Satellite Monitoring of the Caspian Sea, Kara-Bogaz-Gol Bay, Sarykamysh and Altyn Asyr Lakes, and Amu Darya River

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Abstract Satellite monitoring of water resources and land is of great importance for Turkmenistan located in the arid zone especially now when significant changes in the regional climate are observed in Central Asia. Modern capabilities of satellite remote sensing technologies in environmental monitoring and examples of use of satellite data and imagery for the analysis of morphometric characteristics, sea/lake level, sea/lake surface temperature, sea/lake wind and waves, oil pollution of the main water bodies in Turkmenistan are shown. Special attention is paid to the construction and water filling of Altyn Asyr Lake water network. Examples of the processed satellite imagery for Sarykamysh Lake and Amu Darya River are given.

Keywords Altyn Asyr Lake, Amu Darya River, Kara-Bogaz-Gol Bay, Sarykamysh Lake, Satellite monitoring, The Caspian Sea, Turkmenistan

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Contents

1 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 (Fig. 1). 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 six million people, which rapidly grows.

Turkmenistan possesses the world's third-largest proven reserves (8.7%) of natural gas after Russia and Iran, 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, which is becoming warmer and drier. 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 [1], is the main source (84%) of water for all agricultural and non-agricultural uses in Turkmenistan. Water has become the principal strategic resource that determines the region's economic development.

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. Water intake from Amu Darya River is supplemented with surface runoff from three other rivers – Murghab, Tedjen, and Atrek, as well as minor quantities from small rivers and springs. Groundwater plays a marginal role in Turkmenistan's water resources [2].

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 soil. Without proper drainage, soil may become waterlogged due to the 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

Fig. 1 Satellite view over Turkmenistan (MODIS-Aqua, 30 September 2010)

lands the water table has risen above the critical level, and 1.65 million hectares, or fully 73% of irrigated lands, are salinized [2].

The Turkmen Lake Altyn Asyr (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 300 km north of the capital Ashkhabad. The lake will be filled with drainage water through a new collector, the Great Turkmen Collector from the south with a combined length of over 1,000 km. It is planned that the collectors will annually divert to the lake up to 10 km^3 of saline drainage water, which is currently discharged into Amu Darya River and Sarykamysh Lake.

Freshwater resources in Turkmenistan should be discussed with other water resources like the Caspian Sea, Kara-Bogaz-Gol Bay, and Sarykamysh Lake which play a very important role in different sectors of the economy of the country (Fig. 2). Turkmenistan is connected with the other Caspian Sea countries by shipping routes. Offshore, there are oil and gas fields, which are developed by national and foreign companies. The sea is rich in bioresources, and fishery is a part of the economy of the country. Kara-Bogaz-Gol Bay during the twentieth century played a key role in the chemical industry of the Turkmen Soviet Republic and today in Turkmenistan. The national tourist and recreation zone “Avaza” near Turkmenbashi town (see Fig. 2) with several modern hotels, restaurants, cafes, a sandy beach, artificial canal, and park zone is progressively developed at the coast of the warm Southern Caspian Sea. The Caspian Sea water (after desalination) is an immense potential source of potable and technical water for the country, living in the desert conditions.

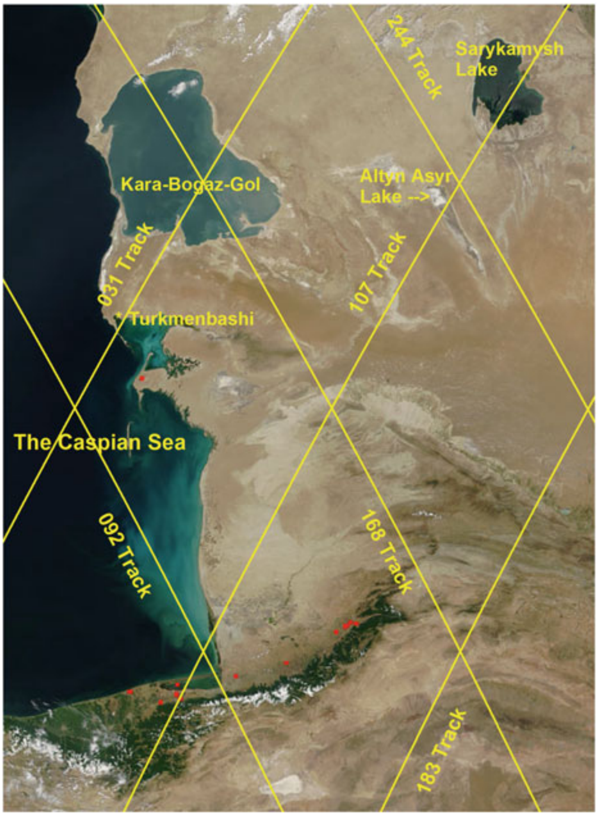

Fig. 2 The Caspian Sea, Kara-Bogaz-Gol Bay, Sarykamysh Lake, Altyn Asyr Lake, and Western Turkmenistan on MODIS image acquired on 28 May 2002 with superposition of the TOPEX/Poseidon and Jason-1/-2 satellites ground tracks

Satellite monitoring of water resources and land is of great importance for Turkmenistan and other Central Asian countries, located in the arid zone, especially now when significant changes in the regional climate are observed. Today, an integral part of any modern environmental monitoring of land, sea, lakes, and rivers is satellite-based monitoring, which has great additional features and advantages over ground-based. First of all, they are: (1) global coverage, (2) instantaneous snapshoting of a vast area, (3) the highest operationality in data acquisition, (4) ability to repeat daily observations, (5) high spatial resolution (from 1 km to 50 cm), (6) receiving of interdisciplinary and multisensor data, (7) ability to ensure comprehensive monitoring at any point of the globe, (8) using the same satellite data for a wide range of supplementary tasks (fires, floods, desertification, vegetation, water resources, etc.), and (9) significantly low cost of satellite monitoring in comparison with in situ observations.

Over the past 20 years in the course of a number of Russian and international projects, P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences

(SIO RAS), Space Research Institute (IKI RAS), Geophysical Center (GC RAS) in cooperation with Marine Hydrophysical Institute of National Academy of Sciences of the Ukraine (MHI NASU) have gained a unique joint experience working with a variety of satellite data on the state of the oceans, seas, lakes, and rivers; have developed and worked out new methods of research that apply for comprehensive environmental monitoring of Russian seas and inland water bodies [3]. We have developed an effective complex (multisensor and interdisciplinary) approach to real-time satellite monitoring of oil pollution of the seas of Russia [3]. This approach was implemented in practice in 2004–2005 in the Southeastern Baltic Sea under the contract with "Lukoil-Kaliningradmorneft," when a full-operational satellite monitoring service was established for oil pollution control. Later, a similar integrated approach has been applied to the Black, Azov, and Caspian seas.

Satellite monitoring of coastal ocean, inland seas, lakes, and rivers is an important method to control their ecological condition. It is based on the reception, processing, and analysis of digital data from different radiometers, scanners, spectrometers, radar altimeters, scatterometers installed mainly on European and USA satellites (NOAA, Terra, Aqua, TOPEX/Poseidon, Jason-1, Jason-2, GFO, ENVISAT, Radarsat-1, Radarsat-2, TerraSAR-X, ERS-2, QuikSCAT, Landsat, IRS, KOMPSAT-2, EROS A, IKONOS, SPOT, QuickBird, FORMOSAT-2, and many others), which give information about fields of the sea surface temperature (SST), suspended matter, chlorophyll concentration, and other optical properties of the water surface and land, oil pollution, as well as anomalies in the sea level, ice cover, variability of currents, wind speed, and wave height with high spatial and temporal resolution. An opportunity to survey huge water and land areas in a short period, as well as a possibility of repeated observations of the same region with a short interval of time (1 day), make the use of remote sensing the cheapest, fastest, and objective method for environmental monitoring. Turkmenistan has supplementary advantages for satellite monitoring, because the country is located in the area with the number of cloudy free days which varies between 240 and 300 and sunshine of 3,100 h/year. These are the highest values in the FSU.

In recent years, with the openning of data banks with global regular satellite information and reanalysis data on the SST, sea level, chlorophyll concentration, ice cover, atmosphere pressure, air temperature, wind, rainfall, snowfall, humidity, heat flux, and other meteorological characteristics (PODAAC JPL, AVISO, UT/CSR, NCEP, GSFC NASA, DAAC GSFC, and many others), there is an opportunity to study not only seasonal but also interannual and even decadal variability of atmosphere, land, and sea parameters. This is particularly important for the study of the regional climate change in Turkmenistan and other Central Asian countries.

We have a long-standing experience in satellite monitoring of water bodies in Central Asia, and first of all this is the Caspian and Aral seas, which are under our permanent attention since 2000 [1, 3–14]. We began satellite monitoring of Turkmenistan with the beginning of water filling the Altyn Asyr water network in July 2009 [15–22]. In this chapter we would like to show only examples of different types of satellite information which can be received, processed, and analyzed, and can be very important for different sectors of economy, science, and education in Turkmenistan. Thus, here we do not intend to analyze satellite images or interannual/seasonal variability of different parameters, but sometimes useful references to the appropriate research will be given. Also, we will focus on the applications generally related to water resources and water quality.

2 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 outer thermohydrodynamic factors, specifically, heat and water fluxes through the sea surface, and river discharge the most important for sea level variability, formation of its 3D thermohaline structure, and water circulation [10, 23]. In the twentieth century, there was the Caspian Sea level regression by 2.5 m until 1977 when the sea level lowered to −29 m (29 m below the ocean level). This was a result of a combination of natural factors (decrease of precipitation over Volga River catchment area) and man-made impact (construction of cascade reservoirs in Volga and Kama Rivers). In 1978 the Caspian Sea level started to rise rapidly, reached its maximum in 1995 (−26.4 m), and now it is going down again with some oscillations. By the end of 2012 the sea level already reached a level of −27.7 m. Sea level variability, river runoff, weather conditions, regional climate change, and anthropogenic pressure have a significant impact on the marine environment and ecological state of the Caspian Sea, including waters of Turkmenistan.

The best instrument to monitor the Caspian Sea level is satellite altimetry [7, 8, 24–27]. Satellite altimetry measures the sea surface height (SSH) relative to a reference ellipsoid (or the gravity center) that allows elimination of vertical Earth's crust shifts from interannual level variation. Thus, satellite altimetry has advantages over the old Caspian coastal gauge stations which were not calibrated against the ocean level for several decades and have no precise 3D GPS stations [26]. Figure 2 shows the ground tracks of the TOPEX/Poseidon and Jason-1/-2 altimetry satellites over the Caspian Sea waters of Turkmenistan and Western Turkmenistan, where they also cross Kara-Bogaz-Gol Bay, Sarykamysh Lake, and the Karashor Depression (future Altyn Asyr Lake). Every 10 days the satellite passes along every line, thus in crossover points we have measurements every 5 days. This is enough to investigate seasonal and interannual variability of the Caspian Sea and other water bodies in Turkmenistan. Spatial resolution of altimetry measurements along the tracks is of 7 km, and accuracy is of 4 cm. Figure 3 shows interannual and seasonal variability in the Caspian Sea level basing on satellite altimetry data acquired in 1993–2012.

