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Mapping of Inner Water Bodies in the Krasnoyarsk Territory Based on the Digital Analysis of Ground True and Satellite Data

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ABSTRACT

In this work historical investigations and modern results of classification of the Krasnoyarsk Reservoir are presented. The paper presents results of studying the dynamics of phytopigments and other optically active components, using multispectral satellite data. Several approaches to interpreting satellite data for optically complex inland water bodies are offered. Based on results of historical investigations it is shown that the spatial distribution of phytoplankton in the reservoir stems back to the time of its formation. Color index in the red spectral region (CIR) is introduced. A relationship between the color index and chlorophyll concentration is investigated. The CIR, derived from the AVHRR data, has been found to be related to chlorophyll concentration. Based on MODIS data, the waters of the Krasnoyarsk Reservoir have been classified in accordance with their optical spectral variability, using the technique of unsupervised ISO data classification. An empirical relationship between multispectral MODIS data and the ground-truth measurements of chlorophyll concentration has been found.

INTRODUCTION

Satellite monitoring is the most effective method for assessing the state of inland water bodies. The assessment is based on three main optically active components of water – phytoplankton, dissolved organic matter and suspended mineral matter. The most important factor is the chlorophyll concentration of phytoplankton because it depends on levels of blooming in the reservoir and levels of human impact. It is well-known that waters of continental lakes are optically complex. That is why they cannot be studied using the ocean type of analysis. Remote sensing of inland water bodies can be used to assess 3 main optically active components: chlorophyll “a” concentration, suspended mineral matter and dissolved organic matter. These parameters are related to the quality of the water. Chlorophyll “a” is of particular interest, because it is the main pigment for various types of phytoplankton in the water; moreover, it serves as the basis for calculation of primary production, biomass etc. In the open ocean waters, where the color of the water is basically determined by phytoplankton, this parameter can be easily and effectively calculated using remote sensing data and simple empirical algorithms based on the sensor channel ratio (Gordon et al., 1983; Gitelson et al., 1988). At the same time, optically complex waters of inland water bodies make this task much more difficult, as they contain large amounts of suspended mineral matter and dissolved organic matter (Bukata et al., 1995; Tiit Kutsera et al., 2005; Curran and Novo, 1988). The optical parameters of these components change independently of phytoplankton and, when monitored by remote sensing, can significantly alter the integrated spectrum registered by the photodetector. What makes it even more difficult is considerable radiation scattering (even in the near-infrared (IR) spectral region) in the shallow water. Thus, the relationship between remote sensing data and optically active components becomes nonlinear, and the determination of water quality parameters, especially Chl “a”, using regression analysis becomes more complicated (Lathrop, 1992; Shevyrnogov et al., 2002; Arst, 2003; Pozdnyakov and Grass, 2003). An alternative approach is classification, in which components are not quantified but rather their relative amounts are estimated (Chernetsky et al., 2006). Using this method, one can make a map of the studied water body. This method is effective when used along with ground-truth measurements. This study was performed at the Krasnoyarsk Reservoir using remote sensing methods (Aponasenko et al., 1985; Gitelson et al., 1985).

The purpose of the study was to investigate spatial and temporal distribution of spectral optical parameters of the surface water layer in the Krasnoyarsk Reservoir. The spectrum received by the satellite sensor is determined by the composition of the major optically active components and can be used to reveal the seasonal and long-term dynamics of biological processes in inland water bodies, which, in turn,serve as an indicator of the state of the water body.

