# SATELLITE MONITORING OF WATER RESOURCES IN TURKMENISTAN

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## ABSTRACT

Satellite monitoring of water resources and land is of great importance for countries located in arid zones especially now when significant changes in regional climate are observed. Modern possibilities of the remote sensing satellite technologies in environmental monitoring and examples of use of satellite data and imagery for the analysis of morphometric characteristics and sea (lake) level of main water bodies in Turkmenistan are shown. We focused on temporal variability of these characteristics for the Southeastern Caspian Sea, Kara-Bogaz-Gol Bay, and the Sarykamysh Lake. Special attention was paid to the construction and water filling of the Altyn Asyr Lake, which we started to monitor since the beginning of its construction in July 2009.

**Keywords:**
Satellite monitoring, Sea level, Water resources, Arid zones

## INTRODUCTION

Turkmenistan is a Central Asian country of about 490,000 km$^2$, the fourth largest by area in the former Soviet Union (FSU) after Russia, Kazakhstan, and Ukraine. It is slightly smaller than Spain and a bit larger than California State in the USA. Over 80% of the country is covered by the Karakum Desert, one of the largest and driest sand deserts in the world. Some regions in the country have an average annual precipitation of only 12 mm. The highest temperature recorded in Turkmenistan was 51.7 C in July 1983. The habitable area is strictly limited, and this huge country has a small population of about 6 million people, which rapidly grows.

Turkmenistan possesses the world's fourth-largest reserves of natural gas after Russia, Iran and the USA, but land and water are the two scarcest and most precious resources in this country. Turkmenistan, like all other Central Asian countries, is critically dependent on water because of its arid desert climate. The Amu Darya River, flowing from the Pamir and Tien-Shan Mountains along the entire length of the northeastern border with Uzbekistan to the tragically dying Aral Sea (Kostianoy and Kosarev [7]), is the main source of water for all agricultural and non-agricultural uses in

Turkmenistan. Limitation in water resources and rapidly growing population and economy in the country have led to the annual water availability per capita decrease by 50% during the last 35 years, dropping to 4,000 $m^3$ in 2004. Water has become the principal strategic resource that determines the region's economic development (Stanchin and Lerman [13]).

Water allocation from Amu Darya River is governed by regional agreements between all Central Asian states. Turkmenistan's share is 22 $km^3$/year, or 36% of the river's total runoff. Agriculture is the main water user in Turkmenistan, consuming 95% of the available resources. The emphasis on the expansion of cotton production in the Soviet era and the strategy of food self-sufficiency implemented since 1992 have led to accelerated growth of irrigated areas, which increased by nearly 4 times in the last 40 years, reaching 2.3 million hectares. Almost half this area – 1 million hectares – has been added during the 15 years since independence of the country in 1991. But irrigation is expanded without proper engineering attention to efficient conveyance of water, using mostly unlined canals and ditches with loss rates exceeding 30%. (Stanchin and Lerman [13]).

Water intake from Amu Darya River is supplemented with surface runoff from three other rivers – Murgan, Tedjen, and Atrek, as well as minor quantities from small rivers and springs. Groundwater plays a marginal role in Turkmenistan's water resources. The total groundwater reserves reach 3.4 $km^3$, of which only 1.3 $km^3$ is usable (actual groundwater use is of 0.4-0.5 $km^3$). Thus Amu Darya River is the dominant source (84%) of total fresh water resources in Turkmenistan (Stanchin and Lerman [13]).

Under conditions of continuous massive irrigation in Turkmenistan, considerable importance is attached to collectors and other drainage facilities intended for the removal of excess water from the soil. Without proper drainage, soil may become waterlogged due to rising water table and its salinity may increase to levels detrimental to crop growing. Expansion of irrigated areas naturally requires expansion of the collector-drainage network. The inadequacy of the collector-drainage network is reflected in severe deterioration of soil quality. In 14% of irrigated land the water table has risen above the critical level, and 1.65 million hectares, or fully 73% of irrigated land, are salinized (Stanchin and Lerman [13]).

The Turkmen Lake or the Altyn Asyr Lake (Golden Age Lake) is a new approach to disposal of drainage water from irrigation. Following a decision adopted in August 2000 by the President of Turkmenistan, the country is constructing a huge artificial lake in the middle of the Karakum Desert, on the site of the natural Karashor Depression. The lake is on the border between Balkan and Dashoguz velayats, some 350 km north of the capital Ashgabat. The lake will be filled with drainage water through a new collector, the Great Turkmen Collector from the south with combined length of over 1,000 km. Starting the construction in July 2009, it is planned that the collectors will divert to the lake annually up to 10 $km^3$ of saline drainage water, which is currently discharged into Amu Darya River and the Sarykamysh Lake. The Altyn

Asyr Lake will be 103 km long and 18.6 km wide with a total capacity of 132 km$^3$ (Stanchin and Lerman [13], The Turkmen Lake…..[14], Kostianoy et al. [8]).

Freshwater resources in Turkmenistan must be combined with other water resources like the Caspian Sea, Kara-Bogaz-Gol Bay and the Sarykamysh Lake which play a very important role in different sectors of the economy of the country (Fig.1). Satellite monitoring of water resources and land is of great importance for Turkmenistan and other countries located in arid zones worldwide especially now when significant changes in regional climate are observed. In the paper we will focus on interannual variability of the sea (lake) level and morphometric characteristics of these water bodies derived from satellite remote sensing (MODIS-Terra and –Aqua, Landsat-1, -5, -7, TOPEX/Poseidon (T/P), Jason-1 and -2 (J1/2)).