In Fig. 3 we see that the Caspian Sea level was decreasing from summer 1995 till winter 2001/2002, then it was rising till summer 2005 with a rate of about 10 cm/year, then again it was decreasing till winter 2009/2010 with a rate of 8.5 cm/year, and it accelerated to about 15 cm/year in the past 3 years till winter 2012/2013. Thus, the sea level has reached −27.7 m, which is already 1.3 m less

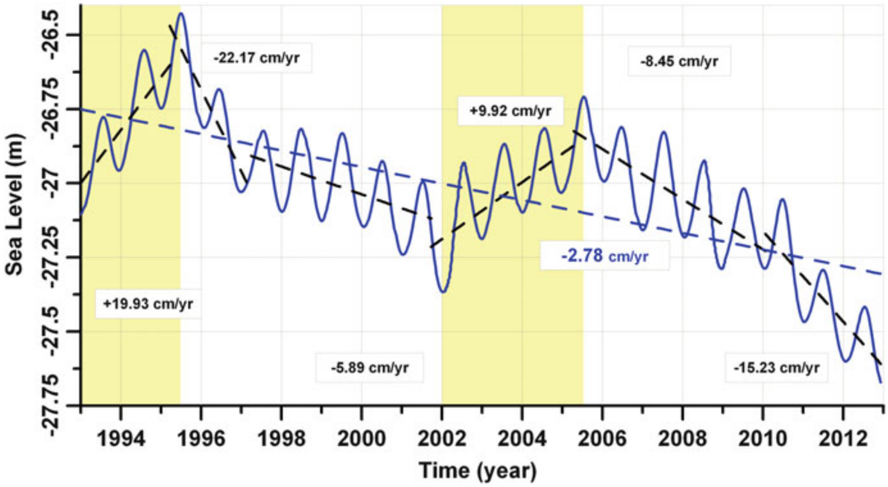

Fig. 3 Seasonal and interannual variability in the Caspian Sea level basing on satellite altimetry data of TOPEX/Poseidon and Jason-1/-2 acquired in 1993–2012. *Yellow* fields show periods when the sea level was rising. *Dashed black lines* show local trends (and trend values in *black*) and *dashed blue line* shows a general trend (and value) for the entire period

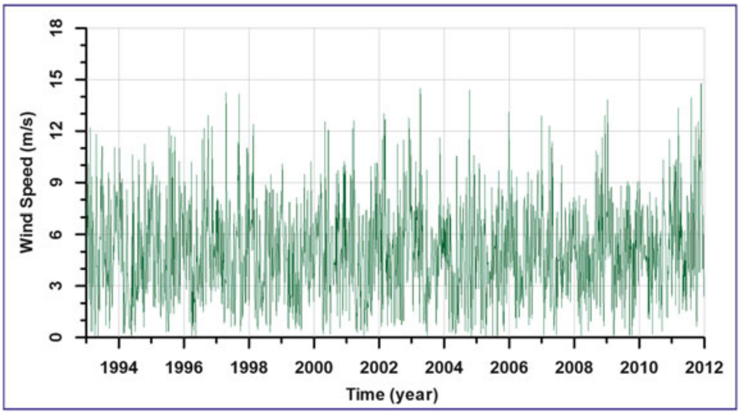

Fig. 4 Seasonal and interannual variability of wind speed at the crossover point of 31/92 tracks (see Fig. 2 for location) in 1993–2011 based on satellite altimetry data

than in summer 1995. Amplitude of seasonal variations of the sea level is of the order of 30–40 cm. All this information is of great importance for Turkmenistan, which has Turkmenbashi port and oil terminals, Turkmenbashi town, and the tourist zone "Avaza" at the shore of the Caspian Sea.

Satellite altimetry also allows to reconstruct values of wind speed (Fig. 4) and wave height (Fig. 5) along the tracks over the sea surface with the same spatial and temporal resolution. This is a very valuable source of information for shipping activities and offshore oil/gas platforms operations at sea. Figures 4 and 5 show

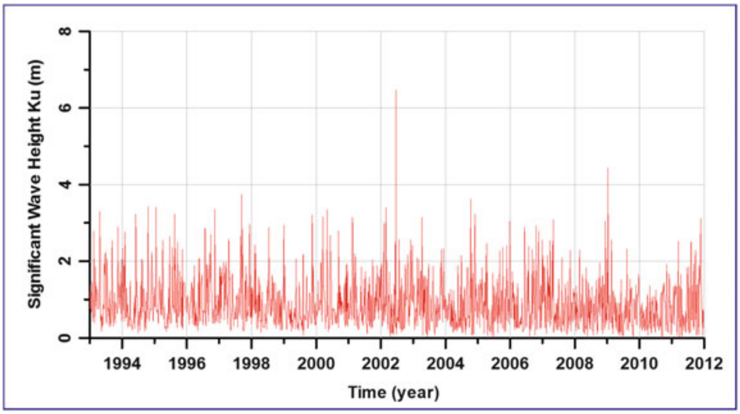

Fig. 5 Seasonal and interannual variability of wave height at the crossover point of 31/92 tracks (see Fig.2 for location) in 1993–2011 based on satellite altimetry data

variability of these parameters at the crossover point of 31/92 tracks (in front of Cheleken Peninsula, see location in Fig. 2) between January 1993 and December 2011 with time step of 5 days.

Satellite synthetic aperture radar (SAR) technologies allow to detect oil spills on the sea surface [3–6, 17]. This satellite technology is widely used for oil pollution control of shipping routes, offshore oil/gas platforms, ports, and oil terminals in the seas. Figure 6 shows a radar image of the coastal waters of Turkmenistan between Turkmenbashi and Cheleken Peninsula on 10 July 2010. In front of Cheleken Peninsula there are dozens of oil/gas platforms which look like a set of numerous white bright dots. Two of them are sources of oil spillages, which are marked by yellow circles. The largest one is stretching from south (location of one of the platforms) to north for 36 km. The spill passed at a distance of 18 km from the national tourist zone "Avaza." The other three oil spills in two circles (closer to the coast) could be released from ships or have natural origin (oil seepages from the bottom). Additional examples of oil pollution in coastal waters of Turkmenistan can be found in [17], where we proposed to organize permanent satellite monitoring of oil pollution in the sea, basing on our experience of operational satellite monitoring of the Lukoil D-6 oil platform in the Southeastern Baltic Sea [3, 28]. This is a very important task to control ecological conditions of the marine environment of Turkmenistan. The same SAR technology can be used for detection of new oil fields in the Caspian Sea basing on statistical data on the location of natural oil seepages from the bottom discovered by specific oil pollution features at the sea surface.

The quality of the marine environment can be controlled by optical imagery acquired by different spectroradiometers like MODIS-Terra and -Aqua and MERIS ENVISAT [3]. These instruments allow to reconstruct fields of suspended matter, chlorophyll concentration, and algal bloom events. High concentrations of these parameters represent another type of chemical and biological contamination of

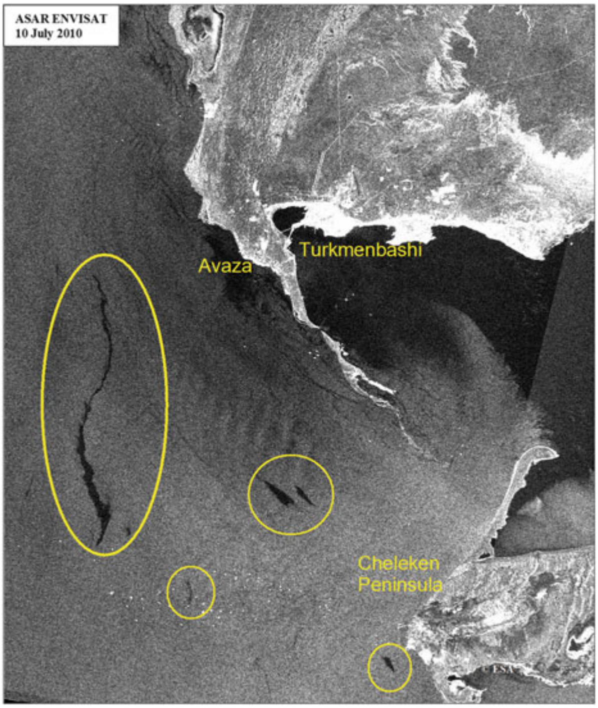

Fig. 6 ASAR Envisat image of coastal waters of Turkmenistan acquired on 10 July 2010. Oil spills (*black patches*) are shown in *yellow circles*. ©ESA, 2010

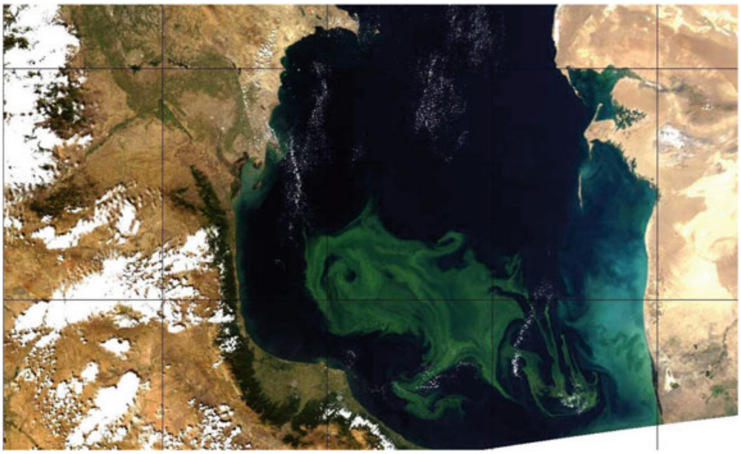

Fig. 7 Anomalous algal bloom in the Southern Caspian Sea (*green* vortical area) on 1 September 2005 revealed by MODIS-Terra

