ISSN 2079-0961, Arid Ecosystems, 2022, Vol. 12, No. 4, pp. 481–495. © Pleiades Publishing, Ltd., 2022.
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WATER ECOSYSTEMS OF ARID TERRITORIES

Hydroenvironmental State of the Agrakhan Bay and Means for Improvement

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Received May 11, 2022; revised July 1, 2022; accepted July 1, 2022

Abstract—Significant degradation of the Agrakhan Bay on the eastern coast of the Terek River delta has occurred in the course of the 20th century as a result of the combined action of natural and anthropogenic factors. Comprehensive studies conducted by the authors in 2018–2020 have made it possible to describe the main causes of this degradation, characterize the current state of the reservoir, and establish scientific bases under recommendations for its improvement. It has been demonstrated that as a result of partial drying and reduction of water surface area the bay has lost its former importance as a spawning and rearing water body providing the West Caspian region with the younglings of valuable commercial fish species. By 2018, the catches decreased by ten times compared to the early 20th century with sturgeons having almost totally disappeared. The state of the northern part of the bay, which has transformed into a group of shallow water bodies almost entirely separated from each other and from the sea is particularly unfavourable. The study of hydrological and morphological, hydrobiological, fishery-related and hydrochemical parameters has shown that the improvement of the wetlands at the former bay site is possible. Detailed analysis of the water balance using multivariate limnological calculations has shown that there is enough water for watering and partial restoration of the water bodies of the Agrakhan Bay hydrographic system. Clearing of silted and overgrown canals, deepening and berming of the remaining water bodies, and directing the necessary amounts of river water into Northern and Southern Agrakhan Bay (in accordance with the calculated delivery schedule) will allow reduction of the overgrowing and siltation of water bodies, restore the water exchange between them, improve water quality, revive the fishery industry in the region, improve the habitats of many rare and protected animal species, and increase the recreational attractiveness of the region.

Keywords: Agrakhan Bay, Caspian Sea, fishery, bay degradation, water quality, ecological state, ecological rehabilitation, spawning and rearing water bodies, rare species, hydrological modeling

DOI: 10.1134/S207909612204014X

In the 20th century, a combination of natural and anthropogenic factors resulted in significant changes in the structure and hydrological regime of the estuaries of the Volga, Terek, Sulak, Don, Kuban, Syr-Darya and Amu-Darya rivers (Mikhailov et al., 2018). The Agrakhan Bay located in the mouth of the Terek River has undergone significant transformation (Gorelits and Zemlyanov, 2011, *Ust'ya rek* ..., 2013).

In the first quarter of the 20th century, this water body was a typical sea bay. Its area (at the level of the Caspian Sea at 25.6 m a.s.l. and the average water content of the Terek) was about 340–350 km^2 and its depth was up to 3–4 m. The water in the bay was closer to fresh water, especially during water runoff periods. The start of the degradation of the Agrakhan Bay dates back to 1914, when during a catastrophic flood near the Kargalinskaya Village the Terek River channel avulsed towards the bay (Baidin et al., 1971; *Ust'ya rek*..., 2013). In subsequent years, a new main branch of the Terek delta, the Karagalinskii Avulsion, formed in this direction. Until 1940, Terek sediments did not reach the bay, depositing in the extensive overflows between the bay and the Kargalinskaya Village. The water surface area in the mid-to-late 1930s was still about 342 km^2. The formation of the Karagalinskii Avulsion watercourse had almost finished by 1940 and large quantities of Terek sediments started to flow into the middle part of the bay. Their annual average discharge is estimated at 18 million tonnes. Active deposition of these sediments in the bay led to the transformation of the part of the sea area into the landmass of the so-called Alikazgan delta and the overgrowth of shallow waters. By 1956, the channel of the main branch approached the western shore of the Agrakhan peninsula and the delta actually divided the Agrakhan Bay into two parts. The final division occurred in 1977 due to the artificial diversion of Terek waters into the sea from the North (into the North Caspian Sea) to the East (into the Middle Caspian Sea) through the Prorez' channel which crosses Agrakhan Peninsula in its middle part. These events occurred on the background of a severe drop in the sea level (almost 3 m by 1977), with a further decrease after 1995 (to –28.2 m a.s.l. BS in 2020). At present, the bay is divided by the Karagalinskii Avulsion into two separate uneven parts, Northern Agrakhan Bay and Southern Agrakhan Bay, which have their own specific characteristics. The open water surface area of the separated water bodies is only 146 km^2; a watered reed area constitutes another 112 km^2, and the rest are land areas.

The changes that have occurred have had adverse hydrological, ecological, and socio-economic consequences (*Serdtse Nizhneterech'ya*..., 2014; Magritskii et al., 2019). The exacerbation of these impacts, especially on the Northern Agrakhan Bay, is related to the continuing decrease in sea level, the increasing aridity of the Caspian Sea region, the poor condition of canals and the lack of river water inflow (Samokhin et al., 2020, Semenova et al., 2020). The negative impacts can be prevented by implementing certain hydro-technical measures, although their development requires scientific justification.

In 2018–2020, the authors conducted a comprehensive study to determine the current hydroecological condition of the Agrakhan Bay and to develop proposals for its improvement. The objectives of the study included:

— the study of morphometric and hydrological parameters of the water bodies;

— analysis of the chemical composition of water and bottom sediments and characterisation of their pollution;

— measurement of hydrobiological indicators including species composition, abundance and biomass of phyto- and zooplankton and zoobenthos and the composition and degree of development of large aquatic vegetation;

— characterisation of the fish population in the water bodies and development of proposals for improving fish reproduction conditions;

— the study of the occurrence of rare and protected animal species in the area and the assessment of their response to the possible increase in water availability;

— developing proposals for the ecological reconstruction of the water bodies.

The results are presented in the present paper.

MATERIALS AND METHODS

The vast and unique body of data on the current state of the former Agrakhan Bay, hydrological processes and their main natural and anthropogenic driving factors was mostly collected by the authors in the course of their nine expeditions to the site from July 2018 to August 2020. During these expeditions, six hydrological stations were established on the lakes and canals and 14 boreholes were drilled to monitor groundwater. As many as 109000 echo sounding data points and 1775 depth measurements made with a depth probe were obtained. Quadcopter macroscale survey, six series of water discharge measurements at 8 gauging stations in the canals and 19 in Karagalinskii Avulsion, eight series of water sampling for chemical composition studies at ten monitoring points and four series at 15 stations were conducted along with hydrophysical measurements at 345 depth verticals, 200 measurements of water turbidity, 653 measurements of bottom sediment thickness, bottom sediment columns sampling at 15 stations and their detailed description; the macrophyte species composition and leaf area was determined 40 times followed by their description and weighting (about 20; Katanskaya, 1981) and phyto- and zooplankton, zoobenthos and periphyton probes were sampled (10–15 samples for each group). Biological analysis of 3252 specimens of fish was performed at 8 stations. Stock and literature materials on the numbers and species diversity of fish populations, their dynamics in the 20th–early 21st century, fishery history, changes in the number of birds over the period from 2010 to 2019 were studied to detail; the habitation conditions and habitation areas of birds were described 88 times along with 15 studies performed for mammals. Chemical and particle size analysis of 56 bottom sediment samples, laboratory analysis of 111 water samples, and turbidity analysis of 24 water samples were performed in the laboratories of Dagvodresursy and the Faculty of Geography of the Moscow State University. The hydrological data was partially obtained from the stations within the State Hydrometeorological Network. In addition, numerous cartographic materials and 157 satellite images (since 1965) were collected and processed to varying detail; the results of the previous expeditionary surveys of the Terek Delta and the objects in the area and their theoretical interpretations presented in published works and available in the Moscow State University, the State Oceanographic Institute, the State Hydrological Institute holdings and those of other national and federal organizations were studied.