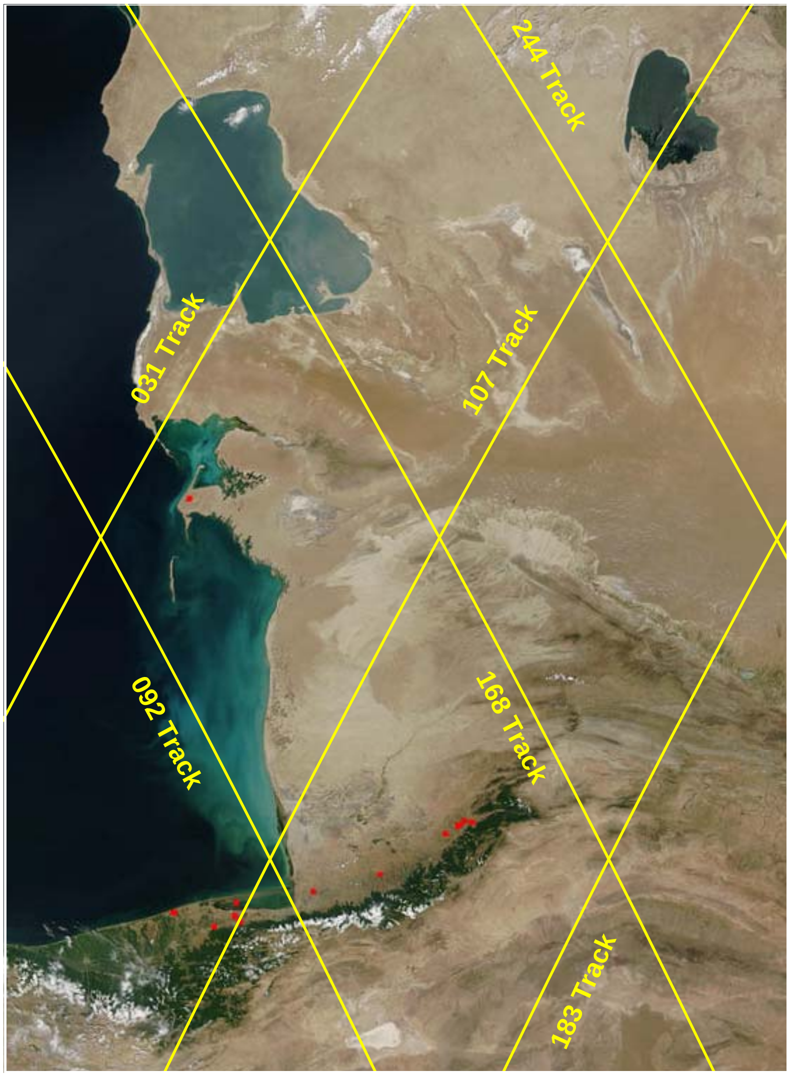


**Figure 1. The Caspian Sea, Kara-Bogaz-Gol Bay, the Sarykamysh Lake, the Altyn Asyr Lake and Western Turkmenistan on MODIS image acquired on 28 May 2002 with superposition of the TOPEX/Poseidon and Jason-1/2 ground tracks.**

## 1. THE CASPIAN SEA

The Caspian Sea is the world's largest isolated water reservoir. Its isolation from the ocean and its inland position make the significance of its outer thermohydrodynamic factors, specifically, heat and water fluxes through the sea surface, and river discharge on sea level variability, formation of its 3D thermohaline structure, and water circulation (Kosarev and Yablonskaya [3]). Over the past half-century, there was the Caspian Sea level regression by 2.5 m until 1977 when the sea level lowered to -29 m (Fig. 2). This was a result of a combination of natural factors (decrease of precipitation over the Volga River catchment area) and man made impact (construction of cascade reservoirs in the Volga and Kama rivers). This sea level drop is considered to be the deepest for the last 400–500 years (Kostianoy and Kosarev [6]). In 1978 the Caspian Sea level started to rise rapidly, reached its maximum in 1995, and now it has stabilized at about -27 m absolute level (i.e. 27 m below ocean level) (Fig.2).

Satellite altimetry measures sea surface height (SSH) relative to a reference ellipsoid (or the gravity center) that allows elimination of vertical Earth's crust lift from interannual level variation. Thus, it has advantages over the old Caspian coastal gauge stations. It was shown that spatial and temporal resolution of satellite altimetry data allows to investigate seasonal, interannual and space-time variability of the Caspian Sea level (Cazenave et al. [1]; Lebedev and Kostianoy [11, 12]; Kouraev et al. [10]).

