

THE APPLICABILITY OF REMOTE-SENSING AND GEODETIC METHODS TO STUDYING WATER BODIES ON THE WESTERN WHITE SEA COAST

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ABSTRACT

The article presents the results of field studies carried out by the Department of Land Hydrology, Faculty of Geography, Lomonosov Moscow State University, in the area near the White Sea Biological Station, Moscow State University (Kandalaksha Bay, White Sea) in January, June, and September 2014 and January 2015. The objects of studies were the unique lakes on the White Sea coast at different stages of their isolation and separation from the sea. Geodetic methods were applied to determine the surface elevation of modern lakes. The degree of isolation of the studied water bodies was estimated and used to identify the following types of lakes: those permanently disconnected from the sea, those having such connection periodically, and those having it permanently in the form of daily tidal influence. The decrease in seawater inflow caused by ice cover was estimated with the use of a conductivity data logger. In winter, the study area is difficult to access and to work in; therefore, remote sensing products such as GlobSnow were used to determine water storage in the snow cover yet another that affects water level and water chemistry in lakes after snow melting. It was shown that large-scale satellite data could be used for assessing the total snow water equivalent in a small area along coast zone. However snow surveys are still in need to determine the local characteristics and spatial variability of snow cover on the ice cover of lakes and lake watersheds. The ground-based observations of snow storage in winters 2010, 2014, and 2015 were compared with remote sensing data obtained by the Finnish Meteorological Institute (the GlobSnow project).

INTRODUCTION

Most of the White Sea coastal zone is currently raising as a result of isostatic land uplift, which began 12.000 years ago after the disappearance of the glaciers of the most recent ice age stage and has continued with a speed of about 40 cm per century (1). The result is the separation of numerous gulfs, small bays, and coastal straits from the sea and the formation of small lakes, which gradually lose their connection with the sea. The geomorphological and hydrological features of the lakes create specific hydrochemical and hydrobiological conditions (2,3,4). The study of lakes, which are at different stages of isolation from the sea, allows tracing the evolution of their hydrological and chemical regime and creating models to describe the evolution of the environmental situation in the coastal zone.

The territory under study is shown in Figure 1. All the lakes, except Trekhtsvetnoee, are located near the White Sea Biological Station (WSBS), Lomonosov Moscow State University. It is located on Kindo Peninsula in the northern Republic of Karelia, Russia. The coordinates of the station are 66°34'N, 33°08'E.

The degree of isolation of the water bodies under study could be determined by levelling the lake surface elevations and comparing them to the sea level. In addition, the influence of the sea on the lake can be evaluated by correlating the data of automated logging of lake level, temperature, and salinity with the appropriate characteristics of the sea.