Study Sites

The main sites for long-term integrated hydrobiological and hydrooptical studies were the Krasnoyarsk Reservoir and the Dnieper cascade reservoirs. The Krasnoyarsk Reservoir is a very large (71.3 km3), deep-water (the mean depth 36.9 m, the maximum depth 105-110 m), weakly circulating (the water cycle rate 1.2 yr-1) water body of an intricate shape. The Dnieper cascade reservoirs are shallow (the mean water depth 6-7 m) and contain much smaller amounts of water. Blue-green algae and diatoms are the predominant phytoplankton. The Secchi disk depth (SD) in the Krasnoyarsk Reservoir decreases steadily, from about 3 m at the dam to 0.5-0.7 m at the reservoir backwater (300-330 km). In the Dnieper cascade reservoirs, SD does not exceed 2-1.5 m, decreasing to 0.2 and less when the water surface is covered with a film of blue-green algae (during their blooming period).

RESULTS

Historical Spectrometric Investigations

As is well known, to investigate ecosystem biotic parameters using satellite remote sensing, it isnecessary to make ground-truth spectrophotometric measurements. Expeditions to the Krasnoyarsk Reservoir were conducted in the 1970-80s, but the spectral data obtained in the course of those expeditions can still be useful (Shevyrnogov and Sidko, 1998). During the expeditions, direct biological measurements of Chl “a” in the surface layer of the reservoir were taken as reference data. In addition to that, the researchers made spectrophotometric measurements of spectral brightness coefficients using a PDSF differential spectrophotometer in different parts of the reservoir, varying in hydrobiological and hydrochemical conditions. Optical measurements in inland water bodies and reservoirs have their specific features uncharacteristic of measurements in relatively pure and transparent open ocean waters. Due to these features, a non-standard approach can be used to interpret remote sensing data (Han and Rundquist, 1997). Our investigations showed that during phytoplankton bloom the near-infrared subspectrum is suitable for the estimation of Chl “a” concentration due to strong reflection of light in this part of the spectrum by the Chl “a” phytopigment. Based on this, we were able to use the Normalized Difference Vegetation Index (NDVI) formula to calculate the color index in the near infrared region (CIR), as opposed to the generally accepted color index in the blue spectrum region, which can be used to estimate Chl ”a” concentration. CIR=NDVI=(R2-R1)/(R1+R2) (1), where R1 is reflectance in the red channel and R2 is reflectance in the near-infrared channel. In our previous studies we showed that measurements in different types of the waters can be performed using different spectral regions. For the open ocean water, the use of the maximum light absorption by chlorophyll at the 434-nm wavelength is the only choice, while for the water bodies with large amounts of dissolved organic matter and high concentrations of phytoplankton and suspended matter the use of the red spectrum region is quite acceptable. That was taken as a basis for determining the CIR, as this region was available at NOAA satellites. Thus, large amounts of satellite data were made available. As the amount and frequency of the data are of particular importance for revealing temporal dynamics, the use of the CIR seems to us quite justified. Using such ground-truth data as chlorophyll concentration and color index in the red spectral region, we made regression analysis. The results revealed an exponential relationship between the variables when the concentration of chlorophyll was lower than 150 mg/m3 (Fig. 1a). To investigate the relationships at concentrations higher than 150 mg/m3, we used the data from similar measurements conducted at the Dnieper cascade reservoirs, which are characterized by extremely high chlorophyll concentrations. Thus, combining the data for the Krasnoyarsk Reservoir and the Dnieper cascade reservoirs, we obtain a pooled array of data on chlorophyll concentration. Regression analysis was used to find the relationship between red radiation reflected from the surface layer and phytopigments present in extremely high concentrations. High concentrations complicate this relationship, and, as a result of linear regression analysis, the correlation coefficient is 0.97 (Fig. 1b).

