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WATER RESOURCES AND THE REGIME OF WATER BODIES

Space Monitoring of Aral Sea Degradation

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Abstract—The results of remote sensing survey of the Aral Sea in its degradation period are given. Satellite images are used to map shoreline retreat from 1961 to 2008 and to measure the decrease in the area. Seasonal variations in shoreline and water area are identified, suggesting seasonal level variations and correlating well with data of satellite altimetry surveys of sea level. Observations covered surge phenomena, seasonal dynamics of landscapes, and the seasonal salinization rhythm in coastal territories with the subsequent formation and weathering of salt crusts. The character of river runoff input into the Great Sea resulting from overbank flooding in artificial water bodies in the Amu Darya delta is identified.

Keywords: space images, the Aral Sea, area contraction, seasonal variations in sea level, seasonal dynamics of landscapes.

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INTRODUCTION

The tragic fate of the Aral Sea [1] still attracts the attention of geographers all over the world. Until 1991, the Aral Sea was the focus of studies of leading Russian scientific organizations, research institutions of Uzbekistan and Kazakhstan; however, regular observations in the Aral region drastically declined after the breakup of the USSR. The hydrological and hydrochemical surveys of the sea were ceased, and hydrological stations were closed [8]. In this situation, where there are no reliable observational data on the Aral Sea, the only data sources on its current state are space images and occasional expedition observations.

The Laboratory of Aerospace Methods, Department of Cartography and Geoinformatics, Faculty of Geography, MSU, has been carrying out Aral Sea observations by space images since the 1990s. The dynamics of Amu Darya delta was examined [7]; changes in the coastline over different time intervals were successively mapped [4, 5], and changes in the coastal zone were analyzed [3]; seasonal variations in the shoreline, water area, and landscapes in the adjacent territories were identified [6]; and surge phenomena and seasonal regime of territory salinization were traced. Of particular interest are the new data on the Aral Sea at the stage of its decay available from the space images of the recent years. The paper gives the results of studies of space images reflecting various phenomena accompanying Aral Sea degradation.

LONG-TERM VARIATIONS IN THE SHORELINE AND SEA AREA

Materials for Studies

Mapping of changes in Aral shoreline by space images at the early stages of its level drop was undertaken by Kazakh Aerogeodesic Enterprise, where photographs from Resurs-F satellites made in 1977, 1984, and 1989 were used to compile aerophotographic plans, to interpret the shoreline for those years, resulting in the publication in 1990 of the "Map of the Dynamics of the Aral Sea from 1957 to 1989 with a Forecast for 2000," which enabled the assessment of the sea water area [2, 11].

The mapping of variations in the Aral shoreline with the use of space images over 1989–2008 (the year of 1989 was included as a link with the previous studies) was continued at the Department of Cartography and Geoinformatics, Faculty of Geography, MSU. The study included several successive stages with different satellite survey materials used for different periods of the long-term study. Photographs from Resurs-F satellites (camera KATE-200, resolution of 30 m), which were used at the first stage, had a limited coverage (180 × 180 km) and required compiling into aerophotographic plan; the observation interval at this stage was large (5–7 years). By contrast, good survey materials in the 1990s were images provided by Resurs-O satellites with MSU-SK system (resolution of 170 m), which covered a scanning band of 600 km and required no compilation, though their transformation into a single cartographic projection was required in order to evaluate the areas. The observation interval decreased to 2 years, and annual images, though made in different seasons, have been used

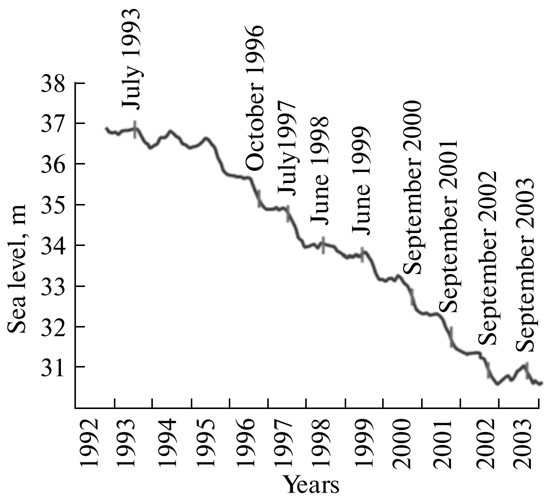

Fig. 1. Long-term variations in Great Sea level from 1993 to 2004 by radio-altimetry data from satellites TOPEX/Poseidon, Jason. Dashes mark the dates of the images used to compile a map of shoreline variations.

since the second half of the 1990s. In 2001, when Resurs-O satellites finished their operation, images taken from the Russian module of the International Space Station by a digital camera with resolution of 50 m were used. After 2001, observations of the state of the Aral Sea became simpler due to the regular supply of images from the US satellite Terra, carrying out daily global survey; the presentation in the Internet of images taken by MODIS system with a resolution of 250 m in two zones of visible and near infrared bands has made it possible to carry out annual mapping in the same autumn season, when the sea level is minimal, and enabled the studying of seasonal variations. Figure 1 gives a plot of Aral Sea level decline according to data of satellite altimetry measurements and shows to which moments refer the images used to compile the maps of shoreline dynamics. As can be seen from Fig. 1, before 1999, the researchers were compelled to use materials on different seasons to fix the water area at different phases of sea level variations. Some images used to compile the map are given in Fig. 2, which demonstrates the ever growing rate of sea area contraction.

