Methodological basics of assessing ecological safety in the zones where waterworks units influence natural habitats with the use of water resources

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Abstract. Relying on the results of the long-term studies on the interrelation, interaction and correlation of waterworks units, called an “activity object”, as a part of natural engineering systems “natural habitat-activity object-population” with the environment within a basin geosystem, the article reports on the methodological framework of evaluating the quantitative and qualitative indicators for the zones of activity object influence as important factors of environment safety assurance.

1. Introduction
The current period of social development both within the terrestrial biosphere of the global system “nature-society-man” and at the local hierarchical levels of river basin geosystems in which almost all types of economic and other activities are conducted is substantially linked with the resource-consuming technologies and water resources.

As the reality shows, the resource consuming technologies under systemic consideration contribute to the growth of the gap between the natural processes of interrelation, interaction and correlation in the systems of various hierarchical levels and the types of economic activity. According to the specialists’ research, about 5-6 billion tons of the living matter disappears annually in the biosphere of the Earth because of such human economic activity (Bondarenko et al. 2009; Bondarenko et al. 2012). Such existing opposition of the biosphere and technosphere causes the urgent need to create basically new technologies for using natural resources including water resources.

The transition to the level of essentially new technologies of natural resource utilization cannot be implemented within the existing framework of the traditional development paradigm by transforming even radically the technological systems that are now in use. Consequently, there is a necessity for essentially new methodological approaches of the creation of technological basis that is integrally interrelated with scientific, productive, social and vital needs of the society. In a general view, this problem was formulated by V. I. Vernadskiy and his followers at the beginning of the XXth century, introducing the concept “noosphere” in which reasonable human activities become a development determinant (Bondarenko and Diachenko 2005).

The utilization of water resources in the manifold kinds of economic activity (industrial and agricultural productions, power generation at nuclear power plants (NPPs), thermal power plants (TPPs), hydroelectric power plants (HPPs), and pumped storage hydroelectric power plants (PSHPPs), public water supply, water disposal, etc.) is integrally connected with operating water systems and the building of new water systems in which various types of hydraulic structures are the main technogenic components. Water systems function within the basin geosystems where water resources develop as a superficial and underground flow. So, the use of water resources in the considered basin geosystems of the Kuban River, the Terek River and the Lower Don River is related to intra-basin and inter-basin
regulation and river flow transfer that assigns the spatial borders of very considerable influence zones of hydraulic structure complex, being a part of a water system (Bondarenko et al. 2007).

The functioning of a hydraulic structure as a part of a water system makes certain changes in the natural processes of interrelation, interaction and correlation between natural (biotic and abiotic) components within the boundaries of the influence zones of the considered hydraulic structure complex, hereinafter referred to as “activity object”, functioning as a part of the natural engineering system (NES) “natural habitat-activity object-population” (NH-AO-P). As the research results prove, the changes in the natural habitats within the influence zones of the activity object in the quantitative and qualitative sense are characterized by the changes in the movement intensity of streams of substance, energy and information, determining all the processes of life activity in the considered spatial limits (Vernadskiy 1988). Under a systematic consideration, the movement of streams of substance, energy and information determines the ecological state in habitats (atmosphere, hydrosphere, top layers of lithosphere, soil layer of pedosphere and sub-soil) that affects all aspects of the vital activity of the living matter including a man. In terms of the water resource utilization, the findings of the long-term studies on operating and being under construction natural engineering systems “NH-AO-P” show that for example, the ecological state in the zones of the activity object influence in the region of the North Caucasus defines the environmental safety as an important factor in the processes of the people’s life activity. Thus, the assurance of environmental safety is the most significant and necessary requirement in the technological processes of using water resources (Saling et al. 2002; Saling and Hafer 2009).

2. Materials and methods

The problem of Water as renewable natural resource determines its use in the economic activity and not less important conditions of nature and types of activity object influence on natural habitats, the spatial limits of basin geosystems where the quantitative and quality indicators of water resources are formed as the determinant of environment safety, depending on the ecological state of the area under study.

The processes of interrelation, interaction and correlation of the activity object with natural habitats were studied within the basin geosystems of the Kuban, the Terek and the Lower Don where over 23 million people live (16.3% of the Russian Federation population). In terms of the spatial-temporal consideration, it was found out that the zones of activity object influence in the interaction with natural habitats are different in their nature, borders and time of influence on the movement processes of the flows of substance, energy and information.

