WP5 Innovation and Application through Use cases
D5.1 Report socio-economic context & selected case studies

VU/VUmc, CNR, WI
2014-04
Global Lakes Sentinel Services
Grant number 313256

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D5.1 Report socio-economic context & selected case studies

STICHTING VU-VUMC, WI, CNR

Due date: 2014-01 (extension granted till 2014-04)
Submitted: 2014-04
Change records

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<th>Date</th>
<th>Description</th>
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<td>Outline</td>
<td>M.A. Eleveld (VU/VUmc)</td>
</tr>
<tr>
<td>0.2</td>
<td>2014-04</td>
<td>Draft</td>
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<td>0.3</td>
<td>2014-04-28</td>
<td>Final</td>
<td>M.A. Eleveld (VU/VUmc), C. Giardino, M. Bresciani, M.A. Gomarsca (CNR), A. Hommersom (WI), Steven Greb (Advisory Board), Sampsa Koponen (SYKE), Ana Ruescas (BC)</td>
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Consortium

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<td>BROCKMANN GEOMATICS SWEDEN AB</td>
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Reference

Abstract
The overall aim of the GLaSS project is the setting up a system that is able to handle large quantities of Sentinel data.

For this Task (WP5.1) the main objective is to select a large number of global lakes that we will monitor based on socio-economic criteria and to analyse Earth Observation (EO) time series to see the possibilities of EO time series for socio-economic use cases.

In the first part of this document the results from a questionnaire on lakes are described. Lakes are categorised based on their optical lakes type (in the GLaSS project these are included as use cases) and their most important optical features are linked to socio-economic use and environmental threads.

In the second part of this document existing EO time series were selected, based on certain criteria (such as publication in ISI journals). The lakes and the time series as published are discussed.
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1 Introduction

After validation/verification of the GLaSS products we will select a number of global lakes that we will monitor, also in cooperation with the international Advisory Board. First, based on literature study a meta-analysis was performed to collect the main socio-economic aspects associated with lakes, which provide major ecosystem services (such as fisheries, tourism) and provide drinking water reservoir functions. The focus will also be on emerging water management and restoration issues. Then existing EO time series for global lakes in various classes will be collected, analysed, documented and compared with published water quality data. Next, the socio-economic data will be matched with major bio-physical lake types, such as deep clear lakes, shallow eutrophic lakes, shallow sediment rich lakes, etc. This WP will support WPs 5.2-5.7, and the output of this WP will be used to support the development of case-studies for training and course material in WP6.

The rationale for looking at socio-economic use is as follows. There are over 300 million lakes globally providing essential ecosystem goods and services. They are fundamental to global food security. There are global concerns over future water security (Unsustainable use; MEA 2005).
2 Socio-economic analysis

2.1 Inventory

Most exiting comprehensive data sets are on lake size (Lehner and Döll, 2004; Nõges et al, 2008). This, together with the ILEC database, which is very diverse, enabled us to develop a questionnaire on lakes.

The questionnaire contained the fields:
- General information: Name, origin, Location (Lat & Long), Tropical status,
- Optics: Expected optical lake type (colour), Absorption and scattering properties (high/intermediate/low),
- Biophysical parameters: Depth, surface, regional type,
- Hazards (risks and events) costs,
- Socio-economic use / Benefits, and
- Links to publications about all these categories (doi or http).

The questionnaire was filled out by the GLaSS consortium and (most of the) the Advisory Board members. The GLaSS nearby lakes were analysed, as well as lakes that are of interest because of other projects and known socio-economic issues were added.

After filling out the questionnaire, the lakes were sorted on GLaSS 'use case' and it was analysed what the relations were between optics or biophysical lake type (shallow etc.), hazards and benefits from this lake. The use cases are:
- Use case 1: Shallow lakes with high eutrophication
- Use case 2: Deep, clear lakes with increasing eutrophication
- Use case 3: Shallow lakes with low transparency due to sediment resuspension
- Use case 4: Highly absorbing lakes
- Use case 5: Mine tailing ponds and other lakes with a very distinct water quality
- Use case 6: WFD reporting based on GLaSS products

The description of Use case 4 was slightly edited with respect to the Description of Work to be able to better classify the lakes.

In section 2.2 the outcomes of the questionnaire are described per 'use case'. Results are written in the socio-economic analysis section (section 2.3).
2.2 Use cases

Use case 1: Shallow lakes with high eutrophication

Shallow lakes, especially the ones in highly populated areas, are vulnerable for eutrophication. Because of the high chlorophyll concentration, the colour of these lakes is green.

Table 1. Lakes listed in use case 1.

<table>
<thead>
<tr>
<th>Lake</th>
<th>Country</th>
<th>Location (bounding box)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake IJsselmeer</td>
<td>Netherlands</td>
<td>53.1085N, 4.9671E; 52.5028N, 5.7691E</td>
</tr>
<tr>
<td>Lake Peipsi</td>
<td>Estonia</td>
<td>59.1360N, 27.0140E; 57.7640N, 28.1470E</td>
</tr>
<tr>
<td>Lake Trasimeno</td>
<td>Italy</td>
<td>43.2021N, 12.0152E; 43.0707N, 12.2147E</td>
</tr>
<tr>
<td>Lake Taihu</td>
<td>PRC</td>
<td>30.9278N, 31.5494N; 119.8756E, 120.6056E</td>
</tr>
<tr>
<td>Winnebago</td>
<td>USA</td>
<td>44.2549N, 88.5539W; 43.7946N, 88.2669W</td>
</tr>
<tr>
<td>Nicaragua</td>
<td>Nicaragua</td>
<td>12.1715N, 86.0806W; 10.9566N, 84.6990W</td>
</tr>
<tr>
<td>Hartbeespoort dam</td>
<td>South Africa</td>
<td>25.7126S, 27.7948E; 25.7772S, 27.9095E</td>
</tr>
<tr>
<td>Lake Bogoria</td>
<td>Eastern Rift Valley, Kenya</td>
<td>0.3418N, 36.0609E; 0.1777N, 36.1362E</td>
</tr>
<tr>
<td>Lake Simcoe</td>
<td>Ontario, Canada</td>
<td>44.6245N, 79.677W; 44.1980N, 79.1441W</td>
</tr>
<tr>
<td>Lake Maracaibo</td>
<td>Venezuela</td>
<td>11.1063N, 72.1897W; 9.0064N, 70.9579W</td>
</tr>
</tbody>
</table>

All listed eutrophic lakes except Lake Maracaibo are known to suffer from cyanobacterial blooms. Therefore, the lakes will occasionally turn blue-green because of the typical colour of the combination of the pigments chlorophyll and phycocyanin.

