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Evaluation of Changes in the Scale and Direction of Thermal Pollution Flows in the Kalinin NPP Cooling Lakes From 1985 to 2020

Alexandr V. Bocharov[1], Sergey A. Lebedev[2,3,4], Pavel N. Kravchenko[1,5]

[1]Tver State University, Tver, Russia
[2]Geophysical Center of the Russian Academy of Sciences, Moscow, Russia
[3]Maikop State Technological University, Maikop, Russia
[4]National Research University Moscow Institute of Electronic Technology, Moscow, Russia
[5]S. Yu. Witte Moscow University, Moscow, Russia
* **Correspondence to:** Alexandr V. Bocharov, bochalex@bk.ru

Abstract: The article evaluates the change in the scale and direction of thermal pollution flows of the cooling lakes of the Kalinin NPP from 1985 to 2020 based on the use of Earth remote sensing data. A retrospective analysis was carried out using satellite images obtained by the sensors of the Landsat series satellites. An analysis of the distribution of surface water temperature over the water area of NPP cooling lakes has been carried out. The change in the structure of thermal pollution after the increase in the capacity of the Kalinin NPP is determined. The temperature of the cooling lakes of the Kalinin NPP was estimated relative to the background indicators in the lakes-analogues, which were used as nearby Lake Navolok and Lake Kezadra. The study identified five stages of transformation of the water mass circulation system in the cooling lakes of the Kalinin NPP.

Keywords: remote sensing, water temperature, thermal pollution, Kalinin NPP, Landsat.

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Research Article

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1. Introduction

Provision of the territory with sufficient power capacity is a necessary condition for economic development. The most advanced way to generate electricity is nuclear power. The advantages of nuclear energy are: huge energy intensity, stability of generation, reduction of carbon emissions, the possibility of reusing fuel. About 10% of the world's electricity is generated by more than 440 operating nuclear reactors [*International Atomic Energy Agency*, 2021]. In Russia, about 20% of electricity is generated by 38 reactors located at 11 operating nuclear power plants, one of which is the Kalinin Nuclear Power Plant.

To cool the nuclear power plant, a circulation system of circulating water supply with a cooling pond is used. Cooling of the heated water flow in cooling ponds occurs due to heat transfer from the water surface. Efficient cooling is a necessary condition for the operation of nuclear power plants. Artificial or natural reservoirs are used as reservoirs-coolers. The Udomelskoye reservoir acts as a cooling reservoir for the Kalinin NPP. It is formed on the basis of the natural lakes Udomlya and Pesvo, which are regulated by a dam on the Syezha River flowing from them.

The history of its appearance begins in the 70s of the XX century, at that time, a powerful source of electricity was required to provide the energy system of the center and north of the USSR. In 1970, a commission was established to select a site for the construction of a nuclear power plant. Of all the possible options, a site was chosen on the southeastern shore of Lake Udomlya, 3 km from the village of Udomlya (Figure 1). In the production cycle of the Kalinin NPP, it was supposed to use the waters of the Pesvo and Udomlya lakes as a coolant.

Figure 1. Overview map of the study area.

Three years were spent on the design of the nuclear power plant. Construction work began in 1973 [*Myasnikov and Scriabin*, 1994]. The first stage involved the construction of two power units with a capacity of 1000 MW. Power unit 1 was launched in 1984, and in 1986 it was brought to its design capacity. Power unit 2 was launched in 1986 and brought to full capacity in 1987.

In 1984, the construction of the second stage of the Kalinin nuclear power plant began. For a number of reasons, the construction of power unit 3 was greatly delayed; it was launched and brought to its design capacity only in 2004. In 2007, the final project for increasing the capacity of the KNPP to 4000 MW was adopted, and in 2011, power unit 4 was commissioned and connected to the power grid.

The construction of such a large-scale facility as a nuclear power plant inevitably leads to anthropogenic transformation of the surrounding natural complexes. During construction, the landscape undergoes complex changes. Significant changes in the natural environment during construction are associated with the need to create hydraulic structures that allow efficient cooling of nuclear power plants.

After the start-up of the power plant, one of the main factors affecting the ecosystems of cooling ponds is heat emission. The issues of thermal pollution of water bodies are always an important part of the environmental impact assessment in the regions of operating NPPs [*Beznosov and Suzdaleva*, 2001].

Thermal pollution of reservoirs is an increase in water temperature compared to the usual for a given reservoir due to the discharge of warm wastewater into it [*Ilshinsky*, 2004]. An increase in water temperature affects both directly the physiology of hydrobionts and the nature of the course of chemical processes in the aquatic environment [*Suzdaleva and Beznosov*, 1999].

According to the temperature distribution of the surface layer, «heated» and «non-heated» zones are distinguished, which was used in most works on cooling ponds. Usually, with such an approach, several zones of different degrees of heating are distinguished: strong, moderate, and weak [*Mordukhai-Boltovskoy*, 1975].

The area of the zone where the increase in temperature is observed is largely determined by the difference between the temperature of waste water and the natural temperature of the surface water of the reservoir at a given particular moment in time. In winter, the heated zone can be reduced due to the rapid cooling of the waters.

Quite often, in the cold season, the boundaries of the entire water mass of the circulation flow from the discharge to the NPP water intake are clearly visible, visually, from the steam above the water and the nature of the formation of the ice cover. In remote areas of the circulation flow, ice forms at a much lower air temperature than in areas occupied by peripheral water masses. In the warm season, it is difficult to visually establish the boundaries of water masses.

