Workpackage 5, Innovation and Application through Use cases

Deliverable 5.4, Shallow lakes with low transparency due to sediment resuspension

WI, CNR, VU/VUmc

in cooperation with Witteveen+Bos

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Reference


Task objective (from DoW)

Shallow lakes can be very turbid due to resuspension of sediment from the lake bed. Turbidity can induce an unfavorable ecologic state. This is also driven by nutrients, depth and lake size, and wind, and often leads to lake restoration projects. Shallow lakes can also serve as indicators of climate change. The objective of this task is to develop a use case shallow lakes with low transparency for education.

Scope of this document

The scope of this document is to show how satellite data, especially GLaSS products, can be used to analyse turbidity and alternate states (clear calm versus turbid windy conditions) in shallow lakes which are dominated by high sediment concentrations. We extended the scope by including lakes with different socio-economic issues from different parts of the world to stress the relevance from a management/policy point of view. This document describes these lakes: Lake Markermeer in the Netherlands, Lake Böyük Şor in Azerbaijan, and pro-and supraglacial lakes in the Himalaya. The report also discusses their current ecological status, relevance and issues, such as the rehabilitation plans for Lake Markermeer and Lake Böyük Şor, and the hazard mapping for the pro- and supra glacial Himalayan lakes. It describes the satellite data which are used to analyse the (trends in) turbidity, the methods used and the results. These results will be used for educational purposes to show the effects wind (in Lake Markermeer), glacial retreat (for Himalayan lakes) or rehabilitation works (in Lake Böyük Şor) on sediment loads and water quality. These Exercises will be generated in GLaSS tasks 6.3 and 6.4.
Abstract

This use case studies turbid shallow lakes. There can be several factors affecting the turbidity: for instance, wind waves causing re-suspension can cause a high turbidity, but also glacier melting adds loads of fine particles to glacier lakes. Within the socio-economic analysis of GLaSS (GLaSS D5.1) it was found that many lakes that present high turbidity are either part of an ecological restoration project, and/or there are large socio-economic risks associated with the lake water.

We chose lakes with three very different kinds of socio-economic situations to study in more detail. The first is Lake Markermeer (Netherlands) which is a lake of the classical type in which wind waves cause high resuspension. It is part of a restoration project to reduce resuspension to increase the underwater light field and the biodiversity.

The second is Lake Böyük Şor (Azerbaijan), which is under high environmental pressure, including oil pollution. A restoration project is ongoing here to increase the general water quality.

The third case is a group of Himalayan lakes, of which several are studied. Some glacial lakes can be source of concern because of their risk to Glacial Lakes Outburst Floods (GLOF) that can have disastrous effects on downstream villages. The observation of water color of these lakes, which reflects the load of sediments in the water, can be an indicator of glacier melting rate and therefore one on the list of useful indicators to predict GLOF. In addition, water color is also linked to the quality of water and is therefore an important property to monitor, especially in places where water depuration systems are not available.

For Lake Markermeer turbidity is derived from satellite data and compared with in situ turbidity measurements to tune the algorithm. Based on this algorithm high resolution maps of the lake can be created. For Lake Böyük Şor oil potential and turbidity maps are made, based on scaling the band ratios to the same level of in situ data. Especially for the oil maps the evolving efforts and results of the restoration project could be followed.

For the Himalayan lakes, an in situ campaign was carried out to validate the remote sensing reflectance obtained from satellite data. Afterwards, the colour of the lakes, their proximity and connection to the glacier and other lakes are studied to create a risk map for the area.
List of abbreviations

<table>
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<tr>
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<td>L8</td>
<td>Landsat 8</td>
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<tr>
<td>SNP</td>
<td>Sagarmatha National Park</td>
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<td>OLI</td>
<td>Operational Land Imager</td>
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<td>GE</td>
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<td>Total Suspended Sediments</td>
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List of related documents

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Clarification of the co-operation between GLaSS and Witteveen+Bos

GLaSS co-operated with engineering company Witteveen+Bos on the chapter on Lake Büyük Şor. Witteveen+Bos provided the in situ data. Also, information on the restoration project was provided by Witteveen+Bos. The satellite data was processed by GLaSS and also the analysis were carried out by GLaSS.
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1 Introduction

Turbid lakes are often shallow and the turbidity is caused by their small (buffering) volume of water and strong lake-land, air-water and water-sediment interactions. Hence, these lakes have a high risk to increase in trophic state (eutrophication) and to develop cyanobacterial blooms.

Large wind-exposed shallow lakes are often turbid because lakebed sediments can be whirled up to the water surface under moderate winds (Figure 1).

*Figure 1. TSM concentrations (in mg/l) for different wind directions and speeds. (Left) High surface TSM concentrations in the northeast under the influence of westerly winds, versus (Centre) a clear directional TSM signal resulting from northeasterly winds followed by (Right) lower concentrations caused by settling when the wind is abating (Eleveld, 2012)*

In case of river inflows that are dominated by TSM, the effect on lake optics is the same as for re-suspension events: the backscattering is relatively high and the water therefore appears bright. The colour of these lakes is generally described as brown/green. A different type of lakes in this category are glacial lakes (fed by glaciers). Because of the high mineral versus organic input, they vary in colour from deep blue to cyan and grey (Eleveld et al., 2014. GLaSS D5.1).

Waters that are rich in sediments can affect the ecology of lakes: the reduction of water transparency inhibits primary production due to the lack of light in the water column and makes higher organisms in the food web hard to survive (Koenings et al., 1990). Lake management or restoration projects usually aim to bring these lakes from turbid to clear water state (Scheffer, 1998). Measures to increase the amount of available light in the water column vary from nutrient management and biomanipulation (such as removal of benthivorous fish) to hydrologic adjustments (of water level and flushing) or dredging and creation of enclosures.

Shallow lakes can serve as indicators of climate change. In shallow lakes, the temperature effects may drive ecosystem functioning via the regulation of the steady-state change, though the evidence is equivocal. Also, teleconnections between NAO and wind-driven variation in wave mixing have been suggested by Spears and Jones (2010). Variations in the depth of the wave-mixed layer have previously been shown to affect sediment disturbance (Eleveld, 2012 and references therein) and internal nutrient loading (Hamilton & Mitchell, 1997).

For the current work, three examples of shallow lakes with high suspended solid concentrations are chosen:

1) Lake Markermeer, a classical example of a lake dominated by resuspension of sediments;
2) Lake Böyük Şor, which is interesting because it is currently undergoing a large restauration project to remove oil, but also influences the turbidity, and
3) a group of glacial lakes in the Himalaya, where the suspended solid concentration is
one of the indicators that can be used to predict dangerous Glacial Lakes Outburst Flood (GLOF) events.

For Lake Markermeer, measures are being sought to overcome high turbidity. It is thought that high TSM concentrations affect the zebra mussels (*Dreissena*) by clogging their gills, and that the associated light attenuation impedes the growth of water plants, whereas algae and (toxic) cyanobacteria thrive at higher TSM concentrations (Van Duin, 1992; Scheffer, 1998 in Eleveld, 2012). Several measures have been investigated (Noordhuis et al., 2014), and anticipated measures (construction of the Markerwadden island) are discussed in this report.

For Lake Böyük Şor, which has additional problems with oil pollution, compartments and sludge depots have been created, and their impact is followed in this report.

