

# Dynamics of Water Bodies of the North Caucasus by Remote Sensing Data in 2015–2017



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**Abstract** Climate and weather changes in recent years, along with other factors, have significantly affected the water regime of the water management complex located in the Kuban River basin in the North Caucasus. Such changes were especially significant in 2015–2016 in influencing the state of the water balance of reservoirs, their area, water volume, and other characteristics. The main components of the complex are Fedorovsky and Belorechensky retaining waterworks, Tikhovsky water-separating waterworks, and four large reservoirs: Krasnodar, Shapsugskoye, Kryukovskoye, and Varnavinskoye, designed to supply irrigation (primarily rice) and fish-reclamation systems, flood control, and prevention of catastrophic floods.

**Keywords** Krasnodar reservoir, Kryukovskoye reservoir, Kuzhorskoye reservoir, Maykop reservoir, Oktyabrskoye (Takhtamukayskoye) reservoir, Remote sensing,

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Republic of Adygea, Shapsugkoye reservoir, Shendzhiyskoye and Cheytskoye reservoirs, Varnavinskoye reservoir

## 1 Introduction

Water reservoirs, lakes, and ponds of the Krasnodar Territory and the Republic of Adygea have accumulated water reserves of about 2.5 billion m<sup>3</sup>. The main water basin of the Krasnodar Territory and the Republic of Adygea is the Kuban River. The total usable volume regulated by 148 reservoirs is 2.7 km<sup>3</sup>, a significant proportion of which (2.2 km<sup>3</sup>) falls on the Krasnodar Reservoir, located in the middle reaches of the river. The main purpose of the reservoir is to provide irrigation for more than 200 thousand ha of agricultural land, to protect about 600 thousand ha of farmland from the lower reaches of the Kuban from floods, and to provide fish spawning and transport releases to the estuaries of the Kuban and Protoka. Kryukovskoye (0.1 km<sup>3</sup>), Varnavinskoye (0.02 km<sup>3</sup>), and Shapsugskoye (0.13 km<sup>3</sup>) reservoirs that regulate the flow of the Trans-Kuban rivers are used to irrigate land and protect agricultural land from floods. The purpose of other smaller reservoirs (Fig. 1) is irrigation and fish farming [1].

Adygea is located in the central part of the Northwest Caucasus, in the basins of the Kuban, Laba, and Belaya rivers. The territory of the republic in the north and northeast is limited by the Kuban River and its tributary Laba River, in the south by the Main Caucasian Range, and in the southeast and southwest the border which runs through a broken line, reflecting the features of the settlement of Circassians in the river basins of Chekhvak, Fars, Belaya, Pshish, Psekups, Afips, and Kurdzhips.

The length of the republic's borders is more than 900 km; one third is water: in the Kuban, Krasnodar Reservoir, Labe, and Belaya rivers.

In addition to Krasnodar and Shapsugskoye, other reservoirs of Adygea – Takhtamukayskoye, Shendzhiyskoye, Maykopsky, Cheytskoye, and Kuzhorskoye – have a small area.

## 2 Water Reservoirs in the Republic of Adygea

The Krasnodar Reservoir is located in the middle reaches of the Kuban River at 248 km from the mouth, directly above the city of Krasnodar, and controls more than 95% of the total flow of the basin. The reservoir bowl is located on the territory of two constituent entities of the Russian Federation: the Republic of Adygea (87% of the area) and the Krasnodar Territory (13% of the area) and extends on the floodplain lands of the Kuban River from the village of Voronezh to the City of Krasnodar. The Krasnodar Reservoir – the largest artificial reservoir in the North Caucasus – was built in 1973 and put into design operation mode in 1975. As of 2017, the reservoir

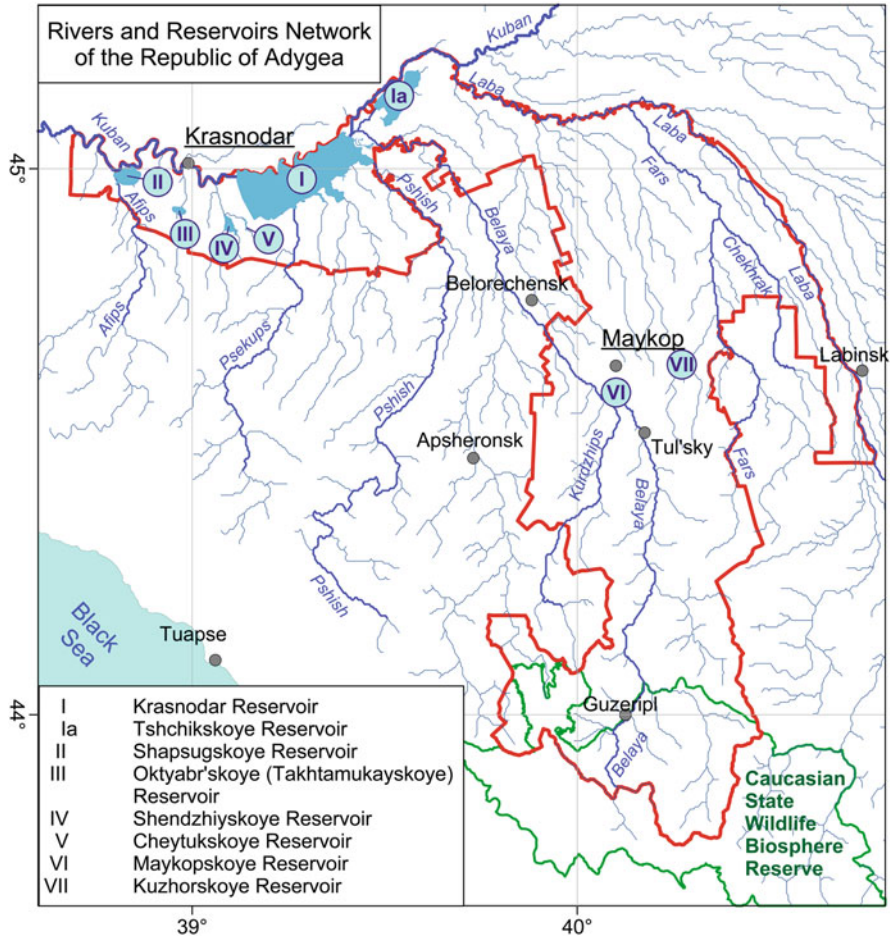


Fig. 1 A map of main rivers and water reservoirs in the Republic of Adygea

has been in operation for 42 years. The mirror area of the reservoir is 397.8 km<sup>2</sup>, the average depth is 5 m, and the maximum is up to 18 m at the dam. Other characteristics are given in Table 1. The Krasnodar Reservoir controls 96% of the annual flow of the Kuban River and is intended for cutting peak floods in order to eliminate flood threats in the territory with a total area of 600 thousand hectares with a population of about 300 thousand people; provision of municipal, agricultural, and industrial water supply; water supply for rice irrigation systems; providing water releases at the mouth of the Kuban River and its right arm of the channel for spawning migrations of sturgeons, fishes, etc.; supply of fresh water to fish farms with an area of about 150 thousand hectares in the Azov estuaries; and improving the conditions of navigation on the Kuban River and the channel on the Protoka for over 400 km [2].

**Table 1** Main characteristics of the Krasnodar Reservoir

Minimum pool level or dead storage level (DSL)		Normal pool level, NPU		Maximum pool level or highest reservoir level (HRL)	
Level, m	Volume, million m <sup>3</sup>	Level, m, abs. (H <sub>NPU</sub> )	Volume, million m <sup>3</sup> (V <sub>NPU</sub> )	Level, m	Volume, million m <sup>3</sup>
25.85	192	32.75 (33,65 in initial project)	1,798 (2,149 in initial project)	35.23	2,794

Over the years of operation of the Krasnodar Reservoir, as a result of channel processes, there has been a constant decrease in the water level in the Kuban River; therefore, there is a danger of violation of the regime in the downstream.