The use of remote sensing data greatly simplifies the assessment of thermal pollution of cooling lakes, allows us to evaluate its dynamics, visualize the circulation flows of the distribution of heated waters, while studies using traditional methods do not provide such a spatial picture, and they are more economically costly and laborious.

The purpose of this study is to assess the change in the scale and direction of thermal pollution flows of the cooling lakes of the Kalinin NPP from 1985 to 2020 based on the use of Earth remote sensing data.

Studies of the thermal regime on lakes Pesvo and Udomlya began in 1972. Prior to the commissioning of the station, observations were carried out at a fairly limited number of points; since 1985, the observation system has been expanded. Detailed and surface thermal surveys were carried out on the lakes, which alternated with surveys of currents, carried out on a limited number of verticals. Standard equipment was used to measure water temperature, current velocities and hydrometeorological characteristics [*Institute FSUE NIAEP*, 2002].

Technical water supply of the Kalinin NPP is carried out according to the reverse scheme using a lake-type cooling reservoir formed on the basis of the natural lakes Udomlya and Pesvo, regulated by a dam on the Syezha River. With the start of the nuclear power plant, the temperature regime of the lakes has changed. The water, heated by the condensers of the turbines by 8–10 degrees, enters the waste channels and then into the lakes. As a result, the water temperature rises, reaching critical values at the mixing points of waste and lake waters. Further, as the circulation flow spreads, as a result of the mixing of lake and waste waters, the water temperature decreases. In the peripheral parts of the lakes, water heating is less pronounced.

Since the start of operation of the Kalinin NPP, several more reactors have been put into operation, the circulating water supply system has gradually undergone a significant transformation, and thermal pollution flows have increased significantly. The main main hydraulic structures in the cooling lakes of the Kalinin NPP as of 2020 are shown in Figure 2.

Water is taken from Lake Udomlya, discharged into Lake Pesvo and Lake Udomlya. After a multi-stage transformation, the system of outlets of heated water used for cooling the systems of the Kalinin NPP, as of 2020, includes: a discharge channel in the lake. Pesvo, a diverting channel in the lake. Udomlya, outlet channel from cooling towers 1 and 2, outlet channel from cooling towers 3 and 4 (Figure 3).

The dam directing the flow of water prevents the direct ingress of heated water into the source of the Syezha River, flowing from the lake. Udomlya. The volume of withdrawn water resources is spent to compensate for irretrievable losses due to natural and additional evaporation from the cooling reservoir; for evaporation and droplet entrainment from cooling towers and spray ponds. Lakes are fed by rivers and streams flowing into them [*ROSATOM*, 2006].

2. Data and methods

In this study, a retrospective analysis of the transformation of the circulation system of water masses and an assessment of the thermal regime of the cooling lakes of the Kalinin NPP were carried out according to the data of remote sensing of the Earth.

The study used images from Landsat series satellite sensors from 1985 to 2020 [*United States Geological Survey*, 2023]. To determine the water surface, in order to identify the boundaries and retrospective analysis of the appearance of hydraulic structures, remote sensing data in the near infrared range obtained by sensors were used:

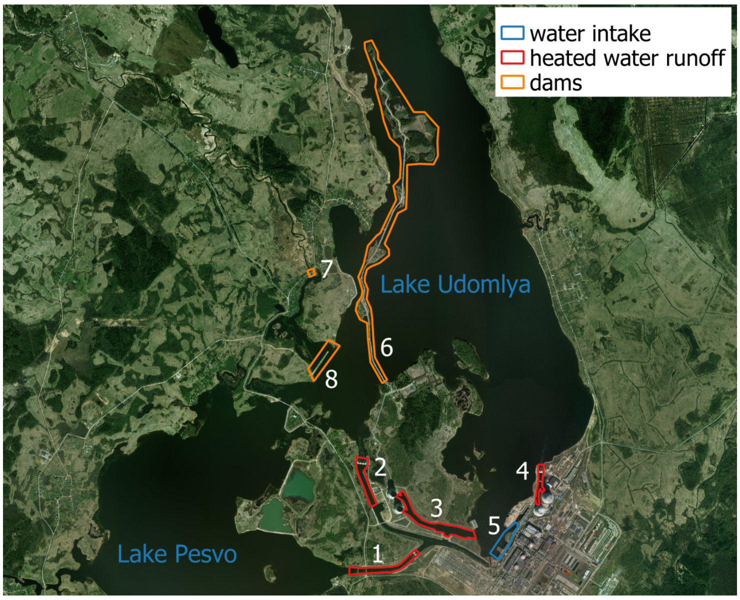


Figure 2. Location of the main hydraulic structures in the cooling lakes of the Kalinin NPP: 1 – water discharge through the canal into the lake Pesvo; 2 – water discharge through the canal into the lake Udomlya; 3 – outlet channel of cooling towers 1,2; 4 – outlet channel of cooling towers 3,4; 5 - water intake; 6 – dam directing the flow of heated waters in Lake Udomlya; 7 – dam on the river Syezha; 8 – dam directing the flow of water at the source of the river Syezha.