Methods of Studies

The technology of mapping improved in parallel with changes in the input materials. The preparation of aerophotographic plans and traditional planimetric measurements of areas have given place to digital technologies. At the early stages, when Resurs-O/MSU-SK digital images were used, the procedure of computer processing of images and maps and the evaluation of areas for different years was mostly based on raster technologies involving the use of Idrisi–Corel Draw program block. Later it was improved, and the evaluation of areas was reproduced with GIS-packages: Idrisi™–ERDAS Imagine for raster images, ArcView™ and MapInfo™ for vector images. The procedure incorporates the following steps: image conversion into the projection of a map at scale of 1 : 1000000 in ERDAS Imagine program; registration of the basic map and transformed images in a single geographic coordinate system in ArcView™ or ArcGIS; the creation of polygonal vector layers by digitizing the coastline at appropriate photographs from a

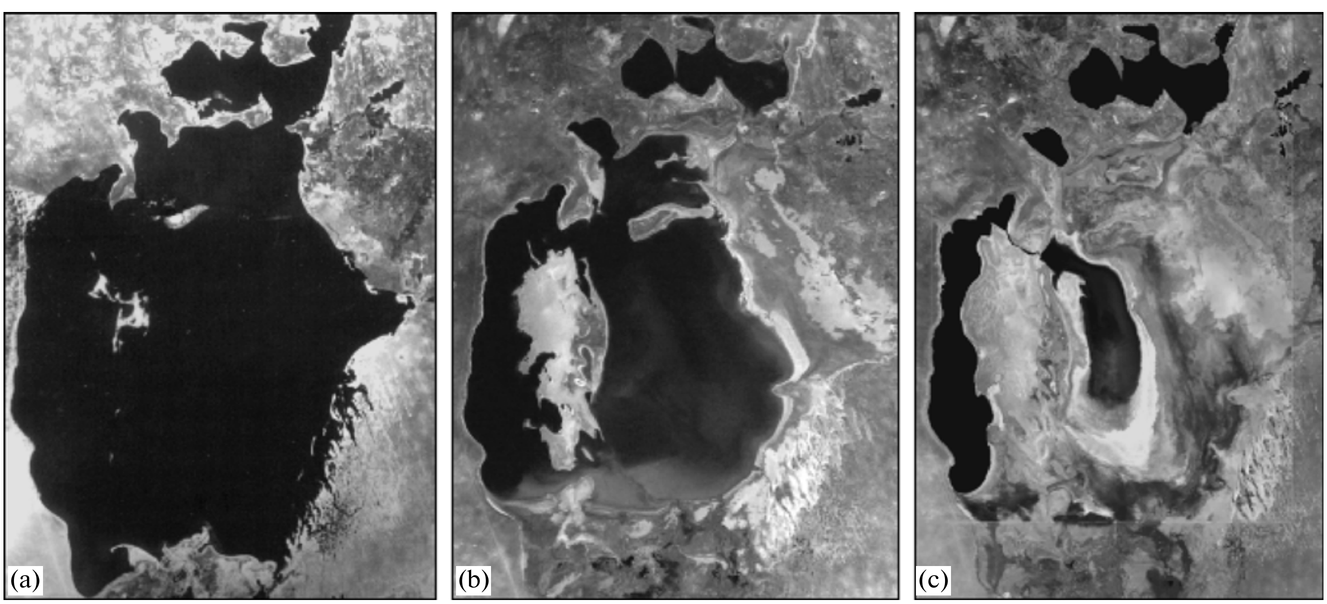

Fig. 2. Representation of the Aral Sea on satellite images. (a) Salyut-4/KATE-140 (June 1975); (b) Resurs-O/MSU-SR (October 3, 1996); (c) Terra/MODIS (October 5, 2008).

Table 1. Variations in the areas of the Aral Sea and its parts from 1957 to 2008, km^2 (bold typed are the areas of the water bodies that really existed, empty cells mean the water bodies have not existed)

Year	Aral Sea as a whole	Great Sea					Small Sea
		total	western part	eastern part			
				total	main water body	separated water bodies*	
1957	**67100**	61200					5900
1961	**66400**	60500					5900
1977	**54900**	50600					4300
1984	**47400**	43700					3700
1989	41500	**38400**	9400	29000			**3100**
1991	36600	**33800**	8200	25600			**2800**
1993	36000	**33000**	7900	25100			**3000**
1996	31300	**28600**	7100	21500			**2700**
1997	31200	**28100**	7000	21100			**3100**
1998	29700	**26500**	6700	19800			**3000**
1999	29300	**26300**	6500	19800			**3000**
2000	26700	**23900**	6200	17700			**2800**
2001	22100	**19400**	5500	13900			**2700**
2002	19900	**17000**	5200	11800			**2900**
2003	19700	**16800**	5000	11800			**2900**
2004	17900	**15100**	4800	10300	9500	800	**2800**
2005	16900	**14100**	4800	9300	8700	600	**2800**
2006	15700	**12400**	4600	7800	6800	1000	**3300**
2007	12200	**8900**	4200	4700	4400	300	**3300**
2008	10400	**7200**	4000	3200	2900	300	**3200**

* The area of separated water bodies is included into the area of the eastern part as a whole, the Great Sea as a whole, and the Aral Sea as a whole.

raster underlay; the compilation of a map of different-time shorelines at a scale of 1 : 1000000 in UTM-1983 projection—universal transverse Mercator projection, whose parameters are similar to those of Gauss–Kruger projection; the evaluation of the area of the sea and the water bodies separated from it. The procedure was analyzed in detail in [4, 5]. Images in the near IR-zone with the resolution of 250 m were used to interpret the shoreline. Some problems with determining its position arose on the coast in the eastern Great Sea with a wide zone of alternating water and land areas; expert estimates were used in such cases. The accuracy of area evaluation was estimated at a few tenths of percent, not worse than 1%. That is why, the data are given rounded to hundreds of km^2, and those for small separated water bodies, to tens of km^2.

Results of Studies

The results of the interpreting and processing of space images are given on the map of Aral Sea shoreline variations from 1957 to 2008 (Fig. 3), and the calculated areas are shown in Table 1, containing the areas of the Aral Sea as a whole and its different parts. Bold type figures are the areas of the features that really existed: the Aral Sea as a whole (before the separation of the Small Sea), and the Great and Small seas after their separation. The other data refer to hypothetic water areas in the Great and Small seas before their real separation and to the western and eastern parts of the Great Sea before their real final separation. Table 2 gives more detailed data on the area of small water bodies that separated in 2003–2008. The contraction of the area of the entire Aral Sea since 1957 is shown in Fig. 4. As it can be distinctly seen, the rate of sea area contraction increased in the past decade.