The Krasnodar Reservoir, being an integral part of the Kuban water management complex, provides regulation of river flow for its optimal use in the national economy. During the operation of the reservoir, significant changes occurred in the bowl of the former Tshchikskoye Reservoir – it turned out to be practically isolated from the western part of the Krasnodar Reservoir and in the estuary of the Belaya River formed a forested watershed, blocking the river from the reservoir. The siltation of the bowl of the former Tshchikskoye Reservoir is much more active than in the rest of the area; the thickness of silt deposits increased up to 2.0–2.5 m here.

The filling of the reservoir begins approximately from mid-November and lasts until May to June, after which it is discharged and the water level in the reservoir decreases. Minimum levels are observed in September to January. The discharge flow to the downstream is determined by the requests of water consumers, the availability of water in the reservoir, the flow of water along the rivers flowing into the reservoir, lateral inflow below the reservoir, and the channel capacity below the reservoir. The Krasnodar Reservoir changed the hydrological regime of the lower Kuban by regulating both liquid and solid runoff, which accelerated the process of deep erosion. A noticeable effect of the reservoir on deep erosion and a decrease in bottom marks in the river are observed over a 50 km stretch (from the dam to Afipsip aul).

The Varnavinskoye and Kryukovskoye reservoirs, located in the left-bank flood-plain of the Kuban River, are mainly used for irrigation and cutting of high flood peaks. Together with the Krasnodar Reservoir and the Kuban and Protoka Rivers deboning system, they are part of a single water management complex for flood protection in the Lower Kuban.

The normal pool level (NPU) of the Varnavinskoye Reservoir is 9.5 m (abs., Baltic height system BHS-77). The total volume of the reservoir at the NPU is 160 million m<sup>3</sup>, the useful volume is 40 million m<sup>3</sup>, the water mirror area at the NPU is 45.2 km<sup>2</sup>, the length of the reservoir is 11 km, the width is 4.23 km, and the prevailing depth is 1.5–2 m. The catchment area is 984 km<sup>2</sup>. The average long-term runoff is 366 million m<sup>3</sup>. The Adagum and Abin rivers flow into the Varnavinskoye Reservoir, and the Kuafo, Shibs, and Shibik rivers are their tributaries. By 2011, the

siltation capacity of the reservoir bed reached 1 m in the confluence zone of the Abin and Adagum rivers. The Varnavinskoye Reservoir, if necessary, receives the waste waters of the Kryukovskoye Reservoir, which does not have an autonomous discharge. For the functioning of the reservoir in the required mode, it is necessary to carry out work to remove sediment.

Kryukovskoye Reservoir was built in 1967–1972 on the site of flooded swamps, impassable shrubs, the so-called waste land, located on the former Kryukovsky estuary, in the Seversky District of the Krasnodar Territory, 17 km north of the village of Severskaya. It is used for irrigation and cutting of high flood peaks, as well as for water supply to the Kryukovsky irrigation system and fisheries, included in the single water management for complex flood protection of the Lower Kuban, and formed by water-damming dams on the site of the Kryukovsky estuary and the surrounding land. The total length of the dam surrounding the reservoir is 23.37 km. The reservoir was created to regulate the floods of several rivers – the Ile, Peschanka, Bugai, Akhtyr, Eybza, Bugundyr, and Sukhoi Khabl, which is a continuation of the Nagorny Canal with an inflow volume of 18.5 thousand m<sup>3</sup>. The main volume of water discharged from the reservoir is carried out along the Kryukovsky discharge channel with a length of 21.5 km and a bottom width of 6–30 m in the amount of 418 thousand m<sup>3</sup>. The NPU is 14.4 m. The total reservoir volume at the NPU is 111 million m<sup>3</sup>, the useful one is 100.4 million m<sup>3</sup>, the maximum is 203 million m<sup>3</sup>, the water mirror area at the NPU is 40.2 km<sup>2</sup>, and the length of the reservoir is about 8 km; width, 5.7 km; average depth, 3.2 m; and maximum, 3.9 m. The reservoir consists of several objects: spillway, water intake, fish protection, forest shelter, waste, and feeding structure. The reservoir includes pumping stations and several dams – western, northern, and southeastern. The water in the reservoir belongs to the class of moderately polluted. In water in large quantities, there is a snag.

In addition to those listed in the Krasnodar Territory, the Neberdzhayev Reservoir, the reservoir of the Belorechensk Hydroelectric Power Station, and the Ganzhinsk Reservoir are operated, but a description of their condition remains outside this article.

### 3 Remote Sensing of Water Bodies

The main problem in ensuring the safety of hydraulic structures of the Krasnodar Reservoir is the need for their reconstruction in order to comply with current regulatory documents, including with the aim of raising the capital class to the first. Currently, the hydraulic structures of the Krasnodar Reservoir have a normal level of safety. Kryukovskoye and Varnavinskoye reservoirs are in good condition but have a reduced level of safety [2].

The most significant and informative ways of providing data with continuous coverage of vast areas of reservoirs and river catchments in the face of a shortage of network field observations of the state of their waters include the use of satellite imagery, which are designed to identify actual areas of water bodies and the nature of

the spread of river sediment over the reservoir, depending from the regime and volume of solid runoff. Such information, combined with the results of observations for different dates of field surveys, allows us to estimate the extent and speed of siltation of the reservoir. The information obtained is important for solving various water management problems, in particular, obtaining a prognostic assessment of the capacity of a reservoir during its intensive siltation.

Analysis of satellite images of the Krasnodar, Kryukovskoye, Varnavinskoye, and Shapsugkoye reservoirs allowed us to show their condition at a NPU (32.75 m abs.), as well as with a significant decrease in the level in emergency situations at water bodies. For example, at the beginning of 2015, the water level in the Krasnodar Reservoir was 28.69 m, and the volume ( $V$ ) was 648 million  $m^3$ . In accordance with the Rules for the Use of Water Resources, the Krasnodar Reservoir at the beginning of the year usually operates in the filling mode. With heavy rainfall on 12 January 2015, there was a rise in water level and river spills in the Abinsky and western regions of the Krasnodar Territory, resulting in partial flooding of some territories. There were no casualties or destruction. In Fig. 2 shows Landsat-8 OLI data from 15 January to 30 October 2015.

### 3.1 *Krasnodar Reservoir*

After heavy rainfall, the influx of water into the Krasnodar Reservoir, part of which was covered with ice, increased from 209, 394, 546, to 800  $m^3/s$  from January 12 to 15, discharge remained within 101–102  $m^3/s$ , and the water level rose slightly from 29.63 to 30.04 m abs. (NPU = 32.75 m abs.). The volume of water in the reservoir varied from 855, 893, to 953 million  $m^3$ . Emergencies at water bodies were not observed. In Fig. 2 (a) according to Landsat-8 OLI data dated January 15, in the eastern part of the image on land there is snow cover; the Krasnodar Reservoir is partially covered with ice.

By the end of March, the water level in the reservoir was 31.98 m, and the volume was 1,512 million  $m^3$ . The intermediate values from January 15 and March 20 (Table 2) correspond to the Landsat-8 OLI satellite data shown in Fig. 2a, b.

Table 2 shows the characteristics of the Krasnodar Reservoir in 2015, corresponding to satellite images in Fig. 2. Note that in the high-resolution image dated March 25 (inflow of 156  $m^3/s$ , discharge of 110  $m^3/s$ , water level is 31.91 m abs., and the volume of water in the reservoir is 1,489 million  $m^3$ ) at a level 74 cm lower than the NPU, the gulf near the village of Starokorsunskaya is still connected by a narrow strait with the Krasnodar Reservoir (see Fig. 3). The color of the water of the Belaya River and the canals differs from the water of the Kuban River, the color of which at a distance of about 1 km returns to the original. In the southern part of the image, the color of Belaya mineral suspension characterizes the growing influx of water into the reservoir.

In early April, the water level in the Krasnodar Reservoir was 31.99 m ( $V = 1,517$  million  $m^3$ ), snow melting in the mountains began, and the average inflow increased.





