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The use of remote sensing to detect and monitor algal and cyanobacterial blooms

At a UK and European level there is currently no suitable way to measure the frequency and intensity of algal blooms. One of the major stumbling blocks is the cost involved in undertaking sufficient sampling (and counting) of the frequency of algal blooms at a large number of sites. Additionally, a single sample may not be representative of an algal bloom, in particular cyanobacterial blooms, which can form surface scums and be blown towards lake shorelines. The use of satellite remote sensing can overcome some of these problems. The MERIS sensor on the Envisat satellite includes channels at 620, 665, 680 and 708 nm which offer the potential of measuring both chlorophyll a and cyanobacterial phycocyanin pigments (C-PC). MERIS has a high repeat cycle, allowing "sampling" approximately every 3 days, cloud cover permitting, with a spatial resolution of about 300 m and a swath width of 1150 km. There is, therefore, considerable potential for high frequency monitoring of large lakes >0.5 km^2, as required under the Water Framework Directive (WFD). While MERIS data have been used to quantify these pigments in open waters/sea water, they have not been validated for the quantification of these pigments in inland waters. However, methods have been developed for measuring both chlorophyll and cyanobacteria pigments from airborne imagery. These methods have been validated at a number of UK lakes (Norfolk Broads, Esthwaite Water, Loch Leven), although the approach is limited by the cost and logistics of hiring suitable aircraft. Therefore, it should be possible for a broadly similar approach and algorithms to be applied using satellite imagery obtained from MERIS.

Inland and near-coastal transitional waters are often optically complex because at least three constituents (phytoplankton - CHL, coloured dissolved organic matter – CDOM, and tripton) may vary independently of one another. These optically active constituents, and water itself, have an impact on the optical signature of water in the visible wavelengths (Figure 1, Klemas, 2012).

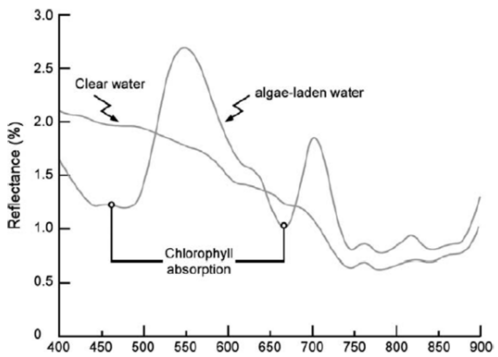

Figure 1: Reflectance for clear and algae-laden water. Chlorophyll-a strongly absorbs blue wavelengths. With increasing chlorophyll concentrations more blue is absorbed and green is backscattered by the phytoplankton (modified from Klemas, 2012).

Changes in phytoplankton biomass, as reported by conventional water-sampling programmes, are often inadequate, especially during bloom conditions when spatial and temporal variability in phytoplankton density is particularly high. Satellite remote sensing has an advantage over traditional monitoring methods for monitoring cyanobacterial blooms because it offers, synoptic coverage and temporal consistency of the data captured. Remote sensing techniques have been used successfully for monitoring lakes in response to the WFD (Bresciani et al., 2011; Odermat et al., 2010). It has the potential to provide useful information on inland and near-coastal transitional waters, which have more demanding requirements on the spectral resolution and sensitivity of instruments, the accuracy of atmospheric corrections, and algorithms for retrieving water constituents (Alikas and Reinart, 2008; Binding et al., 2011; Guanter et al., 2010; Matthews et al., 2010; Olmanson et al., 2011; Tarrant et al., 2010).

Satellites with multispectral sensors such as IKONOS, LISS 3 and 4, SPOT 4 and 5, or Landsat 5 and 7, with high spatial resolutions (4 to 30 m), primarily designed for terrestrial applications, have the capability of measuring the spatial characteristics of lakes as small as a hectare. However, the spectral and radiometric configurations of the instruments generally limit their use for use with aquatic purposes. Their relatively broad spectral resolution impedes the detection of certain types of features, and the absence of near infra-red (NIR) bands makes the correction of atmospheric effects challenging. Sensors of ocean-colour, such as MODIS and MERIS, have acquisition frequencies of between 1 and 3 days), and spectral bands suitable for the detection of water constituents and atmospheric correction. However, a disadvantage for the monitoring of inland waters is their relatively low spatial resolution of between 250 m and 1000 m (Matthews, 2011). Table 1 summarises the main spatial, temporal and spectral characteristics of key sensors.

Table 1. Characteristics of medium resolution satellites and sensors (modified from Olmanson et al., 2011)

Satellite/Sensor	Spatial and Temporal Characteristics		Number of Spectral Bands				
	Resolution (m)	Frequency (days)	Visible	NIR	SWIR	Thermal	Total
Landsat	30	16	3	1	2	1	7
Envisat/ MERIS	300	3	9	6			15
Aqua and Terra/ MODIS	250	1	1	1			2
Aqua and Terra/ MODIS	500	1	3	2	2		7[a]
Aqua and Terra/ MODIS	1000	1	10	6	4	16	36[a]

[a] Includes lower resolution bands.

