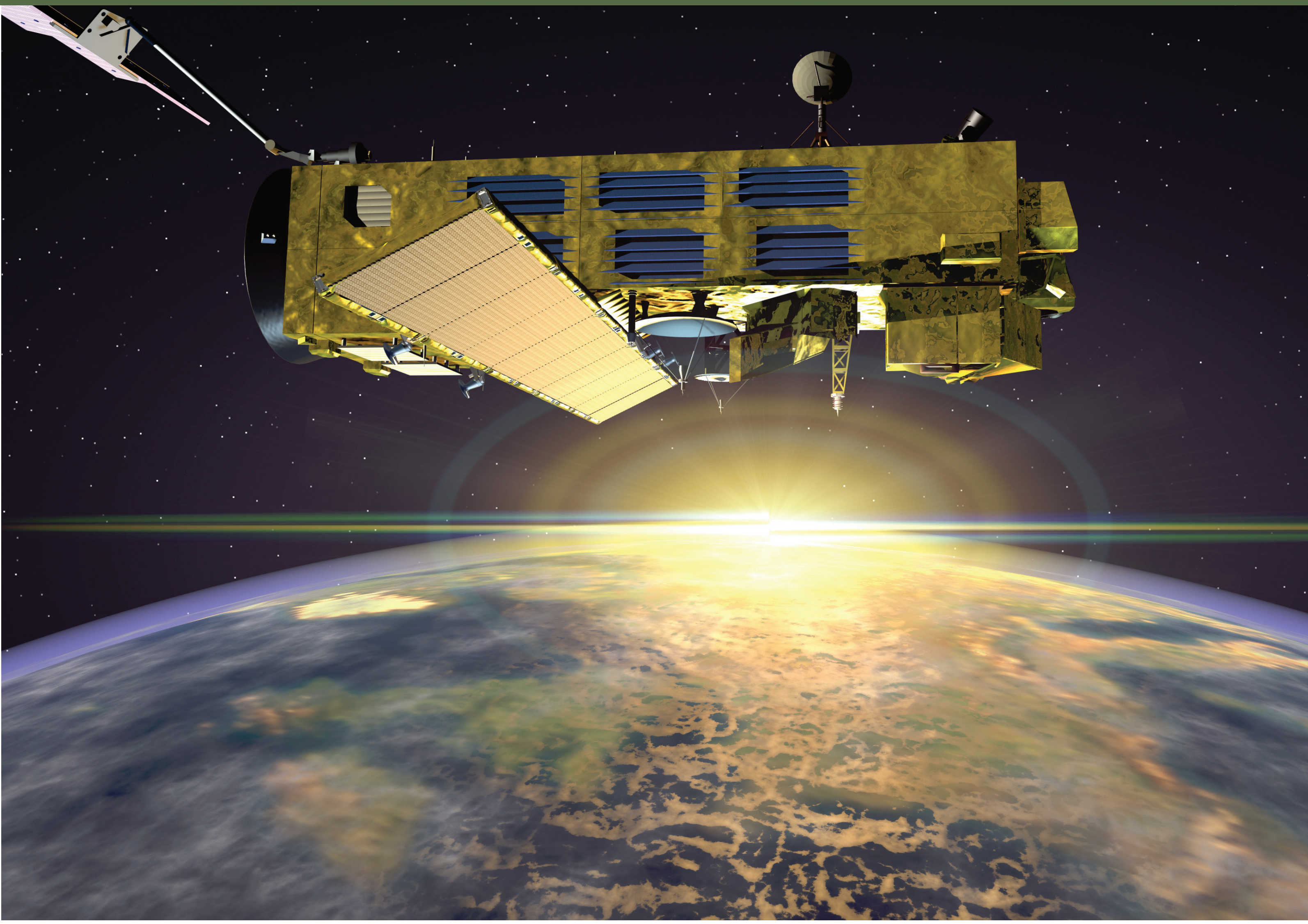
Länsstyrelserna



Brockmann Geomatics
Sweden AB

Satellitdata för övervakning av sjöar - stöd för kvalitetsbedömning och statusklassning

Förord

Miljöövervakningen av Sveriges vatten bedrivs på flera nivåer. Nationella, regionala, kommunala och lokala aktörer bedriver övervakning av olika parametrar med olika frekvenser. I arbetet med EU:s ramdirektiv för vatten ligger övervakningen till grund för statusbedömningar av vattnet. En bra övervakning av vatten är nödvändig för att de beslut som fattas inom arbetet med vattenförvaltning ska bli rätt. Miljöövervakningen i sjöar baseras oftast på ett provtillfälle per år.

Sedan ett antal år tillbaka har forsknings- och utvecklingsprojekt med fokus på satellitbaserad vattenkvalitetsövervakning genomförts för svenska sjöar och kustvatten. Som ett underlag för löpande övervaknings- och planeringsarbete har det här drivits en vattenkvalitetsservice med syfte att förse Naturvårdsverket, HaV, Vattenmyndigheten, Länsstyrelser och kommuner m.fl. med information om vattenkvalitet. En fördel med satellitbaserad vattenkvalitetsövervakning är att satelliten passerar flera gånger i veckan över Sverige. Detta innebär att det är möjligt att mäta vattenkvaliteten i fler sjöar och betydligt oftare än vad som är praktiskt och ekonomiskt möjligt i fält.

Arbetet i detta projekt fokuserades på analys av klorofyll och humus samt satellitdata över Bolmen och drygt 80 mindre sjöar i det undersökta området. Projektet har varit ett samarbete mellan Länsstyrelserna i Jönköpings, Hallands och Kronobergs län, Sydvatten och Brockmann Geomatics med stöd från Rymdstyrelsen. Analysen av satellitdata har utförts av Brockmann Geomatics.

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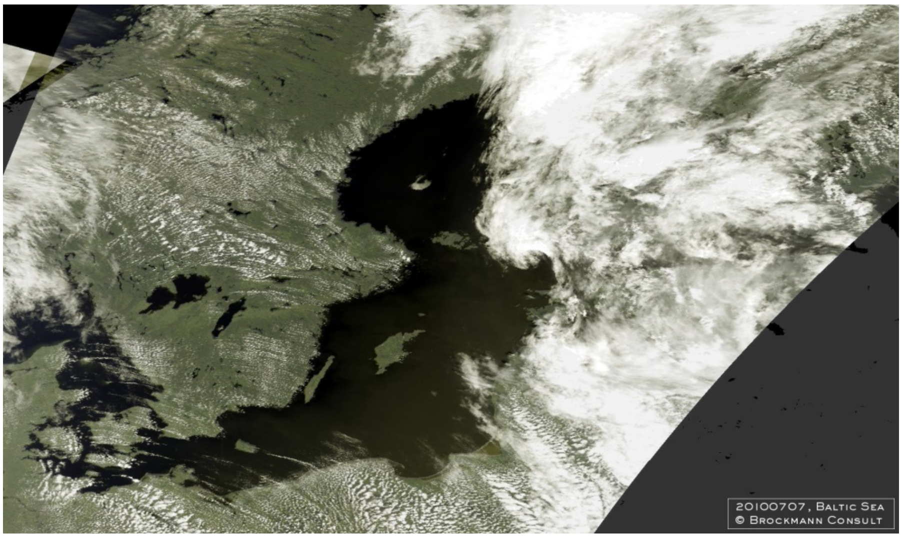
Sammanfattning

Det europeiska vattendirektivet säger att alla medlemsstater ska övervaka den ekologiska statusen i alla sjöar större än 50 ha (0,5 km^2) och att åtgärder måste vidtas om inte god eller hög status uppnås. Statusklassningen baseras bl.a. på ett antal faktorer kopplade till växtplankton, makrofyter, bottenfauna och fisk, som tillsammans ska ge en bild av sjöns kvalitet. Budgeten för miljöövervakning av kust och sjöar har visat sig inte på långa vägar räcka till för att mäta det som krävs för att uppfylla kraven i vattendirektivet och i den senaste utvärderingen från EU klarade inte Sverige att leva upp till kraven i vattendirektivet. Därför behövs det mätmetoder som kostar mindre och ger en mer heltäckande bild av vattentillståndet. Under 2012-2013 genomfördes ett utvecklingsprojekt med syfte att undersöka om och hur satellitbildsbaserad information kan användas för att mäta och övervaka vattenkvaliteten och därmed komplettera den fältbaserade provtagningen i samband med statusbedömningen. Arbetet fokuserades på klorofyll och humus och satellitdata över Bolmen och drygt 80 mindre sjöar i det undersökta området har analyserats (Figur 1). Projektet var ett samarbete mellan Länsstyrelserna i Jönköpings-, Hallands- och Kronobergslän, Sydvatten och Brockmann Geomatics. Arbetet finansierades av Rymdstyrelsen och projektdeltagarna.

Figur 1. Översikt av det undersökta området. Bakgrundsbilden och de beräknade klorofyllkoncentrationerna motsvarar situationen den 3 juni 2011.

Fjärranalys över sjöar och hav sker genom bilder från optiska sensorer. I projektet har vi använt instrumentet MERIS, MEdium Resolution Imaging Spectrometer, som fanns på satelliten ENVISAT. ENVISAT var den största plattformen någonsin utvecklad av ESA, det europeiska rymdorganet, och MERIS var speciellt utvecklat för vatten. Eftersom vatten är mörkt kräver fjärranalys av vatten instrument med andra egenskaper än vad som krävs för att ta bilder över land. Man behöver särskilda ljussensorer som är mycket känsliga och som även kan mäta specifika våglängder av det reflekterade ljuset. Halter av löst och suspenderat material som finns i vattnet avgör mängden reflekterat ljus och därmed vattnets färg. En av de parametrar som kan användas för att mäta statusen för växtplankton är klorofyll. Klorofyll är också en av de parametrar som kan mätas från satellit, eftersom den påverkar färgen på vattnet. Bilderna från MERIS har en upplösning på 300 meter. Upplösningen är ett mått på detaljeringsgraden och innebär i det här fallet att små sjöar inte kan övervakas med just det här instrumentet eftersom upplösningen är för grov. Det finns dock andra satellitburna instrument med bättre upplösning (30 meter) som skulle kunna vara ett alternativ. Utveckling pågår för att definiera möjligheterna med dessa satelliter. En stor fördel med MERIS var istället den goda täckningen och att data för hela Sverige samlas in under loppet av några minuter. Bilden nedan visar MERIS täckningsområde den 7 juli 2010. En annan fördel är att satelliten passerar flera gånger i veckan över Sverige, vilket innebär att det är möjligt att mäta vattenkvaliteten betydligt oftare än vad som är praktiskt och ekonomiskt möjligt i fält.

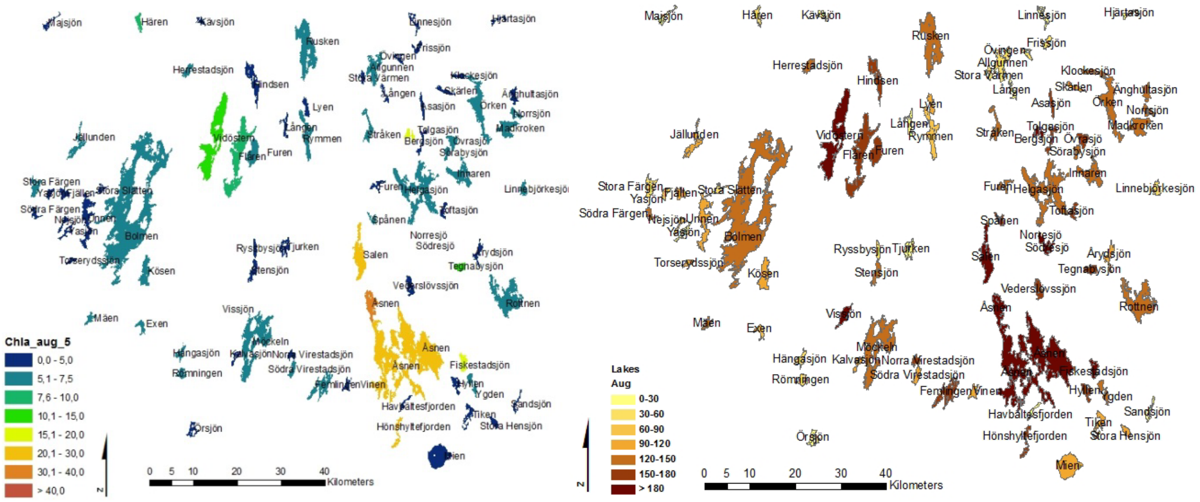


Figur 2. MERIS bild från den 7 juli 2010.

Den av vattnet reflekterade solstrålningen registreras av sensorn och kan sedan via ett omfattande kalibrerings- och processeringsarbete räknas om till koncentrationer av olika vattenkvalitetsparametrar. Processeringen resulterar i koncentrationskartor för de aktuella parametrarna som sedan kan bearbetas vidare. I det avslutade utvecklingsprojektet har bildinformationen analyserats tillsammans med fältbaserad information. Områdesspecifika algoritmer för beräkning av vattenkvalitetsparametrarnas koncentrationer har därefter utvecklats.

Resultaten indikerar att bra produkter, särskilt för klorofyll, kan genereras för sjöar större än 2-3 km^2. Det innebär att det inte är möjligt att övervaka alla sjöar, i enlighet med ramdirektivet för vatten, med hjälp av en satellit med 300 meters upplösning. För de flesta sjöar skulle det däremot innebära ett betydande bidrag till det nuvarande övervakningsprogrammet att lägga till satellitdata. Idag baseras statusklassningen på fältdata insamlade i augusti månad. För de allra flesta sjöarna handlar det om en station och en provtagning per sjö och år. Några enstaka sjöar har fler stationer, men många har ingen alls. Baserat på analysen av satellitdata från de fem år som ingick i projektet (2007-2011) skulle data från cirka 70 dagar per år tillkomma för Bolmen. För en mindre sjö, som exempelvis Furen (11 km^2) skulle ytterligare 40 klorofyllmätningar per år kunna läggas till informationsunderlaget.

Figuren nedan visar klorofyllkoncentration och färgtal i augusti, i varje sjö, i form av ett 5-års medelvärde. Beräkningen omfattar alla godkända pixlar i hela sjön och inte bara vid kontrollstationen. Moln är största anledningen till att en bildpixel sorteras bort. Moln är också den största begränsningen med avseende på teknikens möjlighet att samla in information.



Figur 3. Klorofyllkoncentration och färgtal i de undersökta sjöarna, redovisad som ett 5 års medel baserat på alla satellitobservationer under augusti 2007-2011.

Syftet med arbetet var också att undersöka om den satellitbaserade informationen skulle kunna vara till hjälp för Sydvatten och ge stöd vid driften av Ringsjöverket. För dessa syften var analysen inriktad på färgtal och att undersöka om trender observerade i MERIS data över södra Bolmen återspeglades i de prover som tas vid Ringsjöverket efter att vattnet transporterats genom Bolmentunneln. I analysen ingick också data från en kontrollstation i Skeen vid Bolmens utlopp/tunnelns inlopp. Baserat på de analyserade data var det inte möjligt att dra några slutsatser om hur förändringar i vattenkvaliteten, observerade från satellit, kan användas direkt för att stödja och förbättra adaptiv drift vid Ringsjöverket. Tydliga trender kunde inte ses mellan någon av de tre undersökta datamängderna (satellit, fält, Sydvatten). Ur en ren teknisk aspekt, kan satellitbaserad information om Bolmens status vara möjligt att leverera till Ringsjöverket någon dag efter att data har registrerats, men hur den relaterar till inkommande vatten i Ringsjöverket 1-2 veckor senare kunde inte definieras. Analysen skulle dock kunna förbättras/utökas genom att bearbeta data från tidigare år (2002-2006) eftersom tunneln var stängd för reparation under stora delar av 2007-2011.

MERIS levererade bilder mellan 2002-2012, men slutade tyvärr att fungera 2012. Konstruktion av nya operationella satelliter för övervakning har pågått sedan flera år tillbaka och den första i en serie av satelliter kommer att skjutas upp av ESA (European Space Agency) under 2015. Med flera satelliter i omloppsbana ökar möjligheten till molnfria data. Målet är att få denna teknik som en etablerad del av svensk nationell och regional miljöövervakning och att kunna bidra till nästa omgång av statusklassningen som sker 2019.

Den fullständiga rapporten är skriven på engelska och har bifogats nedan.

CONTENTS

Bilder och data är producerade för Länsstyrelserna i Jönköpings-, Hallands- och Kronobergslän och Sydvatten AB.

1 Introduction

Sydvatten AB is a municipally owned company that produces drinking water to 800 000 inhabitants in southern Sweden. The company was founded in 1966 and treats and distributes drinking water from the waterworks Vombverket and Ringsjöverket. At present, Sydvatten is one of the largest drinking water producers in Sweden. Around 190 000 m^3 of drinking water is produced daily. The raw water comes from lake Bolmen in Småland and lake Vombsjön located in Skåne, and generally known for its fine quality water.

Existing water control programs at different organisations and companies provides invaluable information about the water quality of Swedish lakes and the coastal zone. However, this information is based on laboratory analysis of water samples from a limited, both in time and space, number of sampling stations. The information and knowledge retrieved can be considerably strengthened and increased by including remote sensing data in the monitoring programs. This step is decisive in order to develop a better management of Swedish lakes and to create a sustainable aquatic environment.

Over the past 15 years, the water quality in Bolmen has changed towards more coloured water, with a slight increase in alkalinity. The colour is due to higher content of humus, which in turn impairs the effectiveness of the processes at Ringsjöverket, increases the risk of microbial regrowth in the pipelines and increases formation of disinfection by-products. Rapid raw water quality changes deteriorate the effectiveness of the treatment processes in the waterworks. The time for transportation of the water from Lake Bolmen, through the Bolmen tunnel, to Ringsjöverket is in average one week, so the operating engineers at Ringsjöverket must be able to modify the processes in due time to compensate for the changes in raw water quality in Bolmen. We have therefore evaluated the possibility to use satellite based water quality information to monitor Lake Bolmen and support the operation processes at Ringsjöverket.

2 User needs

The Swedish Agency for Marine and Water Management (SwAM), the River Basin District Authorities, the County administrative boards, the Societies for water conservation, water companies and other organisations have the task to monitor, restore and preserve the natural conditions of the lakes and sea, and to provide the community with high quality drinking water. Their work consists of, for example, sampling, analysis and evaluation of the results from field based programs. They are also responsible for definition, and follow-up, of the environmental goals for the lakes and sea in order to meet, for example, EU Water Framework Directive and make suggestions for actions needed to improve and/or preserve the natural state. A growing demand of a tool with better spatial and temporal coverage for status classification on a general level is expected. This tool must for example be able to separate if a decrease in secchi depth is caused by an increase in dissolved organic matter or if it is caused by increasing concentration of cyanobacteria, i.e. possible eutrophication. A more complete knowledge about the status, generality and variation of the water quality parameters are required and we believe that remote sensing could be the right tool to accomplish that.

More specifically, Sydvatten AB is interested in testing the possibility to improve decision support methods for the operational engineers of Ringsjöverket with the use of remote sensing technique. The average detention time for water in the Bolmen tunnel is seven days. If early and additional information on water quality changes in Bolmen could be available to the operating engineers of the waterworks Ringsjöverket, they could more easily compensate for the changes in the treatment process, which would lead to a more stable and predictable treatment. Step-changes in coagulant dose could for instance be made in smaller but more frequent steps, if the quality change is known with higher precision. This should improve the quality of the delivered drinking water.

3 Purpose and goal

Bolmen is the most important freshwater resource in the water supply system of Sydvatten and the water quality of Bolmen directly affects the preparation processes, distribution and customer satisfaction. The purpose of this project is to define to what extent water quality information derived from satellite data can increase the knowledge about Bolmen, support the water treatment regime and how this technique can be implemented in the routines at Ringsjöverket.

Our primary goals are:

1. To investigate, on a more comprehensive level, how satellite based information (ENVISAT-MERIS) can be used to measure and monitor the water quality status of Lake Bolmen.
2. To investigate if the same satellite data can be used to measure and monitor the water quality status of smaller lakes in the area. Is the spatial resolution of MERIS enough to produce a good representation of the lakes and is it possible to generate reasonable results with respect to the effect of additional reflectance from the surrounding land.
3. To evaluate how changes in the water quality, observed from the satellite data, can be used directly to support and enhance adaptive operation at Ringsjöverket.

4 Study Area

4.1 Bolmen region

Bolmen is Sweden's tenth largest lake, located in Småland, and known for its fine quality water. It is located on 141 meters height, has a surface area of 184 km^2 and a water volume of 1.1 km^3. The lake is not very deep, maximum depth is 37 m, and an average depth of 5.4 m. This gives a replacement time of 2.8 years. The Bolmen river basin area is part of Lagan river basin (Figure 2), covering 1642 km^2.

There are a number of smaller lakes in the region around Bolmen. Only few of these lakes are included in the field based monitoring program and most of them are only sampled once per year. During 2013 another 82 lakes in the region were included in the analysis as well. The minimum lake size was set to 2 km^2. All investigated lakes can be seen in Figure 1 below and Annex 1 where all the lakes are listed.

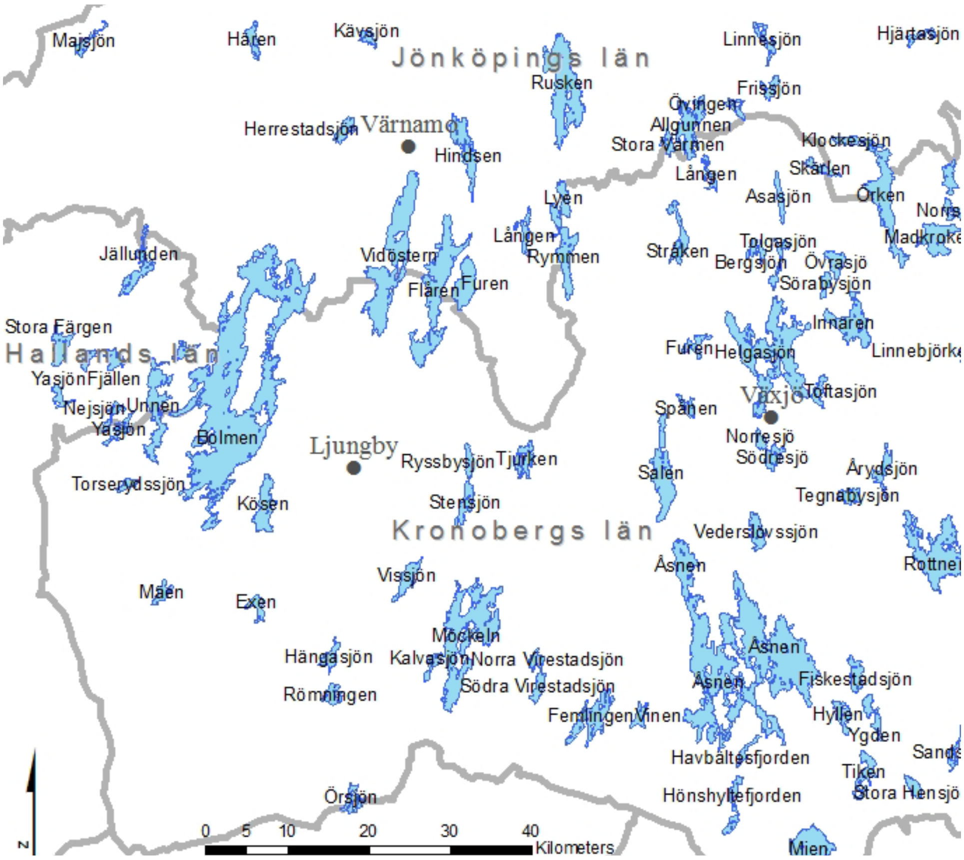


Figure 1. The investigated lakes(>2 km²) in the region around lake Bolmen.

Hydrologic characteristics of lakes are highly dependent on their size and on the climatic conditions prevailing in the catchment area. Each lake has an individual pattern of physical and chemical characteristics which are determined largely by the climatic, geomorphological, and geochemical conditions predominant in the catchment and the underlying aquifers. The chemical quality of the aquatic environment varies according to local deposits, the climate, the distance from the ocean the amount of soil cover and the human activities.

Many factors play an important role in the lake trophic state:

1. Catchment Area - bed rock, soil cover, vegetation, human activities, and land management.
2. Climate Conditions - precipitation, temperature, and the amount of sunlight
3. Morphology - the mean and maximum depth, the lake volume, its surface area, and the ratio of lake surface area to the total catchment area.

Figure 2 shows the area under study, which includes many lakes distributed between the County Administrative Boards of Hallands, Jönkopings, and Kronobergs and is a part of five hydrologic basins named Nissan, Lagan, Mörrumsån, Helge Å, and Ronnebyån.

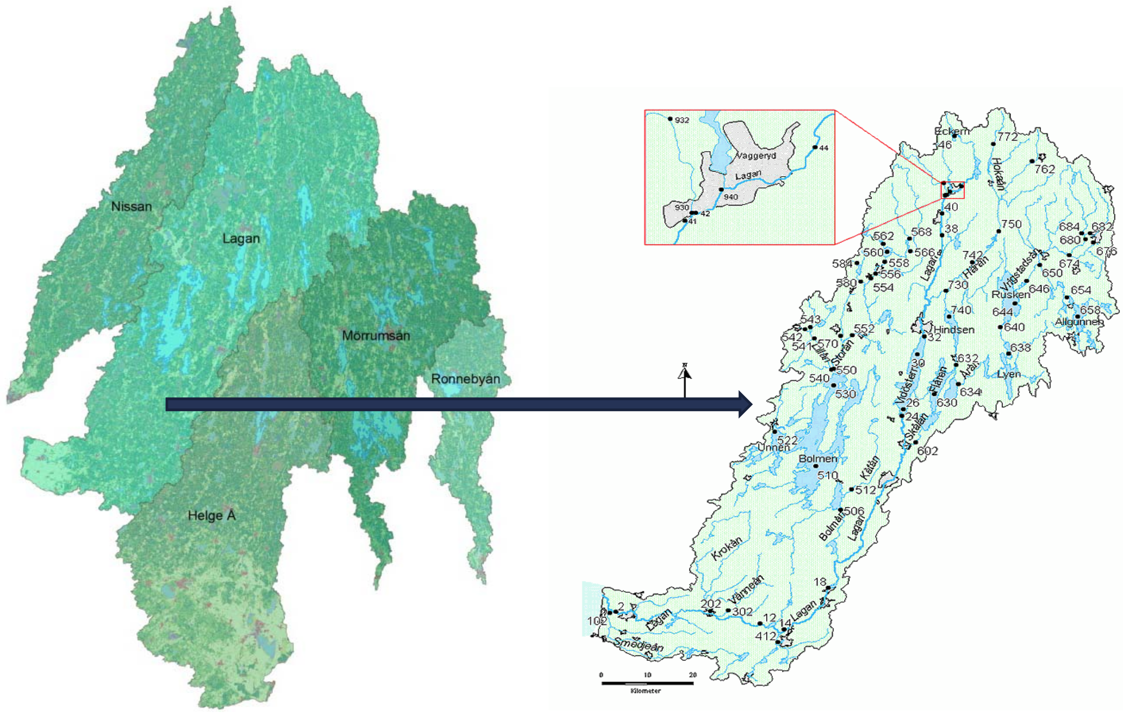


Figure 2. All concerned catchment areas and Lake Bolmen and Lagans river basin district.