(a)



(b)



(c)

**Fig. 2** The dynamics of the coasts of the Krasnodar, Shapsugkoye, and Kryukovskoye reservoirs according to OLI Landsat 8 in 2015: (a) 15 January 2015, (b) 20 March 2015, (c) 23 May 2015, (d) 27 August 2015, (e) 30 October 2015



(d)



(c)

**Fig. 2** (continued)**Table 2** Water management situation in the zone of the Krasnodar Reservoir in 2015 (NPU = 32.75 m, abs.)

Krasnodar Reservoir	15.01	20.03	23.05	27.08	28.09	30.10
Water inflow, m <sup>3</sup> /s	800	105	506	44	61	426
Reset, m <sup>3</sup> /s	103	102	617	425	80	123
Water level, m, abs.	30.04	31.85	32.12	27.77	25.97	26.99
Water volume, million m <sup>3</sup>	953	1,468	1,563	476	206	347

Subsequently, the average discharge was lower than the inflow, which led to an increase in the reservoir capacity. Due to heavy rainfall on the rivers of the Kuban River basin, in the southeastern part of the Krasnodar Territory, floods occurred in May, which were accompanied by an increase in the average inflow into the reservoir. This contributed to raising the level in the upper pool of the reservoir above the level of NPU. Table 2 shows the level (32.12 m) and the volume of water in the reservoir (1,563 million m<sup>3</sup>) on 23 May 2015, and the corresponding satellite Landsat-8 OLI is shown in Fig. 2c). Due to the lack of precipitation in the





**Fig. 3** The northern part of the Krasnodar Reservoir on 25 March 2015: a channel (1) between Belaya River (2) and Kuban River (3), a bay near the village of Starokorsunskaya (4), remote deltas of the Kuban (5) and Belaya (6) rivers. (Image2016 © DigitalGlobe)

summer on the rivers of the Kuban River basin, the average discharge was higher than the inflow, which led to a decrease in the volume of water in the reservoir.

By the end of September, according to the data of the Kuban Basin Water Administration (BWA), one of the lowest water levels in the reservoir in recent years was 25.93 m ( $V = 199$  million  $m^3$ ), and on September 28, a level close to the minimum was 25.97 m (Table 2), which is 6.90 m lower than the oil treatment facilities and only 0.12 m higher than the dead volume level (DSL) of 25.85 m. In Fig. 4 shows a Landsat-8 OLI photograph illustrating the advancement of the boundary of the fixed channel ramparts of the Kuban River, which at a level close to the NPU forms a small coastal bay (region 4 in Fig. 3). However, as the level near the village decreases, the Starokorsunsky Bay completely separates from the reservoir, and the area of the isolated basin decreases. The Kuban remote delta continues to move westward. Only the Pshish River, despite the siltation of the estuary, restored the channel and, like the Kuban, carries water to the reservoir. The remote delta of the Belaya River, at values close to the NPU, which usually dumped water into the reservoir (Fig. 2), no longer reaches it.

Short-period changes in the level and volume of water in the Krasnodar Reservoir were analyzed for the period 2014–2017. Comparison of satellite images of the coastal zone of the Krasnodar Reservoir (plot 4 in Fig. 3) with photographs of the



**Fig. 4** Dynamics of the coastal zone of the Krasnodar Reservoir according to OLI Landsat 8 28 September 2015



**Fig. 5** The coastal region of the Krasnodar Reservoir in the area of the village of Starokorsunskaya on 7 July 2016, at the level of 33.06 m. (Photo by V.I. Sychev)

area of the village of Starokorsunskaya (Fig. 5) shows its dynamics in 2014–2016 (Fig. 6).

By the end of September 2014, according to the Kuban BWA, the water level in the reservoir was 27.24 m ( $V = 395$  million  $m^3$ ), decreasing from 32.9 m in early July, which is 5.51 m lower than the NPU. In Fig. 6a, an exposed wide coastal bank is clearly visible, which in many places is covered with vegetation and flowering algae. In spring, the reservoir level became much higher: 25 March 2015 was



(a)



(b)



(c)



(d)

**Fig. 6** The coastal zone of the Krasnodar Reservoir in the vicinity of the village of Starokorsunskaya: (a) 23 September 2014, (b) 25 March 2015, (c) 8 April 2015, (d) 1 October 2016 (Image2016 DigitalGlobe)



**Table 3** Characteristics of the level, inflow, and discharge of water in the Krasnodar reservoir, corresponding to the data in Fig. 6

Date	Level (upper pool), m, abs.	Inflow, m <sup>3</sup> /s	Discharge (lower pool), m <sup>3</sup> /s
25/03/2015	31.91	155	110
8/04/2016	32.91	195	283
1/10/2016	29.03	394	253

31.91 m (Table 2) and 8 April 2016 – 32.91 m. Moreover, in Fig. 6b, c, there is a noticeable difference in the coastal area at different levels of the reservoir. Prior to flooding, the modern Kuban floodplain towered 0.5–2 m above the water edge. Several steps of various heights, corresponding to seasonal fluctuations in the water content of the river, stood out on its surface. The floodplain terrace of the right bank of the Krasnodar Reservoir was separated from the floodplain by a steep ledge with a height of 5–15 m. Currently, the most intensive reformation process takes place along the right steep and deep bank. In Fig. 5 a steep coast is clearly visible at a level of 33.06 m on 7 July 2016 (Table 3).

In vast areas of the right bank of the Krasnodar Reservoir, the flooded channel of the Kuban comes very close to the shore, and the collapsing material is quickly washed and drifted down. The transfer of collapsed material is facilitated by a deep and intense drawdown. This prevents the formation of an abrasive coastal shallow with a width that would be sufficient to absorb the energy of high waves.

From the side of the village Starokorsunskaya, there is a free passage to the water. In winter, the water level drops, and there forms an extensive sandbank (Fig. 6a, d). In some places, the remains of the banks washed up by the water look like fantastic ruins. Locals sometimes find ancient vessels washed out of a powerful cultural layer located from Starokorsunskaya and further along the former channel toward Ust-Labinsk town. Layers of clay earth fall off the steep banks into the water every spring, exposing traces of the culture of the past millennia, and carry them to the bottom.

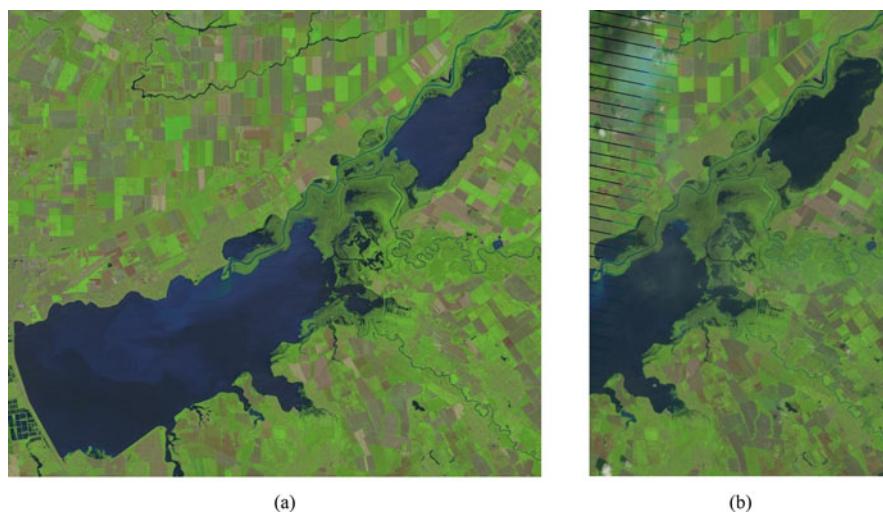
After heavy rains in early June 2016, the discharge of water from the Krasnodar Reservoir was increased; its level was stabilized, but to stop its growth, the discharge of water was increased from 1,100 to 1,200 m<sup>3</sup>/s (Table 4).