Most of the listed shallow eutrophic lakes are natural, only Lake IJsselmeer (which was blocked from the sea by the construction of a 32 km long dike) and the lake behind Hartbeespoort dam were manmade. The dike around IJsselmeer was intended for safety (floods by the sea) while Hartbeespoort dam was built for irrigation, drinking water and industrial use.

Interestingly, more than two thirds of the eutrophic lakes are used as source for drinking water (IJsselmeer, Taihu, Winnebago, Nicaragua, the lake behind Hartbeespoort dam, and Ülemiste), even though the water potentially contains cyanobacteria. Other uses include irrigation (Lakes Trasimeno, Taihu, Nicaragua and the lake behind Hartbeespoort dam), fishing (all), recreation of nature reserve (all), and shipping (various, extent depending on the
size of the lake).

Some lake specific details are discussed below.

The history of dam construction and original plans for complete 'inpoldering' – removal of all the water - from IJsselmeer is described by Kuks. Because of the intense phytoplankton and cyanobacterial blooms, the lake has been subject to many studies on optical properties of these (Gons et al., 1995, Gons et al., 1999, Simis et al., 2005). Over the years, nutrient reduction programs have been carried out but the lake is still highly eutrophic. Because the original dike needs to be renewed, there are plans to simultaneously create more natural areas in the lake, such as marshlands.

Lake Taihu is twice as large as lake IJsselmeer (> 2000 m$^2$ versus >1000 m$^2$), but the main problems of the lake are the same. Located in a densely populated area, nutrient concentrations are very high and cyanobacteria blooms are dominant (Qin, 2008, Qin et al., 2007). In contrast to Lake IJsselmeer, in Taihu marshland formation occurs naturally because of the high concentrations of organic matter; however, this is, seen as a threat for drinking water supply (Qin et al., 2007). Restoration measures that are currently taken are the restoration of submerged aquatic vegetation, and the reduction of nutrients through controlling the pollutants input from the catchment. Also lake Taihu's optical properties are extensively studied (e.g. Liu et al., 2014).

Lakes Peipsi and Ülemiste, both Estonian lakes, have very large concentration ranges. Although the lakes are overall shallow and green, Peipsi has are clear parts as well as very turbid brown parts (Reinart and Valdmets, 2007) and in Ülemiste the variability over the year is very high (Erm et al., 2001). Because these lakes are so shallow (a few meters), they warm up to over 20 degrees in summer, while in winter they have full ice cover. Lake Peipsi contains important marshland areas and although eutrophication is a hazard, the water quality is generally described as 'good'. Lake Ülemiste is the main drinking water source for the capital Tallinn.

While in Lake Trasimeno chlorophyll concentrations are still low compared to those of other lakes in this category (medians of 8 µg/l), the eutrophication leads to disappearance of macrophytes (Giardino et al., 2010).

Lakes Winnebago and Simcoe lay in relatively densely populated areas of North America, temperate region, and are therefore heavily used for recreation and also well studied (e.g. Simcoe: Guan et al, 2010, Winnebago: Wiscosin Department of Natural Resources, 2004). To reduce the eutrophication caused by the runoff, measures are implemented for the agricultural surrounding areas (for Lake Simcoe Oni et al., 2013, Crossmana, 2013). Blooms are generally triggered by temperature, as in the winter the lakes completely freeze. Except of from eutrophication, the ecosystems also suffer from invasive species, such as zebra mussels and spiny water flea.

Lake Nicaragua has a large amount of endemic fish species and is therefore ecologically very interesting. However, the lakes eutrophic status is at risk and, additionally, the lake is heavily polluted (Wikipedia and Fundacion Ciudad Del Saber Universidad Nacional Autonoma de Nicaragua, 2007). Garbage and untreated sewer water are released in the lake, because the economic situation of the country. Only in 2009 the capital started cleaning the sewage water.

Hartbeespoort dam is the reservoir in this list with the highest chlorophyll (median 3872 µg/l) and phycocyanin (median 4462 µg/l) concentrations (Matthews et al., 2013). Also the suspended matter concentrations are extreme (> 500 mg/l, Matthews et al., 2013). Due to
eutrophication, also Water Hyacinth flowers in the reservoir. A large rehabilitation program is set up to restore the water quality. Measures that are currently taken to are reduction of the eutrophication and restoration aquatic macrophytes (Harties website).

Lake Bogoria is a tropical lake. The hydrological cycle of the catchment (influencing the nutrient concentrations, conductivity, and light availability) was found to be the main factor influencing blooms (Oduor and Schagerl, 2007).

Lake Maracaibo is actually a bay, connected to the sea but with fresh/brackish water because of the river inflow. The species that cause most concern in this lake is Duckweed, which is not toxic but blocks the light to the water column and can cause anoxia after the growth. Lake Maracaibos main uses are shipping and fishing. The Duckweed is expected to harm the fish and it also hosts bacteria, including Vibrio cholera, the species causing cholera.

Figure 1. Example of use case 1, Lake Taihu

Use case 2: Deep, clear lakes with increasing eutrophication
Deep, clear lakes are less vulnerable for eutrophication than shallow small lakes are, however, due to continuous inflow of nutrients over the years, via rivers or rain, almost all lakes suffer to a certain extent to increasing eutrophication. These lakes appear blue.

Table 2. Lakes listed in use case 2.

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<tr>
<th>Lake</th>
<th>Country</th>
<th>Location (bounding box)</th>
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<td>Germany</td>
<td>47.9240N, 8.7736E; 47.3672N, 9.8943E</td>
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<tr>
<td>Lake Garda</td>
<td>Italy</td>
<td>46.0218N; 10.3753E;</td>
</tr>
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</table>
The clear, deep lakes are used for most purposes: all are used for shipping and as source for drinking water (except Lake Maggiore), most for irrigation (except Lakes Vättern and Päijänne because in the Nordic regions irrigation is not so urgent) and recreation (the African lakes to a lesser extent), while many are also used for power generation (except Garda, Maggiore, Vättern, Päijänne and most of the Minnesota's lakes).

