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Environmental aspects of operation of irrigation pumping stations in the context of climate change

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Abstract. Increased workloads to meet the needs of a growing population have posed a number of new challenges for professionals working in the field of ecology and other sciences that study the impact of climate on the environment and buildings. The article presents the main goals for the development of pumping stations based on the development of criteria and prioritization of improving the efficiency of operation, which are formulated by the authors for the strategic, functional, morphological structure of pumped water lifting systems operating in various climatic and hydrological conditions. Research methods include the study of the ecological state of water bodies in the Aral Sea basin and their impact on the management of pumped water systems. The main criterion for research is the modernization of pumps, taking into account the operation of the main structures, their operating modes and structures. The negative consequences of the Aral Sea crisis are associated with the use of large irrigation pumping stations for decades. Some technological foundations of the management of machine water lifting systems in the aspect of safety are considered with the participation of specialists from the Institute of Ecology and Geography of the Chinese Academy of Sciences. The scientific novelty of solving a complex of complex and interrelated tasks of a methodological and technical nature is the creation of an effective regional automated system for environmental monitoring of the operating conditions of pumping stations for any region. The lack of priority work on this problem makes it impossible to optimize the modes of pumping stations at the current level of operation. Special difficulties are taken into account, in particular, the wear of pumps with an increase in the temperature of the pumped water and ambient air. The conclusions include an updated calculation of the main elements of the hydraulic unit of pumping stations in various regional conditions, the conditions for changing the water supply and the maximum use of the potential energy of surface water sources.

Keywords: operating efficiency, machine water lifting systems, water supply facilities, pumps, climate, operating mode, environmental monitoring systems.

1 Introduction

For more than three decades, many Republican international forums on hydraulic research of pumping stations (PS) have been considering a wide range of operational issues related to the unfavorable conditions of their work. The experience of operating large machine channels shows that up to 29% of failures in the operation of pumping units are caused by unfavorable hydraulic processes in the interface structures, water level drops of the channels [3,8].

This is exacerbated by the fact that the PS operates on schedule with a wide range of feeds, and numerous combinations of units operation lead to a change in the flow structure in all elements of the hydraulic unit.

Monitoring of natural processes refers to systems of purposeful observations related to solving problems of forecasting and control. In connection with the above, there is a need to create hydrodynamic monitoring on machine water lifting systems, as a subsystem of water management monitoring. At the first stage of solving this problem, it is advisable to monitor the environmental conditions of operation of large irrigation systems with pumping stations.

Considered with the participation of specialists from the Institute of Ecology and Geography of the Chinese Academy of Sciences, some technological foundations for the management of machine water lifting systems (MWS) in the aspect of safety [10,11]. These problems relate to the creation of an effective regional automated system of environmental monitoring of the PS for any region with the solution of a set of complex and interrelated tasks of a methodological and technical nature. The failure rate of PS structures is determined by a multi-parameter function including hydraulic operating conditions, climatic, geological and geotechnical conditions.

2 Materials and Methods

The materials are compiled taking into account the main goals and criteria of priorities for improving the efficiency of the operation of the PS. The main methods of research are the collection, processing and systematization of information and the study of the ecological state in the Aral Sea basin, the creation of a single information database for rational environmental management, the development of recommendations for socio-economic development, scientific, technical and environmental cooperation of all interested parties. In all of these tasks, monitoring of the environmental conditions for the operation of the MWS is necessarily present.

Based on the analysis of the methodological provisions for organizing an observation system, environmental monitoring takes into account databases on the state of water bodies on the dynamics of variability of environmental conditions over tens of kilometers of these systems, which, in principle, integrally reflect environmental conditions in the Aral Sea basin as a whole. Changes in the pump head are analyzed under the influence of water losses, hydroabrasive wear and cavitation erosion of its elements.

3 Results

In the early 70s of the XX century, intensive water intake from the Amudarya and Syrdarya rivers began for irrigation and washing of fields, and other water management needs. In some years (1982, 1989, 1995) the water did not reach the Aral Sea at all. In other shallow years (1985 and others), the annual runoff did not exceed 5 cubic km, despite the fact that the total flow of the Amudarya River is estimated at 65.9 cubic km.