Such an increase in discharge did not lead to flooding in the lower reaches of the Kuban River, which may be possible only if the discharge volume is more than 1,250 m<sup>3</sup>/s. For estimates of changes in the basin area in June to August 2016, Fig. 7 shows the data from Landsat-7 ETM + and Landsat-8 OLI sensors from 18 and 26 June 2016 at a time when the level marks of 32.93 and 33.08 m slightly (<1%) differ from each other and from the mark of the NPU 32.75 m abs. In this case, the characteristics of the reservoir and lintel can be considered to correspond to the value of the NPU.

When the level dropped to 29.03 m, on 1 October 2016, the coastal bank in the northern part of the reservoir was again exposed, but its width in some places was <10 m than that observed in September 2014. Note that high-resolution satellite data (Fig. 6) can be used to assess the width of the shallow, its condition, surface moisture, and other characteristics.

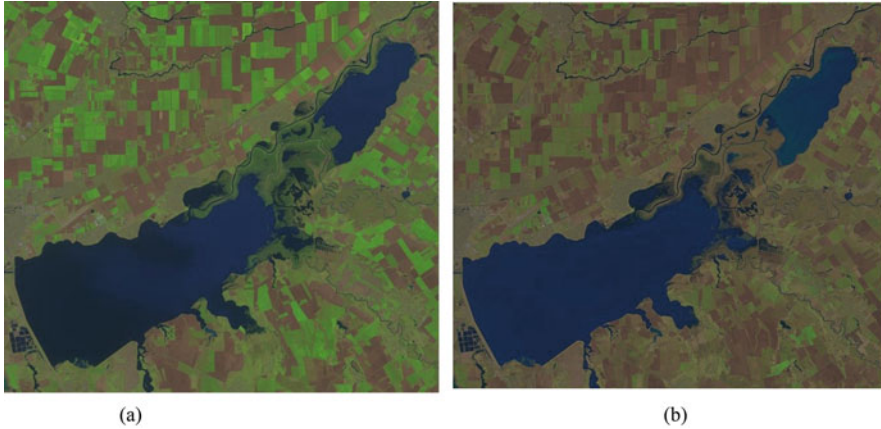
**Table 4** Characteristics of the level, inflow, and discharge of water in Krasnodar Reservoir in May to July 2016

Date	Level (upper pool), m, abs.	Inflow, m <sup>3</sup> /s	Discharge (lower pool), m <sup>3</sup> /s
23/05/2016	32.51	532	558
30/05/2016	32.88	961	562
6/06/2016	32.99	1,334	1,053
13/06/2016	32.94	852	1,018
20/06/2016	32.93	797	600
27/06/2016	33.08	744	733
4/07/2016	33.08	894	931
11/07/2016	33.07	893	930
18/07/2016	32.99	667	703
25/07/2016	32.92	675	619

**Fig. 7** Composite images of ETM + Landsat 7 and OLI Landsat 8 corresponding to level marks 32.93 m on 18 June 2016 (a) and 33.08 m on 26 June 2016 (b)

As an example of assessing the nature of siltation of the reservoir, a satellite image (Fig. 8d) dated 28 July 2016 was used. The water level in the reservoir at the time of the survey (according to the Kuban BWA) was 32.87 m and was 12 cm higher than the NPU. The Belaya Belt Delta continued to form a powerful jumper. Its dry areas are covered with a continuous cover of vegetation. The waters of the Kuban River with the growth of the jumper zone cut mud deposits in the places of their old riverbed, which existed before its flooding by the reservoir. It completely restored the section of this channel from the village of Vasyurinskaya to the village of Starokorsunskaya, formed the river banks, and secured with woody vegetation,





**Fig. 8** Composite images of OLI Landsat 8 corresponding to level marks 31.85 m on 20 March 2015 (a) and 32.97 m on 7 April 2016 (b)

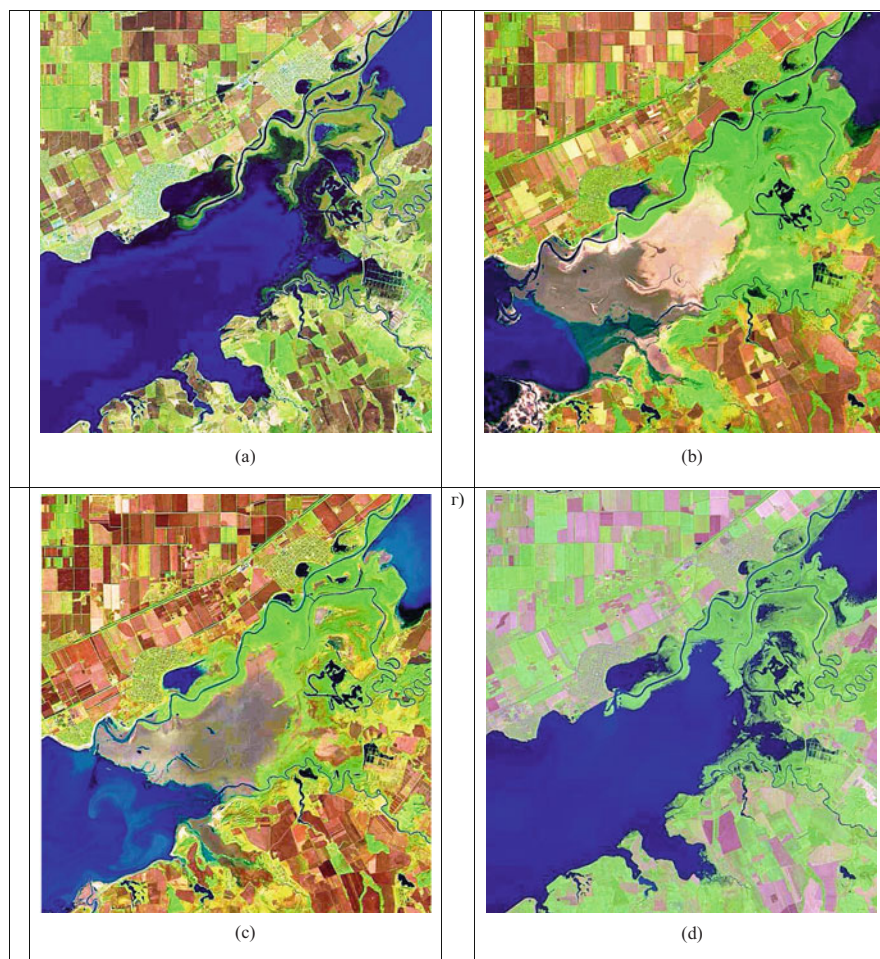
and at the exit from the jumper zone, the Kuban River continued to form its remote delta from the sediment brought by it. The Belaya River, having formed its new channel almost parallel to the Kuban toward the dam, contributed to the growth of the lintel in the same direction.

The jumper can be identified on satellite images and represents areas with reservoirs of various sizes and shapes, mainly swamped by sediments of silty sediments and densely overgrown with aquatic vegetation. The surface of the delta is densely overgrown with forest, in which willows of several species prevail. There are also dense thickets of willows and shrubs and dense undergrowth in the flooded areas of the marsh type with a viscous muddy bottom. There is poplar, acacia, and hazel. Along the dam of the former Tshchikskoye Reservoir, wild fruit trees grow in a narrow strip. In open, moist places, reeds and other marsh vegetation interspersed with young willow shoots in abundance [3].

The jumper is practically impassable for foot, land, and water transport sites. A strip of old trees is visible along the former dam of the Tshchikskoye Reservoir. In open moist places, reeds and other marsh vegetation interspersed with young willow shoots (Fig. 9).