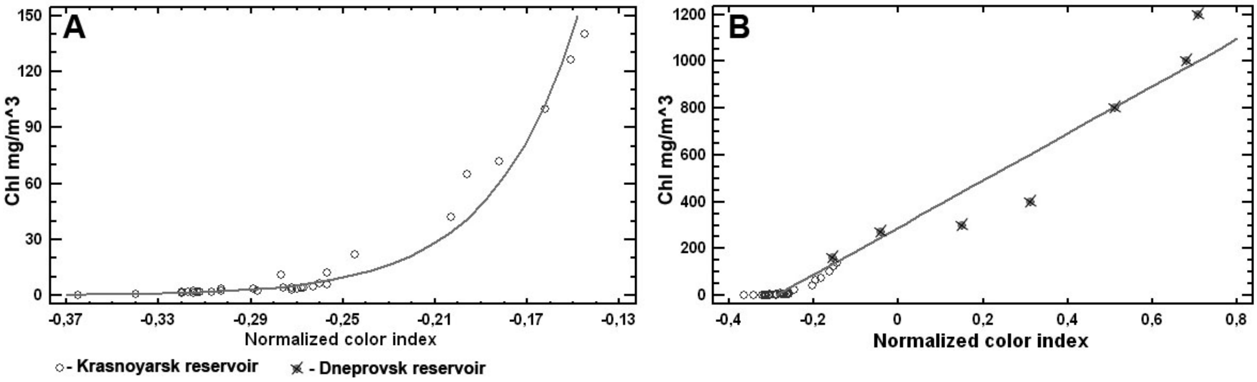

Fig. 1A, B Comparison of ground-truth data on Chl “a” concentration and normalized color index

In the first case, it is more reasonable to use nonlinear regression analysis, and in the second, the best result was obtained using linear regression. Systematic spectrophotometric measurements revealed spatial inhomogeneity of the chlorophyll concentration distribution in the surface layers of the Krasnoyarsk Reservoir. Our measurements revealed small-scale inhomogeneities of phytopigment distribution and a tendency of Chl ”a” increase in the south part of the reservoir. This can be generally accounted for by the shallowness and higher temperatures of the south part as opposed to the north part of the reservoir, where the water is up to 120 meters deep (Fig. 2 a, b).

