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ЭКОЛОГИЧЕСКИЙ ОПЫТ ЭКСПЛУАТАЦИИ ПЕРВОЙ СОВЕТСКОЙ ПРИЛИВНОЙ ЭЛЕКТРОСТАНЦИИ НА РУССКОМ СЕВЕРЕ (КИСЛАЯ ГУБА БАРЕНЦЕВА МОРЯ)

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ENVIRONMENTAL EXPERIENCES OF THE FIRST SOVIET TIDAL PLANT IN RUSSIAN NORTH (KISLAYA BAY OF THE BARENTS SEA)

Экспериментальная приливная электростанция, первая в Советской России и вторая в мире, функционировала в Кислой Губе Баренцева моря с 1968 по 1989 г. и была реконструирована в 2007 г. Воздействие приливной электростанции на экосистему ее бассейна, частично изолированную от моря, может быть оценено как локальное в пространстве, продолжительное во времени и переменное по интенсивности. Основными факторами воздействия приливной электростанции на прибрежную экосистему могут быть сокращение амплитуды приливов, снижение волнового воздействия, сокращение стока распресненной воды из отсеченного бассейна в открытое море, механическое травмирование лопастями турбины рыб и планктона. Экологически наименее опасный суточный режим работы гидроагрегата — непрерывная трехсменная 24-часовая эксплуатация. Методы мониторинга, отработанные в Кислой Губе, могут быть применены на крупных водных бассейнах Русского Севера и Дальнего Востока, где предполагается развитие приливной энергетики.

Ключевые слова: приливная электростанция, мониторинг, экологическая безопасность, прибрежная природно-техническая система, биологические сообщества, бентос.

Experimental tidal power plant, the first one in Soviet Russia and the second in the World, worked in Kislaya bay on the coast of Barents Sea from 1968 until 1989, and was reconstructed in 2007. The influence of tidal plant on coastal ecosystem of the basin, partially separated from the Sea, can be assessed as local in space, long-term in period, and changing in its intensity. Main factors of the plant influence on the coastal ecosystem can be: reduction of tides amplitude; reduction of waves; reduction of freshwater discharge from the dammed basin to the sea; mechanical influence of the turbine on plankton and fish. Environmentally least dangerous regime for hydro-aggregate is the continuous three-shift 24-hour operating. Methods of monitoring, which were tested in Kislaya bay, can be transferred to larger water basins in Russian North and Far East that are planned to be used for the development of tidal industry.

Keywords: tidal power plant, monitoring, environmental safety, coastal natural and technical system, biological communities, benthos.

In 2008 it was the 40th anniversary of operation of the Russian pioneer tidal power plant, Kislogoubskaya TPP (= TPP «Kislaya Gouba»), which is situated at West Mourman coast of the Barents Sea. This TPP, that is a monument for science and technology of Russia, is a one-basin plant of double-sided operation (Fig. 1). The TPP was built as an experimental project to prove that tidal power plants are actually possible to construct in Russia [1]. The construction of TPP was realized during 1964–1967. It was planned to begin the exploiting of TPP in 1967, in the year of 50-years anniversary of the Great October Socialist Revolution, but in fact the TPP started to work one year later.

Fig. 1. The TPP «Kislaya Gouba» at West Mourman coast of the Barents Sea

By Kislogoubskaya TPP construction and operation, the viability of the tidal energy use and the ecological safety of tidal power plants were proved. At the present time, the influence from this TPP on the coastal zone is not significant due to its low capacity — 1,5 MW. Its output capacity, as RSHU professor A.V. Nekrasov used to say, who as a tide expert participated in validation of the TPP exploitation regimes, — is «four hundred electric irons». In fact, the TPP «Kislaya Gouba» served itself. However, in future a significant increase of the tidal power industry influence on coastal zone ecosystems is expected. Several large TPPs are developed for the North of Russia. In particular, Mezen TPP with capacity up to 11 000 MW, and Kuloy TPP — 320 MW are projected in the White Sea; the energy can be directed to the Western Europe by the integrated energy system «East-West» [1, 7, 10].