**Fig. 9** Vegetation on the bridge between the Krasnodar and Tshchikskoye reservoirs, November 2013 (Photo by V.I. Sychev)



**Fig. 10** The jumper between the Krasnodar and Tshchikskoye reservoirs according to the contrasted data OLI Landsat 8: (a) 20 March 2015, (b) 28 September 2015, (c) 30 October 2015, (d) 28 July 2016

At a small channel connecting the Belaya River with the Kuban, the color of the water changes, depending on which one can judge the intensity of sediment intake and, therefore, the size of the runoff. The canal that connected Belaya River with the Tshchikskoye Reservoir remained the only watercourse supplying the reservoir, both during floods and in relatively shallow periods. The zones of river runoff distribution, expressed by mineral suspension, are less often traced in the water area of the Tshchikskoye Reservoir at a level close to the NPU and below. Even at a level close to the treatment facilities in Fig. 10a, d and even more so at a low level (below the treatment facilities by 6 m) in Fig. 10b, c (see also Table 2), the channel

from the Belaya River does not reach the Tshchikskoye Reservoir. As a result, the reservoir area decreases markedly over time.

A significant decrease in the level made it possible to detect masses of wet silt sediments occupying the entire bed of the reservoir. Moreover, their surface is significantly different from satellite data presented in [4–6]. From the differences in the color gamut and the structure of the image, silty deposits can be determined at different stages of moistening, drying, and overgrowing with shrubs or grassy plants, for example, the drying stage of the reservoir bed in Fig. 10b and the wetting stage in Fig. 10c.

In a number of publications, it was noted that the reliability of flood protection of the Lower Kuban reservoirs in modern conditions is lower than that required: long-range embankment dams are not reliable enough; measures are required to improve the technical condition of reservoirs and waterworks. The severity of the problem is determined by the following factors: the level of technical safety of almost all reservoirs is lower than permissible, which threatens accidents with catastrophic consequences for the population and economy of the region; a flow pass below the Krasnodar reservoir of more than  $1,200 \text{ m}^3/\text{s}$  is associated with the risk of breaking through the dams of the Kuban and Protoka rocks due to their poor technical condition; and the risk of flooding due to a decrease in the capacity of the channels for the transfer of runoff as a result of overgrowing and siltation.

The main problems surrounding the Kuban and Protoka lands are the reduction in the throughput capacity of their channels, as well as the insufficient reliability of the dams due to the threat of undermining the base and insufficient cross-sectional dimensions of the dams for most of their length. Due to the insufficient reliability of the dams, deboning occurred, and breaks occur with flooding of part of the protected area. Many dams were built in an emergency, on the eve, or during the flood; they do not meet the requirements of operational reliability and do not provide guaranteed protection against floods. Virtually the entire length of the dam requires repair and reconstruction in accordance with the requirements of building codes.

### 3.2 *Kryukovskoye Reservoir*

A case in point is the operation of the Kryukovskoye Reservoir, the water of which is used to provide rice systems. At the beginning of 2016, the water level in the reservoir was 12.76 m;  $V = 50.5$  million  $\text{m}^3$  ( $H_{\text{NPU}} = 14.40$  m,  $V_{\text{NPU}} = 111$  million  $\text{m}^3$ ), at the beginning of April, it was close to the maximum – 14.56 m;  $V = 114.6$  million  $\text{m}^3$ . Since the beginning of the growing season (end of April), water from the reservoir has been supplied to rice irrigation systems. By the end of June 2016, the reservoir was discharged to the level of 13.49 m; the volume amounted to 76.4 million  $\text{m}^3$ . The minimum level – 12.45 m – was noted on September 12. By the end of 2016, the level rose to 13.74 m; the volume amounted to 86 million  $\text{m}^3$ .

Periodically, repairs and restoration of damaged sections of dams are carried out at the reservoirs, as happened in the case of the northern dam section of the

Kryukovskoye Reservoir on 30 March 2017. The water management situation in the Krasnodar and Kryukovskoye reservoirs did not cause serious concern: their characteristics were close to the NPU. At 1 km from the village of Mikhailovsky Seversky district at 14 h 35 min on 30 March 2017, in the body of the northern dam of the Kryukovskoye Reservoir, soil subsidence to a depth of 1.5–2 m, and a length of up to 150 m occurred. Engineering work was carried out on this site in 2014, which can be obtained by comparing Fig. 11a, b according to satellite imagery data dated 3 March 2013 and 2 August 2014. A photo of the damaged area dated 1 April 2017 is shown in Fig. 11.

At the site of the damage, engineering work was carried out to strengthen the dam, which was completed on 6 April 2017, and the emergency mode on the Kryukovskoye Reservoir was canceled. By April 7, the water level in the Krasnodar Reservoir was 32.82 m and was 7 cm higher than the NPU.

### 3.3 *Varnavinskoye Reservoir*

Access to information from new spacecraft allows you to compare images of different spatial resolutions and to obtain the necessary data at low cost. In Fig. 12 shows images of the Varnavinskoye, Kryukovskoye, and Shapsugkoye reservoirs according to Landsat-8 OLI with a spatial resolution of 30 m and Sentinel-2 with a resolution of 10 m dated 1 April 2017.

As a result, information was obtained not only about the area of reservoirs but also about the flow of water and the nature of circulation in them.

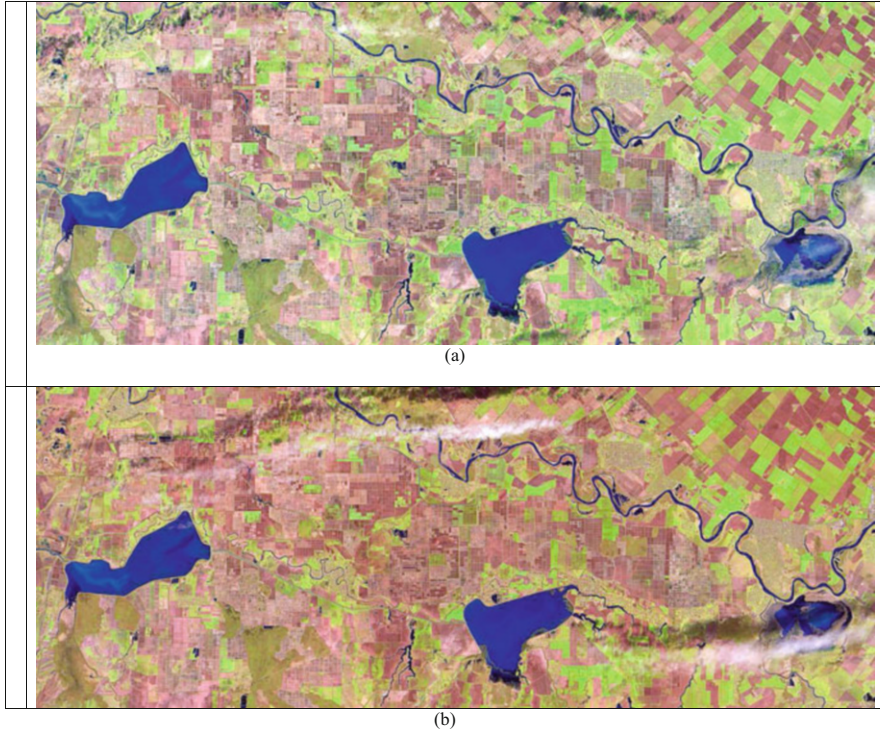
For example, in the fragment of the image (Fig. 13), you can determine the area of the Varnavinskoye Reservoir, which is close to the maximum, as well as determine the flow characteristics of the water entering the Varnavinskoye Reservoir. After the damage, to avoid breaking the dam, the discharge of water from the Kryukovskoye Reservoir was more than doubled from 28.4 to 70 m<sup>3</sup>, and more than nine million m<sup>3</sup> were discharged from the reservoir in 2 days, which was on 1 April 2017. An appropriate message was received from the Krasnodar Territorial Headquarters of EMERCOM (the Ministry of the Russian Federation for Affairs for Civil Defence, Emergencies, and Elimination of Consequences of Natural Disasters). In Fig. 13, water flows are visible, both from Kryukovskoye and from the Varnavinskoye discharge channel. Analysis of satellite images of the Krasnodar, Kryukovskoye, Varnavinskoye, and Shapsugkoye reservoirs allowed us to show their condition at NPU, as well as a significant decrease in the level in cases of emergencies at water bodies, and provide examples from Landsat-8 and Sentinel-2 satellites.