A digital database of stationary and hydrological observations obtained in the Terek delta and Caspian Sea coastal stations (from their opening to 2020) together with a multilayer and highly detailed GIS of the Agrakhan Bay and the Agrakhan region (based on QGIS platform) were created. On the basis of the latter, the maps of the bay featuring its historical boundaries, current landscape structure and depths (scale 1 : 10000) were constructed, the bathygraphic profile were calculated and the maps of aquatic vegetation, bottom sediments and water quality were built. The key hydrometeorological, intra-delta and intra-water as well as the anthropogenic factors which played role in the evolution of the Agrakhan Bay were identified. Unique assessments of the current water regime in the reservoirs of the Agrakhan Bay, water quality and pollution sources, water balance structure and sources and rate of siltation have been obtained. The status of hydrotechnical installations associated with the bay has been evaluated. Numerous graphs, dependencies and diagrams were drawn. Numerical hydrodynamic (ADCIRC) and limnological water balance (GLM) modeling was carried out.

RESULTS AND DISCUSSION

Current hydrological and morphological features of water bodies in the hydrographic system of the former Agrakhan Bay. At present, the former Agrakhan sea bay does not look like a single water body representing a deltaic lake–plavni massif. It is divided by the water bed, floodlands and protection berms of the magistral branch of the Karagalinskii Avulsion into two separate and unequal parts, the northern and the southern one, with their own hydrographic networks, hydrological regimens, landscapes, biota and anthropogenic load at different stages of hydrological and morphological degradation (Fig. 1). The total water surface area of the two disconnected water bodies within the historical boundaries of the Agrakhan Bay is estimated by the authors as 146 km^2 and the area of the plavni as 112 km^2. Thus, the open water surface area has decreased by almost 2.5 times compared to the early 20th century. The remaining areas represent halophytic steppes, salt marshes, pastures and hayfields that are gradually expanding. However, in the register of water bodies and on some maps, the Agrakhan Bay still appears as a sea bay. The morphological dynamics of the Agrakhan Bay illustrates the regular evolution of the coastal lagoon-derived water bodies in river deltas, which many times accelerated by the large-scale fluctuations of the Caspian Sea level, sediment load of the Terek River, water management activities in the delta itself and biogenic water pollution.

Northern Agrakhan Bay is essentially a typical deltaic lake–plavni massif with annually increasing areas of "dry" plavni rapidly developed as agricultural lands, split by the beds of former and existing watercourses and canals, with the Kubyakinskii watercourse and the dried Main Agrakhan Bank being the largest of them (Magritsky et al., 2021). The total area of the Northern Agrakhan Bay (within its historical boundaries) is 233 km^2: the water table, waterlogged reed, "dry" plavni, hayfields, salt marshes and others account for 79.3, 70.7, 60.4, 7.7, 14.3 and 0.9 km^2, respectively. The main part of the area is occupied by the Agrakhan Wildlife Refuge. The length of the Northern Agrakhan Bay is almost 29–30 km from south to north and the width at Chakannye Vorota is 1.9 km; in the widest part it is 11–12 km.

The Northern Agrakhan Bay includes two groups of water bodies, the northern one, consisting of the Konnyi Kultuk and Kara-Murza lagoon bays, and the southern one, with frequently drying, saucer-shaped water bodies and the largest water body in the area, Kuznechonok Lake with the maximum area as large as 25 km^2 and the depth up to 1.5 m (in 2019, depths were not larger than 0.5 m). Water exchange between the two groups is hindered, while the northern group is connected to the sea and has the features of its water regimen. Extensive thickets of periodically watered reeds are common. Submerged aquatic vegetation is scarce. Bottom sediments in the lagoons and Kuznechook Lake have a layered structure, showing the history of transformation of this part of the bay from a sea water body to the lake–plavni massif and dry lands. The soils are saline. The thickness of mechanically permeable sediments varies from less than 0.25 m in the estuarial seashore to 0.5 m in the main part of Kara-Murza and 0.5–1.5 m in the middle part.

The Kubyakinskii watercourse is a fish passage, which is also designed to supply this part of the Agrakhan Bay with river water. It is 33 km long (including the Morskoi watercourse which enters the Bay of Kizlyar) and has maximum depths of 3 to 4.5 m. The watercourse was built in the late 1970s in the place of the large branch, the Kubyakinskii Bank. Its middle part is in disrepair and lacks water.

In the northern water bodies, which communicate with the North Caspian Sea, the course of water levels is determined by fluctuations in the sea level. The range of seasonal fluctuations is 20–35 cm on average. The range of up and down surges is up to 0.5 and 1 m and higher. The saucer-shaped water bodies of the Northern Agrakhan Bay (in its southern and middle parts) are sourced by river and collector waters, rainfalls and melting snow. At the same time, the Kordonka and Roslambeichik watercourses, which are responsible for the water supply from the western direction (from Low Terek reservoir lakes and the Staroterechnaya irrigation system), have remained dry for more than 15–20 years. The Kubyakinskii fish pas-

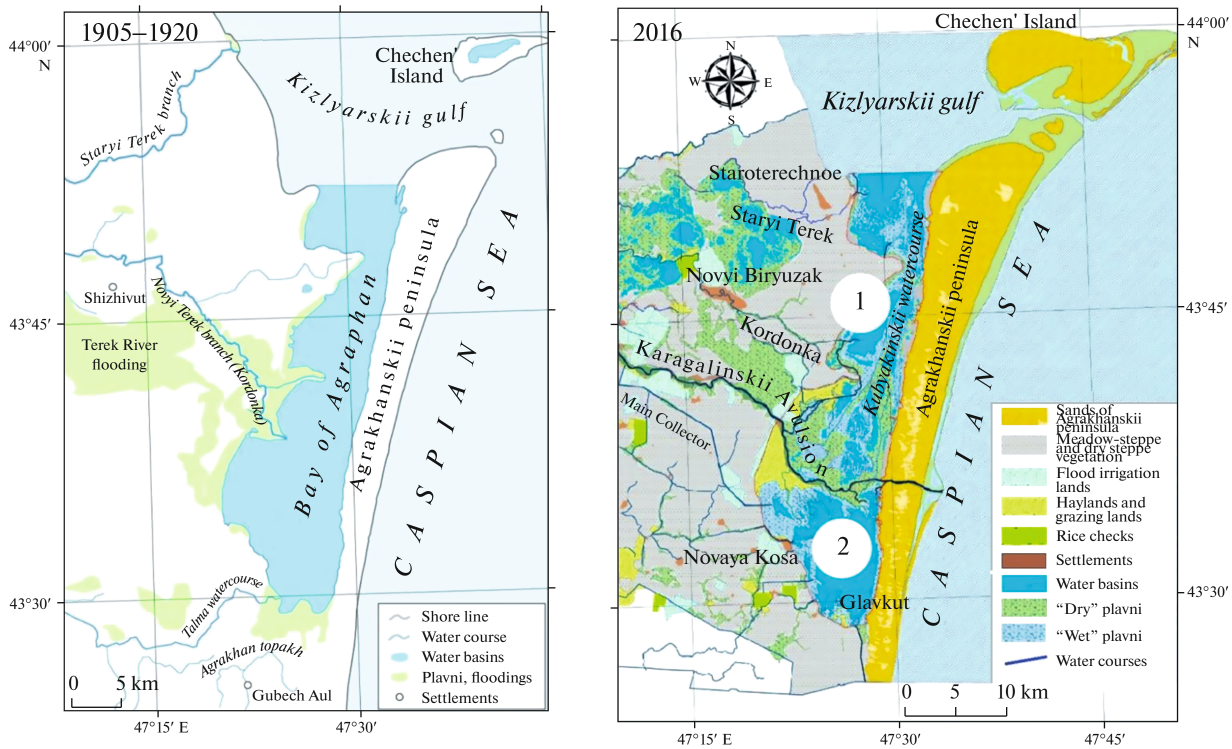

Fig. 1. The borders of the Agrakhan Bay in 1905–1920 and at present time. Legend: (1) Northern Agrakhan Bay and (2) Southern Agrakhan Bay.

sage functions only at high water levels in the Karagalinskii Avulsion and after dredging at the source. Such a water level rise was observed in June–July 2019 and May 2020, which in the latter case resulted in the death of a huge number of fish that entered the watercourse for spawning and couldn't exit it when the water level dropped sharply. Water discharge rates in the watercourse were measured during the expeditions and were about 3 m^3/s at the design capacity of 140 m^3/s. In the absence of connection to the main branch and the watercourses in the northern part of the Terek delta, not only small water bodies may dry up, but even Kuznechonok Lake. This is what happened in 2020, when more than half of the water body area was lost. Small saucer-shaped water bodies may fill up with rainwater and meltwater.

