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Assessment of temporal variations of water quality in inland water bodies using atmospheric corrected satellite remotely sensed image data

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Abstract Although there have been many studies conducted on the use of satellite remote sensing for water quality monitoring and assessment in inland water bodies, relatively few studies have considered the problem of atmospheric intervention of the satellite signal. The problem is especially significant when using time series multi-spectral satellite data to monitor water quality surveillance in inland waters such as reservoirs, lakes, and dams because atmospheric effects constitute the majority of the at-satellite reflectance over water. For the assessment of temporal variations of water quality, the use of multi-date satellite images is required so atmospheric corrected image data must be determined. The aim of this study is to provide a simple way of monitoring and assessing temporal variations of water quality in a set of inland water bodies using an earth observation-based approach. The proposed methodology is based on the development of an image-based algorithm which consists of a selection of sampling area on the image (outlet), application of masking and convolution image processing filter, and application of the darkest pixel atmospheric correction. The proposed method has been applied in two different geographical areas, in UK and Cyprus. Mainly, the method has been applied to a series of eight archived Landsat-5 TM images acquired from March 1985 up to November 1985 of the Lower Thames Valley area in the West London (UK) consisting of large water treatment reservoirs. Finally, the method is further tested to the Kourris Dam in Cyprus. It has been found that atmospheric correction is essential in water quality assessment studies using satellite remotely sensed imagery since it improves significantly the water reflectance enabling effective water quality assessment to be made.

Keywords Outlet · Temporal variations · Water quality · Atmospheric correction · Remote sensing

Introduction

It has been shown by several other researchers, who studied the actual relationship between water properties (i.e., water quality) and satellite

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data for several types of water bodies and geographical extensions, that satellite remote sensing techniques show more important advantages than traditional sampling (Dekker et al. 1995; Pulliainen et al. 2001; Chen et al. 2007; Pozdnyakov et al. 2005; Hadjimitsis et al. 2006; Ormeci et al. 2008; Weiqi et al. 2008). Firstly, the continuous geographical coverage of satellite imageries provides continuous water quality information about the whole water body. Secondly, remote sensing allows us to obtain information about inaccessible places. Finally, historical satellite images provide estimation of historical water quality and offer an excellent way to monitoring the water quality temporal evolution as well. Weiqi et al. (2008) reported that, with the development of remote sensing techniques, water quality monitoring based on remote sensing methods has become accessible and very efficient.

Although several satellite remote sensing systems have been used for water quality assessment and monitoring, the relatively low cost, temporal coverage, spatial resolution, and data availability of the Landsat system make it particularly useful for water quality assessment and monitoring of inland water bodies (Hadjimitsis et al. 2000a, 2006). Several studies have demonstrated a strong relationship between Landsat-5/7 Thematic Mapper (TM) or Enhanced Thematic Mapper (ETM+) data and ground observations of water quality parameters such as chlorophyll-*a*, suspended solids, turbidity, etc. (e.g., Lillesand et al. 1983; Carpenter and Carpenter 1983; Lathrop and Lillesand 1986; Lathrop 1992; Baban 1993; Arenz et al. 1996; Cox et al. 1998; Giardino et al. 2001; Kloiber et al. 2002a, b; Dewidar and Khedr 2001; Wang et al. 2004; Vincent et al. 2004; Hadjimitsis et al. 2006). Most of the published works in which Landsat MSS, TM, Spot HRV, or other image data have been used for monitoring inland water quality studies comprise the use of sampling measurements in combination with the digital imagery either using radiance or reflectance (Harris et al. 1976; Verdin 1985; Lathrop and Lillesand 1986; Gitelson et al. 1993; Mayo et al. 1995; Arenz et al. 1996; Härmä et al. 2001; Kloiber et al. 2002a, b; Dekker et al. 2001; Zhang et al. 2002, 2003; Chen et al. 2007). Many researchers have investigated the temporal changes of water quality in inland water bodies using ground data (for example, Nellis et al. 1998). The use of satellite remote sensing can only replace the ground campaigns after continuous testing and calibration of the proposed image-based methods and after considering the atmospheric effects to the at-satellite receiving signal. Many inland water quality studies have used non-calibrated and non-atmospheric corrected data, producing results that are neither comparable temporally nor spatially (Verdin 1985; Chen et al. 2007). Optical remote sensing data are affected by the atmosphere. These effects can be removed using suitable atmospheric corrections and bi-directional reflectance models (Zhang et al. 2003; Hadjimitsis and Clayton 2008).