The data given in tables allow us to follow the changes in the Aral area contraction in different periods. The mean annual decrease in water area, which was ~700 km^2/year in 1961–1977, increased to 1200 km^2/year in 1984–1989, when water discharge into the sea ceased completely in some years. In 1989–1991, the rate of area decrease was extremely high—2300 km^2/year. This is largely due to the year of 1989,

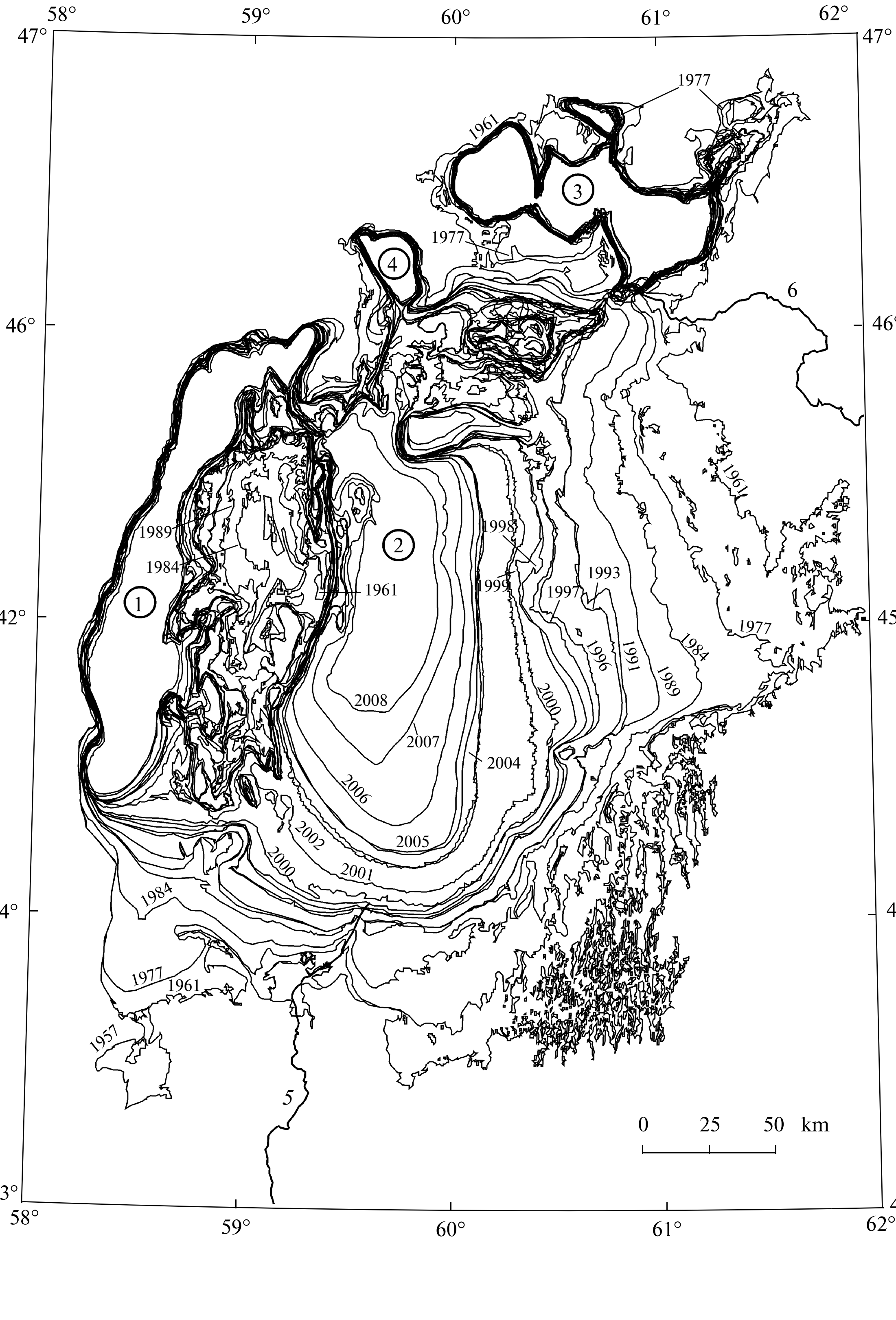

Fig. 3. Map of long-term variations of Aral Sea shorelines in 1957–2008. (1) Western Great Sea, (2) eastern Great Sea, (3) Small Sea, (4) former Tshchebas bay, separated from the Great Sea, (5) Amu Darya, (6) Syr Darya.

Table 2. ariations in the Great Sea area from 2004 to 2008, km^2 (dash means the water body has not existed, dried out)

Year	Great Sea					
	western part and the major water body of the eastern part as a whole	eastern part				
		total	major water body	separated water bodies		
				former bays		small water bodies as a whole
				Tshchebas	Northeastern	
2004	14300	10300	9500	390	400	40
2005	13500	9300	8700	400	–	210
2006	11400	7800	6800	370	430	200
2007	8600	4700	4400	350	–	–
2008	6900	3200	2900	350	–	–

which was extremely dry. In the 1990s, when annual surveys became possible because of the regular sounding from Resurs-O satellite, the contraction of the area in different years was found to be very uneven (this unevenness can be partially due to the involuntary use of images from different seasons before 2000). In that time, periods with rapid area contraction of ~1500 km^2/year (1993–1996, 1997–1998) alternate with periods with contraction rate decreasing to 300–600 km^2/year (1991–1993, 1998–1999) and even ~50 km^2/year (1997). Those abrupt variations are reflected on the map (Fig. 3), where the shorelines of 1991 and 1993, 1996 and 1997 are similar and even coincide. In 2000, the rate of area contraction increased to 2600 km^2/year; and in 2001, when shallows of middle islands merged with the southern shore of the eastern Great Aral Sea, this rate was maximal—4600 km^2/year. In the most recent period, (2001–2008) the mean rate of sea area contraction was 1670 km^2/year and was also uneven—the rate of contraction was minimal in the wet 2003 and 2005 (200 and 1000 km^2/year, respectively), and in the 2007, it was extremely high (3500 km^2/year).

The map given in Fig. 3 allows one to follow the changes in the outline of Aral Sea shoreline accompanying the drop in its level. A large island in the northern part of the sea merged with the land by 1977 to form the Kokaral Peninsula, separating the northern part of the territory—the future Small Sea. A large portion of the Akpetkinskii Archipelago turned into the land. The protrusion of the Amu Darya delta still continued and the area of Dzhyltyrbas and Adzhibai bays decreased.