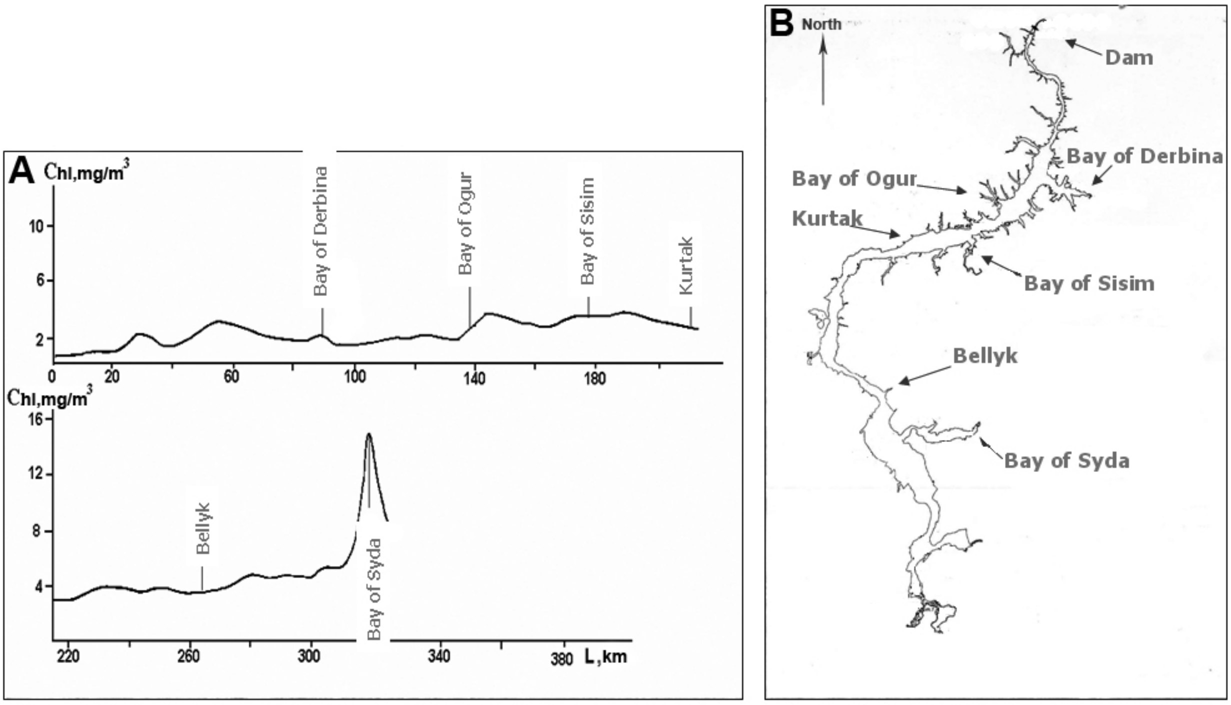

Fig. 2A, B Longitudinal subsurface distribution of chlorophyll “a” concentration in the Krasnoyarsk Reservoir obtained using remote sensing equipment (August 1983).

However, extremely high chlorophyll concentrations can be found in shallow bays of the Krasnoyarsk Reservoir, which have specific hydrologic features and slow water circulation. One of such bays is the Syda Bay. The maximum concentration is observed in the place where the wide and shallow Syda River flows in. The surface layers there are heated better, so the average temperature is 4-5□ higher than in the reservoir itself and the chlorophyll concentration is 2-4 times higher. The concentrations of phytoplankton chlorophyll vary from 1.4 to 16 mg/m3.

Results Obtained Using NOAA/AVHRR Data

The Institute of Biophysics SB RAS has a large archive of NOAA satellite data. These data have low spatial resolution and wide spectral channels. Despite this fact, AVHRR information can be used to determine bloom areas, as blue-green algae form more or less continuous film. Chl ”a” concentration reaches 1000-1400 mg/m3 and more. Under these conditions, the CIR can be calculated on the basis of AVHRR data. Direct hydrobiological measurements of phytoplankton biomass were performed at the same time (Gold, Z.G., 2003). Based on the results of regression analysis, the correlation coefficient between the CIR and chlorophyll concentration was 0.74. So, we were able to use this statistical model to calculate bloom levels (Sirenko et al, 1986). Figure 3 shows changes in bloom levels of the surface waters of the Krasnoyarsk Reservoir from July to September.