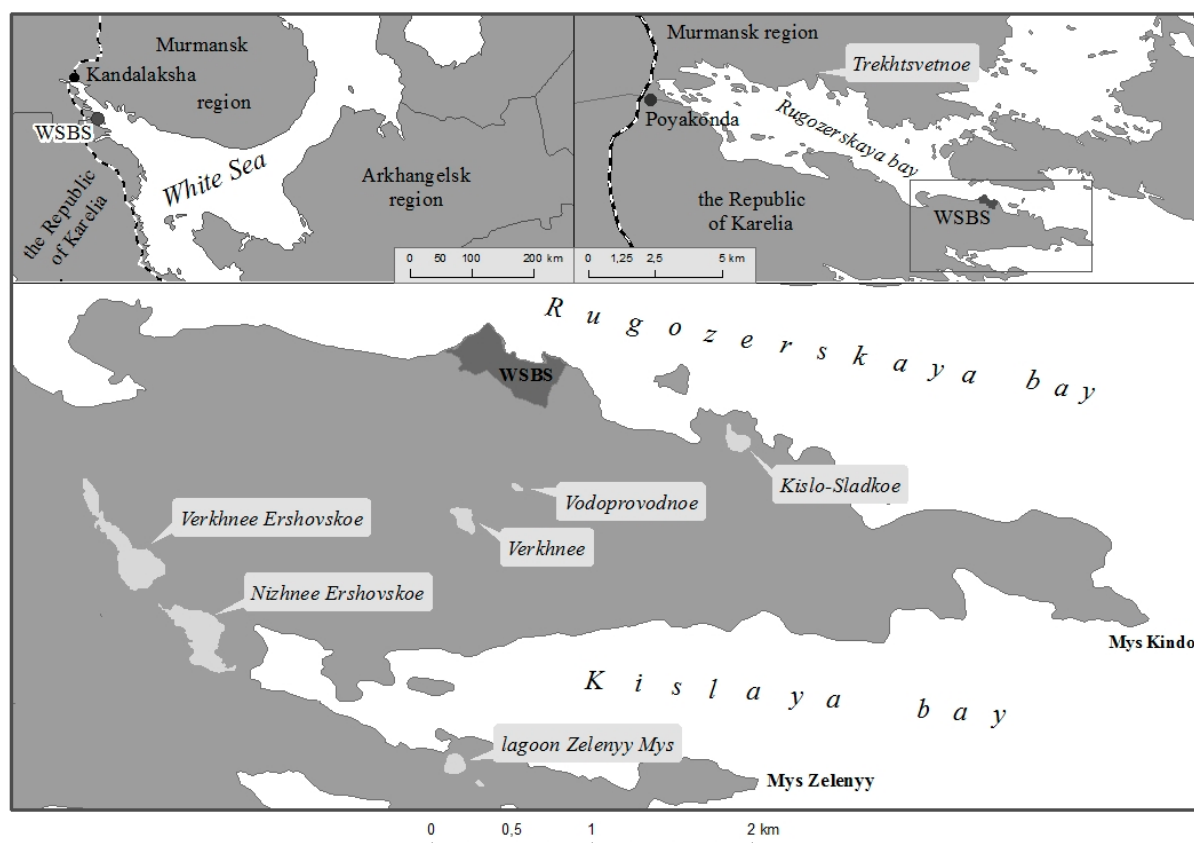


Figure 1: The study region (bottom panel).

Data on the fluctuations of lake water levels show that the level variations in the lagoons (Zelenyi Cape Lagoon, Kislo-Sladkoe Lake) in the ice-free period correlate with the tidal level variations in the sea. Automatic hydrological survey techniques enable tracing water level fluctuations in the sea and in lakes near the dams separating the lake from the sea, including winter, when the water bodies are covered with ice.

Another factor, which can affect water level and chemistry in the lakes, is snow melting. While winter snow surveys are difficult to implement, there are remote sensing products such as GlobSnow, which enable the determination of water storage in the snow cover. Ground snow surveys were conducted by students of the Faculty of Geography, Moscow State University, in winters of 2010, 2014, and 2015 with the aim to estimate snow water equivalent (SWE) and to compare it with GlobSnow (5) data.

The main goal of this paper is to analyse the level regime of the studied waters, which show the effects of sea tides and precipitation (especially its solid component, which determines the snow water storage). In the course of this work, an attempt was made to develop a complex method (which incorporates different geodetic and remote-sensing methods) for studying the lakes that are separating from the sea on the western coast of the White Sea.

DATA AND METHODS

The following data were used in this study:

- geodetic surveying data, including geographic coordinates and normal heights for near-lake reference points and lake surface elevations;
- data from hydrological and hydrochemical surveys;
- data from terrestrial snow surveys;
- SWE data from the GlobSnow project.

Lake elevations

Determination of elevations of the studied lakes was one of the primary objectives of field studies. First, it was necessary to establish reference points on the lake shore, to determine their altitude and planning marks. Leica Geosystems ATX1230 GG (rover station) and GX1230 GG (base station) receivers were used for obtaining the coordinates of the reference points with a centimetre accuracy (Figure 2a). A high precision electronic level Leica Sprinter 100M was then used to perform the geometric levelling of each lake's water surface at shoreline in summer (Figure 2b). In winter, the levelling was performed to the selected ice hole on the surface of the lake.



Figure 2: Survey operations in winter 2014. (a) Reference point positioning. (b) Levelling.

Water level, temperature, and salinity

To study the dynamics of water level, temperature, and salinity, appropriate sensors (Solinst Company) were used. All three parameters were combined within one conductivity data logger, which has a 5-year battery life, and a memory for 16.000 sets of readings, all in a small waterproof housing. The record of water levels was performed with Levellogger Edge loggers with a 10 min sampling rate.

Snow cover

Snow survey was carried out to determine the characteristics and spatial variability of snow cover on the ice of lakes and on lake watersheds. These data will help to determine the water content of the snow cover for a detailed assessment of the water balance in the future.

The route snow surveys were carried out using snow stakes M-104 and a weighting-type snow gauge BC-43. Along most routes, snow depth was measured every 10 metres, and snow density was measured at every fifth point. The coordinates of snow-density measurement points were determined using a GPS navigator. Eight snow survey routes across the lakes and their watershed were performed during the expedition.