A whole different impact of climate change is melting of glaciers and its impact on the formation and colour of glacial lakes. **Glacial lakes** (those lakes originated by melting of glaciers) often do contain high sediment loads. Glacial lakes can be differently connected to their “parent” glacier depending on the oldness of erosion processes: in case of ancient melting activity they simply lie in a “U” shaped valley carved by glaciers now disappeared (e.g. Great Lakes in US or Subalpine Lakes in Italy), while in case of recent glacier shrinkage they can be located in the proximity of glacier tongues, being strongly affected by their activity and dynamics (e.g. lakes in the Himalaya or Patagonia). In this case, the interaction between glacier and lakes is such to influence both size and water turbidity of lakes (Slemmons et al., 2013). Glacial meltwater can even alter chemical processes in glacial lakes, increasing for instance water conductivity and ionic concentrations (Lami et al., 2010). Some glacial lakes can be source of concern because of their risk to outburst. They are usually located between the glacier terminus and its moraine (proglacial lakes) or generate as small ponds on the surface of a glacier tongue (supraglacial lakes) gradually increasing with glacier melting. Recent climate change, in particular global warming, is the leading factor of Glacial Lakes Outburst Flood (GLOF) events. Glaciers gradually increase their melting rates with consequent growth of lakes surface and volume. The accidental damage of the damming moraine as well as rock/ice fall or avalanche events can break the delicate equilibrium of the system, causing the downstream of huge volume of water, with severe consequences for villages, infrastructure and population. GLOF is a serious problem affecting different alpine ecosystems in the world, such as the Himalaya, where from 1935 several catastrophic events occurred in Nepal (e.g. Dig Tsho lake in 1984, Vuichard and Zimmerman (1987)), China (e.g. Boqu River in 1981) and Bhutan (e.g. Lugge Tsho in 1994) with loss of cultivated lands and livestock, destruction of bridges and villages and death of people (Ghimire, 2004-2005). Even in the Andes several serious events occurred in the past, and current rapid refilling suggests the possibility of future anomalous discharges (e.g. Cachet 2 Lake, Dussaillant et al., 2010). Other GLOF events were registered in Norway (Xu et al., 2015), Peru (Vilímek, et al., 2015), Tibet (Liu et al., 2014), Siberia (Margold et al., 2011), Kyrgyzstan (Narama et al., 2010).

Monitoring of lakes expansion and concurrent glacier retreat, together with the geomorphology of lake surroundings, are the most used tools to identify potentially dangerous lakes and their risk of outburst (e.g. Bolch et al., 2008; Nie et al., 2013; Carrivick and Quincey, 2014). Mostly, the evaluation of physical and morphological parameters describing lakes and glaciers evolution is done through the application of remote sensing techniques, which can efficiently monitor less accessible places such as mountainous environments, where lakes are days walking distance far from each other. In addition to this, elements exposed at risk (e.g. persons, fields, livestock, infrastructures) and their vulnerability (i.e. the potential extent of damage) have to be considered too in order to predict possible impacts generated by GLOF events (e.g. Wang et al., 2015).
Following an interdisciplinary approach (i.e. lakes characteristics, conditions of surrounding environment and socio-economic parameters) a recent work by ICIMOD (2011) detected 21 potentially dangerous lakes in Nepal, ranked in three increasing priority classes requiring proportional attention in future monitoring. Within this context, the observation of water color of lakes, which reflects the load of sediments in the water, can be a useful indicator of glacier melting rates. Obviously, water color as a single element cannot provide estimation of GLOF probability, but together with the aforementioned parameters can concur to the assessment of GLOF risk, for instance giving information about sediments transport activated by a GLOF event. In addition, water color is also linked to the quality of water, an important factor in places where water depuration systems are not available.
2 Description of the lakes

2.1 Lake Markermeer (Netherlands)

Lake Markermeer (Figure 2) is a shallow lake in the centre of the Netherlands. It used to be a part of the original Sea Zuiderzee, and later Lake IJsselmeer (see also D5.2). In 1932 Lake IJsselmeer was created (or: dammed off from the Zuiderzee Sea) by closing of a 32 km long dam. Next, several polders were created in this new lake. Lake Markermeer came into existence when a dike (the Houtribdijk) separated the south-western region from the main lake in 1975. This dike runs from Enkhuizen, southeast to Lelystad. This former southern part of Lake IJsselmeer is now the hydrologically separate Markermeer.

![Figure 2, Map of Lake Markermeer](image)

The bottom of Lake Markermeer consists of a layer of mud. Wind waves easily reach the bed of this shallow lake, and resuspend and mix this bottom material up into the water column, where we detect it as turbid waters. Because of all the dam and dike building around the lake, it does not have many natural shorelines. As show in Figure 3, most shores are relatively steep and have no vegetated gradual underwater slope. Therefore, wind waves are not gradually dissipated near the shorelines, and resuspension increases. The local influence
of the wind on suspended matter concentrations was studied by Eleveld (2012). Retrieved surface Total Suspended Matter (TSM) maps from MERIS images matched resuspension maps that were predicted from wind and water depth.

![Figure 3, Photos of Lake Markermeer. Top left: dikes surround Lake Markermeer. Right: Secchi disk reading showing the high reflection but low transparency. Bottom left: fieldwork at Markermeer, in the background a harbour full of recreational sailing boats can just be seen.](image1)

The high TSM concentrations make the lake less attractive for recreation, and for fish and birds that need to see their prey. The high turbidity reduces the underwater light intensity and therefore the amount of submerged vegetation and locations of shelter for macrofauna and prey fish. Therefore, in the period 2009-2015, water manager Rijkswaterstaat has carried out a project to study potential measures to reduce the sediment concentrations in the water column and increase the biodiversity. During this project several experiments have been set up, including the setup of a fence to break the waves. Currently (2015) a new project by nature organisation Natuurmonumenten is taking off. Natuurmonumenten will remove the mud layer from the lake bottom and use the material to create new islands in Lake Markermeer ([www.natuurmonumenten.nl/marker-wadden](http://www.natuurmonumenten.nl/marker-wadden), Figure 4). The dredging will start in 2016.

Landsat 8 data will be used to follow trends in turbidity in Lake Markermeer, especially at the locations of the experiments carried out by Rijkswaterstaat. The idea it that this method (however, using Sentinel-2 data) and the methods as developed by Eleveld (2012) can also be used to follow the trends in turbidity that will result from the project by Natuurmonumenten.
2.2 Lake Böyük Şor (Azerbaijan)

Lake Böyük Şor, located in the Azerbaijani steppe landscape, is a natural salt lake that was exclusively fed by precipitation. The lake dried up in summer and was historically used for salt production. Because of its shallowness and often occurring high winds in the area, the lake's water quality is influenced by resuspension of sediments. However, there is another cause for concern on water quality.

In the area natural petroleum seeps existed, which were exploited since the industrial revolution. In the last century the exploitation increased, originally using extremely polluting methods. The oil from the fields on the east and eastern shorelines of the lake polluted the water and the sediments on the bottom of the lake. Over the last centuries the increasing amount of industrial and residential waste waters from the city of Baku have been discharged into the lake, resulting in a year round high water level. Pollution of the discharged waters has severely deteriorated the water quality of Boyuk Shor. Figures 5 and 6 give an impression of the shorelines of Lake Böyük Şor.
Since 2013 engineering company Witteveen+Bos has started the restoration of Lake Böyük Şor (and other lakes in the surroundings) funded by the Ministry of Economy and Industry of Azerbaijan. The lake restoration is part of the Baku city development plan for 2030. Because of the European Games in Baku in summer 2015, the project started here. The first steps of the restoration had to make sure that the southern shore of the lake would be clean by the time the Games started. The full effect of the measures that were taken will become visible in the coming years.
the lake section in direct proximity to the Olympic Stadium (Figure 7) and focus the restoration efforts on this lake section first. To this end a dam was constructed across the lake connecting the north and south shores. The dam also serves the construction of a new highway connecting the Ziya Bunyadov road with the Balakhani-Binagadi highway. To avoid recontamination of the project area from historical deposits along the north shore a second dam was constructed that runs parallel to the north shore and connects the north-south dam with the east shore.

Over the whole lake solid waste was removed. The isolated lake section was dredged. The polluted sludge was pumped into three sludge depots that were created in the northernmost section of the lake. In the depots the sludge was drained, leaving the polluted oil and sediments behind.

During the project most discharges to the lake were closed. Only the main discharge that is emptying into the lake in the north-west corner was kept open to enable regulation of the water level.

Construction of the dikes and the dredging activities are expected to influence the turbidity, the concentrations of oil in suspension and – as a result – the oil floating at the water surface. It is expected that changes in these properties can be observed with Landsat-8 satellite products.

Figure 7, map of lake Böyük Şor indicating the in situ sampling stations and other points of interest.
2.3 Himalayan lakes (Nepal)

Glacial lakes analyzed in this work are located inside the Sagarmatha National Park (SNP) and its surroundings, including both Chinese (Tibet) and Nepali territory (Figure 8). Approximate coordinates are 27°-28.5° North and 86°-87° East, at the border line of the Solu-Khumbu district (Eastern region of Nepal).