By 1984, Kulandy and Kokaral peninsulas have extended on the north; a pit has protruded southward from Shubartauz Peninsula and almost separated the water area of the future Small Sea. In the southeast, the entire Akpetkinskii Archipelago merged with the land, the shoreline became much straighter, and the Aral type of the shore disappeared. Dzhiltyrbas and Adzhibai bays disappeared in the southern part, and Muinak Peninsula turned into small relic upland among the land. The protrusion of Amu Darya delta continued, but became passive. A vast shallow 70 km from the north to the south and 20–30 km in width appeared around the Vozrozhdeniya Isl.

In 1987, the Aral Sea separated by a crossbar into the Small and Great seas, each representing an independent water body with its own regime and dynamics. The former Berg Strait was replaced by an intermittent arm several tens of meters in width, through which the excessive water from the Small Sea (whose level after the separation stabilized at elevations of ~39.5 m) were discharged into the Great Sea.

By 1989, Saryshyganak Bay considerably contracted in the northern part, resulting in that the shoreline of the Small Sea retreated 30 km from Aral'sk Town, which in 1961 was situated at the sea shore. Straightening of the shoreline is typical of the eastern and southern part of the Great Sea coast. However, the passive protrusion of Amu Darya delta into the mouth of the Urdabai Brabch still continued. The shallow around the Vozrozhdeniya Island extended to 30–40 km, and a large shallow 50 km in length from the north to the south and 5–10 km in

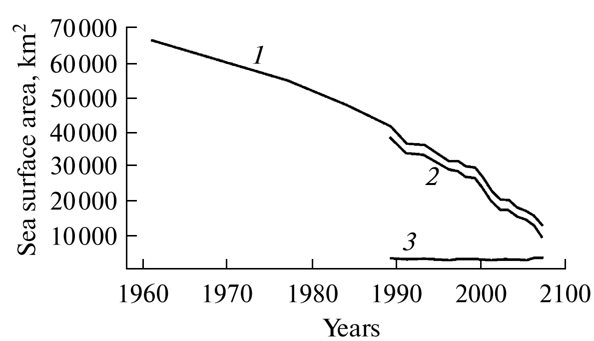

Fig. 4. Plot of long-term variations in Aral Sea surface area in 1957–2008. (*1*) Aral Sea as a whole, (*2*) Great Sea, (*3*) Small Sea.

width with a complicated configuration formed around Lazareva Isl., and a new shallow near the southern shore formed south of it.

By 1991, not only the Amu Darya delta in the Great Sea ceased protruding into the sea, but the projection that has formed in 1989 was partially cut out by shore processes. The shallow that has formed earlier at the southern shore merged to it in the form of a peninsula; the shallows around the former Vozrozhdeniya and Lazareva islands merged to form a single island 150 km in length, and several new islands formed near it.

By 1997, Barsakel'mes Island merged with the land and became a peninsula. However, in the 1990s the most significant changes took place in the extreme northeastern bay, into which empties the arm connecting the Small and Great seas. The shoreline in this part of the sea was the most dynamic and depended on the regime of water supply via the arm.

In 2001 the large central shallow around the former Vozrozhdeniya and Lazareva islands merged with the southern shore, giving rise to concern in the international community because of the biological research ground existing in these islands. The newly formed peninsula almost separated the Great Sea into two parts—the western and the eastern—connected by a narrow arm, then 12–15 km in width, between the shallows of Vozrozhdeniya Island and the northern shore. In 2004, Tshchebas Bay and some other small water bodies separated from the sea; this separation continued and those water bodies existed independently in 2004–2006. The shoreline of the eastern Great Sea very significantly retreated in 2007–2008; the rate of its retreat on the eastern coast in 2005–2008 was 5 km/year. However, the largest retreat rate was recorded in the southern part of the coast, where the shoreline has shifted northward by 12 km by the 2006 (as compared with 2005), by 25 km more by 2007, and by 20 km more by 2008. Thus, the retreat of shoreline over 2006–2008 at the southern extremity of the eastern Great Sea amounted to 57 km. The strait between the western and eastern parts of the Great Sea narrowed to 3–4 km by 2004 and to 1 km by 2007; a narrow strait 300–600 m in width persisted in 2008.

After the construction of a dam, retaining Small Sea water, the watering of the remaining parts of northeastern bay became rarer, and its connection with Great Sea was not permanent any more. This strait has grown over by reed by 2008.

The area of the Small Sea, which generally stabilized after the construction of a dam in Berg Strait, varied depending on the state of this dam. After a new fundamental dam was constructed in 2002, retaining Syr Darya water within the Small Sea water area, the area of the latter started increasing since 2006, which is especially distinct in its extreme northeastern Saryshyganak Bay, where the construction of a recreational zone of Aral'sk Town is planned.

Overall, during the period of modern drop in the sea level from 1961 to 2008, the total area of the Aral Sea decreased from 66400 to 10400 km^2, i.e., by 56000 km^2; its area in 2008 accounted for as low as 15.7% of its area in 1961.

The obtained data on the area of the Aral Sea and its parts, given in Table 1, were used for indirect estimation of some hydrological characteristics. A procedure for approximate assessment of the present-day hydrological conditions of the Aral Sea was proposed at the Department of Land Hydrology, Faculty of Geography, MSU. The method is based on the determination of the surface area of the water body, which is used to evaluate the unknown water level in the sea, which, in turn, is used to evaluate the water volume; additionally, variations in Aral water salinity are evaluated and their trends are identified [9, 10]. This method was especially useful, when observations of sea level at hydrological stations have already ceased, while satellite-based altimetry observations has not become common. The method allowed three problems to be solved: the improvement of relationships between water level in the water body, its area, and volume and their analytical expression; checking the correspondence between Aral water area measured by using space images and the areas calculated from the level with the use of the curve of the area over the period, when data of ground observations of the level were still available; the restoration of water levels over the period when no reliable observational data on the level were already available, by the surface areas of parts of the sea, evaluated from space images, and next, the calculation of unknown volumes of water in the Aral Sea and its parts, as well as its salinity. According to these calculations, the volume of water in the Great Sea in 2002 was 111 km^3 and its salinity reached 67.3‰ [10].

