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Application of Landsat 8 imagery to regional-scale assessment of lake water quality

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ABSTRACT

The aim of the project was to create a tool with which to support regional lake quality assessment using Landsat 8 imagery data. The model of assigning the ecological status was implemented in GIS for the northern part of Poland and classifies lake quality for several classes according to classification of WFD using two basic assumptions. The first is that there exists a combination of OLI bands (OLI2/OLI4 was used) which correlates well with the trophic state of the lakes; the second assumption is that the reference trophic state depends on the mean depth of the lake. The model uses a lake geodatabase which contains lakes outlines, raster masks of lakes and attribute information about their mean depth. There is no need to provide any field data when using this tool, as calibration of the model is done using subsets of lakes which were classified using legally defined methods. The tool allows fast classification of 2800 lakes from the area of interest. The results show good agreement between satellite and expert based methods.

1. Introduction

Lake water quality is of a global interest. Indeed, the high or bad ecological state of rivers, lakes and coastal waters can strongly influence the values of properties along their coasts (McCullough et al., 2012). In nearly every country it is the responsibility of local administration to care for the health of the water bodies. In the EU, the WFD (Water Framework Directive) obligates all member countries to achieve good ecological quality of all inland water bodies until 2015 (Peeters et al., 2009). These demands require the establishment of complex monitoring and assessment systems. They are traditionally based on water sampling at fixed stations and laboratory analyses. This method may be difficult to implement when there are hundreds of separate water bodies to monitor (Kalio, 2000). There are several spots in the northern hemisphere where the lakes are clustered and their number exceeds the thousands. Such places may be found in Canada, Northern US, Sweden, Finland, Poland and Baltic Countries. They have a common origin connected with the end of the last glaciation. They are surrounded by a mixture of land cover and use. Some lake watersheds constitute a nearly unchanged environment, while others are strongly affected by agricultural runoff, erosion, urban development and loss of wetland, all of which have a strong impact on lake health (Torbick et al., 2013). This is the main reason why the trophic status of lakes incorporating relationships between nutrients (mainly phosphorus), phytoplankton and transparency may vary from ultra-oligotrophic to hyper-eutrophic (Solimini et al., 2006). On the other hand however, the trophic status of lakes with minimal human influence may also vary in a natural way depending on the lake morphometry, and especially with regard the mean depth of the water body (Scheffer, 1998).

There are many parameters used in lake monitoring which typically include measures of chlorophyll-a (Chl-a), suspended material (SPM), light attenuation for which the common proxy is Secchi depth (SD) and colored dissolved organic matter (CDOM). The WFD requirements are extremely demanding and aim to assess five qual-

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ity classes (Bad, Poor, Moderate, Good, High) by comparing the current status to reference state using biological, physical as well chemical indicators supplemented by expert knowledge. However, some publications suggest that this may be predicted quite well using water transparency only expressed by Secchi depth (Peeters et al., 2009).

The remote sensing monitoring of lakes primarily uses satellite data, mainly from Landsat TM and TM+ sensors which have the perfect spatial and time resolution for such an aim. Indeed, there are many examples of when this tool has been used successfully, and these can be divided into two groups of applications. The first group uses a singular or multiple images of the area of interest and field data obtained from several lakes (Torbick et al., 2013; Tebbs et al., 2013; Duan et al., 2008; Sass et al., 2007; Brezonik et al., 2005). It has been suggested in several publications that the time gap between lake data collection and satellite data should be no longer then 3–10 days (Olmanson et al., 2008; McCullough et al., 2012). In most cases the band ratio multi regression approach is used to obtain the relation between satellite signal and in-situ measurements. Both raw signal (DN), radiance and reflectance have been used. Several methods of less or more advanced atmospheric corrections were applied and discussed, although there are suggestions that simple dark object subtraction is recommended for classification and change detection applications (Song et al., 2001). The results of these projects are, general speaking, similar. They have proved that it is possible to obtain good results for the mapping of SD and chlorophyll-a, as well as weaker results for SPM and CDOM, cyanobacteria or diatoms. In order to obtain acceptable results, the regression equations have to be calibrated separately for a particular image. The second group used monitoring programs and the community approach to collect Secchi depth data from many lakes over several years (McCullough et al., 2012; Olmanson et al., 2008; Kloiber et al., 2002). They also used the regression approach and conducted additional analyses including change detection.