Proceeding from the unity of actions of the Nature and economic activity, the systematic consideration of interrelation, interaction and correlation of the activity object with natural habitats identified the need for reasoning a new methodological approach to the delimitation of influence zones and specification of the nature of influence and activity of the population, living in these zones, with the use of the system energy-entropy approach (Davis 1990). In view of the concept, the research of the processes of activity object interaction with the biotic (flora and fauna) and abiotic (atmosphere, river hydrographic network and underground waters, the upper layers of lithosphere in the basis of hydraulic structures and soil cover) components of the environment is considered according to the fundamental laws of the Nature (energy conservation, irreversibility of processes, the second law of thermodynamics, etc.) where the Sun is the main source of energy. The study of issues on reasoning the zones borders of activity object influence is discussed by the example of the hydraulic structure complex and buildings of Zelenchuk Hydroelectric Power Plant-Pumped Storage Hydroelectric Power Plant (Zelenchuk HPP-PSHPP/HPP-PSHPP) which is located in the basin geosystem of the Upper Kuban in the territory of the Karachay-Circassian Republic (KCR).

Considering the Nature actions within the Earth’s biosphere and engineering processes of using water resources for the production of electrical energy by the HPP-PSHPP, the interrelation between the processes of transformation of energy forms should be emphasized; in this case it is referred to the transformation of the solar radiant energy into the potential energy of a water flow and then into
electric one with a certain coefficient of performance (COP) according to the laws of thermodynamics. It is important to note that 20% (135.600 TW) of the solar energy, reaching the surface of the Earth’s land (149.1×10^6 km^2) and World Ocean (361.1×10^6 km^2) flows into the global hydrological processes of the water cycle and less than 1% (1.780 TW) – into the photosynthesis processes of the Earth’s flora (Kovalchuk 2010).

The interrelation, interaction and correlation of the activity object in the regulation and intra-basin transfer of the river flow from the local areas of the basin geosystems of the Bolshoy Zelenchuk River (F_{wat}=779 km^2, W_{ann}=7.790 km^2, W_{lii}=233.7 km^2), the Marukha River (F_{wat}=336 km^2, W_{ann}=3.360 km^3, W_{lii}=100.8 km^3), and the Aksaut River (F_{wat}=509 km^2, W_{ann}=5.090 km^3, W_{lii}=152.7 km^3=15) occurs within the boundaries of the basin geosystem of the Upper Kuban River (F_{wat}=11.0×10^3 km^2, W_{ann}=110×10^3 km^3, W_{lii}=3.3×10^3 km^3) that is a basic part of the Earth’s biosphere where the global processes of the water cycle run under the influence of the solar energy.

The formation of the water supply in the local areas of the natural engineering system “NH-AO-P” in the basin geosystems of the Bolshoy Zelenchuk, the Marukha and the Aksaut requires the solar energy in the amount of 273.429×(10^6 kW/h) 117.136×10^6 kW/h, and 178.659×(10^6 kW/h) for the generation of water volumes of 1.232 mln m^3, 290.0 mln m^3, and 446 mln m^3 (according to the long-term annual average data) correspondingly, 26% of which is taken (on average, 512×10^6 (6)m^3) (by the technological system of Zelenchuk HPP-PSHP) to produce the electric power. It is worth mentioning that in the technological processes of the solar energy (E_{fre}=148206×(10^6 kW/h)) is transformed into the object-oriented water flow of 512×10^6 m^3 for the annual production of electric power in the amount of E_{HPP}=400×(10^6 kW/h) at the HPP-PSHP with. In plants the COP is about 0.1 [5].

At the level of the basin geosystem of the Upper Kuban within which the activity object functions as a part of the natural engineering system “NH-AO-P”, its integrity is supported by the continuous processes of self-organization and transformations in the intra-system formations (hydrographic network, flora and fauna, soil cover, top layers of lithosphere, atmospheric boundary layers, etc.) at all hierarchical levels of the basin geosystem. The introduction of the activity object to natural habitats results in the complication of inter-structural relations in the processes of self-organization between natural and technogenic structural formations in the zones of its influence. The irreversibility in the processes of the activity object interaction with the habitats in the zones of influence causes the emergence of new phenomena in the geological environment, hydrographs of stream bottom part of upper and lower pound locks of reservoir hydrosystem, bank areas of inundated parts of river channels, atmospheric boundary layers and basin geosystem as a whole (Kovalchuk and Naraikin 2011).