The Aral Sea, a unique drainless body of water in the Central Asian region, began to dry up before the eyes of one generation, having a negative impact on the ecological, social and economic conditions of the entire region. A significant impact on the volume of water flowing through the main water source of the Amu Darya River is exerted by the largest systems of machine water lifting located on the territory of the Republics of Uzbekistan, Turkmenistan and Tajikistan: Amubukhara, Amuzang, Karshi (KMC), Karakum canals and some large PS (Zhayhun, Sherabad, Bek-yab, etc.)

Based on the foregoing, it should be emphasized the expediency of using the authors' developments on information-advising systems and recommendations for improving the operation of large PS [8,9]. The use of the above methods will make it possible to evaluate complex indicators at checkpoints that characterize the level of pollution of MWS elements, to identify areas for which the increment of these indicators is the largest, and also to assess the impact of the work of the PS on the pollution of water bodies.

Creation of an effective regional automated system of environmental monitoring of the aquatic environment of the PS for any region requires the solution of a complex of difficult and interrelated tasks of a methodological and technical nature [5,19].

Among the most important tasks are the tasks of analyzing regional water bodies (features of the hydrological and hydrogeological regime, priority indicators of the quality of the aquatic environment, the structure of water consumption and water disposal, the main sources of pollution), the choice of technical means that provide the necessary information, its transmission, storage, processing and analysis. When determining the requirements for measuring instruments, the most important issue is the choice of the optimal list of controlled indicators and the operation of the PS parameters [1,14].

The ongoing reconstruction of large PS in Uzbekistan in terms of consumption, power-to-weight ratio, and controls are the largest in the world; failure of them even for a short period of time can lead to huge damage. Therefore, the formulation and solution of theoretical problems for the operation of these facilities, taking into account reliability indicators, is an extremely important national economic task. Until now, the design of PS, including large ones, was carried out without taking into account the quantitative indicator of reliability and safety. The importance of reliability and safety has been underestimated for a long time, and error correction required significant costs [15,20].

In connection with the exhaustion of the resource of the equipment of the PS of the Republic of Uzbekistan up to 50 ... 85%, the problem of safety management becomes extremely relevant. At the National Research University "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" in 2020-21 work has been done on this issue. In accordance with the Law of the Republic of Uzbekistan "On the safety of hydraulic structures" (Article 6), it is necessary to conduct an examination of the safety of the technical condition of irrigation PSs.

The main tasks of monitoring are to establish the factors that determine the risk of a general hazard of the PS, to identify deviations from design solutions, damage, structural defects of structures that can cause technical and environmental accidents.

In the absence of relevant data, information on failure situations of similar objects is used; failure models are built according to the probable assessment of their occurrence. Carry out schematization of the system and external influences; choose the most rational quantitative features. Select quality indicators and areas of acceptable states in terms of quality. The choice is made on the basis of technical and economic considerations, taking into account technological, operational and other requirements.

The wear of the elements of the flow paths of pumps during operation due to cavitation and abrasion by suspended sediments leads to a deterioration in the operating modes of the

PS. The pump diagnostic system makes it possible to increase the operational reliability, including by preventing the installation of defective parts, clarifying the scope of future repairs to restore the performance of the units [4,21].

The flow of failures of structures of the PS in general terms can be determined by a multi-parameter function, which has the following form:

$$\omega(\tau) = f\left[\omega_h(\tau), \omega_{es}(\tau), \omega_{cr}(\tau), \omega_{gg}(\tau), \omega_{cc}(\tau), \omega_o(\tau)\right], \quad (1)$$

where $\omega_h(\tau)$ - generalized parameter of hydraulic conditions;

$\omega_{es}(\tau)$ - conditions of erosion or siltation;

$\omega_{cr}(\tau)$ - constructive reliability;

$\omega_{gg}(\tau)$ - geological and geotechnical conditions of the channel;

$\omega_{cc}(\tau)$ - climatic conditions;

$\omega_o(\tau)$ - operating conditions.