The area is characterized by the presence of several peaks more than 7000 m high (e.g. Pumori, Lhotse and Mount Everest (8848 m)) from where glaciers extend towards lower valleys (4500-5000 m). Terminal tongues are mainly covered by debris, which have the property of altering energy exchanges between ice and atmosphere (Mattson et al., 1993). Glacial lakes in the study area are differently connected with glaciers: some are melting ponds located above the glacier tongues (supraglacial), some others come out from the glacier front and are dammed by the moraine of the glacier (proglacial), others are lakes not directly connected with a glacier, but sharing their basin with it or generated in land depressions formed by glacier erosion (cirque).

Glacial lakes in this area are prevalently fed by perennial snow and ice and they are placed above the tree limit (between 4000 and 5700 m), where climatic conditions are such that only simple ecosystems can survive. Moreover, human influence in this environment can be considered as null: villages are sparse and low populated, people are living with minimal exploitation of natural resources (agriculture and breeding are strongly limited by climate). Water quality of lakes is hence mainly affected by natural processes, such as runoff from sloping lands, river transport and glacier melting. All these processes can introduce in the lake both organic (e.g. decomposition of alpine vegetation such as grass and low shrubs) and inorganic material (e.g. sediments trapped inside and eroded by glacier tongues moving and melting), with prevalence of inorganic sediments, due to the scarcity of vegetation development in such climatic conditions.
Measures of water component concentrations for some of these Himalayan lakes are available from recent studies (Giardino et al., 2010; Yan et al., 2013). From these data it can be assessed that glacial lakes are oligotrophic with total suspended sediments as main variable water quality parameter: TSM was measured to range from 320 gm$^{-3}$ (in China) and 160 gm$^{-3}$ (in Nepal) to less than 1 gm$^{-3}$. Different loads of TSM have consequences for the water color, changing it from bluish (low TSM concentration) to grayish (high TSM concentration) nuances (Figure 9).
Figure 9, Pictures of the 5 lakes sampled during the fieldwork campaign. Numbers correspond to the lake code in figure 7 (lake number 9 is too small to be mapped at Landsat spatial resolution).
3 Methods

3.1 Methods Lake Markermeer

Landsat 8 data was used as a proxy for Sentinel-2 data. Earlier work has already shown that MERIS data can be used to follow resuspension events in Lake Markermeer (Eleveld, 2012). Also time series of MERIS derived TSM concentrations showed good agreement with in situ concentrations (Annex A: MERIS based mapping and time series of Lake Markermeer).

However, more detailed patterns (gyres end eddies) are expected from the use of high resolution data. This information could be useful to study local details during and after the Markerwadden project. Therefore, to prepare for the use of S2 data, Landsat 8 imagery was used for the analysis of Lake Markermeer.

The imagery was downloaded from the GLaSS coresystem (D2.3 System & System implementation report) using the bulk download scripts (D2.4 System Interfaces implementation report). Next, the data was processed to L2 remote sensing reflectance at the water surface, using the C2R-L8 processor in the SNAP toolbox. However, the standard land-water flag was replaced with Equation 1.

\[
\text{water} = \frac{\text{near}_\text{infrared}-\text{red}}{\text{near}_\text{infrared}+\text{red}} < 0.1 \quad \text{and} \quad \text{swir}_1 < 5 \quad \text{and} \quad \text{swir}_1 > 0.0
\]  

(Equation 1)

To derive chlorophyll, the band ratio \(\text{reflec}_3/\text{reflec}_4\) was applied, which was derived in D5.2 on Eutropic lakes. Also, the same ‘tuning’ (a multiplication of with 40) was applied. TSM was derived by the ratio \(\text{reflec}_4/\text{reflec}_2\), after which the data was scaled to be in the same order of magnitude as the in situ data. This led to a ‘tuning’ of the TSM algorithm with a factor 20 (Equation 2).

\[
\text{TSM} = 20*(\text{reflec}_4/\text{reflec}_2)
\]  

(Equation 2)

To generate time series, the PixEx tool which is available in the SNAP toolbox was applied to the processed imagery. The time series were compared with (and TSM was tuned to) in situ data that is available via the water manager Rijkswaterstaat (life.waterbase.nl). The comparison was performed for the reference station for which most in situ data was available, which is called Markermeer Middle (Markermeer midden).

Because an unexpected result was found (higher chlorophyll values in winter than in summer), also long term datasets were analysis: in situ data from the reference station suggested a decreasing trend in one of the geophysical water quality parameters (presented in the results section). Such time series are based on a limited number of measurements, whilst the variability in surface water quality measurements is notoriously high.

To check if such a trend could be substantiated, additional time series were generated based on the MERIS satellite, which has a higher temporal resolution than the in situ data. For MERIS, three chlorophyll indices (MCI, FLH and BRR-MPH), that all aim to quantify Chl peaks in the spectrum were calculated based on the same methods as described for the neighboring Lake IJsselmeer in GLaSS deliverable D 5.2. The standard MCI flags were used for both MCI and FLH. For MPH, the level 1 flags were applied (L1p flag = 0), plus the standard MPH flags (cyan max at 1000 and a Chl threshold for floating vegetation at a value of 350). Then, the BEAM PixEx-tool was used to extract all data for two locations associated with Lake Markermeer midden: coordinates which are indeed located near the centre of Lake...
Markermeer (MMi), and the historic coordinates (1997 to beginning 2002) for Markermeer Midden (MMo), see Fig 2.

3.2 Methods Lake Böyük Şor

3.2.1 Imagery and corrections

Landsat 8 imagery, with a spatial resolution of 30 m has been used for this analysis. Images with cloud cover or too low solar angles (<30 degrees) have been removed. For these oil-rich waters no suitable atmospheric correction methods are available, so instead we worked with top of the atmosphere reflectance (TOA planetary reflectance): \( \rho \lambda \). Drawback of this method is that changes in atmospheric properties (e.g. changes in aerosol type) cannot be distinguished from changes in water quality. TOA planetary reflectance was calculated according to the methods provided by USGS (http://landsat.usgs.gov/Landsat8_Using_Product.php), equations 3 and 4).

\[
\rho \lambda = M \rho Q_{cal} + A \rho \tag{equation 3}
\]

where:
- \( \rho \lambda \) = TOA planetary reflectance, without correction for solar angle
- \( M \rho \) = Band-specific multiplicative rescaling factor from the metadata
- \( A \rho \) = Band-specific additive rescaling factor from the metadata
- \( Q_{cal} \) = Quantized and calibrated standard product pixel values (DN)

Subsequently, \( \rho \lambda \) is corrected for the solar angle using:

\[
\rho \lambda = \frac{\rho \lambda}{\cos(\theta_{SZ}) \sin(\theta_{SE})} \tag{equation 4}
\]

where:
- \( \rho \lambda \) = TOA planetary reflectance
- \( \theta_{SE} \) = Local sun elevation angle
- \( \theta_{SZ} \) = Local solar zenith angle; \( \theta_{SZ} = 90^\circ - \theta_{SE} \)

The resulting \( \rho \lambda \) are called after the Landsat-8 band numbers: reflec_1, reflec_2, etc.

3.2.2 Oil potential and turbidity retrieval

Because oil is the most important polluting factor, oil was a logical parameter to monitor. Satellite data deliver information only on the upper layer of the water column, as far as the light can penetrate; floating layers of oil prevent the retrieval of concentrations from the water column. Therefore, we choose to follow the potential contamination with surfacing oil. It is known that oil generally absorbs the visible light, leading to a lower reflectance. However, in the near-infrared (NIR) the reflectance of water with a layer of floating oil is much higher, because the layer of oil reflects the downwelling light on the surface. Therefore the reflectance in this part of the spectrum is much higher than that of other water surfaces, because pure water highly absorbs light in the NIR. This is illustrated with some reflectance spectra in Figure 10, obtained by Witteveen+Bos with a hand-held radiometer (Figure 11).
Figure 10. Reflectance spectra measured in Lake Böyük Şor in 2013 (wavelength on the x-axis). In green several reflectance spectra with a ‘common’ water shape in productive waters, with low reflectance in the NIR, in blue reflectance spectra with an effect of oil, taken in the northern part of the lake (measurements taken with a WISP-3 radiometer by Witteveen+Bos).