The ground-based observations of snow storage in the winters of 2010, 2014, and 2015 were compared with remote sensing data obtained by the Finnish Meteorological Institute in the GlobSnow Project (6). The project provides satellite-derived areal extent of snow (SE) on a global scale and satellite-derived snow water equivalent (SWE) for the Northern Hemisphere. The SWE record is based on the time series of measurements by two spaceborne passive microwave sensors (SMMR and SSM/I) spanning 1979 to 2012 (7).

The spatial resolution of the product is 25 km on EASE-grid projection. The SWE product is generated using a daily time resolution. A thematic accuracy goal of 30-40 mm for conditions with less than 150 mm of SWE is proposed for the global GlobSnow SWE product, depending on the availability of weather station data (8).

Daily satellite-derived SWE data, averaged over the study period, were used for comparing with in-situ observations. As seen in Figure 3, almost 82% of the Kindo Peninsula is occupied by forests, which also dominate in the surrounding territory. The mean values of SWE for the prevailing land-

scape were calculated for each year based on snow survey data. After that these values for each year for Kindo were taken and extended to the whole pixel.

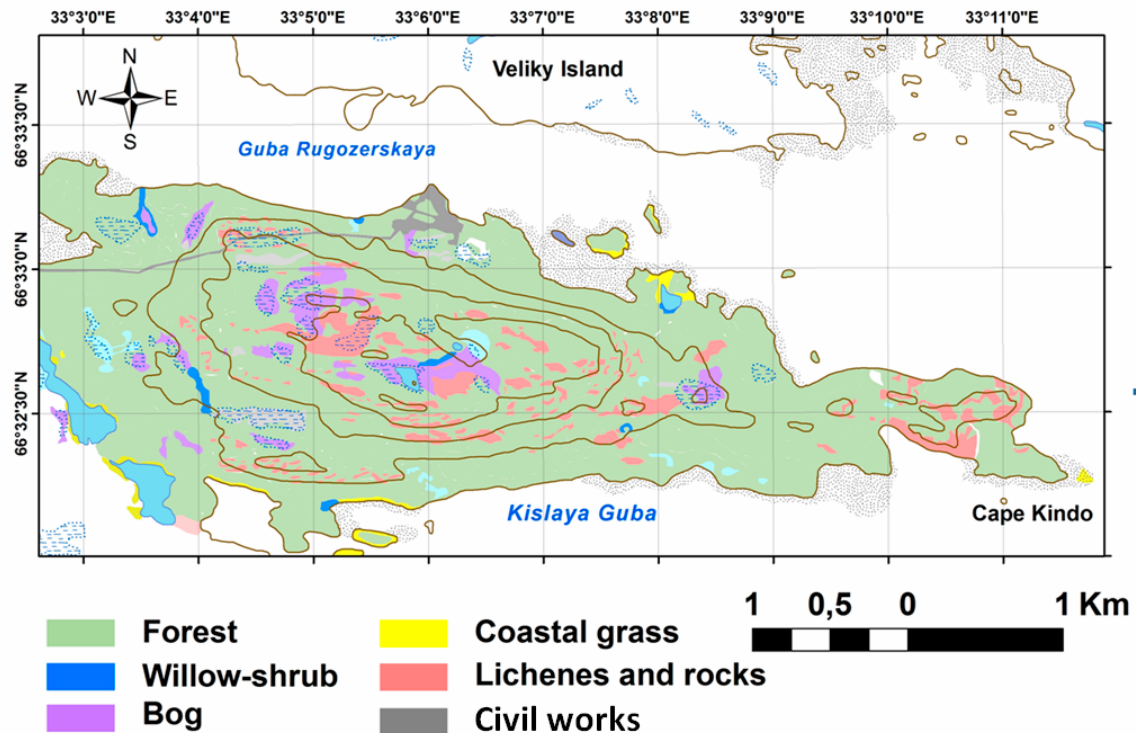


Figure 3: Generalized map of the landscape of the Cape Kindo peninsula.

The averaging period includes the dates of the fieldwork, from January 28 to February 5, for the years when meteorological conditions were quite constant during that time. The exception is 2015, when the period has been divided into two parts: before and after heavy snowfalls (Figure 4).