Lake Constance, Garda, Maggiore are Alpine lakes, fed by glaciers or runoff from the mountains. Chlorophyll concentrations are low in these lakes (Odermatt et al., 2008; Heege and Fischer 2004; Giardino et al., 2007, Bresciani et al., 2011). However, all three of these lakes have a risk of cyanobacterial blooms and the concentrations of phycocyanin concentrations are intermediate and chlorophyll concentrations vary over the area and the year, so regular spatial monitoring is advised (Bresciani et al., 2011). The vulnerability to eutrophication of the Alpine lakes is clear from the history of Lake Constance, which suffered large phytoplankton blooms and low transparency in the second half of the 20th century (Internationale Gewässerschutzkommission für den Bodensee, 2004). The nutrient loads are now reduced and the shores of the lake are recovered. Nowadays, the water is clear and taken care of by an international society, the IGKW (IGKW website).

Lake Vättern and Päijänne are Nordic lakes. Many Nordic lakes have (extremely) high CDOM concentrations, but these two lakes are blue. CDOM is the dominant optical substance, but its concentration is lower than in other Nordic lakes. Both lakes are, compared to other lakes in the area relatively deep (Vättern is a few hundred meters deep, Päijänne almost 100, but on average less than 20). However, the retention time is just over 2 years in Päijänne and almost 60 in Vättern, so the potential degradation time for CDOM is very different. The possible reason for the clear water is that both lakes are not fed by one or more large rivers.

Malawi, Tanganyika, Victoria are African, tropical lakes. Lake Malawi is the clearest of these lakes, with only on very occasionally phytoplankton blooms (Crul, 1997). This lake is very
deep (more than 600 m) and anoxic below 250 m. The deeper waters do not follow the seasonal trends (Eccles, 1974). The occasional intense phytoplankton blooms are probably due to upwelling events that bring nutrients to the surface. In addition to eutrophication, a threat for Lake Malawi is the oil exploitation.

In Lake Tanganyika phytoplankton blooms occur more frequently (Crul, 1997, Bergamino, 2010). Horion et al (2010) show chlorophyll time-series based on EO data for this lake, with chlorophyll concentrations generally less than 1 µg/l, but occasionally blooms with concentrations far over 10 µg/l.

With an average depth of 40 meters, Lake Victoria is the shallowest of the three. Lake Victoria has large eutrophication issues (Msomphora, 2004, Crul, 1995), leading to massive water hyacinth and algae blooms. Water hyacinths are here flowing out of some of the rivers feeding the lake, this invasive species can cover large areas of the lake (Cavallia et al., 2004).

Environmental and socio-economic studies show that for Lake Malawi, the scattered sector-based (fisheries, hydro-power etc) discussions on water resources are harmful for the overall status of the lake, instead, an ecosystem-based approach is advised, while local and national governments of all bordering countries should be involved in setting up protection plans (Bootsma et al, 2006). Around Lake Tanganyika regional projects, e.g. supported by FAO, have been most successful in protection achievements. Also for this lake international cooperation between governmental agencies is advised (Jorgensen, 2006). Lake Victoria, the most polluted of the African lakes, also has the most information on environmental conditions available with an active Lake Victoria Environment Management Project (LVEMP). Three countries bordering Lake Victoria cooperate in this project. In their 2005-report, they describe many water quality parameters that were measured, however, also some data gaps were found (Abuodha et al, 2005). The whole watershed was mapped and pollution sources were identified.

Lake Mendota is the one deep lake in this list that is already heavily eutrophicated. It is used for recreation and well studied (e.g. Lathrop et al.,1998, Winnebago: Wisconsin Department of Natural Resources, 2004). In the past, it suffered from extreme cyanobacteria blooms. To reduce the eutrophication via runoff, measures are implemented for the agricultural surrounding areas.

Minnesota's lakes are in the temperate region. There is a large variety in depth (from 2, 3 meters up to a few hundred of Portsmouth Pit and over 406 m for Lake Superior), surface and water quality (Secchi depth of < 1 meter to approx.. 10 meter for some of the larger lakes) of the thousands of lakes is this region. Clearly, the clarity in these lakes is influenced by the nutrient load from surrounding agricultural land, more in the south than in the north (Olmanson et al. (2008), discussed in more detail in the section on EO-time series).
Use case 3: Shallow lakes with low transparency due to sediment resuspension
When shallow lakes have a soft bottom, the bottom material easily resuspends as an effect of wind waves. The suspended bottom material increases the turbidity of the lake. Another source of sediment in the water column is inflow from rivers or glaciers. In case the river inflow is dominated by the optics of TSM and not by the absorption of chlorophyll and CDOM, the effect on the optics of the lake 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, although glaciers fed lakes turn gray.

Table 3. Lakes listed in use case 3.

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<th>Lake</th>
<th>Country</th>
<th>Location (bounding box)</th>
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<td>Netherlands</td>
<td>52.6840N, 4.9850E; 52.3064N, 5.4560E</td>
</tr>
<tr>
<td>Lake Chad</td>
<td>Chad, Cameroon,</td>
<td>14.5403N, 12.9171E; 12.4358N, 15.2078E</td>
</tr>
<tr>
<td>Lake Arresø</td>
<td>Denmark</td>
<td>56.0202N, 12.0200E; 55.9346N, 12.1924E</td>
</tr>
<tr>
<td>Himalayan lakes</td>
<td>Nepal</td>
<td>28.2N, 86.48E; 27.76N, 86.96E</td>
</tr>
<tr>
<td>Lake Boyukshor</td>
<td>Azerbaijan</td>
<td>40.4761N, 49.8481E; 40.4258N, 49.9199E</td>
</tr>
<tr>
<td>Little Wall Lake</td>
<td>Iowa, USA</td>
<td>42.2771N, 93.6437W; 42.2612N, 93.6286W</td>
</tr>
<tr>
<td>Lake Tana</td>
<td>Africa</td>
<td>12.3288N, 36.9813E; 11.5644N, 37.6810E</td>
</tr>
</tbody>
</table>
Lake Balaton

Hungary

47.1518N, 17.1908E;
46.6730N, 18.2414E

Lakes Markermeer and Arresø are situated in the temperate region and their main issues relate to resuspension because of their shallowness in combination with the effects of eutrophication (Kristensen et al., 1992, Eleveld, 2012). Markermeer is mainly used for transport and recreation, Arresø for fishing and recreation. Both of these lakes are located in rich countries and several areas are appointed as preserves (in Arresø) and measures to improve the ecological status are taken (Markermeer).