5 Satellite data

The developments are focused on MERIS FR data, with a spatial resolution of 300 meters and spectral properties developed for water targets. Details about the spectral properties are summarized in Table 1. An example of the area covered by MERIS during on date (110423) is shown in Figure 3.

Table 1. Spectral band settings, widths and primary applications for MERIS.

MERIS	Primary application	MERIS	Primary application
412.5 (10)	Yellow substance and detrital pigments	**708.75 (10)**	Fluorescence reference, atmosphere corrections
442.5 (10)	Chlorophyll absorption maximum	**753.75 (7.5)**	Oxygen absorption reference
490 (10)	Chlorophyll and other pigments	**760.6 (3.75)**	Oxygen absorption
510 (10)	Turbidity, suspended sediments	**778.75 (15)**	Atmosphere corrections
560 (10)	Chlorophyll absorption minimum	**865 (20)**	Atmosphere corrections
620 (10)	Suspended sediments	**885 (10)**	Vegetation, water vapour reference
665 (10)	Chlorophyll absorption & fluorescence reference	**900 (10)**	Water vapour
681.25 (7.5)	Chlorophyll fluorescence peak		

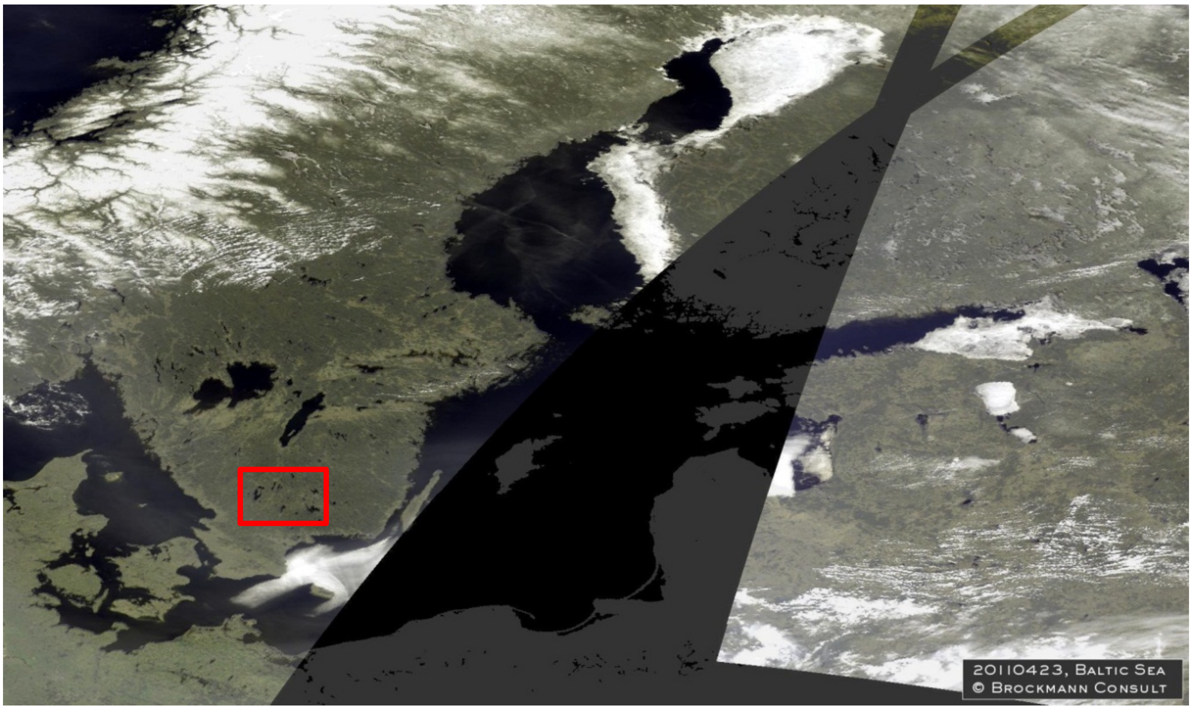


Figure 3. MERIS overflight 110423.

MERIS (http://envisat.esa.int/) was the first ocean colour instrument in space that was optimised for coastal water applications. MERIS on ENVISAT stopped sending data in April 2012, but has covered Sweden approximately 4-5 days per week during 10 years, which have generated a unique data set for environmental monitoring and time series analysis. The actual number of images was limited by clouds and in practice, approximately 20-30 useful images per summer season (April-September) and region was collected. One example of the MERIS coverage is given in Figure 1. For the analyses described in this report, we have processed and analyse all data from April-September, 2007-2011.

In mid-2015 a new satellite, called Sentinel-3 (A), will be launched by ESA as one of the satellites in the Copernicus program. This is the first of a series of satellites that have instruments to continue the mission after ENVISAT – MERIS. ENVISAT was an experimental satellite and the Sentinels-3 is one of the new series of operational satellites. The new “MERIS” is called OLCI (Ocean and Land Colour Instrument) and is very similar to MERIS but with improved radiometric and spectral properties. One year after the first launch Sentinel-3 (B) is planned for launch. With two satellites in orbit, there will be a daily coverage of MERIS like satellite data over Sweden. Before the estimated lifetime of the initial two satellites has expired, Sentinel-3 (C and D) will be launched, to assure continuity in the data.

Before the launch of Sentienl-3, Sentinel-2 will be launched. Sentinel-2 has a much better spatial resolution (10-20 meter), but less spectral information compared to Sentinel-3. However, compared to earlier Sentinel-2 like sensors, the improvement is obvious and it is quite likely that also this sensor could be used for monitoring of lakes and the coastal zone.

6 Field data

6.1 National monitoring data

A number of the investigated lakes are included in the national monitoring program. Most of these lakes are visited annually in August and samples/observations of Secchi depth, “Color”, ABSf (Absorbance filtered sample), Turbidity/Suspended matter and chlorophyll a are made. Not all parameters are measured for each lake. A few is sampled more than once per year. Most of the lakes are not sampled on a regular basis.

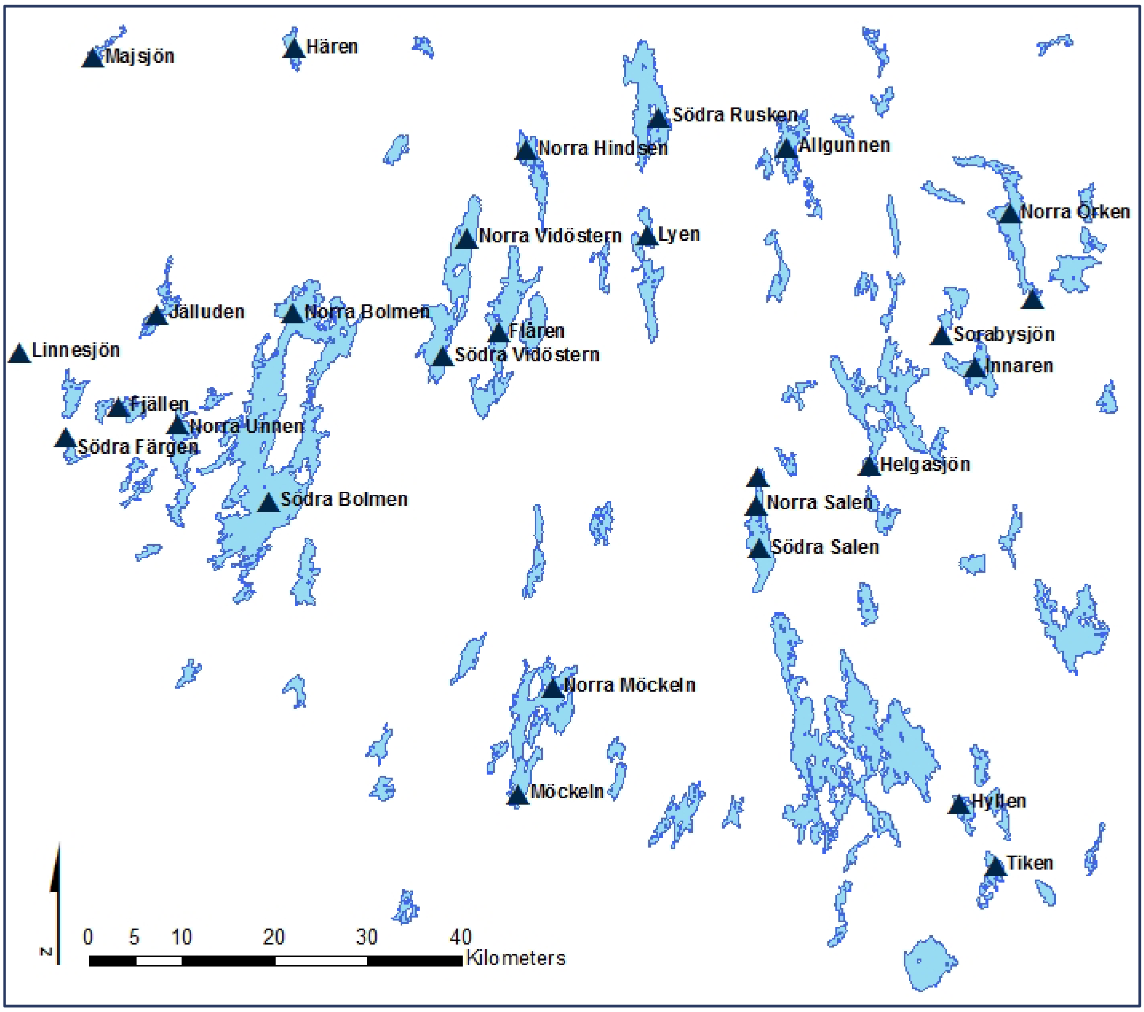


Figure 4. Control stations.

Based on available maps and aerial photos, an assessment regarding the suitability of the location of the station with respect to, primarily, the resolution of the satellite data was made. The judgement was based on if the 1*1 square kilometres centred over the station was close to/over land, in shallow areas or contained islets and rock that most likely would affect the satellite measurement. It is common to use an average of the pixel representing the control station and it closest eight neighbours. Column "Suitability for satellite analysis" below indicates, in green, if all 9 pixels around the station can be used in the analysis or, in orange, if a subset of the 9 pixels could be made and used with caution and/or, in red, if the location of the station is inappropriate for our purposes.

Table 2. Control and reference stations for the area of interest.

Station	X	Y	Suitability for satellite analysis
Allgunnen_658	6343600	1427500	
Bolmen_norr_530	6326150	1374400	
Bolmen_söder_510	6305500	1370500	
Eckern_46	6389500	1400700	Possibly a few pixels
Fjällen_602	6316380	1355270	
Flaten_560	6360100	1386050	Narrow

Flåren_630	6323900	1396250	
Helgasjön_Arabyviken_178	6309000	1436000	Islets and island in the vicinity
Hindsen_norr_740	6343700	1399500	Island affecting W pixels
Hyllen_51	6272280	1445350	Islands affecting wester pixels
Hären_1105	6355000	1374650	40% land
Innaren_305	6319500	1447500	Island in SE
Jällunden_603	6326300	1359500	Small rock mid-N
Lyen_638	6334200	1412400	
Majsjön_norr_406	6354250	1352900	Rocks n mid-S?
Möckeln_109	6285350	1401700	Islands around
Rusken_norr_548	6353150	1412700	Rock in SE
Rusken_söder_644	6347000	1413850	
Salen_norr_150	6304900	1423800	Land in W, island in middle
Salen_norrut_148	6308000	1424000	Land in NW
Salen_söder_152	6300200	1424100	
Södra_Färgen_601	6313090	1349510	
Sörabysjön_125	6323000	1444000	Ok, but very close to land
Tiken_4	6265500	1449150	Ok, but very close to land/island
Unnen_norra_delen_522	6314300	1361600	Shallow areas on NW and SE.
Vidöstern_norr_30	6334000	1392600	
Vidöstern_söder_26	6320000	1389500	
Åsnen_Julöfjorden_157	6281780	1428340	
Åsnen_Kalvsviksfjorden_156	6281700	1434200	
Örken_norr_111	6336100	1451500	
Örken_söder_113	6326800	1453800	

After masking (Ch. 7.5) of invalid pixels, the remaining lake pixels corresponding to an average of a maximum of nine pixels centred on the control station have been extracted from all available images between April-September, 2007-2011. The data has, together with monitoring data from the above described control stations, been used in the analysis as described in chapter 8.2-8.3 below. The analysis is focused on chlorophyll and colour and properties of these parameters are presented as a 10-year average, for the "green" stations in Figure 5 below. For some of these stations the variability is very large over the years and it is clear that the timing of the field sample is crucial. For example, the resulting concentrations for Lake Lyen ranges between 3,8-48 ug/l and Rusken söder ranges between 7,1-73 ug/l in August. However, the extreme value of 73 ug/l (Aug 2003) was removed before the average value displayed below was calculated, in order to make it a bit more representative for the rest of the available field data. The average value for Salen södra is only based on three field samples.

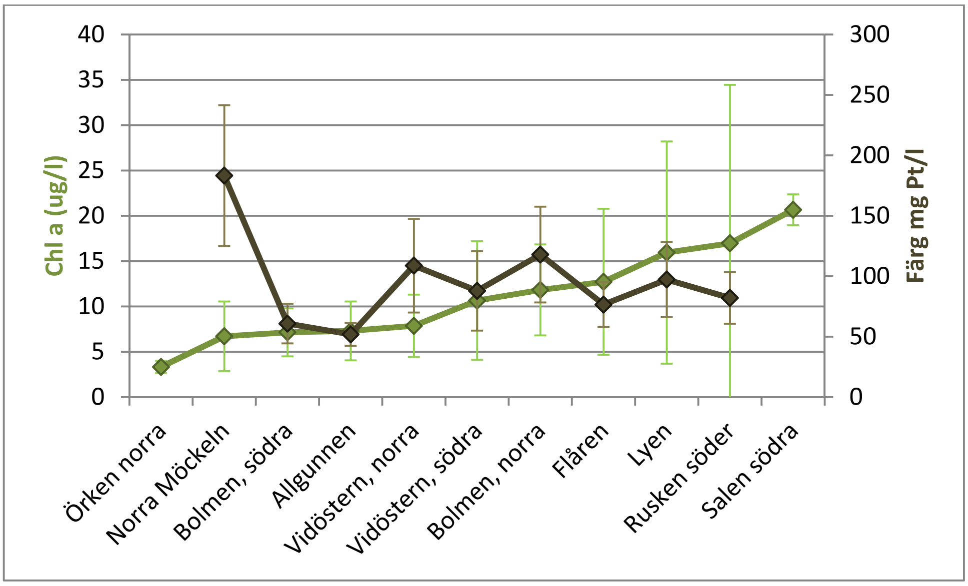


Figure 5. Average concentrations and standard deviation for each "green" station and all available data between 2000-2012. Chl a is shown in light green and Color in dark green.

The data (standard deviation) in Figure 5 indicates that time series with a better temporal resolution should make an important contribution to the understanding of the lake properties and dynamics.

6.2 Sydvatten data

Sydvatten have analytical data on the incoming water to Ringsjöverket, but between April 2009 and March 2011 the Bolmen tunnel was closed for repair, i.e. the water was not taken from Bolmen but from Ringsjön instead. Sydvatten samples the incoming water on a regular basis and the measured color levels from 2011 can be seen in Table 3. During 2013 the data collected between April-September 2011 was analysed together with the satellite based estimations of CDOM to see if similar trends could be found in the data. Data from one of the investigated stations (Södra Bolmen) are included in the regular monitoring program and data from the other stations were extracted for these purposes. During 2013 the analysis was based on data from larger areas as can be seen in Figure 6 (right). The water is transported through a tunnel from Bolmen to Ringsjöverket and it takes approximately one week for the water to pass through the tunnel.

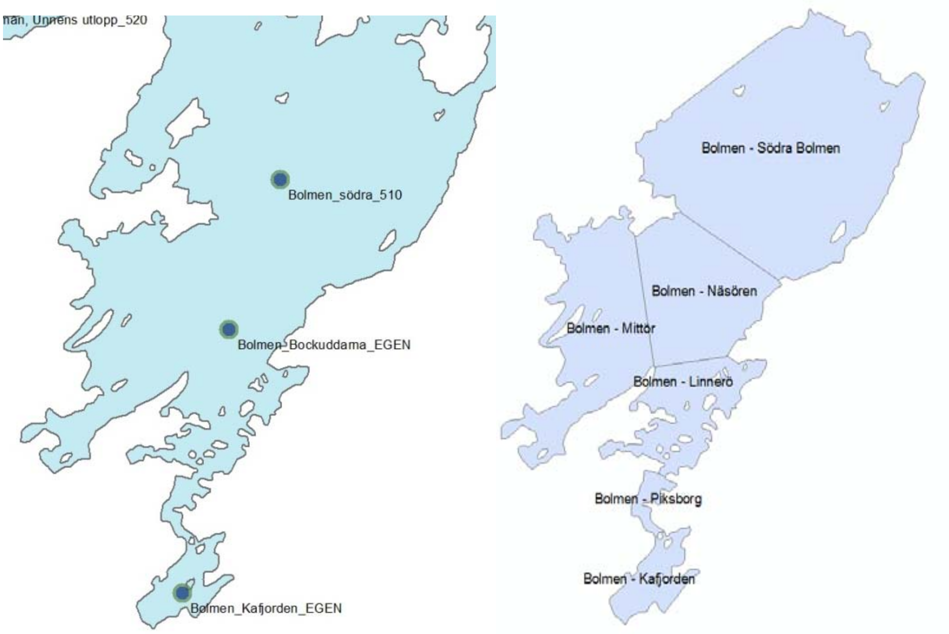


Figure 6. The left map shows the location of the three stations in southern Bolmen that were used in the analysis during 2012. During 2013, the focus was shifted to investigation of data representing larger areas as can be seen in the right map.

The parameters analysed by Sydvatten are the following: temperature, total coliforms, *E.coli* , colour, turbidity, pH, conductivity, alkalinity, ammonium, nitrite, nitrate, fluoride, chloride, sulphate, phosphate-phosphorus, chemical oxygen demand (COD), total organic carbon (TOC), iron, manganese, calcium, magnesium, total hardness, potassium and aluminium. We have focused on the measurements of “Colour” in our analysis. The data can be seen in Table 3. The data measured by Sydvatten has been analysed with satellite based estimates of CDOM/color and the results are described in Chapter 8.5.

Table 3. Colour and turbidity as measured by Sydvatten during 2011.

Datum	Color (mg/l Pt)	Turb (FNU)
2011-04-06	70	1,6
2011-04-13	70	1,4
2011-04-27	70	1,4
2011-05-04	70	1,2
2011-05-11	65	1
2011-05-18	70	1,1
2011-05-25	70	1
2011-05-31	70	1
2011-06-08	70	1,6
2011-06-15	80	1,3
2011-06-29	80	1,2
2011-07-06	80	1,1
2011-07-13	80	0,9
2011-07-20	70	0,8
2011-08-03	80	0,9
2011-08-10	70	0,8
2011-08-17	70	1,1
2011-08-24	70	1,5
2011-08-31	70	0,9
2011-09-07	70	0,9
2011-09-14	70	0,8
2011-09-21	70	1
2011-09-28	70	0,9
2011-10-05	65	0,8
2011-10-12	70	0,7
2011-10-19	80	1,1
2011-10-26	70	

7 Image pre-processing

The source products are MERIS-FR Level 1b data, which corresponds to Top-Of-Atmosphere radiances. L1b data needs to be transferred to water leaving radiance (L2) by accounting for the atmospheric effects and the apparent optical properties of the light field. Besides the atmospheric correction the L1b to L2 processing includes geo-correction, land-water masking and adjacency effect correction. A general overview of the pre-processing sequence is given in Figure 7 and chapters 7.1-7.5 below.

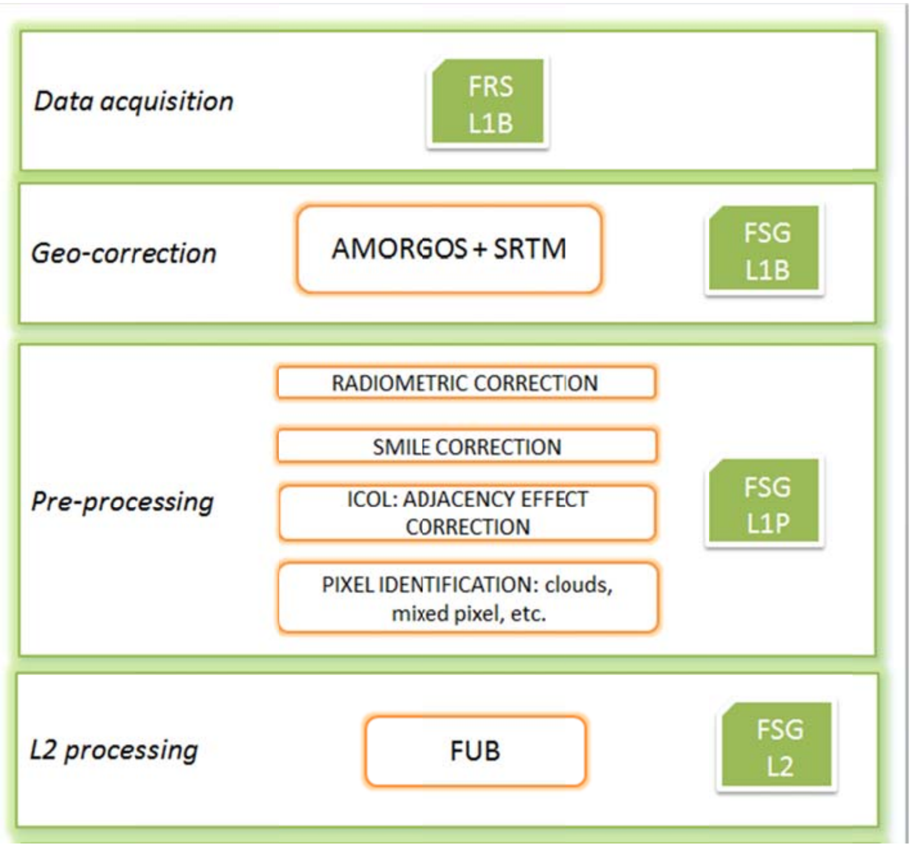


Figure 7. Flow diagram with the processing of the product chain depicting the most important components, algorithms, input and output data.

7.1 Geolocation

Small islands and complex shorelines of coasts and lakes, as well as often patchy structures in the water, cause a high spatial variability. A high accuracy of the geolocation in the order of sub-pixels is necessary for obtaining good spatial and temporal composites. In addition, this high accuracy is a keystone when looking for matchups of in situ data for validation purposes [5].

The data used in this project has been geolocated with AMORGOS [6]. AMORGOS (Accurate MERIS Ortho Rectified Geo-location Operational Software), has been developed by ACRI-ST by funding from ESA (European Space Agency). AMORGOS includes a precise orbit determination, instrument pointing and performs an ortho-rectification. We have earlier performed an evaluation of AMORGOS processed data compared to manually geocorrected data, made by definition of Ground Control Points in otho photo images available in digital format from the Swedish National Land Survey. For most evaluation points, AMORGOS generated slightly better accuracy, and a much better overall quality of the correction was achieved.

7.2 Radiometric/SMILE correction

Data needs to be radiometrically calibrated, which initially means that raw data is converted to Top-Of-the-Atmosphere (TOA) calibrated radiances measured in mWm-2sr-1nm-1. In addition, throughout the lifetime of a sensor the detectors are ageing, which needs to be accounted for by applying an updated radiometric model and coefficients.

Additionally, MERIS is composed of 5 cameras and measures the reflected sunlight using CCD technique. Each camera is equipped with spectrometer and a two-dimensional CCD array. The spectral measurements of each pixel along an image line are made by its own set of CCD sensors. This causes small variations of the spectral wavelength of each pixel along the image that constitute the so-called "smile effect". Even though this variation is small compared to the spectral bandwidth of a band, which is typically 10nm, and can hardly be seen in an image, it can cause disturbances in processing algorithms, which require very precise measurements, for example the retrieval of chlorophyll. These disturbances can result in a visual artefact, "camera borders", or in a reduced accuracy of the Level 2 products. The radiometric correction aims at eliminating/reducing these effects.

7.3 Adjacency Effect Correction

The ICOL (Improve Contrast between Ocean and Land) algorithm addresses the so-called adjacency effect and has been applied to the MERIS data after calibration and before atmospheric correction. Shortly, the adjacency effect means that brighter land in close proximity to darker water gives an apparent increase of reflectance from water due to scattering in the atmosphere. The effect can be seen up to approximately 20 km from land.

7.4 L2 processing

L2 processing consists of atmospheric correction and retrieval of concentrations of the water constituents. During the last couple of years, several independent L2 processors have been developed besides the standard MERIS/ESA and results have been improved. Further development is an ongoing research topic. Today these non-standard processors are widely used and acknowledged by ESA. The most well-known of these independent processors are the Coastal Case 2 Processor (C2R), Boreal Lakes Processor (BOR) and Eutrophic Lakes Processor (EUL), all three from GKSS, Germany, together with the FUB Water Processor from Freie Univeristaet Berlin. The first three of these (from GKSS) have identical atmospheric correction algorithms. However, they all have different water quality algorithms, each adapted to a certain water types. We have earlier evaluated these L2 processors for the Baltic Sea, the Gulf of Bothnia and for Lakes Vänern, Vättern and Mälaren [1,2]. FUB generated the best results for all areas and has been further evaluated in this project. The two parts of L2 processing, i.e. atmospheric correction and retrieval of water quality constituents are discussed a bit further in the following two chapters.

