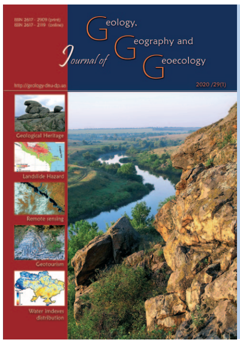

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Use of remote sensing data to study ice cover in the Dnipro Reservoirs

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Abstract. The information on the use of remote sensing data when studying the ice cover of the Dnipro Reservoirs is given. The main source of data was the images obtained by the satellites Sentinel-2, Landsat, Aqua and Terra. In addition, the observation data from the hydrological and meteorological stations were used. The combination of these data enabled to study the patterns of ice regime in the Dnipro Reservoirs, to specify some features that cannot be determined by regular monitoring. A typical feature of the ice cover of all reservoirs of the Dnipro Cascade, besides the Kyivske one, is the impact of hydropower plants (HPP) located upstream. The runoff of the rivers flowing into the Kyivske Reservoir significantly influences its ice cover. This is especially relates to the period of spring flood. Besides the Dnipro and the Pripyat Rivers, relatively small the Teteriv and the Irpin Rivers flowing from the south-west to the north-east have a rather significant effect on the ice cover of this reservoir. The distribution of ice cover in the Kanivske Reservoir, compared to the Kanivske one, is significantly less. In addition to more southern location and warmer climate, the city of Kyiv also influences the ice cover on it, namely due to the discharge of wastewater from several industrial enterprises, Kyivska TPP-5 and Bortnitska Station of Aeration are ones of them. The impact of Trypilska TPP, which located downstream, is also significant. The longest duration of ice cover in the Kanivske Reservoir is observed in its south-eastern part. A point of interest about the Kremenchuts'ke Reservoir is the fact that the ice cover in it remains for the longest period compared to the other reservoirs. The largest duration of ice cover in this reservoir is observed in the Sulska Bay. The typical feature of the Kamianske Reservoir is the accumulation of ice in its narrow parts. Within the Dniprovske Reservoir, the longest freezing period is observed in the Samara Bay. Besides the operation of hydropower station, the industrial enterprises of Kamianske town and Dnipro city have a great effect on the upper part of this reservoir. There are significant differences in the ice regime of the different parts of the Kakhovske Reservoir, which extends from the north-east to the south-west. The distribution of ice in its shallow north-eastern part is usually much larger than in narrower south-western part.

Key words: remote sensing, ice cover, air temperature, the Dnipro Reservoirs

Використання даних дистанційного зондування Землі у дослідженнях крижаного покриву дніпровських водосховищ

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Анотація. Наведено відомості щодо можливості використання дистанційного зондування Землі у дослідженнях крижаного покриву дніпровських водосховищ. Основним джерелом даних були зображення, отримані супутниками Sentinel-2, Landsat, а також Aqua і Terra. Крім того, використано матеріали спостережень на гідрологічних постах, а також метеостанціях, що прилеглі до водосховищ. Поєднання цих даних дало змогу дослідити закономірності льодового режиму у дніпровських водосховищах, знайти деякі особливості, які звичайний моніторинг зафіксувати не може. Характерною особливістю крижаного покриву всіх водосховищ каскаду, за винятком Київського, є вплив розташованих вище за течією ГЕС. Утворення криги у Київському водосховищі починається в його північно-східній частині. На крижаний покрив цього водосховища істотно впливає стік річок, що у нього впадають. Особливо це стосується періоду весняного водопілля. У цей час на крижаний покрив, окрім Дніпра та Прип'яті, впливають навіть порівняно невеликі річки Тетерів та Ірпінь, які течуть з південного заходу на північний схід. Поширення льодоставу у Канівському водосховищі, порівняно з Київським, істотно менше. Це зумовлено південнішим розташуванням водосховища, м'якішим кліматом, а також роботою Київської ГЕС і скидами підприємств м. Києва. До них, зокрема, належать Київська ТЕЦ-5 і Бортницька станція аерації. Нижче за течією додається вплив Трипільської ТЕС. Найдовше в Канівському водосховищі крига зберігається в його південно-східній частині. Цікавою особливістю Кременчуцького водосховища є те, що крижаний покрив у ньому звичайно зникає найпізніше. Найбільша тривалість льодоставу тут характерна для Сульської затоки.

У Кам’янському водосховищі часто утворюються скупчення криги в його звужених місцях. У Дніпровському водосховищі найбільша тривалість льодоставу властива для Самарської затоки. На крижаний покрив у верхній частині цього водосховища, окрім роботи ГЕС, впливають скиди промислових підприємств міст Кам’янське та Дніпро. Значні відмінності в льодовому режимі має Каховське водосховище, що витягнуте з північного сходу на південний захід. Поширення криги в його мілководній північно-східній частині звичайно значно більше, ніж у звуженій південно-західній.

Ключові слова: дистанційне зондування Землі, крижаний покрив, температура повітря, дніпровські водосховища

Introduction. It is well known that ice cover on water bodies has an effect on water quality as well as on the living conditions of fish and other hydrobionts. This also refers navigation and the stability of hydraulic engineering facilities.

The regular monitoring of ice regime in the Dnipro Reservoirs and other water bodies has some disadvantages. The obtained data enable to characterize only local conditions near the banks. The conditions in the remote parts of the water area remain unexplored. In this regard, the use of remote sensing data gives additional information on the ice cover. At the same time, these data also have some lacks, in particular, due to essential cloudiness in winter period. In turn it makes harder to get a sufficient number of high-quality images.