- TM of the Landsat-5 satellite (4th image channel (0.76–0.9 µm));
- ETM+ of the Landsat 7 satellite (4th image channels (0.77–0.9 µm));
- TIRS of the Landsat-8 satellite (5th channel of images (0.85–0.88 µm)).

To obtain the temperature values of the radiating surface, we used remote sensing data in the infrared range obtained by sensors:

- TM of the Landsat-5 satellite (6th image channel (10.40–12.50 µm));
- ETM+ of the Landsat 7 satellite (61st and 62nd image channels (10.40–12.50 µm));
- TIRS of the Landsat-8 satellite (10th and 11th image channels (10.30–12.50 µm)).

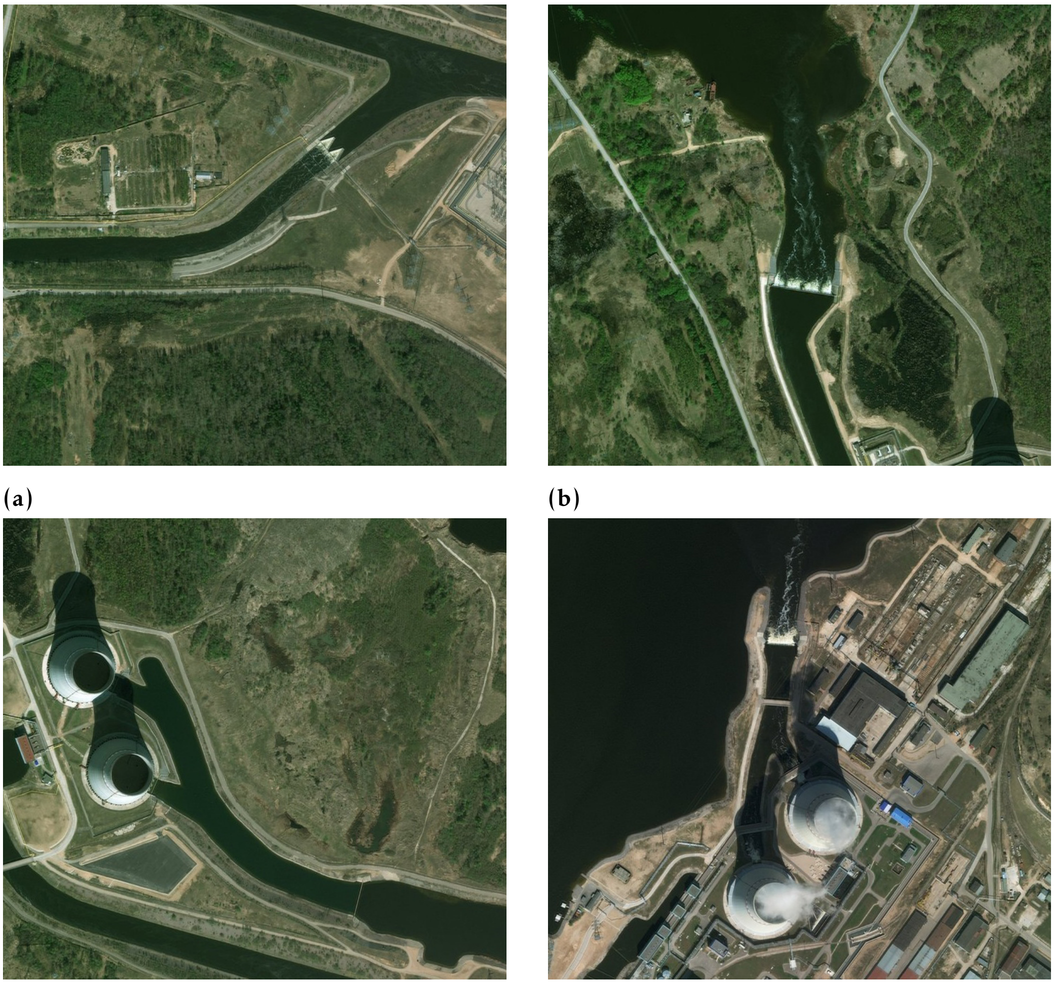
The brightness of satellite imagery pixels was converted into the brightness temperature of the water surface using standard formulas [*Chander and Markham*, 2003]. For pure water, the emissivity is close to unity; therefore, the brightness temperature of the water surface has values close to the actual temperature.

3. Results

To correlate thermal pollution flows with the transformation of hydraulic structures in the Udomelskoe reservoir, an analysis was made of changes in the water mass circulation system from 1985 to 2020. According to satellite images, the increase in bulk objects in the water area of the reservoir was recorded, and areas were identified where the increase in the area of the water surface was determined. It should be noted that during the construction of bulk hydraulic structures, the identification of these objects was carried out using satellite images with a resolution of 30 m / pixel, it was also associated with fluctuations in the water level in the reservoir, and water erosion, so sometimes the outlines of the object may appear, but then be absent on later pictures.

The satellite image of 1985 shows that after the launch of the station, the flow of heated water emission was carried out only through the outlet channel to Lake Pesvo. From 1987 to 1991, the construction of separate sections of the jet-directing dam in the western part of Udomlya Lake was observed.