**Fig. 11** Section of the northern dam of the Kryukovskoye Reservoir: (a) before its damage on 3 March 2013, (b) after work to strengthen it on 2 August 2014, (c) the damaged section, 1 April 2017





**Fig. 12** Region of Varnavinskoye, Kryukovskoye, and Shapsugkoye reservoirs according to OLI Landsat 8 (a) and Sentinel-2 (b) on 1 April 2017

### 3.4 *Shapsugkoye Reservoir*

The Shapsugkoye Reservoir is managed by the Ministry of Agriculture, built in 1939–1952, in order to regulate the flood flow of the Afips River, as well as more economical use of water resources. The reservoir is located in the left-bank floodplain of the Kuban River, in the estuary of the Afips River, and on the territory of the former Shapsugkoye floodplains that went under water. The average depth of the reservoir is 3.5 m; the volume is 130 million m<sup>3</sup>. In the southeast there is a small bay. The bottom is subject to strong siltation in places. The reservoir regulates the winter floods of the Afips River and also protects the lower reaches of the Kuban River (from which it is separated by a narrow braid) from floods; water from the reservoir is used for irrigation of crops. On its banks are the suburban villages of Krasnodar City – Novobrzegokai, Druzhny, Chomuty, and Afipsip.

Figure 14a, b shows the state of the reservoir during its operation in 1984 and 1985. In 1997, it was declared “emergency” and decommissioned. Flood waters are discharged through the Shapsugkoye Reservoir in transit directly to the Kuban River below the City of Krasnodar. The residual volume of water is reduced (by reducing

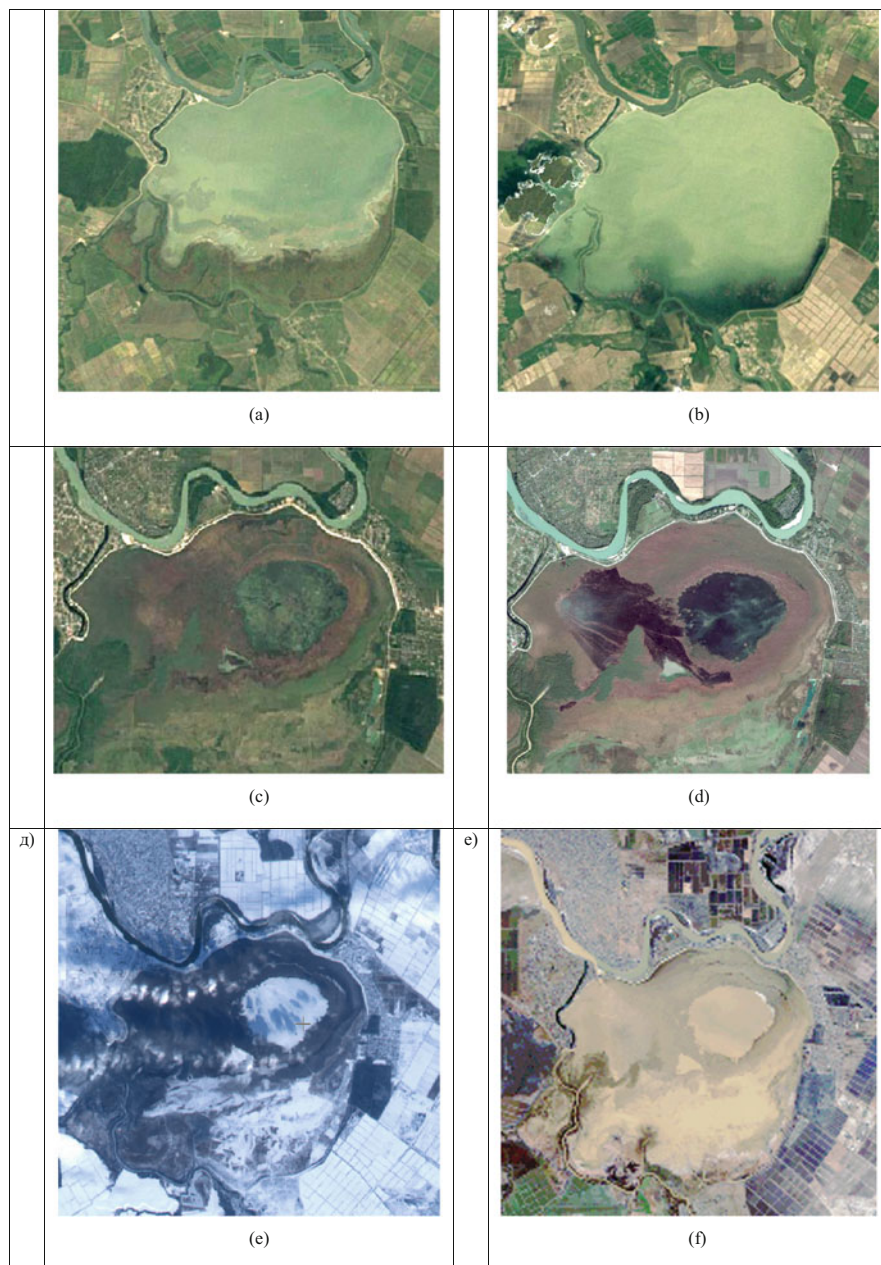


**Fig. 13** Varnavinskoye Reservoir according to Sentinel-2 on 1 April 2017

inflow and evaporation), and the discharge flow from it did not exceed  $1 \text{ m}^3/\text{s}$ . In 2007, reconstruction of the Shapsugkoye Reservoir began, which has been ongoing for 10 years. The filling of the reservoir bowl with water is expected at the beginning of 2018. The total length of the dam of the reservoir is 11.2 km. Work is underway over 800 m of the dam: the construction of an earthen embankment, the installation of reinforced concrete slopes and parapets, asphalt pavement along the dam crest, and the replacement of equipment in an old spillway structure. It is assumed that the completion of the reconstruction of the reservoir will increase flood safety, provide water for 2.5 thousand hectares of rice systems in the Takhtamukaysky District, as well as improve the transport connection of the territory of the Afipsips rural settlement adjacent to the reservoir. The full functioning of the facility can contribute to the solution of a number of social problems, since before the facility was located recreation centers, which became desolate due to the emergency condition of the dam and the road.

In 2015, the water level in the reservoir changed within the DSL border – 17.44 m (with  $H_{\text{DSL}} = 17.40 \text{ m}$ ). According to the instructions of the Ministry of Natural Resources of the Russian Federation and the “Declaration of Safety of the Shapsugsky Hydroelectric Complex,” the Shapsugkoye Reservoir operates in transit mode in connection with the reconstruction of the main hydraulic structures.

In 2016, level changes were more significant. Since the second decade of January 2016, due to an increase in the inflow of the rivers flowing into the Shapsugkoye Reservoir, the rise in the water level in the reservoir has begun. The maximum water level was observed on 10 January 2016, was 18.99 m, and exceeded the DSL by more than 1.5 m; the maximum discharge on that day was  $90 \text{ m}^3/\text{s}$ . Figure 14e dated 2 January 2016 shows the change in the area of the reservoir with an increase in the



**Fig. 14** The area of the Shapsugkoye Reservoir according to Image2016©DigitalGlobe and OLI Landsat 8: (a) 1984, (b) 1985, (c) 17 April 2015, (d) 18 October 2016, (e) 2 January 2016, (f) 14 January 2017

**Table 5** The main morphometric characteristics of reservoirs [7]

Reservoirs	Volume runoff, million m <sup>3</sup>	Area, km <sup>2</sup>	Length, km	Width, km
Oktyabrskoye	15	9.4	4.0	3.0
Shendzhiyskoye	22	7.8	4.0	3.6
Maykop	0.8	0.5	0.5	0.4
Cheytukskoye	1.5	1.5	2.6	2.5
Kuzhorskoye	2.1	0.5	1.3	2.2

level from the maximum to the boundary of DSL. In the second decade of March, the water level returned to the DSL border – 17.44 m – and kept until the end of October (with HDSL = 17.4 m). This state of the reservoir corresponded to its area in Fig. 14c, d. Since November 6, the water level began to rise and reached a maximum on December 12, 19.23 m, but by the end of December, it had dropped to 17.75 m. During January 2017, flood waters were discharged in transit through the Shapsugkoye Reservoir directly to the Kuban River below Krasnodar. The residual volume of water was about 0.1 million km<sup>2</sup>; the reservoir area is close to maximum, as illustrated in Fig. 14e.