Analysis of previous research. There are quite a lot studies devoted to the ice cover on water bodies. Over the last decades, the most popular issue is the changes of ice cover caused by global warming. Based on the long-term observations many authors (Klavins et al, 2009, Korhonen 2006, Rakhmatullina, Grebin’ 2011, Stonevicius, Stankunavicius, Kilkus, 2008, Strutynska, Grebin’ 2010, Yaitskaya, Magaeva, 2018) state that the freezing of water bodies starts later while the ice break-up starts earlier compared to the previous decades. The study of Magnuson J.J. et al (2000) devoted to many water bodies in Northern hemisphere showed that the freezing of water bodies over the last 100 years in average started 5.7 days later while the ice break-up for the same period in average started 6.3 days earlier. The similar results were obtained for some lakes in Northern Poland (Marszelewski, Skowron, 2006) and for the Nemunas River in Lithuania (Stonevicius et al, 2008).

The next important point of the relevant studies is establishing the dependencies between the hydrometeorological conditions, the dates of freezing, dates of ice break-up and ice thickness as well (Brown, Duguay, 2010, Efremova et al, 2010, Kalinin, 2012). Baklagin V.N. (2018), which carried out the research of Onega Lake using remote sensing, found the essential impact of wind and wind waves on ice formation.

The analysis of long term data on the ice cover for the Dnipro Reservoirs was made by Vyshnevskyi V.I. (2011). Based on the data of regular monitoring it was determined that during the last decades the period of ice cover shortened and the ice layer became less thick. The longest period of ice cover, which was observed on reservoirs, lasted 140 days. It was recorded at Adamivka hydrological station on the Kremenchuts’ke Reservoir in a cold winter of 1995-1996. The thickest ice cover was also recorded on this reservoir at Svitlovodsk hydrological station in February 1976, when it reached 77 cm. Some results of this issue, based on remote sensing data, were presented in the research work of Vyshnevskyi V.I. and Shevchuk S.A. (2018).

Despite the large number of studies, the patterns of ice regime, primarily in the water areas, which are far from the banks, remain insufficiently studied.

The study area. The study area covered all six reservoirs of the Dnipro Cascade. The average length of the reservoirs is 100–150 km, while the longest Kakhovske one exceeds 200 km. The average width of the reservoirs is 10–15 km, while the largest (Kremenchuts’ke one) is 28 km. The maximum depth the majority of reservoirs is approximately 20 m; the Dniprovske one, which is the deepest, is 62 m (Fig. 1).

Under natural conditions before the construction of reservoirs the average water runoff of the Dnipro River in its mouth exceeded 50 km^3 per year. Nowadays it makes 42–43 km^3 per year. The decrease in runoff is caused by withdrawing water for economic needs and evaporation from the water surface.

Materials and methods. The main source of data for studying the ice cover was the images obtained by Sentinel-2 and Landsat satellites. In fact, there are two Sentinel-2 satellites which were launched in 2015 and 2017. The advantages of this data are quite high spatial resolution (10 m) and relatively small revisit time (2–3 days). The spatial resolution for the majority bands of Landsat satellites, starting from Landsat 4 (it was launched in 1982) is 30 m, revisit time is 16 days. The greatest attention was paid to the data of Landsat 8 satellite, which has been providing the images starting from March 2013. These data are available on the site of the US Geological Survey (www.glovis.usgs.gov). Another important source of data was the images, obtained by Aqua and Terra satellites. These images are taken daily, but the spatial resolution of Modis onboard spectroradiometer is comparatively not high – 250 m.

The algorithm of ice cover study was the following. First of all, a preview of satellite images was carried out, the number of which for today are thousands. Then high quality images were selected, analyzed and downloaded. In addition, the monitoring data on ice regime, provided by the Hydrometeorological Service of Ukraine, were analyzed. These observations are carried out at 36 hydrological stations. The largest number of the stations (8) is located on the banks of the Kakhovske Reservoir, the smallest number (4) is on the Kamianske one. These data are the dates of the beginning of ice phenomena, ice cover and ice break-up, as well as the dates of the end of the ice cover period and the dates of water area cleaning from the ice. In addition, every 5 days the thickness of ice is measured.

The data from meteorological stations, located near the reservoirs, such as air temperature and wind direction were analyzed as well. Based on these data, the main patterns of the ice regime on the studied reservoirs were determined.

Results and Discussion. The ice cover on the Dnipro Reservoirs is observed every year including warm winters, because even in such conditions there are periods, when the air temperature drops below 0 °C. The average monthly temperatures of January (it is considered to be the coldest month) during the standard observation period of 1961–1990 are the following: Kyiv – minus 5.6 °C, Dnipro city – minus 5.5 °C, Nova Kakhovka town – minus 4.2 °C. During the last decades the average air temperature was higher than usual. Thus, during 1991–2019 the average air temperature of January in Kyiv was minus 3.4 °C. During this period the coldest winter was observed in 1995-1996 while the warmest one was in 2006-2007. The coldest month of 1996 was January, when the average air temperature in Kyiv was minus 9.8 °C (Fig. 2).

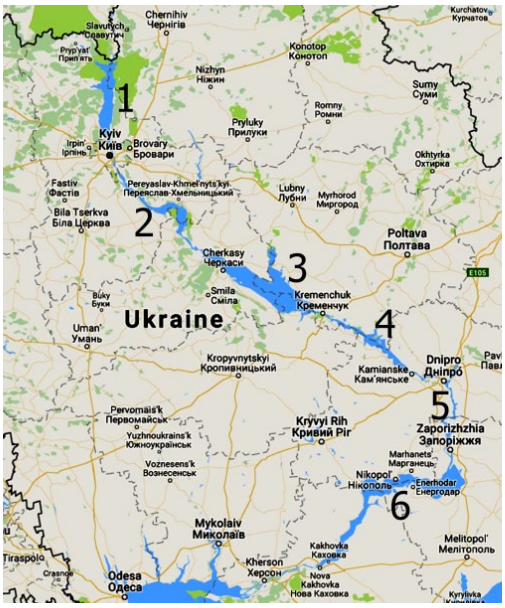


Fig. 1. Location of the Dnipro Reservoirs:
1–6 – Kyivske, Kanivske, Kremenchuts'ke, Kamianske, Dniprovske, Kakhovske respectively