Thus, the significance of the satellite monitoring of long-term variations in the shoreline of the sea runs far beyond the problem of determining the areas of water surfaces, since such areas are used to calculate other unknown characteristics of the water body.

SEASONAL VARIATIONS OF SEA AREA AS AN INDICATOR OF SEASONAL VARIATIONS IN SEA LEVEL

Since 2000, the introduction of regular surveys by MODIS scanning system from Terra and Aqua satellites made it possible to observe changes in the Aral Sea during the year from ice break up of ice freeze up. Images obtained at different time by Terra/MODIS (18 images for the period from August 2001, throughout 2002, to October 2003) were used to map the position of the shoreline at 19 dates in different seasons and to calculate the respective sea areas in different seasons [6]. Such study was carried out for the Great Sea, in whose eastern part shoreline changes on flat shores are most significant. The contraction of the sea

Table 3. Aria variations in the Aral Sea and its parts during 2002, km^2

Date	Aral Sea as a whole	Great Sea			Small Sea
		total	western part	eastern part	
March 13	21490	18640	5530	13110	2850
April 16	21690	18860	5110	13750	2830
May 18	21570	18700	5110	13590	2870
July 10	21740	18840	5140	13700	2900
July 28	21020	18160	5260	12900	2860
August 14	20500	17640	5320	12320	2860
September 19	19320	16530	4960	11570	2790
October 7	19240	16380	5350	11030	2860
November 5	19210	16340	5120	11220	2870

area was found to be uneven within the year (Table 3). The area of the Great Sea slightly increases in March–June with peaks in April (after the snow melting on the plains) and July (during a peak in glacier-nourished river runoff). The second half of the summer and early autumn (from mid-July to October) features an abrupt drop in the water area. The comparison of autumn and spring images shows the area of the ice-covered sea to be stable. Clearly, the step-wise course of sea area variations should correspond to its seasonal variations.

A good correlation was found to exist between the results of sea area measurements and the radio-altimetry data from TOPEX/Poseidon, Jason satellites (Fig. 5). The identified features of the sea, such as the uneven drop of the sea level within the year (a small rise in the spring–early summer and a rapid drop in the late summer–autumn), also manifest themselves in the entire period of radio-altimetry observations from TOPEX/Poseidon satellite since 1993, as can be clearly seen from Fig. 1.

The seasonal variations in water area and the drop in sea level can be attributed to several causes. In the spring and early summer (March–mid-July) the level remains stable and even somewhat rises owing to the melting of snow cover and glaciers in mountains, forming a peak in the hydrographs of the Amu Darya and Syr Darya, whose water discharges into the sea in small amounts. In this period, irrigation waters are being discharged into reservoirs created in the marginal part of Amu Darya delta, and from these reservoirs they sometimes discharge into the sea. In the summer, notwithstanding the large evaporation, water losses are somewhat compensated for because of water thermal expansion, which accounts for the stability of the level. In the late summer and autumn, when water supply ceases and water becomes cooler, the sea level drop is maximal. In the winter, when the evaporation from the ice-covered surface is minimal, the shoreline features no significant variations

WATER-VARIABLE REGIME OF NORTHEASTERN BAY AFTER THE SEPARATION OF THE SMALL SEA

In the most recent period of Aral Sea existence, when regular satellite surveys became possible, the researchers got a chance to observe and study some phenomena in the life of the degrading water body, where field observations are difficult.

After the division of the Aral Sea by a crossbar into two water bodies in 1987—the Great and Small seas—connected by an arm, which has formed on the place of Berg Strait, and Barsakelmes Island in 1996 merged with the land, turning into a peninsula, a bay formed in the northeastern part of the Great Sea. The water abundance and the shoreline of this bay were

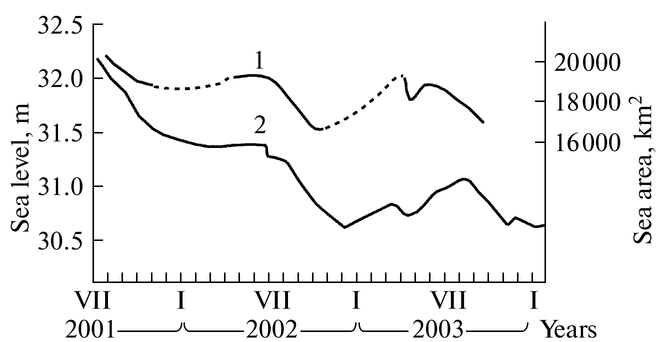

Fig. 5. (1) Seasonal variations in Great Sea surface area, evaluated by images from Terra/MODIS and (2) sea level variations by radio-altimetry data from satellites TOPEX/Poseidon, Jason.