7.4.1 Atmospheric correction

Satellites measure water leaving radiance, but also direct and diffuse irradiance from the sun and sky, and radiance reflected from the surface and the environment. The reflected light is scattered and absorbed by the particles and gases in the atmosphere, which makes the atmospheric correction a key procedure in the process of water colour imagery data. In fact, the main part of the measured signal, over water bodies, in the visible spectrum is due to atmospheric effects. Hence, remote sensing of dark water targets is a challenging task. The surface reflectance is seldom above 1% and the atmospheric contribution to the signal can be several times greater than the actual surface signal. It is therefore critical to perform an, for the area and time, appropriate atmospheric correction. Inland waters make specific demands on atmospheric correction methods. The requirements correspond to terrestrial methods as far as ground elevation and aerosol properties are concerned, but require consideration of air-water interface effects as applied for oceanic targets.

The L1b data derived after ICOL processing has been atmospherically corrected using the FUB processor, producing water leaving reflectances in eight bands. The retrieval is based on an artificial neural network which was trained on the basis of the results of extensive radiative transfer simulations by taking varying atmospheric and oceanic conditions into account [8-9].

7.4.2 Water quality concentration maps

Based on our earlier developments in the coastal zone and open Baltic Sea, it has been shown that both the FUB-chlorophyll and FUB-TSM products are in correspondence with existing field data, also in absolute terms. The CDOM product is a threefold underestimating the true concentration, but this offset has been stable during all evaluations and could therefore be accounted for. For the lakes Vänern, Vättern and Mälaren, FUB has worked well on a relative level but all three products are more or less offset for all three lakes in comparison to the available field data. This is especially expected with respect to the CDOM product as these lakes exhibit concentration levels that are out of range compared to the data used for training of the network.

At this stage, and based on earlier results and conclusions, the retrieval and evaluation of water constituents for Bolmen and surrounding lakes has been based on the FUB algorithm. The L2 products derived by applying the FUB processor comprise daily data sets of chlorophyll-a concentration, total suspended matter concentration and yellow substance absorption. The resulting concentrations of chlorophyll-a concentration and CDOM absorption has been analysed in detail and the results are presented in chapters 8 below. There was not enough time during 2013 to also include a suspended matter, and therefore only the initial results from 2012 are reported in chapter 8.2 below. Recently, algorithms for Secchi depth estimation based on MERIS data have been evaluated with good results in Lake Vänern, Vättern and Mälaren. It would be very interesting to validate if the same algorithm could generate good results in the area of investigation.

7.5 Masking

A good separation between land and water pixels, as well as pixels partly disturbed by land portions (mixed pixels), is needed. This means that all pixels that do not correspond to 300*300 meters optically deep water areas needs to be removed before the statistical analysis of the data. Areas affected by clouds and cloud shadow also need to be masked out. An example of the investigated area after masking of invalid lake pixels can be seen in Figure 8 below. The image was registered on the 3rd June 2011, which was a clear day.

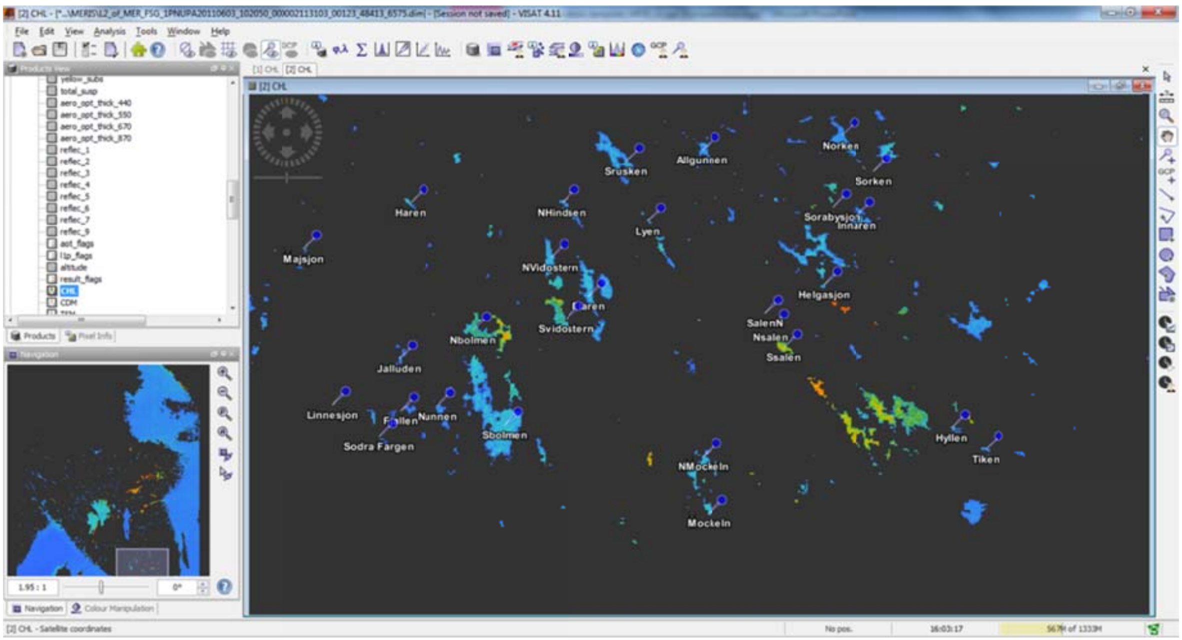


Figure 8. The area of investigation after masking of clouds, cloud shadow, land and mixed land/water pixels.

8 Analysis & Results

Bolmen is one of Sweden's larger lakes but small compared to Lakes Vänern, Vättern and Mälaren, which have been in focus in earlier projects. 300 m resolution should however be enough for Bolmen and several of the smaller lakes in the investigated area, and it should be possible to extract useful data for further analysis and for monitoring purposes. The extracted data has been analysed for trends, differences and changes in the spatial domain and with respect to concentration levels. The satellite based concentration levels has also been compared to field based measurements for evaluation and for investigating the possibility to derive accurate absolute chlorophyll and humic substances.

8.1 Lake size and shape

One of the objectives was to investigate if full resolution MERIS data could be used to measure and monitor the water quality status in smaller lakes. There are many aspects to consider in order to answer this question, i.e. performance of atmospheric correction and algorithms for estimation of water constituent etc., but in this chapter we will focus on size and shape of the lake.

In the framework of the Water Framework Directive, lakes larger than 50 ha (0,5 km^2) have to be monitored for assessing their ecological status. Referring to literature, lakes should have a minimum size of 150 ha (5*5 pixels) to retrieve a water signal with good quality from 300 m MERIS Full Resolution or future OLCI pixels. However, this assumes that the shape of the lake is more or less round so that pixels in the centre of the lake are less influenced by the surrounding land. In nature, this is mainly not the case which means that other properties of the lake need to be considered [5].

Besides the size of the pixel, one should also keep in mind that all pixel based approaches are dependent on the pixel positions within the lake. Figure 9 below shows the influence on the location and number of valid pixels [5]. This means that from one image to another the lake will most likely be represented by pixels of a slightly shifted locational distribution. Figures 9-10 and Table 4 has been produced by K. Stelzer (Brockmann Consult et al. [5]).

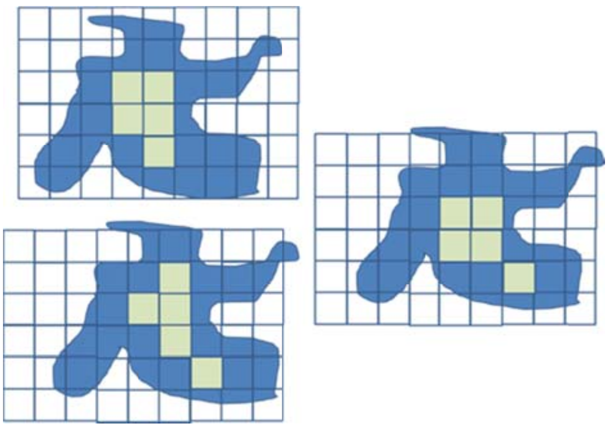


Figure 9. Dependency of valid pixels on the pixel size and position of pixels in relation to the lake [5].

One way to judge if a specific lake is possible to monitor based on MERIS data is to look at the shape of the lake. The shape determines the extent of the water area. The larger the ratio between the boundary and the area the larger/more compact is the water area. The numbers for area and boundary (coastline) presented in Table 7 are retrieved from MERIS full resolution images.

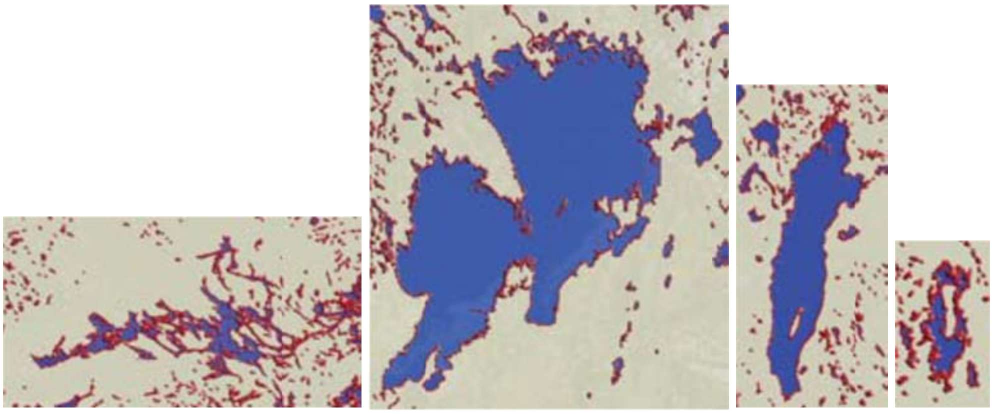


Figure 10 MERIS based identification of surface and boundary pixels as an initial estimation of the morphological complexity of the lake [6].

Table 4. Area and length of boundary and the respective quotient indicating if a lake is suitable for EO application [6].

Lake	Mälaren	Vänern	Vättern	Bolmen
Area (ha)	139 401	637 380	221 193	20331
Boundary (km)	1 090	896	264	203
Index boundary/area	0.78	0.14	0.12	0.56

More lakes need to be investigated in order to define at what ratio the lake most likely is “out of shape” with respect to MERIS/OLCI. This simple approach has some drawbacks and many examples can be found where the same index lead to different shapes of lakes. More sophisticated measures are currently investigated.

In our study area, data has been extracted from 83 lakes. For 34 of these lakes the number of pixels representing a lake has been translated to square kilometres, averaged over all images and then compared to official numbers of lake area (Figure 9).

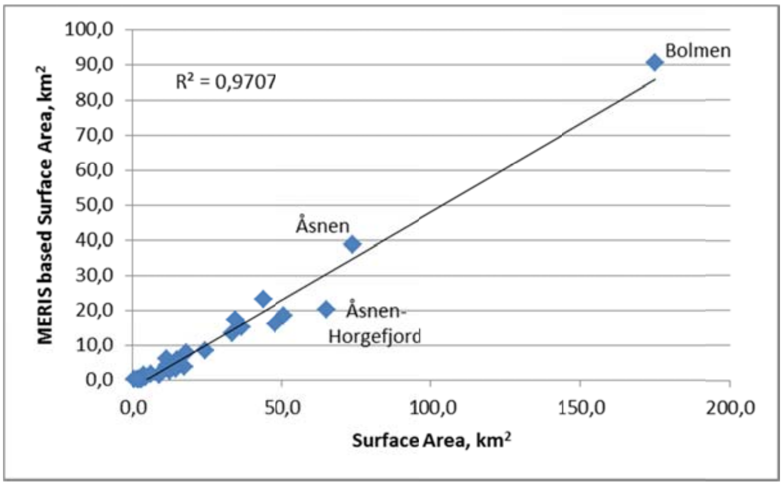


Figure 11. Surface area estimated from MERIS in comparison with official numbers (VISS).

As can be seen in Figure 9 the correspondence is very good, but the image based estimations are much lower than the official number. One reason for this is that we have applied a relatively restrictive filtering operation before the analysis in order to remove erroneous pixels from the statistics, i.e. mixed pixels including both water and land/islets/shallow areas etc. The smallest lakes investigated are Eckern (0,18 km^2) and Räppegölen (0,36 km^2) and the largest lakes are Bolmen (174 km^2) and Åsnen (73 km^2). Based on that data, and the applied level of filtering, lakes below 1,62 km^2 never resulted in any valid pixels for statistical analysis and Havbältesfjorden (2,97 km^2) resulted in one pixel in half of the images. As a comparison, the more round Norresjö (2,25 km^2) resulted in 1-5 pixels in half of the images.

During 2013, 50 more lakes larger than 2 km^2 and much more data (dates and years) where included in the analysis. Based on this data set the number of observations per lake were analysed with respect to the size of the lake (Figure 12). Of all 20 lakes between 2-3 km^2 it is only Sandsjön that never corresponds to valid pixels during these five years. In figure 12 Bolmen (173 km^2) has been excluded in order to increase the readability for the smaller lakes. 374 observations where available for Bolmen. Hjärtasjön and Lången are measured by the satellite one and two times respectively, but all other lakes have at least one observation per year (April-September). See also table 5 and Annex 1. One "observation" means that at least five valid pixels could be extracted from the lake on a certain date.

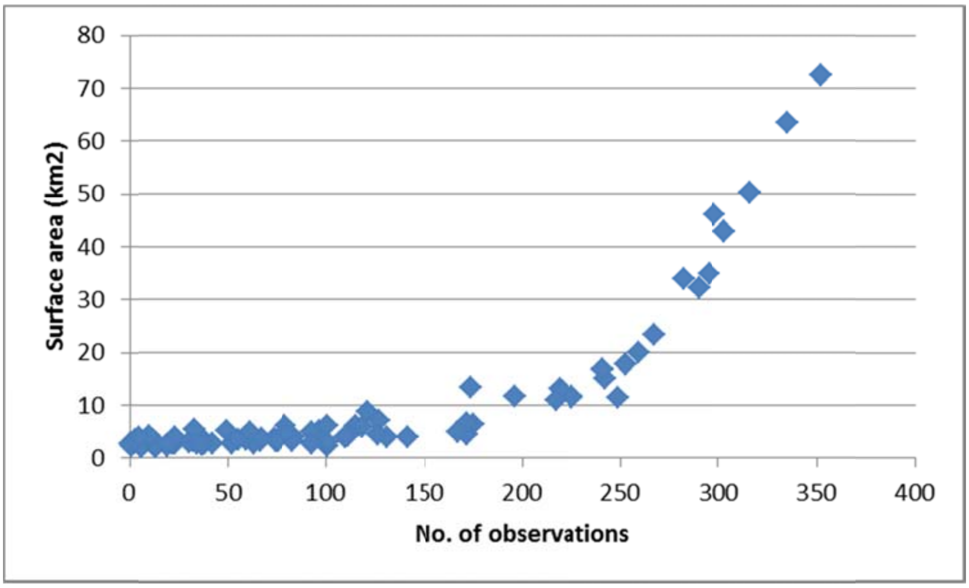


Figure 12. Number of observations per lake plotted against lake size.

Table 5. Number of observations per lake and year for lakes between 2-3 km^2

EU_CD	LAKE	2007	2008	2009	2010	2011	Total
SE626473-143260	**Havbältesfjorden**	1	2	1	1	1	**6**
SE635461-145821	**Hjärtasjön**	0	0	0	1	0	**1**
SE627976-139651	**Kalvasjön**	3	5	1	3	2	**14**
SE634160-144871	**Klockesjön**	10	18	13	11	11	**63**
SE635472-138728	**Kävsjön**	4	0	1	6	2	**13**
SE633976-142928	**Lången**	0	0	0	1	1	**2**
SE635334-135239	**Majsjön**	7	10	4	6	3	**30**
SE630835-135633	**Nejsjön**	3	7	1	3	9	**23**
SE627729-140872	**Norra Virestadsjön**	10	4	11	8	9	**42**

SE630480-143556	**Norresjö**	19	24	25	16	17	**101**
SE630069-140009	**Ryssbysjön**	8	8	8	8	6	**38**
SE626406-145882	**Sandsjön**	0	0	0	0	0	**0**
SE630806-142789	**Spånen**	5	11	9	7	5	**37**
SE631769-136737	**Stora Slätten**	6	5	2	3	6	**22**
SE634076-142599	**Stora Värmen**	7	8	7	7	5	**34**
SE631309-134951	**Södra Färgen**	13	9	9	8	13	**52**
SE632490-144339	**Sörabysjön**	18	24	16	19	16	**93**
SE630037-135928	**Torserydssjön**	5	6	3	3	2	**19**
SE631509-135258	**Yasjön**	10	10	5	6	6	**37**
SE634665-143220	**Övingen**	3	3	9	2	2	**19**

It is clear that both size and shape needs to be considered in order to judge if a specific lake is possible to monitor based on satellite data with 300 meters resolution or not. It is also clear that it will not be possible to monitor the smallest lakes as required by the Water Framework Directive. However, keeping the shape factor in mind, it should be possible to provide some data for lakes with a surface area of 2-3 km^2 or more. See Annex 1 for a complete list of observations per lake.

8.2 Control station analysis – Suspended matter

Earlier evaluations of the FUB-TSM algorithm have shown very good agreement between image and field data for Lakes Vänern, Vättern and Mälaren, as well as the Baltic Sea. Recently, FUB-TSM data derived from images collected in the Gulf of Bothnia have been evaluated and based on that analysis a slight underestimation could be found. It should be pointed out however, that the actual concentrations were very low and that significant errors and/or discrepancies could occur also based on the laboratory measurements. Looking at the data in Figure 13, we seem to experience the same result as in the Gulf of Bothnia, i.e. an underestimation of the true concentrations. One reason for this might be that the higher CDOM levels are affecting more or less the whole visible spectra, and not just the shorter wavelengths, resulting in less reflected light at longer wavelengths, which is interpreted as less suspended matter by the algorithm.

In figure 14 lake averages has been calculated based the data from 2010-2011, which were analyses during the first year of the project. Despite the low concentrations it is positive to see that the general trends are keep between the two years, which indicates that the data also could be useful for monitoring of TSM and that it might be possible to establish a calibration relationships for calculation of absolute concentration levels.

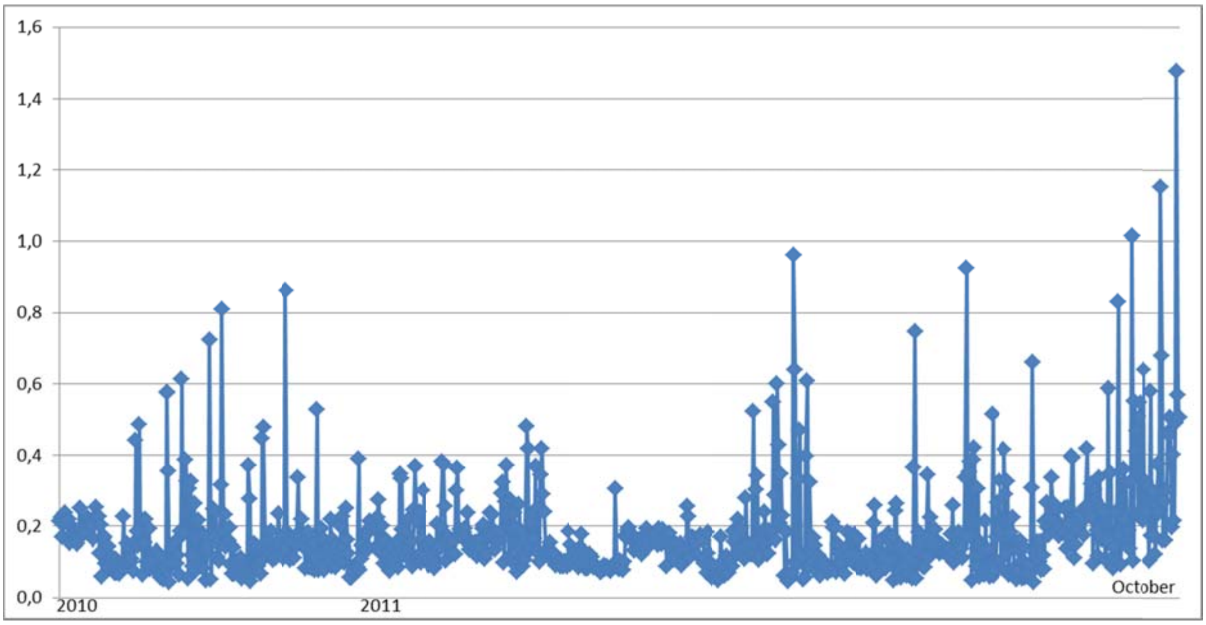


Figure 13. TSM data (mg/l) for 38 control stations during 2010 and 2011.

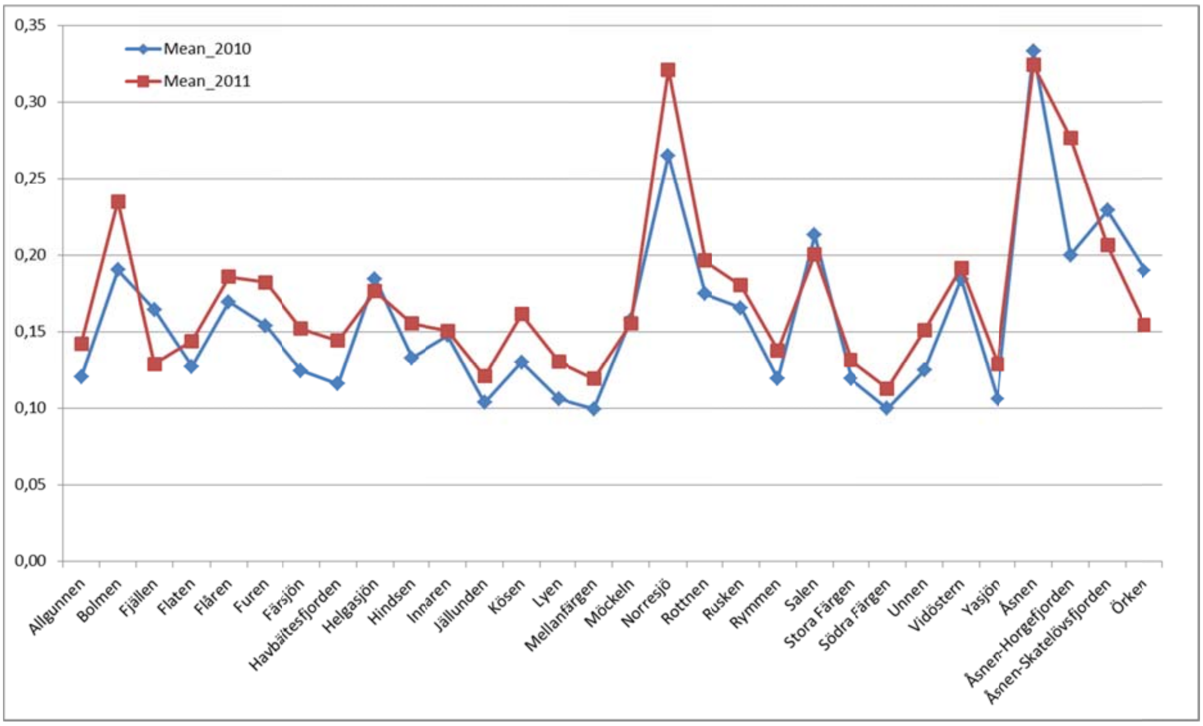


Figure 14. Annual TSM means (mg/l) based on all available pixels in each lake.

8.3 Control station analysis - Chlorophyll & CDOM

The location and properties of existing control stations is presented in chapter 6.1 above. After masking of invalid pixels, the remaining lake pixels corresponding to an average of a maximum of nine pixels centred on the control station have been extracted for each date, from all available images, between April-September, 2007-2011. This station average is referred to as "one observation" and has, together with monitoring data from the control stations, been used in the match up and time series analysis as described in chapter 8.3.1-8.3.2 below.

8.3.1 Match ups – Monitoring data

Chlorophyll a

The Chl a data set was then searched for image and field data collected on the same date. Taking all available stations into account, the field sampling date matched the image date on 22 occasions, during these five years. Two match up points corresponded to "red" stations (see 6.1 above), nine to "orange" stations and 11 to "green" stations. When data is averaged over time, as in the status calculation described in chapter 8.4.3 below, single images of poor (high cloud cover) quality is usually of less significance to the end result, but for this match up analysis it is crucial. Each of the 22 stations/dates was therefore visually checked. Several stations were visited in field on the same date, which for one or two dates corresponded to a relatively cloudy days. For those scenes, a few pixels were identified as valid, but the general quality of the data was poor and these stations were there for not considered reliable. After removing "red" stations and significantly cloudy dates, 5 (of 11) green stations and 3 (of 9) orange stations remained. These match ups has been plotted in Figure 15 below.

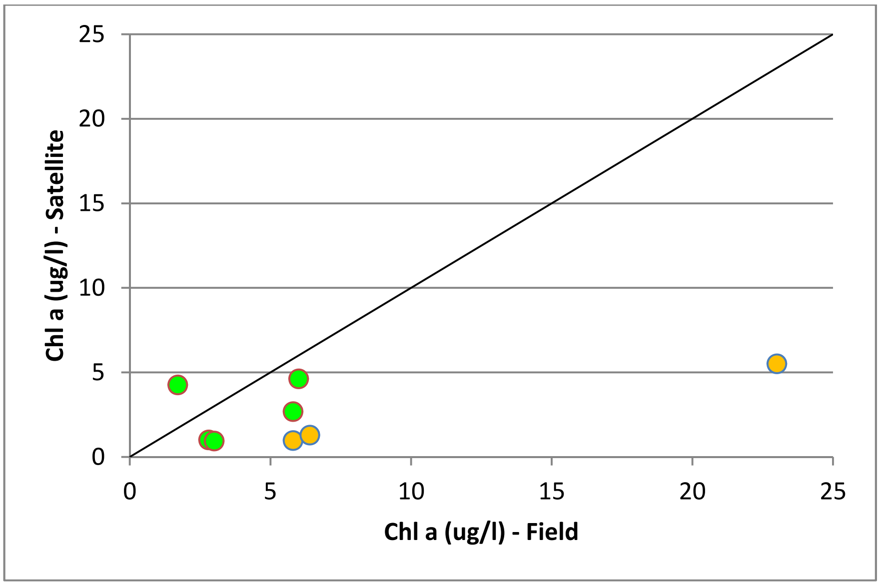


Figure 15. Chlorophyll - Same day match ups between satellite and field data.

The variation in chlorophyll concentrations is low and the less reliable "orange" stations are not in line with the "green" stations. Most of the observations are under the 1:1-line, which indicates that the concentrations estimated from satellite are lower compared with field data. However, the number of data points is not enough to make any final conclusions and to establish a relation that could be used for absolute calibration of the satellite observations.