In the city of Dnipro, located on the Dniprovske Reservoir's banks, the average temperature of January during the years of 1991–2019 was also higher than normal – minus 3.7 °C. The coldest winters were observed in 1995-1996 and in 2002-2003, the warmest ones in 2006-2007. The coldest month during this period was December of 2001, the average

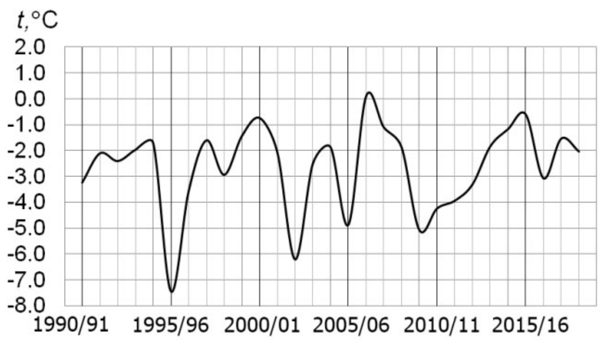
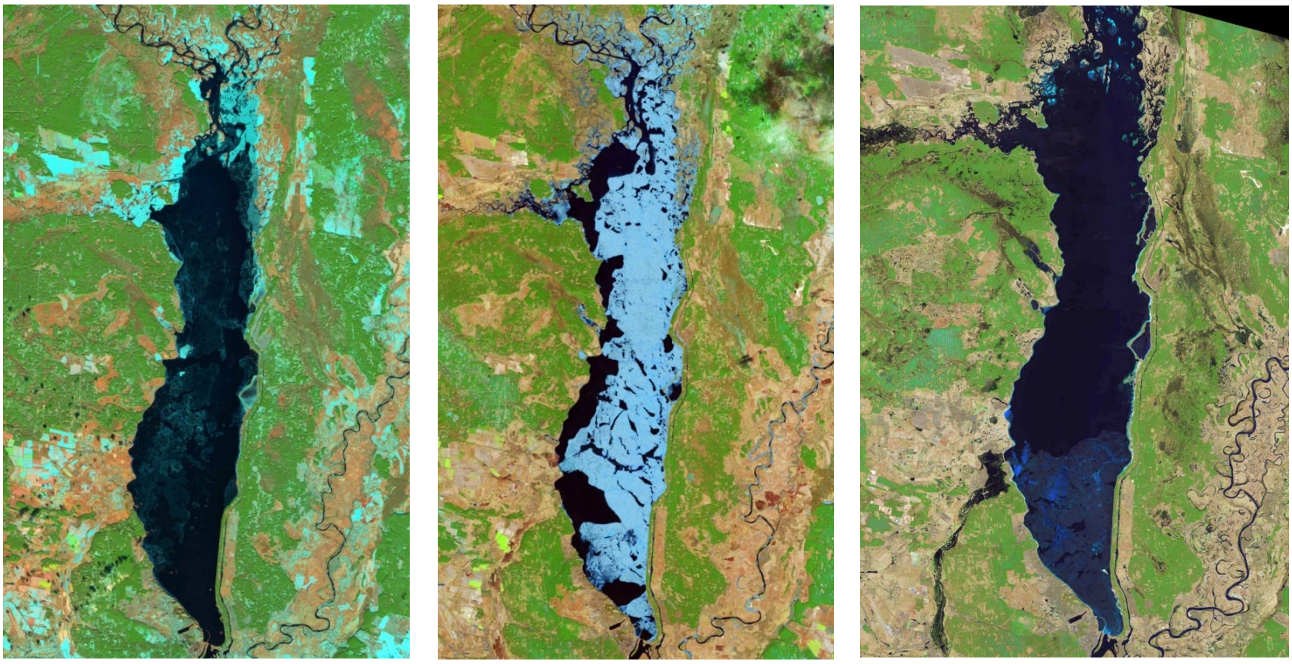


Fig. 2. Fluctuations in winter temperature (December–February) in Kyiv during 1991–2019



a b c

Fig. 3. Ice cover on the Kyivske Reservoir: a – 29.11.2018, b – 02.03.2019, c – 16.04.2013

temperature of which was minus 9.7 °C. On the other hand, January of 2007 was much warmer than usual, its average temperature was +1.5 °C.

The Kyivske Reservoir. According to the available satellite images the freezing of reservoir usually starts in the shallow bays, located in its northern and north-eastern parts. A bit later the freezing is observed near the mouth of the Pripyat River. It can be clearly seen on the image, obtained by Sentinel-2 satellite on 29.11.2018. During the winter period the numerous cracks can be formed in the ice cover – usually transversally the reservoir. As a rule, there is an ice-hole near Kyivska HPSP and Kyivska HPP due to the increased water exchange as a result of these stations operation.

The ice break-up usually starts in the western part of the reservoir. It happens due to the inflow of melting water from the right bank tributaries of the Dnipro River – the Pripyat, Teteriv and Irpin Rivers, the spring flood of which begins earlier than on the Dnipro River itself. In particular, it can be clearly seen in the image, obtained by Sentinel-2 satellite on 02.03.2019.

The cleaning of the water area from the ice in this part of the reservoir has a positive effect on its ecological state – the concentration of dissolved oxygen in the spring period near the western bank of the reservoir is usually higher than it is near the eastern bank (Vyshnevskyi, 2011). The longest period of ice cover in spring period is observed in the southern and south-eastern parts of the Kyivske Reservoir, when having low temperatures the ice can remain here until mid-April (Fig. 3).

The ice regime during the last years is of a great interest. December of 2017 was much warmer than usual, so the formation of ice cover in the Kyivske Reservoir began in January 2018. In particular, in the image obtained by Sentinel-2 satellite on 08.01.2018, there is no ice in the reservoir. The ice started to be visible in the upper part of the reservoir only on the image obtained on 13.01.2018. Almost simultaneously it was also observed at the hydrological stations of the reservoir. In particular, at the Strakholissja station the ice formation started on 12.01.2018, Tolokun station – on 14.01.2018, Lebedivka station – on 15.01.2018.