Figure 11. Fieldwork to obtain reflectance spectra at in Lake Böyük Şor by Witteveen+Bos in 2013 (using a WISP-3 radiometer).

Knowledge on spectral features has been used to define band ratio's which relate to concentrations of oil on water surface. It was also important to flag the land pixels in a way that did not remove the pixels with oily layers, where standard land flags flag pixels with high values in the NIR. To retrieve the oil potential, equations 5 and 6 were used:

\[ \text{land} = \text{reflec}_1 < \text{reflec}_5 \text{ AND } \text{reflec}_5 > 0.15 \]  

(equation 5)
oil_potential = \frac{\text{reflec}_5}{\text{reflec}_4} \text{ AND not(land)} \quad \text{(equation 6)}

The higher the difference between \text{reflec}_5 and \text{reflec}_4, the thicker the layer of oil on the surface (until the extent of a depth that the light can penetrate through) or the larger the surface within a pixel that was covered with an oily layer.

Another parameter that is of interest is turbidity. Turbidity increased because of the dredging activities in the lake, which aim either to generate the dikes, or to remove the oil-containing sediments. Because of a missing suitable atmospheric correction, precise concentrations of e.g. suspended matter or chlorophyll cannot be retrieved. As known, suspended sediments influence the reflectance in the NIR. Because of the high influence of oil in this ratio this algorithm could not be used, so a 'second best' band ratio was applied, according to equation 7.

\text{turbidity} = \frac{\text{reflec}_4}{\text{reflec}_2} \text{ AND not(land)} \quad \text{(equation 7)}

However, because TOA data was used, the relative difference between \text{reflec}_2 and \text{reflec}_4 was too small to follow any trends, nor any relation with in situ data was found. Therefore, band 5 was used to normalise the ratio to the overall intensity, resulting in equation 8.

\text{turbidity} = \frac{(\text{reflec}_4 - \text{reflec}_5)}{(\text{reflec}_2 - \text{reflec}_5)} \text{ AND not(land)} \quad \text{(equation 8)}

Furthermore, the pixels for which oil_probability algorithm lead to values > 1 were flagged away. The reasoning is that when there is a layer of oil floating at the surface, the satellite will not receive any data from below that surface and will therefore not contain information on turbidity.

Some ancillary data was used to improve the land flag to generate the map images (e.g. a re-occurring shadow of a tall building that is not flagged as land because of the low reflectance can be removed).

### 3.2.3 In situ data and time series generation

In situ measured data of several parameters, including Total Hydro Carbon (as $\sum$TPH c10-c40) and turbidity and Secchi Depth was provided by Witteveen+Bos for the five in situ stations on the lake (Figure 6). In situ data was available for the period spring 2014-spring 2015. Three of the monitoring stations are located in the project area. One monitoring station is located in the north section of the lake in the proximity of the sludge depots. To compare the results of oil_potential and turbidity with in situ measured data, the 'PixEx' tool, available in the BEAM and SNAP software was applied to the series of satellite images. Afterwards, the satellite-retrieved data was scaled to the same order of magnitude as the in situ data. For turbidity, the best scaling factor was also applied to the satellite imagery to generate the maps. In this way the turbidity algorithm (equation 5) was 'tuned' with a multiplication by 80. This multiplication was later also used in the generation of the maps. To compare the time series of TPH and oil probability, oil probability was multiplied with 40 and TPH was plotted as mg/l.

### 3.3 Methods Himalayan lakes

#### 3.3.1 In situ measurements

One field campaign was carried on from 14th to 20th October 2014, with the aim of collecting radiometric and turbidity data for 5 lakes between 4532 and 5067 m of altitude.
Radiometric measurements were performed with a field spectroradiometer (WISP-3, WaterInsight) (Figure 12), while turbidity was measured using Secchi disk. In order to avoid bottom influence on radiometric measures, sampling stations were selected in deep water conditions, using an inflatable boat. In the same stations Secchi disk was lowered into the water till it disappeared. It was hauled up and when the disk became visible again, the water depth was recorded. Concurrently, one water sample was collected to be analyzed on the shore with the iQwtr instrument (earlier known as Secchi3000). This is an innovative low-cost and simple-to-operate field analyzer for surface water turbidity estimation, based on a smartphone application (Toivanen, 2013).

### 3.3.2 Satellite data
Two images have been acquired from Landsat OLI (Operational Land Imager) and GeoEye-1 (GE) satellite sensors on 29-10-2014 and 18-10-2014 respectively. The GeoEye-1 acquisition was concurrent to in-situ measures performed on Lake 24, while no images from OLI sensor could be available before 29 of October. Both sensors are multispectral sensors, with classical Blue-Green-Red-Infrared bands, with their pixel sizes ranging from 2 to 30 m (Figure 13).
On both satellite images radiometric calibration and correction of atmospheric effects were performed in order to gather remote sensing reflectance (Rrs) values ($\text{sr}^{-1}$). Radiometric correction of the OLI acquisition was done using the specific coefficients by Pahlevan et al. (2014).

### 3.3.3 Elaboration

Different atmospheric correction codes (6S, Vermote et al., 1997), ATCOR (Richter and Schläpfer, 2015), c-WOMBAT-c (Brando and Dekker, 2003), ACOLITE (Vanhellemont & Ruddick, 2014, 2015) were applied to the satellite images in order to achieve the most realistic Rrs values. Atmospheric profile was set using user defined O$_3$ and water vapor values (Ozone over your house NASA and AERONET station EVK2-CNR), while the continental/rural aerosol model was chosen as most representative of the study site. Aerosol Optical Depth was also derived from AERONET data and set to 0.05. Since the presence of snow covered land around lake targets was observed as significant (snow falls occurred during fieldwork), the adjacency parameter was set during atmospheric correction procedures where the RTC allows (i.e. ATCOR and c-WOMBAT-c), and adjacency affected areas were sized differently in order to achieve the best match between in-situ measured and satellite derived reflectance spectra.

The atmospheric correction procedure was validated using synchronous in-situ measurements and GeoEye-1 overpass. At satellite radiance spectra were simulated on the base of GEOEye-1 radiometric characteristics, sun-target-sensor geometry of GeoEye-1 and modeling atmospheric properties with user-defined O$_3$ and water vapor data (0.127 cm/atm and 0.185 g/cm$^2$ respectively). The continental aerosol model was chosen and AOD was set to 0.05.

The variability of water color was investigated at regional scale. All lakes with size suitable to be mapped within the OLI image were analyzed and classified. Water reflectance in the VIS-
NIR spectral range $R_{\text{VIS-NIR}}$ (as the average water reflectance values in the VIS-NIR satellite bands) were classified in three water color classes, based on intensity of water reflectance and on the observed desaturation of lake colors from dark-blue to gray: $R_{\text{VIS-NIR}} < 0.01$ (blue waters, as those of Lake 10 and Lake 31), $0.01 < R_{\text{VIS-NIR}} < 0.03$ (turquoise waters, as those of Lake 24) and $R_{\text{VIS-NIR}} > 0.03$ (grey waters, as those of Lake 161). The spatial resolution of OLI sensor allowed the detection of 119 lakes. Classification results were compared with previous data (Giardino et al., 2010) and were analyzed together with the more recent glacial extension and morphological data (ICIMOD and Randolph glacier inventory, Arendt et al. 2014).
4 Results

4.1 Lake Markermeer (Netherlands)

4.1.1 Landsat time series

First the in situ results (Figure 14) were studied so it was known which patterns we were looking for. Mostly turbidity and TSM seemed to be negatively correlated, as expected. However, for one data point, August 2013, this was not the case (red circle): both transparency and TSM concentrations were high. Over almost the whole period Chl and TSM correlated, so that Chl was also negatively correlated with transparency. For Chlorophyll and transparency there were several data points around August 2013, at which the relation was as expected (chlorophyll low where transparency was high). Therefore, it is expected that the TSM concentration of August 2013 was incorrect.