To overcome these limitations, the authors provide a new method for assessing temporal variations on the sampling point (outlet) of each inland water body such as water treatment reservoir or water dam.

Materials and methodology

Study areas

The proposed method has been applied into two different geographical areas, the Lower Thames Valley in vicinity of Heathrow Airport in the UK and the Kourris Dam located in the Limassol District area in Cyprus.

Lower Thames Valley, West London (UK) The first study area is located to the south and the west of London Heathrow Airport in the UK. It includes many inland water bodies such as reservoirs, rivers, lakes, and ponds. Emphasis has been given to the larger reservoirs in the Lower Thames Valley (see Fig. 1). The Lower Thames Valley Reservoirs are characterized as eutrophic and are used for a number of purposes such as for storage of water, as the first stage of potable water treatment, and for recreational purposes. Despite the fact that cloud cover is a major problem in this area (Hadjimitsis et al. 2004), it has been found that satellite remote sensing and especially Landsat TM imagery can be a useful tool for monitoring water quality in such reservoirs as well to assist the water resources managers to locate new

Fig. 1 Partial scene of the Heathrow area and Lower Thames Valley reservoirs (Landsat-5 TM image acquired on 2/6/85)

sampling points based on the synoptic assessment of satellite images (Hadjimitsis 1999).

Kourris Dam, Limassol (Cyprus) The second study area is the Kourris Dam which is located in Cyprus, in Limassol District near to Alassa village (see Fig. 2). Grass, roads, and trees are the main nearby features around Kouris dam. The rivers Limnati, Krios, Diarizos, and Kourris provide the source of water that is passed to the Kourris Dam.

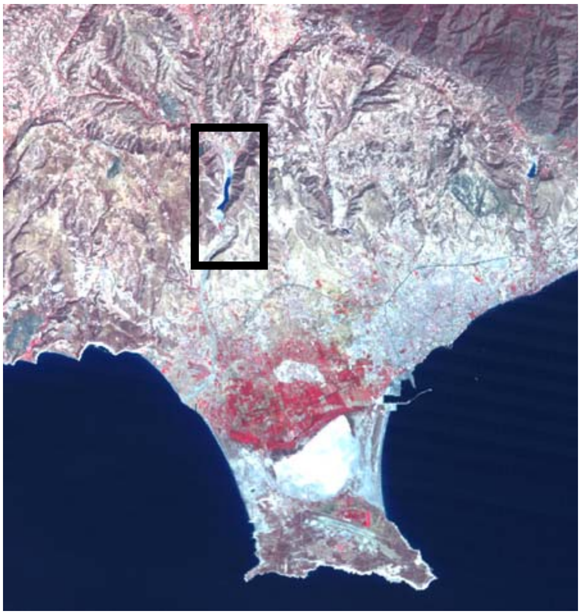

Fig. 2 Sub-scene image of Limassol area including Kourris Dam location (Landsat-5 TM image acquired on 11th of September 1998)

Water from Kourris Dam is used both for agricultural and water supply (potable water) purposes. Indeed, the raw water flows to the Limassol Water Treatment Plant by gravity from Kourris Dam through the Southern Conveyor Main Pipeline. Large dams such as Kourris, which is the biggest dam in Cyprus, have been constructed for the collection and storage of water. In order to meet the required standards, the Cyprus Water Development Department takes periodically in situ samples in all dams especially in the summer period in which the presence of algae is a considerable nuisance. The only tools that have been available to monitor water quality are based on direct physical sampling, which requires considerable resource.

Images

Eight Landsat-5 TM images covering the Lower Thames Valley Area in the UK and acquired on 5-3-85, 17-5-85, 2-6-85, 4-7-85, 29-9-85, 8-10-85, 24-10-85, and 9-11-85 were used for the full application of the proposed method. Five Landsat-5 TM and ETM+ images of Kourris Dam in Cyprus acquired on 11/9/1998, 11/5/2000, 30/1/2001, 30/5/2004, and 7/6/2004 were also used to retrieve the importance of applying an atmospheric correction in water quality assessment studies. Sub-scenes under investigation were extracted for display and further analysis using ERDAS IMAGINE (version 9.3) digital image processing software.