Each generalized parameter can be broken down into separate parameters. Thus, the generalized parameter of the design reliability of the PS can be represented as a function of individual parameters.

Changes in the pump head $H(t)$ under the influence of water losses, hydroabrasive wear and cavitation erosion of its elements during operation can be represented as a product of parameters

$$H(t) = H_T(t)\eta_v(t)\eta_{\mathrm{h}}(t), \quad (2)$$

where $H_T(t)$ - theoretical head as a function of t, m;

η_v (t) - pump volumetric efficiency as a function of t;

η_{h} (t), - hydraulic pump efficiency as a function of t.

The values of the quantities in formula 2 are found by determining the operating points on the characteristics of the pump and pipeline in accordance with the planned water supply schedule for the planned period and the mode of operation of the PS. In the formulas η_p is added - the efficiency of the pipeline, taking into account losses in the pressure pipeline and due to local resistances.

Increased anthropogenic pressures to meet the needs of a growing population have set a number of new challenges for specialists working in the field of ecology and other sciences that study the impact of climate on the environment.

At present, technogenic intervention in the transformation of nature prevails (the construction of dams, the transfer of water). The negative consequences of the Aral Sea crisis are based on the principle of the deceptive well-being of such a transformation, especially the use of large irrigation PS for decades. Errors in nature management lead to the destruction of the environment surrounding a person and, accordingly, a deterioration in the quality of his life. In summer, almost complete drying is observed in the lower reaches of such large rivers as the Amudarya, Syrdarya and their tributaries (Fig. 1).

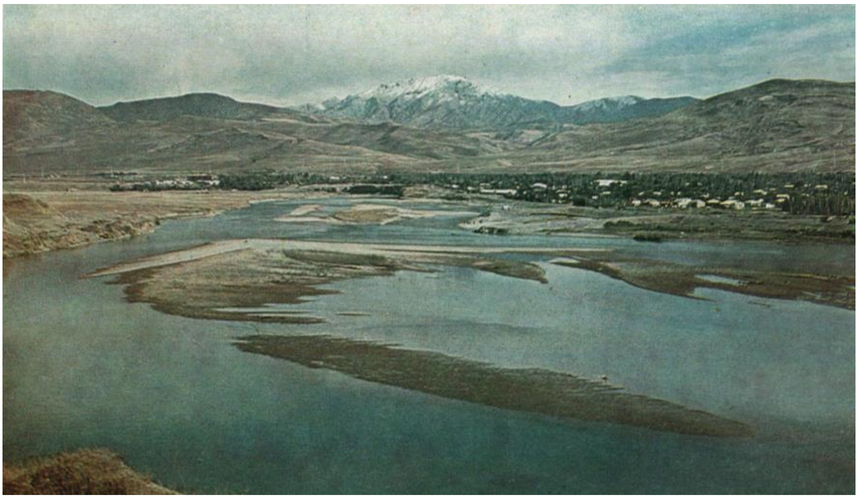

Fig.1. Valley of the Chirchik, the largest tributary of the Syr Darya
"Compiled by the authors"

In the Central Asian region, the increase in water consumption for irrigation and other needs of the national economy will continue. This will lead (without the adoption of appropriate compensatory measures) to further intensification of desertification processes in the Aral Sea region. There will be irreversible changes in the hydrogeological and hydrochemical regimes of the sea - only residual reservoirs filled with water with high mineralization will remain. There will also be a further deterioration in the quality of water, both river and underground.

The conducted studies have shown that a further decrease in the volume of the Aral Sea and a decrease in its warming effect will lead to an inevitable reduction in the growing season with all the ensuing negative consequences for the cultivation of heat-loving crops grown in the Lower Amudarya region [7,16]. The drying up of the sea is proceeding at such a rapid pace that it has already far outstripped all previous forecasts on this issue (Fig. 2,3).