Southern Agrakhan Bay is currently the largest lake in terms of area in the Republic of Dagestan. However, it cannot be considered a natural (residual) water body. It is a hydrotechnically closed water body, with artificially regulated (through a system of water delivery and discharge structures) water balance, volume, level and depth. It is isolated from the sea and Northern Agrakhan Bay. The water level difference in the water body is ~2.5–3.0 m with the bottom being even with the sea level. The reservoir has limited water exchange with the Karagalinskii Avulsion, which in recent years, given the drop in sea level and the incision of the main branch channel, has become even more difficult. At its southern, western, and partly northern borders, Southern Agrakhan Bay is dammed up to 1.5–2 m and higher. The average depths at –25.0 m a.s.l. BS are from 1.5 to 2 m. Depths of more than 2.5 m are confined to the central part. The reservoir volume is 0.16 km^3. Like Northern Agrakhan Bay, it is becoming shallow, experiencing eutrophication and overgrowing with aquatic vegetation. However, these processes occur at a considerably lower rate. The total area of Southern Agrakhan Bay is 136 km^2. Water plate, waterlogged reeds, "dry" plavni, hayfields, flooded solonchaks and other currently account for 66.3, 41.3, 6.5, 16.5, 2.2, and 2.9 km^2, respectively.

Bottom sediments are heterogeneous in their structure, origin and thickness. Three to four layers are well distinguished. Siltation rates with autochthonous materials is 0.6–0.8 cm/year, whereas the rate of river sediments accumulation is an order of magnitude higher, which was clearly confirmed by the rapid growth of microdelta in the north-east of Southern Agrakhan Bay over 2008–2017. The thickness of loosely deposited sediments varies from 10–20 cm (in the middle and southwest) to 1–2 m in the North, imposing limitations on dredging.

For the water regimen, the following has been established. During the year, the maximum water levels are observed in summer and early autumn and minimum water levels in winter and early spring. Their fluctuation range is 0.5 m. Almost the same was observed in the 1980s, when most of the Southern Agrakhan Bay hydrotechnical works were already in operation and the station at Novaya Kosa was functioning. The pattern of annual and seasonal fluctuations in water levels is directly related to the water balance, while the daily variability in water levels is synoptic in nature and has a range of 5–10 cm. The inflow part of the water balance is formed by the waters of the Dzerzhinsky Main collector, which collects excess water from the fields of the vast Dzerzhinsky Irrigation Station and discharges it into the bay. The annual inflow volume is W_{year} ~ 280–310 million m^3 (95–99% of the inflow portion of the water balance), the portion constituted by atmospheric precipitations is an order of magnitude less. Releases to the unregulated Severo-Vostochnyi and regulated Garunovskii (in the South) watercourses, as well as evaporation and transpiration make up the outflow part. All components of the water balance have been studied in detail and quantified, including groundwater exchange.

Hydrochemical characteristics and water quality. Southern Agrakhan Bay waters are brackish (salinity 2–4 g/L), sulphate-magnesium, with their salt composition similar to the waters of the Dzerzhinsky Main collector, which is the main source of water supply for this water body. There are no similarities with seawater. The spatial distribution of chemical parameters is rather homogeneous; the only deviations can be observed near the Main collector. Small exceedances of maximum permissible concentration (MPC) during the study period have been found sporadically for some parameters (for phosphates, ammonium, iron, copper, lead, fishery an MPC exceedance of up to 2 times and for petroleum hydrocarbons and MPC exceedance of up to 8 times). However, there are also elements for which MPCs were exceeded frequently and strongly. These are manganese, zinc, nickel showing up to 5 MPC. For all these elements MPCs were also exceeded in the collector waters, but usually not very strongly. That is, as water from Southern Agrakhan Bay evaporates, pollution accumulates. This has been shown not only by measurements but also by limnological modeling results. A serious problem is the increased input of biogenic compounds (nitrogen and phosphorus) with collector waters and their accumulation in the water body, which leads to an increase in the organic matter content. Water quality is characterized as "dirty" (class 4b) according to the Specific Value of the Combinatorial Water Pollution Index (SVCWPI). Water saturation with dissolved oxygen is generally good, except for the southern section with hydrogen sulphide pollution.

Concentrations of pollutants in the bottom sediments of Southern Agrakhan Bay are more spatially heterogeneous than their concentrations in the water, namely, higher concentrations are recorded in the coastal zones, while in the central part of the lake, the concentrations may be an order of magnitude lower. It can be concluded that sedimentation of pollutants arriving with the inflows is rather fast and they hardly leave bottom sediments, even considering that the water is constantly fully mixed. Nevertheless, the content of pollutants is always below the approximately allowable concentrations. Thus, the state of the bottom sediments is satisfactory and does not require intervention.

Northern Agrakhan Bay is influenced by both river and sea waters in terms of its chemical composition and their geochemical transformation within the area it occupies. In Kuznechonok Lake, water is on average less saline than in Southern Agrakhan Bay, but is also brackish, namely1.5–2.5 g/L, and in Kubyakinskii watercourse and small lakes salinity levels close to those in the Caspian Sea (11–13 g/L) are reached in the seaward direction. In terms of MPC exceedance and according to the SVCWPI ("dirty" to "very dirty" (class 4a–4g)), Northern Agrakhan Bay is the most polluted zone; MPC exceedance is regularly observed for a number of parameters including chromium, lead, iron, ammonium (rarely) with the MPC_{fishery} exceedance order being as high as 2.5 and copper, nickel, manganese, zinc (often) with MPC_{fishery} exceeded by 4–6 times. Most of the elements for which MPC is exceeded are also found in the river waters, but there are those which are specific to sea waters. These are anionic surfactants and hexavalent chromium, which are almost never found in other water bodies. Sea waters are also characterised by the several times higher content of organic matter than the waters of the inland parts of the bay. The degree of pollution of the bottom sediments in small water bodies to the east of the Kubyakinskii watercourse is the highest among all the samples taken. Namely, copper, zinc, mercury, and lead concentrations are close the Approximate Allowable Concentrations (AAC), in two samples AAC is exceeded in the case of nickel. In contrast, in the Kubyakinskii watercourse itself, the degree of DO pollution with metals is quite low, with the corresponding concentrations being similar to those in the central part of Southern Agrakhan Bay. Severe pollution is not recorded; the state is satisfactory.

Hydrobiological characteristics. In the past, relatively deepwater Agrakhan Bay was almost never overgrown. At present, Southern Agrakhan Bay alone is more than for 70% occupied by aquatic vegetation (above-water or underwater). The most underwater vegetation is concentrated in the southern part of the reservoir: projective cover area is 60–100% (Fig. 2a). In the northern and middle part of the water body, the projective coverage is much less, often less than 20%. The plant species composition also differs, with the southern part of the lake being mainly occupied by charophytes, and the northern part predominated by pondweed.