The shallow African Lakes Chad and Tana are under high pressure. The lakes support large fisheries sectors, while the water is also used for hydropower (Tana) and irrigation. The fish in Lake Tana is largely endemic and therefore ecologically important, while the species richness in Lake Chad is low. In both lakes, the water level has decreased to a large extent due to changes in rainfall, which increases the pressure on the remaining water resources for drinking (people and cattle) and irrigation, while overfishing also occurs. For lake Tane, the outflow of the lake (the Blue Nile) is blocked by a dam and the water level is regulated. For lake Chad important monitoring information is missing, while deforestation increases the chances of desertification (World Lakes website) while pollution continues (Akan, et al., 2012). Environmental pressure and socio-economic needs are urgent for both of these African lakes. Lake Tane has an extensive study presenting the current and expected future pressures on the lake for policy makers (McCartney et al., 2010). Lake Chad has a commission to regulate the activity pressure on the lake.

Lake Boyukshor, located in the Azerbaijani steppe landscape, was historically used for salt production. It currently suffers from severe environmental problems such as soil and waste pollution and is hypertrophic (Wikipedia). No scientific information in English was found about this lake. Notwithstanding the pollution, the lake is designated as development area for a recreation area, which includes draining the lake.

Little Wall Lake is located in the US prairie. Both TSM as chlorophyll concentrations are extremely high (Carper and Bachmann, 1984 describe the resuspension events and Iowa Department of Natural Resources, 2005 describe the more recent concentrations in the lake). Its main use is recreation (including sport fishery).

Lake Balaton is the only shallow lake in this list with high TSM concentrations, which is not eutrophic. Its optical properties are described by different projects: Eulakes, Diversity-II and Globolakes (reference used: Eulakes). Its very typical optical properties make the lake appear gray and have effect on what light is available for and used by phytoplankton (Pálffy and Vörös, 2003).

In contrast to the lakes described above, the Himalayan lakes are deep and not eutrophic. The tops of the Himalayes contain large accumulations of snow and ice in glaciers, at altitudes where the temperature is high enough, the lakes are found. The suspended sediment in these lakes, fine powdery dust of the glaciers, is of a very different origin than in the other sediment dominated lakes discussed above. Some lakes also contain relatively large CDOM concentrations. The combination of these gives the water a dark blue to gray colour (Giardino et al., 2010). The lakes are (downstream) used for drinking water. Being one of the most remote areas in the world, the Himalayas are relatively undisturbed. However, the lakes are influenced by air pollution and climate change (Lami et al., 2010).
Use case 4: Highly absorbing lakes

Use case 4 was originally described as small lakes with a high CDOM concentrations. However, during the inventory of lakes, a better description of this type of lakes was found to be highly absorbing lakes, because some of these lakes were actually large, deep and oligo or mesotrophic. The common parameter is the high absorption, which is caused by the river(s) feeding the lakes. The general colour to describe these lakes is yellow/brown.

Table 4. Lakes listed in use case 4.

<table>
<thead>
<tr>
<th>Lake</th>
<th>Country</th>
<th>Location (bounding box)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Võrtsjärv</td>
<td>Estonia</td>
<td>58.4400N, 25.9350E; 58.0830N, 26.1000E</td>
</tr>
<tr>
<td>Frysian lakes</td>
<td>Netherlands</td>
<td>53.2530N, 5.3588E; 52.8335N, 6.2213E</td>
</tr>
<tr>
<td>Loskop Dam Lake</td>
<td>South Africa</td>
<td>25.4116S, 29.2639E; 25.4733S, 29.4205E</td>
</tr>
<tr>
<td>Theewaterskloof dam</td>
<td>South Africa</td>
<td>33.9806S, 19.1246E; 34.0851S, 19.3052E</td>
</tr>
<tr>
<td>Lake Vänern</td>
<td>Sweden</td>
<td>59.3963N, 12.1004E; 58.3341N, 14.1659E</td>
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<tr>
<td>Lake Lammin Pääjärvi</td>
<td>Finland</td>
<td>60.83N, 24.50E; 61.33N, 25.83E</td>
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</table>

Lake Võrtsjärv and the Frysian lakes are shallow and eutrophic. These lakes suffer from nutrients inflow from the surrounding arable lands and sewage from several small towns villages, which decreases the nature biodiversity. Also, regulation of water levels and resuspension events has a negative influence on the water quality. In Lake Võrtsjärv, reed disappears, while in summer, when the water is warm (in winter it freezes) cyanobacteria dominate (Lake Võrtsjärv website). The Frysian lakes are of a diverse type, some are relatively clear, others are located on peat soils and have very dark waters. Dekker et al. (2002) describe the optical properties and measured concentrations in the Frysian Lakes.
Current restoration plans are, next to further nutrient reductions, the generation of more natural lake shores. The main usage of these shallow lakes is recreational.

The Lakes that were formed behind the constructions Loskop Dam and Theewaterskloof Dam are deep and mesotrophic (Loskop Dam is oligo-mesotrophic). The main use of these water reservoirs is irrigation, both are also used for drinking water, various industrial purposes and fishing. While the concentrations of Chl (median 10.1 resp. 16.3 mg m\(^{-3}\) for the lakes behind resp. Loskop Dam and Theewaterskloof dam) and TSM (median 3.3 resp. 16.4 g m\(^{-3}\)) are intermediate or even low, CDOM has a relatively large influence on the optics (absorption at 440 nm 1.07 resp. 1.86 m\(^{-1}\)) (Matthews and Bernard). The hazards are the increasing eutrophication and cyanobacterial blooms. At Dam Loskop also mine tailing is a threat.

Lakes Vänern and Lammin Pääjärvi are large and deep natural boreal lakes, with an oligo-mesotrophic resp. oligotrophic status. Environmental threads are the increasing eutrophication and the expected brownification due to climate change (which is expected to lead to more rain in the boral region, where more runoff from land would increase the CDOM values). In Lakes Vänern also the water-level regulation has its environmental impact on the vegetation on the shoreline.

