Modern hydrological and morphological state of the Agrakhan Bay and its adverse changes

D V Magritsky1*, M A Samokhin1, D I Sokolov1, O N Erina1, A V Goncharov1, M A Tereshina1, V V Surkov1, V M Moreido2, V S Arkhipkin1 and A A Semenova1

1Department of Geography, Lomonosov Moscow State University, Moscow, Russia
2Water Problems Institute of the Russian Academy of Sciences, Moscow, Russia

magdima@yandex.ru

Abstract. The study was based, firstly, on the diverse data collected during field work in 2018 – 2020 in the eastern part of the Terek River delta and long-term hydrological monitoring data on the Rosbydromet gauges. Secondly, on a profound comparative analysis of multi-temporal cartographic materials and multiple satellite images, laboratory analysis of water and sediment samples and other research groups’ field data. The performed analysis resulted in unprecedented complex and profound assessment of the contemporary hydrological, morphological and ecological state of the former Agrakhan Bay of the Caspian Sea. The drivers, dependencies and parameters of hydrological and morphological degradation were described; a multi-layer large-scale GIS was created to design multiple illustrations. The performed assessment allowed for development of measures for partial restoration of the hydrological and ecological potential of the former Agrakhan Bay.

1. Introduction

The Agrahan Bay is situated in the southeastern part of the Terek River delta on the west coast of the Caspian Sea. Genetically, it is a sea lagoon separated from the sea by the Agrakhan Peninsula, composed of the Terek and Sulak River’s alluvial deposits [1, 2]. Until the beginning of the XX century the eastern Agrakhan Bay was hydraulically connected with the Caspian Sea and kept all features of the typical sea bay. Its area was some 340 sq. km, maximum depth up to 3.5 – 4.0 m, and average depth of ~2.5 m. By 2021 the Agrakhan Bay has no features of the sea bay (figure 1).

For what reasons? What processes has led to this? The changes commenced in 1914 when a new arm of the Terek River delta was formed, named Kargalinsky Proryv [3, 4]. It was pointed at the Agrakhan Bay whereas the former delta branches were headed in the northern and northeastern direction. In a short while it became the main delta arm, an extension to the Terek River. The Kargalinsky Proryv discharged water and sediment into the Agrakhan Bay. It should be noted that the annual sediment runoff of the Terek River (18 mln t/yr between 1925 – 2015) is comparable to such large rivers as Ob’, Enisey and Lena rivers (16.1, 12.4 and 22.1 mln t/yr, respectively) at their mouths [2, 5], however the annual water runoff of the Lena River is 58 times higher than the Terek River. The sediment gradually deposited in the bay, significantly decreasing its shape and depth [2, 4, 6, 7]. Between 1940 and 1960, the accumulated formation in area, composed of river sediment, has reached 68 square km and has separated the bay into the northern and southern sections. Some more time the
sections were hydraulically connected by several channels, until the opening of the artificial canal across the Agrakhan Peninsula in 1977. The canal has extended the Kargalinsky Proryv directly to the Middle Caspian Sea. It should be noted that, until 1977, the Kargalinsky Proryv turned to the north before the peninsula, crossed the Agrakhan Bay, and discharged into the Northern Caspian Sea. By 1977 the sediments have covered 130 sq. km of the former bay’s area [2]. These changes developed within the unfavorable hydrological background conditions. Firstly, in October 1977 the Caspian Sea level decreased to -29.16 m a.s.l., the lowest recorded value at the Makhachkala sea station. After 1995 its second decrease started (from -26.46 m in 1995 to -28.0 m in 2020). Secondly, the period of 1947-1987 was relatively low-water for the Terek River (8.41 cubic km/yr vs 11 cubic km/yr in 1925-1946).

Figure 1. Agrakhan Bay in 1926 (a, Map of the Caucasus region), August 23, 1965 (b, Key Hole), summer 1978 (c, aerial photography), May 5, 1986 (d, Landsat 4), September 6, 2002 (e, Landsat 7) and May 12, 2019 (f, Landsat 8). The water is depicted in shades of blue (1), the reed cover are green (3), and the dry steppe is yellow (2).
In the modern conditions the former Agrakhan Bay is separated by the riverbed, floodplain and levees of the Kargalinsky Proryv into 2 independent and unequal parts – the Southern and the Northern Agrakhan (figure 1). They possess separate hydrographic and landscape conditions, hydrological regimes, biocenosis, and anthropogenic load. The total water surface area of separated water bodies is 146 sq. km, the coastal reeds (also known as “plavni”) cover additional 112 sq. km. The rest is land and agricultural land.