Significantly different conditions were observed in the cold period of 2018-2019. Decrease in temperature at the end of November caused the covering of some reservoir's part with ice on 29.11.2018, which can be seen in Fig. 3a. The dates of the ice cover formation at hydrological stations were the following: Tolokun – 28.11.2018, Lebedivka – 30.11.2018. At Strakholissja station, located in the northern part of the reservoir, ice cover was formed earlier – on 18.11.2018. On 02.12.2018 almost all area of the reservoir was frozen.

The last image, which clearly shows the existence of ice in the Kyivske Reservoir in 2018, dated 03.04.2018. Some ice remains were traced on 06.04.2018 as well. The same situation was observed at the hydrological stations. Thus, at Tolokun station ice cover disappeared on 03.04.2018, at Strakholissja – it happened on 04.04.2018. Complete cleaning of water from ice was respectively on 07.04.2018 and 08.04.2018.

In the spring period of 2019 the last existence of ice was seen on the image dated 09.03.2019. According to the monitoring carried by the Hydrometeorological Service the cleaning of water from ice was a few days later. In particular, at Vyshhorod and Strakholissja stations it was recorded on 11.03.2019.

The early cleaning of the Kyivske and other reservoirs from ice in 2019 occurred due to the abnormally warm weather conditions. At Vyshhorod meteorological station the air temperature rose up to +7.0 °C on 06.03.2019, up to +9.2 °C on 07.03.2019 and even up to +17.3 °C on 08.03.2019.

The Kanivske Reservoir. This reservoir is located farther south than the Kyivske one. At the same time, it is the first in the cascade which significantly affected by the HPP located upstream. Kyivska HPP located upstream usually causes the formation of the ice-hole of a few kilometers length; sometimes its length can exceed 20 km. Only in cold conditions the size of this hole reduces up to 200–300 m.

Another important factor influencing the ice regime of the Kanivske Reservoir is the city of Kyiv, in particular the discharges of the thermal power plants. One of them Kyivska TPP-5 operates on the right bank of the Dnipro River. Satellite images also show the impact of Bortnichska Station of Aeration, which purifies the wastewater of Kyiv. The water discharge of this water treatment station is 700–750 thousand cubic meters per day and the temperature of the treated wastewater, discharging into the reservoir on the southern outskirts of the city, is much higher than 0 °C.

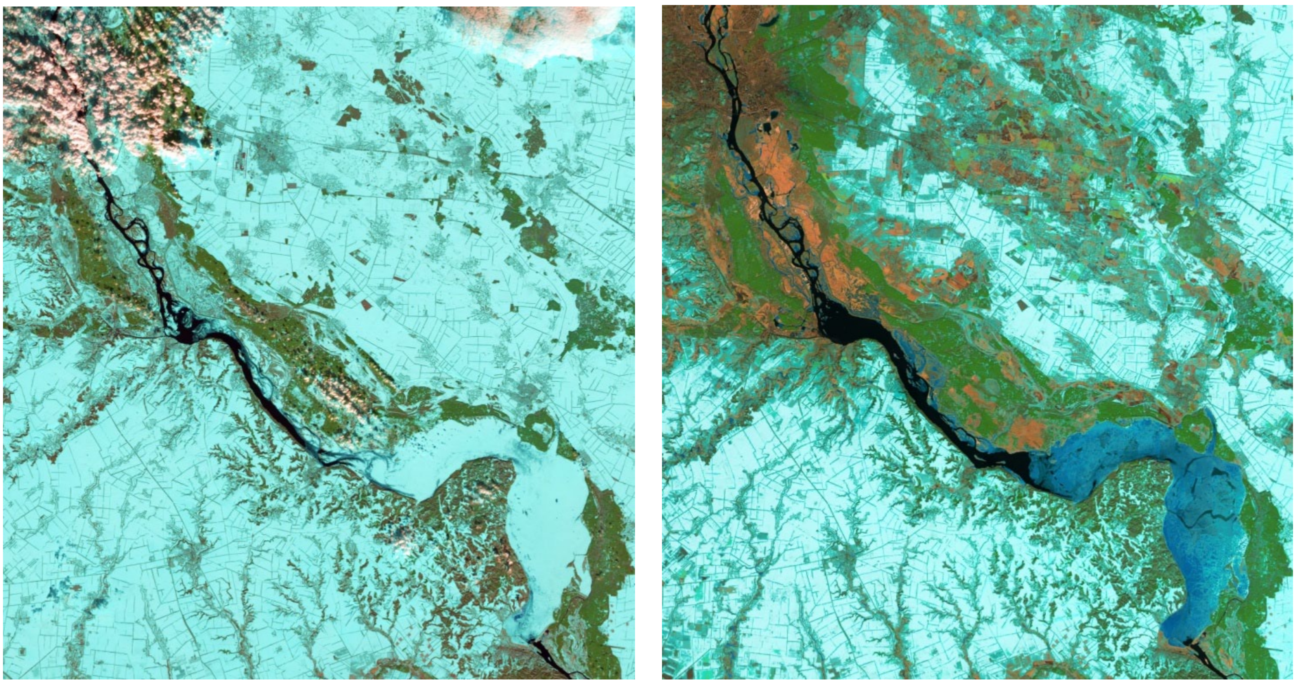
Another important object influencing the ice regime of the Kanivske Reservoir is Trypilska TPP. It is located in Ukrainka town on the right bank of the Dnipro River, 40 km downstream from Kyiv. All these factors determine that the distribution of ice in the Kanivske Reservoir is much less than in the Kyivske one. In general, ice cover is the most stable in the south-eastern part of the reservoir, which is the widest. According to satellite data, it is clearly seen that here (Fig. 4) the thickness of the ice is the largest.