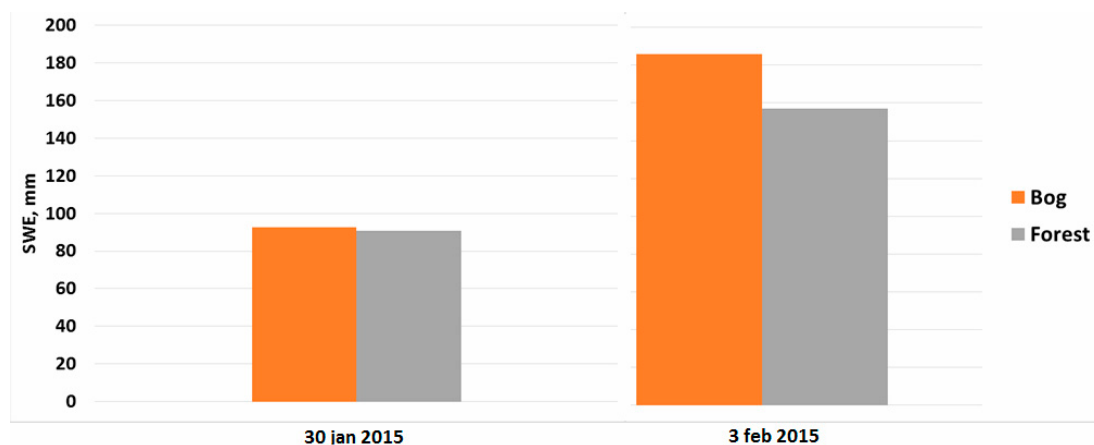


Figure 4: Mean snow water equivalent (mm) before (30 Jan) and after (3 Feb) snowfalls for bog (orange) and forest (grey) landscapes.

RESULTS

Determination of lake elevations

The data demonstrate a significant difference in the elevations of the studied lakes. Every elevation was determined by two observations during the expeditions and was found to be stable (Table 1). The examined lakes are at different stages of their transformation from a sea lagoon to a freshwater body (Figure 5).

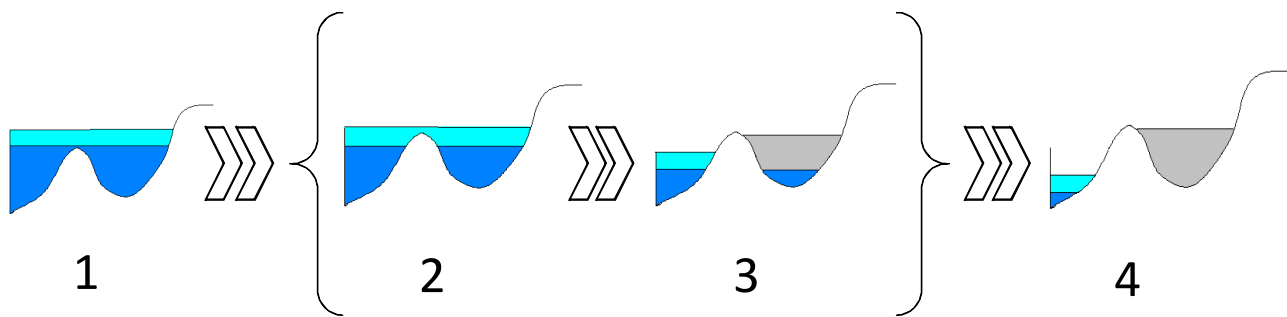


Figure 5: Stages of water body separation from the sea: (1) sea lagoons, (2) water bodies with tidal fluctuations, (3) meromictic water bodies, and (4) freshwater bodies.

The Zeleny Cape Lagoon belongs to the second step of this transformation, water bodies with tidal fluctuation, leading to complete water mixing. The lakes Kislo-Sladkoe, Trekhtzvetnoe, and Nizhnee Ershovskoe are meromictic water bodies. The last stage of separation, freshwater bodies, is reached by Verkhnee Ershovskoe Lake and approached by Nizhnee Ershovskoe.

Two more freshwater lakes (Verkhnee and Vodoprovodnoe) have neither of those types of transformation, as they seem to have formed not by separation of gulfs from the sea during isostatic land uplift. They are located far from the sea shore relatively high within the watershed.

Ice cover was about 40 cm in thickness for all lakes during February 2014 observations and water level fluctuations were negligible within a year. The water level varies slightly during the warm season due to low inflow into the lakes. However, more observations in various seasons are required to assess this hypothesis.

Table 1: Absolute elevations of water levels of the studied lakes (Baltic Height System BHS-1977)

Lake	Water level elevation, m		
	February 2014	June 2014	September 2014
Zelenyi Cape Lagoon	-0.05	-0.01	-0.04
Kislo-Sladkoe	0.42	0.30	0.38
Nizhnee Ershovskoe	1.23	1.29	1.24
Trekhtzvetnoe	1.26	1.21	1.26
Verkhnee Ershovskoe	2.65	2.70	
Vodoprovodnoe	72.98	72.93	
Verkhnee	87.20	87.15	

Level regimes of lakes connected to the sea

Water level, temperature, and salinity sensors, which were set up directly around the dam, were used to assess the possible hydraulic connection between the sea and the lakes. An example of a record of water levels in summer is given in Figure. 6.