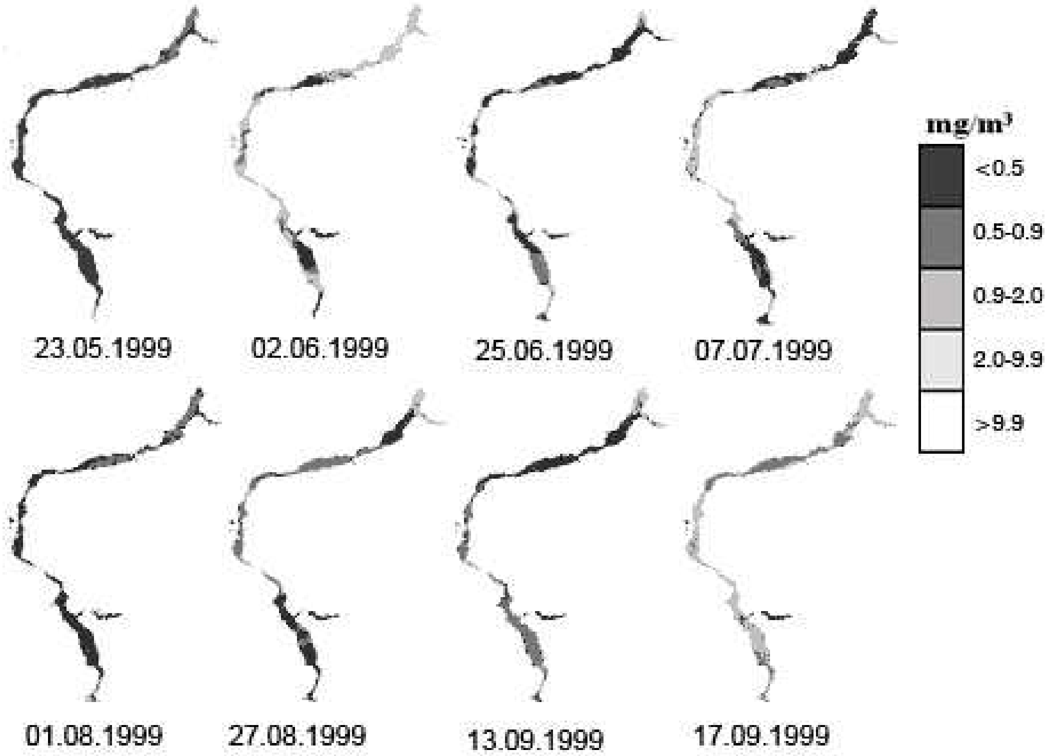

Fig. 3 Bloom classes on the surface of the Krasnoyarsk Reservoir distinguished based on integrated satellite (AVHRR) and ground-truth data.

Results Based on TERRA/ MODIS Data, Using Unsupervised Classification

The TERRA-MODIS space spectroradiometer, which was used to obtain data for this study, has 36 narrow spectral bands with spatial resolutions of 250, 500 and 1000 m. All bands for the ocean Chl investigation have a spatial resolution of 1 km and relatively high radiometric sensitivity. However, these bands have no atmospheric correction for land and lakes. We used 8-day composite images with a spatial resolution of 500 m (productMOD09A1 downloaded from http://edcimswww.cr.usgs.gov/pub/imswelcome/) for classification of the reservoir based on spectral variability. In this product atmospheric effects are removed using a standard MODIS algorithm of atmospheric correction (E. F. Vermote and A. Vermeulen, 1999). The MOD09 product data have 7 spectral channels. In our study we used channels 1-4: 645, 858, 469, and 555, respectively. Unfortunately, at the present time it is difficult to obtain synchronous ground-truth data for the Krasnoyarsk Reservoir. Therefore, most of supervised classifications are unusable, as algorithms of this type require quite a large number of training samples (ground-truth data). Thus, we used unsupervised “ISO data” classification. Other researchers, e.g., (Nellis et al., 1998), reported using this classification method to analyze multispectral satellite data for inland water bodies. Our analysis yielded 5 spectral classes (Fig. 4 A, B).

