Chapter 1. Energy, Power, and Explosions". Physics for Future Presidents, a text book. ISBN978-1426624599, 2001–2002
15. Samuelson, Paul A. “Diagrammatic Exposition of a Theory of Public Expenditure,” The Review of Economics and Statistics,1955, 37(4), 350–56.
16. J Andrew Charles, Paul Tedd, Alan Warren Delivering benefits through evidence, 2011.