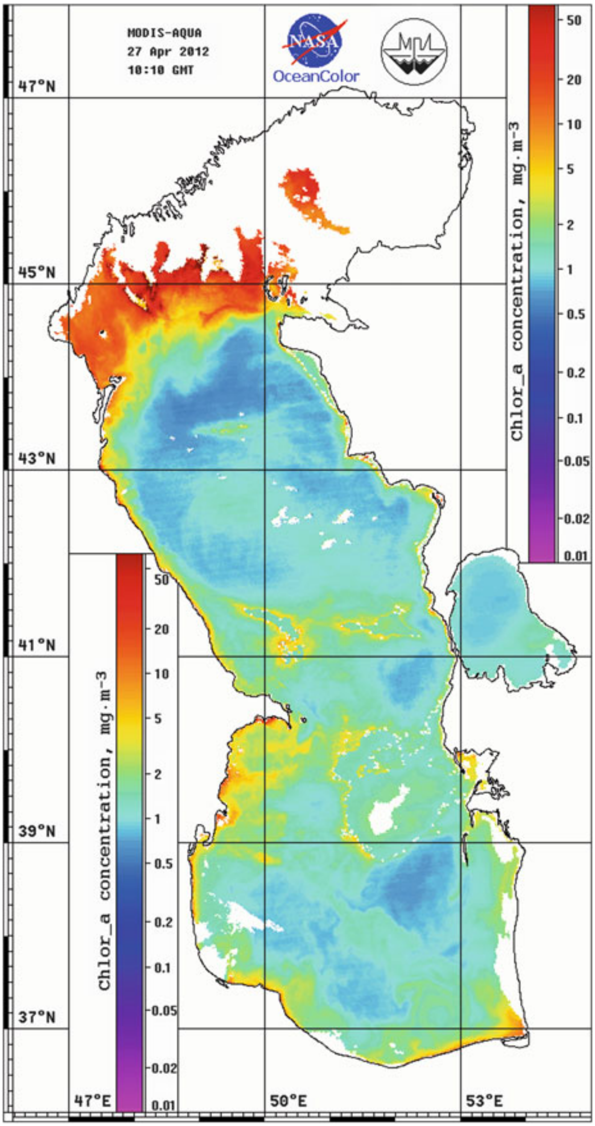

Fig. 8 Chlorophyll concentration in the Caspian Sea basing on the MODIS-Aqua data acquired on 27 April 2012

sea water. Intensive bloom of blue-green algae significantly reduces the quality of sea water and sometimes it may be even dangerous for humans and animals, because a part of these algae may be toxic. This is a well-known phenomenon, for example, in the Baltic Sea, where it occurs yearly in the increasing area and during longer periods of time. Recently, the same events began to appear in the northwestern part of the Black Sea, and a very large anomalous bloom event occured in 2005 in the Southern Caspian Sea (Fig. 7). The bloom area reached 20,000 km^2, and the bloom event lasted almost 2 months during August and

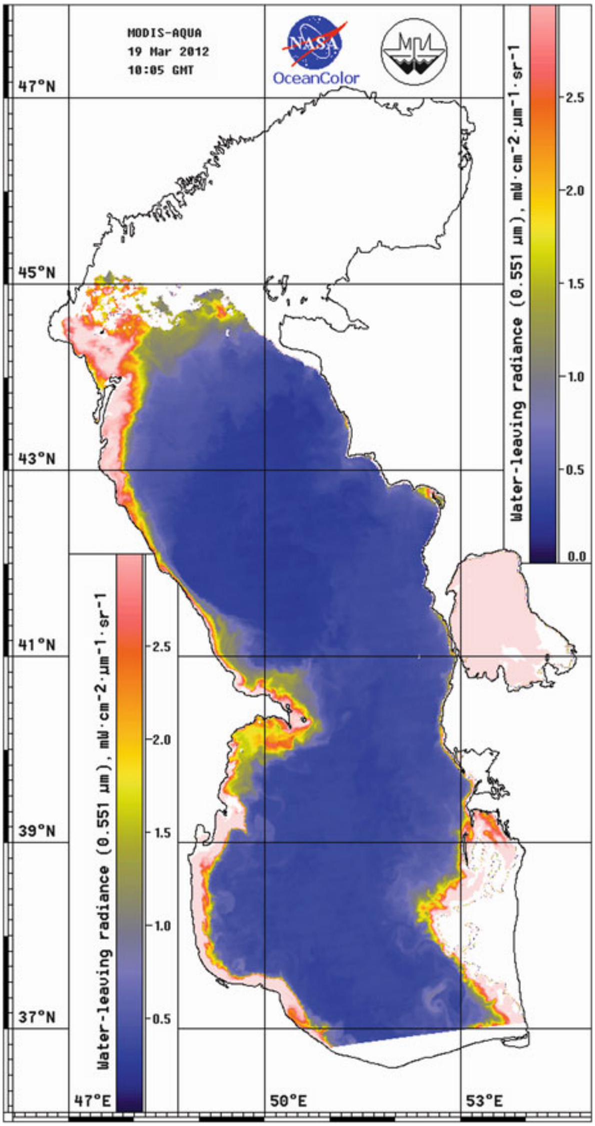

Fig. 9 Spatial distribution of turbid waters in the Caspian Sea displayed by water-leaving radiance acquired by MODIS-Aqua on 19 March 2012. *Blue* color shows clean waters

September. This event was detected and followed by MODIS-Terra daily imagery, which showed that fortunately the bloom area did not reach the coasts of Turkmenistan, Iran, or Azerbaijan (Fig. 7).

There are different algorithms to calculate chlorophyll concentration in the upper layer of the sea from satellite optical data. This technology allows to reconstruct fields of chlorophyll concentration for the whole Caspian Sea and to digitally monitor the quality of sea water. One of the examples is shown in Fig. 8 for 27 April 2012. A typical spatial distribution of chlorophyll suggests larger

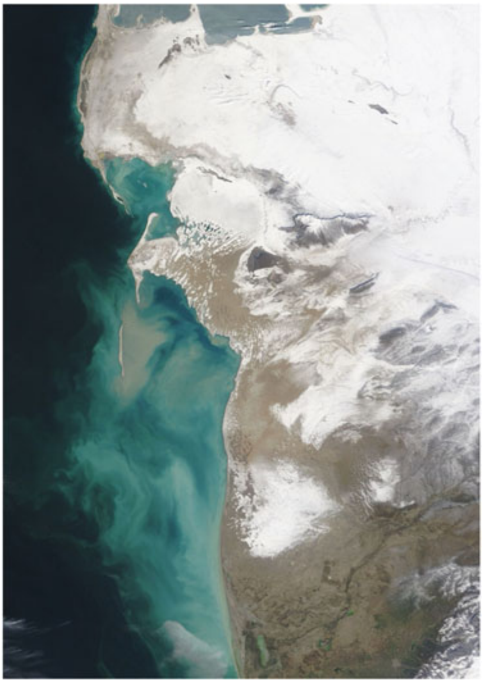

Fig. 10 Spatial distribution of turbid waters along the coasts of Turkmenistan displayed by MODIS-Terra on 15 February 2012. *Light* colors show turbid waters

values in the Northern Caspian, in front of the Volga River Delta, and along the coasts of the sea. Coastal zone of Turkmenistan is normally characterized by low values of chlorophyll concentration (Fig. 8).

The coastal zone from the Turkmenbashi Bay to the southern coast of the Caspian Sea in Iran is characterized by a permanent very large zone of turbid waters (Fig. 9). The turbid area is about 200–250 km long and 100–120 km wide and is displayed on most of the optical satellite images. The shape of the turbid area corresponds exactly to the bottom topography with an isobath of 25–30 m in the case of maximum development. It was found that the reason for generation of these turbid waters is resuspension of bottom sediments due to wind forcing at a very shallow area, moreover the radiances (turbidity) were about twice as high for winds having an offshore component in comparison with the onshore wind conditions [29]. Other wind directions produce also a turbid zone of a different size, this is why it is observed almost anytime [29]. High concentration of suspended matter is typical also for the shallow Turkmenbashi and Kara-Bogaz-Gol bays (Fig. 9).

Total concentration of suspended matter may be characterized by water-leaving radiance measured by SeaWiFS, MODIS-Terra, or -Aqua, or directly calculated in absolute values from the MERIS ENVISAT data, which unfortunately are no more available since April 2012 due to a failure of the ENVISAT satellite. The turbid area is also very well visible in "true colors" displayed by the MODIS instrument with 250 m spatial resolution (Fig. 10). This information is available daily from Terra and Aqua satellites. This turbid area may have a negative impact on fishery,

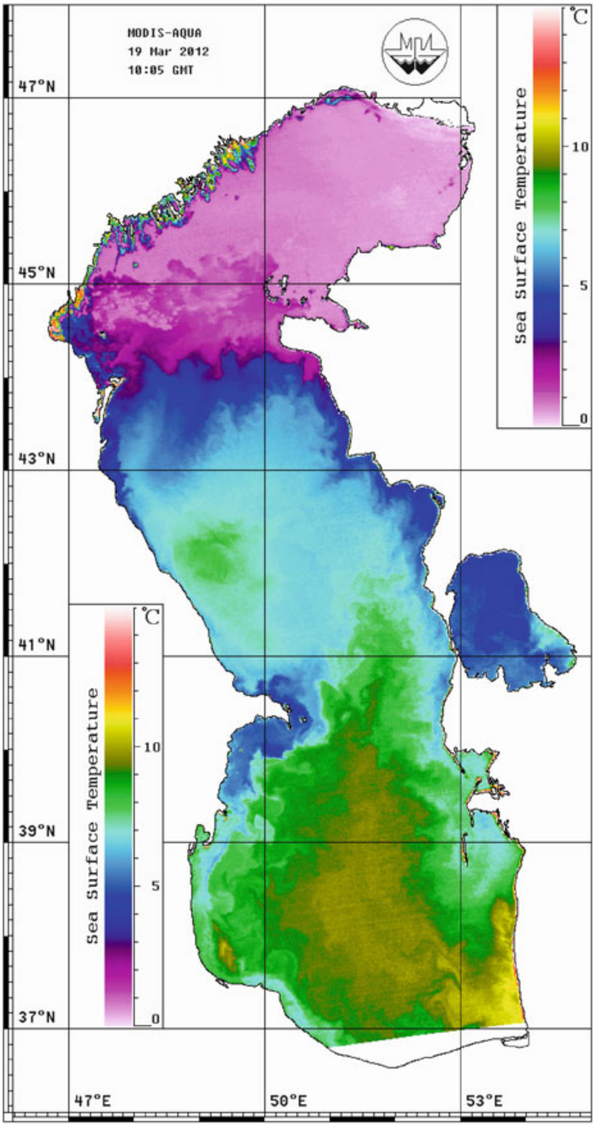

Fig. 11 SST field in the Caspian sea (MODIS-Aqua, 19 March 2012)

and its advection by the coastal current northward may have a negative impact on water quality in the recreation area of the "Avaza" tourist zone.