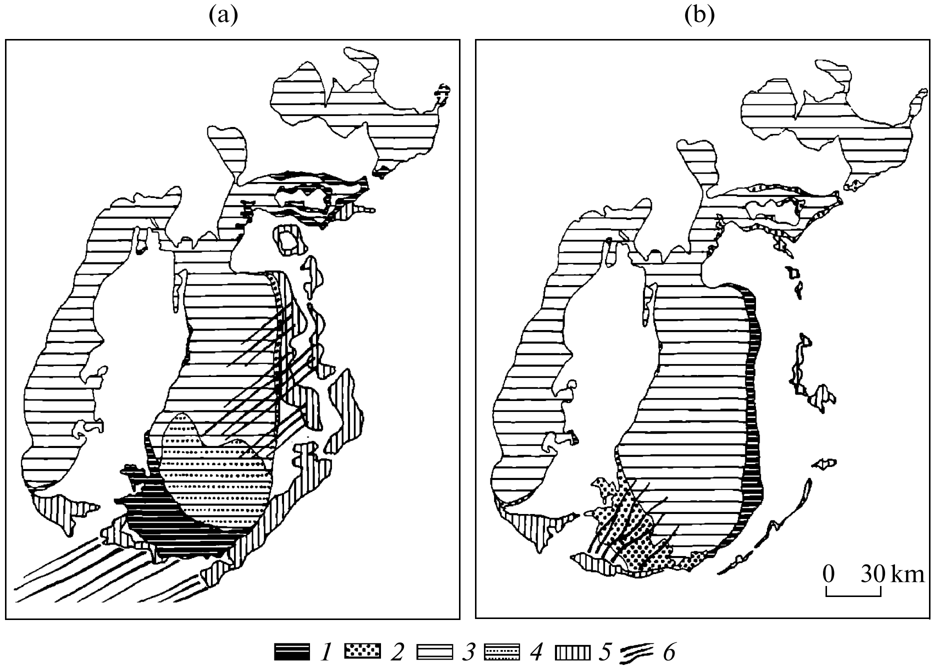

Fig. 6. Surge phenomena and salt storms in Aral region identified by comparison of images Terra/MODIS of (a) October 21, 2002, and April 16, 2003 and (b) April 16, 2003 and May 1, 2003. (*1*) water-free coastal zone on the first date and inundated on the second date (positive wind surge); (*2*) coastal zone inundated on the first date and water-free on the second date (negative surge); (*3*) water on both dates; (*4*) visible seabed; (*5*) salt crusts; (*6*) dust–salt plumes.

most dynamic, and changes sometimes were asynchronous with those in other parts of the Great Sea. With continuing drop in the level, the retreat of shoreline, and the contraction of the surface area of the water body as a whole, water abundance increased in this zone in some years. Such regime of the bay, as established by space images, is due to the state of the arm and the input of runoff from the Small Sea. In the years when runoff was insignificant or zero, the bay dried out (1996, 1998, and 2001); while at the sufficient runoff through the arm, the bay filled with water (1991, 1993, 1997, and 1999). To retain water in the Small Sea, a dam was constructed in 1996, causing a level rise in the Small Sea, which was fixed by satellite altimeter. The destruction of this dam in 1999 resulted in an immediate drop in the sea level. In 2002, 2003, and 2005, when overbank flow into the sea from artificial water bodies in the Amu Darya delta took place, the Northeastern Bay filled with water. Its regime in these years was governed perhaps not only by the state of the arm, but also by the inflow of Amu Darya and post-irrigation waters into the sea. A fundamental dam was constructed in 2006 in the beginning of the arm, and in 2007 the state of the bay was completely determined by the runoff regulation by the dam—the bay was filled with water in June and dried out in November.

WIND SURGES

The constructed maps of shoreline variations within the year showed not only uneven sea level drop in spring and autumn, but also differently directed changes in the position of the shoreline in different parts of the coast—its retreat in some parts was accompanied by an advance in other parts. This is a manifestation of motions of water masses either seaward or landward under the effect of wind, i.e., positive and negative wind surges. Wind surges were also recorded in the Aral Sea before, but now, on flat surface of the former bed, they grew stronger and cover larger areas. For example, a very strong surge was recorded in the image of MODIS/Terra of April 16, 2003 (Fig. 6a), when a zone up to 30 km in width and 1800 km^2 in area was inundated on the southwestern coast of the Great Aral Sea. At the same time, a zone with a width of 2–3 km and an area of 270 km^2 on the eastern shore of the Great Aral Sea got free of water, and the shoreline retreated. The images also reflected the cause of the surge—white bands of salt–dust plumes can be seen in the air. They extend from the dry salt crusts in the southwest direction and can be distinctly seen against sea water, suggesting a strong northeastern wind. This image also indicates to the source of water for the inundation of the southwestern coast as vast as that. Bed can be seen through water in the area of 2300 km^2 in the southern part of the Great Aral. It is possible that water masses from this part of the sea were almost completely transferred by wind in the southwestern direction and covered a wide zone of land.

Another situation was recorded two weeks later on May 1, 2003. It is shown on the second map in Fig. 6b. The surge ceased, and the southwestern coast, which had been inundated before, now got almost free of water, becoming land again. Bottom sediments in the center of the southern Great Aral cannot be seen any more and are covered by water. The shoreline on the eastern coast of the Great Aral shifted 5–12 km landward. Thus, a new surge forms in the direction opposite to the northeastern one, and the inundation zone of the eastern coast of the Great Aral occupies a zone up to 12 km in width extending over 160 km in the direction from the north to the south, covering an area of 1100 km^2.

Surge phenomena were also recorded in 2007 by images of June 1, 4, and 8. The positions of shorelines in this images show that on June 4, a setup formed on the southern and eastern coasts of the eastern Great Sea under northern wind on an area of 360 km^2; and on June 8, a very strong surge under southern wind removed water from a zone on the southern and southeastern coasts with a width of up to 20 km and an area of 840 km^2.

A surge was also recorded in early October, 2007. The comparison of shoreline positions in the images of October 1 and 3 shows that a zone ~8 km in width and 350 km^2 in area was inundated on the southwestern coast of the eastern Great Sea. At the same time, a vast zone of the eastern coast with a width varying from 1 to 4 km and an area of 160 km^2 got free of water. This surge took place under northeastern wind.

RIVER WATER INFLOW INTO THE ARAL SEA

The runoff of the Amu Darya and the Syr Darya, whose losses due to irrigation has determined the fate of the Aral Sea, is somewhat reflected in space images. According to estimates of Uzhydromet, the inflow of Amu Darya water into the Aral Sea decreased from 38.9 km^3 in 1941–1950 to 1.9 km^3 in 1981–1990; nevertheless, the only persisting Urdubai Branch continued protruding into the sea until 1989. A dike constructed in the channel and the construction of dams for retaining water in delta water bodies have resulted in cessation of direct discharge of Amu Darya water into the sea in some years. However, in the wetter 2000s, the Amu Darya regained its flow into the Aral Sea and in 2001–2006 it amounted to 7.6 km^3. The overfilling of constructed water bodies in wet years caused overbank flows, resulting in water discharges into the Great Sea, as can be seen, for example, in the images obtained in September 2004 and October 2005 (Fig. 7). Intermittent flow (either surface of subsurface) causes soil moistening and salt crust erosion, as is distinctly seen in the images, resulting in the appearance of reeds on the dried out bed—reed bands reflect