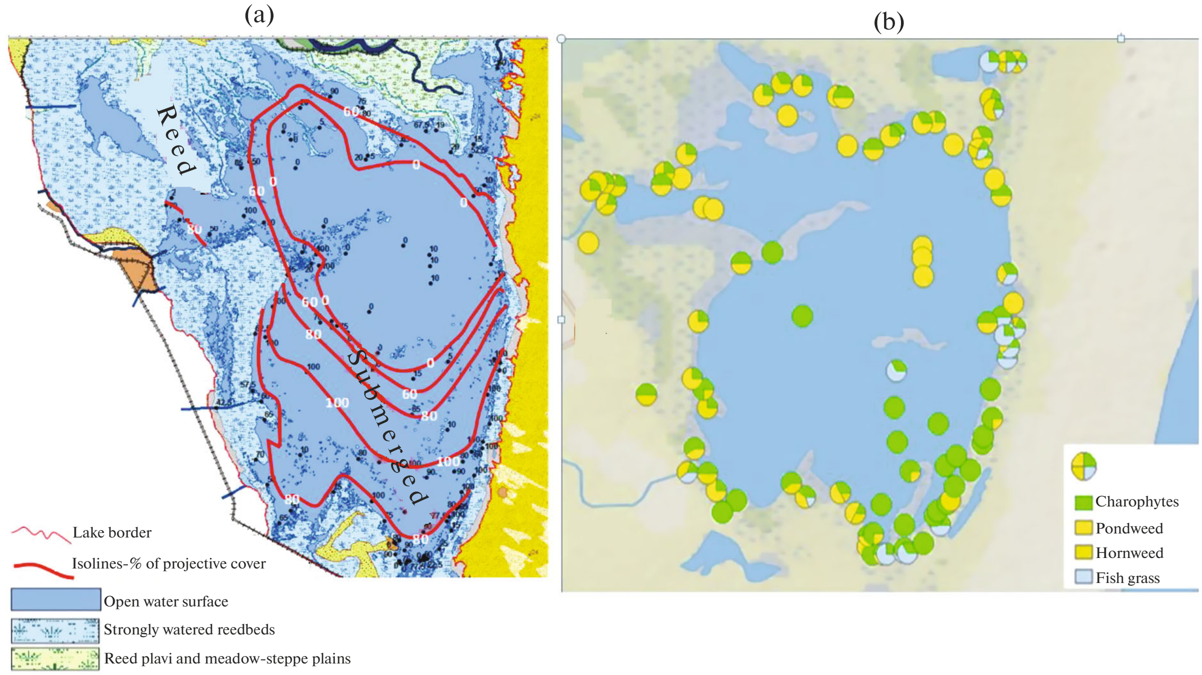

Fig. 2. Mapping of aquatic vegetation distribution in Southern Agrakhan Bay: emergent (reed) and submerged (a) and underwater vegetation species diversity (b) based on the 2018–2020 surveys.

The reason for this is that the northern part of the water body is fed by the river water of increased turbidity, in which the lack of light limits the development of macrophytes. For the same reason, submerged macrophytes are practically absent in the surveyed water bodies of Northern Agrakhan Bay. Water turbidity also increases with an increase in phytoplankton, which is stimulated by the biogenic elements brought in with the inflow into Southern Agrakhan Bay.

The degree of phytoplankton development is unlike that of macrophytes: the turbid waters of Northern Agrakhan Bay (5–100 mg/L) have the highest biomass, while the clear waters of Southern Agrakhan Bay (less than 1 mg/L) have the lowest. The reason for this also seems to be the influx of river water, which are rich in biogenic elements favouring development of planktonic microscopic algae. On the other hand, the development of phytoplankton increases water turbidity.

Thus, it can be stated that the waters of Northern Agrakhan Bay are eutrophic (and even hypertrophic), which is determined by phytoplankton biomass reaching 30 mg/L in 2018 and 100 mg/L in 2019. South Agrahan can also be called an eutrophic (highly productive) water body, but its primary production level is determined not by phytoplankton but by macrophytes, the average biomass of which in the largest parts of the water body is more than 0.8 g/m^2 (absolute dry weight). After vegetation dies, it is decomposed by bacteria, consuming large amounts of oxygen from the water and producing hydrogen sulphide. Some reeds do not decompose, being deposited on the bottom, contributing to shallowing and siltation (*Ekologiya zarastayushchego ozera…*, 1999). Speaking about the role of aquatic vegetation in the life of a water body one can mention not only its negative but also positive properties, for instance, aquatic vegetation acts as a biofilter that reduces the amount of pollutants in the incoming waters and reduces their turbidity. Macrophytes are competitors of phytoplankton and reduce their development. Aquatic plants serve as spawning grounds for fish and as a shelter to protect young fish from predators; fish feed on the numerous organisms that settle on the surface of the plants. Many birds that inhabit the Agrakhan Bay nest, hatch, and feed their young in the aquatic vegetation.

Assessment of invertebrate productivity in the surveyed water bodies (it is required in order to characterise fishery potential) gives contradictory results. The macrozoobenthos is poorly developed and almost absent at some sites. This can be accounted for by the lack of oxygen in the upper layers of silt sediments (in many places the smell of hydrogen sulphide can be felt). It makes invertebrates move upwards into the midwater and populate the surfaces of macrophyte; here, the animals are quite numerous and up to 164 g/m^2 of the bottom area is occupied by plants. Thus, aquatic plant thickets are a favourable place for fish to feed and grow. At the same time, macrophytes themselves are not used in their living state, but are decomposed by bacteria after dying (this process consumes oxygen with possible hydrogen sulphide emis-

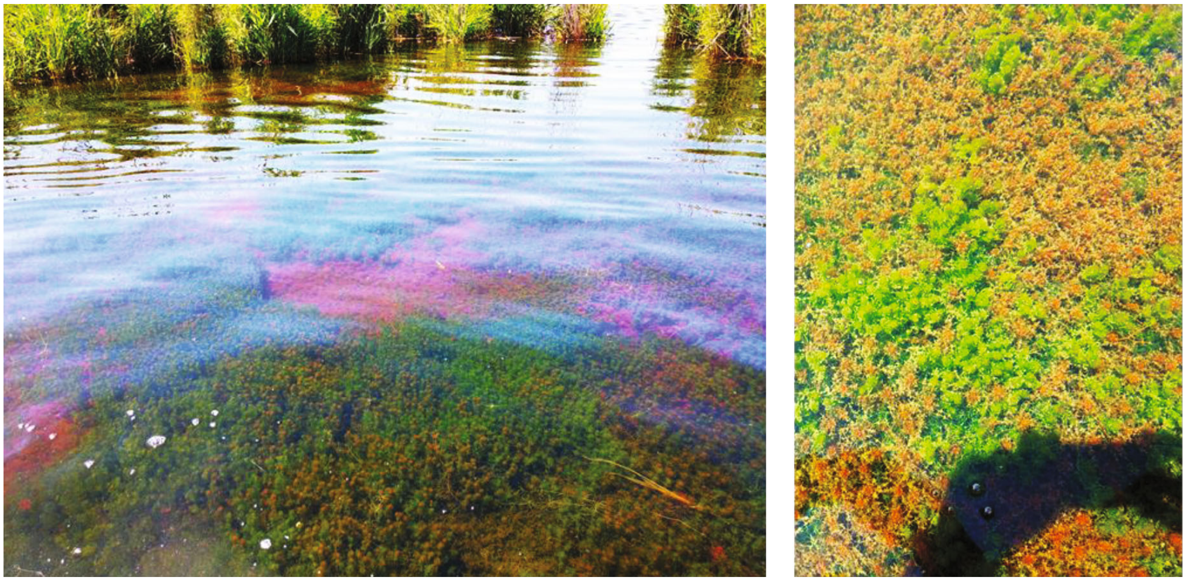

Fig. 3. Underwater meadows of charophytes in Southern Agrakhan Bay (image by A.V. Goncharov, July 2019).

sion). Zooplankton is very poorly developed, a possible reason being that it is actively consumed by fish; in addition, a strong decrease in oxygen concentrations is detrimental to planktonic animals.

The identified hydrobiological features suggest that if the inflow of Terek waters increases, the overgrowing of water bodies in Northern and Southern Agrakhan Bay will decrease, the oxygen regimen will improve (especially at the bottom) and the conditions for the development of benthic invertebrates will improve. In Southern Agrakhan Bay, the inflow of Terek waters will contribute to an increase in biological productivity (biomass of phytoplankton and zooplankton will increase), while underwater vegetation will become less developed, as it will be suppressed by increased water turbidity and competition with phytoplankton for biogenic compounds and light.

Fish and fishery. The changes in the water bodies could not but affect fish and fishery. The fact is that before the shallowing of the Agrakhan Bay, which started with the Karagalinskii Avulsion (1914), it provided for the reproduction of fish stocks in the Tersko-Caspian region."The Agrakhan Bay is the best natural fish breeding factory and nursery for larvae and juveniles in Dagestan, where nature itself creates magnificent conditions for the reproduction of fish and growth of juveniles, the conditions that no artificial fish breeding factory can create," according to the famous ichthyologist I.F. Pravdin (Pravdin, 1925, p. 122). The fish fauna of the Agrakhan Bay included about 40 fish species and subspecies at that time with sturgeon, starry sturgeon, salmon, bream, roach, pike perch, and other fish being caught there.

