Geoinformation technologies for studying the effects of water level fluctuation of Lake Baikal: the case of Angarsky Sor

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Abstract. Lake Baikal is the world’s deepest lake and declared a UNESCO World Heritage Site. The most severe environmental problem facing the lake is the impact of water level regime fluctuation related to natural and human-caused factors. A core region under study is selected a territory of the Angarsky Sor – a shallow bay located in the Northeast of the lake. The research into a changing water content of the territory is based on imagery provided by the Landsat-8 satellite. The study is focused on photographs taken in the high-water summer 2014 and in the low water level year 2015. The outcome of performed calculations is that an area of marshy and excessively wet regions has decreased more than 1.5 times, whereas there is a slight increase in the area of dryland waterless zones. Principal changes have been detected in the northern and north-eastern part of the Sor territory. Geoinformation technologies and remote sensing methods are considered to be efficient for the monitoring water level fluctuations, changes in the water surface area and vegetation mantle state of land ecosystems in the Sor region, what is essential for the preserving unique wetlands of the Angarsky Sor.

1. Introduction

Lake Baikal is declared a UNESCO World Heritage Site. To date, however, a unique ecosystem of the lake has been affected by a number of natural and man-induced risks but their mapping helps keep the situation under control [1, 2]. Level fluctuations in the water body may lead to dramatic consequences.

Most factors of natural origin, which cause a water level change in Lake Baikal, have a cyclic character and are related to the shifting of water balance. For instance, recent climate changes have considerably altered the relationship between input and output water balance constituents of Lake Baikal, what may result in long-term gradual rising and falling of water surface, as well as cause the difference in water volume of the lake. Seasonal water level variations in Lake Baikal depend on the flow fluctuation of rivers entering the lake. It is reported also on wind-driven up and down surges induced by short-term (30-40 hours) ebb-and-flood with a level difference up to 10 cm.

Water level fluctuations in Lake Baikal observed over recent low-water years have impressive consequences for the environment since they pose a real threat to the unique ecosystem of the lake and may provoke a number of ecological and economic problems in the region. For instance, a water shortage brings about the lowering of a ground water level, causes difficulties in water supply and leads to drying up of wells; in addition, it is supposed to be the reason for a high forest fire danger and intensive exogenous geodynamic processes on the lake shoreland – increasing abrasion, shoreline erosion, flooding and bogging up of low-lying shore areas [3].
Several studies have highlighted the necessity of monitoring and forecasting consequences of such situations because of their importance for an economic land use [4]. However, it is a quite challenging issue as the extended Sor area and lacking connection with many of its regions restrict the use of surface techniques to some territories only. Geoinformation technologies and remote sensing methods may be quite effective in seeking for solutions to this problem and provide valuable information for studying spatiotemporal changes of many factors characterizing the state of ecosystems in the Sor.

Water level fluctuations and their consequences in Lake Baikal have been investigated on the example of the Angarsky Sor. As a principal method of analysis we used geoinformation technologies [5] and remote sensing methods. In addition, we collected all necessary data in field surveys, file materials and literature reports.

2. Materials and Methods

The Angarsky or Verkhneangarsky Sor is a shallow bay with an area of 377.3 km² located in the North of Lake Baikal. It includes deltas of the Verkhnyaa Angara and the Kichera; the sand Yarki Island stretching over 11 km and numerous small islands separate it from Lake Baikal, in addition, it is quite unattractive for tourists [6]. In terms of hydrology the Sor is a strongly related to water regime and complex system comprising rivers, creeks, lagoons, esturian lakes, and bogs alternating with dry land areas. A maximal depth in the Sor is about 4 m, ranging to 5.5 m in river beds.

In the early 1960-s prior to the building of Irkutsk Hydropower Plant an overgrowth area of the Sor water zone with aquatic plants was estimated to be around 75%, and rare high and low lands were used for hay production. When constructing the hydropower plant, a water level rose, as a consequence, 120 km² low lands in the Sor were flooded, a total overgrowth area decreased considerably, having affected a natural and economic potential of the territory.

As the territory of interest borders the Baikal-Amur Mainline, it has been an arena of dynamic economic activities [7]. Within its boundaries there are several inhabited settlements with a population of around 7 000 people, the biggest one is an urban-type settlement of Nizhneangarsk. The population of the region has been traditionally employed in fishing; hay production and cattle farming used to be main economic activities in the past. A water level rise in Lake Baikal has increased a water surface area of the Angarsky Sor [8, 9], provoking the flooding and dramatic shrinkage of hay and pasture fields, the expansion of poorly-accessible areas in the Sor and damaging of sand beaches, and accelerated the degradation of the Yarki Island, etc. From the historical literature we know that 100 years ago hay production was a principal economic activity on the entire lowland territory from the Angarakan creek to the Sor water area. Nowadays, these lands are impassable or barely-passable marshes. Fishing conditions have also been changed enormously. These circumstances have given rise to transformations in the structure of ecosystem exploitation and influenced an economic potential of the territory [9].