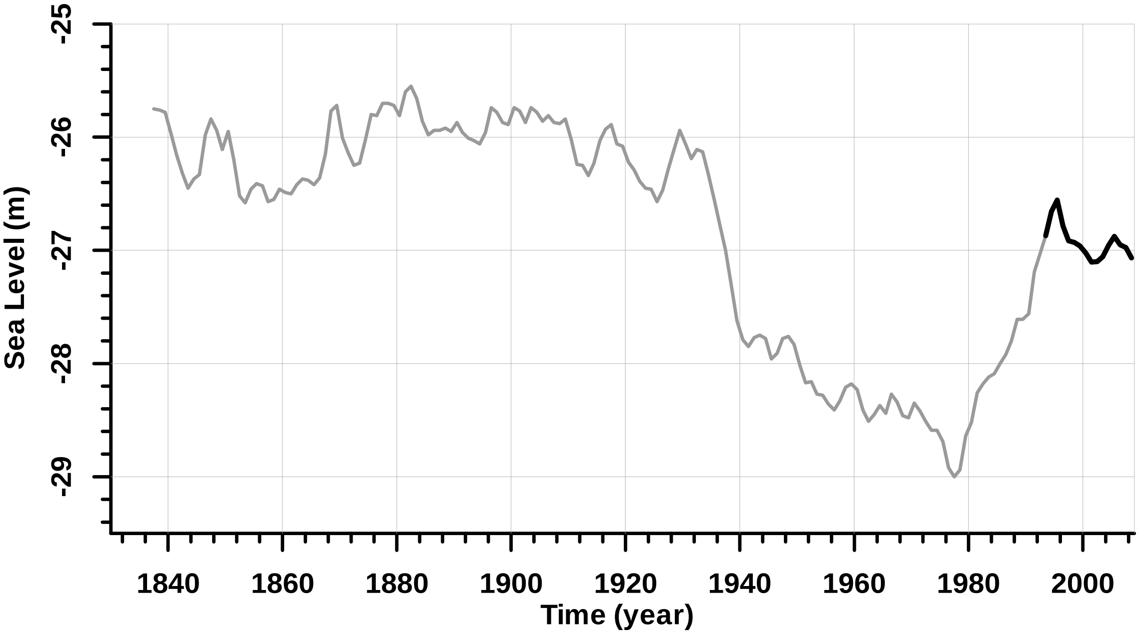


**Figure 2. Interannual variations of the Caspian Sea level measured by sea level gauges (grey line) and satellite altimetry (black line) from 1837 till 2009.**

For this investigation altimetric measurements from both the T/P and J1/2 satellites were used for the following reasons. The position of T/P and J1/2 ground tracks (Lebedev and Kostianoy [11]) is optimal for analysis of sea level variations in the Caspian Sea (Fig. 3). The precision of SSH measurements by T/P and J1/2 to the relative reference ellipsoid is 1.7 cm, which is higher than other altimetry missions. At the same time, accuracy of sea level measurements is of ~4 cm that allows adequate accuracy for specific studies to be conducted. The orbital repeat period of 10 days enables analysis of interannual and seasonal variability of the sea level. The T/P data represent the longest time-series of satellite altimetry measurements from September 1992 to August 2002 with a possibility of the data extension by J1 data along the same tracks from August 2002 to February 2009 and by J2 from July 2008 to present. Satellite altimetry data processing methods and analysis as well as obtained results on the SSH, wind speed and wave height variations in the Caspian Sea were described in detail in the book by Lebedev and Kostianoy [11].

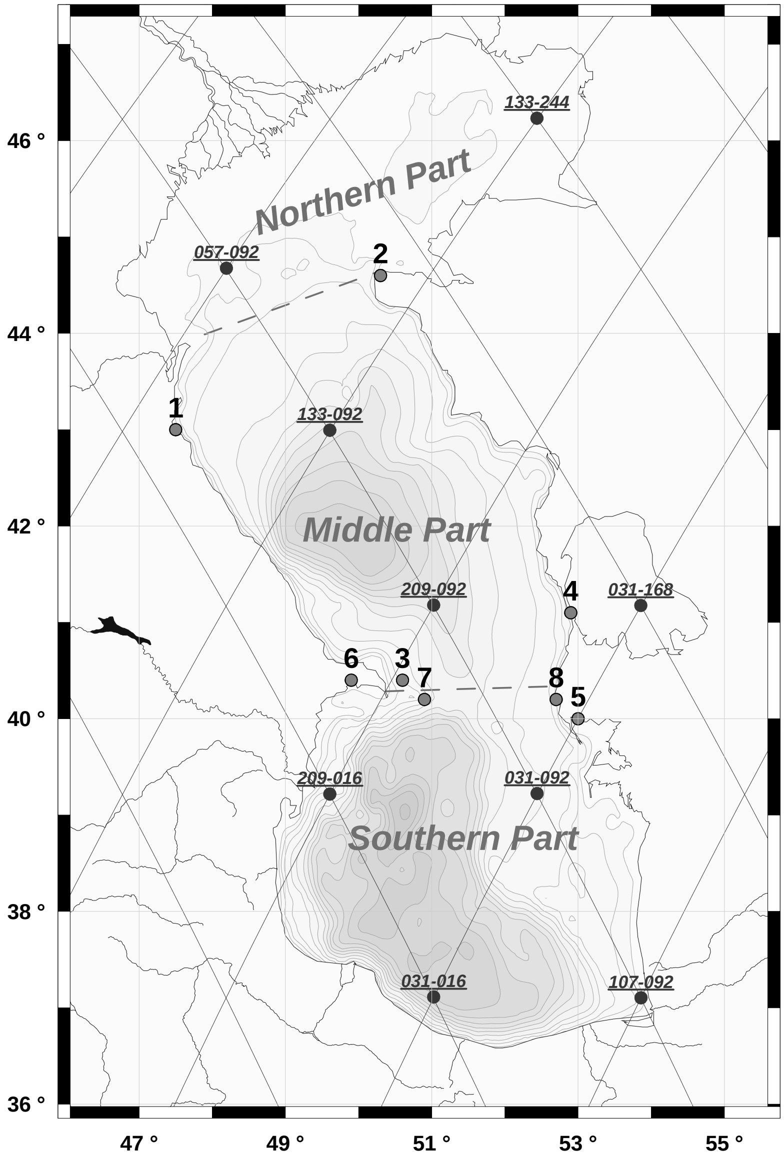


**Figure 3. Map of the Caspian Sea, ground tracks and crossover points of the T/P and J1. Sea level gauges are shown as follows: 1 – Makhachkala, 2 – Fort Shevchenko, 3 – Zhiloy Island, 4 – Kara-Bogaz-Gol, 5 – Turkmenbashi, 6 – Baku, 7 – Neftyanye Kamni, 8 – Kuuli Mayak.**

Investigation of the Caspian Sea level variation was based on the analysis of SSH variability in 7 crossover points (2 – in the Northern Caspian, 2 – in the Middle Caspian and 3 – in the Southern Caspian (Fig.3)). Integrated interannual variability of the Caspian Sea level is shown in Fig. 4. Comparison of SSH variations in 7 crossover points with data of 8 sea level gauges has shown that a maximal value of the correlation coefficient 0.967 was observed between the sea level guage station in Baku and nearest crossover point (Fig. 3). For the sea level time variability of the whole sea, which is traditionally calculated basing on the sea level gauges in Makhachkala, Baku, Fort Shevchenko and Krasnovodsk (nowadays Turkmenbashi), the correlation coefficient for all crossover points is 0.94 (Lebedev and Kostianoy [11, 12]).