To add more data to the analysis two new data sets were created based on available observations ±7 days and ±15 days, centred on the date of the field sample. An average of the observations from all available images within these time spans were calculated and analysed together with field data. Both data sets have been plotted in Figure 16 below. Only averages corresponding to "green" stations and to at least three observations during the specified time period is included. In addition, four outliers (Red dots in Figure 16) where removed in order to capture the general trend as explained by the rest of the data set. The outliers have been further analysed and three of them have single observations on the same level as the field sample close in time, but higher concentrations, usually, after the sample was taken, which affects the temporal average. Two of these outliers correspond to data from station Södra Vidöstern (2007 and 2008), which is exemplified in chapter 8.3.2 regarding time series below. For the last outlier the satellite observations indicate higher, and very variable, concentrations over the investigated time periods (late August- early September), compared to the field sample. This outlier corresponds to observations from station Norra Bolmen in August 2008 and is also exemplified in chapter 8.3.2 regarding time series below.

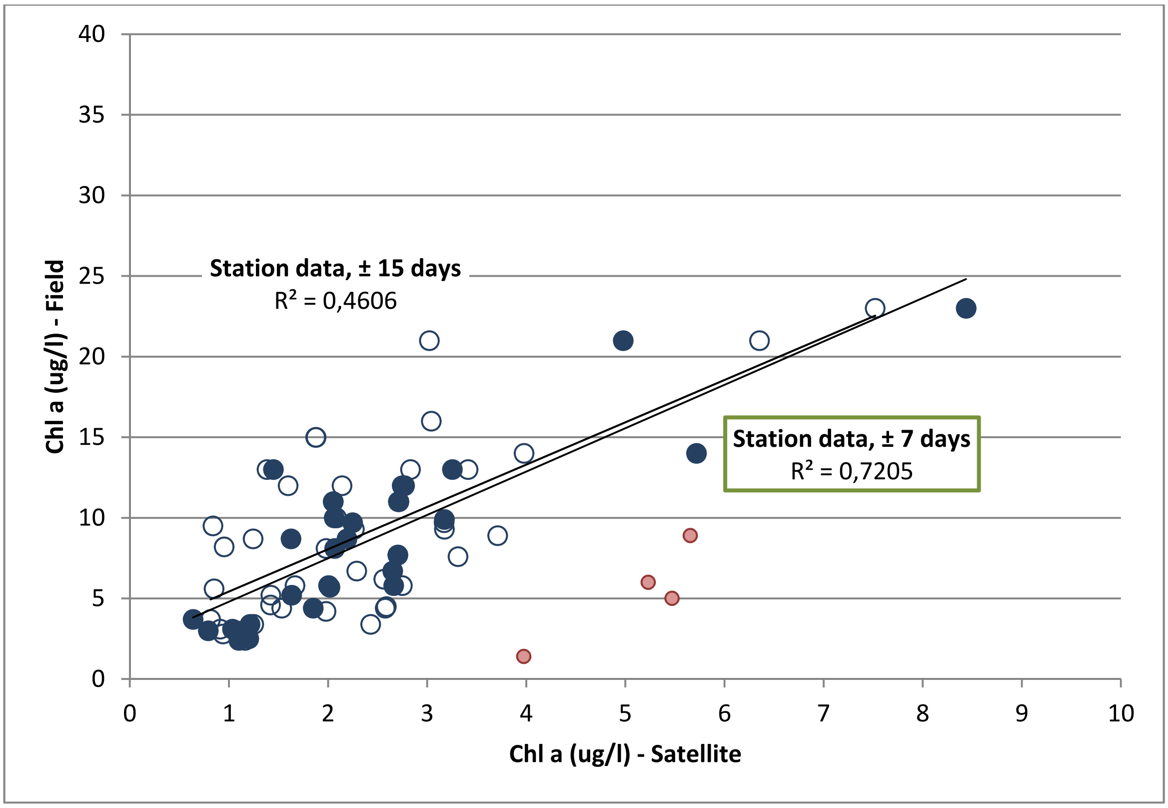


Figure 16. Chlorophyll - ±7 (filled circles) and ±15 days match ups between satellite and field data.

Both datasets shows a similar trend compared to the field observations, whit slightly higher variability based on the satellite observations averaged over a longer time period. This is what could be expected with respect to the usually significantly variable levels of chlorophyll concentrations in August-September. As can be seen in figure 16, the applied algorithm is underestimating the chlorophyll concentrations compared to field data, but captures the relative trends. In order to retrieve data also on absolute concentration levels, the relationship established by the observations from ±7 days of the field sampling data has been used in the rest of the analysis and results, to calibrate the observations.

CDOM - Colour Dissolved Organic Matter

The CDOM data set was then searched for image and field data collected on the same date. Taking all available stations into account, the field sampling date matched the image date on 16 occasions, during these five years. Nine match up points corresponded to “orange” stations and seven to “green” stations. When data is averaged over time, as in the status calculation described in chapter 8.4.3 below, single images of poor (high cloud cover) quality is usually of less significance to the end result, but for this match up analysis it is crucial. Each of the 16 stations/dates was therefore visually checked. Several stations were visited in field on the same date, which for one or two dates corresponded to a relatively cloudy days. For those scenes, a few pixels were identified as valid, but the general quality of the data was poor and these stations were there for not considered reliable. After removing “red” stations and significantly cloudy dates, four (of seven) green stations and two (of nine) orange stations remained. These match ups has been plotted in Figure 17 below.

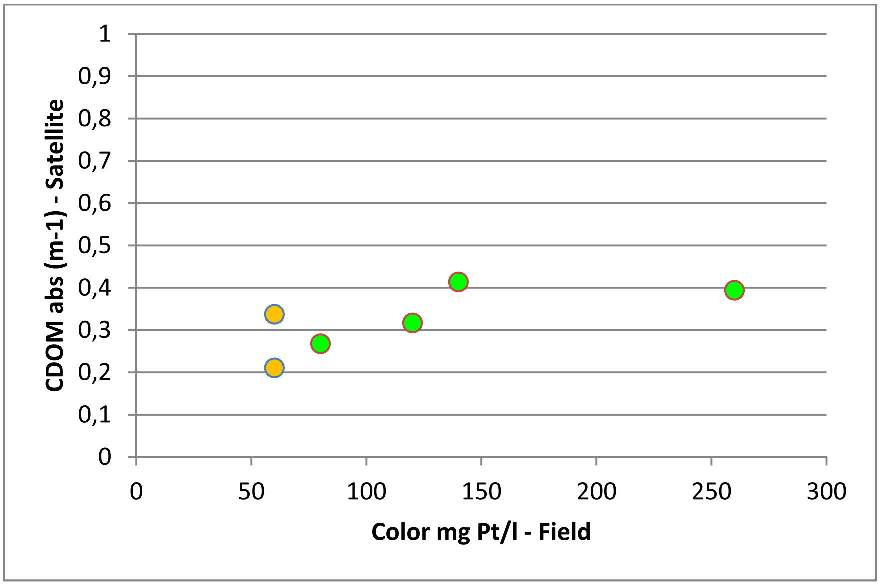


Figure 17. Correlation between Color (Field) and CDOM absorption (MERIS) bas on available match ups.

In this case, CDOM absorption (Colored Dissolved Organic Matter), which is the variable estimated by the algorithm (FUB) applied to MERIS data, has been compared to “Color”, which is a similar variable measured from field samples. 1 $a_{CDOM}(440) \approx 0.03$ ABSf(420) ≈ 15 Color. It would have been better to compare to ABSf, but these measurements were not as frequent as color. For most stations ABSf is only available during 2010-11 (and before 2005). It is therefore important to keep in mind that lower correlation coefficients not only should be attributed to poor satellite estimations, but also to limitations and inaccuracies in the field sample analysis techniques. This is of course always the case, but even more important to stress in relation to color estimates.

In our earlier evaluations of the FUB algorithm, mainly in the coastal zone, the actual CDOM levels was underestimated with approximately a factor three, but with increasing CDOM levels the underestimation seems to be larger. It is not surprising that the algorithm fails in retrieving the absolute concentrations as the FUB algorithm, which is a neural network processor, has not been trained on such high CDOM concentrations as has been observed in these lakes. However, the FUB results have earlier showed an agreement with available field data on a relative scale, in lakes Vänern, Vättern and Mälaren, and we have therefore analysed its applicability also on these humic rich waters.

The variation in field concentrations in Figure 17 above is ok and the image based concentrations are very much under estimated as expected. Four of the observations exhibit a good correlation to field data, but the number of data points is not enough to make any final conclusions and to establish a relation that could be used for absolute calibration of the satellite observations.

To add more data to the analysis two new data sets were created based on available observations ±7 days and ±15 days, centred on the date of the field sample. An average of the observations from all available images within these time spans were calculated and analysed together with field data. Both data sets have been plotted in Figure 18 below. Only averages corresponding to “green” stations and to at least three observations during the specified time period is included.

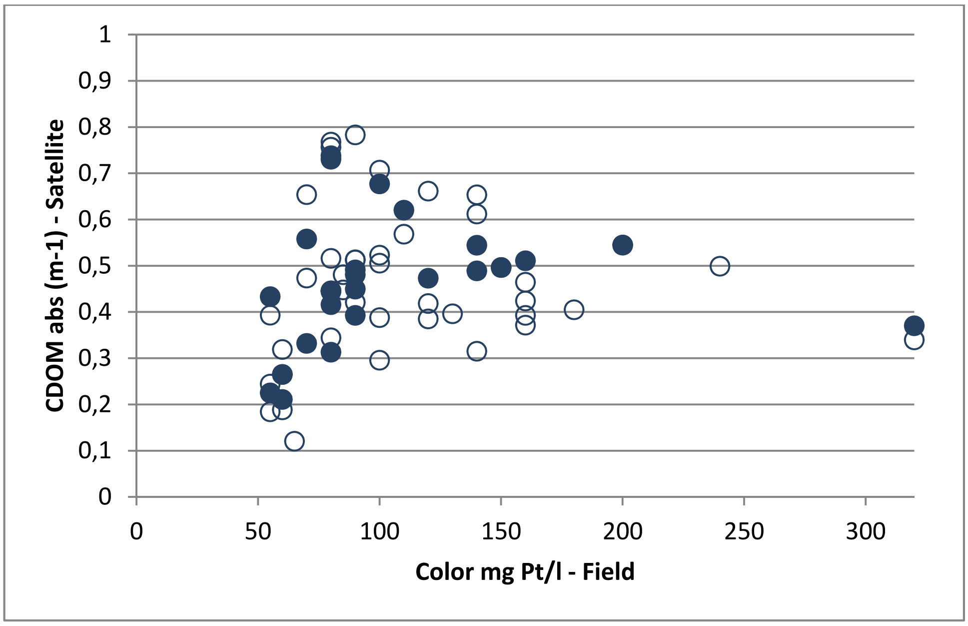


Figure 18. CDOM - ±7 (filled circles) and ±15 days match ups between satellite and field data.

No outliers have been removed in Figure 18 as it is much more difficult to see any "general trends" based on these two dataset. As for chlorophyll the satellite observations averaged over a longer time period exhibits slightly higher variability compared to field data. The data points corresponding to color > 140 is from station "Norra Möckeln" and "Södra Vidöstern". As mentioned before, the investigated algorithm is here applied to CDOM concentrations way out of its training range. It has still produced significant correlation to field data in less humic lakes, but it is also most likely that we now have gone beyond its upper limit and that the relative scale is lost somewhere between 100-150 mg Pt/l. This should be further investigated, but would require adding more data (2002-2006) to the analysis, which is not possible within the present project frame. Adding this time span would also make it possible to analyse ABSf instead, which was limited between 2007-11, but more frequent during 2002-04.

We did not consider it possible to establish a linear equation, as in the case of chlorophyll, to retrieve data also on absolute concentration levels based on these data sets. Instead, we calculated the average of all ratios between CDOM abs and color using the observations from ±7 days of the field sampling data. As before, only averages corresponding to "green" stations and to at least three observations during the specified time period were included. The resulting factor was 240, which has been used in the rest of the analysis and results, to convert the satellite observations of CDOM absorption to color and to make them more comparable to the absolute levels as defined by the field samples.

8.3.2 Time series

All observations of chlorophyll and CDOM absorption between April-September, 2007-2011 was calibrated and converted to color according to chapter 8.3.1 above and plotted in annual time series together with the available field data. Some examples based on the "green" stations are exemplified and commented below. Observations corresponding to only one pixel (i.e. no average has been calculated) has been excluded in all examples below. Observations where the standard deviation of the 2-9 valid pixels around the station is very high has been deleted on a very few occasions for chlorophyll. All observations with a standard deviation > 0.1, with reference to the initial CDOM absorption, have been excluded for CDOM. There has not been time to look at all observations and images, but it is quite likely that the average is based on very few pixels or averages including a pixel/pixels that was not successfully excluded in the masking operation, if the standard deviation of the observation is high.

Chlorophyll

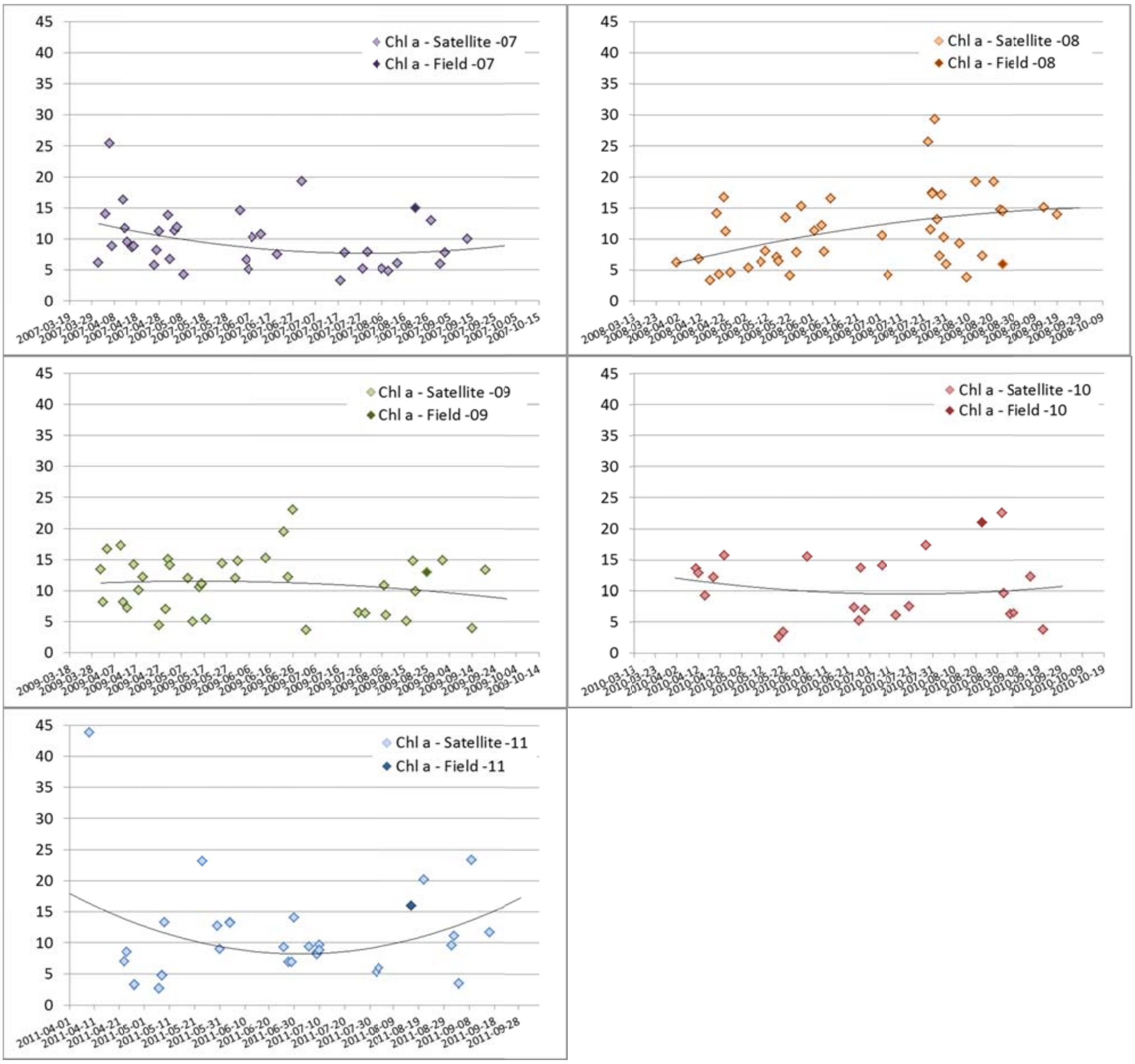


Figure 19. Annual time series for station "Norra Bolmen" between 2007-2011.

The chlorophyll concentrations at station Norra Bolmen exhibit a relatively large variation over the season. Most of the observations are between 5-15 ug/l and slightly higher than Södra Bolmen (Figure 20). For all five years the satellite based estimations are in line with field data but a certain level of variability can be seen during this time period (late August – early September). A trend line (2nd order polynomial) has been added to show the general tendency for each year.

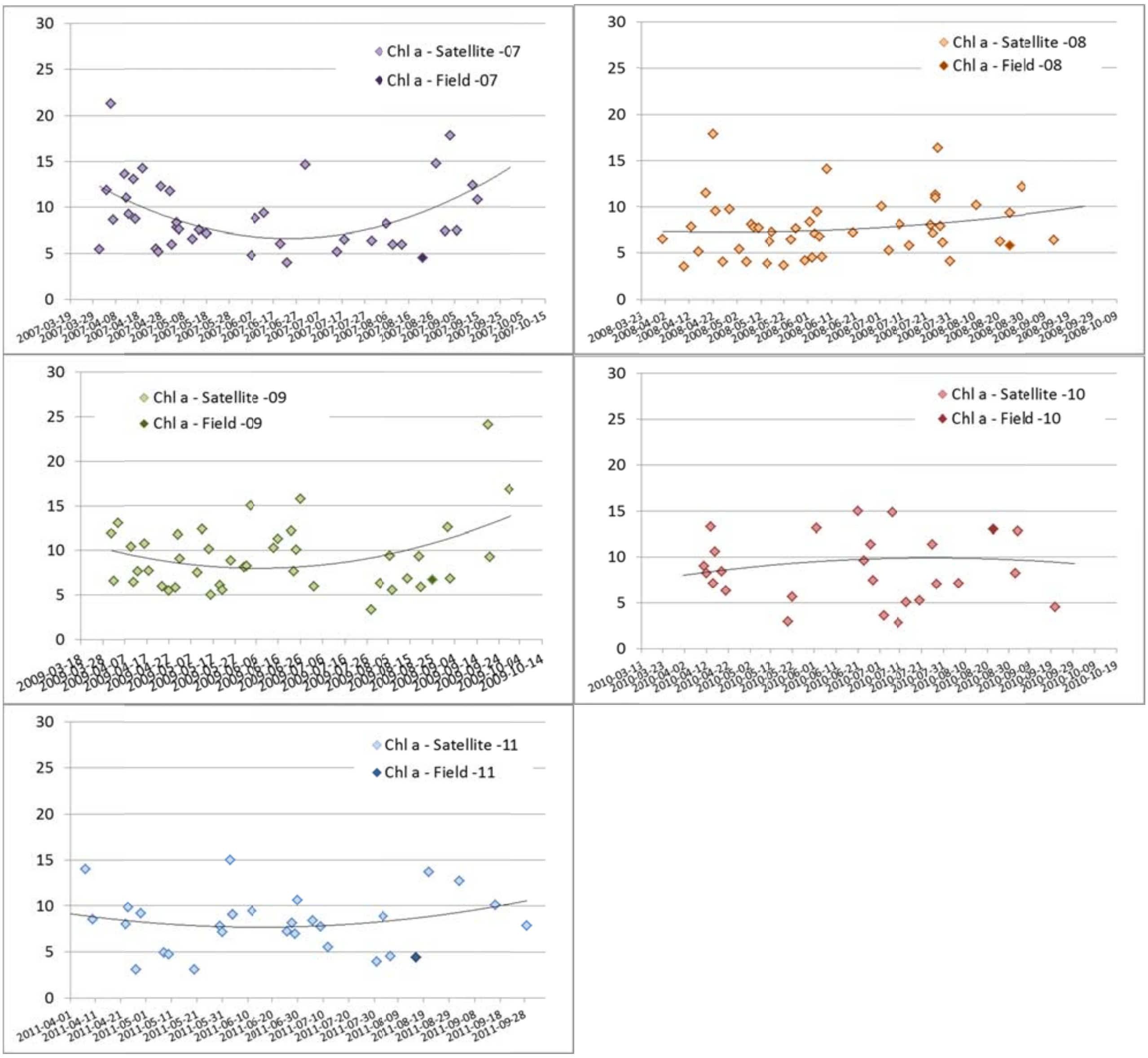


Figure 20. Annual time series for station "Södra Bolmen" between 2007-2011.

The chlorophyll concentrations at station Södra Bolmen seems to be more stable over the season compared to the northern part of the lake (Figure 19). Most of the observations are between 5-10 ug/l. For all five years the satellite based estimations are in line with field. A trend line (2nd order polynomial) has been added to show the general tendency for each year.

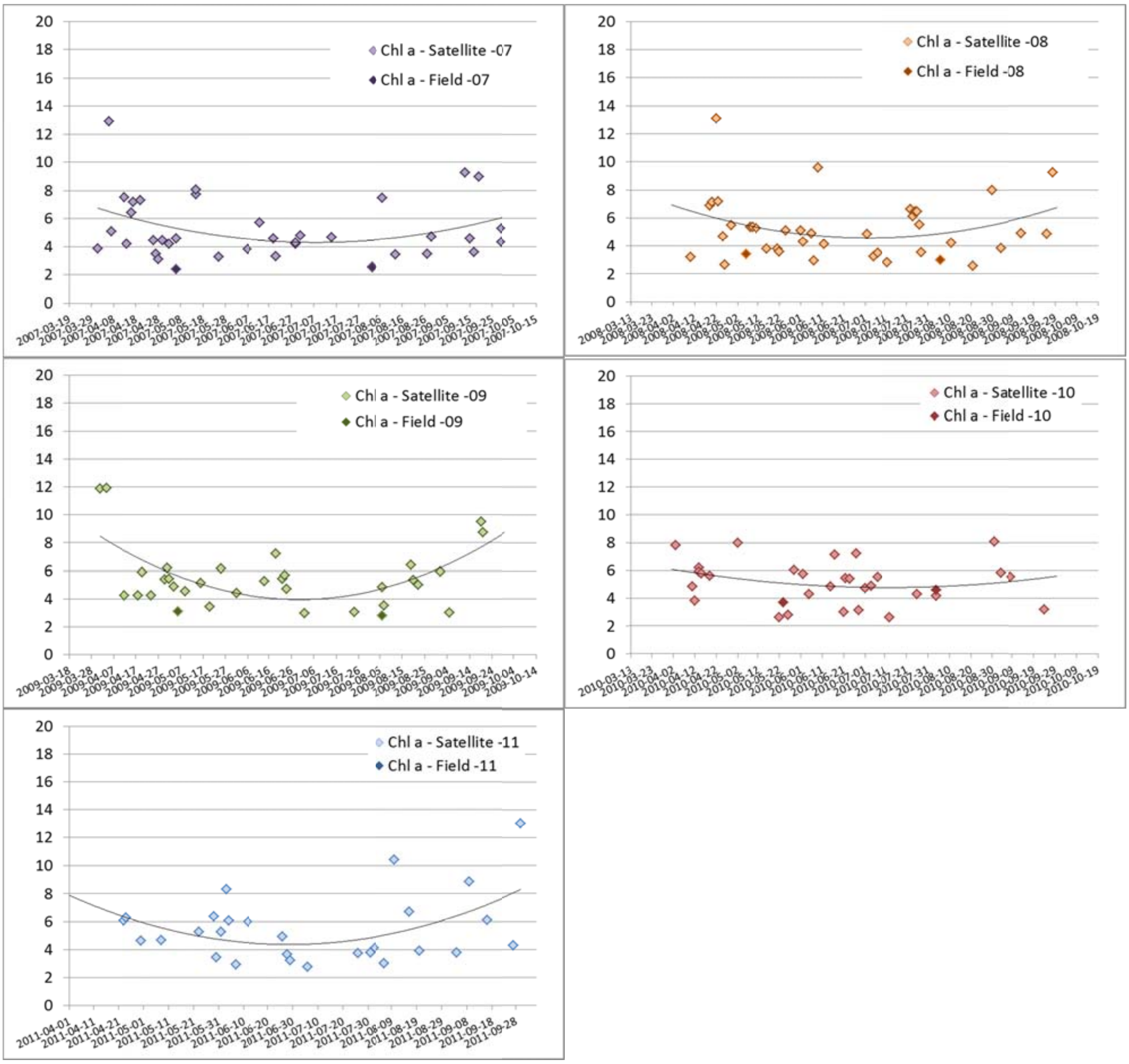


Figure 21. Annual time series for station "Norra Örken" between 2007-2011.

The chlorophyll concentrations at station Norra Örken is stable over the season and most of the observations are between 3-6 ug/l. For the available four years of field data the satellite based estimations are in line with field. During 2007 and spring 2009 the field data is on the lower levels of the satellite based observations, but the absolute difference is approximately only around 1 ug/l. A trend line (2nd order polynomial) has been added to show the general tendency for each year.