The use of satellite images for lake monitoring, especially in places with hundreds or thousands of lakes, is very tempting. Indeed, recent years have seen the emergence of two important facts. The first is there are now new satellites platforms whose resolution is suitable for lake monitoring, and the second is that their usage is free of charge. Using both Landsat 8 and, in the near future, Sentinel 2, it will be possible to obtain at least one uncloudy image nearly every month. This will give environmental managers a chance to use all benefits of RS technology such as simultaneously monitoring many lakes.

The aim of the project was to create a GIS tool to support regional lake quality assessment. The tool should classify lake quality for classes according to classification used by WFD. We assumed that the tool will require only Landsat 8 image which covers a few dozen of lakes, the water mask of the lakes and its mean depth. The tool will not require any field data which will make them more flexible and operational. To fulfill these aims three research problems have to be solved. First, the best method has to be found out for estimation of crucial parameters used in remote sensing lake monitoring. Then, such a model has to be created which allows to compare the current ecological status of the lakes using the results of satellite image analyses. Finally it has to be found out how to calibrate the results of this comparison using the lakes with known current state or defined as reference state lakes. The mean depth of the lake plays an important role. The postglacial lakes may have different depths on which their ecological state in natural conditions is heavily dependent. There is a well-established difference in the structure and functioning of the lakes which depends on their mean depth (Scheffer, 1998; Poikane et al., 2014). The natural ecological state is different in polymictic shallow systems than in deeper seasonally stratified systems. As a result, and in order to minimize natural biological variations, lakes are often divided into arbitrary depth related classes (Phillips et al., 2008). The tool should make it possible to calibrate the classification process in an iterative way so as the subset of lakes whose quality state is known may be used to calibrate the complete set of lakes.

2. Data and methods

The development of the system was carried out in two steps. First the two field experiments were conducted using two Landsat 8 scenes and field observations carried out at nearly the same time as the images were taken. The aim of these experiments was to find out the best combination of satellite image bands for describing the trophic state of the lakes in the area of interest and to prove that our assumption about the role of mean depth is true. On the basis of the results from these two experiments the model of assigning the ecological status using only satellite data was developed and verified using independent expert assessments.

2.1. Description of study area

The study area covers the northern part of Poland, where there are many densely distributed clusters of postglacial lakes. There are approximately 8000 lakes with a total surface of around 3000 km^2 across, and a total area of approximately 116000 km^2 (Fig. 1B). The mean depth of the lakes varies from 0.2–38.7 m. The land cover of this area is a mosaic of agricultural areas (61%), forests and semi natural areas (34%) as well as urban and suburban fabric (2%). The field experiment area (Fig. 1) is placed in the central area of study which is representative of climate and land cover. In Poland, the ecological state of the lakes (required by WFD) is determined by the regional inspectorates of environmental protection which are the branches of the government administration. They use several legally defined procedures in order to divide the ecological status of lakes into five classes using mainly biological based methods supplemented by some abiotic measurements. These methods are expensive and need a lot of laboratory work. This means that a limited number of lakes may be classified each year. For example, only 22 lakes were assessed in 2014 in the Pomeranian District (Fig. 1).

2.2. Lake geodatabase

The geodatabase of lakes for the northern part of Poland was created using three sources: A vector layer from polish hydrographic geodatabase MPHP in the form of polygons (SHP) containing lake names; an analogous atlas of lakes (Janczak, 1996) which contains tables with positions of the central points of the lakes, and their mean and maximum depth; and Landsat 8 images. First the maximum depth from atlas tables was spatially joined with shapes of the MPHP lakes. Following this, the number of lakes was updated as the MPHP geodatabase contains many small lakes which are not currently in existence and which are now covered by vegetation. This was done using Landsat 8 images for the whole area of northern Poland. The area (Fig. 1B) was covered by twelve uncloudy images (paths: 187–192 and rows: 22–24) from the years 2013–2015. The shortwave infrared band (6th band DN) of Landsat 8, which gives the strongest and most stable difference between water and land, and the median statistics were used to find a threshold to select existing lakes only. The same set of images was used to create a raster of lake zones for extracting pixel values for statistics calculation. It was decided that for each lake only pixels with values lower than the median of all lake pixels in band 6 would create a zone with unique lake identifiers. As a result, our geodatabase contains 2800 lakes with the same mean and maximum depth as a vector