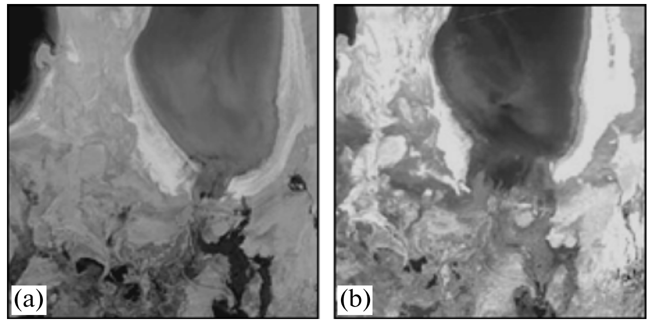

Fig. 7. Water overflows from water bodies in the marginal part of Amu Darya delta in images of Terra/MODIS. (a) September 22, 2004; (b) October 13, 2005.

the persisting subsurface flow. Thus, water discharge from a reservoir in the Amu Darya delta at the place of former Dzhaltyrbas Bay is fixed on the image taken on July 10, 2002. The result was an alluvial fan, which was rapidly destroyed by alongshore marine processes. Water inflow into the Aral Sea from this reservoir was also recorded in the images of May 29 and July 8, 2003. The wet transverse bands on the place of the above-mentioned fan on the image of September 22, 2004 suggest the wedging out of subsoil water and subsurface runoff of Amu Darya water into the Aral Sea. In 2005, when the Amu Darya runoff was higher, water inflow into the sea was recorded both in the summer (July) and in the autumn (October), and the multiple-jet overflow domain covered an area 50 km in width. Thus, while reflecting the economic activity in Amu Darya delta aimed to preserve vast artificial water bodies in this area, which are often full of discharged post-irrigation waters, the images are objective demonstrations of one of the major causes of Aral Sea drying out.

SEASONAL VARIATIONS IN COASTAL ZONE LANDSCAPES

To examine seasonal variations in landscapes of the former seabed by 2002 images, we compiled a map of natural–territorial complexes of the Aral region. The map characterizes the terraces of three levels: those formed 1–2 years ago, 5–6, and 30–40 years ago.

Images of different seasons taken in April, May, July, and September 2002, which demonstrate seasonal variations in landscapes, were used to compile, for the first time, a series of maps of seasonal variations in the state of natural–territorial complexes (Fig. 8). Those maps reflect the phenological changes in the vegetation of the deserts around the sea, a typical feature of which is a green wave of vegetation in the spring and early summer and the wilting of vegetation cover in the late summer and autumn. The maps clearly demonstrate the asynchronous character of the phenological development of vegetation in deserts and reed beds in the delta, which later (toward the sum-