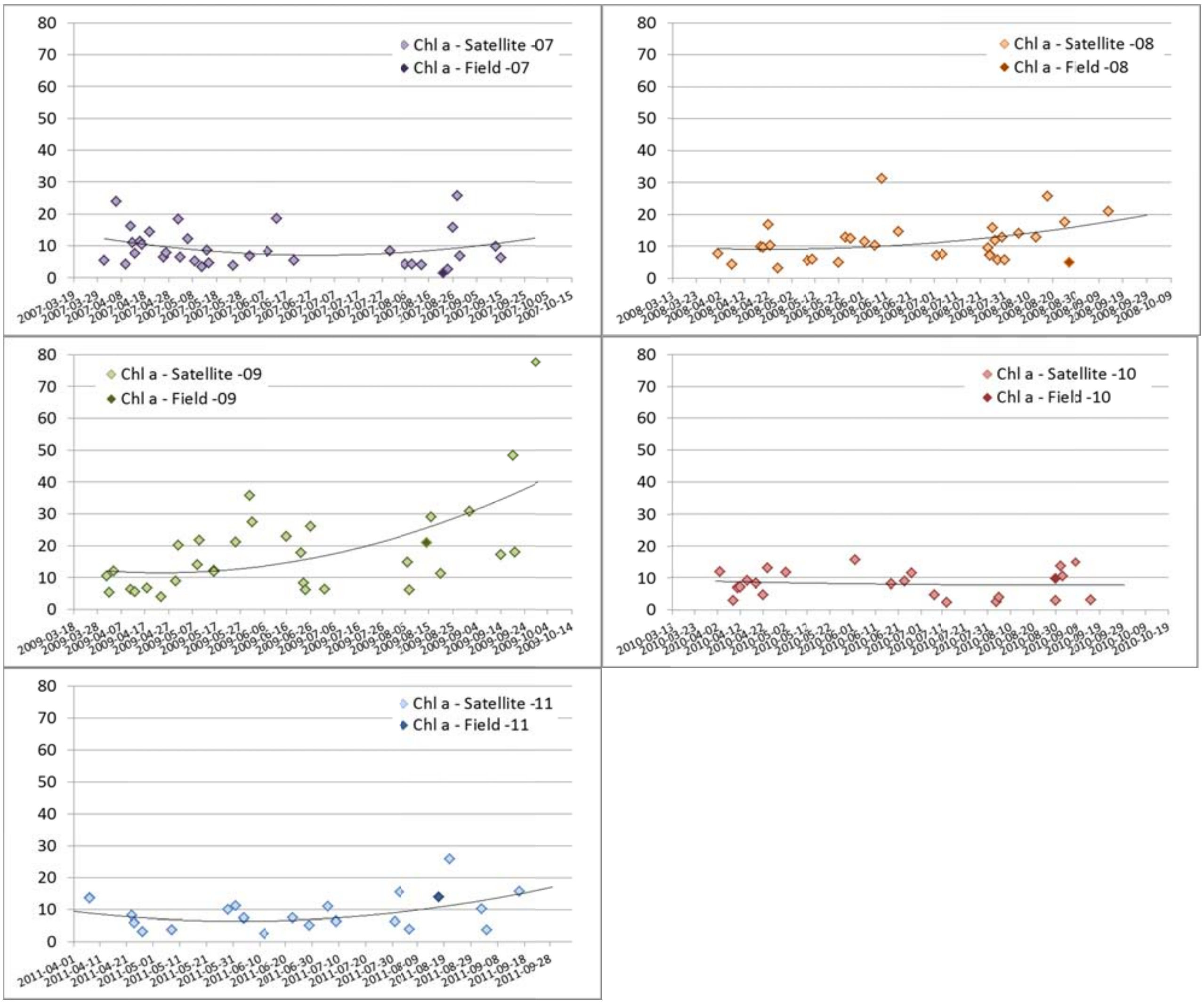


Figure 22. Annual time series for station “Södra Vidöstern” between 2007-2011.

The chlorophyll concentrations at station Södra Vidöstern exhibit some variation over the season. Most of the observations are between 5-15 ug/l, with slightly higher concentrations in the end of 2008 and during longer period in 2009. In 2009, a higher concentration were also measured based on the field sample. For all five years the satellite based estimations are in line with field data and both field data and satellite based estimations indicates relatively large differences in concentration between years for this station. A trend line (2^{nd} order polynomial) has been added to show the general tendency for each year.

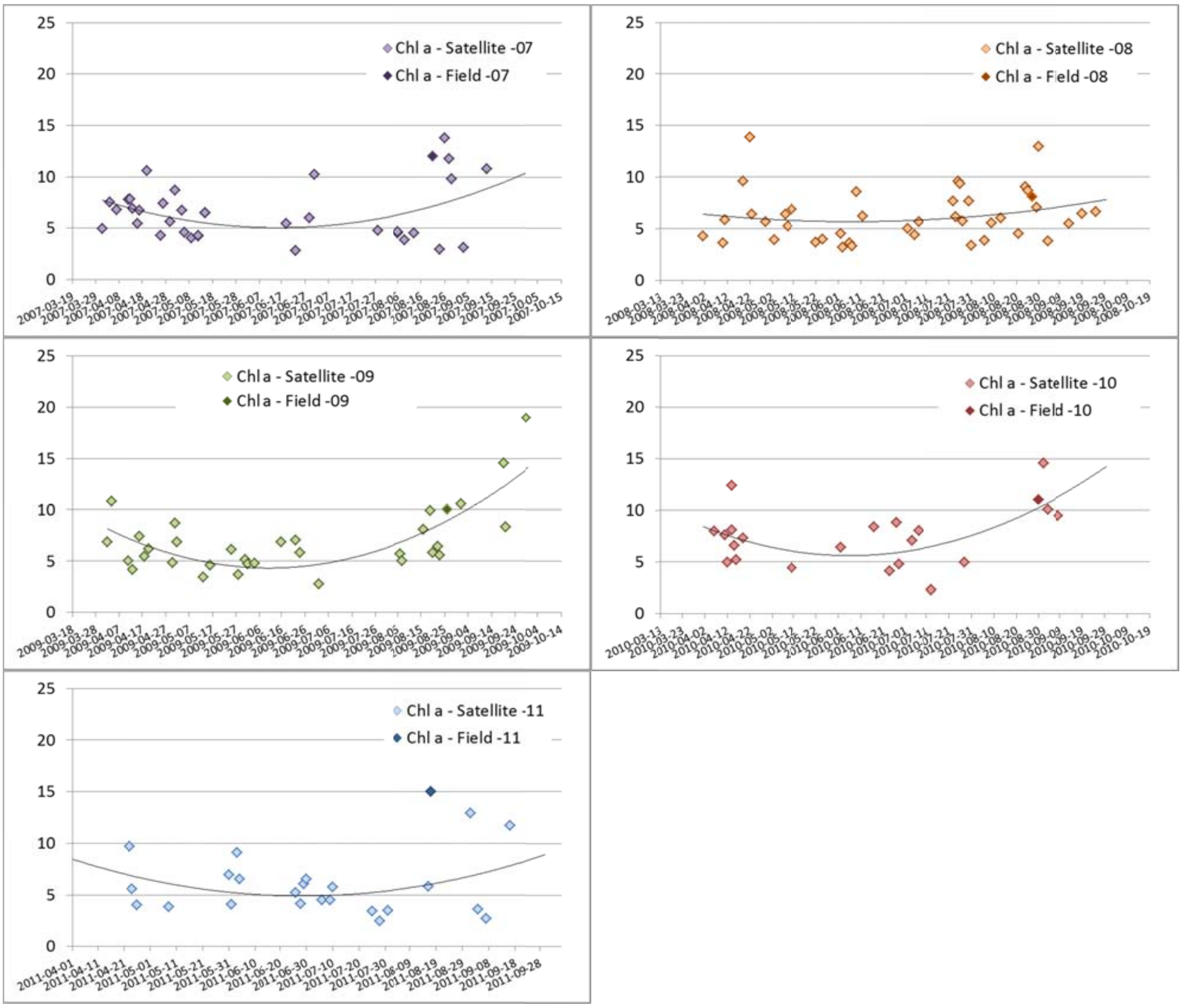


Figure 23. Annual time series for station "Södra Rusken" between 2007-2011.

The chlorophyll concentrations at station Södra Rusken exhibit some variation over the season, but the majority of observations are between 3-8 ug/l. As for most of the stations and year the general trend indicates higher concentrations in April-May and August-September and a bit lower in June-July. For all years, except 2011, the satellite based estimations are in line with field data. During 2011, the in time closest satellite based observation is much lower than what was measured from the field sample, but higher concentrations can be seen also in the satellite observations after the sample was taken. A trend line (2nd order polynomial) has been added to show the general tendency for each year.

To summarize, the time series are in line with available field data. More work could be done regarding how to choose valid observations and how nearby clouds affect the performance of the atmospheric correction of the data, and in the next step the estimation of chlorophyll concentrations.

CDOM

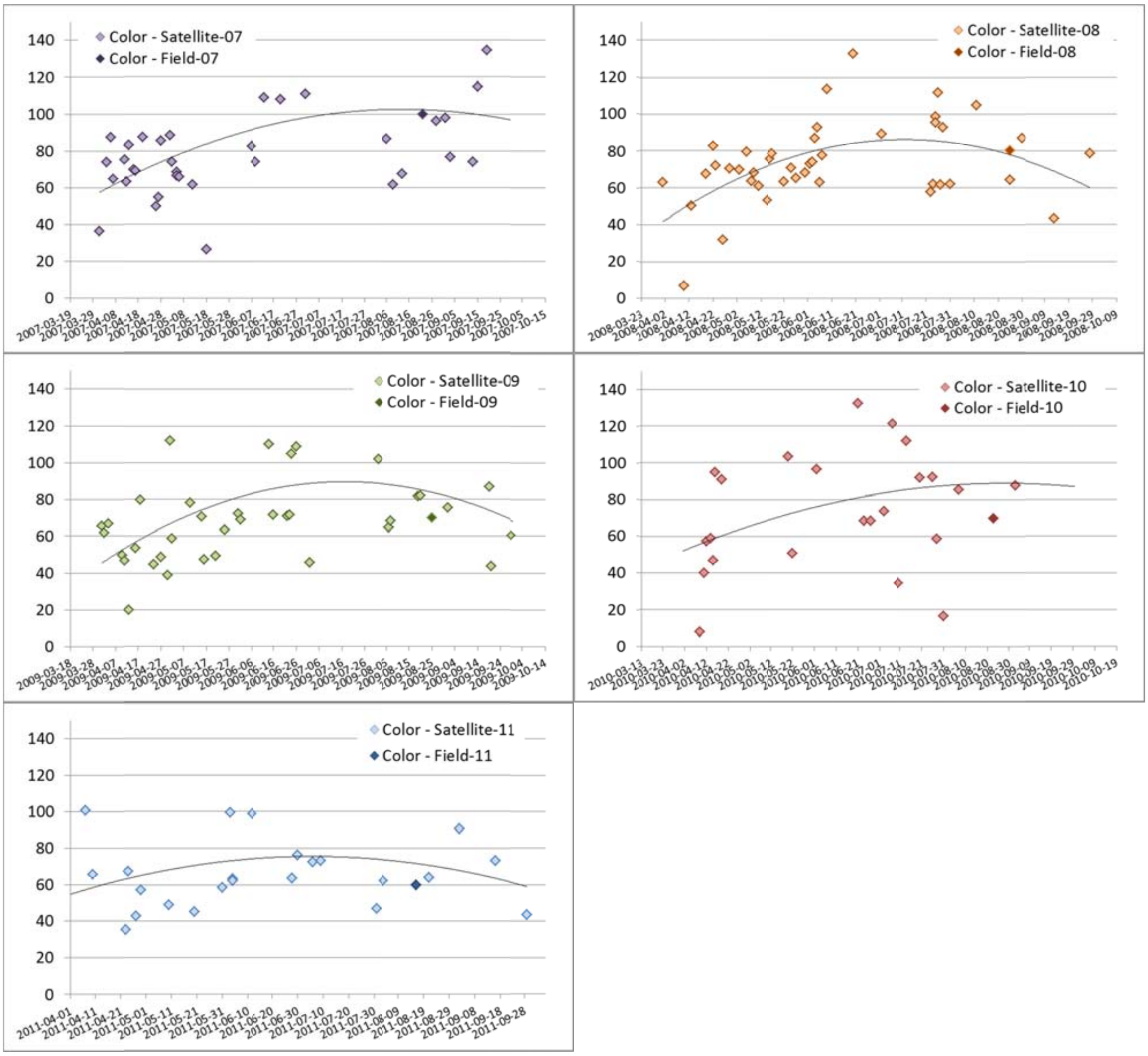


Figure 24. Annual time series for station "Södra Bolmen" between 2007-2011.

The color levels at station Södra Bolmen seems to be relatively stable over time with slightly lower levels in the beginning and end of each year. Most of the observations are between 50-80 mg Pt//l. The satellite based estimations are in line with field for all five years. A trend line (2nd order polynomial) has been added to show the general tendency for each year.

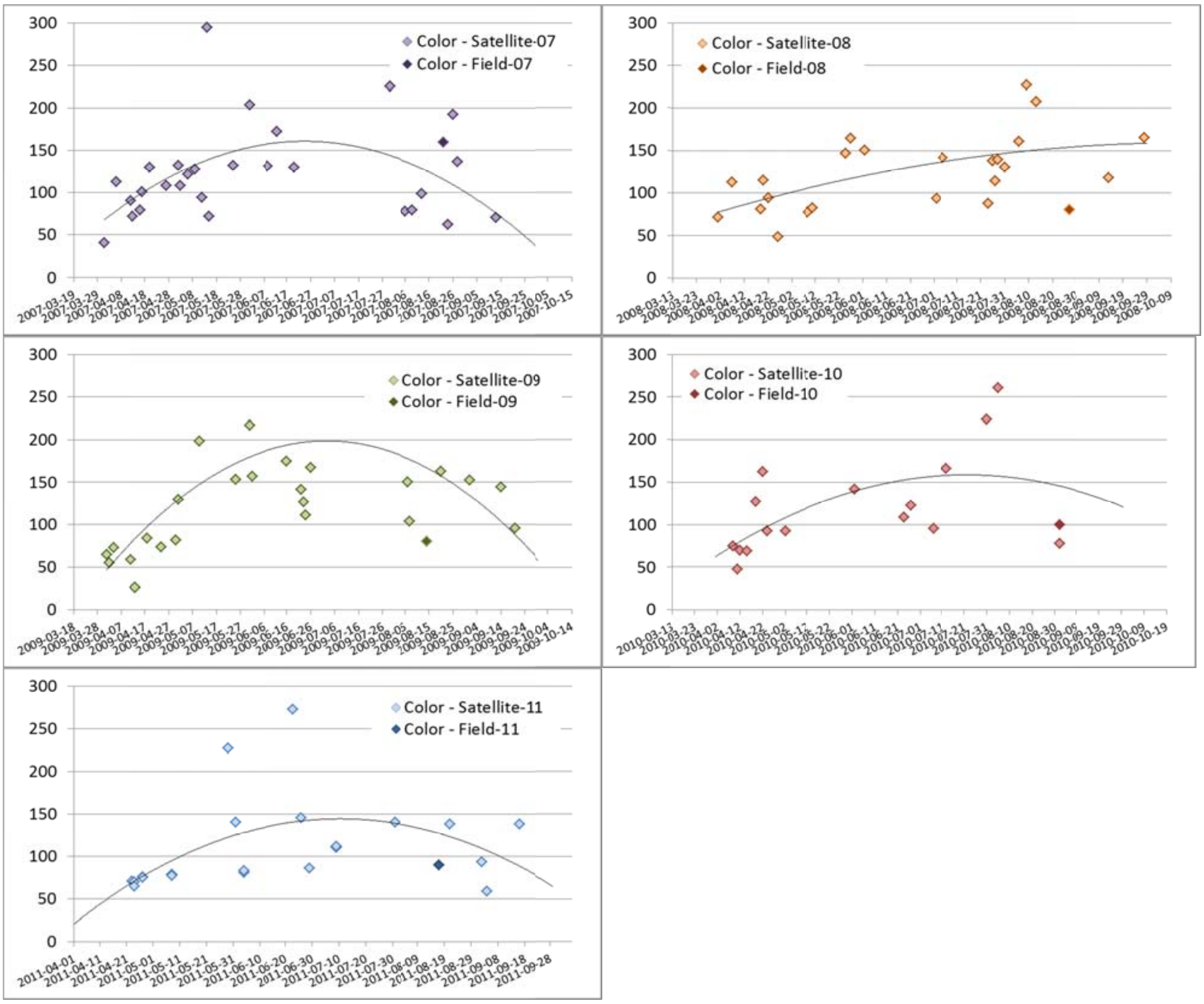


Figure 25. Annual time series for station "Södra Vidöstern" between 2007-2011.

The color levels at station Södra Vidöstern seems to be relatively stable over time with slightly lower levels in the beginning and end of each year. Most of the observations are between 100-150 mg Pt//l. The satellite based estimations are in line with field for all five years. A trend line (2nd order polynomial) has been added to show the general tendency for each year.

To summarize, the time series are in line with available field data for these two example. As for chlorophyll, more work could be done regarding how to choose valid observations and how nearby clouds affect the performance of the atmospheric correction of the data, and in the next step the estimation of CDOM absorption. Again, it is important to remember the limitations and inaccuracies in the field sample analysis techniques and that the validity of the algorithms should be further investigated. A continued analysis should be based on more data (2002-2006) and the analysis of ABSf instead, which was limited between 2007-11, but more frequent during 2002-04.

8.4 Lake data analysis - Chlorophyll & CDOM

The data analysed in this chapter corresponds to lake averages and not station averages as in chapter 8.3 above. After masking of invalid pixels, an average of all remaining lake pixels within the lake polygon was extracted for each date between April-September, 2007-2011 using the predefined water bodies as provided by SMHI (www.smhi.se). Each daily lake average is referred to as "one observation" in this chapter and indicates that at least one valid pixel could be extracted from the lake on a certain date. Data has been extracted from 83 lakes as displayed in Figure 1.

8.4.1 Number of observations

Based on the extracted data from all valid pixels, the number of observations per lake and year are displayed in Figure 26 below. The upper graph corresponds to all available observations. In the lower graph all observations based on less than five pixels have been excluded. On average 45% of the observations are lost and the loss is larger for smaller lakes. The number of resulting observations per lake and year after filtration can be found in Annex 1. These observations should be compared to the 0-2 existing field samples available for these lakes today. Adding satellite based estimations should make a significant contribution to the monitoring program.

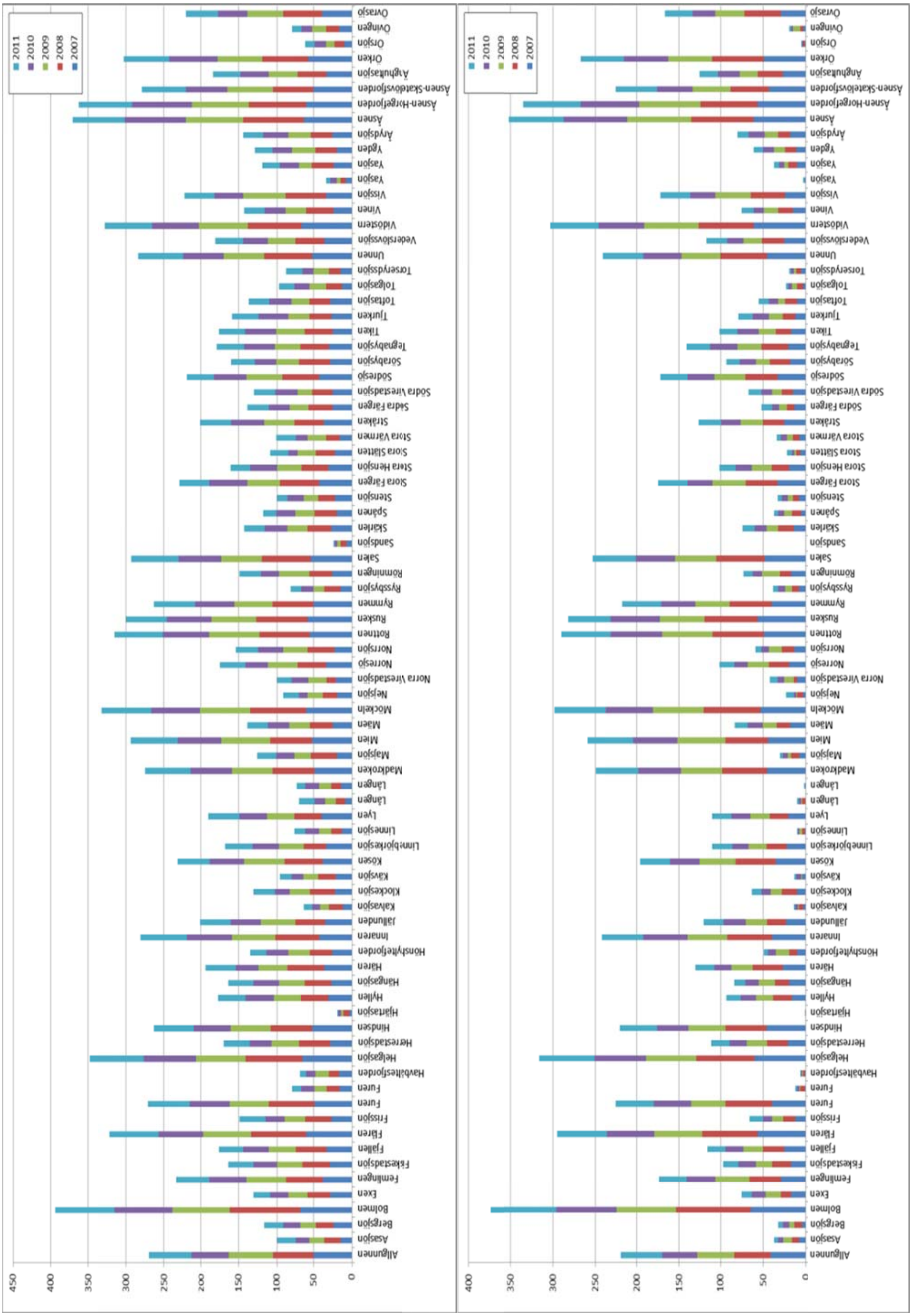


Figure 26. Number of observations per lake and year, before and after filtering of observations based on <5 pixels.

As the ecological status of a lake is assessed by averaging concentrations, e.g. chlorophyll, over time, an investigation was made based on the 5 years average for each lake. In Figure 27 the 5-year chlorophyll average for each lake before and after removal of observations based on < 5 pixels is plotted. A third version was also investigated, where all observations corresponding to less than 50% of the maximum available pixels for each lake were removed. All three versions are plotted in Figure 27 below.

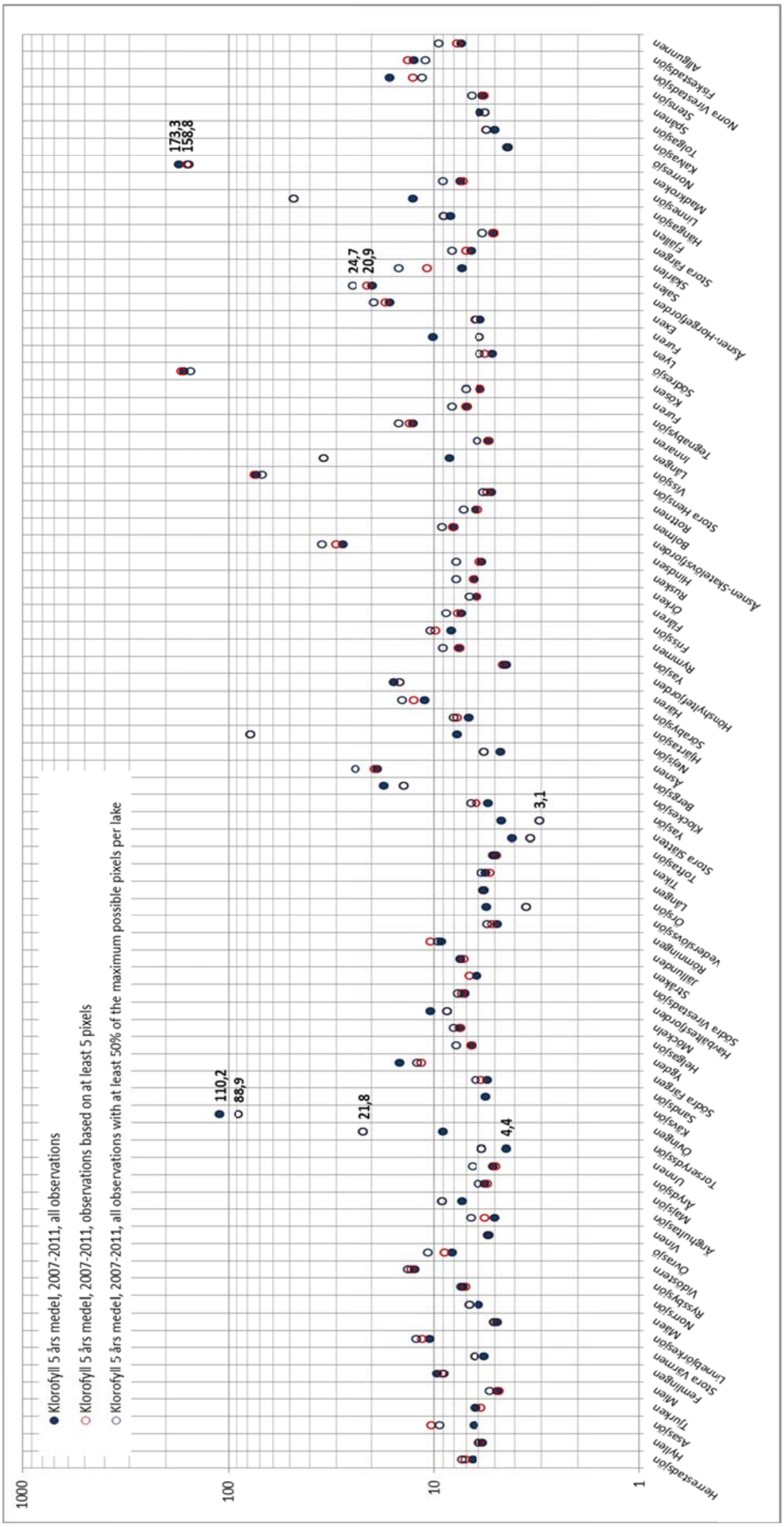


Figure 27. Comparison of 5 year averages based on all observations (filled blue circles), observations including at least five pixels (red circles) and observations including at least 50% of the maximum possible pixels per lake (blue circles).

For most lakes the major difference occurs when removing all observations based on less than five pixels. The third version reduces the data amount significantly, but does not change the average very much. A decision was made to use the “at least five pixels per observation” data for the following time series, status and trend investigations.

8.4.2 Time series

All observations of chlorophyll and CDOM absorption between April-September, 2007-2011 was calibrated and converted to color according to chapter 8.3.1 above. In Figure 28-29 two examples of time series for chlorophyll corresponding to lake averages (blue circles) has been plotted together with available field data (red circle). In addition, the time series corresponding to the control station average (See ch. 8.3.2) has been included for comparison (cross). The exemplified lakes are Lake Bolmen and Lake Tiken. For Lake Bolmen the included field data corresponds to control station “Södra Bolmen”. Lake Tiken is one of the smaller lakes with a surface area of 6 km^2.