Interestingly, Chl values do not show much of a seasonal pattern, but – as mentioned before - generally follow TSM. Sometimes chlorophyll values are higher in winter than in summer.

Figure 14 in situ data (Chl (µg/l), TSM (mg/l), Transparency as Secchi depth (cm).) of Lake Markermeer (by Rijkswaterstaat) which was used for validation. We place a small question mark with the high TSM value in summer 2013 which occurred at a moment with high transparency.

Figure 15 shows time series of Landsat 8 derived turbidity, in situ turbidity, in situ transparency and wind speed. After ‘tuned’ the data to a suitable right scale it appears that the same pattern is found between wind speed, L8 turbidity and in situ turbidity. Indeed, around August 2013 the L8 turbidity values are low (where the – probably incorrect – in situ concentration is high).
Figure 15, Time series of Landsat 8 derived TSM ("TSM band ratio" mg/l), in situ TSM (mg/l), in situ transparency (Secchi depth in cm) and wind speed (average of the means of three days, m/s). Note that this data was ‘tuned’ to the right scale.

For Chlorophyll the time series of L8 and in situ versus wind speed and turbidity are shown in Figure 16. The general pattern suits very well between L8 and in situ data and is also negatively related to transparency. However, the values are not always on the same level: where the scaling (as taken from D5.2) leads to almost similar values for the period May-August 2014, the L8 derived concentrations are somewhat higher in summer/autumn 2013 and much higher in spring 2014. This could be due to comparing different properties (an average value over a 30 times 30 m pixel versus a surface water point sample), or because of a not fully suitable algorithm.

Figure 16, Time series of Landsat 8 derived chlorophyll ("Chl bandratio" (μg/l)), in situ
chlorophyll (μg/l) in situ transparency (Secchi depth in cm) and wind speed (average of the means of three days, m/s).

Indeed, also Landsat data shows that both TSM and Chl are related to wind speed, and therefore also co-variate. A literature study explained this correlation.

In Lake Markermeer, in contrast to other Dutch lakes, the ratio Chlorophyll/Phosphate has in the last decades increased, following a decrease of the amount of mussels in the lake. Also, especially in the winter, the chlorophyll concentrations increased (in the period 1996-2007 in contrast to the period 1987-1995) (Noordhuis, 2010). The first hypothesis for the increased winter concentrations of Chl was that these were related to the water temperature and the increased sunshine and water temperature in winter (Noordhuis, 2010). Noordhuis (2010) also compared the size classes of phytoplankton were: in the period 2002-2006 the amount of phytoplankton small enough to be grazed by mussels was significantly larger than the 1990’s, while the amount of larger phytoplankton decreased (except for the month October). Especially the very small (< 5 μm), undeterminable green algae cells in summer increased, due to a decreased grazing by mussels and/or zooplankton (Noordhuis, 2010). However, while the transparency of Lake Markermeer had clearly decreased around 1992/1993, it increases again since 2003 (Geest and Noordhuis, 2013). The increase in transparency is expected to be due to the increase in the number of Quagga mussels, filter-feeding the suspended matter including phytoplankton. The mussel beds on the bottom also reduce the sediment resuspension due to wind (Geest and Noordhuis, 2013).

A newer study suggests that next to the effect of mussels, floc formation between the smaller algae cells and suspended sediments has increased, because of changes in the phytoplankton community. These flocs increase the settling velocity of phytoplankton and therefore decrease the amount of chlorophyll in the water column during the calmer periods (Geest and Noordhuis, 2013). It has been shown that the cyanobacteria Aphanizomenon, which used to be common, does not form flocs, while the now common cyanobacteria Aphanothece easily forms flocs with sediments. This effect explains the higher chlorophyll values in winter (when generally higher wind speeds occur), the relations between wind speed and chlorophyll and the co-variance between Chl and TSM that were found. Geest and Noordhuis (2013) conclude that the floc formation and sinking of cells, combined with the increased number of mussels (since 2009), that filter the water and release their pellets at the bottom, the food chain moved from the pelagic to the benthic zone.

4.1.3 Landsat based maps

There were very few relatively cloud free maps of Landsat 8 that cover most of Lake Markermeer. However, an example is shown in Figure 17. Note the curved patterns (gyres, eddies) that can be seen in these high resolution images. For Sentinel 2 much more frequent imagery will become available (every 6 days with 1 satellite in orbit, every 3 days when two are in orbit) compared to Landsat 8 (every 16 days). This will also increase the chance of cloud free images.
Figure 17, ‘True colour’ Landsat 8 image of 19 March 2015.

When an image is processed to L2 (using C2R for L8) and then processed using the same band ratio’s as were used for Figures 14 and 15, maps of TSM (Figure 18) and Chl (Figure 19) can be created.

Figure 18, TSM (mg/l) distribution derived from Landsat 8, 19 March 2015.
Figures 18 and 19 show a large amount of detail. Such images might become very useful during the dredging and island-creation of the Markerwadden project. It is expected that changes in turbidity as an effect of the project can be followed like the oil-probability in Lake Böyük Şor.

4.1.3 Long term time-series analysis and seasonal changes

The effects of wind-induced resuspension of the sediments influence distribution and concentration of TSM and Chl. Therefore, to evaluate the conditions of the water, it could be important to evaluate the seasonal changes of these parameters over the years. In situ Chl and TSM data for monitoring station Markermeer midden, during the period of MERIS acquisition for this region (20 May 2002 until to 8 April 2012) show high variability, and no prominent seasonal signal (Fig. 20), except of a period with lower concentrations around days 200-230 (19 July-18 Augustus), which agrees with the plots in Figures 15 and 16.
Time series of in situ Chl and TSM concentrations show no significant trend for TSM (P>0.213), but they do suggest a decreasing trend for Chl (P<0.01) (Figure 21).

Figure 20. Seasonal change in concentrations of TSM and Chl, based on in situ data collected at Markermeer midden

Figure 21. Time-series of concentrations from in situ data collected at station Markermeer midden (top: TSM, bottom: Chl).

An additional analysis based on all available medium resolution imagery was carried out to check if such a trend could be substantiated from Chl indices based on MERIS data (Figs. 22 and 23). The remote time-series obviously produced a larger number of observations, but the decreasing trend was not confirmed for matchup station MMi). Only one significant indicator for a decreasing trend was found for MPH for MMo, a historic station south of the actual matchup location).
Figure 22. Time-series of different Chl indices from remote sensing data extracted at MMi (top: MCI, second: FLH, third: MPH, bottom: MPH based Chl).

The MPH algorithm also produces presence/absence indicators for cyanobacteria. 28% of the matchup points at MMi, and 35% MMo were classified as immersed cyanobacteria. No presence of floating cyanobacteria or floating vegetation was observed.
Figure 23. Time-series of different CHL indices from remote sensing data extracted at MMo. (top: MCI, middle: FLH, bottom: MPH – without flagging).

The following plots (Figure 24) show how these indices perform when compared with in situ Chl. MCI is significantly related to in situ Chl. FLH values (indicators of Chl concentrations) are close to zero or distinctly negative, and are significantly negatively related to in situ CHL, likely because the fluorescence signal is relatively weak in a region of the spectrum where water absorption and TSM scattering can be substantial. MPH has a significant relation with in situ Chl.
Figure 24. Scatterplots of MCI, FLH and BBR MPH indexes and MPH Chl versus in situ Chl for matchups at MMi with a maximum time difference of one day.
4.2 Lake Böyük Şor (Azerbaijan)

4.2.1 Time series / tuning

The time series of in situ TPH and oil probability based on Landsat 8 was plotted in Figure 25 for the five stations. During the winter period Landsat 8 imagery is missing, partly because of too low solar angles and partly because of cloud cover. For the spring and summer period 2014 there is more satellite data available than in situ data.
Figure 25, TPH (in situ) and oil probability times 40 (Landsat 8) over the period May 2014-May 2015.