The increase in water level during high tides is accompanied by a decrease in water temperature and an increase in its salinity. The plot shows a significant rise in water level due to a pileup caused by a strong and prolonged northern and north-eastern wind.

The question of possible isolation of water bodies in winter was resolved partly in the expedition of 2015. At Kislo-Sladkoe Lake, neither of the two loggers installed in the basin and near the dam in winter 2015 recorded any periodic oscillations of hydrological characteristics that could be attributed to the effect of tides. No signs of water exchange between the Kislo-Sladkoe Lake and the White Sea in winter were observed.

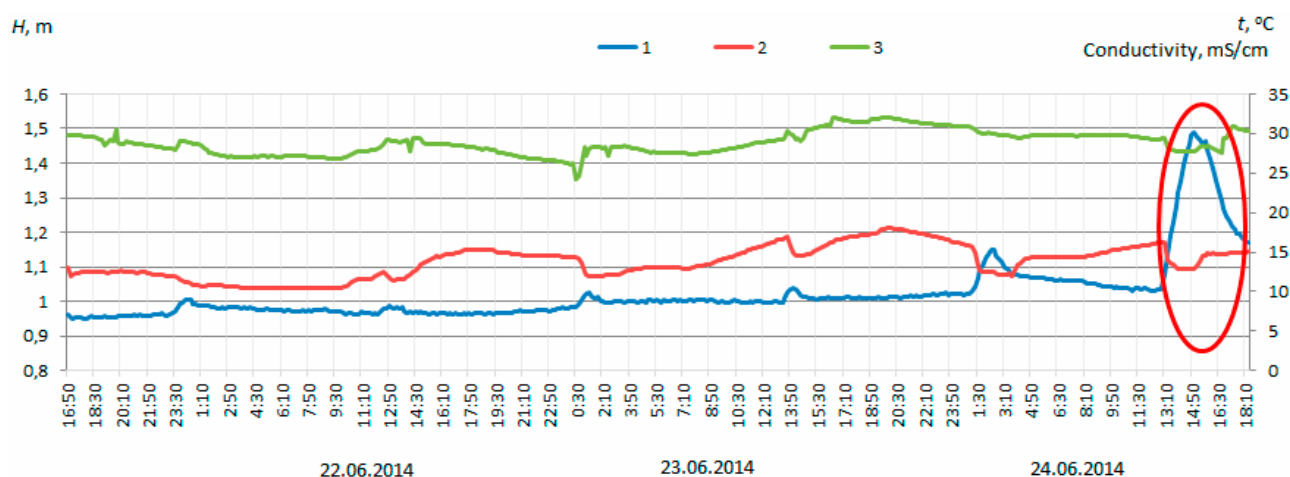


Figure 6: A record of variations of water level (1), (2) temperature, and (3) conductivity with a sampling rate of 10 min at the dam in the Zelenyi Cape Lagoon (21-24.06.2014).

The values recorded by loggers near the dam, separating Zelenyi Cape Lagoon from the sea show that the water level in the lagoon was also stable. However, the temperature and salinity fluctuations in some periods (especially on February 2 and 3, Figure 7) are likely to have a tidal nature. This is evidenced by the fact that the sharp changes in the values of both characteristics coincided in time with high tide of the sea. At the same time, water temperature and salinity in the lake decreased, implying that the characteristics of the lake water became more similar to the sea water that was colder and a little less salty. These findings may indicate that, in the winter 2015, a small amount of seawater had got into Zelenyi Cape Lagoon. Unfortunately, it is not clear how the seawater enters the lake (through an existing duct or by filtration through the body of the dam).