In addition to Krasnodar and Shapsugkoye, other reservoirs of Adygea have a small area. The Oktyabrskoye (Takhtamukayskoye), Shendzhiyskoye, Maykop, Cheytukskoye, and Kuzhorskoye reservoirs were created for a more rational and efficient use of surface water resources (Table 5).

### 3.5 *Oktyabrskoye (Takhtamukayskoye) Reservoir*

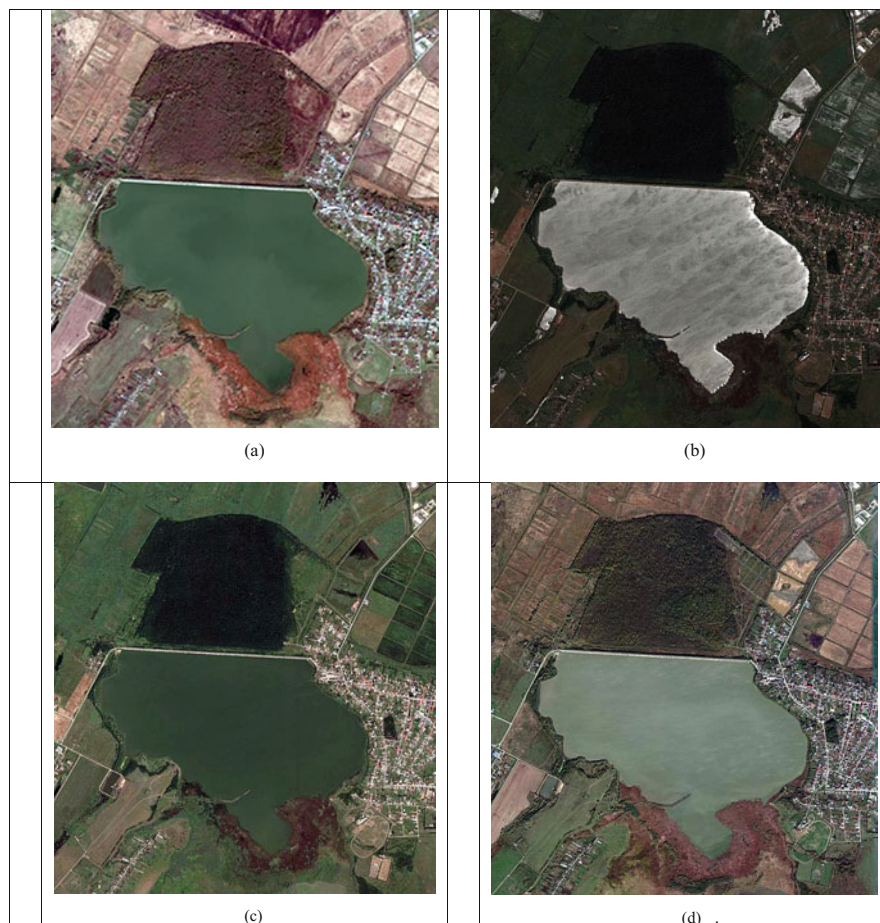
The Oktyabrskoye (Takhtamukayskoye) Reservoir is located at the Takhtamukai aul, 9 km south of Krasnodar, in the floodplain of the Sups River. Its mirror area is 9.4 km<sup>2</sup>, the average depth is 2.5 m, and the volume is 15 million m<sup>3</sup>.

Figure 15 shows an example of changes in the area of a reservoir. The scenes obtained for the neighboring dates on 3 and 4 of July 2016 are of interest. Figure 15b represents the water surface in solar flare, which allows us to evaluate its heterogeneity in detail and also to determine the area of the reservoir and rice checks with greater accuracy. Figure 15c allows to determine the heterogeneity of the land surface and, using the data of the thermal range, to assess the degree of its humidity.

### 3.6 *Shendzhiyskoye and Cheytukskoye Reservoirs*

The Shendzhiyskoye Reservoir is located at the Shenjiy aul, 10 km south of the eastern outskirts of Krasnodar. The mirror area is 7.8 km<sup>2</sup>; the reservoir capacity is 22 million m<sup>3</sup>. To the east of it is the Cheytukskoye Reservoir with an area of 1.5 km<sup>2</sup>.





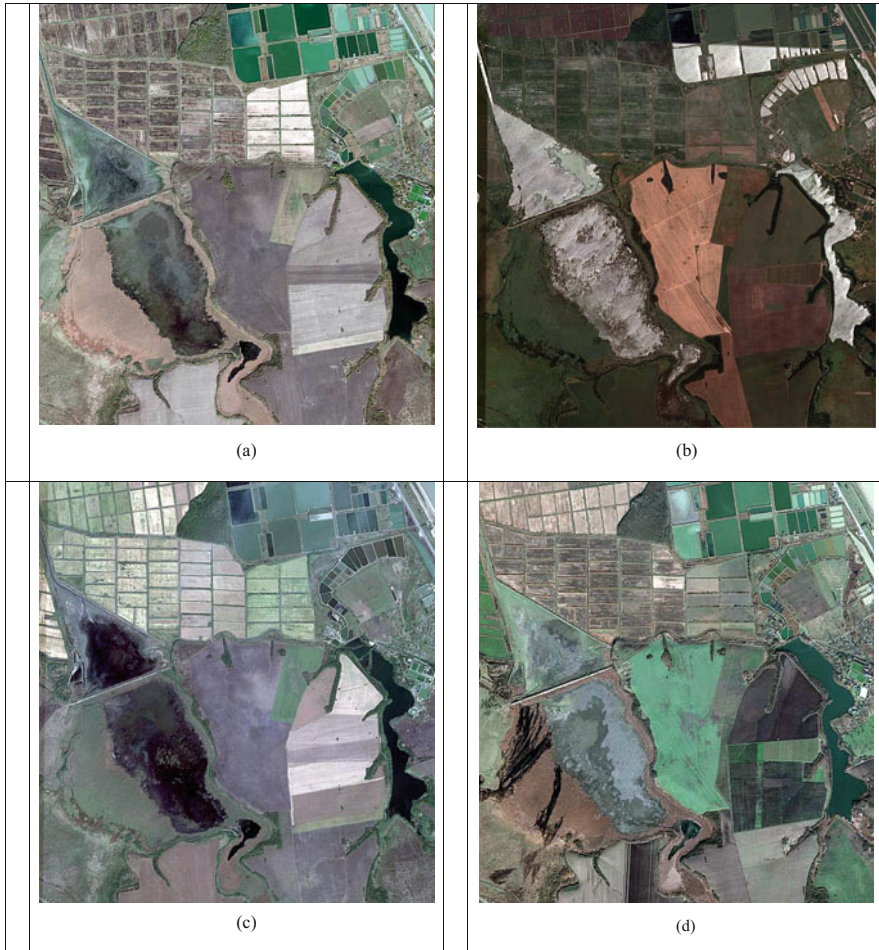
**Fig. 15** Oktyabrskoye (Takhtamukayskoye) Reservoir area according to Image2016 © DigitalGlobe: (a) 29 October 2014, (b) 3 October 2016, (c) 4 October 2016, (d) 26 October 2016

For the region of these shallow water reservoirs, sufficiently detailed information can also be obtained on their area, as well as on the condition of field lands and rice receipts (Fig. 16).