The alterations in hydrological regime and morphological structure have led to a plethora of unfavorable hydrological, ecological and socio-economic consequences, partially described in [7]. The future projections are adverse, particularly for the northern part due to sea level decrease, climate aridization, insufficient canals’ maintenance and river runoff shortage. Thus, the Republic of Dagestan loses a unique hydrological and ecologically valuable wetland system keeping diverse, rare and protected species of animals, fish, fowl and vegetation, and, furthermore, a valuable recreational and tourist object. It should be emphasized that the Agrakhan Bay sustains sufficient groundwater levels to prevent secondary salinization of the surrounding areas and serves as a barrier for the propagation of the Agrakhan peninsula sands further inside the delta.

To prevent the negative scenario a set of hydro-technical measures is required, however the scientific argumentation of the list and areas it will be aimed at requires new complex hydrological data about the object, the features of its hydro-morphological degradation and efficiency analysis of the formerly applied measures. Before 2018 the data on the Agrakhan Bay was scarce and no hydrological data was available on its northern part. Furthermore, in the Russian water management practices there were no such examples of ecosystems restoration situated in the mouth of a large unregulated (by water reservoirs) river with tremendous sediment runoff and discharging into the sea with highly unstable water level. Yet by 2020 the authors prepared a thorough Agrakhan Bay restoration program positively successfully reviewed by the Russian water authorities.

2. Materials and methods
The main initial dataset on the contemporary hydro-morphological conditions of the separated water bodies in the Agrakhan Bay, hydrological processes and its features was collected during 9 field campaigns between 2018 and 2020. These included:

- setting up 9 water posts on the lakes and river channels equipped with Onset HOBO level loggers, 14 wells for groundwater monitoring;
- 1775 manual depth readings and 109 000 echo sounder data with GARMIN;
- macroscale UAV surveys;
- 6 series of discharge measurements on 8 gauges in river channels and 19 cross-sections in the Karagalinsky Proryv (from the Alikazgan gauge to the sea);
- 8 series of water sampling for chemical analysis on 10 monitoring sites and 4 series on 15 stations;
- measurements of hydro-physical conditions on 345 vertical profiles with hydrological probes YSI Pro 30 and MARK-603, and 200 optical turbidity readings with HACH 2100p turbidimeter;
- 653 measurements of bottom sediments thickness (with manual probe), 15 bottom sediments core samples (with tube sampler GOIN TG-1) and its detailed descriptions;
- 40 definitions of water plant’s species structure and its area assessment, their weighing;
- zoo- and phytoplankton samplings (minor Juday net), zoo benthos ant periphyton – 10-15 samples within each group.

The laboratories of the Dagestan water administration and Faculty of Geography of the Moscow State University (MSU) performed chemical and grainsize analysis of 56 bottom deposit samples, 111 water samples (main ions, salinity, hardness, pH, dissolved nutrients and organics, heavy metals, and petroleum products, phenols and dissolved oxygen). 24 water samples were filtered through paper and membrane filters for volumetric turbidity. Part of the dataset was obtained from the Roshydromet river, lake and sea gauges and MELIOVODHOZ gauges.
Moreover, diverse cartographic materials were collected and analyzed, starting from XVIII century, 1 aerial photography in 1978, 157 satellite images since 1965 (obtained from USGS [https://earthexplorer.usgs.gov/]). Images were processed in ArcMap 10.3 basing on different indexes (figure 1). The multi-seasonal field surveys of relevant sites with limited access in the former Agrakhan Bay helped to successfully satellite image classification. The results of surveys conducted by other institutes, published as articles and books, and also MSU, State oceanography institute (GOIN), State hydrological institute (GGI), and Dagestan institutions archives, were additionally examined.

A multi-layer large-scale GIS of the Agrakhan Bay and surrounding areas was created (on basis QGIS). Based on this GIS it were created maps of historical and modern bay shoreline, of its current landscape structure, bathymetry (100 m scale), water vegetation, bottom sediments, water quality, and graphs of depth to area relations were built. Main factors of centennial, intra-centennial and intra-annual dynamics of the Agrakhan Bay were revealed. The characteristics of modern water regime, water quality and pollution sources, water balance structure, and sources and rate of sedimentation of the Agrakhan Bay water bodies were obtained. Current technical conditions of the water control structures was assessed. Closure of the cross-peninsula canal and change of the Karagalinsky Proryv back in northern direction was assessed by numerical simulations of inundation of the northern part of the bay with the ADvanced CIRCulation model for oceanic, coastal and estuarine waters [9] model.