3. Results and discussion
Analyzing the results of the studies on the types of activity object influence on habitats, the specific influence were identified with the classification characteristics: low-active, active and highly active (seeFig. 1).

Low-active zone of influence I (see Fig. 1) is defined by the intra-basin transfer of water flow in the basin geosystem of the Upper Kuban and is characterized by minor changes of hydrographs on the tributary streams of the first (the Bolshoy Zelenchuk and the Maly Zelenchuk) and second (the Marukha and the Aksaut) order.

Active zone of influence II (see Fig. 1) is determined by the influence of water bodies and water surface on the microclimate parameters in the atmospheric boundary layers with the growing sum of temperatures over 70 and consequently the duration of the frostless period of 10-15 days. This zone of influence is located on the water storage reservoirs and water catchment areas of hydro-systems, along the route of open areas of the derivational canal “Zelenchuk-Kuban” and in the areas of the upper and lower basins of balance storage (see Fig. 1). It should be pointed out that it is necessary to take into account in the operation period that the air humidity increases with fogging when temperatures go beyond certain limits.
Highly active zone of influence III (see Fig.1) is defined by the considerable changes in natural hydrological, river channel forming and hydraulic processes and the life activity of land and water biocenoses lower the route of the derivational canal “Zelenchuk-Kuban” on the Bolshoy Zelenchuk and the Malyi Zelenchuk. The major factor of influence is 50% of water catchment during the flood season (April-October) from the Bolshoy Zelenchuk, the Marukha and the Aksaut. To reason the possibility of 50% of floodwater catchment, the complex studies (2005-2006) were carried out, engaging the professionals from various scientific fields (biology, ichthyology, zoology, botany, soil science, sociology, hydraulic engineering, etc.) that enabled to assess the nature and level of influence and changes introduced to the natural interaction of natural components between themselves and the population, by reference to the vital needs in the NES“NH-AO-P” under creation.

Highly active zone of influence IV (see Fig.1) is formed by the change of natural hydrograph of the Kuban River in the part (15 km) from the dumping by the hydraulic units of Zelenchuk HPP-PSHHP (70m³/sec) to the facilities of the waterfront of Ust-Dzhugutinsky storage reservoir from which water is pumped to the Great Stavropol Canal (GSC). The factors of influence on the natural hydrograph of the Kuban River is the consumption growth of water discharged by the hydraulic units of the plant, forming the unbalanced hydraulic mode of channel flow movement on the river part under consideration (15 km). The unbalanced changes of water levels in Ust-Dzhugutinsky storage reservoir affect the safety of hydraulic structures of the waterfront, functioning of the water catchment structure of the GSC and the hydraulic operating mode of the canal.

Active zone of influence V (see Fig.1) is specified by the processes of the interaction between the activity object and the upper layers of the lithosphere - geological environment in which the composition, condition and level of natural soil waters change under the influence of seepage waters from the structures (reservoirs, derivational canal “Zelenchuk-Kuban”, upper and lower basins of balance storage). The laboratory research of the seepage processes in the geological environment of the zones of the active activity object’s influence, conducted by the filtration laboratory of Novocherkassk Engineering and Land Reclamation Institute named after A.K. Kortunov set the quantitative indicators that were used to define the borders of influence zones in the geological environment.

The generalized quantitative indicators of zones of activity object influence are characterized by spatial values of local volumes (W) which specify the changes in the natural habitats: atmosphere (Wₐ), upper layers of the lithosphere (Wₖ), the bank areas of river channels below site of water catchment hydro-system on the Bolshoy Zelenchuk, the Marukha and the Aksaut (tributaries of Malyi Zelenchuk) and in the part of the Kuban River from the site of Zelenchuk HPP-PSHHP to Ust-Dzhugutinsky storage reservoir and in the local areas of the land surface as well (FZP) (Bondarenko et al. 2009).

The research data of assessment of influence of Zelenchuk HPP-PSHHP objects as a part of the NES“NH-AO-P” on the natural habitats in the basin ecosystem of the Upper Kuban were applied to obtain the following quantitative indicators:

So, the draw of the design water flow in the flood period (April-October) from the Bolshoy Zelenchuk and Malyi Zelenchuk makes from 25.9% to 26.5% and from 39.5% to 43.4% correspondingly, causes the negative phenomena in the natural habitats of the influence zones and reduces the zones of waterlogging and flooding beyond the area of the site of water catchment systems; the area of the NES “NH-AO-P” under discussion amounts to FNES=117, 3 km², the volume of the atmospheric boundary layers – WNES(at)=1,173 3 km³, the lithosphere volume WNES(lit)=35, 2km³and the total amount makes WNES=1.212 km³.