On the contrary, even a slightly fluctuating water level in recent years may be a reason for serious problems. A striking example is the level lowering in the late autumn 2014 related to the significantly falling water content in the Verkhnyaa Angara – main feeding river of the Sor. A water shortage was observed till the autumn 2015. As a consequence, in summer 2015 a shoreline became shallow, serious changes were detected in the water degree of Sor ecosystems, as well as in the vegetation cover, among other consequences there is the overgrowth of the basin with aquatic plants, fish kill, and prohibition on the navigation of capture and small size vessels. To illustrate, in 2014 fishing vessels used to enter the Angarsky Sor through channels in the Yarky Island, but in August 2015 the entrance into the Sor, as well as into the Verkhnyaa Angara and Kichera was rather difficult due to low depths (somewhere less than 70 cm).

To assess the potential of remote sensing materials [10, 11] for analyzing a water degree fluctuation on the territory we used imaginary data provided by the Landsat-8 satellite (camera OLI), a spatial resolution of zonal images is 30 meters. We studied pictures taken on July, 17 2014 (before a sharp drop of the water level) and those of the low-water summer in the year 2015 (July, 20).

At the preliminary stage of satellite data processing we carried out radiometric calibration in the software package ArcGis 10.3 using tool Raster Calculator in section Map Algebra (menu ToolBox). Then, fragments of a needed territory were generated and color images were synthesized (Figure 1).
Figure 1. The Angarsky Sor in the synthesized Landsat-8 image (July, 20 2015; a combination of channels 6, 5, and 2). The blue line indicates a boundary of the zone under study.

To analyze how the watering degree behaves in the Sor ecosystems we needed to select an area maximally sensitive to water degree fluctuations and ecosystems related to it. For this purpose horizontals were drawn and a map of relative altitudes was developed for the region of interest in the software package Global Mapper using data provided by Digital Terrain Model SRTM X-band (a cell size 30x30 m) and contrasted with DTM ASTER GDEM (a cell size 15x15 m). A horizontal countering the level and matching with a high flood plain was accepted a basic one, but a boundary zone was slightly expanded and first terraces of an alluvial-lacustrine plain of the the Angarsky Sor southeastern part were included because the region under study represents an important commercial fishing and environment-oriented object (Figure 1).

A review of literature focused on methods of exploring wetlands and determining a water surface area with the help of remote sensing techniques has revealed a number of approaches and methods of image processing can be adapted for this purpose: identification of multichannel spectral indexes (so-called water indexes), subject-based classification combined with learning, linear division, single-channel classification related to the difference threshold, etc. Interpretation methods involving multichannel water indexes are used most widely.

The most popular method currently is NDWI index – Normalized Difference Water Index (Water Level Index) introduced for the first time in 1996 by S.K. McFeeters as an index capable for the separating water surface and land [12, 13, 14]. The index is frequently applied to evaluating the water content in a green biomass, detecting wet, excessively and insufficiently wet zones. NDWI indexing uses green and near-infrared wavelengths of images Landsat-8 (GREEN and NIR).

3. Results and Discussion

The construction of Irkutsk Hydropower Plant in 1959-1962 is thought to be the most serious man-induced interference; as a result, a water level in Baikal rose by 1.2 m. Since a Resolution of the Government of the Russian Federation was adopted in 2001 Baikal has been an artificially controlled lake having a water level difference of one meter in a range of 456-457 m as determined in the Pacific Scale (Figure 2).

Nevertheless, to date, one of the serious problems in the region of Lake Baikal is reported to be a registration of water level falling in the lake. For instance, in April from 2010 to 2014 a water level was critically low, 456.04 m. The water level dropped abnormally in the autumn 2014, as a
consequence, a low minimum ever of 455.86 m (i.e. 14 am less than a maximally permitted value) was registered in the late April 2015; a water level in summer was also very low.

![Water level in Lake Baikal](image)

**Figure 2.** Water level in Lake Baikal before and after introducing in 2001 a range of level regulation from 456 to 457 m of the Pacific Scale (data provided by Irkutsk Territorial Administration for Hydrometeorological and Environmental Monitoring Rosgidromet and State Reports “On the state of Lake Baikal and measures of its protection”) [8].

For a preliminary assessment of the changing open water surface over two years under study we addressed to the asynchronous synthesis procedure. For this purpose we used zonal images in near infra-red wavelengths for 2014 and 2015, respectively. From the data given in Figure 3 it is apparent in which zones on the territory of interest a water level dropped maximally and a shoreline dried up. For instance, maximally extending dried up zones shown red in the picture are located in the delta of the Verkhnaya Angara, where numerous small zones between river arms and a shoreland of the Yarky Island turned to be dry.
Figure 3. Asynchronous synthesis of Landsat-8 imaginary over 2014 and 2015 taken above the territory of Angarsky Sor carried out in the software MultiSpec – synthesis of fifth channels (zones dried up in 2015 as opposed to 2014 are shown in red).