![Figure 4. Example of use case 4, Lake Võrtsjärv (Photo: Peter Gege)](image)

**Use case 5: Mine tailing ponds and other lakes with a very distinct water quality**

This use case contains lakes with various colours, depending on the dissolved substances. They vary from red and pink to cyan. During the inventarisation, next to man-made mine-tailing ponds, also natural lakes, some of them man-tailored by dike constructions, used for salt mining and mining of other chemicals were found to be interesting for this use case.

<table>
<thead>
<tr>
<th>Lake</th>
<th>Country</th>
<th>Location (bounding box)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Almásfüzitő and Neszmély</td>
<td>Hungary</td>
<td>47.7351N, 18.2712E;</td>
</tr>
</tbody>
</table>
The Hungarian mine tailing ponds Almásfüzitő and Neszmély are closed but still contain the highly alkaline waste of aluminum bauxite mining or red sludge (MBFH–ELGI–MÁFI cooperation, 2012). The main concern is that Neszmély is a storage behind a dike. A break in the dike could cause environmental damage downstream in the Danube River. An accident occurred in 2010, where three villages, the River Marcal and the Danube were affected (Schweitzer, 2010).

Lake Zigh is a natural salt lake, which has been used for salt mining (source: ECO Azerbaijan). Currently the threats include eutrophication and resuspension by wind waves.

The Sivash Sea is a natural area, blocked off from the sea by a couple of peninsulas. Because of its extreme shallowness (on average 1.5 meter) and the heat in summer, the salt concentrations are very high. The Sivash Sea itself can be divided in several parts, in which the western, middle and eastern part are the easiest to distinguish. The eastern part is the largest and has two connections with the Sea of Azov. Its colour is generally blue-greenish, although some separated ponds in this area are bright pink. In the middle part the concentrations salt range higher and the water has a more bright, cyano-green colour. The western part has the highest salt concentrations. The main basin here is pink, while a significant portion of the south-western area has extensively been used for extraction of salt and other chemicals such as bromide and titan. Some ponds have been surrounded by dikes and colours range bright cyano, pink, red and bright green. The area is a large and important bird sanctuary, however, the birds favour the eastern and middle parts (AEME, 2000).

<table>
<thead>
<tr>
<th>Lake</th>
<th>Country</th>
<th>Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Zigh</td>
<td>Azerbaijan</td>
<td>47.7259N, 18.4038E</td>
</tr>
<tr>
<td>Sivash Sea</td>
<td>Ukraine</td>
<td>46.2434N, 33.5893E; 45.9673N, 34.4270E</td>
</tr>
</tbody>
</table>

*Figure 5. Example of use case 5. Western area of the Silvash Sea (Photo: Fyva Icyken)*

**Use case 6: Evaluation of GLaSS products against the requirements of WFD reporting**

This use case contains lakes that, being located in EU countries, need to be monitored according to the WFD (Directive WFD, 2000). The WFD includes guidelines which define the
categories of quality and the required components and parameters. As some of these parameters can be determined by EO data with a reasonable accuracy, EO-related technologies may be integrated in the monitoring programs defined by the WFD, provided they can be demonstrated to independently assess Water Quality Parameters. SYKE has a long experience in the field as it makes the national guidelines for e.g. ecological classification and monitoring in Finland, and prepares in practice the WFD reports to EU. More recently, Bresciani et al. (2011) showed how MERIS time series are supporting the implementation of the WFD by estimating chlorophyll-a concentration in peri-alpine lakes. The lakes which are part of this Use case are of course included in the previous use cases: for instance, both Finland and Estonia have different highly absorbing lakes (Lammin Pääjärvi and Võrtsjärv, which are part of Use case 4); Italy, Germany and Sweden have several clear lakes with increasing eutrophication (Garda and Maggiore, Constance and Vättern, which are part of Use case 2), Italy and The Netherlands have shallow lakes with low transparency due to sediment resuspension (Markermeer and Trasimeno, which are part of Use case 3). Practically, the lakes which are part of Use case 6, are included in the previous cases and therefore are not included in the following analysis.
2.3 Matching of socio-economic data and bio-physical lake types

Figure 6 shows the global distribution of lakes whose information have been used to build the matching of socio-economic data and bio-physical lake types.

Use case 1: Shallow lakes with high eutrophication
Because of their shallowness, these lakes are vulnerable to eutrophication. The overload of nutrients to a lake can originate from rivers, runoff of nearby agricultural areas, from air pollution and from sewer systems. These diverse inputs, and the historic load of nutrients in the sediments of the lake that can easily resuspend, make it hard to reduce the nutrient concentrations again. These lakes have in common that they are relatively shallow and not too large and located in populated areas.

Eutrophication can lead to e.g. cyanobacterial blooms and generally reduces the biodiversity. Regardless of their eutrophic status, a portion of these lakes is used as drinking water source. Other services typically offered by these lakes are shipping, fishing, irrigation. Because of the potential of toxins originated from cyanobacteria, drinking and irrigation water from these lakes must be checked properly before use.

Use case 2: Deep, clear lakes with increasing eutrophication
Clear, bluish lakes occur in all areas of the world (Nordic, Alpine, African and temperate lakes are described here). The main physical parameter they share is their depth and therefore usually large water volume, which makes that these lakes only very slowly respond to eutrophication and other pollutions. Also probably because of their generally large volume and clear water, these lakes are used for all kinds of services: fishing, irrigation, recreation, drinking water etc. The environmental concern is that although these lakes seem invulnerable for (nutrient) pollutants and overfishing, they are not.

Use case 3: Shallow lakes with low transparency due to sediment resuspension
Turbid lakes are often shallow. They are turbid because the windwaves can resuspend sediment from the bed. These lakes have a high risk to increase in trophic state (eutrophication) and for cyanobacterial blooms. A distinct type of lake in this category are those fed by glaciers.

Because of their vulnerability, some of the lakes in this category listed in this document are under severe environmental pressure. This seems to be mainly related to their geophysical
location (Africa, Middle East) in areas where there is less money available for protection measures. Because in the same areas the lakes are important for all kinds of socio-economic services, the environmental degradation is followed by socio-economic problems.