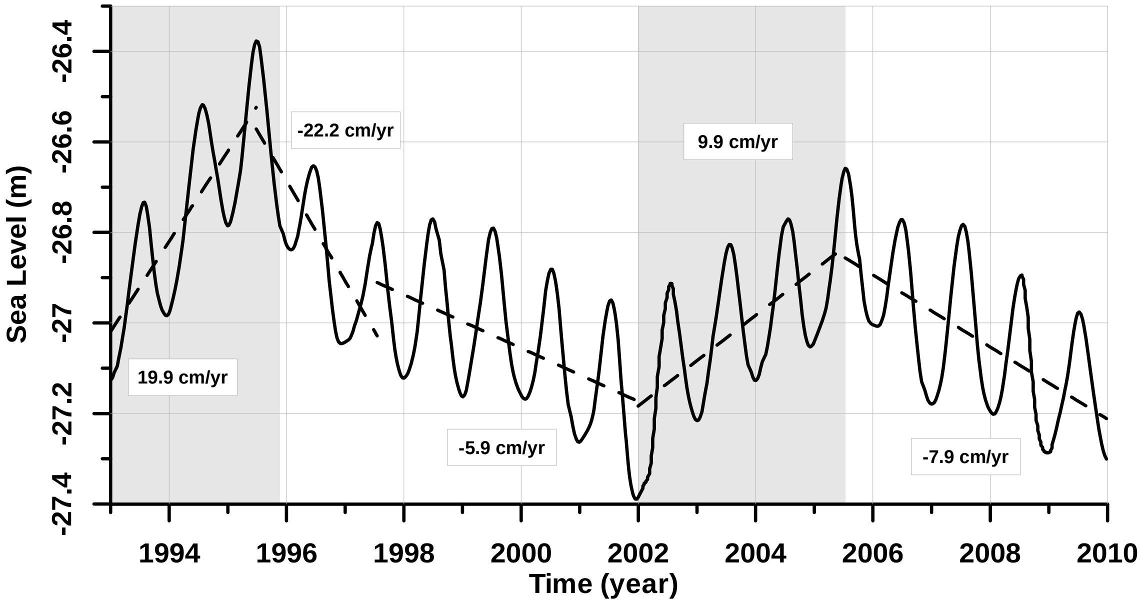


**Figure 4. Interannual and seasonal variability of the Caspian Sea Level (m) at 7 crossover points (see Fig.3) in September 1992 – December 2009. Grey areas show time periods when the Caspian Sea level was rising.**

According to the variation of the interannual Caspian Sea level change (Lebedev and Kostianoy [11, 12]; Kouraev et al. [10]) we determine five time periods: a strong rise in 1993–1995 with a rate of +19.9 cm/year, a strong drop in 1995–1997 with a rate of -22.2 cm/year, a slow drop in 1997–2001 with a rate of -5.9 cm/year, a slow rise in 2002–2005 with a rate of +9.9 cm/year, and a slow drop in 2005–2009 with a rate of -7.9 cm/year (Fig.4). Seasonal variability of the Caspian Sea level is of the order of 30-40 cm.

## 2. KARA-BOGAZ-GOL BAY

Kara-Bogaz-Gol is a bay that incises deeply into the mainland and forms a highly saline bay on the eastern side of the Caspian Sea (Fig. 1) (Kosarev and Kostianoy [4], Kosarev et al. [5]). This is the Caspian's largest salt-generating lagoon separated from the sea with two sand spits extending meridionally for more than 90 km (Fig.1). These sand spits form a strait 7–9 km long, 120–800 m wide, and 3–6 m deep. Due to the difference of water levels in the Caspian Sea and the bay the waters from the sea rush at a speed of 50–100 cm/s along the strait to the bay where they evaporate completely (at a rate of 800–1000 mm/year, on the average). Therefore, with the average annual atmospheric precipitations in this region being no more than 110 mm Kara-Bogaz-Gol represents an enormous natural evaporation basin of seawater.

Due to high evaporation the bay is filled with brine the salinity of which reaches 270–300 psu. This brine is a concentrated solution of salts such as chlorides of sodium, magnesium, and potassium, magnesium sulfate, and small quantities of rare-earth elements. Kara-Bogaz-Gol Bay is the largest salt deposit where up to 20 salt minerals were found. The salt deposits of the bay accumulated dozen billion tons of various salts that make the most valuable raw material for development of the chemical industry, agriculture, nonferrous metallurgy, medicine, and other branches of the economy of Turkmenistan (Kosarev et al. [5]).

In March 1980, in order to restrict losses of Caspian waters and to decelerate the fall of the level of the Caspian Sea, which, in 1977, had been at its lowest for the past 400 - 500 years (-29 m) (see Fig.2), the Kara-Bogaz-Gol Strait was closed by a sand dam. After the separation of the bay from the sea, it rapidly dried off. By the middle of 1984, the bay had become an almost completely dry salt lake.