Methodology

The overall methodology of this study is presented in Fig. 3. The novel parts of the proposed methodology which has been developed to assess the temporal variations of water quality for any inland water body include the following prior to the sub-setting, application of geometric correction, conversion of raw digital numbers to units of radiance, and reflectance:

> *Masking*: Mask out the land so that only the inland water bodies (e.g., reservoirs) could be seen using the masking algorithm of the ERDAS Imagine 9.3 software.

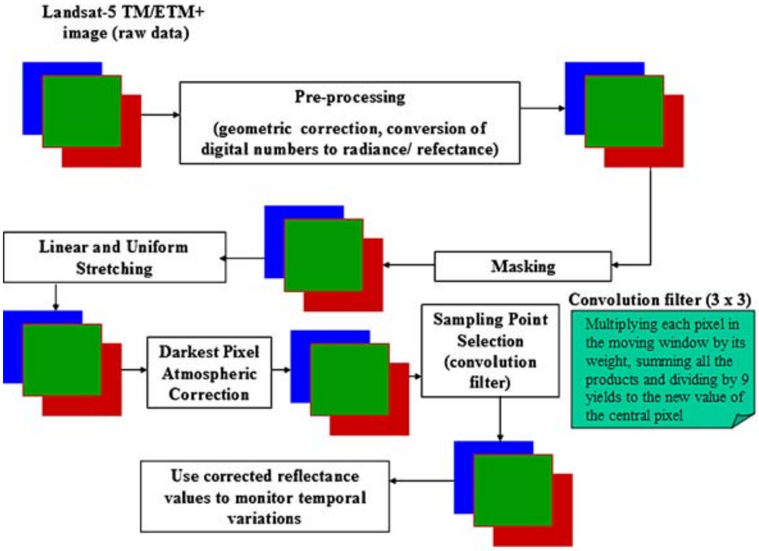

Fig. 3 Overall methodology

Stretching: Apply an automatic linear stretch to each image. Then apply a uniform stretch to all the images, to expose temporal variations in image brightness.

Atmospheric correction: Apply the darkest pixel atmospheric correction.

Sampling point selection: Select an area of interest that corresponds to the outlet sampling point of the water treatment reservoir using masking and convolution filters.

Then, by applying contrast stretch and unsupervised classification techniques (choose five or more classes), mapping of the water quality temporal variation can be achievable. Indeed, by retrieving the atmospheric corrected reflectance values, the comparison of reflectance values from image-to-image date, an assessment of the water quality variations can be done for each spectral band.

The steps of the overall methodology shown in Fig. 3 are explained below:

Geometric correction: Images were registered to the Universal Transverse Mercator (UTM) coordinate system using and nearest neighbor resampling. Careful selection of approximately twenty five (25) well-defined and well-distributed ground control points such as road intersections, airport runway intersections, bends in rivers, and corners of inland water bodies resulted in positional accuracy (RMSE) equal or smaller than ±0.25 pixels, or 7.5 m.

Radiometric correction-conversion of DN to units of radiance and reflectance: An important step in the development of methods for monitoring change is the ability to compare images from different dates and sites in different scenes. These comparisons require the digital numbers from each image to be calibrated to common reference values. The raw data values recorded by the sensors on the satellite are not consistent in this way. Based on the fact that the proposed method is valid for multi-date images, the satellite imagery were converted into units of radiance and finally to at-satellite reflectance (i.e., reflectance recorded at the satellite sensor) using standard calibration values for Landsat-5 TM. The methodology that based on the conversion of DN to at-satellite radiance (i.e., reflectance recorded at the satellite sensor) values using calibration offset and gain coefficients for each spectral band is well accepted. The information about sensor calibration parameters is usually supplied with the data (Mather 2004). Ideally, all images would be calibrated to reflectances. Reflectance, which is defined as the percentage of incident radiation reflected by the surface material, is a physical property of every substance. So, the next step is to convert the at-satellite radiance (or radiance recorded at the satellite sensor) values into at-satellite reflectance.

$$\rho_{tg} = \frac{\pi \cdot L_{ts}}{E_0 \cdot \cos(\theta_0) \cdot d}$$

where

ρ_{tg} is the “at-satellite” reflectance
L_{ts} is the spectral target radiance at the sensor (or “at-satellite” radiance)
E_0 is the spectral solar irradiance at the top of the atmosphere, sometimes termed as exo-atmospheric or extra-terrestrial irradiance
θ_0 is the solar zenith angle
d correction factor accounts for variation of sun–earth distance: ratio of mean to actual earth/sun distance

Masking: Using a mask image to eliminate the undesired area of an image is an important technique in remote sensing analysis. The principle behinds the mask technique is to multiply the source image by the mask image that contains two values,—1 for preserved areas and 0 for undesired areas. ERDAS Imagine has a building mask function, which is hidden in the Interpreter\Utilities menu.