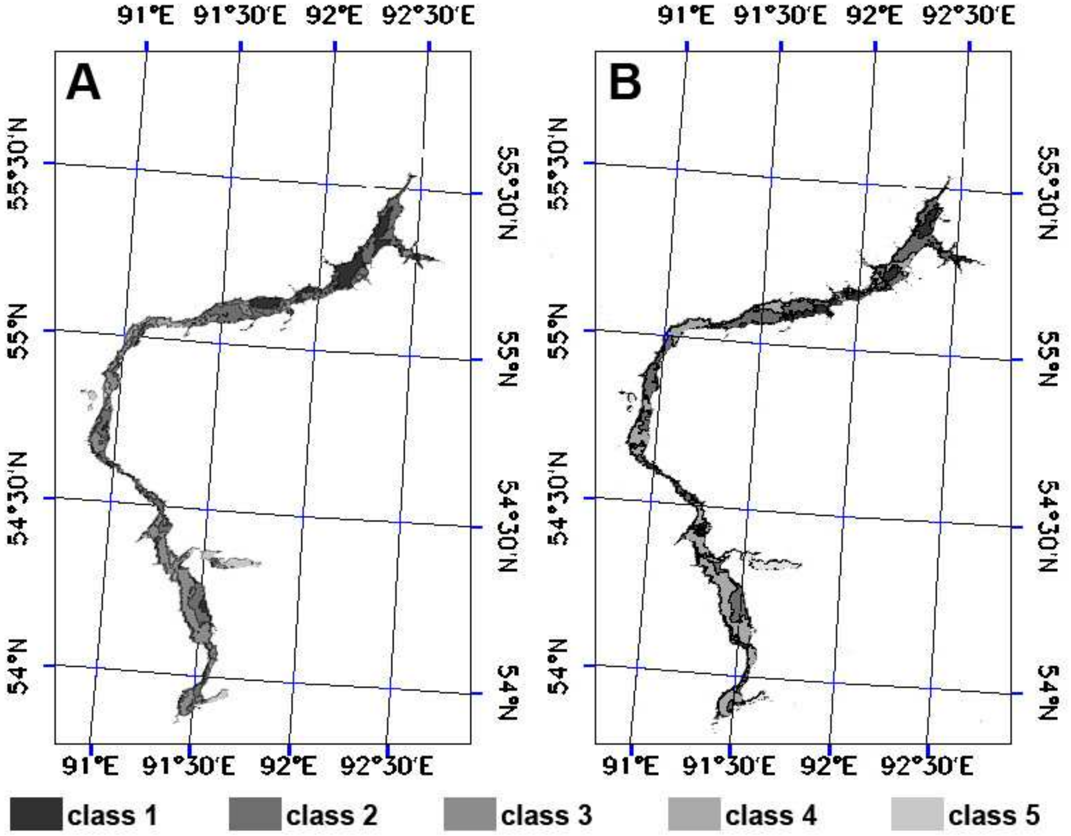

Fig. 4 8-day composite MODIS images mapped using unsupervised classification. A – 2005.08.20, B – 2005.08.28.

Results of the analysis visualized as a map of spectral classes show rather gradual changes in the spectral types and an increase in the level of reflection from north to south. The Syda Bay clearly has the highest reflection level. The increase in the reflection level in the green and red spectral regions is probably related to the increase in Chl "a" concentration. The increase in reflection values, which can be seen in the graphs of different classes, generally indicates an increase in water turbidity. Nevertheless, the discovered nature of spatial changes is similar to changes in chlorophyll concentration and spectral optical characteristics obtained in field investigations of 1983. MODIS spectral bands designed for measuring Chl concentration in the ocean and featuring high radiometric sensitivity can be used along with land channels. MODIS "water" bands were interpolated to increase the spatial resolution to 500 m and united with land bands. In this case, standard atmospheric correction was unavailable as this image was constructed using 1B level MODIS data. Thus, only Rayleigh scattering correction was used. As can be seen in the satellite image of August 2005 (Fig. 4 A, B), the spectra changes along the reservoir are similar to the changes of June 2004 (Fig. 5 A).