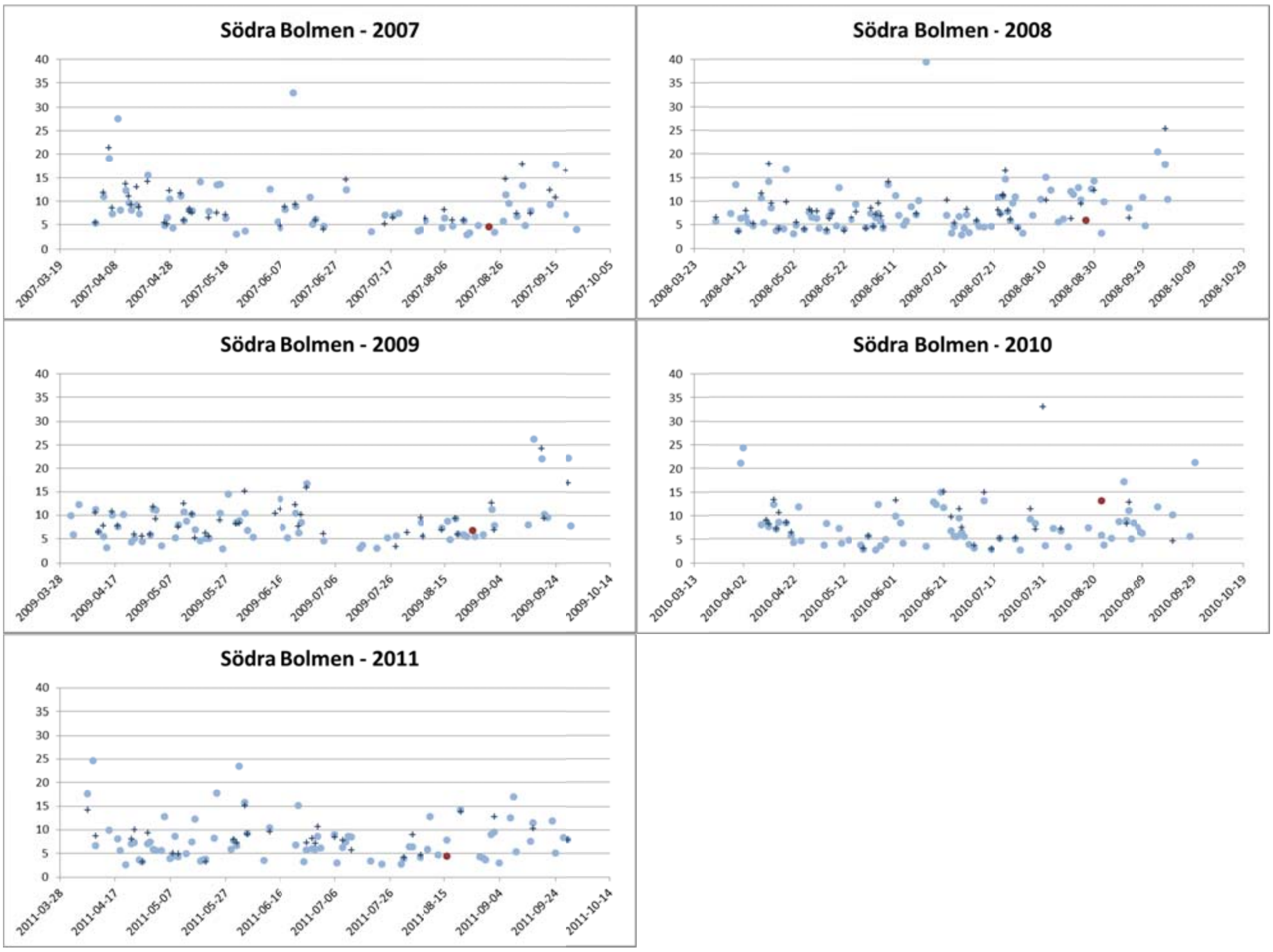


Figure 28. Annual time series for Lake Bolmen between 2007-2011.

As concluded in Ch. 8.3.2., most of the observations are between 5-10 ug/l, also for the lake averages. In most cases, the station average corresponding to station Södra Bolmen is almost identical to the lake average, but there are also discrepancies up to 5 ug/l, which indicates that the station is not representative for the whole lake during these dates. It should be noted that higher concentrations in April could be due to lake ice. Dates with ice cover should be filtered out if this information is available.

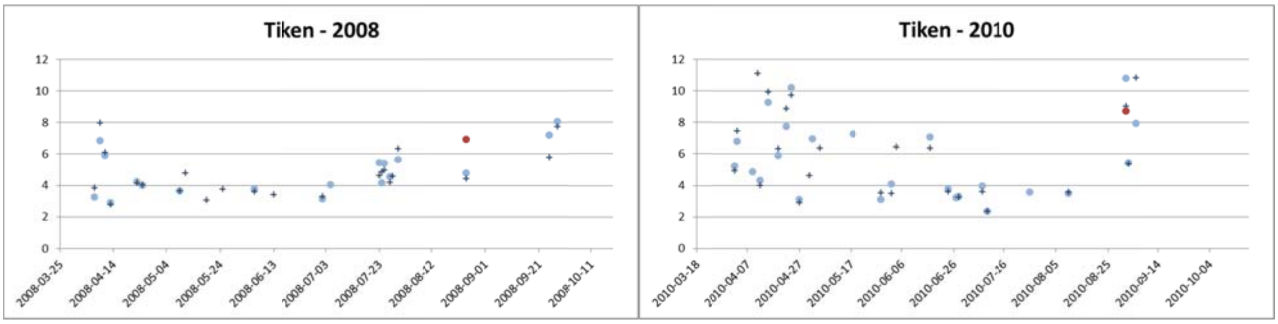


Figure 29. Annual time series for Lake Tiken between 2007-2011.Field data was only available during 2008 and 2010.

Lake Tiken is much smaller, which reduces the number of observations significantly. Still, quite a few observations could be added to the data base presently consisting of two field samples during these five years. It should be noted that higher concentrations in April could be due to lake ice. Dates with ice cover should be filtered out if this information is available.

8.4.3 Status maps

In Figures 30-31 below average concentrations based on all August observations available for each lake has been calculated and plotted.

Chlorophyll

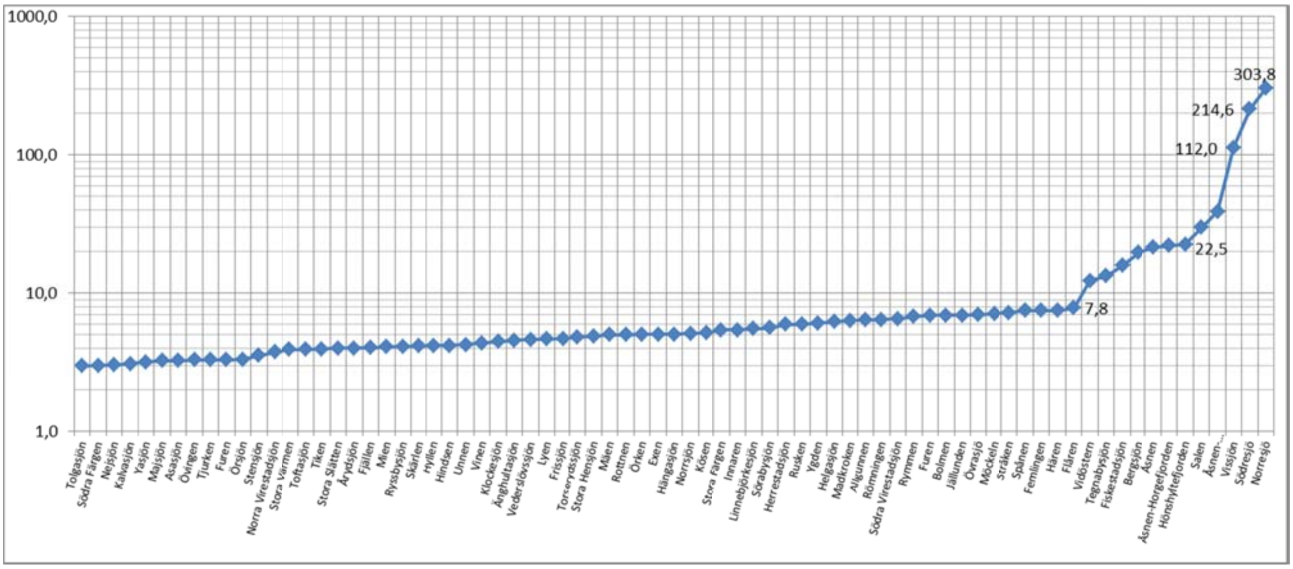


Figure 30. Chlorophyll – Five years average for all satellite observations made in August sorted from low to high concentrations.

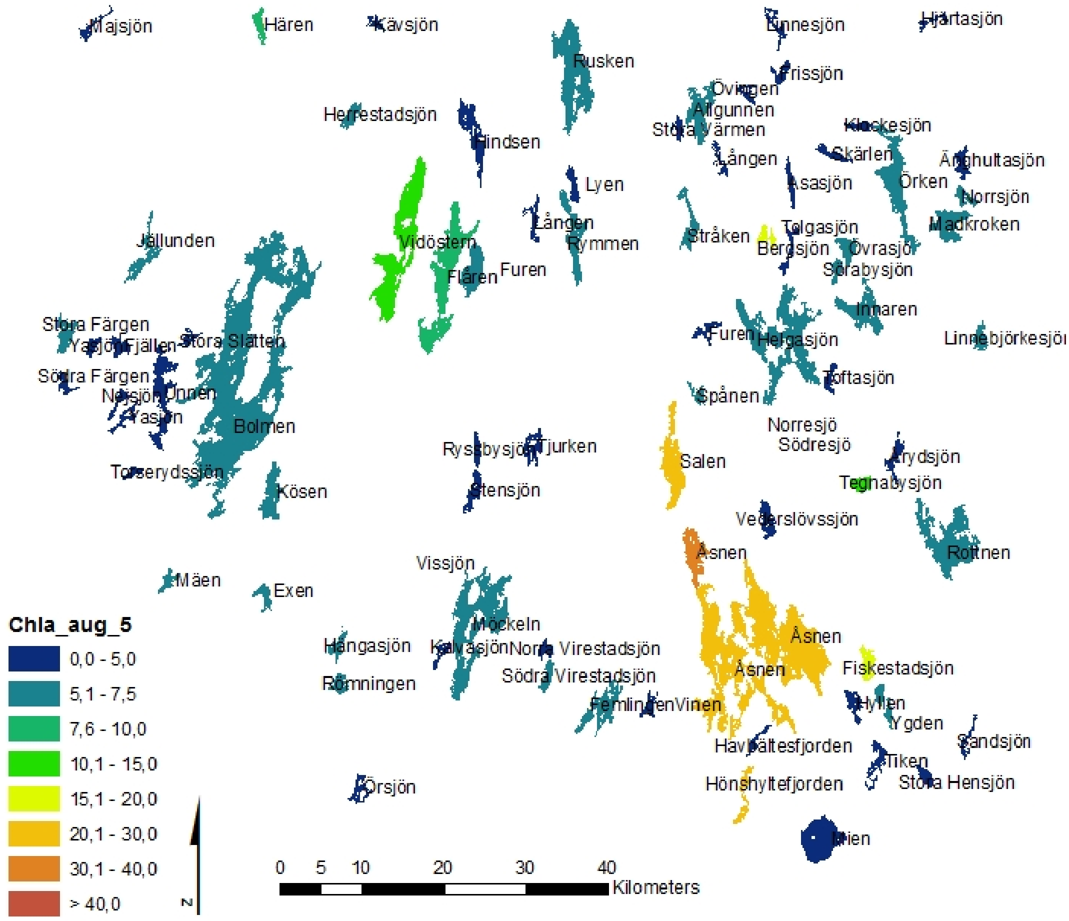


Figure 31. Chlorophyll – Concentration map showing the five years average for satellite observations made in August.

The annual chlorophyll average, 5 years average and the standard deviation for each lake can be found in Annex 2.

CDOM

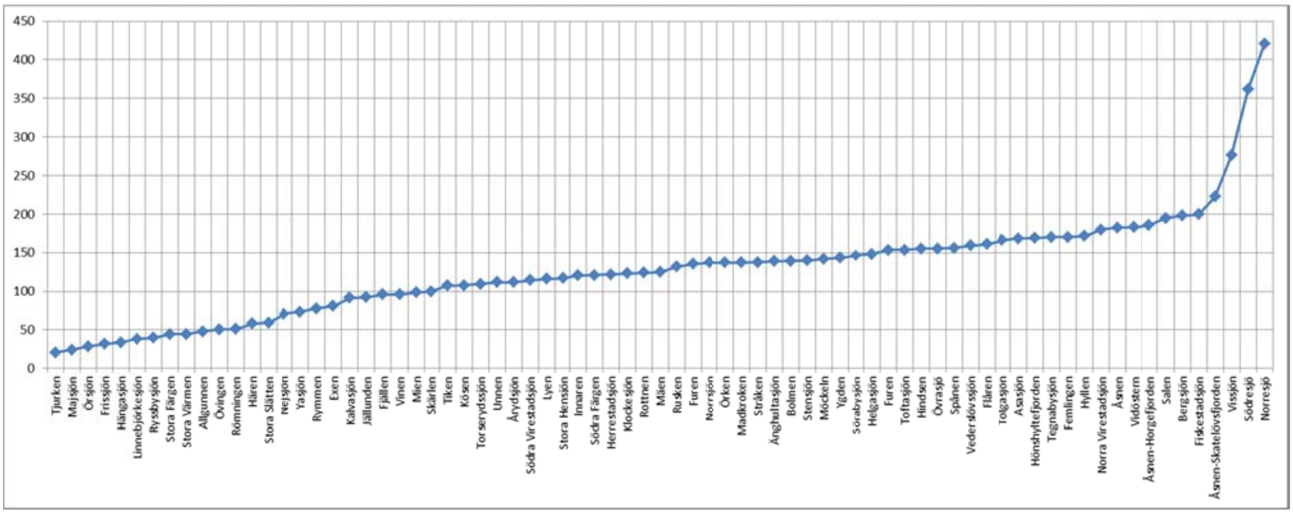


Figure 32. Color – Five years average for all satellite observations made in August sorted from low to high.

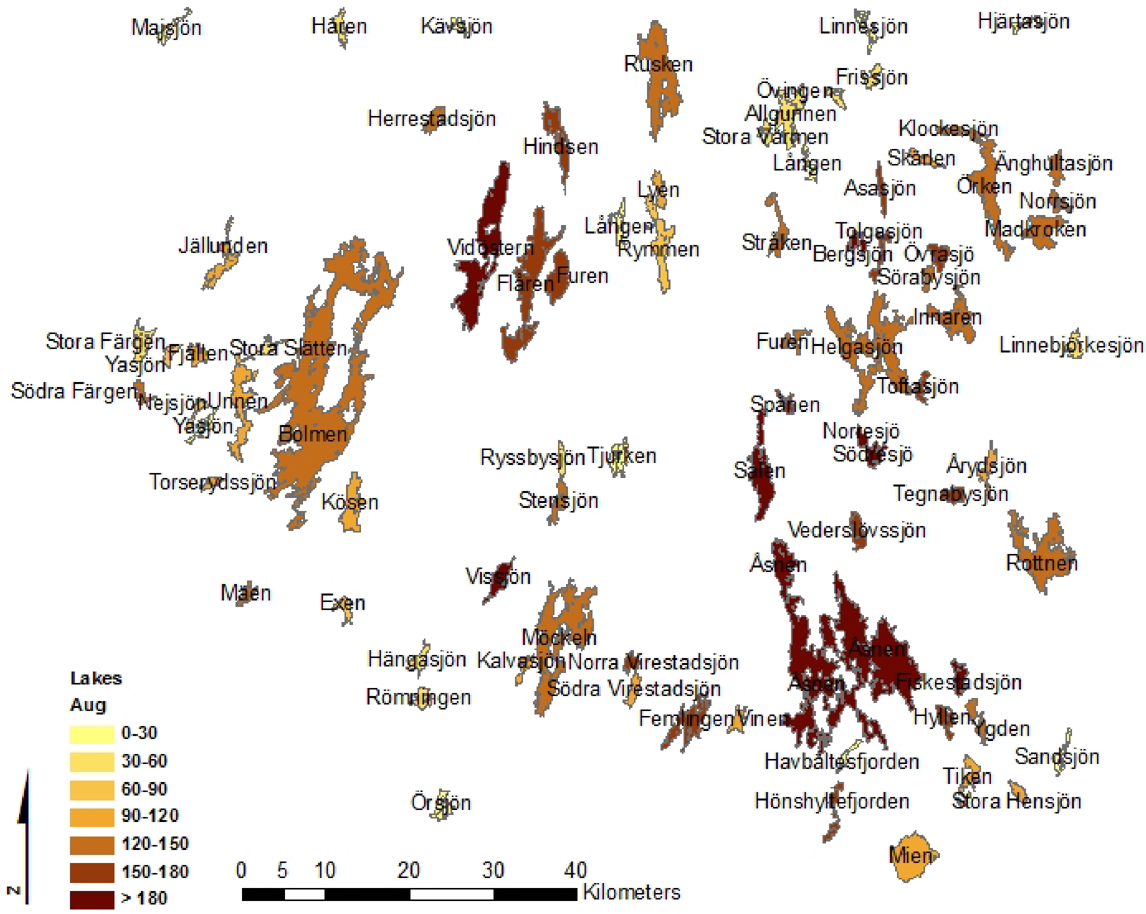


Figure 33. CDOM – Status map showing the five years average for satellite observations made in August.

The annual color average, 5 years average and the standard deviation for each lake can be found in Annex 3.

8.4.4 Ecologic status - Chlorophyll

The average chlorophyll concentrations from august 2007-2011 as listed in Annex 1, have been used to calculate the ecological status for chlorophyll according to the instructions, reference values and class limits as described in “Bedömningsgrunder för sjöar och vattendrag”. Most of the lakes could be classified but not all lakes have data during all years (Annex 1). The resulting status is shown in Figure 34 below. In Figure 35 an example of the status for some of the “green” lakes, as described in chapter 6.1 above, is shown. Reference value “2.5” is used for the three lakes to the left in the figure and reference value “3” for the five lakes to the right. Corresponding class limits have been plotted in the figure as well as the standard deviation of each five year average.

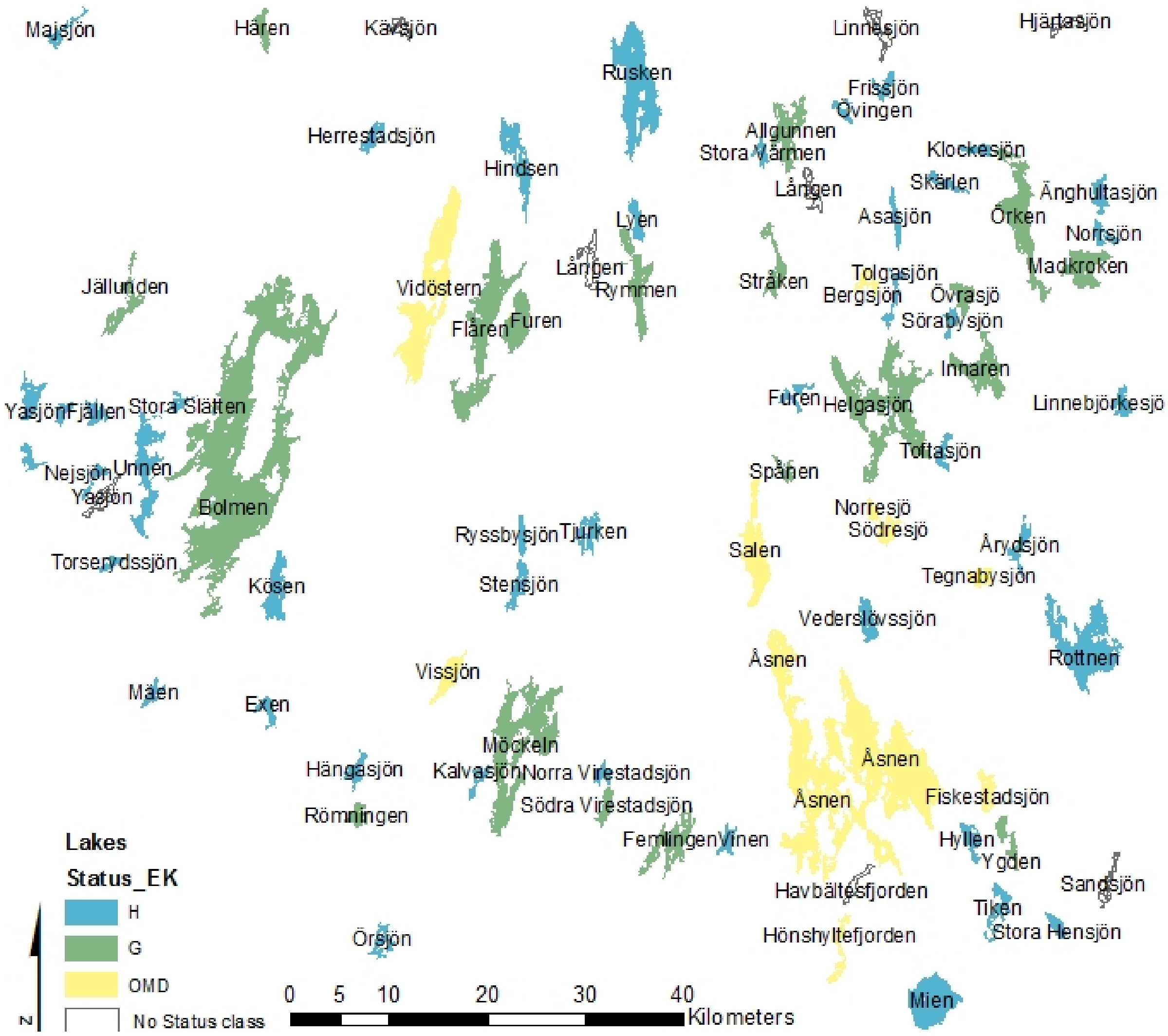


Figure 34. Ecological status (chlorophyll) based on satellite observations from August 2007-11.

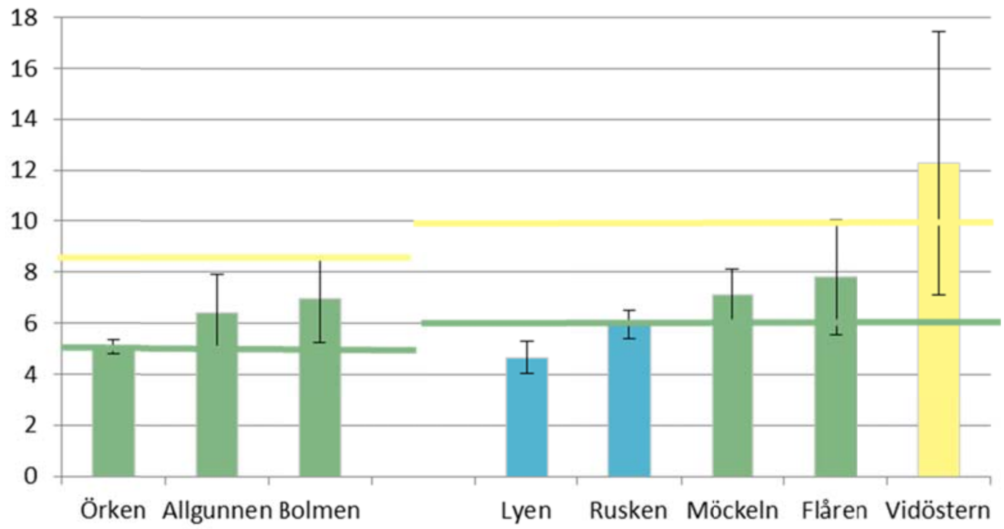


Figure 35. Chlorophyll a (ug/l) – Status class based on 5 years August averages, 2007-2011.

8.5 Sydvatten data analysis

8.5.1 Station analysis 2012

During 2012, the chlorophyll concentrations for four (See Chapter 6.2) Bolmen stations were analyzed. The data corresponding to station Södra Bolmen and Bolmen-Bockuddarna were almost identical, while Norra Bolmen indicated higher concentrations on most dates. Bolmen-Kafjorden corresponded to lower concentrations than the other three stations but the number of valid pixels was very limited for this station. This indicates that this area is on the limit on what we can monitor in terms of required size. The data was very noisy and a decision was made to include more data and data averaged over a larger spatial surface during 2013.

During 2013, data corresponding to sub divisions of the southern part of Bolmen were further investigated (Figure 36). Spatial averages were extracted from area Södra Bolmen, Näsören, Mittör, Linnerö, Piksborg and Kafjorden and used in the analysis.

Figure 36. The sub basin used in the analysis 2013.

The primary objective was to investigate if correlation could be found for color estimates as described by satellite data from the sub basins, field data collected at control station "Skeen Bolmens utlopp" and/or Sydvatten's analysis of the incoming water, with an expected delay of seven days or more due to the transportation of the water through the tunnel.

Investigation of satellite based sub basin data

Initially, the correlation between sub basins was investigated. Näsören and Södra Bolmen were strongly correlated and can be considered to correspond to similar water type and water quality status (Figure 37). These two basins also exhibited the lowest concentration levels. Basin Piksborg was too small to generate valid data. Basin Kafjorden, generated some, but very few observations. However, basin Linnerö indicated a good correlation to Kafjorden and as this area is closest to Skeen and the start of the Bolmen tunnel, the focus of the analysis as describen below has been on data from this area.

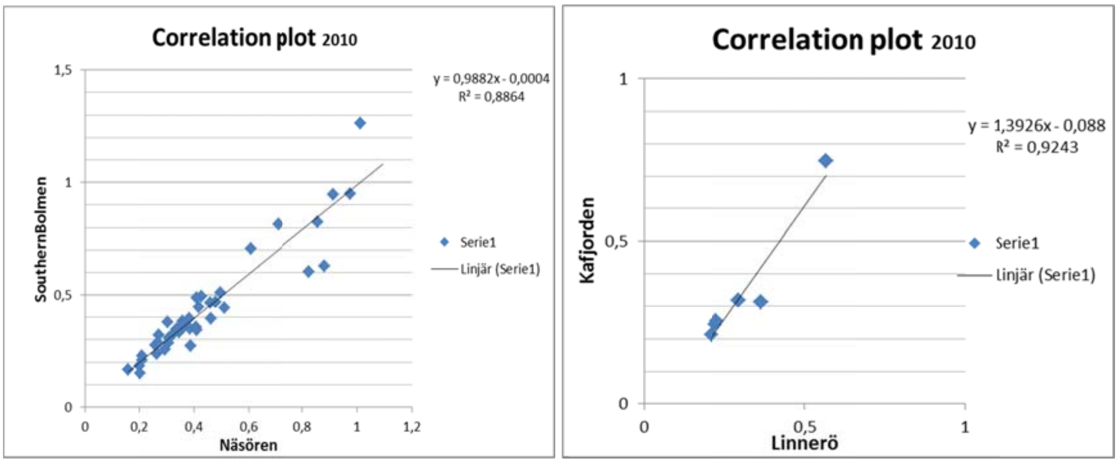


Figure 37. Correlation plot for CDOM between different sub basins, Södra Bolmen-Näsören (left) and Kafjorden-Linnerö (right).