By 1960, the area of the bay was significantly reduced; the depth had dropped to 0.3–0.4 m and even less at the entrance to the bay. This was a serious obstacle to the passage of fish to the spawning grounds; wintering and growth conditions for juveniles had worsened dramatically and catches decreased. For example, in 1930–1934 up to 2700 tons of fish were caught in the Agrakhan Bay (with fish productivity of about 100 kg/ha); then, catches decreased and at present, they are about 100 tons (fish productivity is about 10 kg/ha; Demin, 1963; Daniyalova and Nadiradze, 1984; Abdusamadov et al., 2014).

To change the current situation, it is proposed to implement fishery reconstruction in the Agrakhan Bay (Fig. 4). This consists of a regulated river water supply to Northern and Southern Agrakhan Bay, construction of fish-passing facilities, reconstruction of Kubyakinskii watercourse, damming and deepening of water bodies in Northern Agrakhan Bay and amelioration of spawning grounds. The latter includes local extraction of silt and removal of aquatic vegetation and for lithophilic fish species, the addition of a gravel–sandy substrate.

The diagram of the future fishery status of the Agrakhan Bay (Fig. 4) shows sturgeon that could emerge if the fish passage at the Kargalinslii hydroengineering complex is improved. Sturgeon will pass upstream of the Karagalinskii Avulsion and Terek, shedding their eggs on gravel–sandy substrates. The emerging juveniles will go downstream and it is possible that some of them will enter the water bodies of Northern Agrakhan Bay where they will gain weight in favourable conditions. The inverted image of a fish in Fig. 4 in Northern Agrakhan Bay in its present state is an indication that there may be situations where fish come in from the sea to spawn during an increase in water levels and then die during a decrease in water levels.

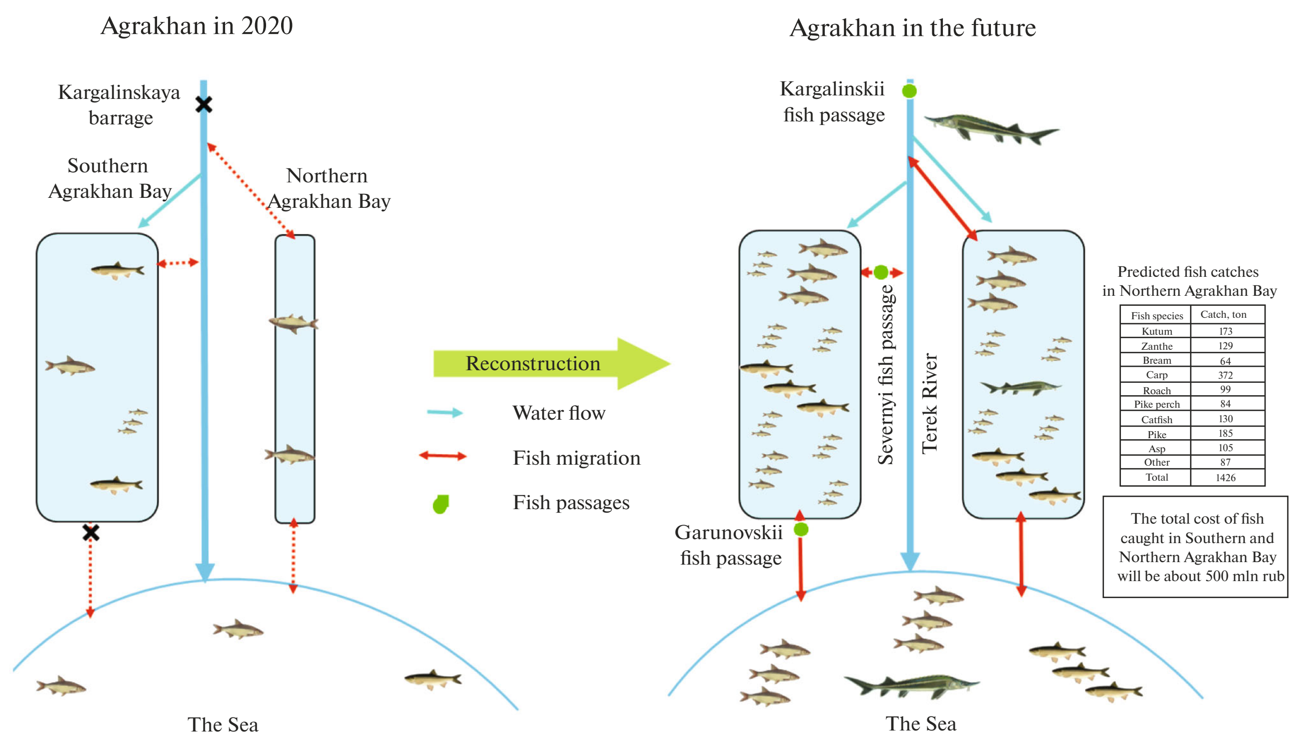

Fig. 4. A schematic representation of fishery reconstruction in the Agrakhan Bay.

As a result of fishery reconstruction, the function of spawning and rearing water body is returned to the Agrakhan Bay: spawning and larval growth takes place there, while fattening continues in the sea. Thus, the feeding base and fish productivity of the reservoir are increased by many times. After the reconstruction, fish catches will increase by a factor of approximately 10. According to the calculations made by the scientists in the Caspian Research Institute of Fishery, the annual fish catch in Northern Agrakhan Bay will be: kutum, 173 tons; zanthe, 129 tons; bream, 64 tons;carp, 372 tons; roach, 99 tons; pike perch, 84 tons; catfish, 130 tons; pike, 185 tons; asp, 105 tons; and others, 87 tons. The calculations are based on the numbers of juvenile fish in the bay in 1980–2010, when the reservoir was in a relatively good condition (*Instruktsii* ..., 2011), and on the data on fishery returns from juveniles, calculated according to the method in the (*Prikaz Minsel'khoza Rossii* ..., 2020). The economic efficiency of the proposed measures in Northern and Southern Agrakhan Bay due to increased fish catches will be about 500 million RUB per year.

Rare and Protected Animal Species in the Agrakhan Bay and Agrakhan Region. Despite the critical state of its ecosystems, the Agrakhan Bay continues to be an area of high biodiversity and is home to rare and endangered terrestrial vertebrates, as well as valuable and commercial bird and mammal species (Fig. 5).

A total of 289 bird species were recorded in the study area. In terms of species abundance the following Orders are distinguished: Passeriformes (102 species), Charadriiformes (57 species), Falconiformes (30 species), Anseriformes (28 species), Ciconiiformes (13 species), and Gruiformes (13 species). In different years, a total of 53 bird species have been registered in the area under study, which are included in the Red Books of Russia (49 species) and the Republic of Dagestan (52 species; Bukreev and Dzhamirzoev, 2016).

The water bodies of the former Agrakhan Bay and adjoining areas of Agrakhan peninsula, Chechen' Island and Terek delta are inhabited by 51 mammalian species, including Insectivores (4 species), Chiropterans (10 species), Lagomorphs (1 species), Rodents (20 species), Carnivores (13 species), Pinnipeds (1 species), and Artiodactyls (2 species). The main mammalian game species in the area under study include wolf, jackal, common fox, corsac, raccoon dog, badger, muskrat, common hare, and wild boar. Eight mammalian species inhabiting the area under study are rare and protected species listed in the Red Books of Russia and Dagestan. In the riparian woodlands of lower Terek and the adjacent reedbeds of the Agrakhan Bay, a unique lowland population of the Caucasian red deer has been preserved.

The fauna of amphibians and reptiles of the Agrakhan Bay and the adjacent areas of the Terek River delta includes 4 species of amphibians and 13 species of reptiles, including 1 turtle species, 5 lizard species, and 7 snake species. The list of rare and protected

Fig. 5. A colony of pelicans and cormorants on Southern Agrakhan Bay Lake, 2022 (image by V.B. Stepanitsky).

amphibians and reptiles species in the Agrakhan Bay and the adjacent territories of the Terek River delta includes common spadefoot, javelin sand boa, and the eastern steppe viper.