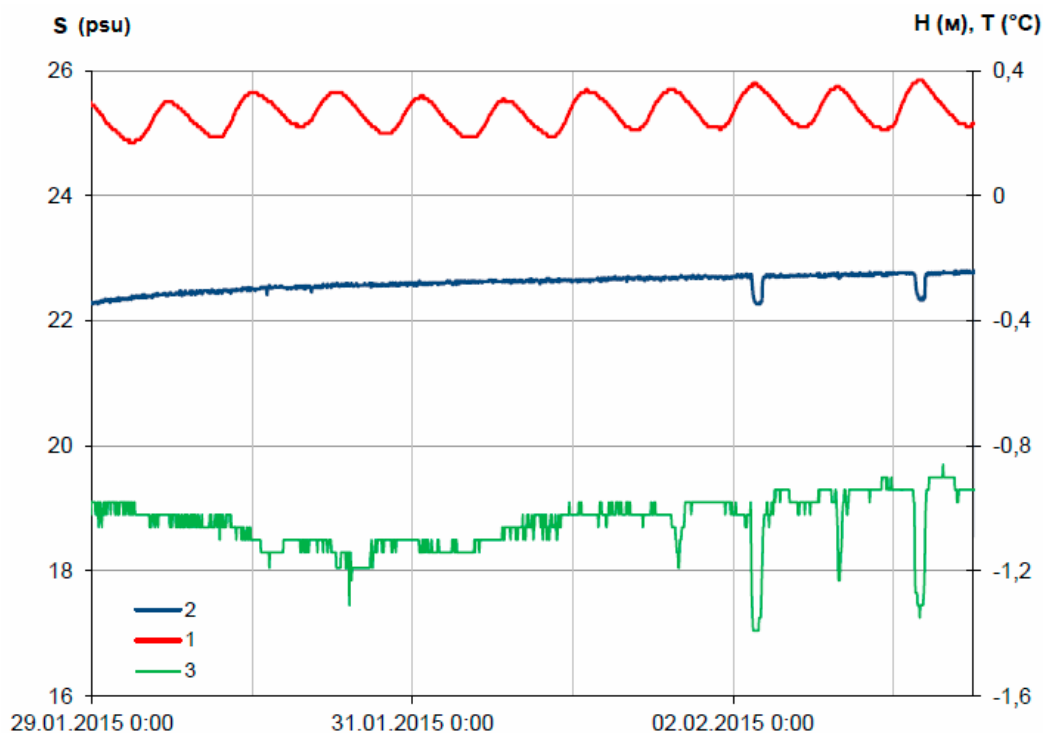


Figure 7: A record of variations of water (1) level, (2) conductivity, and (3) temperature with a sampling rate of 10 min at the dam in the Zelenyi Cape Lagoon (28.01-03.02.2015).

Characteristics of snow cover

Values of snow cover thickness were obtained in the course of field measurements. These values reflect the characteristic landscape of the studied lakes and their watersheds. In January 2014, the average thickness of snow on the surface of the watershed was 47 cm. The thickness of snow cover on the surface of the lakes was significantly lower (Figure 8). In winter 2015, these values varied from 30 cm on the surface of lakes to 80 cm on the surface of watersheds. That kind of distribution occurs because of the snowdrift transfer being active in the open surface of lakes and much less active on the vegetated watershed surfaces and built-up areas.

The authors tried to evaluate the potentialities of using satellite-derived data on snow storage for the area by comparing these data with the ground-based data. The comparison involved the values for the winters of 2010, 2014, and 2015, and its results are shown in Table 2. According to the field study, the average snow storage in 2010 was about 80 mm with variations in forested areas from 45 to 110 mm. According to the remote-sensing data for the given period (late January), snow storage varied from around 70 to 90 mm in the area near the studied area, as shown in Figure 9. Thus, the satellite data and field snow surveys data are comparable. Similar results were obtained in 2014. In 2015, the difference between the snow surveys and satellite-derived data is highest, especially for measurements before a snowfall. Altogether, this indicates the plausibility of satellite-derived SWE.