The main stream of the Dnipro River alongside the right bank influences the ice cover of the reservoir as well. The period of ice cover and its thickness near the right bank are less compared to the left one. That is proved not only by satellite images, but also by the traditional monitoring data obtained at Ukrainka, Rzhyshchiv, Pereyaslav and Kaniv hydrological stations.

Mainly the formation of ice cover in this reservoir starts on its shallow bays near the left bank, namely in an elongated bay near Pereyaslav town. From there ice extends gradually upstream and downstream.

The first formation of ice in winter 2017-2018 was observed in the image of Sentinel-2 satellite obtained on 15.01.2018. In the cold period of 2018-2019, the first formation of ice in the bays of the reservoir can be seen in the image dated on 27.11.2018.

The longest period of ice cover in spring period is observed in the south-eastern part of the Kanivske Reservoir. In particular, this fact proves the information shown in the image obtained on 17.02.2019 p. The latest image demonstrating the ice in the spring of



a b

Fig. 4. Ice cover on the Kanivske Reservoir: a – 07.02.2019, b – 17.02.2019

2019 dated 09.03.2019. It was stored near the banks in the south-eastern part of the reservoir.

There are some features about the ice regime within the territory of Kyiv. They are closely connected to the vicinity of Kyivska HPP, the distance from which to Obolon urban district of Kyiv is about 8–9 km. The research findings showed that daily fluctuations of water level near Kyivska HPP are equal to 0.5–0.8 m, close to the central part of city they are 1.5 to 2 times less (Vyshnevskyi, 2011).

In this area the formation of ice cover starts in the bays of Matviyivska, Vydubytska and Berkivshchyna. Then ice appears in the large bays in the northern part of Kyiv: Verbljud, Sobache Hyrlo and Obolon. The next stage is the formation of ice on the secondary branches of the Dnipro River: the Dovbychka and the northern part of the Rusanivska Strait. The Venetian Strait begins to freeze later. The freezing of the main branch of the Dnipro River starts last of all. At first the formation of ice is observed in front of the main bridge of Podilsko-Voskresenskyi bridgework crossing, which is now under construction. This is partly due to the accumulation of ice carried by the Desna River. The next place with an early formation of ice locates downstream in the secondary branch of the Dnipro between Small and Great islands and the right bank of the river. The third place of ice formation is located downstream the Southern Bridge and coincides with the zone of significant increase of the water area (Fig. 5).

a b c

Fig. 5. Ice cover in the upper part of the Kanivske Reservoir near Kyiv on 07.12.2016 (a), on 16.01.2017 (b), on 25.02.2017 (c):

1 – Verbljud Bay, 2 – Sobache Hyrlo Bay, 3 – Obolon Bay, 4 – Harbor, 5 – Vydubytska Bay, 6 – the Desna River, 7 – Desenka branch, 8 – Domania Bay, 9 – Matviyivska Bay, 10 – Rusanivska Strait, 11 – Venice Strait

In case of thaw period, the water area is partially released from the ice. First of all, it refers the Dnipro main branch. At the same time, bays usually remain frozen.

In spring period, the first melting of ice is observed on the main branch of the Dnipro River. Gradually this process extends to the secondary branches. This is followed by cleaning the straits connecting the bays with the river branches. The longest duration of ice cover on the Dnipro River is observed in the Matviyivska Bay as well as in the bays in the southern part of the city. In all these cases, the impact of the Kyivska HPP, namely its uneven discharges during the day, is significant.

The analysis of the satellite images points to the special conditions in the Domania Bay close to the Desenka branch, marked with the number 8 in Fig. 5. This bay has the largest depth within Kyiv - more than 25 m. It is likely the ground water unloading, which takes place here, effects the ice regime. Sometimes ice cover is absent not only in this bay, but also along several kilometers downstream, on the Desenka branch.

The Kremenchuts'ke Reservoir. Similar to other reservoirs, there is an impact of HPP, located upstream, on the ice cover of this reservoir. Generally, downstream Kanivska HPP the ice cover is absent on the length more than 20 km. The ice cover in this reservoir is often in a form of a cluster of ice floes, which, depending on wind strength and direction, shift to one or another side. Throughout the cold period, the west winds dominate in this area, which cause large waves and shift the ice towards Kremenchuts'ka HPP.

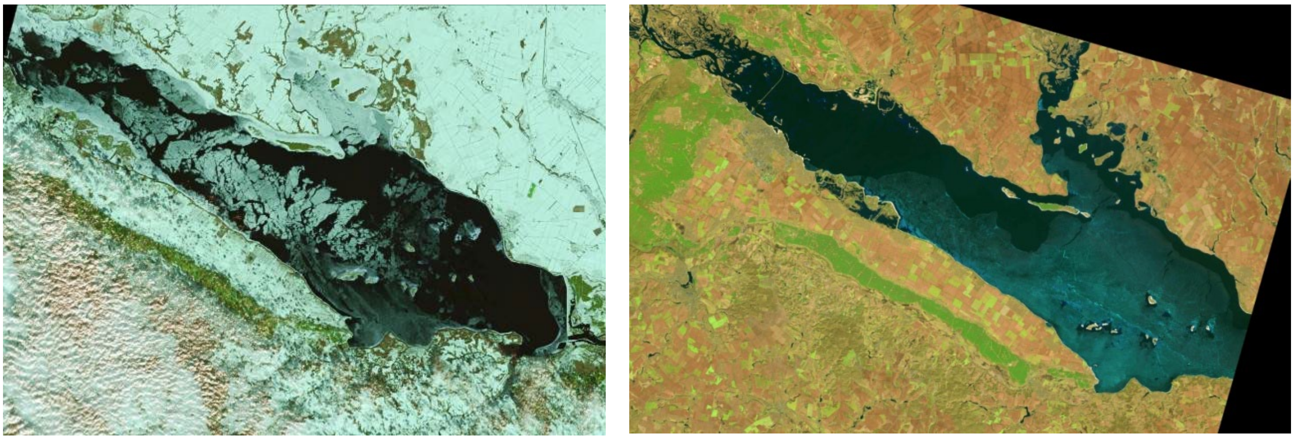
The formation of ice cover in this reservoir usually starts from its shallow bay where the Sula River (left tributary) inflows. The longest period of ice cover duration is observed on the south-eastern part of the reservoir, which is the deepest one. It can be seen in the images obtained by Landsat 8 satellite dated 11.03.2014 (Fig. 6).