Stretching: Linear stretching is an important part of interpretation of digital imagery. It is one of the methods used to re-scale the image brightness to ranges that can be accommodated by human vision and computer displays (Campbell 2007). Linear stretch converts the original digital values into a new distribution using minimum and maximum values specified by the user. The algorithm then matches the old minimum to the new minimum and the old maximum to the new maximum, respectively. All the old intermediate values are scaled proportionately between the new minimum and maximum values (ERDAS 2008; Campbell 2007; Mather 2004). The effect of a linear stretch is to make the original bright areas to appear brighter and the original dark areas to appear darker.

Then a linear stretching will be applied to a series of Landsat TM images. The effect of a linear stretch is to increase contrast, whilst brightening the image. In order to retrieve visual information regarding the temporal variations in the reservoirs and to find evidence for the need to apply atmospheric correction, the automatic and uniform stretching was carried out after applying the masking window algorithm (Hadjimitsis et al. 2000b) (see Fig. 4a).

The comparison of all the images acquired on different dates cannot be applied without using a uniform stretch which is the third step of the proposed procedure. When a uniform stretch is applied, image-to-image brightness variations (temporal variations) will be more apparent.

Atmospheric correction: Any sensor that records electromagnetic radiation from the earth’s surface using visible or near-visible radiation will typically record a mixture of two kinds of energy. The value recorded at any pixel location on a remotely sensed image does not represent the true ground-leaving radiance at that point. Part of the radiance or reflectance is due to the radiance or

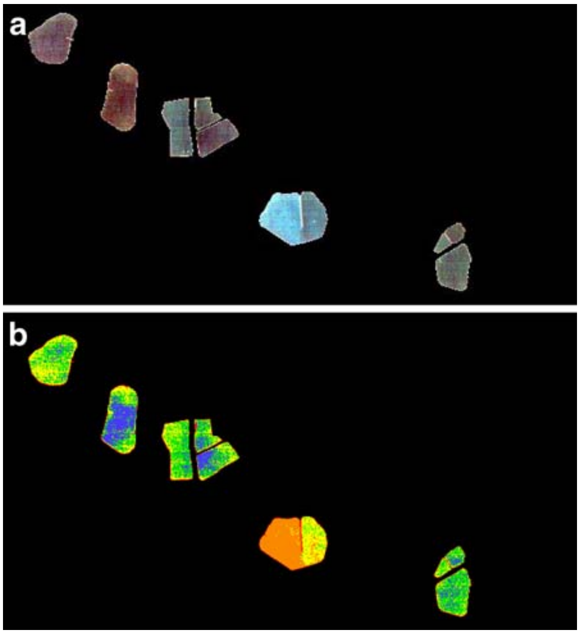

Fig. 4 **a** Illustration of a masked image (after contrast stretch), **b** illustration of the unsupervised classification (5-classes) map of the Lower Thames Valley in the West London

reflectance of the target of interest and the remainder is derived from the brightness of the atmosphere itself. The separation of contributions is not known a priori, so the objective of atmospheric correction is to quantify these two components so that the main analysis can made on the correct target reflectance or radiance values. The darkest pixel (DP) atmospheric correction method, also termed histogram minimum method (Hadjimitsis 1999, 2008; Hadjimitsis et al. 2000b, 2003, 2004, 2006; Hadjimitsis and Clayton 2008), was applied to the eight satellite images of the Lower Thames Valley reservoirs. The DP method was found to produce reservoir reflectance values within the range of ground measurements acquired in the reservoirs using a field GER1500 field spectro-radiometer Hadjimitsis et al. (2004).