**Use case 4: Highly absorbing lakes**

Highly absorbing lakes can be both deep and shallow, the absorbing properties depend on the source (river inflow) of the lake. These lakes tend to be used as source for drinking water, irrigation (depending on their location) and for recreation. The lakes listed in this document are to a small (Pääjärvi) or larger extent (Võrtsjärv) affected by eutrophication, which seems to be unrelated to their absorbing properties.

**Use case 5: Mine tailing ponds and other lakes with a very distinct water quality**

Mine-tailing ponds obviously contain highly contaminant substances. Other lakes with very distinct water colours are salt lakes, which occur in regions with high (summer) temperatures. To allow the water to warm enough to allow evaporation and salination, the lakes must be very shallow.
3 Published EO time-series

3.1 Selection of the published time series

Published time-series to further demonstrate how the lakes have been selected according to socio-economy are described in the next section.

Since the 1980s, satellite remote sensing represents an opportunity for synoptic and multi-temporal viewing of water quality of lakes. For the large lakes (relative to the spatial resolution of the remote scanner that is), remote sensing has been used to also evaluate spatial variability of optical water constituents (e.g., Lindell et al., 1999).

Despite a lot of similarity between ocean-colour- and inland-water- remote sensing (e.g. the same water constituents had to be retrieved), most of the initial works have been mainly based on Landsat or on airborne images rather than on specifically ocean colour sensors because: 1) ocean colour sensors were only suitable to capture largest lakes due to their medium spatial resolution; 2) traditional ocean-derived algorithms were unsuitable in optically complex waters (Witte et al., 2009). Conversely, Landsat was the only sensor that despite both its broader bands and lower radiometric sensitivity (both compared to ocean colour sensors) was equipped with a band operating in the blue (which has a major role in aquatic optic applications) and providing a spatial resolution enabling the mapping of more lakes. In fact, Lehner and Doll (2004) estimate 1.5 million for lakes ≥ 10 ha, and 15 million for lakes ≥ 1 ha.

Subsequently, during the first decade of 2000, the advent of MODIS and MERIS and the open access to the whole USGS Landsat archive\(^1\), provided an enormous source of free images suitable for lake water applications at global scale. In those years, the numbers of applications where EO data have been used for retrieving both optical properties and water constitutes in lakes increased enormously. More recently, Landsat 8 (with improved radiometric resolution with respect to the previous Landsat missions) and the imminent launch of Sentinel-2 in 2015 and next Sentinel-3, are making EO an efficient technique for lake water monitoring.

The numbers of scientific papers where EO data have been used for both detecting optical parameters (e.g., attenuation coefficient of the downwelling light) and water quality parameters (e.g., chlorophyll-a, suspend solids, coloured dissolved organic matter) increased significantly. The histogram in figure 7 shows the increasing number of papers that have been published from 1994 to 2013 in scientific journals selected within the ISI-WoS database by searching for three topics (i.e., remote sensing+chlorophyll-a+lakes) and three research areas (i.e., Marine Freshwater Biology+Remote Sensing+Environmental Sciences Ecology). It is quite obvious how the progress of remote sensing of lakes accelerated since the second decade of 2000.

\(^1\) The excellent data quality, consistent global archiving scheme, and reduced pricing ($600) of Landsat 7 led to a large increase of Landsat data users. In October 2008, USGS made all Landsat 7 data free to the public (all Landsat data were made free in January 2009 leading to a 60-fold increase of data downloads).
With respect to the application, there are also different excellent contributions taking aquatic ecosystem remote sensing beyond the traditional measuring constituents domain (e.g., chlorophyll-a). For instance Kutser et al. (2005a, b) showed how lakes play a significant role because they serve as regulators of climate and as sinks and buffers for organic carbon (through CDOM and DOC and its interaction with CO$_2$).

The scientific and technologic progresses of EO of lakes also facilitated the linkage between remote sensing and limnology (a connection that remote sensing scientists and oceanographers already had many years ago); e.g. in a recent review on limnological research in the deep southern subalpine lakes Salmaso and Mosello (2010) draw the conclusion that, “in limnological applications/studies, synoptic analyses at a macro-regional scale are mandatory”.

We can conclude that over the last few decades, satellite technology has allowed measurements on a global scale over long time periods (~40 years), and is now proving useful in lakes and reservoirs (but of course also coastal waters and estuaries). In this project we used published EO time-series to further demonstrate such capabilities.

The EO time series selection (hundred of papers exist on this topic; cf. Figure 7) was based on the following criteria:

- to use only ISI-WoS papers,
- to include a number of lakes distributed over the world (to ensure the global perspective of GLaSS, cf. Figure 7),
- to include at least one example for each of the water quality parameters on which GLaSS is working (i.e., chl-a, TSS and CDOM, cf. Task 3.4),
- to include papers where the use of EO time series for a certain lake has a clear link with some socio-economy indicators (e.g., water use, hazards).

Finally, 10 studies have been selected (Table 6 and Figure 8) and in the following section socio-economical indicators are described and linked to the results achieved by EO-time series analyses. For each study we show the main environmental issue/s, socio-economy
The lakes described in the following works have been also included in the long list of GLaSS lakes.

Table 6. Selection of papers showing how and when EO time series have been successfully applied in recent years.