Radiometers AVHRR NOAA, spectroradiometers MODIS-Aqua and -Terra provide information on the SST, which is very important characteristics for any water body (Fig. 11). SST fields are used to detect meso- and small-scale water dynamics in the sea, which is required, for example, for the analysis and forecast of pollutants transport; to locate and investigate zones of coastal upwellings [30, 31], which play a key role in fishery and have a significant impact on recreation zones

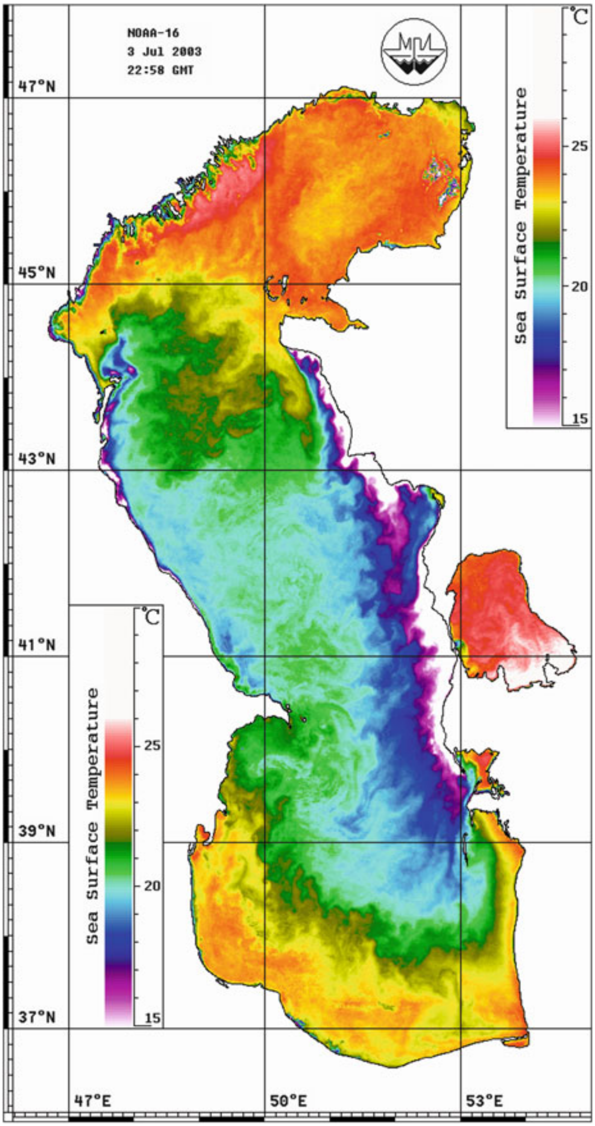

Fig. 12 SST field in the Caspian Sea (NOAA-16, 3 July 2003)

due to a decrease of the water temperature; and to investigate seasonal, interannual, and climate variability of the sea [32–34]. Figure 12 shows an upwelling event along the eastern coast of the Caspian Sea, which is stretching from Tyub-Karagan Peninsula (Kazakhstan) in the north to Cheleken Peninsula (Turkmenistan) in the south for 550 km. The width of the upwelling zone varies from 25 to 75 km. This is a yearly seasonal feature, observed from June to August. SST along the shores is less than 15°C (white color in Fig. 12), which is too cold for swimming in the summertime. There is an evident similarity between the upwelling zone in

Fig. 13 Satellite view on the ship loading in the port of Turkmenbashi. ©2013 DigitalGlobe (accessed on 26 March 2013 via Google Earth)

Portugal and in the eastern Caspian Sea, because their maximum development is observed only in July–August, which has a significant impact on the recreation and tourist areas, because very low SST prevents swimming in the sea during the vacation season. The tourist zone "Avaza" may be influenced by this natural phenomenon (see Fig. 12), which requires daily satellite monitoring of SST in the summertime and investigation of its seasonal and interannual variability.

In this chapter we will not discuss ice cover monitoring, because this is a very rare and local event in coastal waters of Turkmenistan, which is mainly observed in the Turkmenbashi Bay, for example, in winters 2007/2008 and 2011/2012. Finally, we can mention high resolution optical imagery provided by IKONOS, SPOT, QuickBird, FORMOSAT-2, and many other satellites. Spatial resolution of this imagery may be as high as 0.5–8 m which allows to monitor coastal and offshore infrastructure like ports (Fig. 13), oil terminals, oil/gas offshore platforms and pipelines, construction of buildings, and changes in the landscape and shoreline.

3 Kara-Bogaz-Gol Bay

Kara-Bogaz-Gol is a bay in the eastern part of the Caspian Sea which penetrates deeply into the mainland of Turkmenistan (Figs. 1 and 2) [35, 36]. This is the Caspian's largest salt-generating lagoon separated from the sea with two sandy spits extending meridionally for more than 90 km. These sandy spits form the Kara-Bogaz-Gol Strait 7–9 km long, 120–800 m wide, and 3–6 m deep. Due the difference of water levels in the Caspian Sea and the bay, waters from the sea rush at a speed of 50–100 cm/s along the strait to the bay where they completely evaporate (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 [18, 35, 36].

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

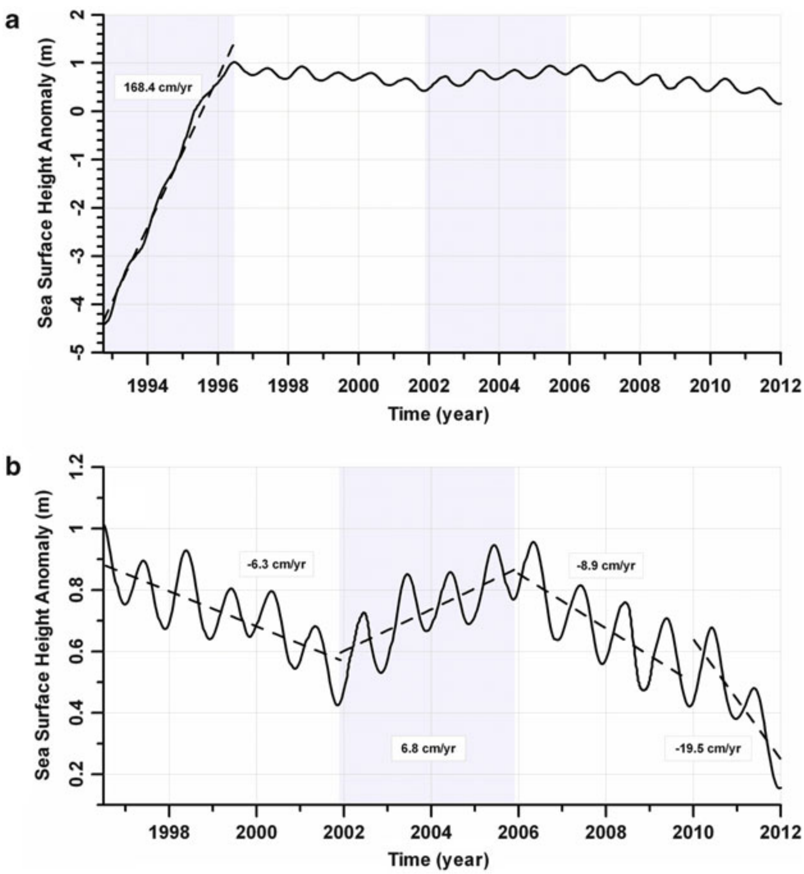

Fig. 14 Relative water level variability in the Kara-Bogaz-Gol Bay basing on the TOPEX/Poseidon, Jason-1, and Jason-2 satellite altimetry data: (**a**) for the time period September 1992–December 2011 and (**b**) for 1996–2011

of sodium, magnesium, 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 the development of the chemical industry, agriculture, nonferrous metallurgy, medicine, and other branches of the economy of Turkmenistan [18, 35, 36].

In order to prevent further fall of the Caspian Sea level, which, in 1977 had been at its lowest for the past 400–500 years (−29 m), the Kara-Bogaz-Gol Strait was closed in March 1980 by a sandy 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, the Caspian Sea water was fed into

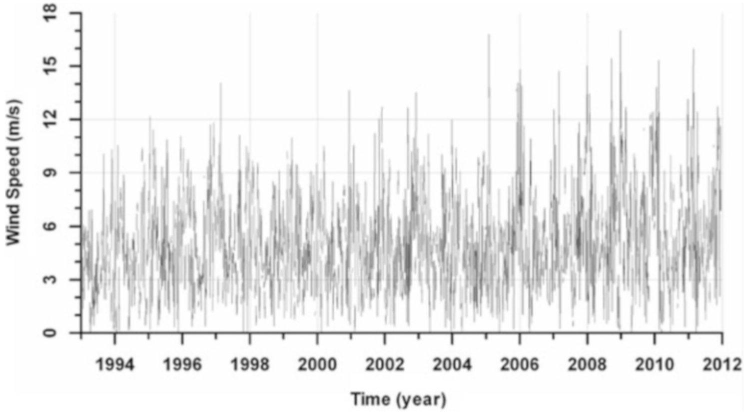

Fig. 15 Seasonal and interannual variability of the wind speed in Kara-Bogaz-Gol Bay at the crossover point of 31/168 tracks (see Fig. 2 for location) in 1993–2011 based on satellite altimetry data

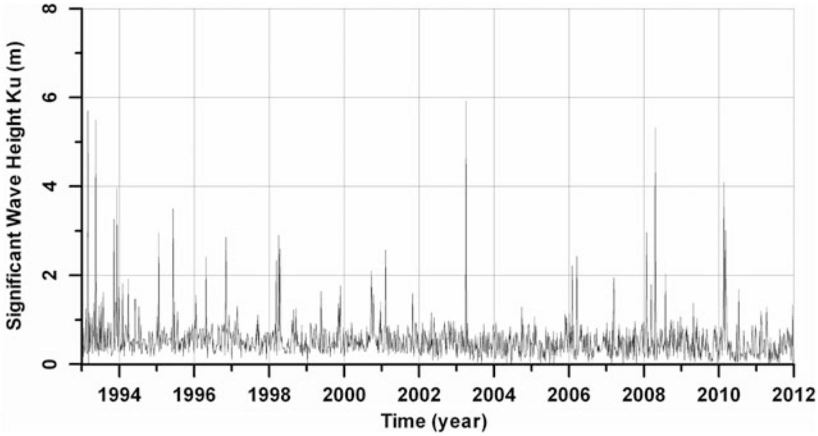

Fig. 16 Seasonal and interannual variability of the wave height in Kara-Bogaz-Gol Bay at the crossover point of 31/168 tracks (see Fig. 2 for location) in 1993–2011 based on satellite altimetry data

the bay at a rate of 1.5–1.6 km^3/year. This amount did not result in the restoration of the hydrological and hydrochemical conditions in 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 [18, 35, 36].