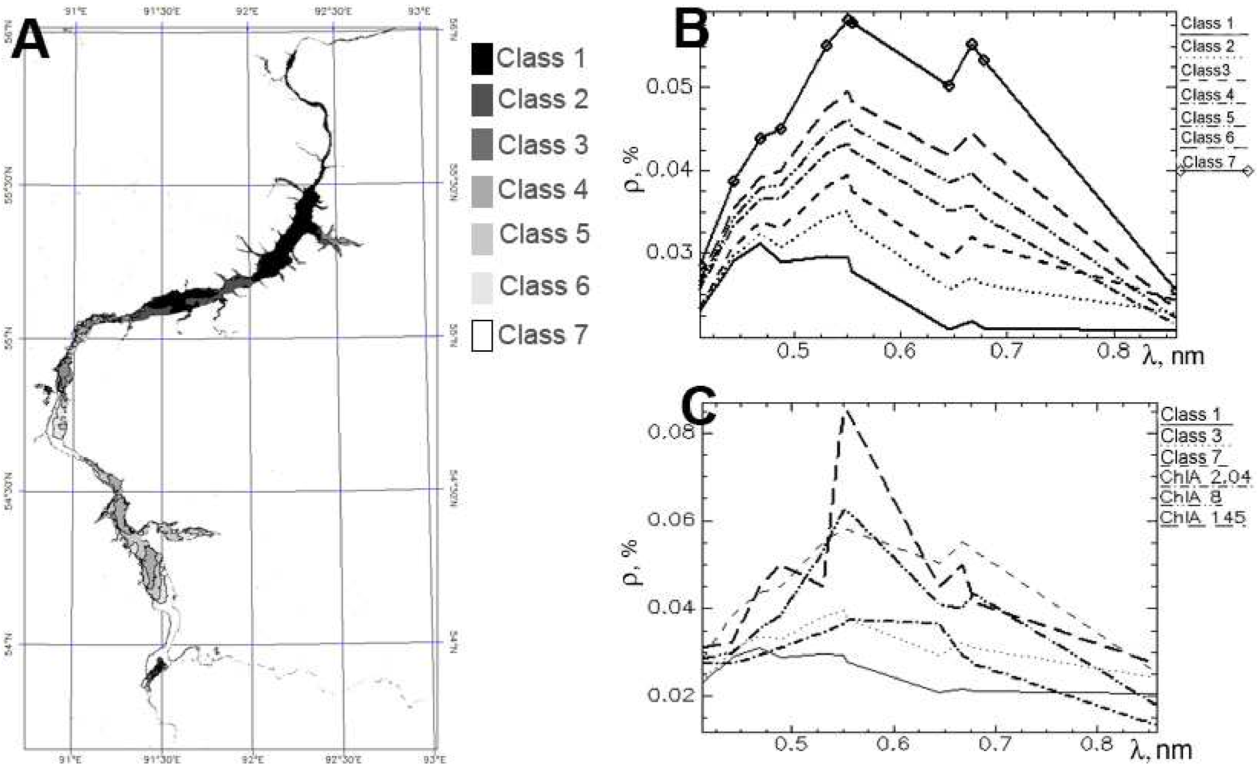

Fig. 5 Unsupervised classification by IsoData method. 2004.06.04. A - Unsupervised classification by IsoData method, B - Spectra obtained from classification, C - Satellite and ground-truth spectra.

The use of additional channels improves statistical significance of the obtained results as the spectra contain more points. This processing results in more effective comparison between the satellite spectra and the high resolution spectra obtained in the on-ground investigations. We have shown that the satellite reflectance spectra (Fig. 5B) are similar to the spectra of field measurements. In Figure 5C the spectra based on the field data are superimposed on the spectra based on the MODIS data. As chlorophyll concentration increases, the peaks grow 0.6 and 0.7 nm higher in the spectra based on ground-truth and satellite data. Analysis of the spatial distribution of areas with different spectral classes shows that reflectance increases southwards. The previously obtained ground-truth data show that chlorophyll concentration in the Krasnoyarsk Reservoir increases southwards. The more southerly classes correspond more closely to the spectra with higher chlorophyll concentration (Fig. 5 A,C).

Results Based on TERRA/ MODIS Data, Using Regression Analysis

We performed regression analysis of field data using the following values: surface chlorophyll concentration according to the ground-truth hydrobiological measurements taken at the beginning of August (Gold, Z.G., 2003) and satellite data of 01 August 2005, 17 August 2005, and 25 August 2005. The satellite data obtained at different dates were used to verify statistically the correlation between the satellite and ground-truth data time-synchronized to different extents. Table 1 illustrates the results of the analysis. Processing of the data obtained at different dates distinctly showed better results of regression analysis for the data of 01 August 2005, i.e. for the data that was maximally time-synchronized. Thus, two conclusions can be drawn. One is methodological – for small water bodies with highly inhomogeneous spatial distribution of dissolved and suspended matter it is particularly important to interpret satellite information using the data that are maximally time-synchronized with it. The other conclusion is related to the properties of the studied environment – the Krasnoyarsk Reservoir. Its hydrobiological properties are so variable that the most appropriate way to monitor them is to perform instantaneous space measurements. Thus, we deduced the following quantitative relationship between chlorophyll concentration and reflectance values for the Krasnoyarsk Reservoir: $CChl = 674.4 - 10369.7*b1 - 681.7*b2 - 10207.6*b3 - 3851.1*b4$, (1) where CChl is surface chlorophyll concentration, mg/m3; b1, b2, b3, b4 are reflectance values in the corresponding bands.