The expert assessment of the impact of the expected increase in the water content in the Agrakhan Bay on biological objects has shown the following. On the whole, out of 351 terrestrial vertebrate species, positive impacts are predicted for 149 species, no impacts, for 171, and negative impacts, for 31 species. Out of 53 rare and protected bird species, negative consequences are predicted for a single species, the eagle owl, whose habitat area and numbers will insignificantly decrease. Out of the seven rare and protected mammalian species, habitat reduction and a decline in numbers is predicted for only one species, the red deer. Therefore, as a matter of priority and necessity, a programme for the conservation of Dagestan's unique and only lowland population of red deer should be developed and a breeding center for this rare species should be created on the basis of the Agrakhansky State Natural Reserve where deer could be bred and then released into their natural habitat. Among the valuable game birds and mammals, the populations of grey partridge, pheasant, European brown hare, common fox, and wild boar will be negatively affected. To optimize the protection of the eagle owl and its habitats, as well as to improve the habitat conditions of some valuable commercial birds and mammals (grey partridge, pheasant, European brown hare, common fox, and wild boar), grazing along the banks of the Agrakhan Bay should be prohibited and cattle stock should be restricted on Agrakhan Peninsula and along the western borders of the Agrakhan Bay during the breeding season. In order to prevent a significant reduction in the numbers of the grey partridge, pheasant, European brown hare, wild boar, and red deer, biotechnical activities should be organized for their feeding on the territory of the Agrakhanskii State Reserve and the Dagestanskii Wildlife Refuge. It is also necessary to introduce a 5-year ban on hunting of grey partridge, pheasant, European brown hare, fox, and wild boar in the entire area of the Agrakhan Bay outside the borders of the Agrakhanskii State Natural Reserve. In order to enhance legal protection at the international level, it is proposed to prepare an environmental feasibility study and an application to grant the water bodies of the Agrakhan Bay and the Terek River delta the official status of a Ramsarkoe farming and hunting acreage.

Recommendations for Hydrotechnical Amelioration of the Agrakhan Bay. When justifying the recommendations provided for the Northern Agrakhan Bay, the following needs were taken into account: (1) to ensure

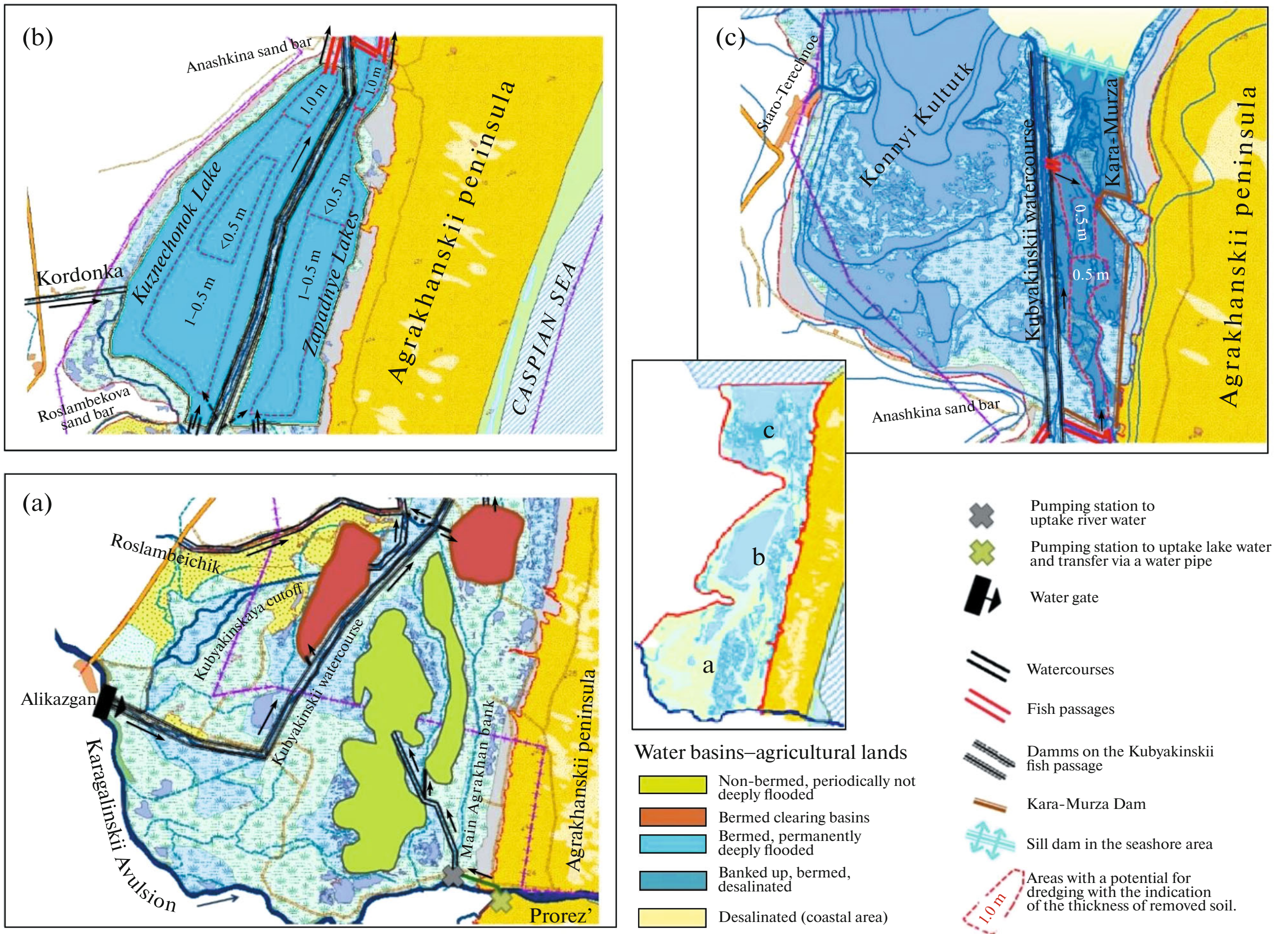

Fig. 6. A schematic representation and landscape structure of the southern (a), middle (c) and northern (c) sections of North Agrahan and hydraulic engineering measures proposed for their improvement.

the free passage of fish for spawning in both Karagalinskii Avulsion and Northern Agrakhan Bay water bodies and rolling of juveniles back to the sea, primarily during the period from March to August; (2) to increase the area and depths of these very water bodies during these months and to maintain fresh and brackish water conditions in them; (3) to create a freshened mixing zone at the estuary seashore; (4) to water the plavni massifs; (5) to preserve the safe and comfortable habitats for terrestrial animals inhabiting and protected in the Agrakhanskii State Reserve with possibilities for their migrations and staging; (6) to accept to some extent the current hydromorphological state of the area and its sub-areas; (7) to keep records of the character of channel deformations and water level changes in the Karagalinskii Avulsion; (8) to monitor sea level dynamics, and (9) to take into account already established land-use patterns. The main proposal is to abandon the equivalent treatment approach to hydrotechnical amelioration of Northern Agrakhan Bay in relation to its entire former territory/aquatorium and to develop instead individual lists of measures for each of its three sections (Fig. 6).

For the southern section of Northern Agrakhan Bay, restoration of a single water body is considered impossible and is not feasible due to (1) higher elevation levels in relation to the branch and the sea, the presence of increased gradients, (2) higher permeability of soils, (3) impossibility to achieve acceptable fishery depths and effective water retention in such water bodies, (4) proximity of the section to the main branch and the threat of possible in-rush of water, flooding and filling with sediments, (5) current land management practices and (6) existing biocoenosis, abundance of water in which would worsen the habitats for rare and protected animal species. However, individual small pools surrounded by berms (or in natural surroundings, permanent or intermittently filled) may be in the eastern part of it, in suitable depressions with water levels reaching –26.8 to –27.4 m a.s.l. BS and an area of about 16 km^2 . Water can be delivered into them through the earth bed of the former North Bank from the main branch and from the Northeast outlet. The delivery mode is from April to September. The required volumes are 67 million m^3/season in order to fill the depressions with water to create depths of less than 0.5 m and to water the planvi and to compensate for infiltration and evaporation losses. No dredging is foreseen here. The main objective of this measure is to water and moisten the area, preserve its wetland status and create favourable conditions for aquatic and semi-aquatic animals and birds. It is proposed to collect water from the branch using pumps and discharge it into a sedimentation basin and then into a new watercourse at the site of the former Northern Bank. It would be 10 m wide, 4.5 km long, and 1.5–2 m deep between berms. This will require 45000 m^3 of dredging and the construction of 9 km of berms at least 1–1.5-m high. It is suggested to collect water from the Northeast outlet, which discharges the "clarified" waters of Southern Agrakhan Bay into the Karagalinskii Avulsion, by means of pumps (not before July), transfer it through a water duct running in the supports of the former bridge over the Prorez' watercourse, and discharge it into the North Bank watercourse or transport it through the water duct.