To assess the optimal water level, inlets and water removing in the Southern Agrakhan the water balance modelling was performed using the General Lake Model [10].

3. Results and discussion

3.1. Hydrological, morphological and ecological state of the southern part of the Agrakhan Bay

At present, almost 50% of the South Agrakhan’s area is open water (figure 2). Present-day South Agrakhan can be considered a hydrotechnically contained and unbroken water body with artificially maintained (via a system of canals with regulated water inflow and outflow) water level and volume. It is separated from the Caspian Sea and the North Agrakhan (with 2.5-3.0 m difference in elevation), has limited water exchange with the Kargalinsky Proryv, connection to which currently continues to deteriorate due to a decline of the sea level and channel erosion. From the south, west, and, partially, north, the South Agrakhan’s shore is reinforced by levees 1.5-2 meters high and in some places taller. At the level of -25.0 m BS, the average depth ranges from 1.5 to 2 m. Depths of more than 2.5 m were found in the central part (figure 2). The total water volume is 0.16 km$^3$.

About 42% of the southern part of the former Agrakhan Bay is covered by reed beds, primarily in its coastal area (figure 2). At the same time, 30% of the open part is overgrown by submerged charophyte algae, pondweeds, and hornworts. Not only the excessive growth but also the dying out of the plants poses a threat. Firstly, plant remains are decomposed by bacteria, which consume large amounts of oxygen, thus creating a layer of hydrogen sulfide. Secondly, some of the plants remain not decomposed, depositing at the bottom and causing rapid siltation. Bottom sediments in the South Agrakhan are uneven in structure, genesis, and thickness. 3-4 layers with distinctive age, origin, and composition can be distinguished in the top 1m layer of sediment. The autochtonous siltation rate is assessed as 0.6-0.8 cm/year, while the rate of siltation via river sediment is much greater (up to several cm per year). This was clearly confirmed by the rapid growth of a small delta in northeastern South Agrahan in 2008-2017, as was established by satellite imagery and confirmed in the field. The thickness of loose sediments suitable for dredging varies from 0.1-0.2 m in the middle part and in the southwest to 1-2 m in the north (figure 2).

Regarding the water regime of the South Agrakhan, as a single and artificially regulated water body, the following was identified. Maximum annual water levels are observed in summer and early fall, minimum – in winter and early spring. The range of water level fluctuations is 0.5 m.
Figure 2. Spatial variability of the hydrological and morphological characteristics of the modern South Agrakhan (in 2019–2020): a – Bathymetric chart, b – Map of the distribution of water plants, c – Map of thickness (in meters) of loose sediments suitable for dredging, d – Map of heavy metal pollution of bottom deposits mcg/kg. Map legend: 1 – plavni, 2 – % cover with submerged water plants, 3 – open water, 4-5 – reed beds (plavni), 6 – sands, 7 – settlements, 8 – salt flats, 9 – copper, 10 – nickel, 11 – zink, 12 – arsenic concentrations.

The same dynamics were typical in the 1980s when most of the hydrotechnical facilities of the South Agrakhan were already in operation. The nature of inter-annual and seasonal fluctuations of the water level is directly dependent on the water balance, while the daily variability of levels is mostly caused
by synoptic processes and has a range of 5-10 cm. Up to 95-99% of the inflow is formed by the main collecting canal of the Dzerzhinsky irrigation system, which collects excess water from a vast agricultural area and has an annual runoff about 280-310 million m³ discharging into the South Agrakhan. The rest comes with precipitation and (a negligible amount) with groundwater. Water outflows consist of discharges to the unregulated Northeastern canal (through a weir spillway) and to the Garunovsky canal (through a gate lock). Evaporation, transpiration, and, possibly, underground outflow towards the sea compose 45-55% of water loss.

Among key chemical characteristics of the South Agrakhan, it should be mentioned that the waters are brackish (2-4 g/L), with a predominance of sulfates and magnesium. The chemical composition is close to that of the Dzerzhinsky sewer canal. No notable patterns were found in the vertical and horizontal distribution of hydrochemical characteristics. The only significant anomalies were detected near the mouth of the Dzerzhinsky sewer canal and in shallow waters to the west of the Agrakhan Peninsula. Small exceedances of national environmental guidelines were detected, particularly often and significantly for Mn, Zn, and Ni. Waters are classified as "dirty" according to the Specific Combinatorial Index of Water Pollution (SCWPI; a national water pollution index). A major issue is the increased nutrient inflow with collector waters and their accumulation, which leads to further eutrophication of the South Agrakhan.