The images obtained by Terra and Aqua satellites prove that the ice cover in the Kremenchuts'ke Reservoir often disappears later than in other reservoirs. It can be clearly seen in the images dated 10.04.2003, 17–18.04.2003, 08.04.2005, 10.03.2015 etc. Only occasionally, as in 2013 and 2018, the ice in the Kyivske reservoir remained longer than in Kremenchuts'ke one (Fig. 7).

The Kamianske Reservoir. This reservoir like the two other ones located upstream is significantly influenced by the HPP, namely Kremenchuts'ke. At the same time this reservoir has its specific feature – alternating wide and narrow parts. Here ice often accumulates in the places of relatively small width.

The freezing of the reservoir usually begins in its shallow bays close to its north-eastern bank. Then ice extends to the central and widest part of the reservoir. Gradually the ice extends to the south-east and partly towards the north-west. In general, the largest distribution of ice is observed in the south-eastern part of the reservoir. In the spring period, the longest presence of ice cover is registered in bays and in south-eastern part of the reservoir (Fig. 8).

It was impossible to obtain the correct date on the ice formation by the satellites in the winter period of 2017-2018 owing to the significant cloudiness in that



a b

Fig. 6. Ice cover in the Kremenchuts'ke Reservoir: a – 14.12.2013, b – 11.03.2014

period. The ice is clearly visible only in the image of Sentinel-2 obtained on 23.01.2018. The weather conditions made it difficult to determine the correct dates of freezing in the cold period of 2018-2019 as well. The first image in which the ice can be seen near banks dated 08.12.2018. The image, where the ice can be seen for the last time in 2018, dated 02.04.2018, in the spring period of 2019 – 08.03.2019.

In the winter period of 2017-2018, the ice formation in the Kremenchuts'ke Reservoir began in mid-January. For the first time it is seen in the image of Sentinel-2 satellite dated 15.01.2018. In the cold period of 2018-2019 that happened much earlier – on 29.11.2018. The image, demonstrating the ice cover for the last time in 2018, is dated 03.04.2018. Similarly, in the spring period of 2019 the image demonstrating the ice cover for the last time was obtained on 16.03.2019. As it can be seen, in the Kremenchuts'ke Reservoir the ice disappeared later than in the Kyivske and the Kanivske ones.

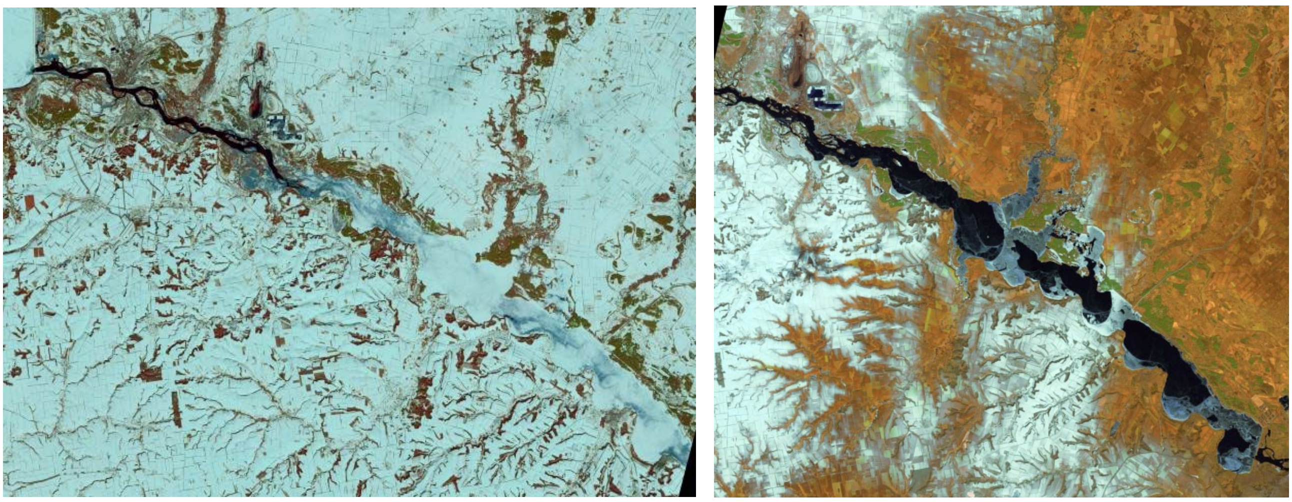
The Dniprovske Reservoir. The features of this reservoir, influencing its ice cover, are relatively small width and the largest depth among the others ones.