Generally, a similar trend can be found in the satellite based data as it is seen in the in situ data. At the four stations in the southern part of the lake (LWS2, LWS5, WLS8, and LWS10 (Figure 7) there is a downward trend over 2014 and somewhat higher values in 2015. At station LWS11 the satellite data produces relatively higher values in 2014 compared to the in situ data. It is expected that this is caused by a change from oily layers floating at the surface to oil in resuspension in the water column. In case of a floating layer of oil, the satellite will record this and contain no information on substances in the water column, while during in situ data sampling a sample gets better mixed. After dredging the most polluted northerly part of the lake probably got well mixed and contains more oil in suspension, connected to suspended sediments instead of surface layers.

In Figure 26 the time series for turbidity and Secchi depth are plotted for the five stations based on in-situ measurements and Landsat 8.
Figure 26, Turbidity (NTU) in situ and derived from Landsat 8 and Secchi depth (centimeters) over the period May 2014-May 2015. The grey line is the wind speed in meters/s (averaged over 3 days to remove the noise, wind speed values read on the y-axis)

The turbidity derived from Landsat 8 generally agrees with the pattern found in situ: in 2014 increasing values, in 2015 somewhat lower values. However, at LWS10 some high turbidities were derived from Landsat in summer 2014, which were not measured in situ. These points coincide with a period of relatively high wind speed. The lowest turbidity value in spring 2014 at this station is missed because there was no satellite image available. Also for the turbidity plots, there is a gap in the winter period caused by clouds and low solar angles.

Interestingly, in the in situ data sometimes high Secchi depths are recorded at the same time as high turbidity values (for stations LWS2, 5, and 8 in the winter 2014/2015). For pure resuspension dominated lakes, this would be a contradiction. Therefore, it is expected that this effect is cause by oil. Secchi depth is measured by lowering the disk into the water. The water is than relatively undisturbed. When a sample for turbidity is taken, the water is shaken. This could have caused the oil to get suspended in fine drops in the sample, causing a higher turbidity reading.
4.2.2 Water quality mapping Lake Böyük Şor

For oil potential, the following colour scale was applied:

<table>
<thead>
<tr>
<th>Colour</th>
<th>Value</th>
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<tbody>
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<td></td>
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<td>0.1</td>
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<td>1.2</td>
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<td>1.5</td>
</tr>
</tbody>
</table>

**Oil potential**

Potential of the presence of oil:
- < 1 small probability, > 1 large probability
- Land, clouds, no data are flagged out in black.

For turbidity, the following colour scale was applied:

<table>
<thead>
<tr>
<th>Colour</th>
<th>Value</th>
</tr>
</thead>
<tbody>
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<td>45</td>
<td></td>
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<tr>
<td>60</td>
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</tbody>
</table>

**Turbidity**

For turbidity, often not the complete lake can be taken into the analysis because the high oil probability. In cases of high oil probability turbidity needs to be flagged out because probably no signal can be received from the water column. Therefore, the right column often misses parts of the lake.

<table>
<thead>
<tr>
<th>Oil probability</th>
<th>Turbidity</th>
</tr>
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<tbody>
<tr>
<td><img src="image1.png" alt="Oil probability" /></td>
<td><img src="image2.png" alt="Turbidity" /></td>
</tr>
</tbody>
</table>

Lake Böyük Şor before the start of the restoration project. The northern part is influenced by clouds, the low values are cloud shadows. The northern part is the most polluted with oil.
10 June 2013

19 July 2013
Swirls of resuspended sediments as effect of wind waves

13 August 2013

29 August 2013
Most coloured areas in the surroundings are small lakes. However, some coloured pixels are other items that have spectral properties that are somehow similar to water. In the south-west of this image for example, pixels show up that appear to be shadows of tall buildings, which are as dark as water.

The diagonal line is just the edge of the satellite image.

Restoration measures have started. The newly constructed temporary dam in the southern part is visible. The part in the south-east which is dammed off is called 'East lake'.
3 May 2014

Construction of dams in the northern part, creating the sludge depots, has started.

12 May 2014

Second dam in East lake, parallel to the north shore, is under construction, increasing the turbidity at the construction site. This dam will prevent polluted water to leak into the main part of East lake.

20 June 2014

Three dams in the north and two dams in the south are present.
15 July 2014
Start of dredging works in East lake, disposal in the sludge depots. Turbidity in inlet of one sludge depot and around the location of the dredging pontoon. The black area in the south is no data due to clouds.

22 July 2014
Dredging activities in East lake, sludge is disposed in the second depot.

31 July 2014
7 August 2014

In the East lake, the effect of dredging activities are visible.

16 August 2014

Sludge depot on the right is in use.

On the locations with the lowest oil potential (middle part and the small lake on the west of North lake) the turbidity seems to be better recorded.

23 August 2014

At the entrance (south end) of the most eastern sludge depot there is a thick layer of floating oil/waste, which is hard to distinguish from land and therefore shows up as no data (black).

This sludge depot has just been filled with new material. In the next images the size of the affected area changes.
8 September 2014

Construction of the main north-south dam have started.

Turbidity from north-south dam construction

24 September 2014

The white dots are clouds.

Decrease in turbidity after completion of dams

12 March 2015
29 April 2015

After checking with in situ observations, it was concluded that the line which is visible along the dike in the Eastern lake is the foam that is caused by one of the ships.

(Photo: Witteveen+Bos)

31 May 2015

Highest oil concentration found in the north adjacent to the oil field. Oil concentrations decrease from north-west to south-east.

16 June 2015
Again, relatively low values are found in the Northern Interception, the small lake on the northern side of East lake. In this case the concentrations are even lower than those in East lake.

Generally, the water quality seems to be much improved due to the restoration project. Mostly the probability of presence of oil has decreased.

When looking into more details, the oil_probability and turbidity maps show patterns that were expected from changes that were made to the lake during the restoration project. For example, on May 12th 2014 an increase of turbidity around construction site of the north dam is seen. The effect of dredging is visible in the image of the 15th of July 2014. Ex expected, the oil probability is the highest in the North lake and is sometimes extreme in the sludge depots.

Also irregular higher turbidity due to resuspension by wind waves occurs. Like for Lake Markermeer, swirls of resuspended sediments as effect of wind waves can be seen (e.g. 19 July 2013).

However, for the North Interception (the small lake on the northern side of East lake) the oil_probability is often lower than expected based on the frequent observations of oil layers (Figure 27). In a small part of the North Interception, the area around 40°26′33.3″N 49°54′30.0″E (Figure 28) there is always a high oil_probability, which is comparable with that in North Lake and the sludge depots. This area seems to be sheltered from the wind. A possible explanation is therefore that the oil in the North Interception is blown to the shore (as visible on the photo of Figure 27) or to the sheltered locations. With that it must be taken into account that the layers on or close to the shore will be flagged out as land or mixed pixel on the satellite data. It is expected that with Sentinel 2 (and smaller pixels) also smaller floating layers might be detected.
For this analysis, turbidity has been flagged out when the oil potential was > 1, because a layer of floating oil on the surface will prevent retrieval of information from the water column. However, another effect of oil is that high fractions of suspended oil in the water column might have such a high absorption that reflecting by suspended solids might be masked (not visible any more in the reflection spectrum). Since the turbidity algorithm is based on the assumption that suspended sediments scatter and therefore increase the reflectance, such a high absorption might interfere with the turbidity retrieval (e.g. 16 August 2015).

Figure 27, observations of oil in the North Interception (Photo by Witteveen+Bos)

Figure 28. Left: location of the area that always shows high oil probabilities (image: Google Maps). Right: Map of the same area of 24 September 2014 (as shown earlier but now zoomed in – same colour scale)
4.3 Himalayan lakes (Nepal)

4.3.1 Results

Figure 29 shows the WISP-3 Rrs spectra for the five surveyed lakes and SD measurements.

Figure 29, Reflectance spectra measured with the WISP-3 field spectroradiometer during fieldwork. Note that lake 9 and lake 10 are spectrally identical. The measured SD depths are indicated close to each spectra.