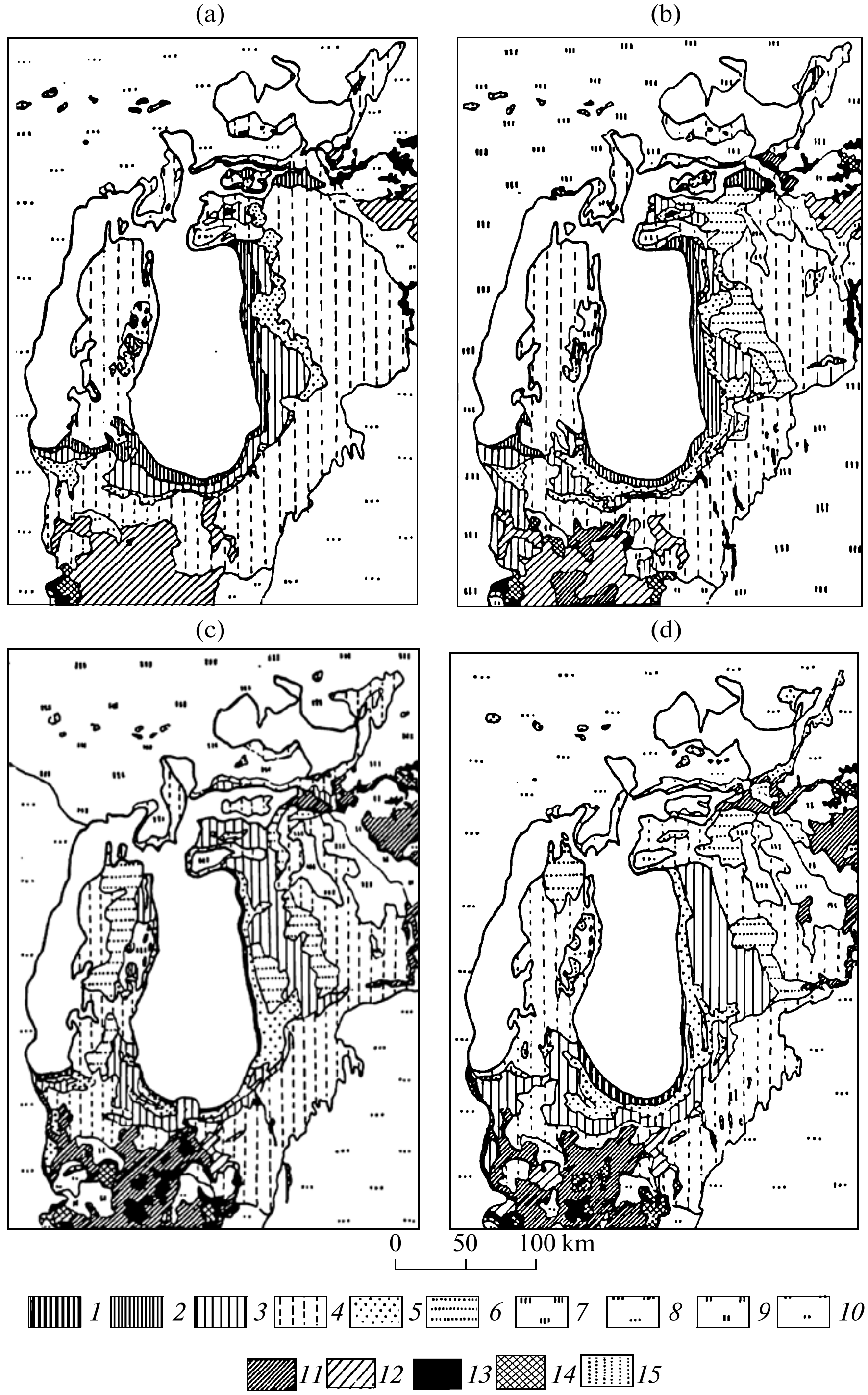

Fig. 8. Maps of seasonal variations in the state of natural–territorial complexes in 2002. (a) April 16, (b) May 18, (c) July 10, (d) September 19. (*1*) Marshes (alternation of water and dry-bed areas; loam–silt wastelands and sand–colonchak deserts on former seabed: (*2*) heavily wetted, (*3*) wetted, (*4*) dried. (*5*) salt crusts on the edges of wetted areas on the former seabed; (*6*) precipitation of wind-eroded salts and salt blooms on dried areas of former seabed; desert vegetation on base land: (*7*) vegetating (ephemeral), (*8*) wilted; desertified vegetation of delta plains: (*9*) vegetating, (*10*) wilted; reed vegetation in river deltas and on seashores: (*11*) vegetating, (*12*) dried; water bodies: (*13*) with open water surface, (*14*) covered by reed; (*15*) solonchaks.

mer) regain their vegetation and also later (in the autumn) finish it.

THE SEASONAL WETNESS AND SALINITY RHYTHM OF THE FORMER SEABED

The state of the natural–territorial complexes changes with bed drying after winter–spring wetting. The salinization regime of the area is closely related to variations in moistening. These processes could be seen in a series of images taken in different seasons and were showed on a map (Fig. 9). A wide (20–30 km) zone of low terraces around the sea is wetted in the spring. A salt crust, fringing the wetted terrace surface by a continuous band 2–10 km in width, forms on its margin because of evaporation.

As the territory dries out, the crust goes drier and becomes subject to wind erosion, just forming a source of salt storms, resulting in its gradual destruction. Two–three months later, it decomposes into fragments, and the nearby territories acquire a salt film. The traces of salt completely disappear by late summer. Parallel to the destruction of the first band of salt crust (the spring, thickest, crust), new salt crusts form along the edge of the narrowing wet band during the drying of low terraces. These crusts are wet at first, and next they dry up and become subject to destruction by deflation processes. Two or even three bands of salt crust can coexist for some time, each band passing an individual stage in the cycle of their formation along the edge of the wet terrace, drying up, and deflation destruction and blowing around.

Thus, the major processes of the seasonal dynamics of the former seabed are due to the regime of wetting and salinization, soil drying, and the formation and destruction of salt crusts along the edge of a narrowing wetted band.

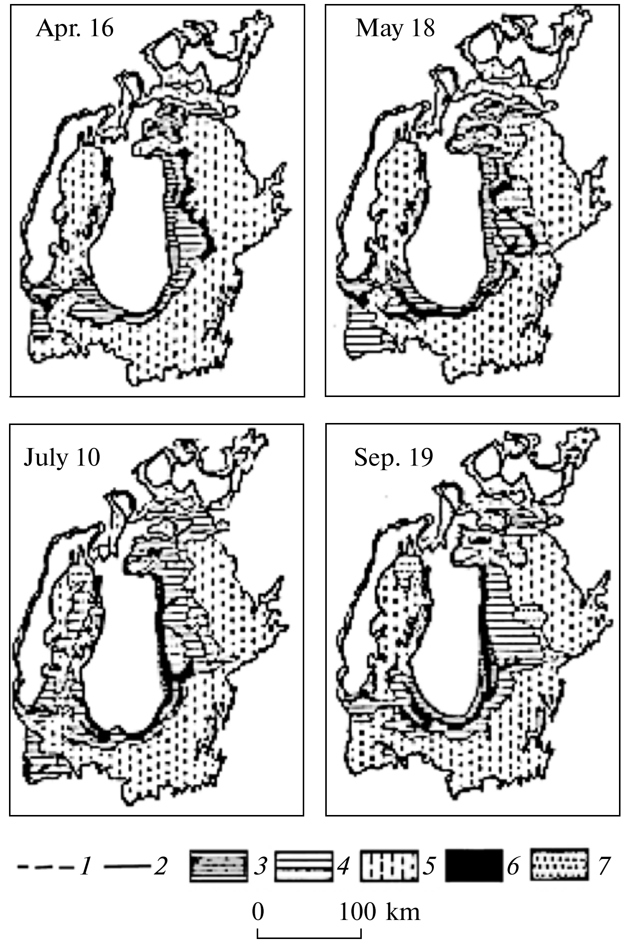

Fig. 9. Seasonal variations in wetting and salinization of the the former seabed in 2002. ShorelineL (*1*) in 1961, (*2*) in 2002; former seabed areas: (*3*) heavily wetted, (*4*) wetted, (*5*) dry, (*6*) salt crusts, (*7*) areas of salt settling after deflation of salt crusts.

CONCLUSIONS

Regular satellite surveys enabled the monitoring of the degrading Aral Sea, whose area in 2008 amounted to 15.7% of that in 1961. The obtained images demonstrate the separation of the Aral Sea into individual water bodies with different fate. The shallow eastern part of the Great Sea rapidly dries out, while the contraction of its western part is slower, and the state of the Small Sea is stable (its area even started increasing after the construction of a fundamental dam in Berg Strait). The materials of regular surveys made it possible to follow seasonal variations in the shoreline and sea water surface area, which adequately reflect sea level variations fixed by satellite altimeters. The variable-water state of the Northeastern Bay, separated by former Barsakel'mes Island, which merged with the land, was described; the watering of this bay depends on the operation regime of the dam in Berg Strait and on the inflow of Amu Darya water into the Aral Sea. The images allow the setup phenomena affecting large areas in the shallows in the eastern Great Sea to be analyzed. They also showed the input of Amu Darya water into the Aral Sea, which continued up to 2007 mostly due to overflows from reservoirs, thus demonstrating the contribution of Amu Darya water retention in reservoirs within its delta to the degradation of the sea. The seasonal cycle of area salinization was determined: the formation of salt crusts during drying of wetted coastal zones, their erosion by wind, and salt transportation by salt–dust storms; this provides better understanding of salt redistribution processes.

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