According to satellite images of the 1990s, permanent changes in the configuration of the outlet channels to the Pesvo and Udomlya lakes are observed, but the scale of the



(a) (b) (c) (d)

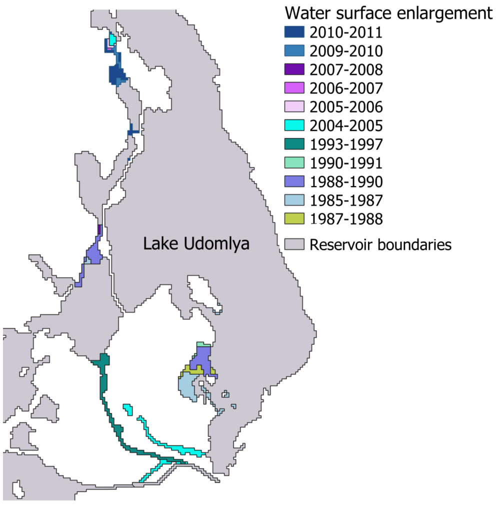
Figure 3. (a) Discharge of water through the canal into Lake Pesvo. b) Discharge of water through the canal into Lake Udomlya. c) Outlet channel of cooling towers 1,2. d) Outlet channel of cooling towers 3,4.

data used does not allow a detailed assessment of these transformations. But at the same time, the used remote sensing data allow us to establish that the construction of the canal to Lake Udomlya began after 1993. By 1997, the contours of the channel on the satellite image become more visible. From 1997 to 2005, no strong changes were found in the water area of the Udomelskoye reservoir.

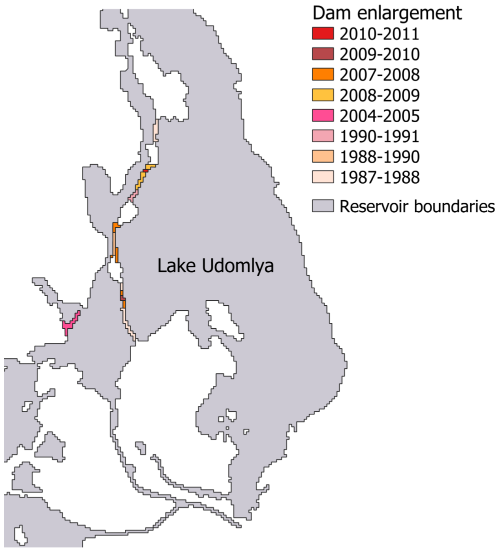
On the satellite image of 2005, the outlines of a jet-directing dam at the source of the Syezha River appear, and a discharge channel from cooling towers 1 and 2 appears. In 2008 in Lake Udomlya, the construction of a jet-directing dam to the north is observed, and in 2009 another large section of the dam is added. In 2010, in the northern part of Lake Udomlya, near the village of Shcheberino, work began on creating a continuation of the canal to divert the heated waters of the jet-directing dam to the northernmost part of the lake, which, according to satellite imagery, were completed in 2011. Since that time, significant changes in the configuration of hydraulic structures have not been determined.

It should be noted that from 1985 to 1991 in the southwestern part of the lake. Udomlya, east of cooling towers 1 and 2, there is an intensive increase in the area of the water surface. This is probably a consequence of the withdrawal of materials for the construction of hydraulic structures and other infrastructure of the nuclear power plant, as well as an increase in the water level due to the construction in 1987 of a hydroelectric complex on the Syezha River [*Obyazov et al.*, 2019], flowing from cooling lakes. As a result of this, the area of Lake Udomlya increased by 1.9%. The increase in the area of the lake has increased evaporation from the water surface. This makes a small contribution to the hydrothermal regime of the reservoir.

All major changes in the water area of the Udomelskoye reservoir, obtained from the analysis of remote sensing data, are shown in Figure 4.