Table 1 Regression analysis of the data on surface chlorophyll concentration using ground-truth and satellite measurements.

Statistical characteristics	01 August 2005	17 August 2005	25 August 2005
Multiple correlation coefficient, R	0.98	0.65	0.68
`F – value	46.04	0.57	0.64
Multiple determination coefficient, R2	0.97	0.42	0.47
Adjusted multiple determination coefficient, R*2	0.93	-0.33	-0.22
t – value	12.707	-2.5668	2.48
Standard error of estimate	23.78	124	118

DISCUSSION

The best results can be attained by combining the presented methods. That is, continuous groundtruth measurements of the spectra of radiation emerging from the water and simultaneous measurements of phytoplankton chlorophyll must provide the basis for constructing empirical relationships. Data provided by different satellites have different features. The AVHRR data archive is the most complete and can be used to study long-term changes in the state of water bodies. MODIS satellite data are of better quality and can provide nearly continuous monitoring of the state of water bodies. The CIR method is workable only if there is a 720-nm band because at high chlorophyll concentrations, in the 720-nm band there is a narrow peak that determines whether CIR values will be negative or positive. Moreover, this method is more effective at high chlorophyll concentrations. The AVHRR sensor works in the broad range from 725 to 1000 nm. That is, although this sensor has a low sensitivity, it will "see" the bloom. The MODIS sensor has no spectral bands that would correspond to the 720 nm wavelength, so measurements of chlorophyll concentration are not related to absorption in the red spectral region. The reason is that in all MODIS bands in the near-IR spectral region reflection is much lower than in the visible red bands. Dall'Olmo and co-authors (2005) reported using red and near-infrared bands to study inland water bodies. When MODIS data are used, reflection values in different channels contain useful information on chlorophyll concentration. Due to optical complexity of the reservoir water it is difficult to find the combination of spectral channels and respective coefficients that would yield reliable estimates of chlorophyll concentration. Thus, it would be rational to use multivariate linear regression. Linear regression analysis was used to relate field and satellite data for inland water bodies by other authors (Buttner et al, 1987). Although the sensitivity of these methods is rather low, they can be used to determine extreme hydrobiological and hydrologic states of inland water bodies, such as dramatic increases in the amounts of suspended matter or phytoplankton “blooms”. In addition to this, the described methods can be used to monitor in time spatial changes in “blooming” regions.

CONCLUSIONS

This work presents results of different types of investigations using remote sensing. Field spectrometric measurements during the period of formation (The period of formation is the time when the reservoir was being filled with the water and the hydrologic conditions were being formed) of the hydrobiological properties of the Krasnoyarsk Reservoir compared with the satellite data showed that the general pattern of the chlorophyll concentration distribution had been formed in the 1970-80s. Our investigations showed that in certain cases, when chlorophyll concentration is high (during blooming), the near-infrared region can be used to estimate the concentration. For this purpose a criterion was developed - color index in the red region (CIR). This index can be used in some situations for other inland water bodies. At chlorophyll concentrations lower than 150 mg/m3 the correlation between chlorophyll concentration and CIR has exponential form. The possibility of using unsupervised classification to map spectral optical characteristics of the Krasnoyarsk Reservoir was demonstrated. - Using clustering, it was shown that both the spatial distribution of phytoplankton and the form of the spectra are similar to the ground-truth data. A significant relationship between multispectral satellite data and the ground-truth hydrobiological measurements of chlorophyll concentration was found. The results show a good potential of both continuous monitoring and investigation of time series of inland water bodies using TERRA/MODIS satellite data, although this is not a standard procedure of processing MODIS data.

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