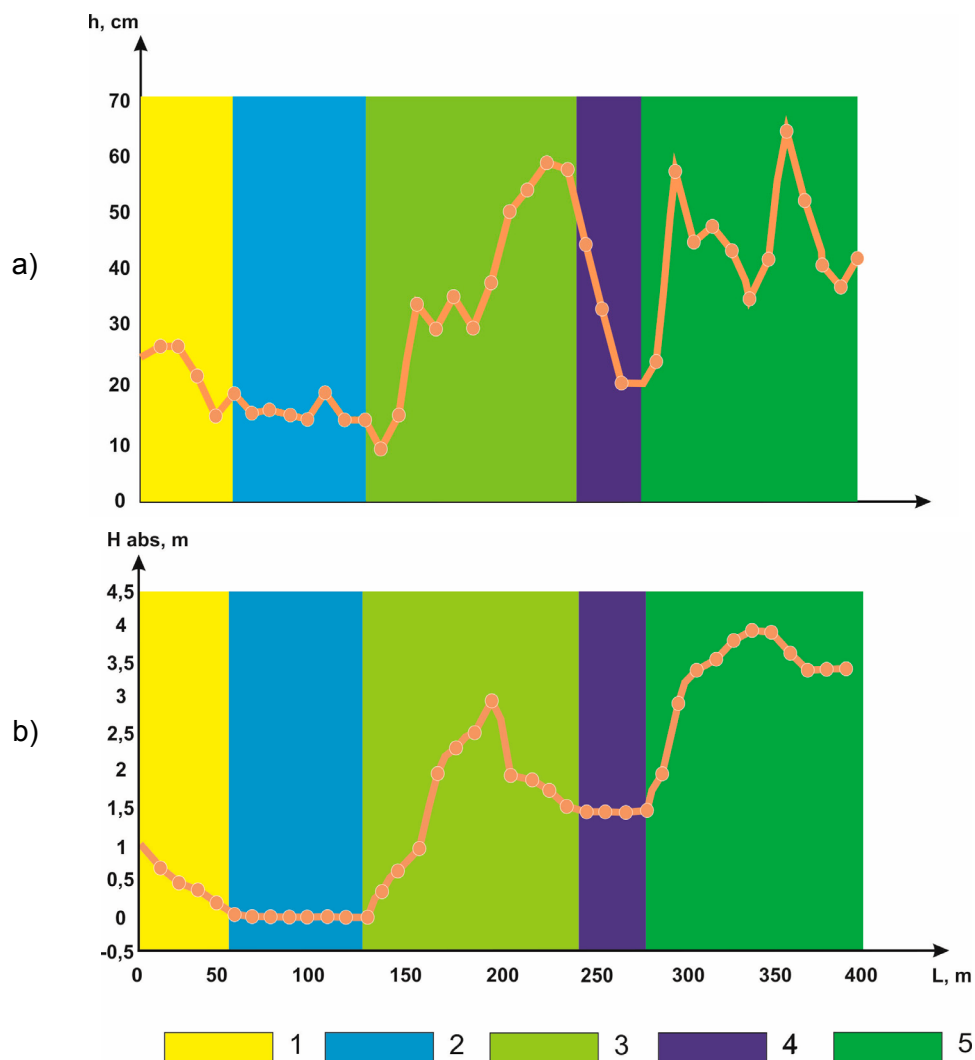


Figure 8: Profiles of (a) snow cover thickness (h , cm) and (b) relief (H_{abs} , m), Zelenyi Cape Lagoon: 1, 3, 5: sites on gentle slopes under fir-tree, pine-and-birch and pine wood; 2, 4: surface of the lakes.

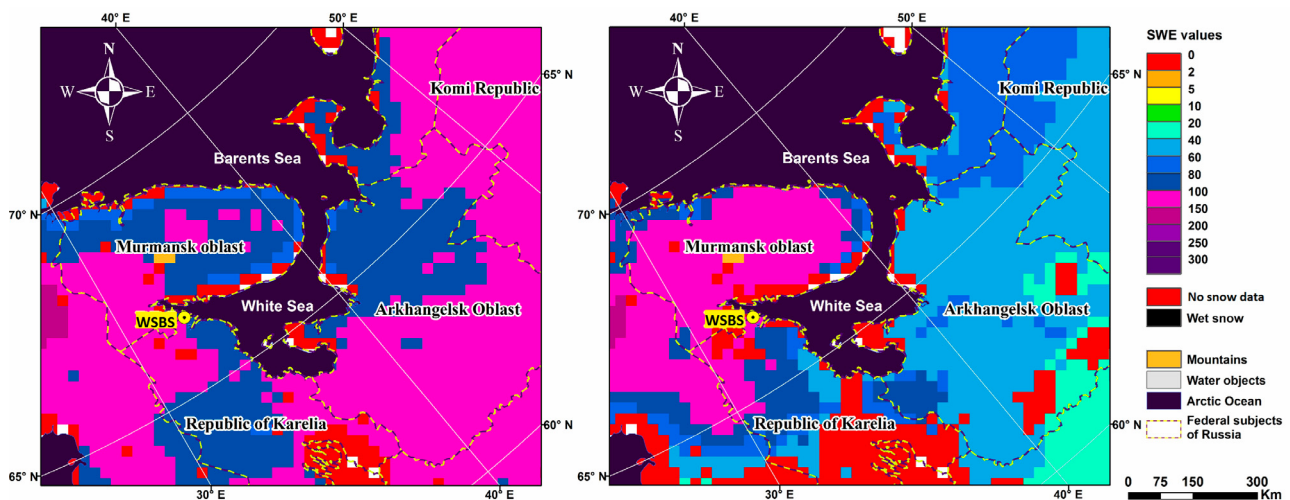


Figure 9: Water reserves in the snow cover (variable: GlobSnow SWE) for the studied area in (left) February 4, 2010 and (right) February 4, 2014.