Evidently, only the complex environmental monitoring can be the source of the objective information for the assessment of environmental safety of TPPs. But the development of TPPs monitoring methods is late in comparison to the development of tidal power industry [6, 8].

The convenient object for the development and testing of monitoring system is the basin of Kislogoubskaya TPP. The assessment of the ecological situation in this basin is interesting for the forecast of possible changes in the basins of designed TPPs in the future [4, 9].

Methodology of research

The basin of Kislogoubskaya TPP is Kislaya gouba. In old Russian «pomor» sleng the word «gouba» was used for the small bay (in our case — 1,1 km2). Geomorphologically, Kislaya gouba is a fjord 3.5 km long, that is through the narrow sound in its northern part connected to Barents Sea (Fig. 2). The sound is dammed with the TPP barrage. Mean depth of the bay is 12.5 m. The basin includes two smaller sub-basins (depressions) in its central and upper parts, about 36 m deep, divided by a step about 5 m deep. The number of small river fall into the top of the bay.

Fig. 2. Location of Kislaya bay («gouba») and Kislogoubskaya TPP [9]

The rocky coasts of the Kislaya bay are covered by tundra. In the central part of the bay, the small island Tyulen (what means «Seal») is located (Fig. 3).

Fig. 3. Coasts of the Kislaya bay, and the Tyulen Island

The unregular study of environmental conditions in the Kislaya bay area has begun since 1924 [2, 3], and was continued in 1964–1982 by Polar Fisheries and Oceanography Institute (PINRO) [5]. Detailed study of environmental impact from Kislogoubskaya TPP is carried out since 1983, involving experts from PINRO, Moscow State University named after M.V. Lomonosov and Russian State Hydrometeorological university (RSHU) [4, 5, 7, 11, 12].

In the second half of 1990s (1996–1998) the programme of complex environmental monitoring of Kislogubskaya TPP area was successfully fulfilled in frames of the UNESCO project «Baltic Floating University (BFU) — the Northern component» [11, 12]. On the basis of results of this programme, the analysis of the process of forming and functioning of «coastal natural and technical system» (CNTS) in tidal power plant area was carried out. The complex assessment of the situation in the Kislaya bay ecosystem was carried out for stages of forming, exploitation and modernization of CNTS. According to the data on coastal biological communities' diversity the changes of their sustainability were defined. The speed of returning of the transformed ecosystem to the initial state after the elimination of stress influence was evaluated [6, 7, 8].

The following information on CNTS state was collected: information on technical object, on abiotic environment and on coastal biological communities. Benthos was chosen as a most informative and practically handy object for monitoring. Its high informativeness in relation to the state of the coastal water environment in comparison to other groups of organisms is determined by the fact that benthos is stable in time, characterizes the local situation in space and is capable to present the changes of ecosystem in retrospective. For the assessment of benthos state disturbance the 6-score scale was used (Fig. 4).

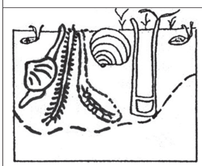
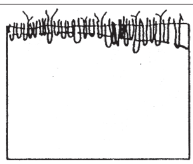
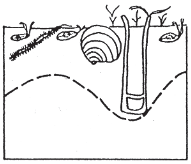
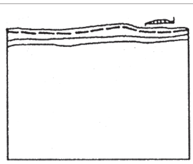
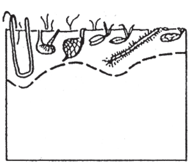
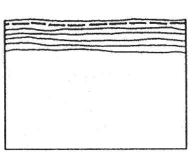
Soft silts communities	Biota alteration index BAI	Qualitative assessment of state	Score, points	Soft silts communities	Biota alteration index BAI	Qualitative assessment of state	Score, points
	> 1	Improved	**6**		0,55–0,75	Moderate	**3**
	0,9–1,0	Normal	**5**		0,3–0,55	Bad	**2**
	0,75–0,9	Good	**4**		< 0,3	Cata-strophic	**1**