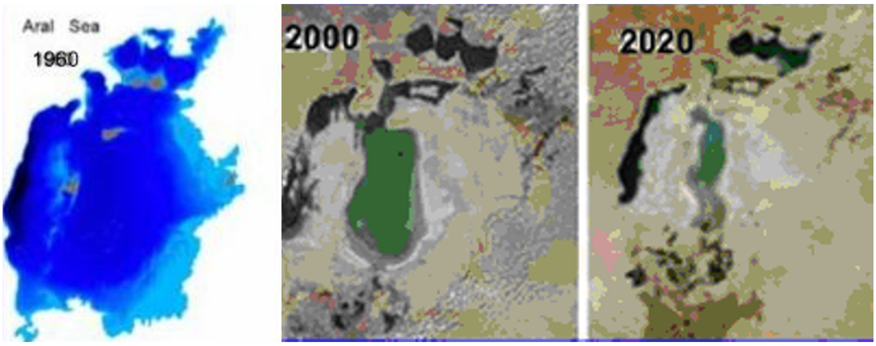

Fig.2. Changes in the water area of the Aral Sea with a decrease in its level "Compiled by the authors"

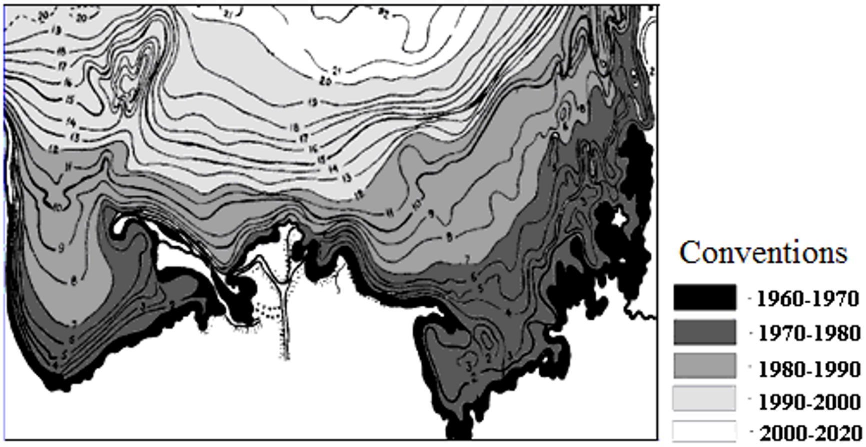

Fig.3. Drainage map of the Aral Sea "Compiled by the authors"

The drying up of the sea has already led to a noticeable change in climatic conditions in the territories adjacent to the Aral Sea, in particular, in the direction of strengthening the continentality of the climate. It can be expected that more than 70% of the seabed, or about 45-50 thousand km^2, will be exposed and turn into a salt desert.

In view of the fact that it is not possible to restore and even stabilize the level of the Aral Sea (there are no water reserves necessary for this - in the amount of at least 40-54 km^3 annually), the only realistic task at this stage is to maintain this reservoir at least at a minimum level. Options for pumping this volume from the Caspian Sea with the help of large PSs and their power supply by nuclear power plants are currently being considered.

An urgent and paramount task that needs to be addressed now is to provide the population, nature and economy of the Aral Sea region with household and drinking water. This will require the allocation of about 5-6 km^3/year of water, a revision of the scheme for the use of water resources in the direction of reducing water consumption for irrigation, in particular, in its middle course by large machine canals.

The regional climatic conditions for the operation of the PS on the territory of the Central Asian Republics are characterized by rather cold winters and hot, long summers. The temperature distribution is zonal. The average air temperature in January varies from -11ºC in Ustyurt to 3-4ºC in the city of Termez in the south of Uzbekistan. In some years, severe frosts are observed down to -35ºC in the lower reaches of the Amudarya River and even down to -50ºC in the mountains (Lake Karakul in the Pamirs). The average July temperature on the plains and in the foothills in Termez reaches 31-33ºC. In the south of Uzbekistan, the sum of air temperatures for the period with a stable temperature above 10ºC reaches 5400ºC in the Karshi steppe. In the last 2018-21 there is a feature of a sharply continental climate, similar to the northern regions of China, Mongolia, and Kazakhstan. This imposes special difficulties on the operation of irrigation PSs associated with the development of methods for assessing the mutual influence of climate and optimizing the energy-saving regimes of PSs [2,12].