In order to revive, protect and develop this unique bay and salt field on the Caspian Sea, it was decided to renew the water supply to Kara-Bogaz-Gol Bay. In September 1984, Caspian water was fed into the bay at a rate of 1.5-1.6 $km^3$/year. This restricted seawater supply did not result in an active restoration of the hydrological and hydrochemical conditions of the bay. In April 1992, the area of the bay reached 4,600 $km^2$, the absolute level mark was -33.71 m, and the depths varied from 0.2 to 1.4 m. In June 1992, the dam was destroyed and the natural seawater runoff to the bay resumed.

The process of refilling of Kara-Bogaz-Gol Bay and its acquisition to a climatic regime is well traced in the satellite altimetry data of the T/P and J1/2 (Fig. 5 and 6) (Lebedev and Kostianoy [11, 12]). Fortunately, the start of the T/P mission successfully coincided with the beginning of the filling of the bay and the area of the bay is crossed by two ground tracks of the above-mentioned satellites (Fig. 1 and 3). By the mid-1996, the rapid filling of the bay with the Caspian Sea water had caused a rate of the bay level rise of about 168 cm/year (Fig. 5) (Lebedev and Kostianoy [11, 12]). Then, the level rise stopped and its variations started to reflect seasonal changes well correlated with the seasonal level changes in the Caspian Sea (see Fig. 4 and 6). Thus, the rate of the level fall (until winter 2001/2002) in both basins was approximately -6.3 cm/year. For the time period 2002–2006 the bay level has been rising again with the rate +6.8 cm/year. Since 2006 till present the level of the bay is falling with a rate of 8.9 cm/year (Fig. 6). Integrally the Kara-Bogaz-Gol Bay water level oscillations are near an absolute mark of -27.5 m.

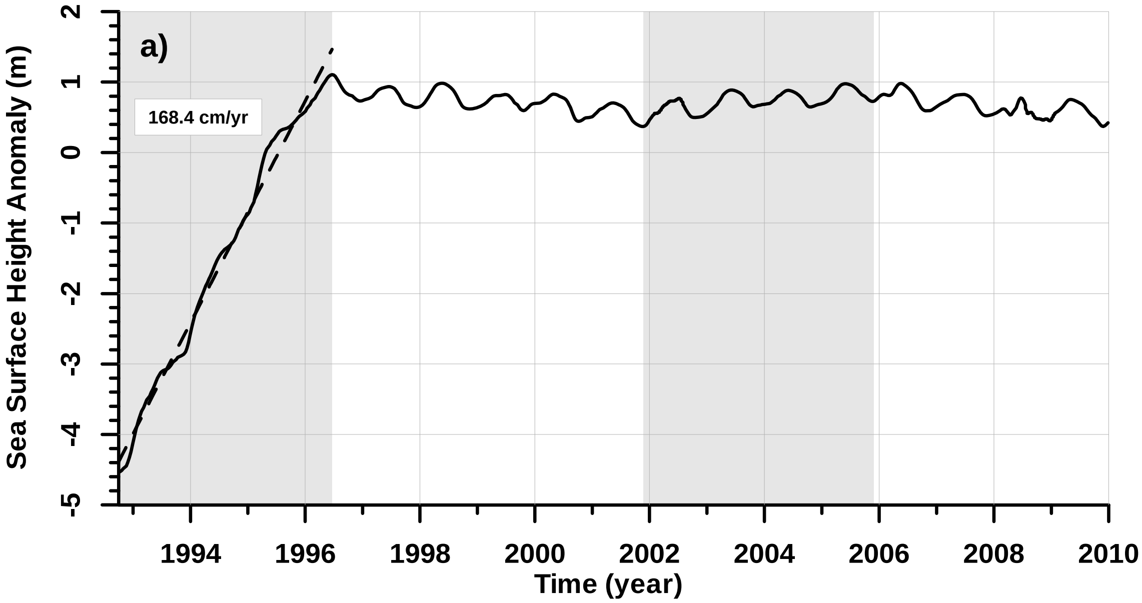


**Figure 5. Interannual and seasonal variability of SSH (m) in Kara-Bogaz-Gol Bay at crossover point of 031 pass and 168 pass in September 1992 – December 2009. Grey areas show time periods when the bay level was rising.**