### 3.7 *Maykop Reservoir*

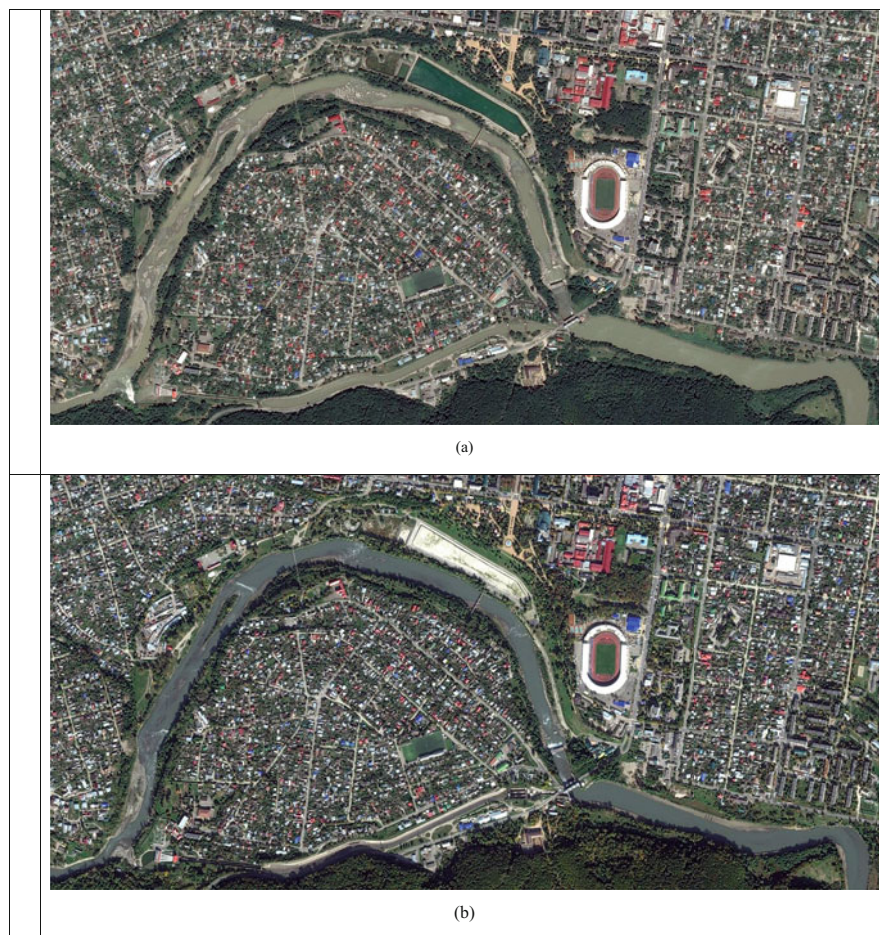
Maykop Reservoir on the Belaya River near the City of Maykop was built in March 1944 by the method of public construction without technical, working projects and estimates. The derivation channel from which construction began was dug manually. In the national archive of the Republic of Adygea, information about the allocation





**Fig. 16** The area of the Shendzhiyskoye and Cheytukskoye reservoirs according to Image2016 © DigitalGlobe: (a) 17 September 2014, (b) 29 October 2014, (c) 3 July 2016, (d) 24 November 2016

of transport for construction by the regions of Adygea was preserved: “... Giaginsky District: motor transport – 10 units, tug-transport – 36 horses, 30 bulls ....” The reservoir is intended for limited flow control and water intake for operation of Maykop hydroelectric station and is the source of domestic and drinking water for Maykop with a design volume of water consumption of 35 thousand  $\text{m}^3$  per day. The mirror area of the reservoir is 0.5  $\text{km}^2$ , length 0.5 km, width 0.4 km, and volume about 1 million  $\text{m}^3$ . The first unit of the Maykop hydroelectric station was put into temporary operation on 23 June 1950. The hydroelectric power station was put into commercial operation on 5 November 1951.



**Fig. 17** The area of the City of Maykop, Maykop hydroelectric power station and reservoir according to Image2016 © DigitalGlobe: (a) 12 July 2016, (b) 7 October 2016

Figure 17 shows the scenes of the Maykop City region of 12 July and 7 October 2016. Figure 18 illustrates the state of Maykop's water bodies in 2014–2016. The bottom of the images shows a derivation channel filled with water in summer with traces of water discharge below the hydroelectric station building (Figs. 17a and 18b) and drained in the image in the autumn (Figs. 17b and 18d) – there are no traces of water discharge below the hydroelectric station.

In the upper part of the images (Fig. 17), a regular-shaped design attracts attention. This urban swimming pool (length 500 m, width 50 m, depth 3 m) is the only one preserved in the country of this size. The pool is filled with running water during the hot summer period (Fig. 17a) and drained in the fall (Fig. 17b). Despite significant costs, local authorities are trying to keep it clean and ensure the safety of

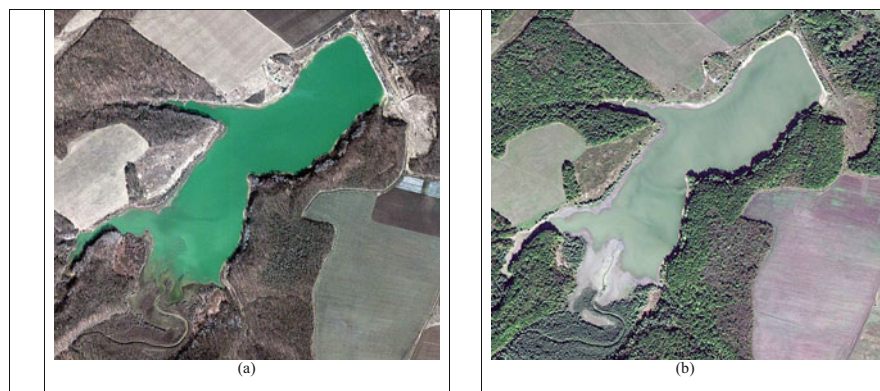




**Fig. 18** Maykop hydroelectric station and reservoir according to Image2016 © DigitalGlobe: **(a)** 30 September 2014, **(b)** 12 July 2016, **(c)** 15 July 2016, **(d)** 7 October 2016, **(e)** 25 November 2016

vacationers. Below the basin along the Belaya River, the construction of the water park under construction is visible.

Maykop Reservoir was subjected to intense siltation. After 4 years of operation, up to 70% of its total volume and more than 20% of its useful volume were lost. 1.84 million  $\text{m}^3$  of sediment settled in the reservoir. The total volume of the reservoir



**Fig. 19** The area of the Kuzhorskoye Reservoir according to Image2016 © DigitalGlobe: (a) 1 March 2013, (b) 18 October 2015

decreased from 2.76 to 0.40 million m<sup>3</sup>, i.e., decreased by almost 90%, turning into a shallow pool.

### 3.8 *Kuzhorskoye Reservoir*

The reservoir is formed by the spill of the Kuzhora River of the influx of the village of Kuzhorskaya, the path of which is blocked by a dam installed on the north side of the reservoir. The western banks of the reservoir are mainly represented by meadows (Fig. 19).

## 4 Conclusions

These examples of satellite data of different ranges allow to identify different types of underlying surfaces: in the visible range – by the value of reflected radiation of the sun, in infrared – by the value of its own thermal radiation of the surface. The infrared image helps to clarify the surface area of reservoirs in the spring (the beginning of warming), as at that time the thermal properties of land and water surface are quite distinctly different. Analysis of satellite data of the Belaya River and the ducts in the visible range allows to estimate the intensity of its water flow into the Kuban River. But, as a rule, traces of its runoff in Tshchikskoye Reservoir and directly to the Krasnodar Reservoir were not traced. The water of the Pshish and Psekups rivers, distinguished by the color of the mineral suspension, characterizes the growing flow of water directly into the southeastern part of the reservoir.



Thus, regular satellite monitoring in the coming years during periods of floods, filling, and running out of reservoirs will allow you to quickly monitor the development of siltation processes, determine the change in morphometric characteristics, and predict further transformation of water bodies.

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