The process of refilling of Kara-Bogaz-Gol Bay coincided with the beginning of the TOPEX/Poseidon satellite altimetry mission, then followed by Jason-1 and Jason-2 missions (Fig. 14a) [7, 8, 18, 35, 36]. The area of the bay is crossed by two ground tracks of the above-mentioned satellites (Fig. 2), and in the

Fig. 17 Satellite view over Kara-Bogaz-Gol Bay on 20 March 2013 (MODIS-Terra, spatial resolution 250 m, true color with adjusted contrast and brightness)

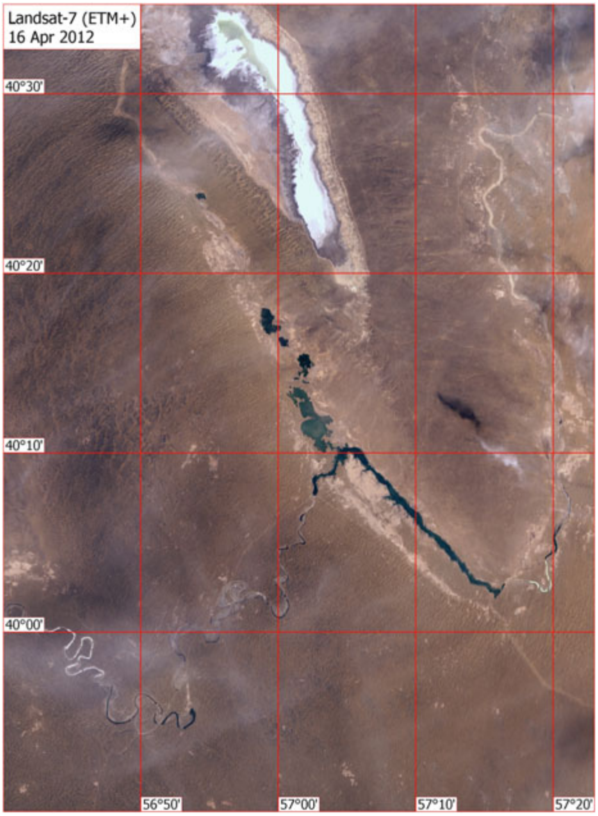

Fig. 18 Satellite image of the southern part of the Karashor Depression and the surrounding collectors acquired by Landsat-7 (ETM+) on 16 April 2012

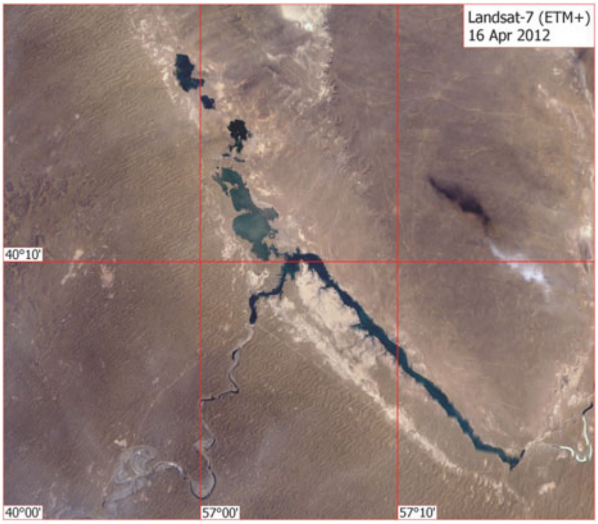

Fig. 19 Satellite image acquired by Landsat-7 (ETM+) on 16 April 2012 – a zoom on the collector southward of the Karashor Depression

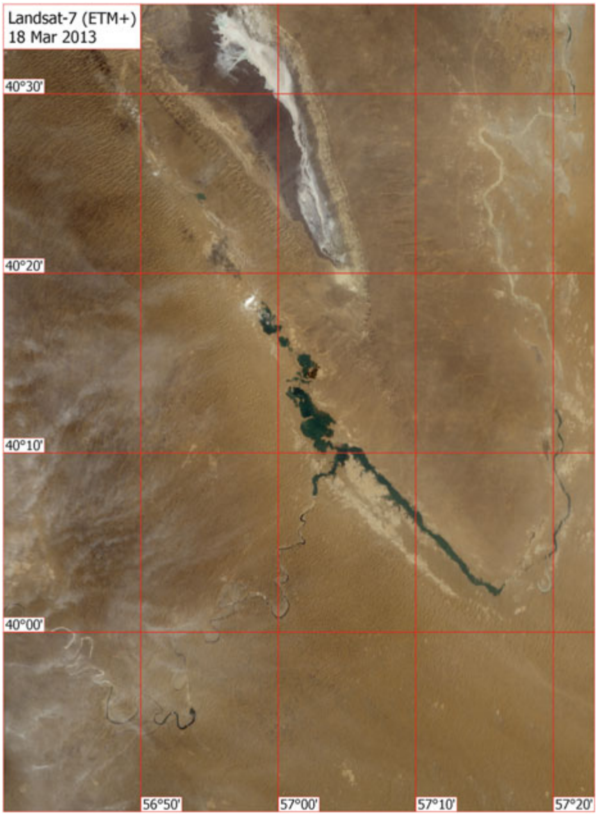

Fig. 20 Satellite image of the southern part of the Karashor Depression and the surrounding collectors acquired by Landsat-7 (ETM+) on 18 March 2013

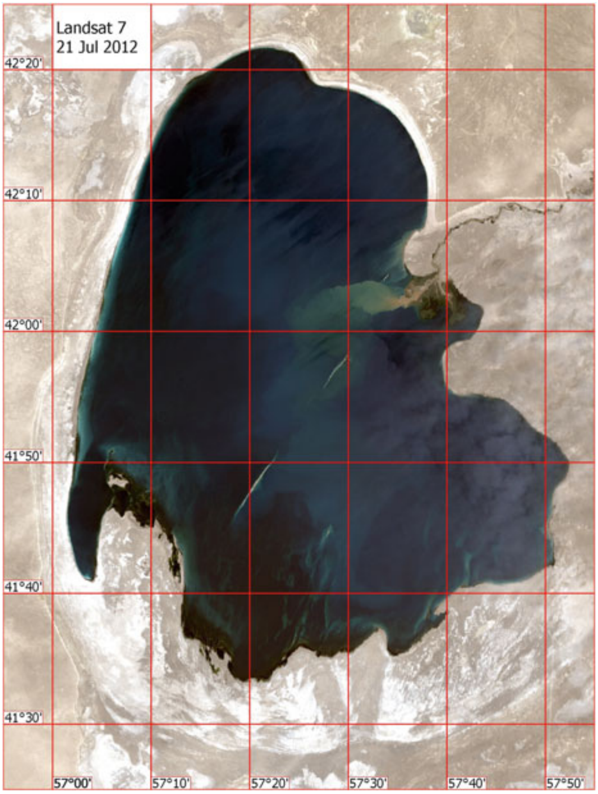

Fig. 21 Sarykamysh Lake on the Landsat-7 image acquired on 21 July 2012 (true color)

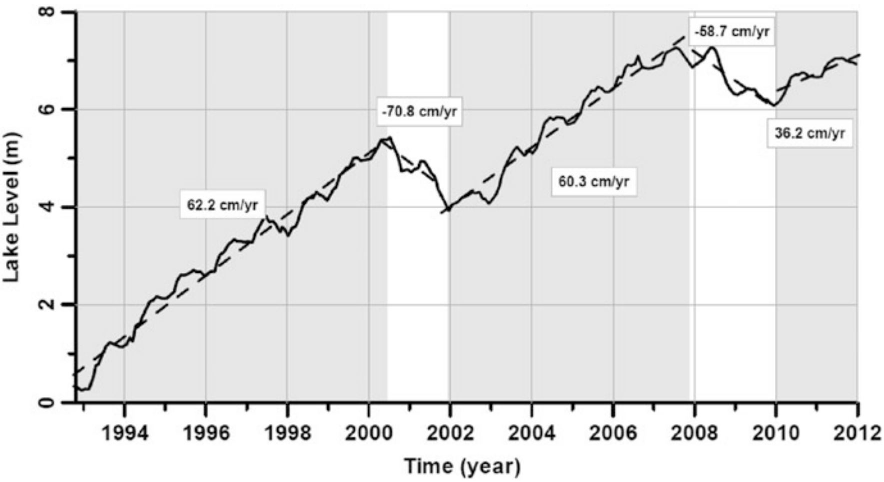

Fig. 22 Relative interannual and seasonal variability of the Sarykamysh Lake water level (m) in September 1992–December 2011. *Grey* areas show time periods when the lake level was rising

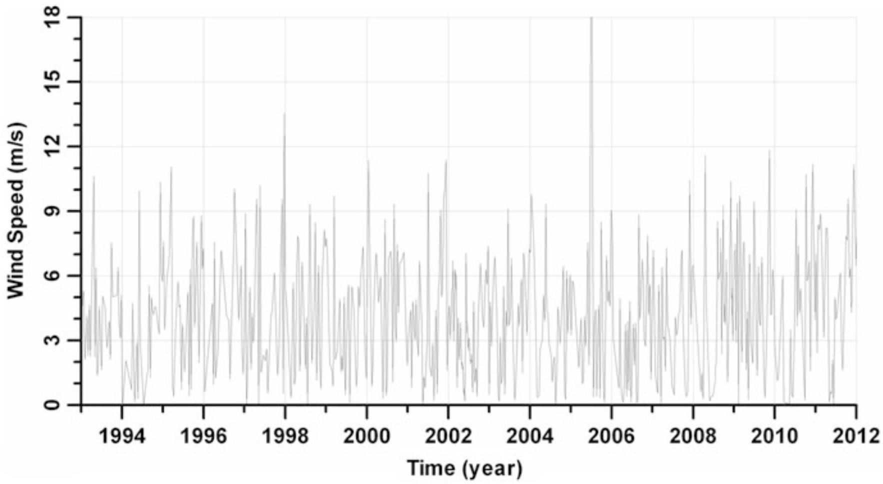

Fig. 23 Seasonal and interannual variability of the wind speed in Sarykamysh Lake in 1993–2011 based on satellite altimetry data

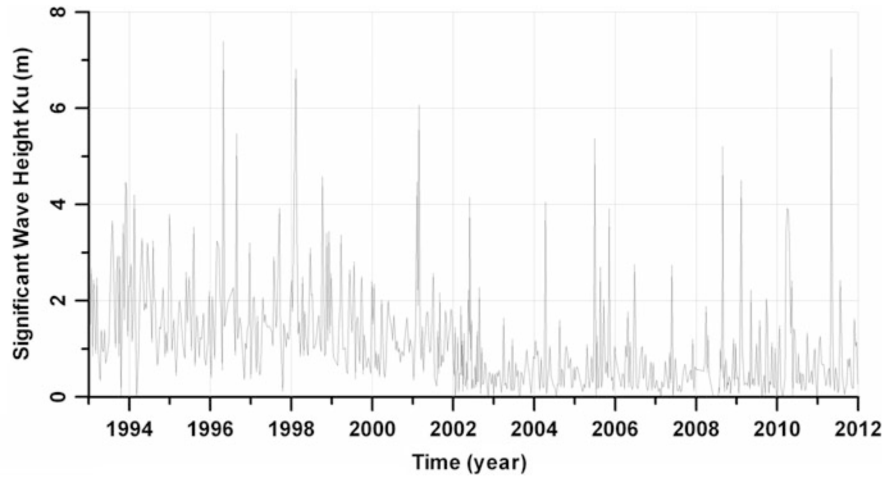

Fig. 24 Seasonal and interannual variability of the wave height in Sarykamysh Lake in 1993–2011 based on satellite altimetry data

crossover point we have water level measurements every 5 days. This allowed to monitor the filling of the bay, which occurred with a rate of 168 cm/year (Fig. 14a) [7, 8, 18, 35, 36]. Then, the level rise stopped in the bay and its variations started to reflect seasonal changes well correlated with the seasonal level changes in the Caspian Sea (Figs. 3 and 14) [18, 35, 36]. Thus, the rate of the level fall (until winter 2001/2002) in the bay was 6.3 vs. 5.9 cm/year in the Caspian Sea. For the time period 2002–2006 the bay level has been rising again with the rate +6.8 vs.