a b

Fig. 7. Ice cover on the Dnipro Reservoirs: *a* – 10.04.2003, *b* – 10.03.2015

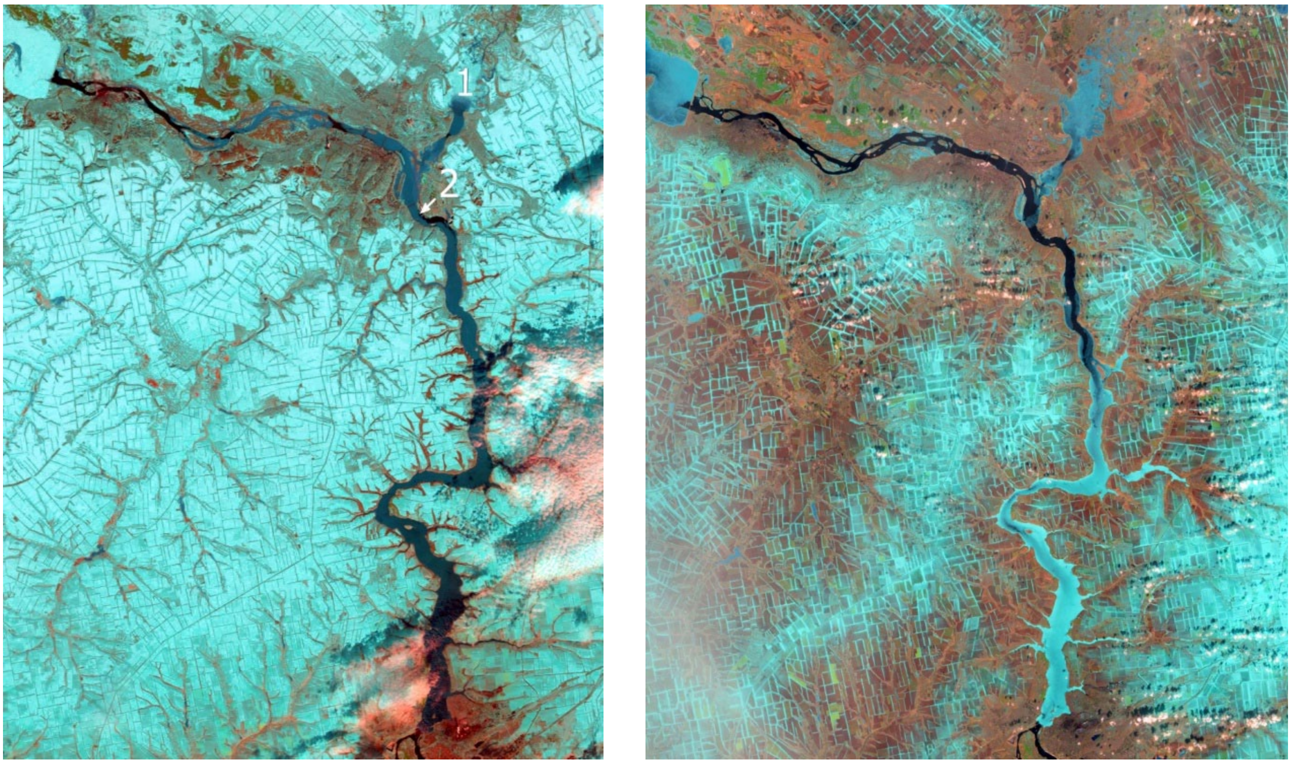
Another important factor is its southern location, compared to the Kamianske Reservoir. As a result, the freezing of the deepest southern part of the reservoir is observed rather late, at least later than it is in its central part. There are some local factors which influence the ice regime as well. The distinguishing feature is the presence of a shallow bay at the mouth of the Samara River in the north-eastern part of the reservoir. The ice cover duration in this bay is the largest. But there are no reliable data proved this fact due to the absence of hydrological observations.

The anthropogenic activities, namely HPP located upstream, as well as the wastes of industrial enterprises (in particular, metallurgical ones) of Kamianske town and Dnipro city, significantly influence the ice regime of the Dniprovske Reservoir, especially in its upper part. As a result, there is usually no ice cover in the upper part of the reservoir along the distance of about 25 km. Generally it is formed on the upper outskirts of Dnipro city, where the river is divided into several branches. Downstream in the distance from the Kaydatskyi to the Amurskyi bridges, the wastes of industrial enterprises, in particular Dniprovskyi Metallurgical Plant, significantly influence the ice cover. There are some places downstream, where storm water drainage comes from the right bank of Dnipro city. One more large enterprise, significantly influencing the ice regime of the reservoir, is Pridneprovskaya TPP. It is located in the south-eastern part of the city downstream the mouth of the Samara River. As a result of that even in cold winters an ice-hole is formed here (Fig. 9).



a b

Fig. 8. Ice cover in the Kamianske Reservoir: a – 23.01.2017, b – 12.02.2015



a b

Fig. 9. Ice cover in the Dniprovske Reservoir on 17.01.2019 (a) and 26.02.2017 (b):
1 – Samara Bay, 2 – location of Pridneprovskaya TPP

The ice regime of the upper part of the Dniprovske Reservoir is significantly influenced by weather conditions, in particular thaws. In this regard, upstream the Lotsmano-Kamianka hydrological station the ice cover is unstable, during the winter period it can be formed and disappear several times.

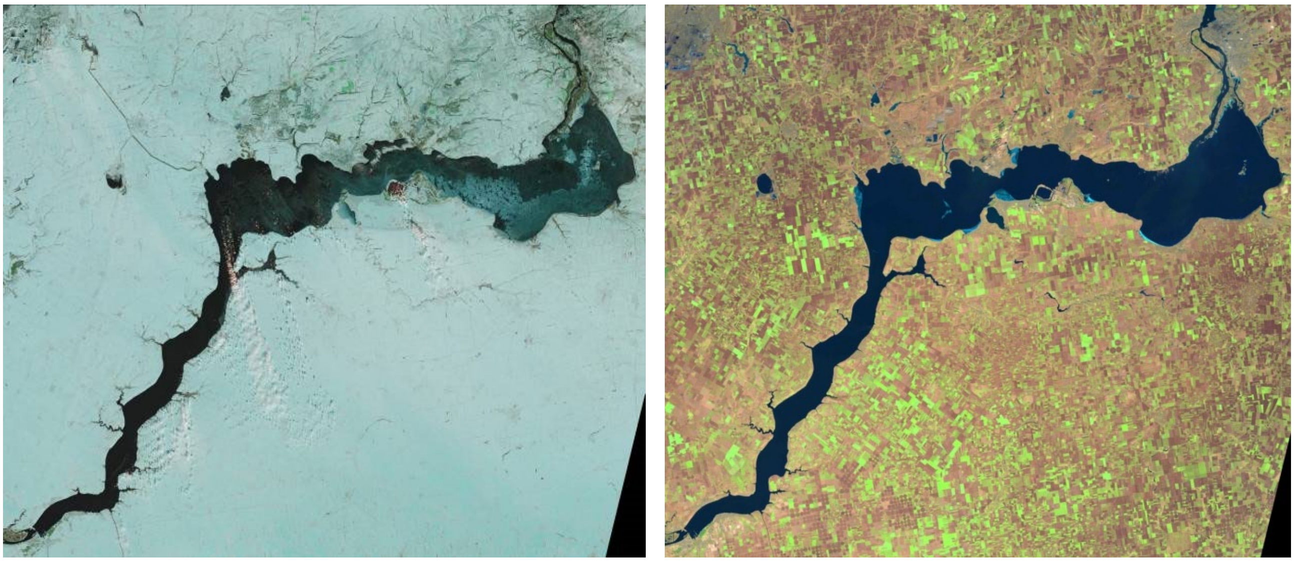
The freezing of the reservoir usually begins from the Samara Bay, as well as from the other shallow bays. Then the freezing is observed in the middle part of the reservoir. The ice cover extends from here downstream and partly upstream. These phenomena are similar to those ones, which can be observed in Kamianske and partly Kanivske and Kremenchuts'ke reservoirs.