Fig. 4. Scale of evaluation of the intensity of biota state disturbance

According to this scale the «normal» (reference) state of biota had the score «5». Communities of soft silts — with the high species diversity and domination of filtrator bivalves and digging polychaetes that dig deep down into the bottom and structure its surface layers significantly — corresponded to this state in the Kislaya bay ecosystem. The disappearance of filtrator mollusks indicates the change of community state from «normal» to «good» (score «4»). «Moderate» state is attributed to the communities represented by chironomids and oligochaetes that are resistant to pollution (score «3»). When the state of the community is «bad» only the actively migrating hydrobionts that to not dig into the silt are found here (score «2»). Finally, when the community state is «catastrophic» the living organisms are absent in the sample (score «1»). The situation of improving of «normal» state of the community is possible when, for example, the mollusks with developed siphons, bottom digging crustaceans and others are introduced into the community — in this case the score «6» is possible.

Results of the «BFU — North» cruises showed that forming of CNTS with a TPP is a complex long-term process when natural factors acting in the TPP basin are significantly transformed by man.

Ecological succession of natural and technical system with tidal plant «Kislaya Gouba»

Before the regulating, Kislaya bay was the typical fjord for West Mourman coast, with the diverse marine biota. In winter it was only partially covered with ice. Before the TPP construction, a water exchange with the sea was unconstructed. The tide was regular, semi-diurnal.

During the 4 years of TPP construction (1964—1968) the bay was dammed from the sea with the solid barrage. The water exchange with the sea decreased down to few percents from the natural one (Fig. 5). Water of the streams flowing from the bald mountains made the surface layer of freshwater 5—7 m thick. In winter the entire surface of the bay was frozen. As a consequence, all littoral biota down to 5 m deep was destroyed. High density gradients on the border of fresh and marine waters prevented mixing and saturating of bottom waters with oxygen. In the deep areas (deeper than 15 m) benthos was poisoned with the accumulated hydrogen sulfide. The survived pieces of marine fauna remained in suppressed state on depths from 5 to 12 m. Traces of this ecological catastrophe are still found in the bay as deposits of dead shell.

After the plant start in 1969 and its work in design regime the marine conditions in TPP basin were partly restored, although the water exchange was 5 times lower than natural (Fig. 5). The tidal amplitude became significantly lower than before; the tidal cyclicity was broken. Partial restoration of biodiversity was possible due to the introduction of brackish-water species.

In 1974 the TPP authorities ignoring the objections of projecting organization moved to two-shift and then — to one-shift operation regime (for the reduction of maintenance staff). Due to the long-lasting stops with the water lines closed the water exchange with the sea was frequently interrupted for the periods from a few days to a few months. The second ecological catastrophe happened in the basin with the biota kill.

In 1983 the TPP moved to the almost projected three-shift 24-hour regime of hydro-aggregate operation. As a result the water exchange rose up to 25—30 % from natural (Fig. 5). The restoration of marine communities and the washing-out of hydrogen sulfide zones in the deeps began. From 1989 after the breakdown of hydro-aggregate the regime close to the recommended was sustained with the idle water passing through the bottom spillway (and through the surface spillway in spring). Through this in 1990s and 2000s the gradual recovery of normal marine communities appeared in the bay.

Observation period, years	Reference	Operation regime	Water exchange in relation to the natural	Biocenosis changes	Index	Score	Ecosystem state	Observations made
Before 1964	Гурьянова и др., 1928, 1929	Natural regime	100 %	Natural state	1,0	5	Normal	Individual observations
1964–1968	Семенов, 1991	Construction, commissioning	Up to 6 %	Destruction of bottom fauna	< 0,3	1	Catastrophic	Individual observations
1969–1973	Семенов, 1991	Projected	Up to 20 %	Introduction of brackish-water species	0,3–0,55	2	Bad	Individual observations
1974–1982	Семенов, 1991	One- and two-shift	2–3 %	Kill	< 0,3	1	Catastrophic	Individual observations
1983–1991	Марфенин и др., 1995	Projected three-shift	25–30 %	Beginning of recovery of marine communities	0,55–0,75	3	Moderate	Regular observations
1992–1999	Fedorov, Shilin, 1996; Марфенин и др., 1995	Idle passing of water; hydro-aggregate not in operation	30 %	Recovery of depleted marine communities	0,75–0,9	4	Good	Geoecological monitoring
1999–2004	Kluikov et al., 1999	Axial flow turbine removed; preparation of orthogonal turbine	Up to 50 %	Restoration of normal marine communities	> 0,9	5	Normal	Geoecological monitoring