Annually, up to 7-8 billion kW/h is spent on the PS of irrigation systems, not counting diesel fuel. It is possible to reduce the electricity consumption at the PS by approximately 10-15%, mainly due to the control of the energy saving of the MWS. In connection with the sharp rise in prices and the growing shortage of energy resources, the problem of reducing their consumption by large PS comes to the fore. The lack of priority work on this problem makes it impossible to optimize the PS modes at the current level of operation.

This imposes special difficulties on the operation of irrigation PSs, in particular, in terms of pump wear with an increase in the temperature of the pumped water and ambient air.

Their impact on the liquid causes: cavitation associated with pulsations and collapse of cavitation bubbles, vortex effects in the form of microflows, acceleration of diffusion processes [18,22]. The kinetic energy of collapsing bubbles, concentrated in a small volume of the flow part of the pumps, is converted partly into a power impulse and partly into thermal energy. In the flow, electrokinetic phenomena also occur, due to the directed movement of particles, which affect the wear processes of casing and working units of pumps [19].

In flows that have only volume elasticity, mainly longitudinal waves propagate, in which particles of the medium are displaced in the direction of wave propagation. For a plane longitudinal wave, the wave equation has the form

$$\frac{\partial^2 y}{\partial t^2} = c^2 \frac{\partial^2 y}{\partial x^2}, \tag{3}$$

where y — flow particle displacement;

c — wave speed;

x — coordinate.

Periodic compressions and expansions of each flow layer in which an elastic wave propagates can be considered as a result of the action of a variable pressure, the amplitude of which is equal to:

$$P = \rho c A = \rho c V_a \tag{4}$$

where ρ — density of water;

V_a — particle velocity magnitude amplitude;

A — velocity amplitude.

The scale of investment policy renewal requires tougher requirements for resource-intensive projects. Reconstruction of the MWS can give the greatest economic and environmental effect. The development of a strategy to improve the efficiency of water use in the MWS in the Zarafshan river basin showed that, first of all, it must be implemented by reducing the consumption of water, energy carriers, optimizing operating modes and pump characteristics [6,17].

The listed directions take into account the environmental aspects of the operation of the PS, the reduction of unproductive losses of water and other resources. The primary problem of operation and reconstruction of the MSW in the Aral Sea basin is currently being activated by the development of new energy- and resource-saving operating technologies with a possible MWS ring and the transfer of their water intakes. The main energy saving measures are related to the development of information-advising systems for controlling the modes of structures and pumping and power equipment according to the main criterion of their efficiency.

The refined calculation of the efficiency of the main elements of the hydraulic unit of the PS in various regional conditions takes into account the elimination of water oversupply in the absence of regulation of the supply of the head of the MWS to the PS and the maximum use of the potential energy of surface water sources. Combined devices have been introduced to change the flow structure at damless water intakes and fore chambers of the PS (Fig. 4).

Fig.4. Combined devices for changing the structure of the flow "Composed by the authors"

Due to the increase in water temperature, while keeping all other operating conditions unchanged, the water vapor pressure increases and cavitation occurs in the pump. For each pump, there is a certain minimum value $Hs\upsilon_{\min}$, which determines $H_{s\max}$, the so-called critical suction lift.

The combined structures being developed should prevent the ingress of sediments and driftwood into water supply structures, overgrowth with reeds and deterioration of water quality.

The best solution would be to prevent sediment and fin from entering the MWS, which can be achieved by installing protective control structures and jet guide structures in front of the water intake structure or the installation of settling basins (head or network) in the head of the main line. Mechanized cleaning in the presence of one or another of the listed facilities is an additional measure.

The fight against sediment deposition at water intake facilities is carried out by straightening and water-damping works, which ensure the passage of the flow remaining in the river past the front of the water intake facility, at speeds sufficient to carry driftwood and sediment. With a significant percentage of water intake, this measure is insufficient, and in order to achieve the required speeds, it is necessary to resort to creating a concentrated pressure drop, carried out by installing a partitioning structure. The calculation of structures is based on the theory of parallel-jet movement of the flow and the movement of sediments by the action of longitudinal velocities; this includes issues of preventing silting up of canals, settling of sediments in settling basins and sand traps, washing of sediments deposited.