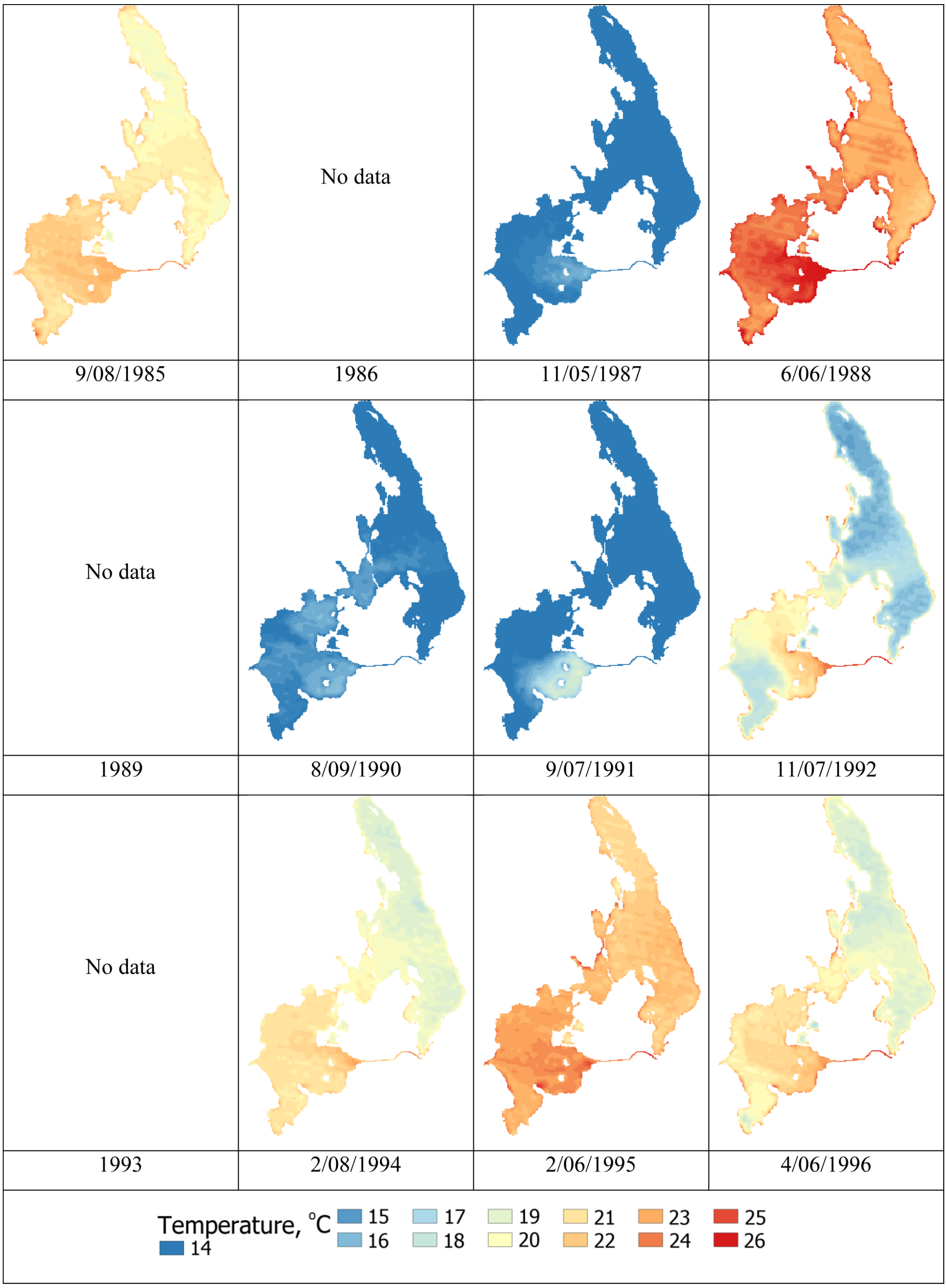
(a)



(b)

Figure 4. (a) Retrospective analysis of the increase in the area of the water surface of the Lake. Udomlya according to sensors of Landsat series satellites. b) Retrospective analysis of the construction of hydraulic structures in Lake Udomlya according to the data of sensors of Landsat series satellites.