Investigation of Sydvatten and control station data

Sydvatten data was available from 2006-2008 and 2011 (Figure 38).

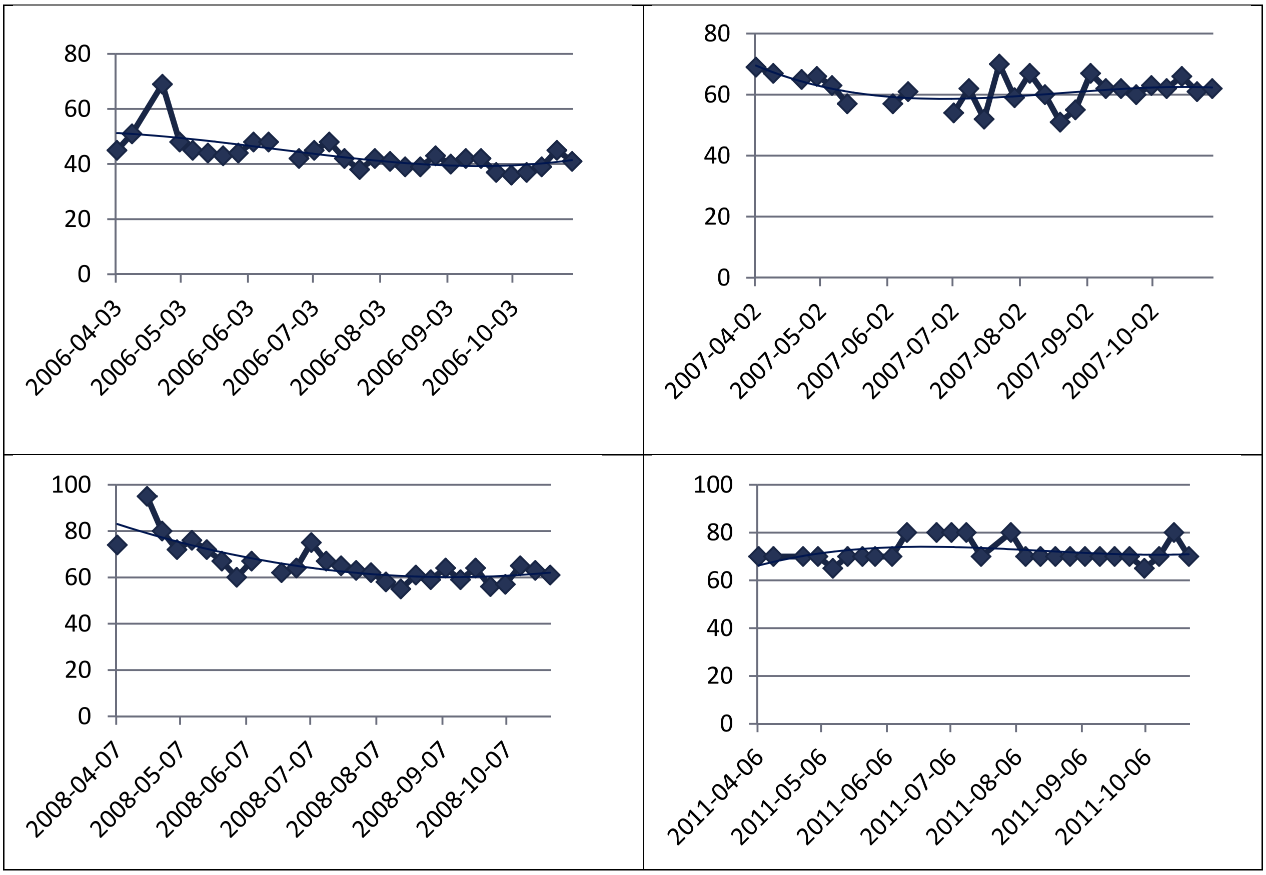


Figure 38. Colour (mg/l Pt) levels based in the incoming water from Bolmen to Ringsjöverket 2006, 2007, 2008 and 2011.

The pattern is quite similar for 2006-2008 with slightly higher concentrations in the beginning of the season. In general, the concentration levels are quite stable and the variation is low.

Data from control station “Skeen, Bolmens utlopp” has mainly been used in the analysis, but Bolmen södra and Murån data has also been included as reference. The data from stations Skeen and Murån is compared in Table 6, and it is obvious that the levels at Murån are much higher and most likely of less relevance for our investigations. The amount of available data was limited: Södra Bolmen is sampled once per year in august, i.e. five observations in total. Both Skeen and Murån was sampled six times per year during 2010 and 2011, but only three times between April-September.

Table 6. Comparison of the two reference stations Skeen and Murån.

	Färg, (mg Pt/l) - Field	
	Skeen	Murån
2010-04-20	90	280
2010-06-15	100	500
2010-08-24	80	700
2010-10-21	60	250
2011-02-23	100	140
2011-04-19	70	160
2011-06-22	70	450
2011-08-17	90	600
2011-10-19	80	550
2011-12-14	100	180

A comparison of Sydvatten data and field data from the control stations was made based on the data collected during 2011, the only year with data from both sources (Figure 39). No obvious and consistent trends could be seen for the two data sets.

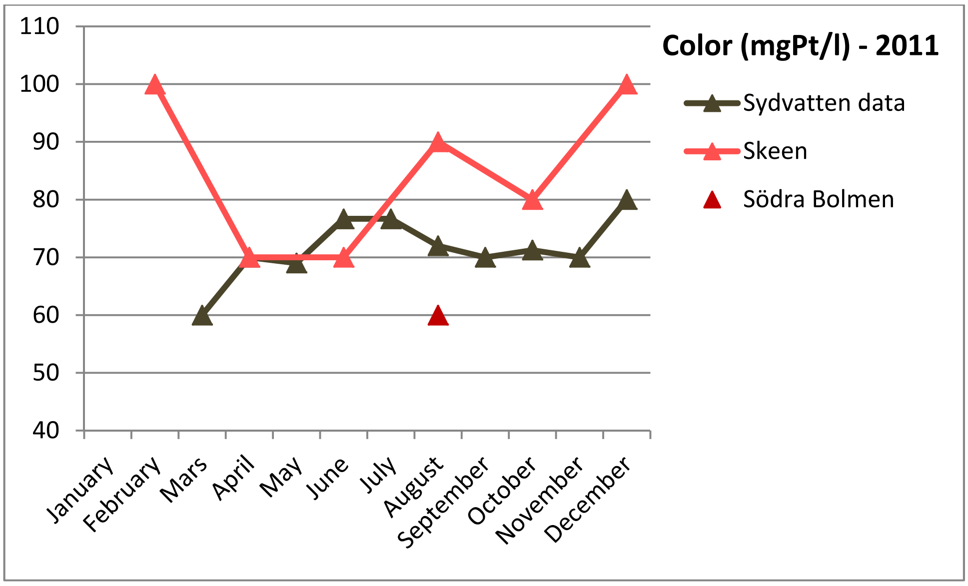


Figure 39. Colour - Sydvatten data (monthly averages) compared to control station data from Skeen 2011.

Investigation of satellite based concentrations and control station data

Field data from Skeen was available from 2010 and 2011. As only a few observations were available from the control station, and no exact match up dates could be found, a decision was made to calculate monthly means based on the satellite observations and compare this to the control station data. The CDOM values have then been converted to colour by multiply with a factor 240 as described in chapter 8.3. The data has been plotted in Figure 40a-b.

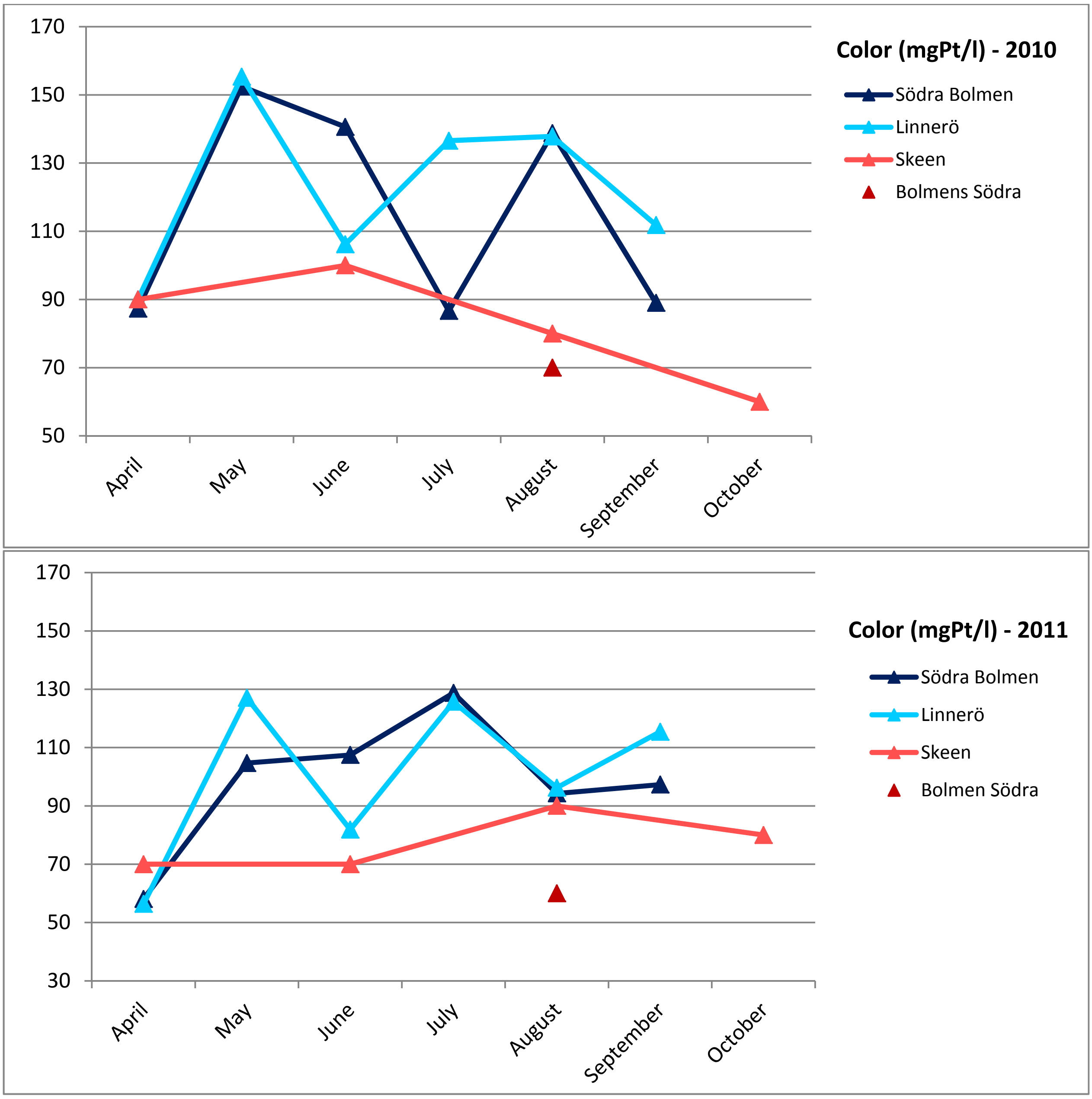


Figure 40 a-b, Color - Satellite based monthly averages corresponding to basins Södra Bolmen and Linnerö compared to control station data from Skeen and Södra Bolmen, 2010 and 2011.

Näsören and Södra Bolmen are most similar, but none of the basins exhibits similar trends as control station Skeen. Linnerö is closest to Skeen but the satellite data from this basin shows a much larger variability over the season compared to Skeen.

Investigation of satellite based concentrations and Sydvatten data

The interpretation of the comparison between satellite based estimations of color and Sydvatten data was difficult. The amplitude of the MERIS data is much larger than for the Sydvatten data and no obvious and consistent trends could be seen for the two data sets. It should also be noted that the variation in the samples analysed by Sydvatten is very small. Calculation of weekly and monthly averages did not help and a great variability can still be seen (Figure 41-44). Slightly higher concentrations can be seen in both data sets in July, but the variability of basin Linnerö is too big to make any conclusions regarding similar trends.

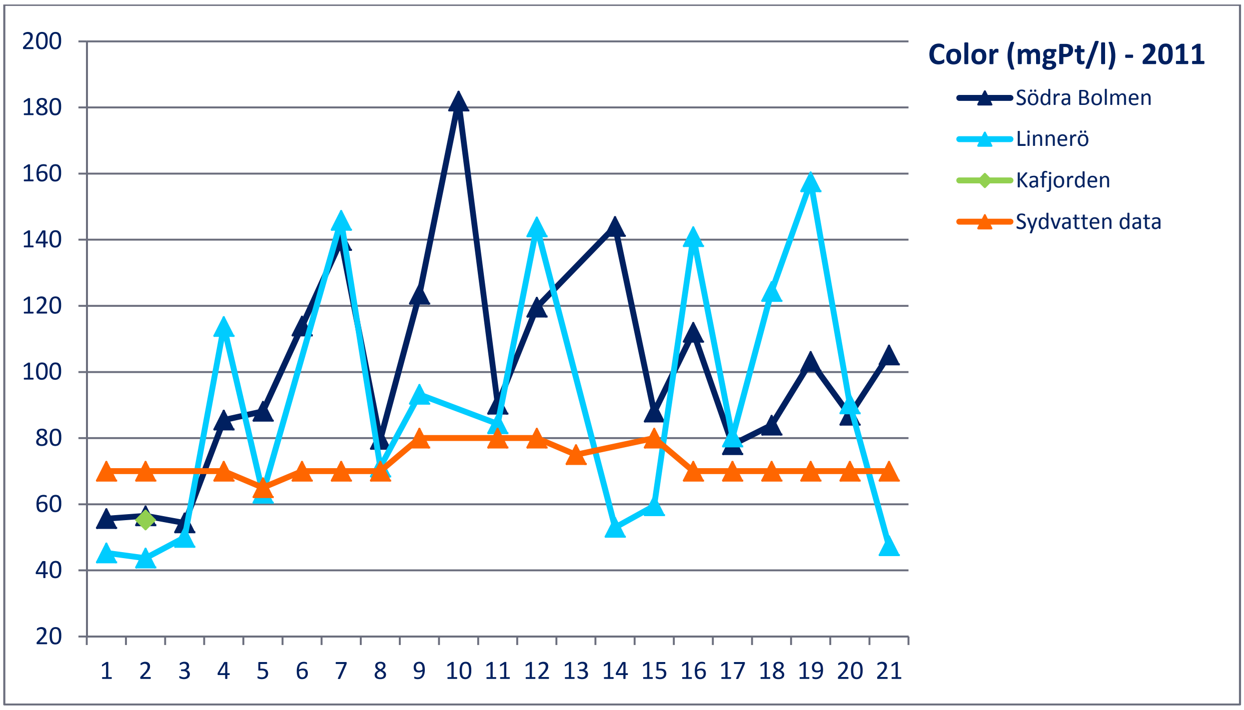


Figure 41, Color - Satellite based weekly averages from April to September corresponding to basins Linnerö, Kafjorden and Södra Bolmen compared to control data from Sydvatten/Ringsjöverket (weekly averages), 2011.

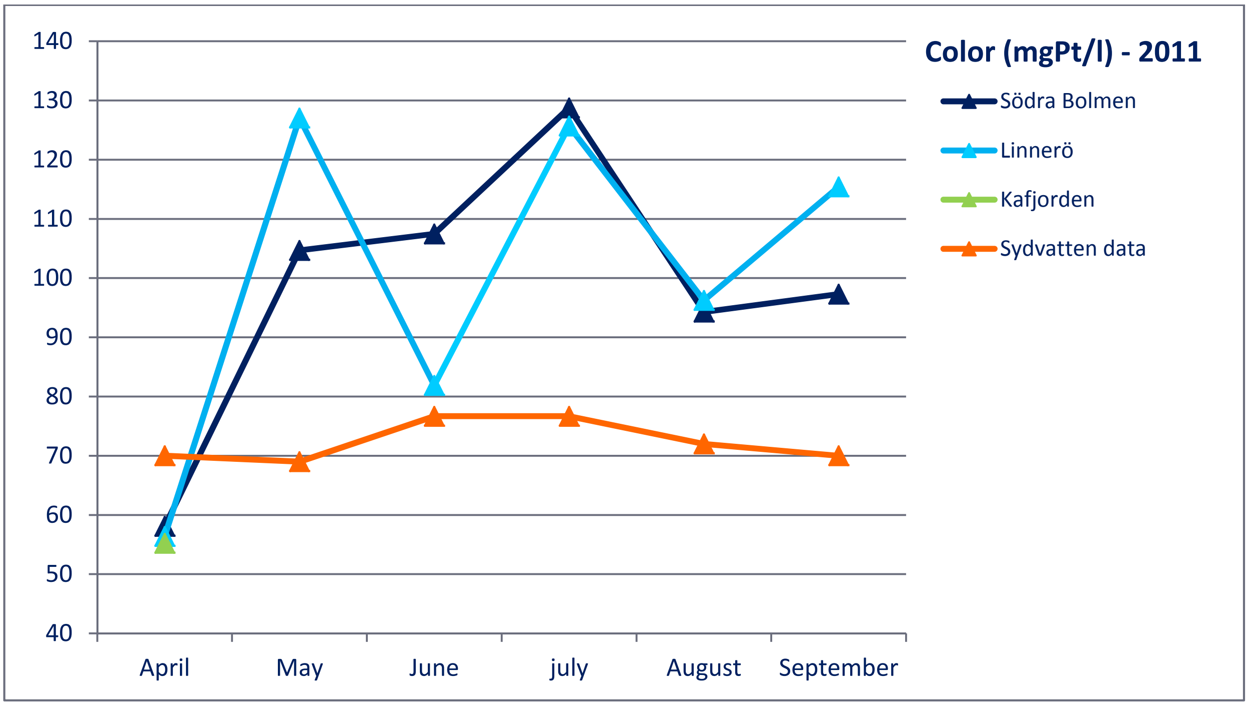


Figure 42, Color - Satellite based monthly averages corresponding to basins Södra Bolmen, Linnerö and Kafjorden compared to Sydvatten data (monthly averages), 2011.

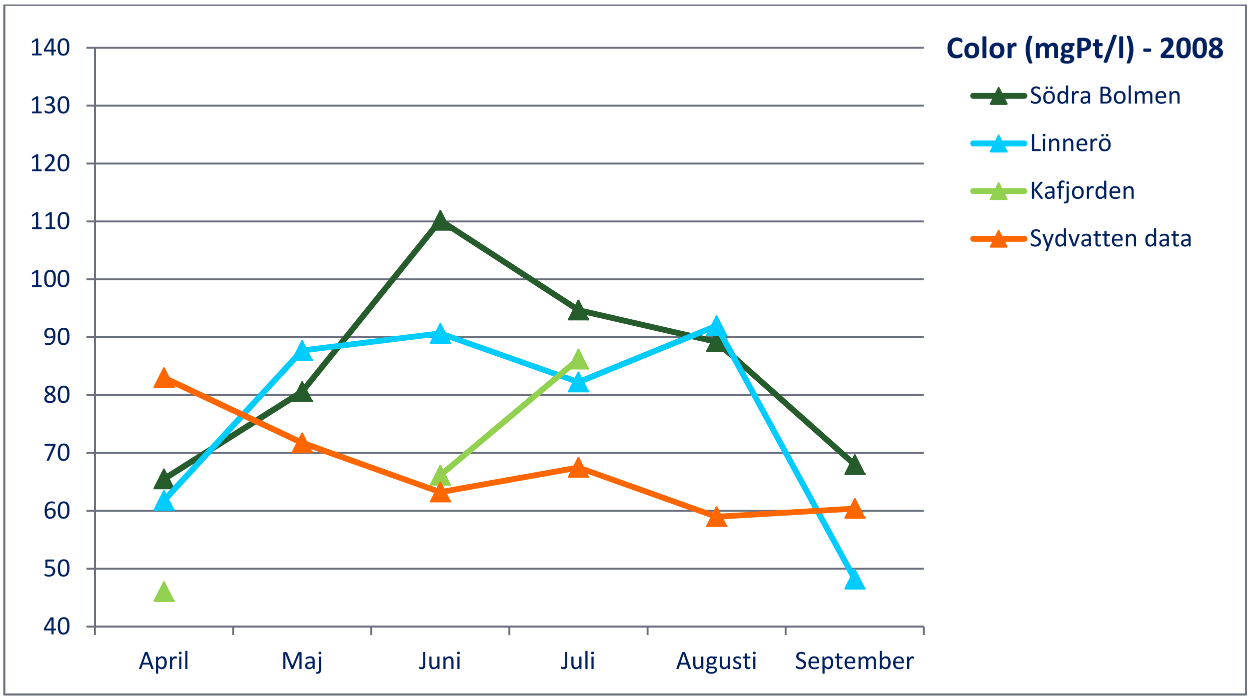


Figure 43, Color - Satellite based monthly averages corresponding to basins Södra Bolmen, Linnerö and Kafjorden compared to Sydvatten data (monthly averages), 2008.

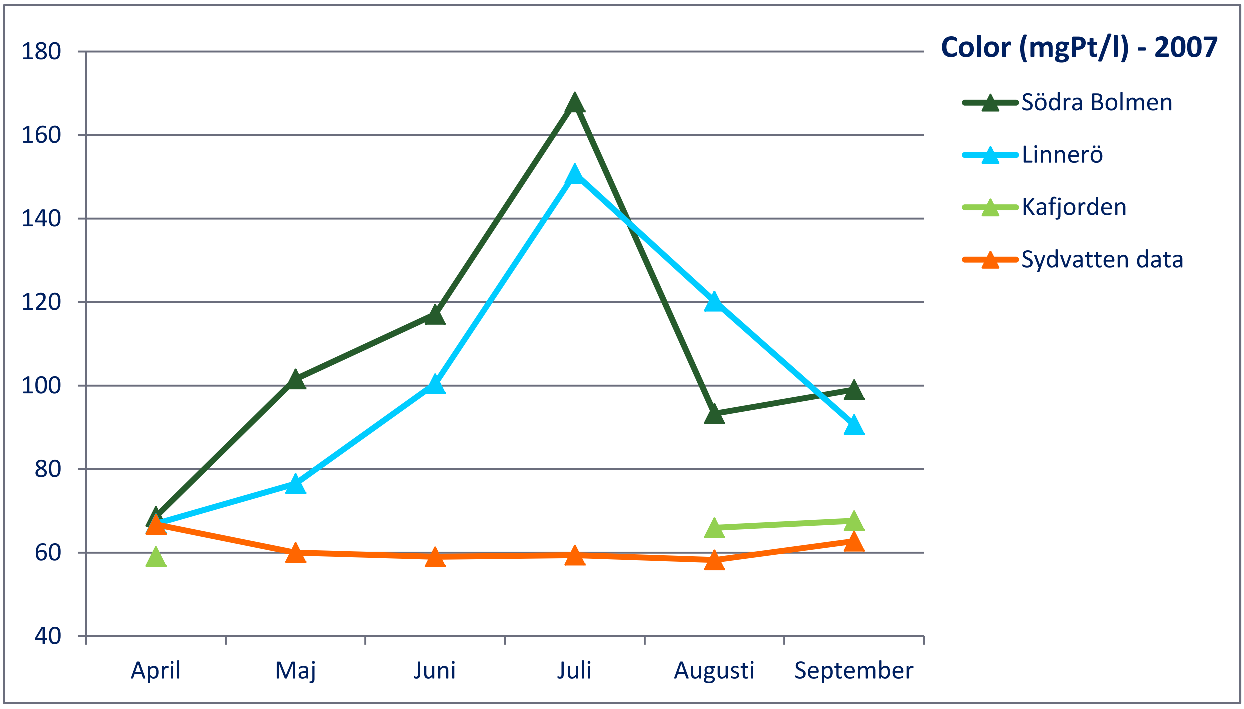


Figure 44, Color - Satellite based monthly averages corresponding to basins Södra Bolmen, Linnerö and Kafjorden compared to Sydvatten data (monthly averages), 2007.

To compensate for the fact that it takes some time for the water to go get from Bolmen to Ringsjöverket, shifts of 1-5 weeks of the weekly averages plotted in Figure 41 were made and further analysed. No significant correlation could be identified.

To summarize, based on the data included in the analysis it seems impossible to make any conclusions on how changes in the water quality, observed from the satellite data, can be used directly to support and enhance adaptive operation at Ringsjöverket. Significant trends could not be seen between any of the three investigated datasets. From a technical aspect, the data should be possible to deliver one to two days after it has been registered, but the interpretation of the data, and message to deliver is more difficult to concretize.

9 Conclusions

It is clear that both size and shape needs to be considered in order to judge if a specific lake is possible to monitor based on satellite data with 300 meters resolution or not. It is also clear that it will not be possible to monitor the smallest lakes as required by the Water Framework Directive. However, keeping the shape factor in mind, it should be possible to provide some data on lakes larger than 2-3 km^2.

Averaging over the whole lake and over time is most likely a better way to use this technique than, as the focus have been before, to use and compare spatially very limited data to even more limited water samples from control stations. The match up and time series analysis described earlier indicates a potential to include this technique in the monitoring program, and the possibility to even look at single observations. However, the sometimes noisy appearance and varying concentration levels between neighbouring pixels, indicates that more reliable status and trend estimates can be calculated based on spatially and temporally aggregated data. It should be pointed out that it is not necessarily the original image that is noisy, but rather the result after the limited performance of the atmospheric correction procedure. This suggests that even if the station data for the small and very heterogeneous lakes shows low correspondence when compared to field data, spatial and temporal aggregates might generate useful products.

As mentioned in the report, the investigated CDOM algorithm used, is here applied to lakes with CDOM concentrations way out of its training range. It has still produced significant correlation to field data in less humic lakes, but it is also most likely that we now have gone beyond its upper limit and that also the relative scale is lost somewhere between 100-150 mg Pt/l. This should be further investigated, but would require adding more data (2002-2006) to the analysis, which was not possible within the present project frame. Adding this time span would also make it possible to analyse ABSf instead, which was limited between 2007-11, but more frequent between 2002-04.

The work presented in the report has been focused on chlorophyll and CDOM/color. Recently, algorithms for Secchi depth estimation based on MERIS data have been evaluated with good results in Lake Vänern, Vättern and Mälaren. It would be very interesting to validate if the same algorithm could generate good results in our area of investigation, as Secchi depth is one of the important parameters for the status classification with reference to the water framework directive.