The darkest pixel approach requires identification of a dark object within the image, estimation of the at-satellite radiance (radiance recorded at the satellite sensor) over the object, and subtraction of that level from every pixel in the satellite image. To determine the target reflectance at ground level (i.e., reflectance of the inland water body) after taking into account the assumed values for the transmittance (equal to one), the following simplified equation can be used (Hadjimitsis et al. 2006):

$$\rho_{\mathrm{tg}} = \frac{(L_{\mathrm{ts}} - L_{\mathrm{ds}})}{E_0 \cdot \cos(\theta_0) \cdot d}$$

Where

ρ_{tg}	is the target reflectance at the ground
L_{ds}	is the dark object radiance at the sensor
L_{ts}	is the target radiance at the sensor,
$E'_0 = E_0 \cdot d$	is the solar irradiance at the top of the atmosphere corrected for earth–sun distance variation, i.e., $E_0 \cdot d$
θ_0	is the solar zenith angle

Sampling point selection: One of the most important steps is acquiring a representative image sample from each inland water body such as reservoir near the outlet source. Ideally, the sample should represent the center portion of the inland water body or at the outlet sampling station in a 'safe distance' of water, where reflectance from vegetation, the shoreline, or the reservoir bottom will not affect the spectral signature.

By applying a masking filter using the ERDAS Imagine software v.9.3, a "water-only" image has been done (ERDAS 2008). Then a convolution filter of minimum 3 × 3 pixels is applied. Convolution filtering is the process of averaging small sets of pixels across an image. Convolution filtering is used to change the spatial frequency characteristics of an image (ERDAS 2008). A convolution kernel is a matrix of numbers that is used to average the value of each pixel with the values of surrounding pixels in a particular way (see Fig. 3). The numbers in the matrix serve to weight this average toward particular pixels. Each pixel value is replaced by the average over a square area cantered on that pixel. This square array is called a moving window, or kernel, since in the computer manipulation of an image the array can be envisioned as moving systematically from one pixel to the next. This filter eliminates the possibility of a background effects by determining the average water reflectance value at the outlet.

Variations of reflectance values after atmospheric correction indicate that such changes are due to variations of water quality.

An unsupervised classification is performed on the water-only image (as shown in Fig. 4b). Average brightness values from the unsupervised classification of this image are graphed to show spectral signatures of each class using atmospheric corrected data. These signatures along with the location where the pixels occur can be used to differentiate classes containing clear water, turbid water, and shallow water as well as map both spatial and temporal variations of water quality. This is an optional step of the proposed method.

Results and discussion

Lower Thames Valley Area (UK)

When a uniform stretch was applied, image-to-image brightness variations (temporal variations) were more significant than the reservoir-to-reservoir variations (spatial variations). Very noticeable variations in brightness occurred, temporally (but not spatially), with the brighter images being those acquired on 17/5/85 (see Fig. 5) and 4/7/85 (see Fig. 6) in comparison with the others, e.g., the one acquired on 2/6/1985 (see Fig. 7). These temporal variations provide evidence of significant atmospheric effects. Indeed, in order to get a true picture of the real values of water reflectance which will provide tool for assessing the temporal variations of water quality from image-to-image dates, as it has been mentioned in the previous section, an atmospheric correction has been applied. Table 1 shows the reflectance values in Landsat TM band 1 and band 2 before and after the application of the atmospheric correction for the Queen Mary reservoir (the largest reservoir in the scene). Previous studies related to the retrieval of water quality parameters using ground spectroradiometric measurements show that chlorophyll-*a* is best retrieved in Landsat TM band 1, particulate organic carbon (POC) in Landsat TM band 2, and turbidity in Landsat TM band 3 (Hadjimitsis 1999; Hadjimitsis et al. 2006).

The green pigment chlorophyll is present in photosynthetic organisms and provides an indirect measure of algal biomass (the amount of algae present in water) and an indication of the *trophic status* of a water body. The most common indicator of algae is chlorophyll-*a*. Chlorophyll-*a* is usually included in the assessment programs for lakes and reservoirs and is an important parameter for the management of water abstracted for drinking water supply since any excessive algal growth makes water more difficult to treat and may cause problems in the water treatment filters (blocking). The growth of algae in a water body is related to

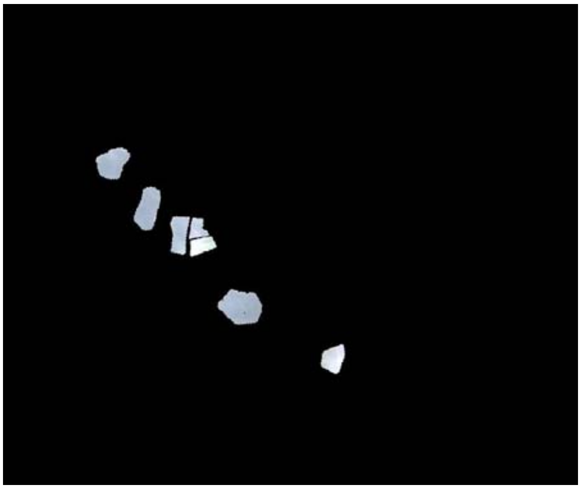

Fig. 5 Illustration of a masked image acquired on the 4th of July 1985 after uniform stretch