<table>
<thead>
<tr>
<th>Lake(s)</th>
<th>Continent</th>
<th>Country</th>
<th>Parameter</th>
<th>EO data</th>
<th>Time-window</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peri-alpine lakes</td>
<td>Europe</td>
<td>Italy, Switzerland, Germany, France</td>
<td>chl-a</td>
<td>MERIS-FR</td>
<td>2003-2009</td>
<td>Bresciani et al., 2011</td>
</tr>
<tr>
<td>Lake Maggiore</td>
<td>Europe</td>
<td>Italy, Switzerland</td>
<td>CDOM, chl-a, Z90, TSS</td>
<td>MERIS-FR</td>
<td>2003-2011</td>
<td>Giardino et al., 2014</td>
</tr>
<tr>
<td>Lake Tana</td>
<td>Africa</td>
<td>Ethiopia</td>
<td>TSS</td>
<td>MODIS-Terra</td>
<td>2000-2010</td>
<td>Kaba et al., 2014</td>
</tr>
<tr>
<td>Lake Bogoria</td>
<td>Africa</td>
<td>Eastern Rift Valley, Kenya</td>
<td>Cyanobacteria and scum</td>
<td>Landsat-7</td>
<td>Nov 2003 to Feb. 2005</td>
<td>Tebbs et al., 2013</td>
</tr>
<tr>
<td>Lake Tanganyika</td>
<td>Africa</td>
<td>Burundi, DR Congo, Tanzania, Zambia</td>
<td>Chl-a, attenuation coefficients at 490 nm</td>
<td>MODIS-Aqua</td>
<td>2002-2006</td>
<td>Horion et al., 2010</td>
</tr>
<tr>
<td>Minnesota's 10,000 lake</td>
<td>North America</td>
<td>Minnesota, USA</td>
<td>Secchi Disk</td>
<td>Landsat-4, 5 and 7</td>
<td>1985-2005</td>
<td>Olmanson et al., 2008</td>
</tr>
<tr>
<td>Lake Simcoe</td>
<td>North America</td>
<td>Ontario, Canada</td>
<td>Secchi Disk</td>
<td>Landsat-5</td>
<td>1987-2008</td>
<td>Guan et al., 2010</td>
</tr>
<tr>
<td>Lake Maracaibo</td>
<td>South America</td>
<td>Venezuela</td>
<td>Floating vegetation</td>
<td>MODIS-Aqua</td>
<td>2003-2006</td>
<td>Kiation and Walker, 2010</td>
</tr>
<tr>
<td>Lake Taihu</td>
<td>Asia</td>
<td>RPC</td>
<td>TSS</td>
<td>MODIS-Terra</td>
<td>Jan. to Dec. 2007</td>
<td>Zhang et al., 2010</td>
</tr>
<tr>
<td>Lake Taihu</td>
<td>Asia</td>
<td>RPC</td>
<td>Cyanobacteria</td>
<td>MODIS-Terra and Aqua</td>
<td>2000-2008</td>
<td>Hu et al., 2010</td>
</tr>
</tbody>
</table>
Figure 8. Overview of the global distribution of lakes where EO-time series have been successfully used to address an environmental issue.
3.2 Description of the published time series

**Peri-alpine lakes**

Water of these lakes is extensively used for the production of hydroelectric power, is intensively used in agriculture and industry, becoming a life-sustaining element for the economy of the surrounding areas. Waters from the largest lakes (e.g., Lake Zurich and Lake Como) are even used directly as fresh water supply of the nearby cities. In addition, these water bodies are one of the key elements for the tourist economy of the Alpine region (for instance Lake Garda is visited by about 20 millions per year).

Bresciani et al. (2011) and Giardino et al. (2014) both observed that time series MERIS data represents a suitable and cost-effective technology to support the WFD, depicting the dynamics of the surface waters of lakes in agreement with the evolution of natural phenomena (Figure 8).

![Figure 8. Yearly means and time series of Chl and CDOM in peri-alpine lakes (Bresciani et al., 2011; Giardino et al., 2014)](image)
### Lake Tana

The most pronounced advantage of Lake Tana is its storage characteristics, in that it accommodates a live storage which amounts to more than two times that of the five large reservoirs in Ethiopia, rendering a relatively low cost per unit of utilizable water. In the Ethiopian highlands, conservation practices are being installed by government and NGO’s to reduce soil erosion and thereby reduce sediment concentration in streams. Millions of dollars were invested but very few measurements are available on the effectiveness of these interventions.

Kaba et al. (2014) showed that MODIS images are potential cost effective tools to monitor suspended sediment concentration and obtain a past history of concentration for evaluating the effect of best management practices (Figure 9).

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**Figure 9, TSS time series at a station in lake Tana (Kaba et al., 2014)**
Lake Bogoria

It is a significant conservation site due to several species of bird which inhabit the lake, but the flamingos in particular are of great economic importance because they attract many visitors. In this unique ecosystem, essential to the life cycle of Lesser Flamingos (*Phoeniconaias minor*), monitoring primary producers, thus distribution of food available, provides valuable information for their future conservation.

Tebbs et al. (2013) showed that in November 2005, approximately 0.1% of the flamingos present at Lake Bogoria were dying each day; the carcasses were underweight on average, so it is likely that they were dying as a result of lack of food (Figure 10). Frequent revisit of sensors contributes to providing a complete picture of spatial and temporal variability in food sources utilised by Lesser Flamingos at a chain of lakes throughout the Rift Valley, which will be extremely valuable for ensuring their future conservation.

*Figure 10, time series of Chl, standard deviation and scum area of lake Bogoria (Tebbs et al., 2013).*
Lake Tanganyika

It is one of the world’s most important freshwater ecosystems, providing fundamental resources for 10 million people living in its catchment’s area as well as a unique reservoir of biodiversity. It is estimated that 25–40% of the protein in the diet of people living around the lake comes from lake fish.

Horion et al. (2010) showed that a comparison between surface chlorophyll-a concentrations estimated from field monitoring and from the MODIS based dataset shows that remote sensing allows improved detection of surface blooms in Lake Tanganyika (Figure 11).

![Figure 11](image-url)

*Figure 11, time series of Chl obtained via MODIS and in situ of lake Tanganyika (Horion et al., 2010).*
Minnesota’s lakes

Minnesota’s numerous lakes are important recreational and aesthetic resources that add to the economic vitality and quality of life of the state. Protecting and monitoring lake water quality is a major concern for many state and local agencies and citizen groups. Olmanson et al. (2008) showed that mean water clarity at the statewide level remained stable, while decreasing water clarity trends were detected in southern Minnesota, where agriculture is the predominant land use. Satellite imagery can provide an accurate method for obtaining comprehensive spatial and temporal coverage of key water quality characteristics that can be used to detect trends at different geographic scales. Water clarity can also be used in conjunction with morphometric, land-use and demographic data to analyze spatial patterns and temporal trends in water quality and develop better understanding of the factors that affect these patterns and trends. Results of such analyses will aid local and state agencies in making informed decisions about development policy and improve the management of lake resources.

![Figure 12, Mean water clarity in Minnesota’s lakes over several years (Olmanson et al., 2008)](image-url)
Great significance has been empowered to this lake, where the fishery is an important industry generating more than 200 million dollars per year. Water-quality problems have existed since the 1970s, when the increasing phosphorus load to this lake contributed to the recruitment failure of cold-water fish, as well as the excessive growth of aquatic macrophytes and algae.