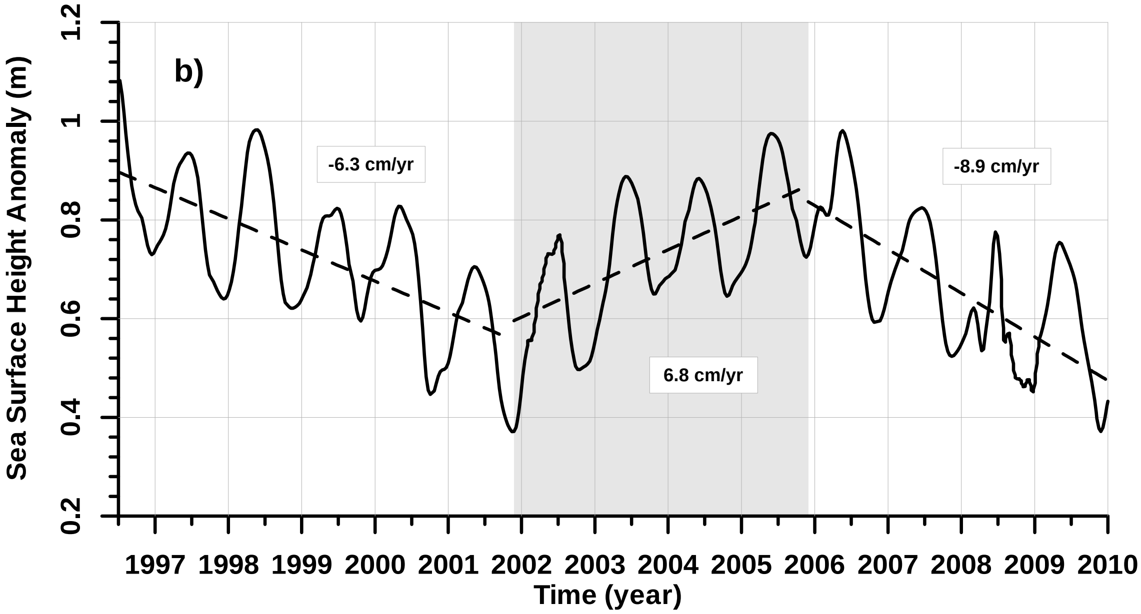
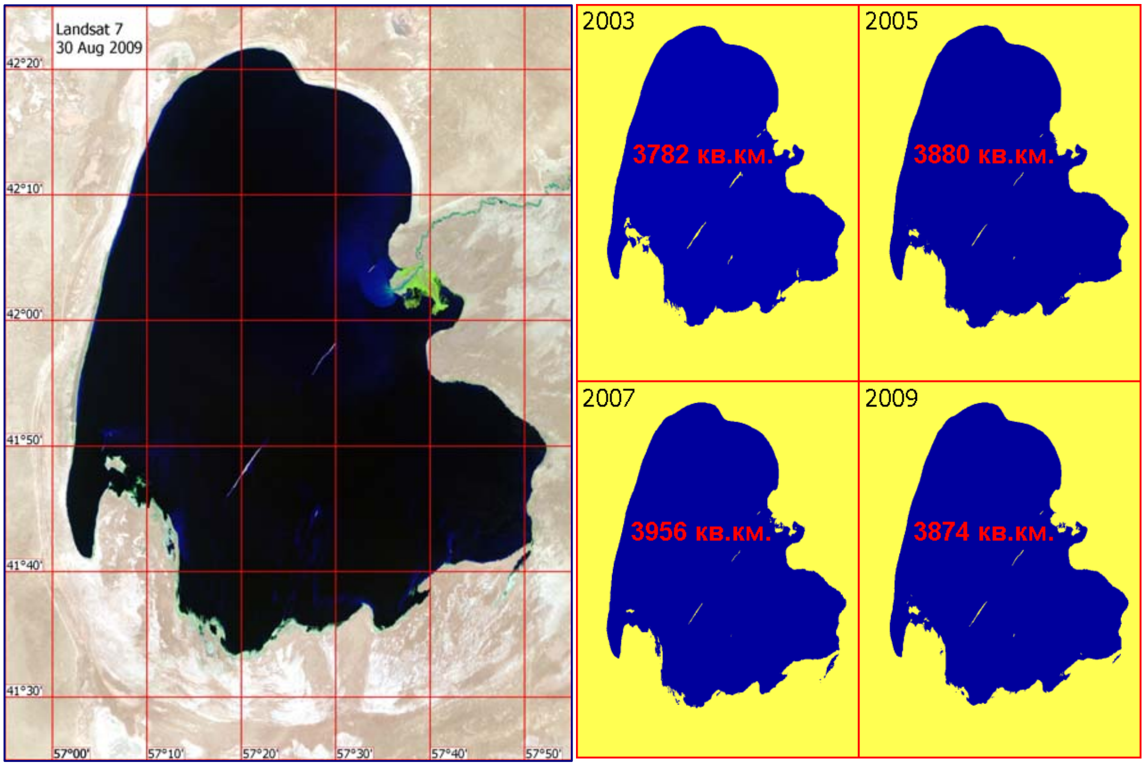


**Figure 6. Interannual and seasonal variability of SSH (m) in Kara-Bogaz-Gol Bay at crossover point of 031 pass and 168 pass in July 1996 – December 2009. Grey area shows the time period when the bay level was rising.**

## 3. THE SARYKAMYSH LAKE

The Sarykamysh Lake was formed in 1971 as a result of flooding of a set of small Sarykamysh lakes located at the bottom of natural Sarykamysh Depression located 200 km southwestward from the Aral Sea (Fig. 1 and 7). Its bottom lies at the -38 m absolute level (below ocean level). This depression periodically was filled by the Amu Darya waters via Daryalyk riverbed. Now the Sarykamysh Lake is a large drainage water body, which has been used as a discharge collector of salty irrigation water from the fields (Kostianoy et al. [9]). Currently, the lake covers an area about 3,900 km$^2$. Salinity of the lake waters has been continuously increasing: from 3-4 g/l in the early 1960s to 12-13 g/l in 1987 (Glazovsky [2]).

Since 1992, the Sarykamysh Lake has been progressively increasing in size, reaching its maximum level at the beginning of 2000 with an increase of almost 5 m at a rate of 0.6 m/year as observed by the TOPEX/Poseidon and further by the Jason-1/2 altimetry missions (Fig. 8). Then, during 1.5 years its level dropped by 1 m, and then since 2002 its level is rising again with about the same rate (0.6 m/year). High resolution (30 m spatial resolution) Landsat imagery (Fig.7) allows to follow changes in the shape of the lake and its morphometric characteristics in details.