Fig. 5. Forming of Kislaya Guba CNTS

Before the TPP construction and in the first 15 years of its operation the TPP monitoring was not conducted as the «environmental monitoring conception» itself was formed only in the mid-1970s [13]. Some individual observations in this period were carried out by various authors that compiled the lists of biota [2, 3]; this allows to define retrospectively the state of biological communities of Kislaya bay in comparison with the adjoining areas of the Barents Sea as «catastrophic» and «bad» (scores «1» and «2»).

Systematic survey in Kislaya Guba in monitoring style was started from 1983 with PINRO and Moscow State University [4, 5]. This was exactly the time of plant moving to the designed three-shift operation regime and recovering of biological communities to «moderate» state (score «3»).

In the second half of 1990s the «BFU-North» expedition evaluated the biota state as «good» (balanced) with the score «4». In the beginning of 2000s due to the removal of axial flow turbine and the increase of water exchange in the bay up to 50 % of the natural one the restoration of normal marine communities occurred.

Present ecological situation in the basin of TPP «Kislaya Gouba»

The purpose of the «BFU-North» expeditions was to develop a monitoring technique for marine coastal natural and technical systems and for estimation of the change of the condition of the Kislaya bay ecosystem.

Two basic types of benthos associations are recognized within the zone of tidal influence. A stony littoral association is formed basically by 10 species. It is a barnacle «sea acorn» *Semibalanus balanoides*; gastropods (snails) *Littorina littorea*, *Testudinalia tesselata*, *Margarites groenlandica*, *Buccinum undatum*; clams *Mytilus edulis*; amphipoda *Gammarus setosus*; urchins *Strongylocentrotus droebachiensis*; polychaete worms *Nereis virens* and pagurians *Pagurus pubescens*.

The association formed by three leading species: *Chironomus salinarius*, clams *Mya truncate* and amphipoda *G. setosus* is observed in small lagoons of the western coast of Kislaya bay on silty-sandy shallows.

The first association is a marine one by its structure, the second — a transitive from saltish-water to marine. Borders of littoral communities were stabilized, a number and a biomass of leading species are increasing.

The washing-out of hydrogen sulfide zones in the deeps was continued. The colonization of depressions by benthic organisms began. Rarefied settlements of clams *Modiolus modiolus* (in the middle part of the gulf) and colonies of sea anemones *Metridium senile* (in the top and the middle parts of the bay) are found in lower sublittoral (Fig. 6). A scallop sandbank was charted on the border between top and middle parts of the gulf by results of diving researches.

The forming ecosystem differs from the initial one, which corresponds with new conditions of the lowered water exchange.

Analysis of joint observations conducted in the ecosystem allows to define the optimal operating regimes for hydro-aggregate. Environmentally least dangerous is the close to projected three-shift 24-hour operating regime when the tendency to normalization of situation in the TPP basin occurs.

Main factors of TPP influence on the coastal ecosystem can be:

- reduction of tides amplitude;
- reduction of waves;
- reduction of freshwater discharge from the dammed basin to the sea;
- mechanical influence of the turbine on plankton and fish.

In abnormal «high water years», like 1996, the biological communities in TPP basin are exposed to the short-term shock impact as a result of the strong water desalination due to the great volume thawed and drain waters.

It was shown that the management of CNTS with the TPP is possible with accounting for and controlling of all defined affecting factors. It is evident that in future during the TPP construction in semi-enclosed marine bays that leads to the reduction of tides amplitude and the increase of the dry period, the decrease in biomass of bottom organisms and the slowing down of production processes in littoral zone are to be expected.