To study the thermal pollution of the Udomelskoye reservoir from 1985 to 2020, 33 satellite images were selected, from which the rasters of the water surface temperature distribution were constructed (Figure 5). The obtained data allow: to study the spatial and temporal distribution of the temperature of water masses in lakes; highlight overheated and stagnant areas; evaluate the input characteristics of thermal conditions for the river Syezha flowing from Lake Udomlya; find solutions to other problems.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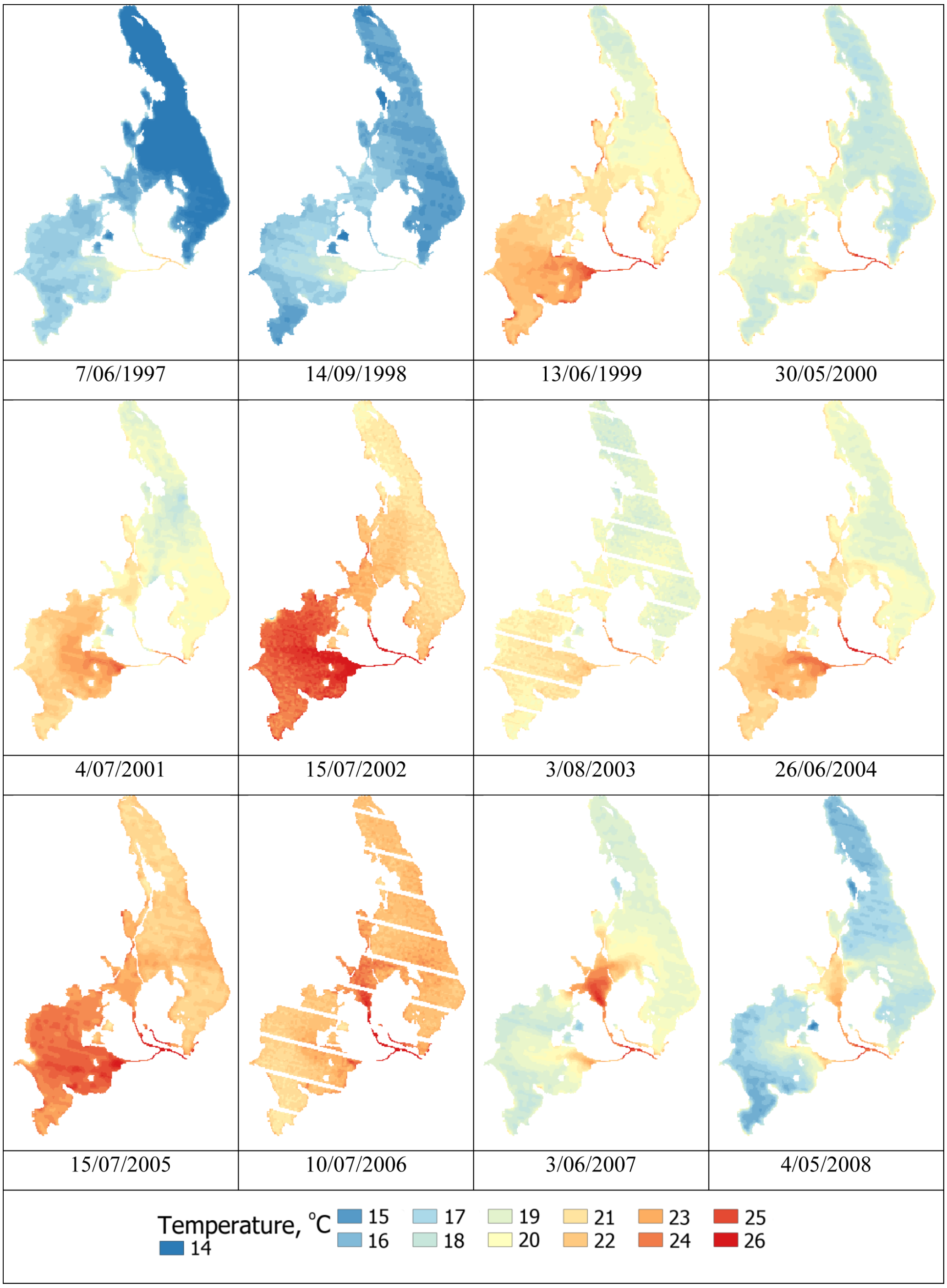
(a)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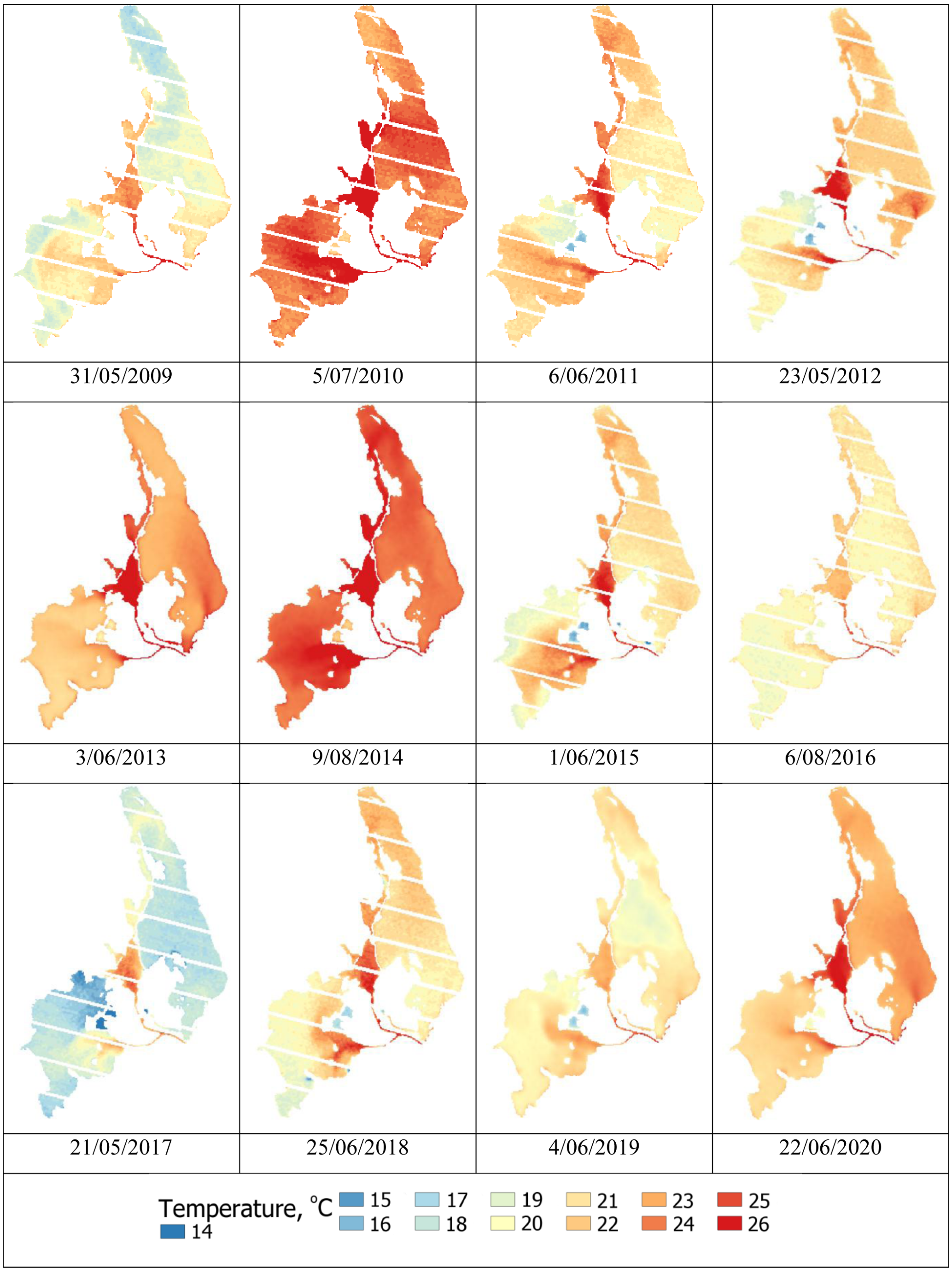
(b)



(c)

Figure 5. Water surface temperature of the cooling lakes of the Kalinin NPP according to the sensors of the Landsat series satellites for 1985–2020.