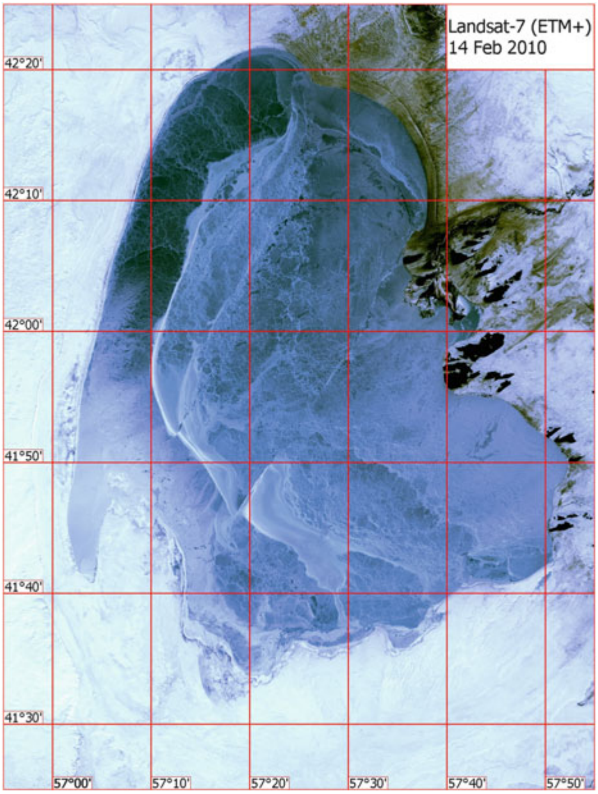

Fig. 25 Sarykamysh Lake covered by ice (*blue color*) on 14 February 2010 (Landsat-7, true color)

9.9 cm/year in the Caspian. Since 2006 till the end of 2009 the level of the bay was falling with a rate of 8.9 vs. 8.5 cm/year in the Caspian, and till the end of 2011 it accelerated to19.5 vs. 15.2 cm/year in the Caspian.

Satellite altimetry also allows to reconstruct values of the wind speed (Fig. 15) and wave height (Fig. 16) at the crossover point of 31/168 tracks right in the center of Kara-Bogaz-Gol Bay. This can be a valuable source of information for the coastal chemistry industry only, because there are no shipping activities and offshore oil/gas platform operations in the bay, as well as there are no tourist and recreation facilities. Figures 15 and 16 show variability of these parameters at the crossover point of 31/168 tracks between January 1993 and December 2011 with a time step of 5 days. It seems that the wind speed is quite reasonably reconstructed, which can be checked by a coastal meteorological station if there is any. The wave height of 0.5–1 m is in general fine, but several picks exceeding 2–3 m seem to be unrealistic.

We are not sure that SST, suspended matter, or chlorophyll concentration fields in Kara-Bogaz-Gol Bay are required for the chemical industry, but it is possible to obtain these parameters on a regular basis (see Figs. 8, 9, 11, and 12).

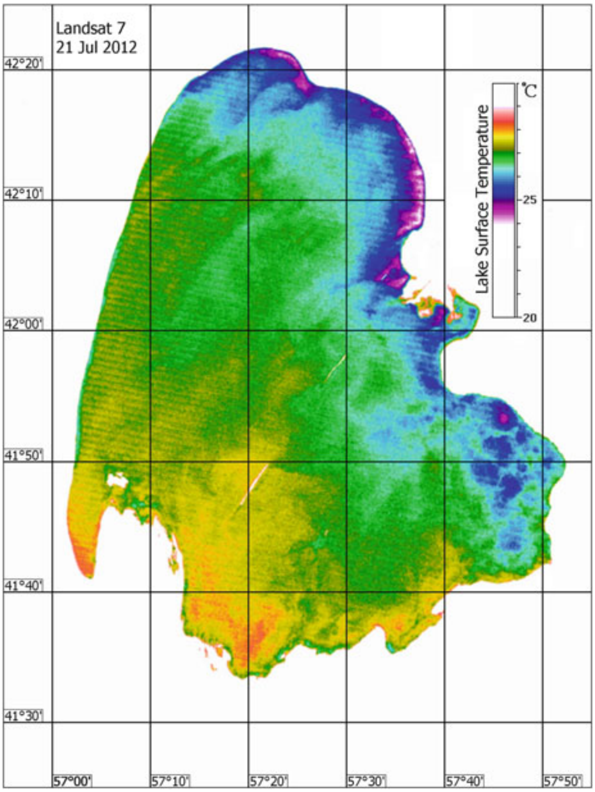

Fig. 26 SST distribution in Sarykamysh Lake on 21 July 2012 (Landsat-7)

For example, Fig. 17 shows peculiarities of suspended matter distribution in the bay on 20 March 2013. Wave-like areas with light colors represent waters with higher concentration of suspended matter.

4 Altyn Asyr Lake

The idea of Altyn Asyr Lake (Golden Age Lake) is to collect drainage waters from irrigated lands of Turkmenistan and forward them to the Karashor Depression by a system of canals. The project is described in details in [37, 38]. The Karashor Depression is located between Kara-Bogaz-Gol Bay of the Caspian Sea on the west and Sarykamysh Lake on the northeast (Figs. 1 and 2). Karashor is a deep dry depression. Its length along the long axis is about 110 km, it is 20 km wide in northwest, and it is gradually narrowing to the southeast. The bottom of the depression is located at a level of -28 m (28 m below the ocean level), which corresponds approximately to the present Caspian Sea level (−27.7 m by the end of 2012).

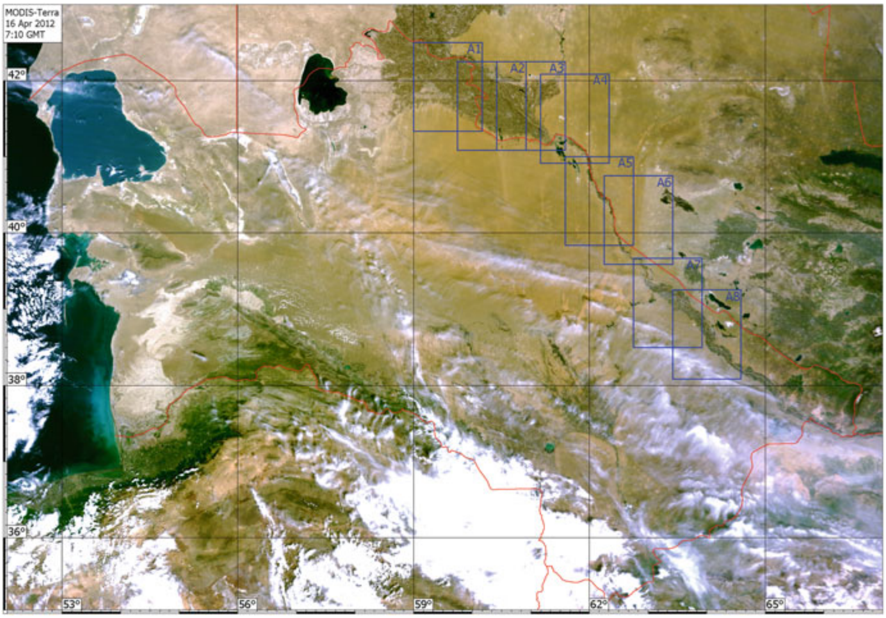

Fig. 27 Satellite view over Turkmenistan and Amu Darya River from MODIS-Terra (250 m resolution) on 16 April 2012. *Red lines* show borders between countries. *Blue rectangular frames* A1–A8 show the geographic location of a series of Landsat-7 (30 m resolution) images focused on the Amu Darya and surrounding areas (Figs. 28, 29, 30, 31, 32, 33, 34, and 35)

According to the Project, Altyn Asyr Lake will be 103 km long, 18.6 km wide, and 69 m deep. It will have a surface of about 1,915.8 km^2 and a volume of 132 km^3 [37, 38]. It is planned that the depression will receive annually 10 km^3 of CDW, thus it will be filled during about 15 years. When accumulation of water is completed, the lake will look similar to the modern western part of the Large Aral Sea [1]. Fortunately, the 107 ground track of Jason-2 satellite crosses the bottom of the northern part of the Karashor Depression (Fig. 2), and in the future it will be possible to follow water filling of the lake basing on satellite altimetry data as it has been done since 1993 for the Kara-Bogaz-Gol Bay case study (see Fig. 14).

On 15 July 2009 filling of collectors by water began in the vicinity of the Karashor Depression. Since that time, P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences (Moscow, Russia), has combined efforts with Geophysical Center, Russian Academy of Sciences (Moscow, Russia), and Marine Hydrophysical Institute (Sevastopol, Ukraine) in order to monitor the Karashor Depression and surrounding collectors and canals by means of satellite remote sensing. For this task we have used optical scanners of medium spatial resolution (250 m) MODIS-Terra and -Aqua, as well as of high resolution (30 m) Landsat-5 (TM) and Landsat-7 (ETM+) [15–19, 21, 22, 38]. Satellite images of medium resolution are daily available and that of high resolution – about once a month, which is sufficient for the observed rate of construction.

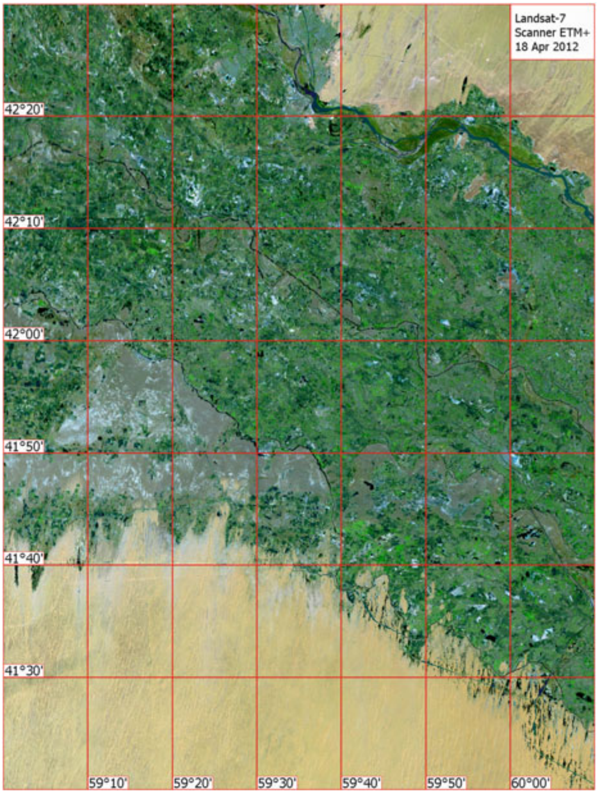

Fig. 28 High resolution satellite view on Amu Darya River and surrounding areas (frame A1, see Fig. 27 for location) from Landsat-7 (30 m resolution) on 18 April 2012

In the above-mentioned papers, as well as in this book, the chronology of the construction of the collectors in the vicinity of Altyn Asyr Lake is followed by means of satellite imagery. In this chapter we will not repeat this chronology, but will show recent satellite images of the area close to the Karashor Depression. Figures 18 and 19 show the state of water filling in the canals leading to the Karashor Depression on 16 April 2012. Due to the intensive deposition of salt (white color) and changes in the landscape we clearly detect the ancient meandering riverbed of Uzboy River as well as a system of canals leading to the Karashor Depression. The bottom of the southern part of the Karashor Depression is covered by salt (white area). In the southeastern corner of the satellite image we can see the Transturkmen (Main) collector which is dry. In the northwestern corner of the frame we can observe an 18-km section of the collector which joins the northernmost flooded area (dark colors) with the Karashor Depression. Almost 1 year later, on 18 March 2013, we did not detect significant changes in the working area close to the Karashor Depression as well as canals remain filled by the same amount of water (Fig. 20).