In the winter period of 2017-2018, the formation of ice cover in the Dniprovske Reservoir began in January, but it was impossible to obtain the correct satellite date due to the significant cloudiness in that time. In the cold period of 2018-2019, the ice cover began to form earlier than usual – it can be seen for the first time in the Samara Bay in a clouded image obtained by Sentinel-2 satellite on 21.11.2018.

The ice melting in spring period starts from the upper north-western part of the reservoir. At the same time the ice cover in bays can still remain. The long presence of ice cover is observed in the Samara Bay and in the southern part of the reservoir as well. The ice melts last of all in the Samara Bay. It can be seen in the image, obtained by Sentinel-2 satellite on 28.03.2018. The large duration of ice is observed in Mandrykisvka bay close to the right bank in the southern part of Dnipro city. The last image on which the ice is visible on the reservoir in spring of 2019 has the date 06.03.2019.

The Kakhovske Reservoir. The important feature of this reservoir, influencing the ice cover, is the most southern location of it. Another distinguishing feature is the large size and considerable length of the reservoir – more than 200 km. The north-eastern part of the reservoir is much shallower and wider than the opposite part near HPP. The climatic conditions in winter period are also different – in the north-eastern part they are colder. These factors cause the spreading of ice cover in the shallow north-eastern part of the reservoir is significantly larger than it is near Kakhovska HPP. According to the monitoring data, the duration of the ice cover at Plavni hydrological station, located in the north-eastern part of the reservoir, is 20–25 days longer than near Nova Kakhovka town.

In warm winters, ice cover in the area near Kakhovska HPP does not form. It is proved by the images obtained by Landsat 8 satellite on 24.01.2014, 12.02.2015, 30.01.2016, 20.02.2018, 23.02.2019 etc. Moreover, in warm winters ice cover in the north-eastern part of the reservoir cannot be the continuous as well. That is proved by the images dated 20.01.2014, 12.02.2015 and 20.02.2018 (Fig. 10).



a b

Fig. 10. Ice cover in the Kakhovske Reservoir: a – 20.01.2014, b – 20.02.2018

The largest duration of ice cover in this reservoir is usually observed in the bays in the north-eastern shallow and wide part of the reservoir. It is proved by the image obtained on 20.02.2018.

The ice regime of the Kakhovske Reservoir, like most others, is influenced by industrial wastes. Namely, they are Zaporizka TPP and Zaporizka NPP, to the west of which an elongated ice-hole is usually formed. There is also a rather narrow water area in the upper part of the reservoir with the length of about 30 km that is also greatly influenced by Dniprovska HPP and enterprises of Zaporizhzhya city. That prevents ice formation in this area.

During the winter of 2017-2018, the ice in the Kakhovske Reservoir can be seen for the first time in the image of Sentinel-2 obtained on 24.01.2018. Before that date the reservoir was covered by clouds for more than a week. Next winter, the ice began to form much earlier. In particular, some small plots of ice can be seen in the image dated 03.12.2018. The image where the ice cover in the Kakhovske Reservoir can be seen for the last time in the spring period of 2018 dated 26.03.2018, in 2019 – 24.02.2019. In last case it were very small areas close to the banks in wide part of the reservoir. As it can be seen, the duration of ice phenomena in the Kakhovske Reservoir is much shorter than in the ones located upstream.

Conclusions. Using remote sensing data enables to characterize the ice cover in the reservoirs, constructed on the Dnipro River. The important factor influencing the ice regime is the location of the reservoirs and correspondingly climatic conditions. Thus, the duration of ice phenomena and ice cover in the Kyivske Reservoir is significantly larger than they are in the Kakhovske one located in the lower reach of the Dnipro River. In most reservoirs, besides the Kyivske and Kakhovske ones, their central parts freeze first. Freezing of water area, located upstream, is restricted by the operation of HPP. In turn, freezing of deep-water area adjacent to the dam is restricted by the significant heat storage of water mass as well as wind waves.The combination of several factors (more southern location, the operation of Kyivska HPP, discharges from some enterprises of Kyiv cause the extension of ice cover in the Kanivske Reservoir is much less than it is in the Kyivske one. The largest duration of ice cover, as a rule, is observed on the Kremenchuts'ke Reservoir, located in the middle of the cascade. In the Kamianske reservoir ice often accumulates in its narrow places. In general, the extension of ice in its southeastern part is the greatest. The Dniprovske Reservoir has the smallest duration of ice phenomena and ice storage in its upper part. In addition to the impact of the upstream hydroelectric power station, this is due to the influence of discharges from industrial enterprises of Kamianske town and Dnipro city. The longest ice phenomena in this reservoir is observed in the Samara Bay. In general, the shortest duration of ice cover is observed in the Kakhovske Reservoir, which has the most southern location. This especially relates to the southwestern part of this reservoir adjacent to the dam.

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