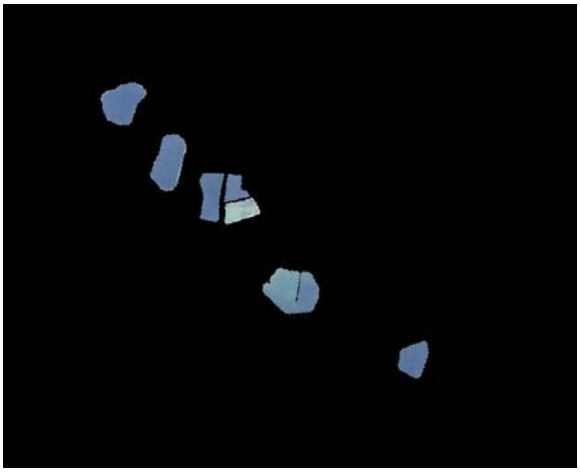

Fig. 6 Illustration of a masked image acquired on the 17th of May 1985 after uniform stretch

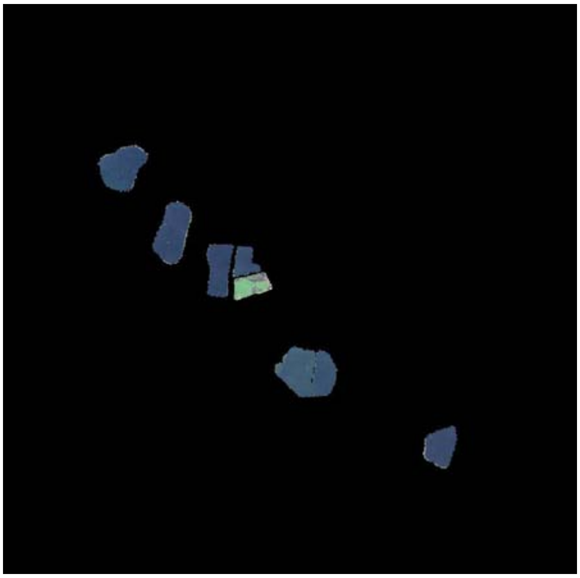

Fig. 7 Illustration of a masked image acquired on the 2nd of June May 1985 after uniform stretch

Table 1 Reflectance values of the Queen Mary Reservoir before and after atmospheric correction in Landsat-5 TM bands 1, 2, and 3

Image date	TM band 1 (%)		TM band 2 (%)	
	Before AC	After AC	Before AC	After AC
5/3/85	11.7	1.9	8	2.4
17/5/85	12.3	1.1	8.8	1.1
2/6/85	9.8	1.9	6.4	2.1
4/7/85	13.7	0.5	10.7	0.4
29/9/85	13.3	1.9	9.6	2.4
8/10/85	13.7	3.9	10.4	4.4
24/10/85	15.8	5.8	11.5	7.2
9/11/85	13.8	2.4	9.1	3.1