Guan et al. (2010) observed that the addition of MODIS images to the dataset can improve monitoring actions (Figure 13). The high temporal resolution of MODIS images can guarantee an adequate late summer data selection, while the fair spatial resolution of Landsat images can exhibit the spatial patterns of water quality parameters.

Figure 13. Water clarity maps of lake Simcoe obtained via MODIS (Guan et al., 2010).
**Lake Maracaibo**

It is an important source of food and livelihood for the local communities. Eutrophication accrues from different sources: agricultural, sewerage from population around the lake, livestock waste, petrochemical plants. Excess nutrients stimulate plant growth especially algae and nuisance plant weeds, such as duckweed, that interfere with the recreational use of water bodies, the health and diversity of aquatic life. In 2004 a large portion of Lake Maracaibo (Venezuela) was covered by floating aquatic plants and the Venezuelan government spent about $2 million per month on clean-up and mechanical removal of the duckweed.

Kiage and Walker (2009) showed that main causes of proliferation in floating vegetation lay at rainfall anomalies in the previous months (higher local rainfall would produce more runoff into the lake from the about 30 rivers) and population growing in the major surrounding cities of Maracaibo, Cabimas, and Ciudad Ojeda (Figure 14). Frequent remote sensing surveillance of the lake would play a central role in any mitigation efforts.

*Figure 14, trend in floating vegetation: time series and maps, of lake Maracaibo (Kiage and Walker, 2009)*
## Lake Taihu

It is important for water supply, flood control, tourism and recreation, shipping and aquaculture. The lake Taihu most eutrophic region is Meiliang Bay, which serves as a source of drinking water for more than two million people in nearby Wuxi City. Of particular concern is the lake’s blue-green algae or cyanobacteria (mainly *Microcystis aeruginosa*), which, if ingested, produces toxins that can damage the liver, intestines, and nervous system. Moreover, the degradation of water quality due to high TSM concentrations has become a major environmental problem in Lake Taihu also.

The study of Hu et al. (2010) provides strong evidence that operational remote sensing, such as MODIS observations, can provide unique information on bloom characteristics that are difficult or impossible to obtain using in situ surveys. Zhang et al. (2010) observed that the variation range of TSM concentration in the open area is much larger than that in the bays, affected by higher wind velocities in the open area (Figure 14). The minimum variation range is located in East Taihu due to the sheltered environment and dense hydrophytes. As TSM determines the transparency of water and can also serve as a transport medium for various pollutants, e.g., heavy metals. The management of hydrophytes might help in controlling the TSM load and dynamics.

![Figure 6. Percentage of MODIS measurements when cyanobacteria blooms (FAI > 0.004) were found from MODIS FAI imagery.](image)

![Figure 7. (a) Spatial variations in TSM in each region of Lake Taihu, 2007; (b) Temporal variations in TSM in each region of Lake Taihu, 2007.](image)

Figure 15, Maps of percentage of measures per year (MODIS) where cyanobacteria were found; and spatial and temporal variations in TSM (Hu et al., 2010 and Zhang et al., 2010)
4 Conclusion, outlook and place in the GLaSS system

We have seen that some of the most important characteristics include the lake’s morphometry (size, shape and depth), the activities that occur in the lands that drain into it (watershed or basin), the location (or ecoregion in which the lake is located, and when and how the lake basin was formed). Lakes and rivers within ecoregions often have similar physical characteristics, water chemistry, and biological communities, because they occur in an area of similar land type. The number, appearance, and condition of lakes vary among ecoregions because of glacial history, geology, soil type, land use, and climate. A lake is also a reflection of its watershed: what happens on the land and the basic characteristics of the land (soil, geology, vegetation, drainage, etc.) affects the quality and health of a lake or stream. These factors, acting in various combinations, have created the multitude of lake types, with different trophic state, and use. Trophic state is related to CHL (Odermatt et al., 2012) and has a link to transparency (e.g. Carlson, 1977).

Thus, the use cases reflected bio-physical lake types through the descriptors of lake ecosystems (morphometry, hydrodynamics, and trophic state), its environment (hydrology and land use in the watershed, ecoregions, geology), use, and optics. Trophic thresholds may vary with morphometry (a rough classification can be made as Surface/volume ratio <10 alpine oligotrophic, surface/volume >50 meso- to eutrophic (Claudio Giardino, personal communication), or ecosystem-specific limitations to primary productivity, whereas the optics are determined by the variability in optical properties of the lake. The GLaSS system can be used to produce time-series of the atmospherically corrected remote sensing imagery that can demonstrate the spatio-temporal variability in optical properties that indicated current (internal) lake dynamics such as primary production and succession, and resuspension.

Multiple use creating multiple pressures on lakes
Mankind benefits from a multitude of resources and processes supplied by large lakes. These benefits, known as ecosystem services, include the use of lakes as sources of drinking water and fish, sites for recreation, waterways or places for dumping wastes. Multiple use of large lakes creates multiple pressures on the ecosystems that may lead to regime shifts, degradation of water quality and loss of some or most of the ecosystem services. Decision-making concerning the protection and management of large lakes is complicated and requires broadly based public participation. To support sustainable development, environmental education has to be on a high level (Várkuti et al., 2008), which is what we aim at in WP6.

Climate change as an additional pressure on ecosystems
Climate change occurring on top of all other anthropogenic pressures may worsen the ecological status of lake ecosystems (Nõges et al., 2008). Size and depth matter (Weyhenmeyer, 2008). It is often difficult to detect the responses of lake ecosystem parameters to weak climate change signals and to distinguish them from those caused by large seasonal or inter-annual variability or other factors.

Management
Directive 2000/60/EC of the European Parliament and Council, widely known as the Water Framework Directive (WFD), aims to protect water bodies from further degradation. This is further taken up in WP5.7.
References


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Global Lakes Sentinel Services (313256)


Other sources of data:

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- IGKB: http://www.igkb.org (visited 16 April 2014)
- Lake Võrtsjärv website: www.vortsjarv.ee/vortsjarv-eng (visited 10 April 2014)
- World lakes: http://www.worldlakes.org (visited 14 April 2014)