For the middle section, seasonal watering of depressions and a significant enlargement of their water tables with the maximum depths not less than 1.5 m at the site of Kuznechonok Lake (westwards from the Kubyakinskii watercourse) and Western Lakes massif (eastwards from the watercourse), as well as construction of a fish passage system for fish migrations to spawn and back to the Northern Caspian and juvenile fish downstream migration are suggested. Fish passages at the Kubyakinskii watercourse side and at the border with the northern (seaside) section with the approximate parameters of B = 15 m and h = 1 m can run within the beds of the existing or abandoned channels and will also be responsible for water discharge from the lakes from March to September and consequently for water regeneration in them. From October to February they are recommended to be closed, thus preventing a critical decrease in the water level in the created water bodies. At Western Lakes, it is the northern fish passage watercourse with the access to the Sea watercourse and the Kara-Murza lagoon. The main water delivery and filling season is defined by the key fish species passage and return dates, which is mostly from March to September. Maintaining the required depths and reducing water losses will require the construction of berms separately around Lake Kuznechonok and the adjacent area and around Western Lakes with a height of at least 1 m in order to reach the water level of –26.5 m a. s. l. BS.

At the boundary with the Kubyakinskii watercourse, the reconstructed left bank and right bank dams of the fish passage itself will serve as a berm. The required volume of ground to construct the berm is 82500 m^3. In addition, in order to obtain the required depths and increase the number, area and distribution of the reaches, the following is suggested: (1) sequential dredging in Kuznechonok and Western lakes, with switching from one site to another (i.e., spreading works over 5–10 years) and with zoning into the sectors which should be 0.5 m (~5–6 km^2), 0.5–1 m (<20 km^2) and 1 m (2 km^2) deeper, (2) using excavated soil to build berms (as an additional source of material), and (3) creating bottom grooves for fish passage. The main source of water supply to fill the middle section lakes would be the river waters of Karagalinskii Avulsion, transferred via the Kubyakinskii watercourse. Additionally, suspended sediment-free water could be supplied (into Kuznechonok Lake) via the Roslambeichik and Kordonka watercourses with a total water discharge rate of at least 5 m^3/s, although their capacity is much higher. However, this would require considerable hydromelioration of Nizhneterskie reservoirs, the Zen'kovskii and Zhdanovskii watercourses, and Roslambeichik and Kordonka watercourses themselves.

There is an option for feeding the middle section with the river water that would not require any prior engineering preparation of water bodies and their banks to receive it, only for the purpose of watering the wetlands and improving the existing aquatic and near-water biocenoses without significantly improving the fishery conditions of this part of Northern Agrakhan Bay.

In the northern section, the water surface area is large enough with the existing connection to the Caspian Sea. Water salinity here is high (12.5 g/L), while a salinity level of less than 3–5‰ is desirable for fish. A close correlation between the water level regimen and depths and the sea level exists. When sea level is low (less than –28.5 to –29.0 m a.s.l. BS) and there is a strong negative water surge, the bottom is exposed in most of Kara-Murza. The following measures are proposed to remedy the current situation. First, the construction of a piled stone-and-concrete solid berm along the existing underwater beach ridge running along the marine border of Northern Agrakhan Bay (with bottom elevations of –28.2 to –28.35 m a.s.l. BS) in order to block water outflow from the lagoon during the negative water surges and low sea water levels. This berm would maintain the depths required for fish and at the same time would not impede water exchange between the lagoon and the sea and fish migration during high sea levels and wind-driven surges. It is estimated to be 2 km long and 0.5 m high. At lower sea levels, fish would be able to enter Kara-Murza via fish passages from Morskoi watercourse.

Second, a berm (0.5–1 m high) is also required along the eastern and southern borders of Kara-Murza. In the West, the Kubyakinskii watercourse capital dam will act as such a berm. Third, it is necessary to desalinate Kara-Murza and seashore waters to the target values. Water for desalinization will be supplied through the Kubyakinskii watercourse and fish passages in the volumes depending on the volume of desalinated prism and background sea salinity values, as well as on the “floating” by months critical (for fish) value of salinity (from ~ 5% in October to February to less than 3% in March to September), on rate of water exchange with the sea and full replacement of the desalinated prism by sea water, etc. Fourth, dredging of a 2.3 km^2 area by 0.5 m and a 1.4 km^2 area by 1 m should be performed.

Only the Kubyakinskii fish-passage should be considered as the main route for the transit of Terek waters towards the middle and northern sections. Its reconstruction (removing bottom sediments, deepening and damming) should provide the passage of at least 25 m^3/s (the average, by month, in/out balance of the watercourse is calculated), depths of 1.6–1.9 m and flow rates of 0.6 to 0.7 m/s during the time when fish come in for spawning. These discharges and their feeding regimen are well provided by the discharges of the Karagalinskii Avulsion in the channel’s head gate at its sill level of –25 to –25.5 m a.s.l. BS. at the water discharge rates in the branch more than 300 m^3/s, which (and above them) occur every year from June to August on average. In the case of gravity water supply into the watercourse, high flow velocities and discharges become critical and even destructive at 500 m^3/s. The only way to address this problem is to equip the water inlet system to supply the watercourse with a water retention dam or with an adjustable threshold dam. Since sediments from the Terek River will be taken in with the water and will be deposited entirely in the watercourse, annual cleaning of the watercourse from sediments is necessary. Alternatively, river water entering the canal should be distributed over a nearby dammed depression and then “clarified” water should be discharged back into the canal and into the middle section lakes.

Since the reconstruction of water bodies is planned in the area that is home for many rare and protected species, compensatory measures should be implemented as proposed by the Dagestanskii Reserve. It should be noted that the scientists from the Dagestanskii Reserve propose not to carry out large-scale hydraulic engineering works in the Agrakhanskii Natural Refuge and limit them to providing seasonal water flow from the Terek to the Kubyakinskii watercourse.

For Southern Agrakhan Bay (Fig. 7) in order to fulfill its fishery potential, the following measures were justified and proposed: (1) changing the amount of discharges into the Garunovskii watercourse (from March to October) in order to achieve flow rates of 0.6–0.7 m/s and depths of 1.6–1.9 m and desalination of the mouth part of the Yuzbash-Sulakskii collector and also the arrangement of an additional stepped fish passage and removal of aquatic vegetation from the watercourse, (2) cleaning (from sediments and coastal aquatic vegetation) the Northeast outlet canal, (3) arrangement of spawning grounds in the form of 1 km long 5 m wide coastal sand–gravel bands on each side of the fish passages or along the entire perimeter of the reservoir, (4) arrangement of several wintering pits, and (5) partial removal of reedbeds outside the main nesting and staging areas of migratory birds.

In addition, the hydrological structure of the inflow part of the water balance of South Agrahan should be improved in order to achieve optimum water discharges into the fish passages and elevation of the level surface, desired depths, and desalination and improvement of water quality in the reservoir. Water balance structure modification solutions are obtained using the GLM limnological model (General Lake Model; Hipsey et al., 2014). The maximum water flow rates should be maintained in the fish passages during the periods of mass fish spawning run to the bay and breeding, i.e., in April–June. During the autumn–winter period, after the downstream migration of spawners and juveniles to the sea, sanitary water pass necessary for fish wintering should be maintained in the fish passages. With the functioning of the Garunovskii fish passage alone, this would increase the modern flow from Southern Agrakhan Bay by two-thirds and with the functioning of both fish passages, by more than two times. In order to improve the hydrological-hydrochemical regimen, reduce overgrowing, increase forage supply, and provide comfortable spawning and growth of fish, it is recommended to keep the water level in Southern Agrakhan Bay close to the normal headwater level (–25 m a.s.l. BS) either all year round or in the spring–summer period. Then, the maximum depths in Southern Agrakhan Bay will be 1.8–2.9 m and shallow areas with depths no more than 1.0 m will not exceed 20–25% of the total area. Recharge in February–March will create favourable conditions for the forthcoming spawning, and the winter drawdown will allow annual amelioration of spawning grounds on the drained shallows, which includes mowing of rigid aquatic vegetation, plowing of the waterbed and sowing of meadow grass at spawning grounds of carp, bream, roach and other fish species.