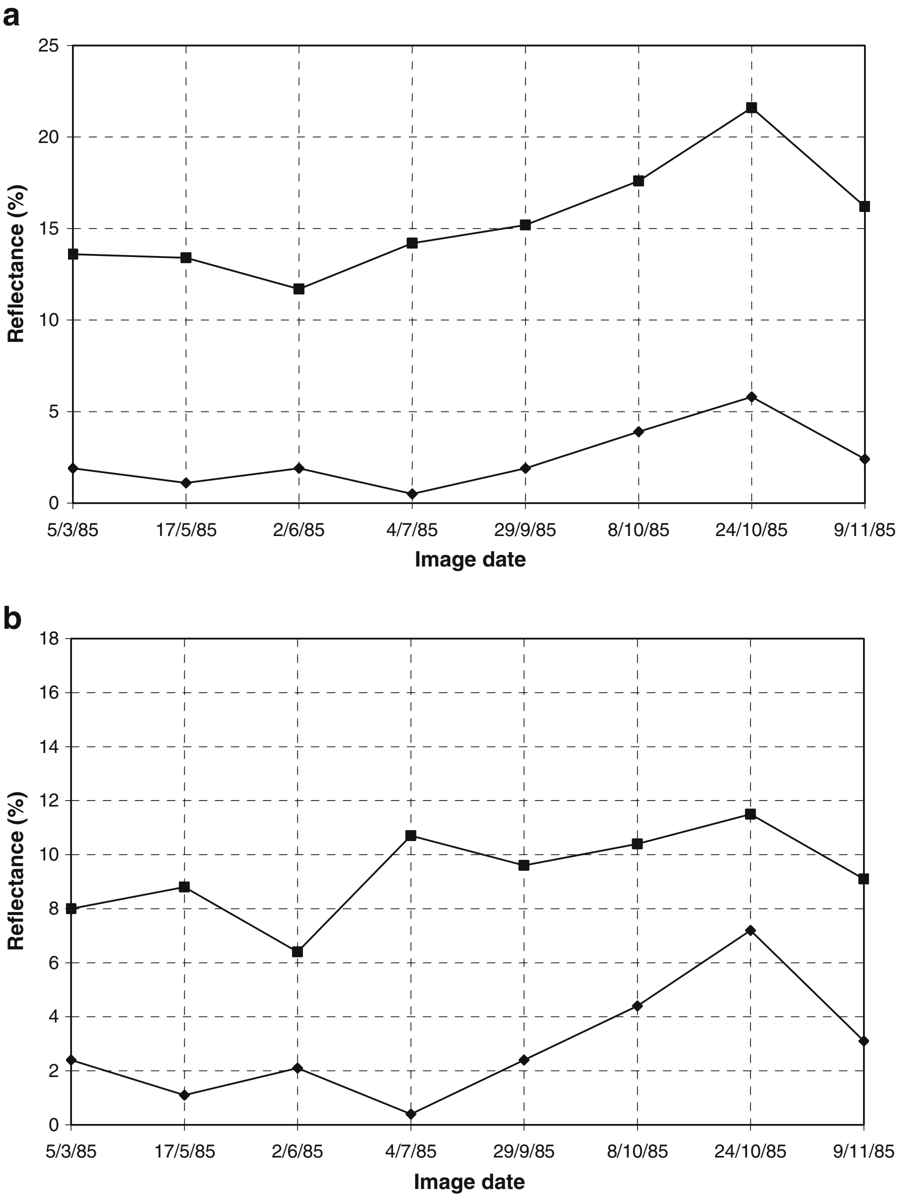

Fig. 8 Temporal variations of reservoir's reflectance values before and after atmospheric correction for Landsat TM bands 1 (**a**) and 2 (**b**)

the presence of nutrients, temperature, and light. Concentrations of chlorophyll change daily and seasonally, and vary with water depth depending on the prevailing environmental conditions.

For the images acquired on 5/3/85 and 8/10/85, sampling data were available during the satellite overpass for the Queen Mary reservoir such as:

- Chl-*a*: 6.8 mg/l, POC: 836 mg/l for the image acquired on the 5th of March 1985
- Chl-*a*: 13 mg/l, POC: 1,221 mg/l for the image acquired on the 8th of October 1985

From Table 1, it is apparent that low Chl-*a* concentrations correspond to a low reflectance value, 1.9%, and relatively high concentrations correspond to high reflectance value, 3.9%, in the Landsat TM band 1. This is also valid for the POC concentrations.

Figure 8 shows the temporal variations of the water reflectance value using atmospheric corrected data for TM bands 1, 2, and 3. From previous investigations, it has been found that, for reflectance values of greater or equal to 7% in the TM band 2 (Hadjimitsis 1999), the reservoir is considered as hypertrophic (i.e., high concentrations of chlorophyll-*a*). Such case is considered to be the 'alert sign' for possible blockage of the water treatment filters, so a considerable care is required to 'stop' the water passage from the reservoir's outlet to the treatment plant for reflectance values near or equal/greater than 7%. It is apparent that non-atmospheric corrected data lead to inadequate water quality assessment since erroneous results are produced as shown from Table 1 (much overestimated values).