An analysis of remote sensing data showed that until 2005, the used space images almost always showed an excess of the average water surface temperature in Lake Pesvo over Lake Udomlya. In 2004, power unit 3 of the Kalinin NPP was put into operation. After 2004, there is a change in the structure of thermal pollution in the cooling water bodies of the Kalinin NPP, and the average water surface temperatures in Lake Udomlya become predominantly higher than in Lake Pesvo (Figure 6). In 2011, power unit 4 of the Kalinin NPP began to operate. Also in 2011, the water circulation scheme changed significantly and took on a modern look. This caused an even greater increase in water temperature in Lake Udomlya.

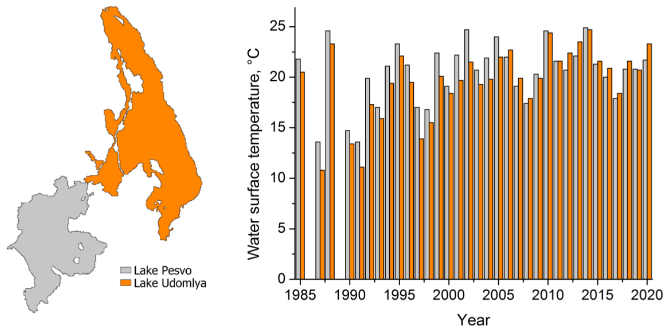


Figure 6. Change in the average temperature of the water surface in the cooling reservoirs of the Kalinin NPP according to the data of sensors of the Landsat series satellites.

In 2011, the construction of jet-directing dams was completed, as a result of which "hot" and "cold" areas began to be clearly observed in Lake Udomlya (Figure 7). The analysis of remote sensing data after 2011 showed that the average water surface temperature in the "hot" area exceeded the "cold" area by 1.3–3.3 °C.

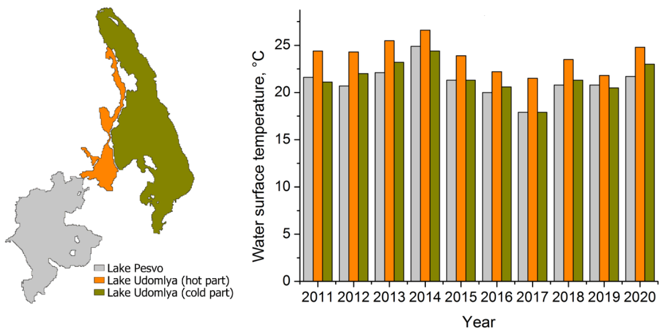


Figure 7. Analysis of temperature differentiation in the "hot" and "cold" areas of Lake Udomlya according to the data of sensors of Landsat series satellites.

To assess the temperature of the cooling lakes of the Kalinin NPP relative to the background indicators, a comparison was made with analogous lakes, which were used as nearby Lake Navolok and Lake Kezadra (Figure 1). An analysis of space images obtained by the sensors of the Landsat satellites showed that from 1985 to 2020. The Udomelskoye reservoir has always had an excess of surface water temperature over the background values within 1.3–7.7 °C (Figure 8). On average, over the period under study, the temperature of the cooling lakes of the Kalinin NPP was higher than that of the analogue lakes by 3.1 °C. At the same time, there is an increase in water temperature relative to the background values after the completion of work to increase the power of the station. From 1985 to 2010 the temperature rise relative to analogue lakes was 3.3 °C, after 2011 it is 4.8 °C.

According to the rasters of the temperature distribution of the water surface of the cooling lakes of the Kalinin NPP, the direction of heat flows can be traced. A comparison of heat flows and a retrospective analysis of the time of the appearance of hydraulic structures provides good opportunities for analyzing the changes that have occurred from 1985 to 2020. The use of remote sensing data made it possible to trace the main stages of the transformation of the water mass circulation system. Based on a retrospective analysis of space images, five main stages of the transformations that took place were identified (Figure 9).