Further, we used NDWI images to evaluate and compare a watering degree for two investigated dates. Calculated images of the index are presented in Figure 4, and estimated areas of zones with various watering degrees are summarized in Table 1. To find a ratio between watering degree and numerical value we adapted formulae provided on the website of Harris Geospatial Solutions (http://www.harrisgeospatial.com).

Table 1. Compared watering degrees of the territory

| NDWI index value | 2014 | 2015 |
|------------------|------|------|
|                  | km^2 | %    | km^2 | %    |
| Droughty, non-aqueous surfaces | -1 to -0.3 | 225.81 | 46.84 | 240.08 | 49.8 |
| Moderate droughty, non-aqueous surfaces | -0.3 to 0 | 35.94 | 7.46 | 25.38 | 5.27 |
| Flooding, humidity | 0 to +0.2 | 19.66 | 4.08 | 12.5 | 2.59 |
| Water surface | +0.2 to +1 | 200.65 | 41.63 | 204.1 | 42.34 |

In addition we calculated a NDVI image (Figure 5), which was used in the analytical assessment alongside with the data on zones with various watering degrees. NDVI index (Normalized Difference Vegetation Index) is the most frequently used criterion for an amount of photosynthetically active biomass. It is calculated by formula:

\[
\text{NDVI} = (\text{NIR} - \text{RED}) / (\text{NIR} + \text{RED})
\]

where NIR – reflection in near infra-red wavelength; RED – reflection in the red region of spectrum.
Figure 4. NDWI-based watering degrees calculate for July, 17 2014 and July, 20 2015

NDVI index is a tool to assess the green cover productivity and state, the efficiency of forestry and agriculture, biological recourses in the region, etc. It can provide data for assessing the dislocation and suppression of vegetation communities. A combination of NDVI index and water index makes possible a more detailed spatial interpretation of results when analyzing a territory-related structure of the vegetation cover in wetlands and helps reveal plant communities in harmful moisture conditions. Furthermore, an application of the index allows a distinct separation of plants from other nature objects. Water bodies shown with the help of this index have negative values in images (below 0), whereas other nature complexes – positive values (0 to 1).
Figure 5. An example of calculating a NDVI index on July, 2015

From the data obtained it is seen that a water level fall in 2015 provoked certain changes within the boundaries of the Angarsky Sor. To be more precise, an area of marshy and excessively wet zones shrank by more than 1.5 times, areas of moderate droughty and poorly watered zone decreased slightly. A 3% increase of droughty, non-aqueous surfaces is reported. A maximal expansion of the water surface in 2015 is supposed to be related to a suppression state of aquatic and wetland vegetation caused by a falling water level. As a consequence, water surfaces covered in the past with floating plants (Nymphoides peltata, Nuphar pumila, Nymphaea tetragona, Sagittaria natans, Persicaria amphibian, etc.) were not categorized as water according to spectral characteristics, turned out to be opened in 2015, increasing therefore an area of water surface in a low-water year. Dramatic changes in the watering were recorded in the eastern and northeastern part of the territory under study in the region of the Verkhnaya Angara, as well as near Lakes Sikili, Poliguevskoye, Bludnoye. The watering change on a territory makes a difference for the state, productivity, and species composition of vegetation communities. A deeper investigation of this issue needs an application of high spatial resolution multi-zone images and further field surveys.

4. Conclusion

The study has revealed that Sor regions – unique shallow bays in the delta of the Selenga [15] and the Verkhneangarsky Sor, territories with outstanding biological productivity and biodiversity are most sensitive to potential dangers related to a falling water level in Lake Baikal. These are areas for the spawning of Baikal endemic species, as well as countries for a great number of amphibian and mammal species, aquatic and semi-aquatic birds. The drying up of wetlands in these regions may distort a water regime of ground waters and existing self-cleaning mechanisms of Baikal waters. A further drop of the Baikal level may cause a gradual extinction of wetlands.

Water level fluctuations in Lake Baikal and a watering degree in wetlands near it are closely related to natural factors [16]. An unstable hydrological state leads to hazardous situations for ecosystems in wetlands and poses a threat to animal and bird species living there, makes difficult an economic use of
the territory. Therefore, the constant monitoring of the situation is needed, as well as appropriate and timely protective measures. Since a majority of wetlands are extended and poorly accessible territories, remote sensing methods may be quite effective for the in-process monitoring of their state and its dynamics. Data of multi-zone satellite acquisition provide valuable and continuously updated information about the entire territory. Geoinformation and remote sensing techniques can make an important contribution to the preserving wetland ecosystems of the Angarsky Sor, because with their help it is possible to monitor water level fluctuations, the water surface behavior, as well as the dynamics of the vegetation cover in land ecosystems.

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