MODIS and MERIS provide standard operational algorithms to produce products relating to Chlorophyll (CHL). Simple, semi-analytical methods, employ band ratios of the secondary CHL absorption maximum (wavelength of around 675 nm) and adjacent spectral bands which are not affected by CHL absorption. These latter spectral bands are the near-infrared (NIR) reflectance peak near MERIS' 709 nm, MODIS' 748 nm, or a combination of MERIS' 709 nm and 754 nm. Simultaneously acquired sets of limnological, atmospheric and remotely sensed data are used to derive site-and-time specific algorithms for study specific parameters using statistical regression techniques. Generally, these experimental algorithms produce robust results for the geographic areas and datasets from which they are derived (Gurlin et al., 2011; Matthews, 2011).

The mapping of cyanobacterial blooms is commonly based on the assumption that such features are the only cause of an increased signal in the imagery. However, several challenges require to be overcome if remote sensing techniques are to be used to assess water quality in inland and coastal waters on a routine basis. These include the development of appropriate methods for atmospheric corrections, a detailed evaluation of existing sensors and the development of sensors and satellites with spatial and spectral specifications suited to the task, and development of algorithms to extract water quality information from raw sensor data. In particular, alternative atmospheric correction methods are necessary to enable extraction of information in very turbid waters, in which the reflectance in the NIR exceeding reflectance in visible bands (Kratzer et al., 2008; Olmanson et al., 2011; Klemas, 2012).

Key issues relating to the use of remote sensing methodologies for monitoring water quality in inland waters are:

- the availability of satellite data being limited by orbit characteristics of different types of satellites, cloud cover, and contamination due to sun-glint,
- limited generalisations from algorithms, which are often image specific and not applicable to images obtained under different conditions,
- lack of availability of *in situ* measurements,
- a need for methods for *in situ* collection of cyanobacteria from subsurface layers or surface scum when developing algorithms and validating satellite maps,
- the relatively coarse spatial resolution of nearly all satellites compared to the spatial heterogeneity of cyanobacterial blooms,

- poor quality estimates of chlorophyll from algorithms due to: i) high amounts of dissolved organic matter, ii) suspended matter in the water (e.g. silt and particulates), and (iii) the saturation of relevant spectral channels in cases of heavy algal blooms.

Results from modelling studies (e.g. Kutser et al., 2006) show that multispectral sensors like those on Landsat or MODIS are incapable of distinguishing waters dominated by cyanobacteria from waters dominated by algae species. This is because their spectral band configuration does not allow the detection of absorption features caused by phycocyanin (present in cyanobacteria), or any other spectral features that are characteristic of cyanobacteria. MERIS allows the detection of phycocyanin absorption near 630 nm, and a small peak in reflectance spectra near 650 nm which is characteristic of waters dominated by cyanobacteria. Thus, MERIS can be used in identifying cyanobacteria if they are present in relatively large quantities. However, the detection of emerging blooms may not be possible because the phycocyanin absorption feature only becomes detectable by MERIS when chlorophyll-a concentrations reach values of approximately 10 to 30 mg/m^3 (depending on species).

MODIS and MERIS imagery have been used routinely for global-scale assessments of oceanic and sea CHL (e.g. Hansson and Hakansson, 2007; Kratzer et al., 2008; Kutser et al., 2006; Park et al., 2010; Reinart and Kutser, 2006), but only a few studies have examined their use for studies of coastal waters and lakes (e.g. Alikas and Reinart, 2008; Binding et al., 2011; Guanter et al., 2010; Matthews et al., 2010; Olmanson et al., 2011; Tarrant et al., 2010). Findings from these latter studies indicate that MODIS and MERIS offer good potential for monitoring CHL and coloured dissolved organic matter (CDOM). MERIS is perhaps the best suited of these sensors for monitoring coastal inland water-quality, with a full resolution of approximately 260 × 300 m at nadir and 15 spectral bands in the visible and NIR wavelengths.

In conclusion, recent studies showed that environmental monitoring of surface waters can take advantage of remote sensing techniques which provide a synoptic view over large areas and frequent acquisitions. For this, *in situ* data are necessary for the calibration and validation of satellite based models. Both MODIS and MERIS imagery are well-suited for regional assessments of CHL and other optically related water quality characteristics of large inland lakes, but their coarse spatial resolution greatly limits the number of lakes that can be assessed. The spatial resolution of Landsat satellites allows lakes < 4 ha in area to be assessed, but its low spectral resolution limits it to assessments of water clarity (Olmanson et al., 2011). However, there is evidence that remotely sensed imagery and analysis could be exploited for the implementation of the EU-WFD (e.g. Bresciani et al., 2011).

The benefits of MERIS and MODIS satellite imagery merit further research to assess their capability for addressing challenges to the monitoring of cyanobacterial blooms. Such research would include the application of algorithms developed and validated for UK lakes using airborne imagery and *in situ* data.

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