For most lakes in Sweden the available field data set is very limited, which is also the main reason for evaluating this technique. The additional information that could be derived from satellite based measurements should constitute a substantial complement to the regular monitoring programs.

With respect to the objectives related to the needs of Sydvatten, and based on the available data, it seems impossible to make any conclusions on how changes in the water quality, observed from the satellite data, can be used directly to support and enhance adaptive operation at Ringsjöverket. Significant trends could not be seen between any of the three investigated datasets (satellite, field, Sydvatten). From a technical aspect, the data should be possible to deliver in one to two days after it has been registered, but the interpretation of the data and message to deliver is more difficult to concretize.

10 Future application of project results

Official legislations, both Swedish and European, have declared the demand for documentation of natural habitats (HELCOM 2007). For aquatic environments, this is an acknowledged problem, as their nature and status effectively is very hard to assess and Sweden has received some criticism from EU regarding a number of shortcomings in the existing Swedish monitoring programs. Phytoplankton (Chl a) and water transparency, often measured as Secchi depth (SD), are indicators of eutrophication and climate change, and two key factors used for assessing the ecological status within the Water Framework Directive (WFD). However, with respect to the present monitoring programs based on field samples data is usually only available as spatially and temporally limited point samples. The results from the suggested project would be a cost-efficient complement to conventional monitoring data in order to reach the demanded spatial coverage of Chl a, and contribute to enhanced water type classification of water bodies. It would also help in classification of the humic status of the lake which

If the method and products prove successful and applicable, we believe the chance for operational implementation with respect to many of the directives and management plans is good and could be realised within a relatively short time. There is a strong interest from the end user organisations to identify and introduce alternative and/or complementary methods for assessment of the ecological status in Swedish waters.

11 Project group

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12 Outreach activities

The project plans and ideas were presented at Lagans Vattendag by Petra Philipson in September 2011. Kenneth M Persson, Sydvatten, presented the project at Nordiska Dricksvattenkonferensen i Stockholm, 19-20 juni 2012. A presentation was also made by Petra Philipson, Brockmann Geomatics, at Nationella Dricksvattenkonferensen in Gothenburg, 16-18 april 2013.

Satellitbilder kan ge klarhet om Bolmens vatten

Satellitbilder kan ge klarhet i hur vattnet i Bolmen blir brunare och brunare. Länsstyrelserna i Halland, Kronoberg och Jönköping vill ta reda på hur bilderna kan användas och om de ska köpas in.

Mindre sjöar

Rymdorgan

Inbrott i Kånna

The project received some attention in "Smålänningen" during 2012.

13 References

1. Status report 2006 – "Operationalisation of Remote Sensing Methods to Support Swedish Water Quality Monitoring Organisations" (Dnr 188/05).
2. Final report 2009 – "Satellite products development for water quality monitoring in the Great Lakes and Himmerfjärden" (Dnr 189/07 and 124/09).
3. Årsrapport 2010 – "Satellitbaserad vattenkvalitetsövervakning"
4. Diversity II – D5.1 Algorithm Theoretic Baseline Document, ESA DUE DIVERSITY II – Supporting the Convention on Biological Diversity, Issue 1.0, Dec 2012.
5. K. Stelzer, P. Philipson,J. Geißler, A. Ruescas, *Requirements on Pre-processing for Retrieval of Water Quality of Lakes with Medium Resolution Data,* 3rd MERIS/(A)ATSR & OCLI-SLSTR Preparatory Workshop, Frascati, Italy, 2012.
6. The AMORGOS MERIS CFI Software User Manual & Interface Control Document: http://earth.esa.int/services/amorgos/download/Amorgos_ICD-SUM_3.0a.pdf
7. The colour of water – Climate induced variation of dissolved organic carbon in Nordic surface waters, The project was financed by the Working Group on Environmental Monitoring and Data at

the Nordic Council of Ministers (http://www.norden.org), the Department of Environmental Assessment, SLU (http://www.ma.slu.se), the Finnish Environment Institute (http://www.environment.fi/syke) and the Norwegian Institute for Water Research (http://www.niva.no). At the home pages you can obtain further information and get access to water chemistry data.

8. Schroeder, T., Behnert, I., Schaale, M., Fischer, J., & Doerffer, R. (2007). Atmospheric correction algorithm for MERIS above case-2 waters. *International Journal of Remote Sensing*, *28*(7), 1469–1486.
9. Schroeder, T., Schaale, M., & Fischer, J. (2007). Retrieval of atmospheric and oceanic properties from MERIS measurements: A new Case-2 water processor for BEAM. *International Journal of Remote Sensing*, *28*(24), 5627–5632.

Annex 1

Number of observations per lake and year after masking out invalid data. One "observation" means that at least five valid pixels could be extracted and averaged from the lake on a certain date. In column 8, the remaining part of the observations (in %) after excluding observations corresponding to less than 5 pixels are listed.

LAKE	2007	2008	2009	2010	2011	Total	Remaining observations (%) after filtering	Surface area (km^2)
Allgunnen	41	43	45	41	49	219	81	13,1
Asasjön	8	8	10	6	5	37	37	3,59
Bergsjön	4	9	6	8	5	32	27	3,17
Bolmen	64	90	70	72	78	374	95	173,01
Exen	17	12	18	16	12	75	57	3,5
Femlingen	29	37	40	35	33	174	74	13,42
Fiskestadsjön	17	22	19	21	18	97	59	5,03
Fjällen	25	25	23	21	21	115	65	6,2
Flåren	56	67	56	56	60	295	92	34,9
Frissjön	12	14	13	11	16	66	44	3,21
Furen	39	55	42	44	45	225	83	11,43
Furen	1	5	1	3	2	12	15	3,54
Havbältesfjorden	1	2	1	1	1	6	9	2,05
Helgasjön	60	70	59	62	65	316	91	50,23
Herrestadsjön	21	24	24	20	22	111	65	4,16
Hindsen	46	48	45	37	44	220	84	12,69
Hjärtasjön	0	0	0	1	0	1	5	2,29
Hyllen	16	22	20	18	17	93	53	4,77
Hängasjön	19	17	19	16	13	84	51	3,89
Hären	27	35	25	20	24	131	68	4
Hönshyltefjorden	10	9	16	9	5	49	36	5,11
Innaren	39	53	48	52	50	242	86	15
Jällunden	23	22	25	26	25	121	60	8,7
Kalvasjön	3	5	1	3	2	14	22	2,77
Klockesjön	10	18	13	11	11	63	48	2,69
Kävsjön	4	0	1	6	2	13	14	2,07
Kösen	35	47	44	35	35	196	84	11,75
Linnebjörkesjön	22	24	21	19	24	110	65	3,95
Linnesjön	1	3	3	2	1	10	13	3,75
Lyen	20	22	23	22	23	110	58	3,85
Lången	0	4	1	3	2	10	14	4,07
Lången	0	0	0	1	1	2	3	2,77
Madkroken	45	53	50	50	51	249	91	11,5
Majsjön	7	10	4	6	3	30	24	2,95
Mien	44	50	58	52	55	259	88	19,89
Mäen	18	16	16	18	15	83	60	3,14
Möckeln	53	68	60	55	62	298	90	46,05

Nejsjön	3	7	1	3	9	23	25	2,69
Norra Virestadsjön	10	4	11	8	9	42	42	2,77
Norresjö	19	24	25	16	17	101	58	2,16
Norrsjön	13	15	15	9	7	59	38	3,33
Rottnen	49	60	61	61	59	290	92	32,32
Rusken	56	64	53	58	51	282	94	33,93
Rymmen	40	49	42	40	46	217	83	10,81
Ryssbysjön	8	8	8	8	6	38	46	2,8
Römningen	17	13	21	11	11	73	49	3,75
Salen	48	57	50	46	52	253	86	17,59
Sandsjön	0	0	0	0	0	0	0	2,68
Skärlen	14	18	14	14	14	74	52	3,18
Spånen	5	11	9	7	5	37	31	2,56
Stensjön	8	7	6	7	5	33	33	5,41
Stora Färgen	33	37	39	31	35	175	76	6,27
Stora Hensjön	19	21	23	19	19	101	63	3,05
Stora Slätten	6	5	2	3	6	22	20	2,65
Stora Värmen	7	8	7	7	5	34	34	2,59
Stråken	25	25	26	23	28	127	63	7,06
Södra Färgen	13	9	9	8	13	52	37	2,8
Södra Virestadsjön	15	13	11	13	15	67	52	3,6
Södresjö	33	38	36	33	32	172	78	4,32
Sörabysjön	18	24	16	19	16	93	58	2,67
Tegnabysjön	20	32	28	32	29	141	79	4
Tiken	17	18	20	25	21	101	57	6,03
Tjurken	12	15	16	19	17	79	50	6,05
Toftasjön	10	14	8	11	12	55	40	3,31
Tolgasjön	3	7	6	4	3	23	24	3,86
Torserydssjön	5	6	3	3	2	19	22	2,1
Unnen	45	55	47	45	49	241	85	16,84
Vederslövssjön	25	26	22	19	26	118	65	5,73
Vidöstern	61	66	64	55	57	303	92	42,93
Vinen	15	17	17	12	14	75	52	3,19
Vissjön	24	40	42	31	35	172	77	6,46
Yasjön	0	0	0	1	2	3	9	3,36
Yasjön	10	10	5	6	6	37	31	2,52
Ygden	11	13	13	13	11	61	47	4,86
Årydsjön	18	14	16	19	13	80	56	4,71
Åsnen	61	75	75	76	65	352	95	72,33
Åsnen-Horgefjorden	56	69	72	70	68	335	92	63,34
Åsnen-Skatelövsfjorden	43	45	46	42	49	225	81	11,73
Änghultasjön	27	29	21	26	23	126	68	4,3
Örken	49	61	53	52	52	267	88	23,28

Örsjön	1	2	0	1	1	5	8	4,02
Övingen	3	3	9	2	2	19	24	2,4
Övrasjö	29	43	34	28	33	167	76	4,96

Annex 2

		Chl a (ug/l) – Satellite Aug mean									
EU_CD	**VYNAMN**	**2007**	**2008**	**2009**	**2010**	**2011**	**5 years, 2007-2011**	**Stdav**	**Rv**	**EK**	**STATUS_EK**
SE634690-142635	Allgunnen	7,5	6,7	5,6	8,3	4,0	6,4	1,5	2,5	0,4	G
SE633151-143906	Asasjön	3,7		3,3		2,8	3,3	0,3	3	0,9	H
SE632683-143660	Bergsjön	26,8		22,7	9,7		19,7	7,3	3	0,2	OMD
SE629511-136866	Bolmen	5,6	10,1	6,6	5,6	6,7	6,9	1,7	2,5	0,4	G
SE628376-137474	Exen	5,1					5,1	0,0	3	0,6	H
SE626855-141154	Femlingen	5,6	8,2	9,6	4,1	10,0	7,5	2,3	3	0,4	G
SE627748-144801	Fiskestadsjön	6,5	11,1	5,3	40,5		15,8	14,4	3	0,2	OMD
SE631638-135527	Fjällen	3,3	5,2	4,1	4,3	3,4	4,0	0,7	3	0,7	H
SE631542-139354	Flåren	5,1	12,0	7,3	7,6	7,1	7,8	2,3	3	0,4	G
SE634984-143880	Frissjön	6,5	3,1	3,5		5,8	4,7	1,4	3	0,6	H
SE631615-142651	Furen		3,3				3,3	0,0	3	0,9	H
SE632814-140041	Furen	5,9	10,4	5,6	6,8	5,8	6,9	1,8	2,5	0,4	G
SE626473-143260	Havbältesfjorden								3		No status class
SE630764-143570	Helgasjön	7,5	6,7	6,1	5,9	4,9	6,2	0,9	3	0,5	G
SE634225-138425	Herrestadsjön	5,4	7,5	6,6		4,3	6,0	1,2	3	0,5	H
SE634580-139854	Hindsen	4,9	5,0	4,3	3,3	3,5	4,2	0,7	2,5	0,6	H
SE635461-145821	Hjärtasjön								3		No status class
SE627285-144615	Hyllen	5,0	4,4	2,9	4,8	3,7	4,2	0,8	2,5	0,6	H
SE627691-138264	Hängasjön	5,6	8,8	4,2	2,6	4,1	5,1	2,1	3	0,6	H
SE635589-137323	Hären	7,6	10,3	7,3	4,9		7,5	1,9	3	0,4	G
SE625684-143098	Hönshyltefjorden	47,4	16,3	3,8			22,5	18,3	3	0,1	OMD
SE631978-144393	Innaren	5,3	5,0	4,7	5,8	6,4	5,4	0,6	2,5	0,5	G
SE632375-135738	Jällunden	4,2	13,3	4,7		5,6	7,0	3,7	3	0,4	G
SE627976-139651	Kalvasjön	3,5	2,7				3,1	0,4	3	1,0	H
SE634160-144871	Klockesjön		5,9	3,4		4,1	4,5	1,0	2,5	0,6	H
SE635472-138728	Kävsjön								3		No status class
SE629447-137590	Kösen	4,4	5,1	4,9	6,4	5,0	5,2	0,7	3	0,6	H
SE631522-146051	Linnebjörkesjön	13,0	4,7	3,5	3,6	2,9	5,6	3,8	3	0,5	H
SE635659-143585	Linnesjön								3		No status class
SE633331-141180	Lyen	4,8	5,6	4,3		3,9	4,7	0,6	3	0,6	H
SE633118-140608	Lången								3		No status class
SE633976-142928	Lången								3		No status class
SE632867-145547	Madkroken	6,5	6,6	5,6	6,6	6,6	6,4	0,4	3	0,5	G
SE635334-135239	Majsjön	4,1	2,9	2,9			3,3	0,6	3	0,9	H
SE625184-144083	Mien	4,3	3,6	3,6	4,1	4,8	4,1	0,5	2,5	0,6	H
SE628781-136365	Mäen	4,7	3,8		5,5	6,0	5,0	0,8	3	0,6	H
SE628323-139679	Möckeln	6,3	8,9	6,1	7,3	7,0	7,1	1,0	3	0,4	G
SE630835-135633	Nejsjön	3,8	2,6			2,7	3,0	0,5	3	1,0	H
SE627729-140872	Norra Virestadsjön	4,1				3,4	3,8	0,3	3	0,8	H
SE630480-143556	Norresjö	299,7	311,5	300,4			303,8	5,4	3	0,0	OMD
SE633177-145970	Norrsjön	4,9	3,4	4,3	7,8	5,2	5,1	1,5	3	0,6	H

SE629022-146127	Rottnen	5,6	4,5	4,9	5,7	4,4	5,0	0,5	3	0,6	H
SE634172-141113	Rusken	6,3	6,7	6,0	5,1	5,7	6,0	0,5	3	0,5	H
SE633038-141057	Rymmen	5,9	9,5	7,9	4,7	5,8	6,8	1,7	3	0,4	G
SE630069-140009	Ryssbysjön	4,1					4,1	0,0	3	0,7	H
SE627451-138444	Römningen	7,4		5,5			6,4	0,9	3	0,5	G
SE629786-142525	Salen	14,4	19,5	13,9	89,8	11,7	29,9	30,1	3	0,1	OMD
SE626406-145882	Sandsjön								2,5		No status class
SE633959-144217	Skärlen	4,8	5,3	3,1	3,8	3,9	4,2	0,8	2,5	0,6	H
SE630806-142789	Spånen	15,0	3,5			3,9	7,5	5,3	2,5	0,3	G
SE629520-139912	Stensjön	3,5	3,6				3,5	0,0	3	0,8	H
SE632043-134980	Stora Färgen	5,0	6,5	5,0	4,5	6,2	5,4	0,8	3	0,6	H
SE626258-145514	Stora Hensjön	7,1	4,7	2,9			4,9	1,7	3	0,6	H
SE631769-136737	Stora Slätten	4,0					4,0	0,0	3	0,7	H
SE634076-142599	Stora Värmen	2,9	4,4	3,9	4,4		3,9	0,6	3	0,8	H
SE632688-142513	Stråken	5,9	10,2	4,1	10,0	6,0	7,2	2,4	3	0,4	G
SE631309-134951	Södra Färgen	3,7	2,8		2,5	3,1	3,0	0,5	3	1,0	H
SE627373-140736	Södra Virestadsjön	5,7	10,7	3,2			6,6	3,1	3	0,5	G
SE630406-143665	Södresjö	215,2	228,0	160,4	170,5	299,2	214,6	49,4	3	0,0	OMD
SE632490-144339	Sörabysjön	8,0	6,8	6,9	3,5	3,0	5,6	2,0	3	0,5	H
SE629771-144547	Tegnabysjön	11,3	15,2	10,2	15,2	15,0	13,4	2,2	3	0,2	OMD
SE626085-144795	Tiken	4,8	4,8	3,2	3,5	3,5	4,0	0,7	3	0,8	H
SE630195-140578	Tjurken	3,9		2,9	3,5	3,0	3,3	0,4	3	0,9	H
SE631050-144241	Toftasjön	5,1	4,2	3,6		2,8	3,9	0,8	3	0,8	H
SE632319-143784	Tolgasjön	2,7	3,4			2,9	3,0	0,3	3	1,0	H
SE630037-135928	Torserydssjön	5,0	4,6				4,8	0,2	3	0,6	H
SE630956-136285	Unnen	4,2	5,0	3,8	4,4	3,9	4,3	0,4	3	0,7	H
SE629148-143516	Vederslövssjön	4,8	5,5	3,2	3,6	6,1	4,6	1,1	2,5	0,5	H
SE631841-138929	Vidöstern	7,6	17,8	17,3	4,9	13,8	12,3	5,2	3	0,2	OMD
SE627275-142183	Vinen	4,9	3,8	4,5			4,4	0,5	2,5	0,6	H
SE628620-139129	Vissjön	13,8	158,3	230,8	56,5	100,6	112,0	76,3	3	0,0	OMD
SE631509-135258	Yasjön	3,2					3,2	0,0	3	0,9	H
SE630732-135868	Yasjön								3		No status class
SE626980-144922	Ygden	5,8	6,8	8,3		3,6	6,1	1,7	3	0,5	G
SE630037-144977	Årydsjön	6,3	3,4	3,4		2,9	4,0	1,4	3	0,7	H
SE627964-143691	Åsnen	25,7	22,1	18,7	19,7	20,9	21,4	2,4	3	0,1	OMD
SE627546-143054	Åsnen-Horgefjorden	16,9	26,5	22,4	18,9	25,6	22,1	3,7	3	0,1	OMD
SE628984-142652	Åsnen-Skatelövsfjorden	10,2	29,7	47,8	98,2	8,7	38,9	32,9	3	0,1	OMD
SE633494-145972	Änghultasjön	4,9	4,1	4,3	3,8	5,6	4,6	0,6	3	0,7	H
SE632981-145227	Örken	5,0	4,9	5,4	5,3	4,7	5,1	0,3	2,5	0,5	G
SE626148-138684	Örsjön	3,6			3,0		3,3	0,3	3	0,9	H
SE634665-143220	Övingen	2,9		3,7			3,3	0,4	2,5	0,8	H
SE632582-144486	Övrasjö	7,6	8,2	6,4	7,6	5,0	7,0	1,1	2,5	0,4	G

Annex 3

EU_CD	VYNAMN	2007	2008	2009	2010	2011	5 year, 2007-2011	Stdav
	Colour (calibrated from CDOM- Satellite) Aug mean							
SE634690-142635	Allgunnen	55,0	56,2	53,0	50,6	25,3	48,0	11,5
SE633151-143906	Asasjön	123,8		198,5		182,5	168,3	32,1
SE632683-143660	Bergsjön	148,7		178,5	266,7		198,0	50,1
SE629511-136866	Bolmen	103,4	149,0	147,1	163,4	134,5	139,5	20,2
SE628376-137474	Exen	81,2					81,2	0,0
SE626855-141154	Femlingen	93,8	158,9	177,5	209,4	212,0	170,3	43,1
SE627748-144801	Fiskestadsjön	128,8	196,2	244,7	229,0		199,7	44,5
SE631638-135527	Fjällen	67,9	180,5	70,3	84,5	77,0	96,0	42,6
SE631542-139354	Flåren	120,5	161,3	146,5	228,8	148,9	161,2	36,3
SE634984-143880	Frissjön	49,0	15,5	29,4		32,9	31,7	11,9
SE631615-142651	Furen		135,7				135,7	0,0
SE632814-140041	Furen	134,7	132,3	131,4	230,9	137,6	153,4	38,8
SE626473-143260	Havbältesfjorden							
SE630764-143570	Helgasjön	139,8	152,2	147,4	159,9	142,3	148,3	7,2
SE634225-138425	Herrestadsjön	70,3	191,7	94,9		129,9	121,7	45,6
SE634580-139854	Hindsen	143,4	135,8	152,5	169,9	173,9	155,1	14,8
SE635461-145821	Hjärtasjön							
SE627285-144615	Hyllen	83,6	186,3	237,9	175,2	175,4	171,7	49,8
SE627691-138264	Hängasjön	42,9	53,7	31,3	16,1	26,5	34,1	13,1
SE635589-137323	Hären	53,3	68,2	69,6	41,3		58,1	11,6
SE625684-143098	Hönshyltefjorden	173,4	199,3	134,1			168,9	26,8
SE631978-144393	Innaren	84,7	130,0	128,1	128,7	131,0	120,5	17,9
SE632375-135738	Jällunden	90,9	101,9	73,7		103,3	92,5	11,8
SE627976-139651	Kalvasjön	122,9	59,9				91,4	31,5
SE634160-144871	Klockesjön		58,1	170,6		141,5	123,4	47,7
SE635472-138728	Kävsjön							
SE629447-137590	Kösen	85,5	92,6	112,8	144,3	103,5	107,7	20,5
SE631522-146051	Linnebjörkesjön	84,4	32,5	23,8	35,0	15,8	38,3	24,0
SE635659-143585	Linnesjön							
SE633331-141180	Lyen	76,7	104,7	157,7		126,1	116,3	29,6
SE633118-140608	Lången							
SE633976-142928	Lången							
SE632867-145547	Madkroken	123,7	126,7	136,5	134,8	165,5	137,4	14,8
SE635334-135239	Majsjön	38,3	16,1	17,8			24,1	10,1
SE625184-144083	Mien	94,5	108,3	71,9	130,0	88,8	98,7	19,5
SE628781-136365	Mäen	75,3	189,4		119,3	115,5	124,9	41,1
SE628323-139679	Möckeln	114,9	139,0	140,1	174,3	142,3	142,1	18,9
SE630835-135633	Nejsjön	57,9	52,1			102,3	70,8	22,4
SE627729-140872	Norra Virestadsjön	59,9				299,9	179,9	120,0
SE630480-143556	Norresjö	410,3	421,7	430,7			420,9	8,4
SE633177-145970	Norrsjön	98,8	142,0	132,6	182,6	130,1	137,2	26,9

SE629022-146127	Rottnen	96,2	143,0	123,7	137,9	119,3	124,0	16,4
SE634172-141113	Rusken	92,2	119,0	128,9	195,7	124,2	132,0	34,3
SE633038-141057	Rymmen	72,6	86,5	85,9	63,6	80,2	77,8	8,7
SE630069-140009	Ryssbysjön	39,5					39,5	0,0
SE627451-138444	Römningen	53,6		48,6			51,1	2,5
SE629786-142525	Salen	145,0	200,2	201,7	261,7	165,2	194,8	39,8
SE626406-145882	Sandsjön							
SE633959-144217	Skärlen	69,2	110,1	73,3	128,3	119,1	100,0	24,2
SE630806-142789	Spånen	123,7	150,5			193,8	156,0	28,9
SE629520-139912	Stensjön	101,6	178,6				140,1	38,5
SE632043-134980	Stora Färgen	44,9	51,2	54,2	34,0	37,3	44,3	7,7
SE626258-145514	Stora Hensjön	71,1	129,6	150,3			117,0	33,5
SE631769-136737	Stora Slätten	59,2					59,2	0,0
SE634076-142599	Stora Värmen	24,2	63,0	43,0	47,3		44,4	13,8
SE632688-142513	Stråken	102,8	111,7	124,6	202,1	147,1	137,7	35,5
SE631309-134951	Södra Färgen	58,7	160,7		126,0	138,2	120,9	38,0
SE627373-140736	Södra Virestadsjön	82,3	113,2	148,1			114,6	26,9
SE630406-143665	Södresjö	347,6	371,3	346,6	341,0	400,1	361,3	22,0
SE632490-144339	Sörabysjön	115,9	190,5	101,7	171,7	153,2	146,6	33,3
SE629771-144547	Tegnabysjön	110,1	180,6	160,6	224,3	175,4	170,2	36,8
SE626085-144795	Tiken	106,9	58,5	173,7	65,0	133,7	107,6	43,1
SE630195-140578	Tjurken	26,8		19,0	25,0	11,3	20,5	6,0
SE631050-144241	Toftasjön	162,7	135,9	193,0		122,5	153,5	27,0
SE632319-143784	Tolgasjön	68,1	214,4			215,7	166,1	69,3
SE630037-135928	Torserydssjön	72,0	146,9				109,4	37,5
SE630956-136285	Unnen	78,6	107,3	115,3	155,8	101,1	111,6	25,3
SE629148-143516	Vederslövssjön	135,4	118,2	181,7	200,5	159,5	159,1	29,9
SE631841-138929	Vidöstern	125,5	194,6	197,3	230,1	166,7	182,8	35,0
SE627275-142183	Vinen	70,7	86,3	131,4			96,1	25,8
SE628620-139129	Vissjön	138,7	308,4	381,8	278,5	275,5	276,6	78,9
SE631509-135258	Yasjön	73,4					73,4	0,0
SE630732-135868	Yasjön							
SE626980-144922	Ygden	101,9	81,3	241,5		149,0	143,4	61,7
SE630037-144977	Årydsjön	113,8	132,6	98,5		101,9	111,7	13,4
SE627964-143691	Åsnen	134,4	189,7	201,2	183,0	204,7	182,6	25,3
SE627546-143054	Åsnen-Horgefjorden	131,3	195,1	205,6	191,4	204,2	185,5	27,7
SE628984-142652	Åsnen-Skatelövsfjorden	140,2	248,3	250,2	293,0	180,5	222,5	54,7
SE633494-145972	Änghultasjön	170,0	88,3	98,0	173,8	166,0	139,2	37,8
SE632981-145227	Örken	109,1	115,7	136,1	159,5	166,6	137,4	22,9
SE626148-138684	Örsjön	25,2			32,4		28,8	3,6
SE634665-143220	Övingen	52,0		49,5			50,8	1,3
SE632582-144486	Övrasjö	120,2	161,9	172,7	156,7	165,5	155,4	18,3

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