**(a)** **(b)**

**Figure 7. The Sarykamysh Lake on Landsat 7 image on 30 August 2009 (a) and surface (km$^2$) and shape of the lake in 2003, 2005, 2007, and 2009.**

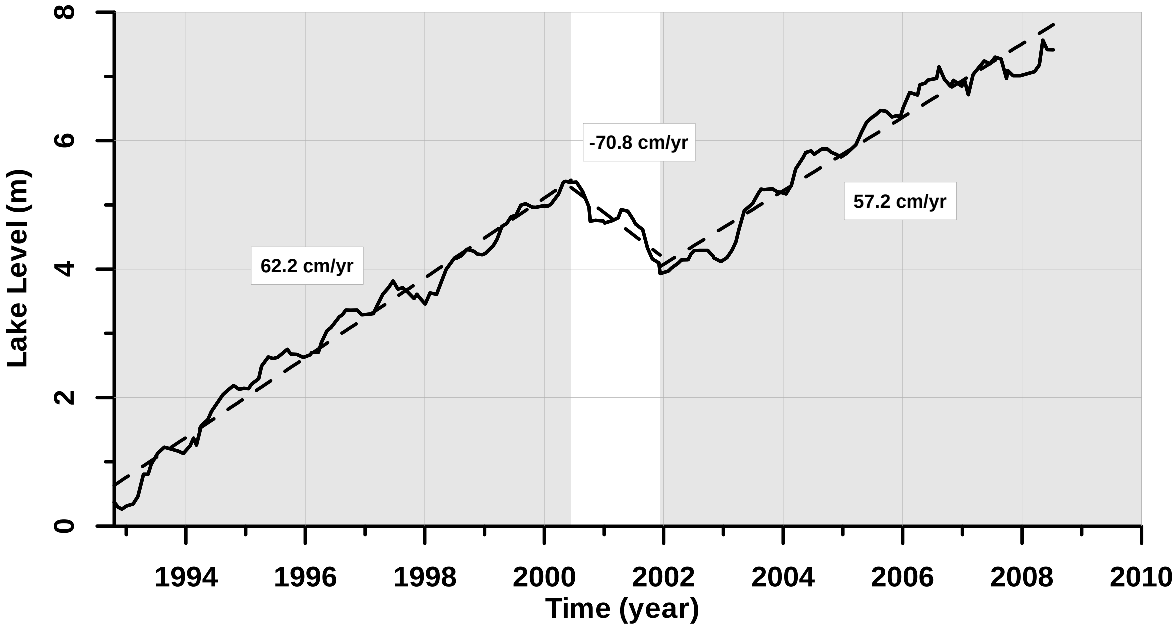


**Figure 8. Interannual and seasonal variability of the Sarykamysh Lake water level (m) in September 1992 – December 2009. Grey areas show time periods when the lake level was rising.**

## 4. THE ALTYN ASYR LAKE

The idea of the Altyn Asyr Lake (Golden Age Lake) is to collect most of sewage waters to irrigate some new 400,000 ha for pasture and orchards, and to create with the residual waters a new lake, located in Karashor salt depression in the northern part of Turkmenistan (Fig. 1, 9 and 10). The project is to fill the depression with waters conveyed by past rivers, such as the Uzboy, a past bed of Amu Darya, running from Dashoguz in its present delta to the Caspian Sea, for waters coming from the turkmen cultivated part of the Amu Darya delta, down from Lebap, and through a new system of canals and collectors in Dashoguz and Akhal velayats (Fig. 9).

The Altyn Asyr Lake is planned to be 103 km long and 18.6 km wide with a total surface of 1915.8 km$^2$, and capacity of 132 km$^3$ (The Turkmen Lake…..[14], Kostianoy et al. [8]). Starting the construction in July 2009, it is planned that the collectors will divert to the lake annually up to 10 km$^3$ of saline drainage water. Fortunately, one of the ground tracks of Jason-2 satellite crosses the bottom of Karashor Depression (Fig. 1) and in future it will be possible to follow the water filling of the lake basing on satellite altimetry data as it was done for the Kara-Bogaz-Gol Bay case study (see Fig. 5).

Since July 2009 we perform satellite monitoring of the Altyn Asyr Lake construction. Today, when water did not reach yet the bottom of Karashor Depression, we use medium (250 m) and high resolution (30 m) optical imagery from MODIS-Terra and -Aqua and Landsat-5 and -7 satellites to trace water filling of the canals feeding the lake (Fig. 10) (Kostianoy et al. [8]).