Table 2: Calculated values of water reserves in the snow cover according to microwave remote sensing measurements (variable GlobSnow SWE) and the ground-based observations.

Year	satellite-derived data (mm)	ground-based observations (mm)
2010	85	80
2014	105	110
2015 (30 Jan)	165	90
2015 (3 Feb)	180	160

DISCUSSION

Level regimes of the lakes

The lakes are found to be at different stages of separation of the original marine water bodies from the lagoon with tidal fluctuations (Zelenyi Cape Lagoon) to become freshwater bodies (Verkhnee Ershovskoe) through meromictic stage (Trekhtsvetnoe Lake, Kislo-Sladkoe Lake, and Nizhnee Ershovskoe Lake). Three lakes are classified as freshwater lakes; two of them are located within the watershed (Verkhnee and Vodoprovodnoe)

In winter, the ice cover is not only a cause of surface desalinisation (9) for a water body, but also a factor of seasonal isolation, creating an additional obstacle for the tides. The ice thickness is sufficient to build up the threshold and completely block the passage for seawater, providing seasonal isolation of such a water body as Kislo-Sladkoe Lake. The integrity of the ice cover on the lake (it does not have cracks which would allow level fluctuations, hummocks, or signs of water spills) may count in favour of seasonal isolation during the period of maximum ice cover.

Characteristics of snow cover

Snowdrift removes snow away from the surfaces of lakes to the land. The maximum snow thickness, which often forms at the forest–lake boundary, also comes from this fact. In addition, a gradual transformation of snow into ice on the surface of lakes takes place (snow ice makes up most of the thickness of lake ice). It is important to note the significant variability of snow cover properties for the studied territory of the White Sea coast.

Almost 82% of the Cape Kindo Peninsula is covered with forests, which dominate over the surrounding territory. Other types of landscape occupy a much smaller area. The bogs with their 8% rank second after the forest, but the difference in the mean values of snow extent (SE) and water equivalent (SWE) between the forest and bogs is not so large. The relief also does not play any

significant role in the distribution of SE and SWE values, which are very variable characteristics of the research area. Thus, the main factors of the sharp decreases or increases in SE and SWE are boundary conditions between different landscapes or local elevations and depressions. GlobSnow SWE remote sensing data show no-data for the coastal zone and the mountain areas (Figure 8). However, the lake catchments and the Cape Kindo Peninsula as a whole were covered by satellite-derived data for entire research period.

Satellite-derived values of SWE differ from ground-based data by 5-20 mm for several research years. The significant difference (about 70 mm) in the late January 2015 could be due to the uneven snowfalls within the territory of a pixel during a couple of days, or by some peculiarities of snow cover formation on the peninsula. Nonetheless, at the lack of monitoring observations, the satellite-derived data is a good source of additional information for the analysis of important snow cover characteristic such as snow water equivalent and the absolute water content of snow on the lake watersheds in the target area.

CONCLUSIONS

The use of data obtained from different sources and by different research methods showed these data to have a high information content and effectiveness in solving a wide variety of global and local hydrological problems. These include the determination of the morphometric and hydrological characteristics of water bodies, the analysis of spatial and temporal variability of snow cover, etc.

GNSS positioning and geometric levelling were used to determine lake elevations with an accuracy of up to a few centimetres. The use of these methods allowed the authors to establish that, in the majority of cases, water level fluctuations are negligible at the annual scale, while the water level varies slightly during the warm season because of a small inflow into the lakes. The sharp water level rises could be caused by the unusually high tides heightened by wind.

Automated level, temperature, and salinity recorders were used to show that the Kislo-Sladkoe Lake has no connection with the sea in winter. Zelenyi Cape Lagoon is influenced by seawater apparently all the year round.

The distribution of snow cover was studied in detail. An important component of the water balance, its characteristics also contribute to level variations in the lakes in addition to its variations caused by tides in summer.

Passive microwave remote sensing methods also could be used for SWE evaluation on the watersheds of target lakes and for the analysis of their water balance. The difference between satellite-derived and *in situ* data for 2010 and 2014 is as little as 5-10 mm. However, for data of 2015, it reaches 20 and even 70 mm, a deviation, which can be attributed to some peculiarities of meteorological conditions.

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