The redistribution of velocities within the flow with the transformation of its movement has already been carried out by us in a number of cases for a closed flow in the flow part of pumps.

The main differences in MSW are: free flow surface; often very stretched and non-symmetrical shape of the cross-section of the flow; large cross-sectional dimensions (antechambers), requiring the use of special water intake designs [8,9].

Recently, due to the transition of the Nurek reservoir from irrigation to energy operation, autumn-winter releases have been increased by 2-3 times and, conversely, summer releases have decreased by 2 times, which leads to artificial low water, complicating the provision of water intake in summer, causing floods and additional destruction of canal slopes (Fig. 5).

Fig.5. Destruction and siltation of sections of KMC canals "Compiled by the authors"

At the first level of the hierarchy of optimization calculations of the MWS, the criterion is the minimization of two types of losses: for filtration and evaporation.

This obliges the use of impervious screens on main and inter-farm irrigation systems, as well as measures that do not allow an increase in the surface of reservoirs and canals in the hottest period of the year (advanced drawdown of reservoirs and their filling in winter).

Our studies show that during the growing season, 74... 78% of the annual norm evaporates from the water surface, and more water evaporates from the overgrown vegetation of the water surface than from the open one. Therefore, the use of devices for changing the flow structure, which make it possible to stabilize the velocity diagram, preventing local silting, clogging, etc. on open water sources, gives only on the Amudarya river savings in total runoff losses of 3.4 km^3.

The concept of rational use of water resources developed by the authors makes it possible to achieve the greatest economic effect.

4 Discussion

In the safety study of the PS, an accurate description of failures of elements and failure modes is central, and failure modes are identified using the fault tree method. Based on a detailed analysis of possible events using the methods of the fault tree and the event tree, as well as the sequence of hazardous situations, the elements of the PS are determined, which are subjected to a detailed analysis in order to eliminate the hazards that lead to an accident [9,13]. These studies do not take into account ecological regional climate changes.

When assessing the risk, using operational or experimental data, graphs of only time dependences for the elements of the PS are built. Using the latter, one can only determine the probabilistic parameters that characterize the reliability of the elements for the full cycle of their operation.

Obviously, the less stable the operation of the water management system when considering these parameters, the greater the probability of failure and the greater the damage that can be caused to the national economy with an increase in costs to compensate for it.

5 Conclusion

1. Increased workloads to meet the needs of a growing population have set a number of new challenges for specialists working in the field of ecology and other sciences that study the impact of climate on the environment. Measures to improve reliability and safety under various adverse climatic conditions should be based on the accumulation of experience in the operation of the MWS. The processing of statistical materials on operated large PS and

their elements makes it possible to concentrate the relevant data in a form that allows them to be used by the operating personnel. The analysis of these statistical data makes it possible to develop appropriate measures, sharply reducing research related to the theory of probability and mathematical statistics.

2. Measures have been developed for energy and resource saving, using information-advising systems for controlling the regimes of PS structures in various regional conditions; maximum use of the potential energy of surface water sources. At the same time, it is allowed to eliminate unproductive losses of electricity, pressure and drops in water levels, and reduce the height of the water rise. The authors have created a number of fundamentally new technical solutions to improve the efficiency of water use in the face of climate change.

3. During cavitation tests of pumps, an increase in head and efficiency of the pump was recorded before the start of cavitation. This can be explained by the fact that before the start of cavitation, the separation of water from the walls of the channels of the impeller begins and the friction resistance decreases with a corresponding increase in the efficiency of the pump. The introduction of combined devices for changing the flow structure in the water supply structures of the PS was carried out. However, with large dimensions of water intake structures of modern large stations, these devices are not always able to actively influence the distribution of whirlpool branches over the entire depth of the flow, which leads to an intensification of the exchange of velocity and pressure pulses between transit and whirlpool layers with the opposite direction of velocities. Theoretical and practical studies are needed to reduce the intensity of funnel formation in the water intake chambers of pumping stations, to prevent air leakage into the suction pipes of hydraulic units.

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