To reduce the risks of disruption of the recommended hydrological regime of Southern Agrakhan Bay, it is recommended to raise (to a height of 2.5–3 m) and maintain protection dams along the water body boundaries (with installations for emergency discharge of excess water and maintenance of road connection during floods).

The recommended increase in discharges while maintaining the current water balance structure in Southern Agrakhan Bay will inevitably result in the shallowing of the reservoir. Therefore, in order to maintain the recommended water level, the inflow needs to be increased as well. To compensate for the losses associated with the watering of the Garunovskii fish passage, the inflow must be increased by 60–75 million m^3 per year (15–19% of the current inflow rate); if the Severo-Vostochnyi fish passage is also watered, then by 120–135 million m^3 per year (31–

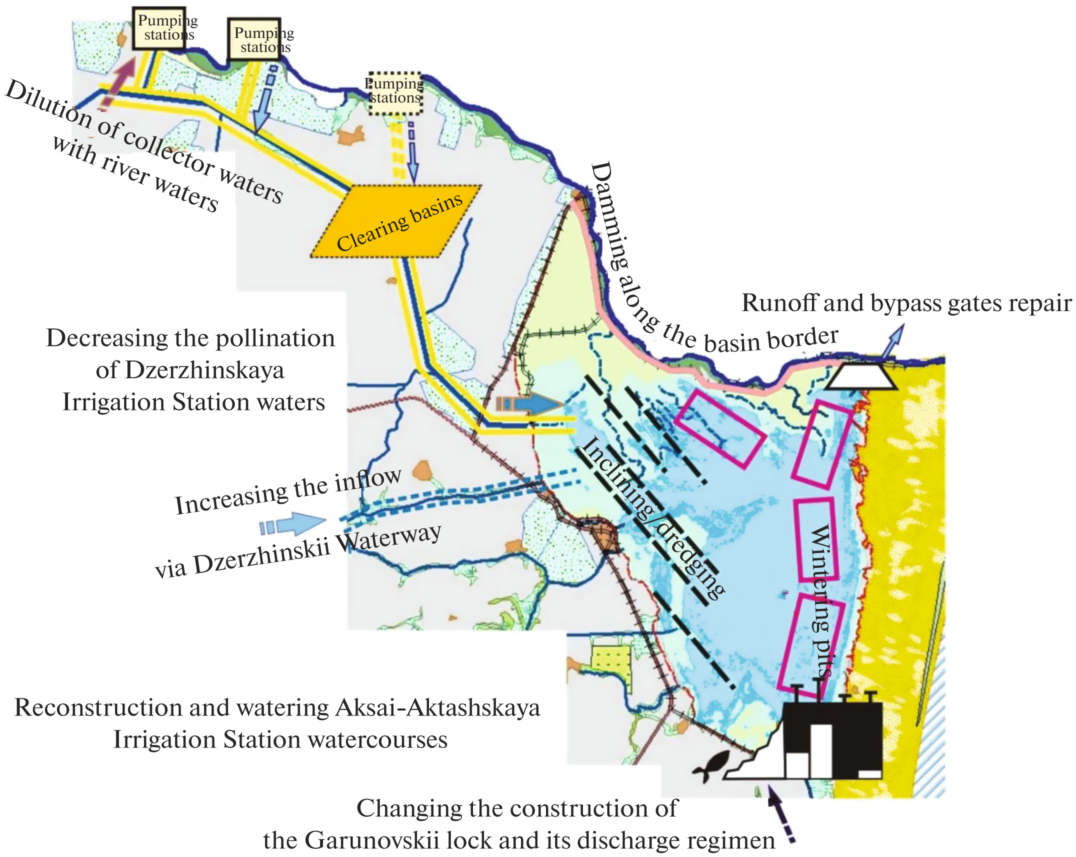

Fig. 7. Mapping of rehabilitation activities in Southern Agrakhan Bay.

35%). The main inflow deficit, which needs to be made up for, occurs in winter and early spring. To increase the water inflow into Southern Agrakhan Bay is possible by increasing the inflow of river water through the Dzerzhinsky Magistral Watercourse, as well as by diluting drainage and collector waters of the Main Dzerzhinsky Collector with the river water from Karagalinskii Avulsion, through the site of the existing pump station building in the sector PK-660.

The need to use the waters of the Terek River to feed Southern Agrakhan Bay is obvious. This will not only provide the necessary inflow volumes, but will also desalinate Southern Agrakhan Bay, which should have a favourable effect on water quality, provide more comfortable conditions for the fish fauna and reduce the water body overgrowth rate, in particular by charophytes. In addition, if Terek waters are clarified in the clearing basins, this will contribute to the reduction of shallowing rates.

The authors also consider it advisable: (1) to reduce water pollution in the Dzerzhinsky irrigation system and to establish monitoring of water runoff and water quality, (2) to ensure mineralization of the water supplied to Southern Agrakhan Bay to be at the level of 1 mg/L (to maintain the current hydrochemical conditions of Southern Agrakhan Bay) or 0.5–0.6 mg/L (to desalinize the waters in the reservoir), and (3) to reconstruct and water the watercourses of the Aksai-Aktashskaya irrigation system.

In addition to the above, integrated (hydrological, hydrochemical, and ecological) monitoring of the entire system of the former Buy of Agrakhan should be established.

CONCLUSIONS

During the 20th and early 21st centuries the Agrakhan Bay in the Terek River delta has undergone a considerable transformation:

— Its area has decreased from 340–350 km^2 at the beginning of the 20th century to 146 km^2 in 2018–2019 (only water surface area is considered); it has been divided into a number of isolated water bodies that often dry up in its northern and southern parts.

— The previously intensive fishery has gone into decline as the bay ceased to serve as a spawning reservoir to reproduce fish stocks. The fish that come from the sea to spawn in Northern Agrakhan Bay die in the drying floodlands. Sturgeon cannot reach their spawning grounds in the Terek River because it is blocked by the Kargalinskaya Dam. The fish in Southern Agrakhan Bay are almost isolated from the Caspian Sea and their forage supplies are extremely limited.

— Water bodies have become shallow and overgrown, water quality is deteriorating, and the productivity of zoobenthos and zooplankton has decreased.

However, the studies carried out by the authors in 2018–2020 indicate that there are possibilities to improve the state of the Agrakhan Bay. Hydrological calculations have shown that there is sufficient freshwater in the region to be used for watering Northern and Southern Agrakhan Bay. It is important that the suggested activities do not significantly disturb the many rare and protected animals that occur in the area, which is the part of the Dagestanskii State Natural Reserve (Refuge). The proposals on the watering of the Agrakhan Bay are based on the idea that it should regain its function as a spawning and rearing water body in both its southern and northern parts. These measures will help to significantly restore the lost fishery potential of the West Caspian region and contribute to the development of the economy and recreation and the improvement of the habitat conditions for rare and protected animal species in the area. At the same time, it is necessary to provide compensatory measures for some representatives of the local fauna, because increased water content may be unfavourable for red deer, wild boar, European brown hare, eagle owl, pheasant, and grey partridge.

FUNDING

Materials collection and analysis was supported by the State Contract with the West Caspian Basin Water Management Board (grant no. NIR-18-01). Manuscript preparation was supported by the State Task (TsITIS no. 121051400038-1) within the framework of the Research Project of the Department of Land Hydrology of the Department of Geography of the Moscow State University.

COMPLIANCE WITH THE ETHICAL STANDARDS

No experimentation involving animals or human was performed by any of the authors.

Conflict of interest. The authors declare no conflict of interest.

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Translated by E. Martynova