3.2. Hydrological, morphological and ecological state of the northern part of the Agrakhan Bay

In contrast to the southern part of the bay, North Agrakhan is a typical deltaic wetland massive, cutting by former and existing canals and branches. Its former area is 233 km². The area occupied by vegetation of arid steppe and semi-desert, sparse and partially dry reedbeds, and agricultural lands increases every year, partially due to the increasing aridity of the climate in this part of the coast. The Northern Agrakhan consists of the southern and northern groups of water bodies. Water exchange between them is limited. The southern group consists of almost ephemeral, lens-shaped, shallow (usually <0.5 m) lakes. The largest water body here is Lake Kuznechonok with maximum area <25 km² and depth <1.5 m (<0.5 m in the summer of 2019). The northern parts include lagoon bays Konniy Kultuk and Kara-Murza, separated by the Kubyakinsky canal. They are connected with the Kizlyar Gulf of the Northern Caspian Sea and have a similar water regime. Their prevailing depths are 0.5-1 m. The largest watercourse of the Northern Agrakhan is the abandoned Kubyakinsky canal, built in 1979 for transit of fresh water to the north and passage of fish from the Northern Caspian Sea to the Terek River. The maximum depths in the end section of the Kubyakinsky canal reach 3 to 4.5 m. The main part of the territory is occupied by the Agrakhan Natural Reserve.

Only 34% of the North Agrakhan area is covered by separated water bodies and submerged reed beds cover additional 30% of the area. Surface elevation decrease from south to north from -25 to -27...-28 m a.s.l., almost reaching the Caspian Sea level in the middle section and reaching -28.5...-29 m a.s.l. (on the bottom of lagoons) in the northern section. Periodically submerged reed areas are extensive, whereas fully submerged water plants is scarce.

Bottom sediments have a layered structure that demonstrates the North Agrakhan’s transition from a marine bay into a wetland and landmass. The soils are saline. Mechanically permeable sediment is overall less thick than in the South Agrakhan, varying from <0.25 m near the seashore to 0.5 m at the main part of the Kara-Murza and to 0.5-1.5 m in the middle section.

In parts of the North Agrakhan that are connected with the Northern Caspian Sea, water levels correspond to fluctuations of the sea level. The mean range of seasonal level fluctuations is 20-35 cm. The range of surge fluctuations is up to 0.5-1 m and higher. The lens-shaped lakes of the North Agrakhan rely on river water inflow, snowmelt waters and rainfall. But Roslambeychik and Kordonka canals that were built to supply water from the Lower Terek reservoirs and the Stary Terek irrigation system have remained dry for more than 15-20 years. The Kubyakinsky canal – fish passage only functions at high water levels in the Kargalinsky Proryv and after dredging at its upper part. In 2019 it functioned in June and July, in 2020 – only in May. This led to the death of a tremendous amount of fishes that entered it to spawn and did not have time to exit. In the absence of connection to the
Kargalinsky Proryv and the canals of the northern part of the delta, not only small lakes may dry up, but even the larger Lake Kuznechnok. This is exactly what is happening now since 2020, and the area of Kuznechnok Lake has halved.

Some issues related to water quality and salinization have been noticed in the North Agrakhan. Salinity of the Lake Kuznechnok water was 1.5-2.5 g/L, of the Kubyakinsky canal water – 1.2-3.5 g/L. Towards the sea, salinity increases to 11-13 g/L. In Lake Kuznechnok sulphates dominate, in the Kubyakinsky canal – sulphates and chlorides, in the Kara-Murza Bay – chlorides. The SCWPI characterizes the waters as "dirty" to "very dirty". High values of BOD and COD and some elements specific to the sea water are detected in the closed lakes. High levels of sediment pollution are observed.

3.3. Main measures for partial restoration of hydrological and ecological potential of the former Agrakhan Bay

The measures have to be individual for each part of the former bay. Furthermore, different sections of the North Agrakhan require specific solutions as well. For the southern section of the North Agrakhan, full restoration of a sea unified water body is impossible to achieve and is inadvisable. In its eastern part, however, it is desirable to artificially inundate ~16 km² of reedbed plains periodically to maintain <0.5 m depths in order to sustain the valuable wetland. In the western section, a reconstruction of the Kubyakinsky canal is crucial, with construction of a gate lock at its source, and sediment traps, and reconstruction the Roslambeychik canal. In the middle section, seasonal augmentation of Lake Kuznechnok and Zapadnykh lakes with water from the Kubyakinskiy canal is recommended, preceded by banking them with levees, dredging, and constructing fishways with a possibility of maintaining the depths above 1.5 m during spawning period. In the northern section, firstly, water from the Kubyakinskiy canal should be supplied in order to reduce the salinity in Kara-Murza and mouth near-shore to ~5‰ in October-February and to <3‰ in March-September. Secondly, necessary depths should be maintained in Kara-Murza to prevent its drying during the sea level drop or wind-induced down-surges, which can be achieved through building levees, dredging and construction of a retaining dike (2 km long with crest height of -27.5...-28.0 m a.s.l.) at its northern (marine) boundary.