Kourris Dam (Cyprus)

From a previous study, Hadjimitsis et al. (2006) show how the turbidity has been determined in the Kourris Dam in Cyprus using Landsat TM band 3 image data. The proposed method has been applied to a series of Landsat TM/ETM+ images acquired on the following dates: 11/9/1998, 11/5/2000, 30/1/2001, 30/5/2004, and 7/6/2004. Turbidity values were available for each of the above image dates acquired in situ on the outlet point of the dam. When atmospheric corrected logarithmic reflectance (Log *r*) in the Landsat TM band 3 were correlated against turbidity, before atmospheric correction correlation coefficient was $R = 0.46$ and after atmospheric correction was $R = 1$. This means that the use of calibrated and atmospheric corrected data increases the correlation coefficient between satellite data and turbidity and the assessment of the temporal variations can be more effectively produced. From Table 2, it is apparent that values of reflectance (before atmospheric correction) of 8% and 7.6% in the TM Band 3 for the images acquired on 11/9/1985 and 07/06/2004 may correspond to turbid water. However, after the application of the proposed method in which atmospheric correction has been applied, values of reflectances reduced to 4.6% and 1.8%, respectively, which are much closer with the acquired turbidity values. Variations of reflectance values after atmospheric correction indicate temporal variations of water quality as shown in Fig. 9.

Table 2 Reflectance values of the Kourris Dam before and after atmospheric correction in Landsat-5 TM/ETM band 3

Image date	Turbidity (NTU)	TM band 3 (%)	
		Before AC	After AC
11-9-1998	8.8	7.6	4.6
11-5-2000	5.52	5	2.7
30-1-2001	11.2	9.8	3.8
30-5-2004	2.56	8	1.7
7-6-2004	2.86	7	1.8

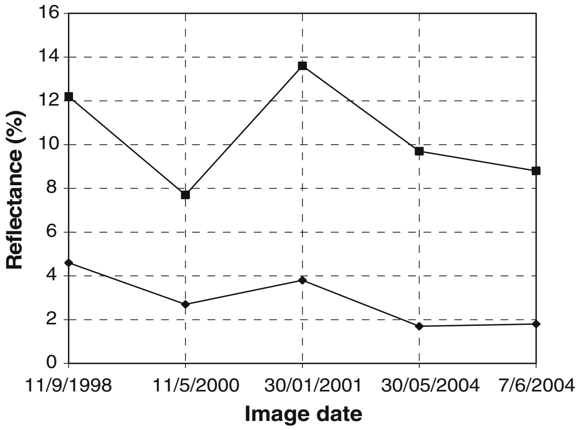

Fig. 9 Temporal variations of Kourris Dam reflectance values before and after atmospheric correction for Landsat TM bands 3

Conclusions

This study shows that the satellite remote sensing has been found to be useful for assessing the water quality using atmospheric corrected image data in the Lower Thames Valley water treatment reservoirs in UK and in the Kourris Dam in Cyprus. In particular, the proposed method has been found effective to image temporal variations of water quality between scenes.

For the Lower Thames Valley area, it has been shown that high reflectance values after applying atmospheric correction correspond to very turbid water on the 24th of October 1985, so the water could not pump to the water treatment plant. For the period March to September, the temporal variations stay within the limits of eutrophic status; however, on October to November, considerable attention must be taken into account to control problems of hypertrophic status. Very noticeable variations in brightness occurred temporally when the uniform stretch has been applied. Indeed, the application of convolution filter assists the selection of the appropriate sampling position of the outlet of the inland water body.

For the Kourris Dam in Cyprus, it has been shown that the application of the atmospheric correction in the Landsat TM/ETM+ band 3 data increases the correlation coefficient between the reflectance values and the turbidity data acquired during the satellite overpass.

It has been found that atmospheric correction is essential in water quality assessment studies using satellite remotely sensed imagery since it improves significantly the water reflectance. This permits the qualitative water quality assessment from the images themselves. The production of masked images has been found useful to the water resources managers for understanding the water quality distribution.

An ideal setup of this study requires a large dataset in space and time (more satellite images, more in situ water quality observations and in situ spectro-radiometric measurements) to test further the proposed method.

Future tasks consist of the following: further validation of our method including more ground water sampling data during the satellite overpass and the use of trophic state index for the production of temporal variations maps. Subsets of in situ samples in some "test water bodies" must be carried out on a systematic basis, in order to test calibrate the relationships between water quality properties and satellite imaginary information continuously. Besides, this satellite remote sensing-based approach could be applied to other basins and to other image data such as Moderate Resolution Imaging Spectroradiometer (MODIS) and MEdium Resolution Imaging Spectrometer (MERIS). Modern advanced satellite sensors such as MODIS and MERIS can provide a better understanding of water quality monitoring, since they are able to measure the radiance leaving surface water in six or more bands in the VNIR region (Kallio et al. 2005).

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