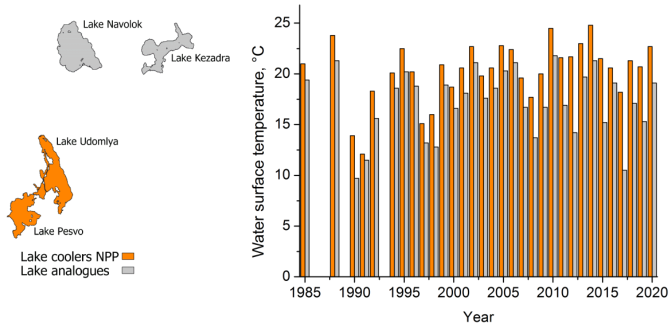
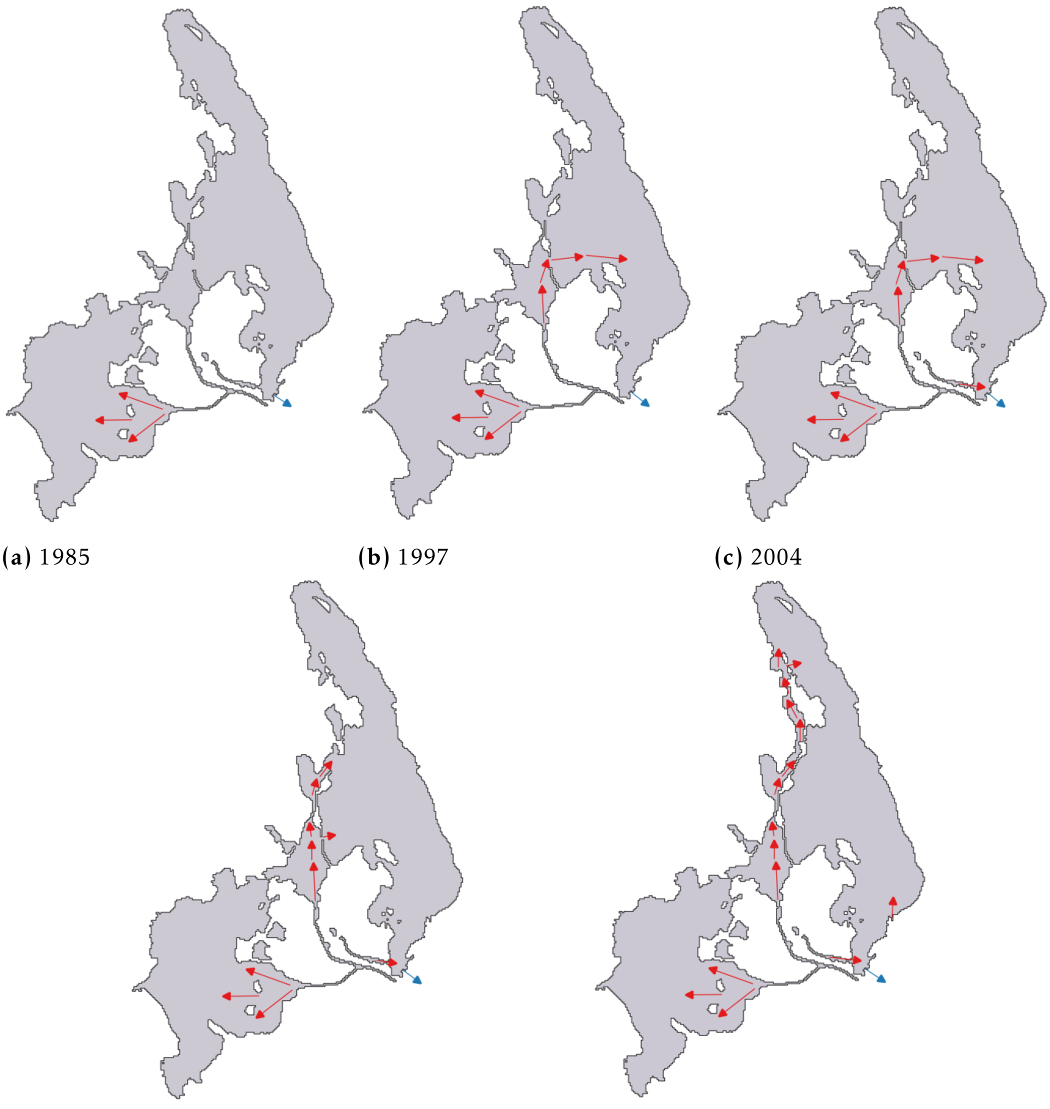


Figure 8. Analysis of temperature differentiation in the Udomelskoye reservoir and lakes of analogues according to data from sensors of Landsat series satellites.



(**a**) 1985 (**b**) 1997 (**c**) 2004

(**d**) 2008 (**e**) 2011

Figure 9. The main stages of changes in the sources of thermal pollution emission and its circulation in the cooling lakes of the Kalinin NPP according to the data of the sensors of the Landsat series satellites.

4. Conclusion

The analysis of the temperature distribution of the water surface of the cooling lakes of the Kalinin NPP based on Landsat satellite images confirms the promise of using remote sensing data to assess the magnitude and direction of thermal pollution of the cooling lakes of the NPP. The application of these methods made it possible to study the spatial distribution of water temperature in lakes, identify overheated and stagnant areas, evaluate circulation flows in cooling lakes, and compare with background values in analogue lakes.

The study showed that, after 2004, there is a change in the structure of thermal pollution of the cooling reservoirs of the Kalinin NPP, and the average water surface temperatures in Lake Udomlya become predominantly higher than in Lake Pesvo.

The construction of jet-directing dams caused the division of Lake Udomlya into a “hot” and “cold” area. The analysis of remote sensing data showed that the average temperature of the water surface in the “hot” area exceeds the “cold” one by 1.3–3.3 °C.

The assessment of the temperature of the cooling lakes of the Kalinin NPP relative to the background values in the lakes-analogues, which were used as nearby Lake Navolok and Lake Kezadra, showed an excess in the range of 1.3–7.7 °C.

When comparing a retrospective analysis of the appearance of hydraulic structures and rasters of the distribution of water surface temperature, five stages of the transformation of the circulation system of water masses in the cooling lakes of the Kalinin NPP were identified. As a result of the increase in the capacity of the Kalinin NPP in the Udomelskoye reservoir, there was an increase in thermal pollution of the environment. At the same time, there was an increase in the efficiency of the use of existing cooling reservoirs. After the completion of the last stage of the construction of hydraulic structures, a more uniform distribution of water temperature in the main water areas of the cooling lakes is observed.

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