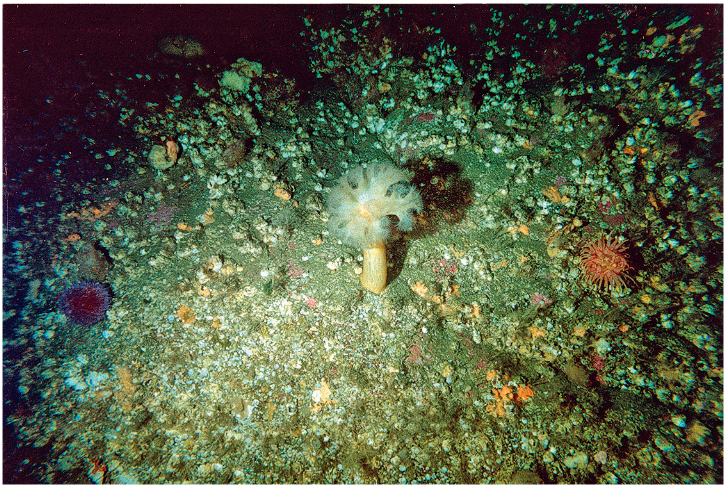


Fig. 6. Sea anemones *Metridium senile* in benthic communities in Kislaya bay

In general, the influence of Kislaya Gouba TPP on coastal ecosystem can be assessed as local in space, long-term in period and changing in its intensity. In present this influence is not significant and hazardous. Modern environmental situation in the basin of Kislaya Gouba TPP can be assessed as non-dangerous; the ecosystem state is normal (natural). At the same time it was shown that at the individual stages of CNTS formation the environmentally hazardous situations can occur that can lead to catastrophic consequences for coastal ecosystems.

The specific feature of the environmental situation in present time and in future is a real practical capability to control all influencing factors on CNTS. The main means of control is the sustaining the projected regime of hydro-aggregate operation which is based on three-shift 24-hour running.

Additional means of control is the possible engineering support of TPP basin ecosystem — non-traumatizing passing of plankton through the TPP hydro-aggregates; the supply of TPP barrage with selective spillways for fresh surface water; creation in the littoral zone of artificial biotopes in the form of a synthetic seaweed which does not react on the desalination and attracts mobile forms of hydrobionts; supply of cold aerated water into hollows with deficiency of oxygen by the pipeline from the open Barents Sea.

It is interesting to see that for more than 36 years of TPP operation the systematic observations of Kislaya Gouba state were conducted during 16 years, but the regular monitoring — for only 8 years. In present time the first in the world experimental orthogonal turbine with 1.5 MW capacity is installed on the TPP, which was made in 2006 on «Sevmash» enterprise in City of Severodvinsk by order of JSC «GidroOGK» [10].

It is undoubted that the return of the Kislaya Gouba TPP to the operating regime requires the restoration of the monitoring system and the permanent observation of the factors of anthropogenic influence on the TPP basin ecosystem. Complex environmental monitoring must be the compulsory element of management of CNTS with the TPP as a source of information for the decision making for providing the ecological safety of the coastal zone. Tested methods of monitoring of CNTS with the TPP can be transferred to larger water basins that are planned to use for the development of tidal industry.

Conclusion

Carried out researches enable to consider an ecological situation in Kislaya bay as «quasi-stable». On the one hand, the biological communities at the present time are supported at the high level. On the another hand, the ecosystem formation and stabilization in Kislaya bay is not finished till now. The system which is forming differs from the initial one, corresponding to new abiotic eciological conditions. The biological communities in TPP basin can be especially vulnerable to the short-term shock impacts — like strong water desalination due to the great volume thawed and drain waters.

Impoverished biological diversity, smaller stability in comparison with control natural ecosystems on the open coasts of Barents Sea, and the dependence from the TPP regime can be considered as basic features of the «natural and technical system» of the TPP «Kislaya Gouba». Littoral (due to the possible intensive desalinating of sea waters) and depressions of sub-basins (due to the deficiency of oxygen) could be named zones of ecological risk.

Optimization of ecological situation in the TPP basin is possible by means of the system of engineering measures.

Realization of ecological monitoring in Kislaya bay enabled to collect material for substantiation of ecological safety of powerful TPP projects in Russia. Detailed researches of possible ecological consequences of TPP environmental impact conducted at natural conditions at experimental Kislogubskaya TPP have brought essential contribution to development of designing, construction and operation principles for tidal power plants.

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