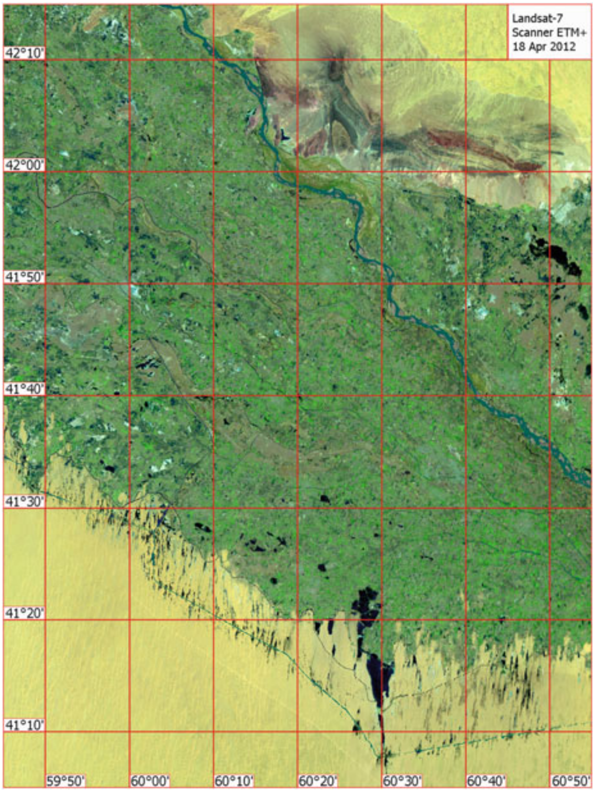

Fig. 29 High resolution satellite view on Amu Darya River and surrounding areas (frame A2, see Fig. 27 for location) from Landsat-7 (30 m resolution) on 18 April 2012

High resolution Landsat optical imagery (see a zoom in Fig. 19) showed its effectiveness in the monitoring of the Altyn Asyr Lake construction. Many details, including the wave-like structure of sandy dunes in the desert, canals, roads, salt deposits, small-scale features of the landscape, are clearly visible in the satellite images.

5 Sarykamysh Lake

Sarykamysh Lake was formed in 1971 as a result of flooding of a set of small Sarykamysh lakes located at the bottom of the natural Sarykamysh Depression located 200 km southwestward from the Aral Sea (Figs. 1 and 2). Its bottom lies at the −38 m absolute level (below the ocean level). This depression periodically was filled by the Amu Darya waters via the Daryalyk riverbed. Now Sarykamysh Lake is a large drainage water body, which has been used as a discharge collector of salty irrigation water from the fields (Fig. 21). Currently, the lake covers an area of about 3,900 km^2 [18]. Salinity of the lake waters has been continuously increasing: from 3 to 4 g/L in the early 1960s to 12–14 g/L in 1987 [9, 39, 40]. The maximum

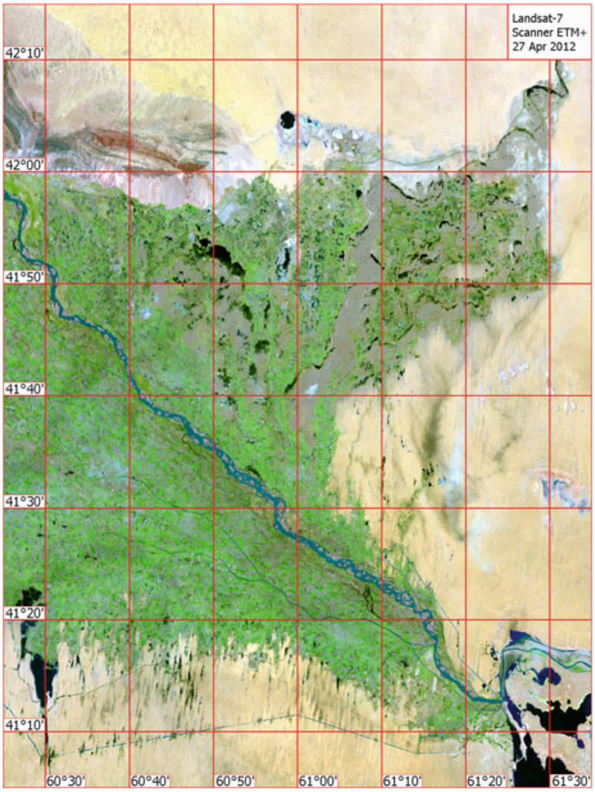

Fig. 30 High resolution satellite view on Amu Darya River and surrounding areas (frame A3, see Fig. 27 for location) from Landsat 7 (30 m resolution) on 27 April 2012

depth is about 40 m. Water of Sarykamysh Lake is salinized and contains biogenic matters, admixtures of pesticides, defoliants, and fertilizers, nevertheless there is a local fishery activity in the lake. Today Sarykamysh Lake is shared between Turkmenistan (the southern part) and Uzbekistan (the northwestern part).

Again, the same 107 ground track of TOPEX/Poseidon, Jason-1, and Jason-2 satellites crosses Sarykamysh Lake (Fig. 2). Since September 1992, 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 62 cm/year as observed by the TOPEX/Poseidon and further by the Jason-1/-2 altimetry missions (Fig. 22). Then, during 1.5 years its level dropped by 1 m with a rate of about 71 cm/year, and then since 2002 its level was rising again with about the same rate (60 cm/year) till the end of 2007. During these 6 years the lake added about 3 m to its level. From the beginning of 2008 till the end of 2009 the level again dropped by 1 m with a rate of 59 cm/year. From the beginning of 2010 it has been rising again with a rate of 36 cm/year, and by the end of 2011 it almost reached the same level as it was in summer 2007 and 2008.

It seems that the wind speed (Fig. 23) is quite reasonably reconstructed from the altimetry data, which can be checked by a coastal meteorological station if

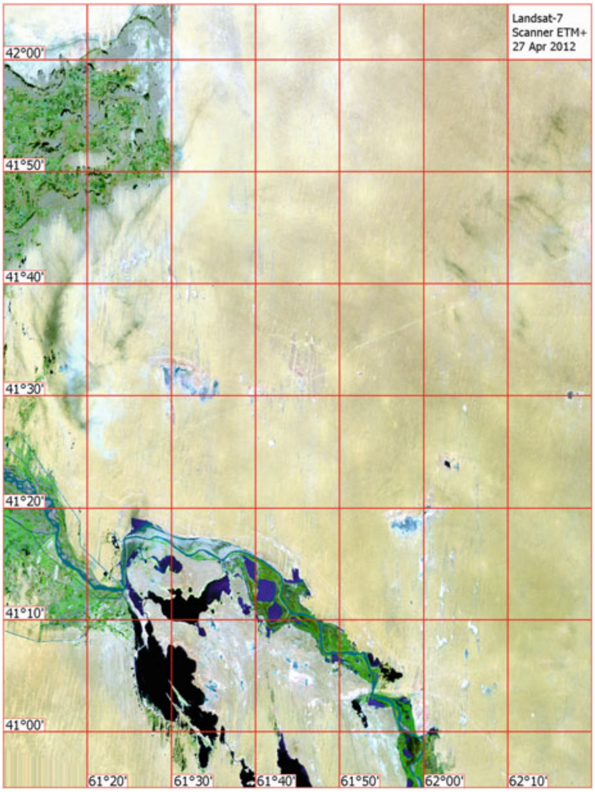

Fig. 31 High resolution satellite view on Amu Darya River and surrounding areas (frame A4, see Fig. 27 for location) from Landsat 7 (30 m resolution) on 27 April 2012

there is any. As concerns the wave height, there are too many picks exceeding 2–3 m, which are unrealistic for such a small lake (Fig. 24). Moreover, a notable shift of a signal to more logical lower values of the wave height has been observed since 2002. Less credible convertation of satellite altimetry data into the wave height is explained by a small size of the lake with known interference of the land with the signal.

High spatial resolution of Landsat imagery (30 m) (Fig. 21) allows to follow changes in the shape of the lake and its morphometric characteristics in details and to calculate with high accuracy the lake surface [18]. For example, in 2003 it was 3,782 km^2, in 2005 – 3,880 km^2, in 2007 – 3,956 km^2, and in 2009 – 3,874 km^2. The same optical images can very well show suspended matter distribution in the lake (Fig. 21), as well as the ice cover or distribution of floating ice in the lake (Fig. 25). The fine structure of the ice cover is visible thanks to high spatial resolution of Landsat imagery. Finally, Landsat sensors allow to measure SST in the lake, which is shown in Fig. 26. This SST map reveals a notable upwelling event along the northeastern coastline due to northeasterly winds. The upwelled water (blue colors) along the coast has SST, which is about 3°C less than waters in the opposite side of the lake (about 27.5°C).