The quantitative ratio of the spatial influence zone, formed by the NES “NH-AO-P” (WNES =1.212 km³) to the special boundaries of the basin ecosystem (BG) of the Upper Kuban (WBG =113.3 thou.sand.m³ km⁻²) is WNES/ WBG=0.011 that means 1.1% and makes the conditions for a considerable dominance of the natural processes in the movement formation of the flows of substance, energy and information within the spatial borders of the zones of activity object influence.

The study results enable to formulate the following concept-based statements on the ecological state in the zones of activity object influence (I-V) and environment safety:
The environment safety in the zones of activity object influence is interrelated with the processes of the life activity of population and proceeding processes in natural habitats.

- The environment safety is directly interlinked with the energy consumption, providing the generation, storage and transformation of energy forms (thermal, mechanical, chemical, electric, etc.).

- The threat of environment safety damage is activated by the uncontrolled emission of energy and substance, accumulated by the activity object, into the external environment in relation to the activity object, for example, the destruction of waterfront of reservoir hydrosystem.

- The uncontrolled emission of energy and substance into the external environment results in the extreme negative change in the processes of the life activity of population in natural habitats and is accompanied by harm (material and ecological).

- Under systematic consideration, the environment safety damage in the zones of activity object influence is a result of the expression of cause-effect chain of prerequisites that develop at the stages of designing, building and operating of activity object.

- The links of the cause-effect chain in the environment safety damage within the system “protection object-source of environmental hazard-protective measures” (“PO-SEH-PM”) is the activity object that does not meet the environmental and designing requirements.

The complex assessment of the environment safety in the zones of activity object influence (I-V) was carried out by applying the results of different studies (geochemical, nuclear chemical, lithochemical, biogeochemical indications, the pollution of hydrosphere (river network), atmosphere, upper layers of lithosphere, pedosphere, the energy flows, emitting by vehicles, mechanisms and equipment) and the analysis of structure and principles of flora and fauna distribution. The assessment results were used to define the qualitative (I) and quantitative (I) component indicators of the ecological state in the zones of activity object influence as factors of the environment safety.

In terms of quantitative and qualitative parameters, the indicators (I and I) of component group are characterized by maximum permissible concentration, maximum permissible level and maximum permissible emission in relation to original (background) ecological state.

The first component group of indicators I involves the main kinds of the activity object influence on the natural habitats: I(i) – atmospheric boundary layers; I(i) – surface and I(i) – ground waters; I(i) – soil cover and sub-soil; I(i) – flora and I(i) – fauna. Using these indicators, it was found out that the ecological state in the zones of activity object influence features minor and quite permissible pollution level. It should be mentioned that the dynamics of the ecological state within the low active zone of activity object influence (I) is dominantly affected by the other types of economic activity, unrelated to the utilization of water resources at Zelenchuk HPP-PSHPP.

The second group consists of quantitative indicators (I) that characterize the changes in the natural processes of water resource formation (hydrological, hydrogeological and in river channels) with in the basin geosystem of the Upper Kuban under study: I(i) – indicator of maximum allowed inverse catchment of water at the HPP-PSHPP from the river network; I(i) – indicator of the intra-basin partial diversion of flow with the change of hydrographs in river channels; I(i) – indicator that forms river channels and is related to the processes of data transport and suspended sediments in a stream flow in upper and lower canal pounds; I(i) – indicator of the seepage security in the basements and bank abutments in the interaction of hydraulic structures with the geological environment; I(i) – indicator of microclimate change in the zones of interaction of water surface of water storage reservoirs, upper and lower basins of balance storage and water supply structures (canals and aqueducts) with the atmospheric boundary layers.
Figure 1. The zones where the complex of hydraulic engineering structures of Zelenchuk HPP influences on the environment of the basin geosystem of the Upper Kuban: I – low-active zone of influence within the territory of the water collecting territory on the Upper Kuban (11,000 km²); II – active zone of influence of the complex of hydraulic structures on the microclimate indicators ($I_{MC}$); III – highly active zone of influence of the complex of hydraulic structures on the Bolshoy Zelenchuk and Malyi Zelenchuk ($I_{MAC}$); IV – highly active zone of influence in the fifteen kilometers part of the Kuban ($I_{BPDF}$); V – active zone of influence of water storage reservoirs and the complex of hydraulic structures on the geological environment ($I_{BSR}$).