For the South Agrakhan, restoring its connection to the sea is inadvisable and as it may lead to negative hydrological and environmental consequences, to the extent of its complete draining. Nevertheless, to support its fish and waterfowl, and to restore its recreational potential it is suggested to: 1) change the volume and regime of the discharge into the Garunovsky canal in order to achieve flow velocities of 0.6-0.7 m/s and depths of 1.6-1.9 m in March-October, and construct an additional stepped fishway; 2) change the structure of the water intake of the South Agrakhan by increasing the inflow of less nutrient-enriched river water via the Dzerzhinsky main supply canal or the Dzerzhinsky sewer canal; 3) dredge specific areas to create wintering pits and spawning grounds for fish, biomelioration.

4. Conclusion

Morphological and hydrological degradation of the Agrakhan Bay is indisputable; it is an example of evolution of former lagoons in river deltas, accelerated by large-scale changes in the Caspian Sea level, siltation of the bay with Terek sediments, intensive water use and nutrient pollution. Typical development of this process is described in [11, 12]. The main current issues of the South Agrakhan are mainly of hydro-ecological nature, and the concern shown by the local community in [7] about its siltation, overgrowth of vegetation and insufficient water supply is ill-founded. Adverse hydrological and morphological changes in the North Agrakhan are more abundant and more serious. These include insufficient depths and water-covered areas, continuous decrease of depths and areas of lakes and their declining overall amount, lack of fresh water and pollution of the sea water, inoperative state of canals and lack of opportunities for fish passage and spawning; negative outlook of future progression due to the sea level drop, lack of water inflow from the river and the collector canal, climate aridification in the Terek delta. Nevertheless, there is still a chance for successful recovery if the scientifically
substantiated recommendations (as proposed by our study) are implemented in the nearest future to partially restore the hydrological potential of the former Agrakhan Bay.

Acknowledgement
The research was carried out within the framework of the state research assignment (MSU).

References
[1] Leontiev O K, Moroshkina T N 1949 The origin of the material of the Agrakhan Peninsula. Izvestia of the USSR Academy of Sciences vol 13 4 12–25
[2] Mouths of rivers of the Caspian region: history of formation, modern hydrological and morphological processes and dangerous phenomena 2013. Ed. V N Mikhailov (Moscow: GEOS) p 703
[3] Belyaev I P 1963 Hydrology of the Terek delta (Moscow: Gidrometeoizdat) p 208.
[4] Hydrology of the Terek and Sulak mouths 1993. Ed. A N Kosarev and V N Mikhailov (Moscow: NAUKA) p 160
[5] Magritsky D V 2016 Factors and patterns of spatial and long-term variability of river sediment inflow into the seas of the Russian Arctic. Questions of geography. Ser. Geography of the polar regions 142 444–466
[6] Baidin S S, Skriptunov N A and Steinman B S 1971 Hydrology of mouth areas of the Terek and Sulak rivers (Moscow: Gidrometeoizdat) p 198
[7] Lake South Agrakhan: problems of ecological reconstruction 2014. Ed. E M Eldarov and M A Guruev (Makhachkala: Publishing House Epoch) p 156
[8] Semenova A A, Magritsky D V, Samokhin M A et al. 2020 Hydrological and morphological degradation of the Agrakhan Bay: features, reasons, solutions. Sat. reports of the international scientific conference "The Fourth Vinogradov Readings" (Saint-Petersburg) 524–529
[9] Luettich R, Westerink J 2004 Formulation and Numerical Implementation of the 2D/3D ADCIRC Finite Element Model Version 44. XX. Morehead City and Notre Dame (University of North Carolina at Chapel Hill and University of Notre Dame) p 74
[10] Hipsey M R, Bruce L C and Hamilton D P 2014 GLM - General Lake Model: Model overview and user information. AED Report no.26 (Perth: The University of Western Australia) p 42
[11] Mikhailov V N, Rogov M M and Chistyakov A A 1986 River deltas. Hydrological and morphological processes (Leningrad: Gidrometeoizdat) p 280
[12] Mikhailov V N, Mikhailova M V and Magritsky D V 2018 Fundamentals of hydrology of river mouths: textbook (Moscow: Triumph) p 316