*In-situ* data shows differences among the five lakes surveyed during the field campaign. Mostly, we can recognize three groups of waters, with increasing degrees of brightness and decreasing water transparency (SD values). Lakes 9, 10 and 31 are clear water lakes, with reflectance values decreasing from blue towards longer wavelengths, due to water absorption. Lake 24 was observed with turquoise-milky water color in the field and even reflectance values show higher magnitude, probably due to the increased light scattering caused by the presence of more sediments in the water with respect to blue water lakes (e.g. lake 9). Secchi disk depth also reflects this, being lower than 1m. Higher reflectances were observed in Lake 161, where definitely beige-grey color was observed during fieldwork and clear patterns of sediments were visible by eyes on the water surface. Even suspended sediments data collected during a previous field campaign in 2008 reflects differences among these lakes: TSM values vary from 0.63 gm$^{-3}$ for lake 10 to 102 gm$^{-3}$ for lake 161, with intermediate values of 1.7 gm$^{-3}$ and 6.69 gm$^{-3}$ for lakes 31 and 24 respectively. Lake 161 is one of the most prone to GLOF event (Bajracharya et al., 2007), because of its origin (supraglacial lake), its increasing size during last decades, its position (it receives melting waters from three glacier tongues) and it is actually studied and monitored in order to minimize possible damages.

Figure 30 a shows reflectance values derived from the application of different atmospheric correction codes to the OLI and GeoEye-1 images for sampling stations on lake 24.
Figure 30. a) Comparison between in-situ and GE/OLI derived reflectance spectra using different atmospheric correction codes for the field station in lake 24. WISP-3 spectrum was resampled to GE spectral characteristics. b) and c) Normalized in-situ and GE/OLI derived reflectance spectra (6S atmospheric correction code) for the field station in lake 24. Normalization bands are 545nm for GE and 561.3 nm for OLI sensors. In-situ spectra were resampled to satellite sensors spectral characteristics.

When compared with in-situ radiometric measures, Rs spectra showed the same trend, but higher magnitude (Figure 30 a). Higher Rs values were recorded both by GeoEye and by OLI sensor with reference to radiometric measures taken in Lake 24. It has to be noticed that the GeoEye acquisition was synchronous to in-situ measures (the same day), while OLI overpass was 11 days after. If the same reflectance spectra are normalized to the green band (545 nm and 561.3 nm for GeoEye and OLI sensors respectively), in-situ and satellite derived Rs are coincident (Figure 30 b ) and c)). The possible reason of such a difference in spectral magnitude was probably linked to the presence of important snowfall event occurred on October 14th 2014, which might introduce significant adjacent effects on water reflectance retrieval. As reported by Bélanger et al. (2007) the adjacent effects due to sea ice on the water-leaving reflectance might reach 45%. We suppose that snow cover around the lakes, can cause an increase in the total radiance recorded by the satellite sensors overall the acquired scene, creating a sort of background signal generated by the high reflective power of the snow cover. To verify this hypothesis, satellite radiance values were simulated using the 6S code in a forward way, setting a 200m wide adjacency effect and in-situ reflectance values as input. The wide adjacency range is large enough to include snow covered surfaces.
adjacent to lake boundaries. Results of the simulation fit well the satellite recorded radiances, giving reliability to our hypothesis (Figure 31). The exercise has been performed for GeoEye-1 only because these data were acquired the same day of \textit{in-situ} WISP-3 data used in the simulation.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{radiance_plot}
\caption{Comparison between at satellite radiances measured by the GeoEye/OLI sensors and simulated radiances with the 6S code for the field station in lake 24.}
\end{figure}

Figure 32 shows the result of the classification procedure performed on 119 lakes in the OLI image (the maximum number of mappable lakes at the OLI sensor resolution).
Figure 32, Water color classification of the 119 investigated lakes (lake codes above and below the bars). Asterisks indicate lakes located in China.
Each bar identifies one lake and percentage of pixels classified as blue-turquoise-grey water is expressed in the stacked bars. Overall, 52% of lakes have predominantly grey waters (>50% of pixels classified as grey waters), 24% have blue waters and 21% have waters mainly turquoise, with 3% of lakes showing “mixed” waters. Mixed-classified lakes have half blue and half turquoise waters. Nepali lakes (96) show higher variability of water colors, with a majority of grey water lakes (45%) and less blue (27%) and turquoise (25%) water lakes, while Chinese lakes (23) are decisively with predominately grey waters (83%) and few blue (13%) and turquoise (4%) water lakes.

4.2.2 Analysis

Lakes shape and surface were analyzed in relation to water color classes, highlighting that grey water lakes are generally more extended and more elongated than blue water lakes (Figure 33).

Surface area of grey lakes can exceed 1km², while blue and turquoise lakes never reach this size. The Frohn et al. (2006) index indicates the proximity of an object to a square (i.e. index=1): if we look at Figure 33 b, we can see that going from blue to grey water lakes the shape is likely to be gradually far from a square. This can be an indicator of lake origin: more circular-shape lakes are usually cirque lakes, with a well-defined basin modeled by ancient glacier carving, while ellipsoidal-shape lakes can be more characteristic of supraglacial and proglacial lakes, formed by direct melting of glacier tongues and adapting to its form.

Most recent available data about glaciers extension (Randolph glacier inventory: Arendt et al. 2014) were also related to water lake color. Grey water lakes showed lower minimum distances to glacier tongues (median <0.25 km) than blue water lakes (median >0.5 km). We can hence recognize the tendency of grey water lakes to be larger, more elongated and nearer to glaciers. Proximity to glacier can suggest possible relation between lake water color and glacier melting, while shape and surface of the lake can be indicators of GLOF hazard. Lake surface is directly connected with the lake volume and reasonably more extended lakes contain larger volumes of water, which increases the damages caused by an outburst. The lake shape, instead, can discriminate more and less dangerous lakes, since the more elongated ones usually follow the shape of the glacier tongue and are potentially directly linked to glacial grow/melting balances in time.
Classification results coming out from the elaboration of the OLI image were compared with classification performed on one ALOS acquisition (2008). We observed that 71% of lakes showed differences in percentage composition of water color classes and the majority of changes (62%) went towards less clear/more reflective water conditions. Concurrently, data about glaciers in the SNP (ICIMOD 2014, 2015) relative to the last four decades indicate a progressive glacial shrinkage, with increase of the minimum elevation of glacier tongues (shift of about 40m), a reduction of glacier thickness (about 7m) and a total surface regression of 261km². This tendency, can give reasonability to possible relations between water color variations observed in the 2008-2014 time interval and glacial retreat.

Of course water lake color cannot be considered alone when evaluating the risk of GLOF or climate change consequences in general, but our study suggests relations between water color and some parameters directly linked to climate change and GLOF occurrence.

4.3.3 Implications of the results for the socio-economic situation

As previously stated the main concern about glacial lakes in the Himalaya is the risk of GLOF. Events in the past (e.g. Dig Tsho in 1985 and Tam Pokhari in 1998), dating up to 450 years ago, give examples of damage entity that can be generated by such happenings. Consequences of GLOF events can be diverse, interesting both the environment (e.g. morphological changes, sediment transport) and the people community (e.g. destruction of properties, infrastructures). Besides direct losses such as single lives, houses, bridges and lands, indirect impacts have also primary importance, for instance decreasing of touristic values, due to deterioration of hiking tracks or the reduction of provisions supply to higher and more isolated villages as a consequence of interrupted paths usually covered by porters.

Fourteen GLOF events have been recorded in Nepal in recent decades; several others in Tibet Autonomous Region in China have crossed the international border to cause extensive damage in Nepal. Not every detail of each event could be recorded, sometimes the date of occurrence or the quantitative evaluation of losses is missed. Most of these events occurred by collapse of the moraine keeping the lake. For instance the moraine collapse at the Pokhre valley, where about 50 m of debris covered the entire valley, causing the loss of human lives, destructing villages up to 71 km away from the lake, an hydropower station and more than 10 bridges in a single event. The case of Dig Tsho was probably one of the most famous and studied GLOF events (e.g. Vuichard and Zimmermann, 1987), since it generated from a relative small and ‘clean-ice’ glacial lake. A large ice and rock avalanche formed a devastating surge wave discharging an estimated 6-10 million of cubic meters of water to the lower valley. Damages were calculated in more than three million dollars, destroying the downstream community of Khumbu for several months (ICIMOD 2010).