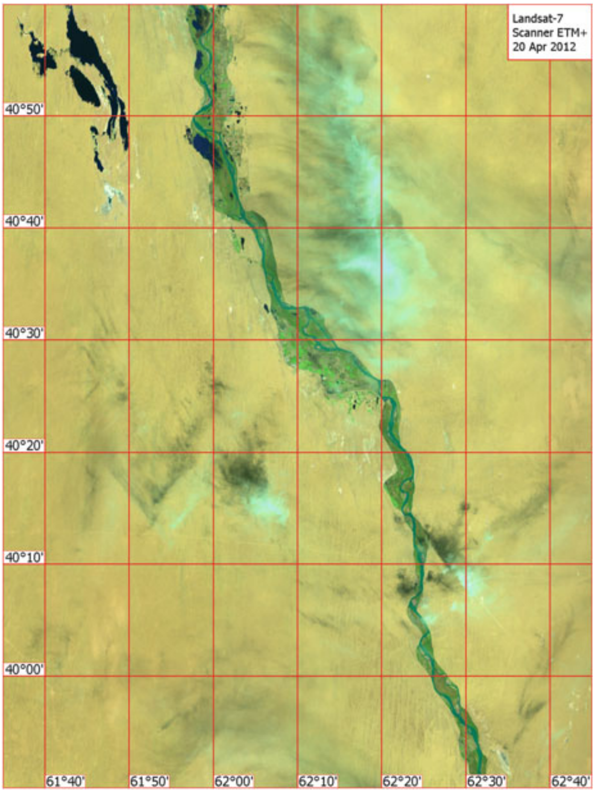

Fig. 32 High resolution satellite view on Amu Darya River and surrounding areas (frame A5, see Fig. 27 for location) from Landsat-7 (30 m resolution) on 20 April 2012

6 Amu Darya River

The Amu Darya is the largest river in Central Asia and it is formed as a result of confluence of Pyandzh (catchment area of 114,000 km^2) and Vakhsh (39,000 km^2) Rivers. The Amu Darya River length is about 1,450 km from the confluence of these rivers to the Aral Sea. The total catchment area is estimated as 465,000 km^2, the area of the effective drainage basin is 300,000 km^2 [41]. The river flows from the southeast to northwest partially in Turkmenistan, along the border with Uzbekistan, and in Uzbekistan before reaching the Aral Sea via a vast delta (Fig. 27).

Downstream of Atamurat town in the southeastern part of Turkmenistan (former name – Kerki), the Amu Darya water is consumed due to irrigation of areas, lost by evaporation in flooded alluvial plains, and transpiration by hydrofilous plant vegetation. Hydrometric works on Amu Darya River have been conducted since 1870s, but before the first quarter of the twentieth century the hydrological observations had not been systematic. The longest series of observations is available from the gauging stations of Kerki (1910–1920, 1925–1937, 1952–2006) and Chatly (new name – Samanbay, Uzbekistan) (1913–1917, 1931–1973) [41].

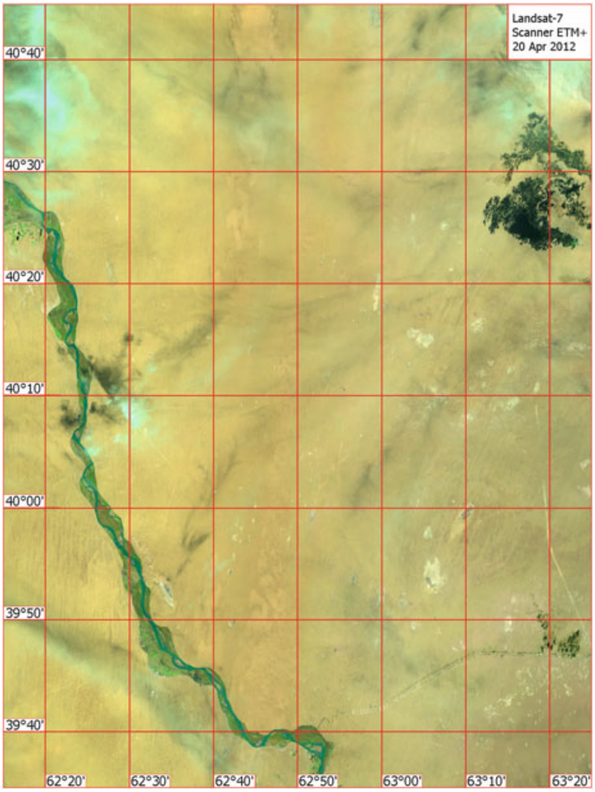

Fig. 33 High resolution satellite view on Amu Darya River and surrounding areas (frame A6, see Fig. 27 for location) from Landsat-7 (30 m resolution) on 20 April 2012

The range of annual river flow variation makes up to 51 km^3 (from 54 km^3 in 1986 to 105 km^3 in 1969). The 5-year period (1961–1965) was very dry with a mean volume of 62.2 km^3/year, i.e., 10 % less than long-time average, very abounding in water was the 8-year period from 1952 till 1959 with a mean annual volume of 74 km^3. Beginning from 1956 a considerable volume of the Amu Darya water is transferred by the Karakum Canal to arid regions of Turkmenistan. In last years the water delivery in the canal amounts to 10–11 km^3/year. According to the Basin Water Organization “Amudarya,” in the 2001–2007 period, the total volume of water withdrawal from the Amu Darya varied from 26 to 44 km^3/year [41].

High resolution satellite imagery allows to monitor the areas around Amu Darya River, to control desertification processes, to calculate the normalized difference vegetation index (NDVI) and the normalized difference water index (NDWI) for further seasonal and interannual analysis and estimates of the state of vegetation and water capacity in the Amu Darya River area. This information is of vital importance for agriculture and water management in Turkmenistan and Uzbekistan. Figures 28, 29, 30, 31, 32, 33, 34, and 35 show the satellite image frames A1–A8, focused on Amu Darya River, which cover almost the whole length of the river in

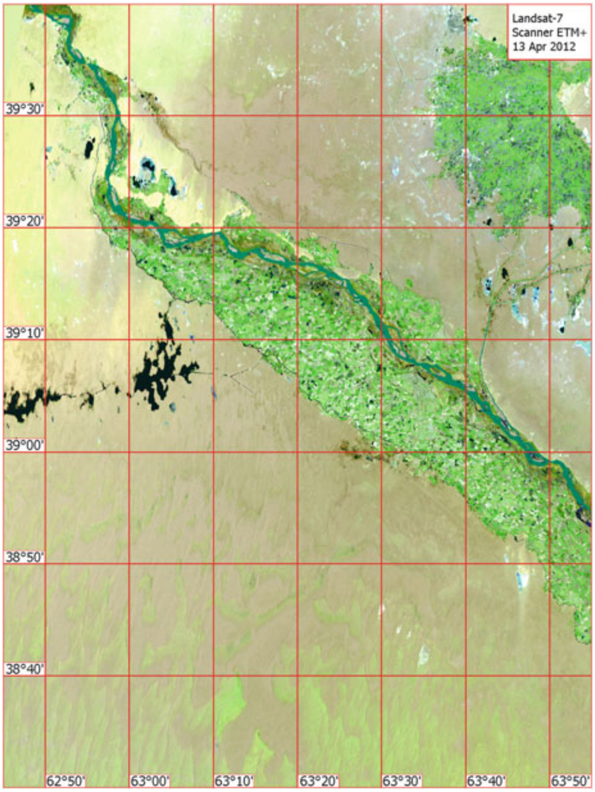

Fig. 34 High resolution satellite view on Amu Darya River and surrounding areas (frame A7, see Fig. 27 for location) from Landsat-7 (30 m resolution) on 13 April 2012

the eastern part of Turkmenistan at the border with Uzbekistan (Fig. 27). The images were acquired from Landsat 7 ETM+ scanner during 2 weeks in April 2012. Amu Darya River, a "green belt" of a different width along the river, a system of canals, lakes, and water reservoirs are clearly visible on the high resolution satellite imagery.

7 Conclusions

During the last two decades 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 monitoring of the Southeastern Caspian Sea, Kara-Bogaz-Gol Bay, Sarykamysh

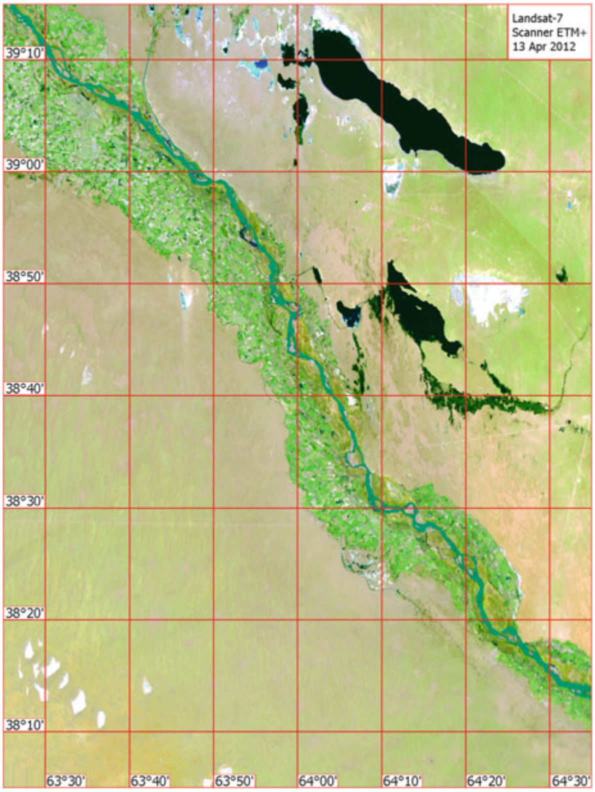

Fig. 35 High resolution satellite view on Amu Darya River and surrounding areas (frame A8, see Fig. 27 for location) from Landsat-7 (30 m resolution) on 13 April 2012

Lake, and artificial Altyn Asyr Lake, which since July 2009 has been under construction in Turkmenistan. It can be applied also to monitoring of 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 Turkmenistan and other countries located in arid zones especially now when significant changes in regional climate are observed.

In this chapter we demonstrated modern capabilities of satellite remote sensing technologies in environmental monitoring and showed examples of the use of satellite data and imagery for the analysis of morphometric characteristics, sea/lake level, temperature, water quality, wind speed, wave height in the main water bodies in Turkmenistan. Special attention was paid to the drainage lakes Sarykamysh and Altyn Asyr, which we started to monitor since the beginning of its construction in July 2009. High resolution satellite imagery is very effective in monitoring of the Amu Darya River area.

Further sea level, wind and waves, SST, suspended matter and chlorophyll concentration, and oil pollution monitoring at various points of the Caspian Sea and Kara-Bogaz-Gol Bay with the use of satellite remote sensing and other observations should allow us to follow the ecological state and future changes which are extremely important for designing, constructing, and operating industrial installations and infrastructure in the sea and on its coasts, and first of all for providing ecological security for economic activities in the Caspian Sea region.

In June 2011, we proposed to organize in Ashkhabad the National Center for Satellite Monitoring and Regional Climate Change in Turkmenistan with the support of the European Space Agency (ESA) and the Committee on Space Research (COSPAR) [17]. This Center could effectively monitor the ecological state, oil pollution, and sea level of the Caspian Sea waters of Turkmenistan, especially in such sensitive areas as the National tourist zone “Avaza,” as well as in the areas of offshore oil and gas production, and in the areas of new offshore projects, such as the Trans-Caspian gas pipeline. The Center could monitor the state of Sarykamysh Lake and the filling of the new Altyn Asyr drainage lake, Amu Darya River, as well as other water bodies and land areas. The regional climate change in Turkmenistan and Central Asia should be an important task for the research in the Center. Satellite monitoring and climate research performed by the Center could provide very useful information for agriculture, water management, and science in Turkmenistan.

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