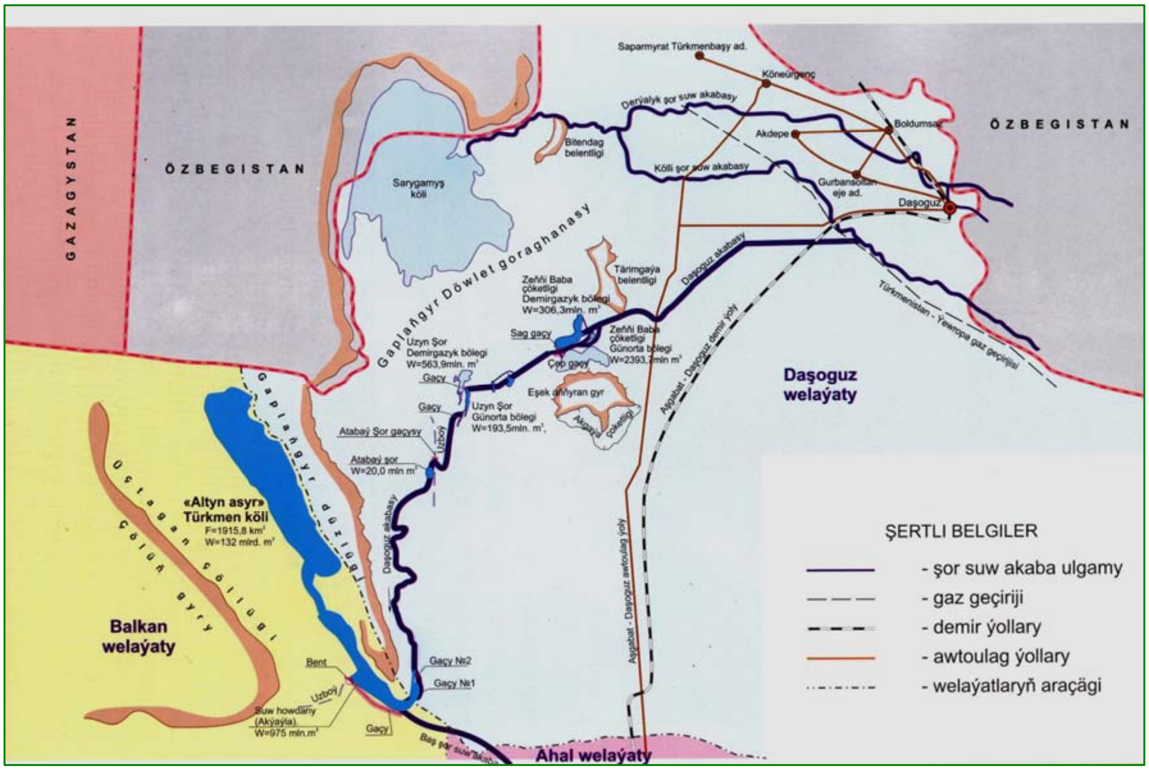
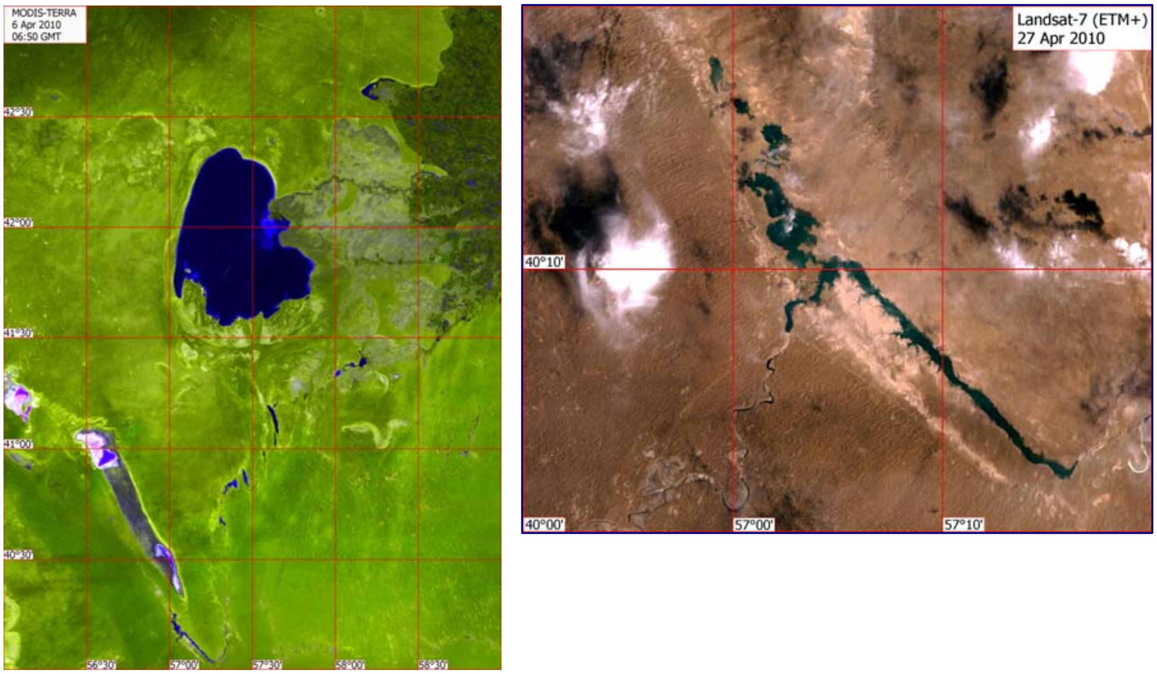


**Figure 9. The map of the Altyn Asyr Lake and supporting water systems.**



(a) (b)

**Figure 10. Geographic location of the Altyn Asyr and Sarykamysh lakes on MODIS-Terra image acquired on 6 April 2010 (a) and progressive water filling of the Karashor Depression via Uzboy riverbed on Landsat-7 image acquired on 27 April 2010 (b).**

## CONCLUSIONS

During the last decade P.P. Shirshov Institute of Oceanology of the Russian Academy of Sciences (RAS) together with Geophysical Center RAS and Marine Hydrophysical Institute (Ukraine) performed a set of national and international scientific projects focused on the new satellite remote sensing technologies and developed complex satellite monitoring systems for the Caspian, Aral, Black, Azov, Eastern Mediterranean and Baltic seas. Our experience in receiving, processing and analysis of different multisensor satellite data was applied to the monitoring of the Southeastern Caspian Sea, Kara-Bogaz-Gol Bay, the Sarykamysh Lake, and artificial Altyn Asyr Lake, which since 2009 is under construction in Turkmenistan. It can be applied also to the monitoring of the reservoirs, lakes, rivers and for agriculture by the analysis of the index of vegetation (NDVI) and vegetation liquid water content (NDWI). Satellite monitoring of water resources and land is of great importance for countries located in arid zones especially now when significant changes in regional climate are observed.

The report demonstrated modern possibilities of the remote sensing satellite technologies in environmental monitoring and showed examples of use of satellite data and imagery for the analysis of morphometric characteristics and sea (lake) level of main water bodies in Turkmenistan. Special attention was paid to the construction and water filling of the Altyn Asyr Lake, which we started to monitor since the beginning of its construction in July 2009.

### Acknowledgements

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