This catastrophic event and the increasing frequency of GLOFs interested the entire world (Wirsing et al., 2013) and triggered more and more attention of the scientific community. Efforts were concentrated in the comprehension of such phenomena, in the evaluation of GLOF risks and in the identification of possible solutions to minimize the connected damages. Detailed studies such as the one by ICIMOD (2010) go through each aspect to be set for a complete risk assessment evaluation: from the hazard of a GLOF, that is, its probability of occurrence, which depends on morphological, physical and hydrological aspects, to the modeling of the GLOF event, and the evaluation of the vulnerability, which is the potential damage, directly linked to the exposure of sensible elements such as people and properties. Preventive estimated damages in terms of money necessary to restore an area to its status before the GLOF goes from 1.847 to 8.781 US dollars for Tsho Rolpa Lake and from 11894 to 35501 US dollars for Imja Tsho Lake in a more and less optimistically scenario (ICIMOD, 2010), with an average of 3500/6700 persons damaged by the event
because living or owners of properties located inside the flood prone area, 250/600 houses destroyed and 75/3500 ha of land (rain fed and irrigated) lost. As a comparison, the event of 1981 (Bhote Koshi-Sun Koshi) caused 5 782 persons to be damaged, 731 houses to be broken and 35.5 ha of land to be loss.

When assessing the potential economic impact of a GLOF only the tangible damage can be expressed in monetary units and can hence be calculated, while intangible damage such as impacts on social life (e.g. insecurity, distress and depression) and loss of environmental quality (e.g. water quality) cannot be estimated in monetary terms. These consequences, although not quantifiable, have however an impact on living population. Another estimate for the possible GLOF event of Tsho Rolpa by Shrestha and Nakagawa (2014) suppose that about 3939 people up to 65 km downstream from the lake are likely to be affected by flooding. In addition, a total of 18 bridges including three truss/girder highway bridges up to about 65 km downstream from the lake could also be damaged due to potential floods. Highway and food trail roads are also potentially affected and two hydroelectric projects could be damaged. Schools, a police station, forests, cultivated lands, temples, and an airport could also be harmed in an outburst flood event. Local population is then here on the mountains among the poorest people in Nepal, with no means to overcome a catastrophic natural disaster such as a GLOF. Furthermore, life on the mountains gives restricted access to education, resources and national decision-making processes.

Findings of this study can help in the comprehension of the GLOF phenomenon and its generation, contributing in the estimation of sediment amount that can be transported in the case of GLOF events and providing information about water quality conditions, which is primarily important in such an environment, where few infrastructures are available for drinkable water depuration.
5 Conclusions

Three shallow lakes cases with high suspended sediment concentrations are selected for this analysis, based on socio-economic interests.

Lake Markermeer is a classic example of a lake dominated by resuspension of sediments. To increase its ecological diversity, a restauration project is planned, during which tidal-flat like islands will be created (‘Markerwadden’). It is expected that satellite data can be valuable to follow the work and its effects with a spatial perspective.

Lake Böyük Şor was selected because it is currently undergoing a large restauration project to remove oil, which could be followed based on EO data.

The third case is a group of glacial lakes in the Himalaya, where the suspended solid concentrations as estimated from EO data can be used as one of the indicators to predict dangerous Glacial Lakes Outburst Flood (GLOF) events.

For Lake Markermeer the focus was to obtain methods to analyse water quality changes based on high resolution data, to prepare the monitoring of the Markerwadden project. For Lake Böyük Şor just recent satellite data was needed, with a resolution that was high enough to apply in this not-so large lake. For the Himalayan lakes, high resolution imagery was the most important because of the small size of the lakes, with as second criterion that the EO data had to match with the in situ campaign. Because the case studies were so divers, also the methods were different for the three cases. For Lake Markermeer a combination of Landsat 8 and MERIS data was used, for Lake Böyük Şor just Landsat 8 data and for the Himalayan lakes a combination of Landsat 8 and GeoEye-1 was used. For all three cases in situ data was available for validation.

In Lake Markermeer, good relations between in situ and EO data were found when time series were compared; there were not enough matches for direct validation of data that was obtained on the same day. Some example maps show the potential of high resolution monitoring for this lake. More detailed results can be obtained with EO sensors with more spectral resolution, such as MERIS, S3 OLCI, and potentially S2. For Lake Böyük Şor oil potential and turbidity was mapped. Generally, the patterns agreed with what was expected from the field: the effects of dredging, dam construction and resuspension due to wind-waves could be followed. However, the oil hampers standard atmospheric correction methods and there are some concerns on turbidity in the presence of highly absorbing oil.

For the Himalayan lakes lake water colour was derived from high resolution EO data and compared well with in situ data. The colour for each lake, together with the their proximity and connection to the glacier and other lakes, allows to pinpoint those lakes for which potentially GLOF events might occur. This allows to take mitigation actions (e.g. building protection for the downstream villages). The water colour also provides an estimate of water quality, an important property in these regions without purification plants.

Although the results of the studies was positive, it becomes clear that to detect small scale effects (e.g. swirls in Lake Markermeer) or to detect changes in medium (Lake Böyük Şor) or small lakes (Himalayan lakes), high resolution satellite data is key. In this study the available high resolution data means a trade-off with other properties: the spectral bands and the revisit time.

For Lake Markermeer the frequency of Landsat 8 data (maximum every 16 days) leads to a comparable number of samples per location as the standard monitoring lab measurements. The spatial overview still has its added value, but for monitoring e.g. phytoplankton blooms...
the more frequent S2 data will be very important. In Lake Böyük Şor the dams could be distinguished based on Landsat 8 data, so the spatial resolution was sufficient. However, a higher spatial resolution (e.g. Figure 22, based on Google maps – SPOT) allows detecting much more details. Probably individual floating layers of oil can be distinguished when S2 data is available. However, to improve the results for this lake, a fully suitable atmospheric correction method is also important. Current methods either relay on in water specific optical properties (e.g. MIP), which are very different for water containing oil), are based on training data (e.g. L8-C2R) which does not contain oily waters, requires a large range of atmospheric properties (e.g. ATCOR) or is still under development and at the moment insufficient (e.g. USGS surface reflectance). Last, more spectral bands could probably improve the oil and turbidity algorithms, as the Landsat 8 bands are relatively broad.

The remote area of the Himalayan lakes makes EO an important tool for monitoring. Where five lakes could be sampled in situ during the campaign, 119 lakes in the area could be mapped based on the spatial resolution of Landsat 8. This allows making a quick scan of lakes that are vulnerable for GLOF events and update these regularly. A high overpass frequency is of less importance, because changes in the physical landscape (amounts of glacial meltwater, connectivity) do not change very quickly. However, spatial resolution is of large importance. The smaller the resolution, the more lakes can be mapped, as many lakes are in the order of minimum mappable magnitude. Smaller lakes might in general be less dangerous, but this also largely depends on the shape of the lake (e.g. long and narrow lakes can also contain much water). Therefore, S2 data is very welcome for this purpose. In the snow and ice covered landscape the high reflectance leads to a large adjacency effect. Corrections for this effect are therefore also very important.

Based on EO data, three very different lake cases are studied. Although the results were positive, we expect a great additional value of S2 data (with regard to spatial resolution, band settings and revisit time), with and even without additional developments (improved atmospheric correction, adjacency effect correction). For an impression: one of the first S2 images ESA released from S2 includes Lake Markermeer, shown in Figure 34, on the next page.
Figure 34. One of the first officially released S2 images, showing Lake Markermeer. Taken on August 5th, ESA.
References

Global Lakes Sentinel Services (313256)

- Vermote E., Tanré D., Deuzé J. L., Herman M., Morcrette J. J. (1997) - Second simulation of satellite signal in the solar spectrum (6S), 6S User guide (v. 2) and 6S code (v. 4.1), pp. 54.


Annex A. MERIS based mapping and time series of Lake Markermeer

The following figures show some results of MERIS satellite based mapping and time series generation from the FP7 FRESHMON project.
TSM Concentration IJsselmeer (NL)
Seasonal average: February-March 2011
TSM Concentration IJsselmeer (NL)
Seasonal average: April-June 2011

Map Overview

Legend
TSM concentration (mg/L)

Processing and Analysis
MERIS Iib data (ESA), preprocessed with ICOs, processed to L2 with C2R and into concentrations with the WISP algorithm.

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