The systematic study of the interaction of activity object with the natural habitats showed that the indicators ($I_j$) in quantitative terms are defined by the ratio of the spatial borders of the determined influence zones ($W_i$) to the spatial borders of local basin geosystems, the Bolshoy Zelenchuk ($W_{BZ}$), the Marukha ($W_{BM}$) and the Aksaut ($W_{BA}$), and the basin geosystem of the Upper Kuban as a whole ($W_{BG}$) where water resources develop.

So, $I_{MAC} = W_{MAC}/W_{BG} = 0.0065 (0.03\%); I_{BPDF} = W_{BPDF}/W_{BG} = 0.0003 (0.003\%); I_{RC(BZ)} ≥ 1.0 \ m$; $I_{MC} = W_{MC}/W_{BG} = 0.0057 (0.57\%)$.

According to the local elements of the basin geosystem $I_{BZ} = W_{BZ}/W_{BM} = 0.055 (5.5\%); I_{K} = W_{K}/W_{BA} = 0.024 (2.4\%); I_{Z} = W_{Z}/W_{BZ} = 0.0092 (0.92\%); P_{M} = W_{M}/W_{BM} = 0.0063 (0.63\%); I_{A} = W_{A}/W_{BA} = 0.0012 (0.12\%); I_{Z} = W_{Z}/W_{BM} = 0.015 (1.5\%); I_{C} = W_{C}/W_{B} = 0.0008/0.08\%; I_{Z} = W_{Z}/W_{BZ} = 0.0003/0.003\%; I_{M} = W_{M}/W_{A} = 0.002/0.02\%; I_{A} = W_{A}/W_{A} = 0.0000/0.008\%; I_{ES} = W_{ES}/W_{BG} = 0.125/1.25\%.$

The analysis of the quantitative indicators $I_j$ suggests the domination of natural processes of interaction between biotic and abiotic components over technogenic processes of interaction between the activity object and natural components in the form of the changes introduced to the natural habitats. The domination of natural processes over technogenic changes in the natural habitats within the zones of activity object influence specifies the ecological state in the considered areas which are characterized by sufficient sustainability. The ecological sustainability in the influence zones in relation to the original background state in the natural habitats is characterized by the ratio of the spatial borders of NES“NH-AO-P” ($W_{NES(at)} = 1,422.94 \ km^2$) where the technogenic processes take place to the spatial borders of the basin geosystem of the Upper Kuban ($W_{BG} = 113,300 \ km^2$) where the natural processes proceed and the flow is formed (on average 3000 mln m³ annually). So, the ratio of $W_{NES}/W_{BG} = 0.0125 (1.25\%)$ reflects the quantitative domination of natural processes with the probability rate of 98.5% - 99.003% that determines the ecological state and environmental safety in the zones of activity object influence.

The results of the ecological state monitoring in the influence zones of the activity object “Zelenchuk HPP-PSHPP” that was implemented in the period from 2006 to 2014 prove the facts mentioned in the previous paragraph.
4. Conclusion
The conceptual principles of methodology for the definition of quantitative ($I_q$) and qualitative ($I_i$) component indicators of the ecological state as an important factor of providing ecological safety in the determined zones of influence of functioning activity object or activity object under construction as a part of the NES “NH-AO-P” were scientifically grounded, relying on the results of the systemic studies of assessing the zones of waterworks unit influence on the natural habitats within the spatial limits of river basin geosystems.

The obtained results were tested under operational conditions by the activity object “Zelenchuk HPP-PSHPP”, the Irrigation Water Distribution System of Stavropol Krai and Rostov Region that confirmed the accuracy of methodological approach for assessing the zones of activity object influence on the natural habitats in the spatial limits of the considered basin geosystems where water resources develop.

The qualitative relations of special borders of influence zones ($W_I$-$W_V$) to the spatial borders of local basin geosystems ($W_{BG}$) and NES “NH-AO-P” ($W_{NES}$) reflect the changes, introduced by the activity object into the natural systems on the background of natural interaction processes. Thus, the ratio $W_{NES}/W_{BG}=0.0125$ (1.25%) means the dominance of the natural processes over technogenic processes that defines ecological state and environment safety in the zones of activity object influence.

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