Lake water quality monitoring using hyperspectral airborne data—
a semiempirical multisensor and multitemporal approach for the
Mecklenburg Lake District, Germany

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Abstract

This study presents an approach for the determination of the trophic parameters Secchi disk transparency and chlorophyll-α from hyperspectral airborne CASI and HyMap data with multitemporal validity. Based on in situ water sampling and reflectance measurements, algorithms have been developed. For Secchi disk transparency, the area between a base line and the spectrum from 400 to 750 nm was calculated and correlated to the Secchi disk transparency measured in situ; chlorophyll-α concentration was quantified using the existing reflectance ratio at 705 and 678 nm, which showed a linear relationship to chlorophyll-α concentration from laboratory spectrophotometric measurements. The algorithms have been adapted to the spectral characteristics of the airborne sensors and applied to these data recorded in September 1997 and 1998 and May and June 1999. The validation using independent in situ reference data showed mean standard errors of 1.2–1.3 m for Secchi disk transparency and of 10.2–10.9 μg/l chlorophyll-α. © 2002 Elsevier Science Inc. All rights reserved.

1. Introduction

The investigation and description of the system properties of inland waters, as well as water pollution control and water maintenance, are some of the main tasks in applied limnology (Schwoerbel, 1991). In this context, registration and monitoring of the trophic state are important tools. Secchi disk transparency and chlorophyll-α concentration are among the most common trophic parameters (Carlson, 1977; Schäfer, 1997; Schröder, 1994; Vollenweider, 1989) because they are relatively easy to be obtained in situ (Vietinghoff, 1999). Secchi disk transparency is a measure of the transparency of a water body, and it is influenced by the abundance of organic and inorganic particulate and dissolved matter (Schäfer, 1997). The availability of light is important for the photosynthesis of phytoplankton and submersed macrophytes (Schwoerbel, 1994). Chlorophyll-α concentration is an indicator for the bioproductivity of a lake based on the nutrient availability. Both Secchi disk transparency and chlorophyll-α concentration may also be determined from hyperspectral remote sensing data. The advantage of high spectral resolution reflectance data (hyperspectral data) is the possibility of quantitative analysis due to diagnostic absorption bands. Morel and Gordon (1980) differentiated empirical (purely statistical), semiempirical, and analytical approaches for the analysis of remote sensing data regarding the estimation of water constituents. Hyperspectral data allow for semiempirical methods based on the knowledge of the specific absorption characteristics of water constituents in connection with regression approaches (Dekker, 1993; Gitelson, 1992; Kallio, Kutser, Koponen, Hannonen, & Herlevi, 1998; Thiemann, 2000), as well as for analytical approaches including radiative transfer calculations based on backscattering and absorption characteristics (Dekker, 1993; Doerffer, 1992; Gege, 1994; Heege, 2000). The latter requires sound knowledge of the inherent optical properties of the water body to be implemented into the model.

We demonstrate that multitemporal remote sensing based maps of Secchi disk transparency and chlorophyll-α can be obtained by applying semiempirical algorithms. We collected field data that are representative for the entire range of values present in those waters. For the multitemporal comparison of the remote sensing data a good atmospheric correction is essential.

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2. Test area

The Mecklenburg Lake District is located about 70 km northwest of Berlin, Germany, about half way to the Baltic Sea. It covers about 300 km² with more than 30 lakes (Fig. 1). The lakes are remnants of the last glaciation in the form of dead ice kettles of different sizes and depths. Some are interconnected to each other by rivers or canals; others are isolated with no surface supply or drainage. Lake Wumm (Fig. 1, no. 6) is an oligo-mesotrophic lake with a maximum depth of 36 m and has very low nutrient content. Its chlorophyll-α concentration varies from 1 to 3 µg/l, and its Secchi disk transparency ranges between 7 and 8.5 m. On the contrary, Lake Bramin (Fig. 1, no. 2), a very shallow lake about 3 m deep, shows chlorophyll-α concentrations between 50 and 100 µg/l and Secchi disk transparencies around 0.25 m—it is highly eutrophic. All the other lakes vary between these two extremes (Thiemann & Kaufmann, 1998).

3. Data

3.1. In situ reference data

Secchi disk transparency, water samples for chlorophyll-α laboratory analyses, as well as in situ reflectance data about 50 cm above the lake surface, were taken during seven field data recordings in the years 1997 through 1999 (exact dates indicated in Table 1). The field work was carried out on 5–16 lakes (Fig. 1, nos. 1–6 and 13–26).

Secchi disk transparency was measured with a Secchi disk, a white disk (diameter 25 cm), which is lowered into the water body on the shadowed side of a boat as far as it is just still visible (Schwoerbel, 1994; Wetzel, 1983). Secchi disk transparency is a general measure of extinction and is used as an important overall indicator of trophic state (Gunkel, 1994; Kirk, 1994). For chlorophyll-α analysis, water samples were taken with an integrating water sampler down to the Secchi disk transparency and filled into 1-l bottles of polyethylene. The samples were kept as cool and dark as possible to reduce further bioproduction after sampling. Chlorophyll-α was analysed for all sampling dates in the laboratory using spectrophotometric measurements of absorbance at 665 nm after extraction in 90% ethanol according to DIN 38 412-Part 16 (1986). The results were corrected for phaeopigments after acidification with hydrochloric acid and remeasurement of the absorbance. Spectral reflectance measurements were taken using a portable spectrometer (FieldSpec FR, ASD) with an 8° fore-optic attachment. Spectra were recorded relative to a white reference panel (Spectralon) to obtain absolute reflectance values. The measurements were taken about 50 cm above the water surface almost perpendicular with a small inclination following the propagation of sunlight to prevent sunglint. The shading from the boat was avoided.

Since the data were taken only on clear and sunny days, the influence of sky reflection at the water surface was minimized (Gege, 1994). The data were resampled to the wavelength range between 400 and 850 nm in steps of 1 nm.
3.2. Hyperspectral airborne data

A multitemporal database was built including data of the casi (Institute of Space Sciences, Free University Berlin, Germany) and HyMap (HyVista, Australia) airborne hyperspectral sensors (dates indicated in Table 1); casi is a pushbroom scanner operating in spectral and spatial mode. In the spectral mode, 288 bands between 430 and 970 nm can be recorded in 1.9-nm steps with a nominal bandwidth of 2.8 nm (Czapla-Myers, Gray, Hollinger, Miller, & Duggan, 1999). However, due to the readout capability in this mode, only up to 39 so-called look directions can be recorded as spatial pixels across track. For our purpose, we have chosen the spatial mode with 512 spatial pixels, where up to 19 nonoverlapping spectral bands of varying spectral width can be user defined; casi recorded three flight strips on September 1, 1997, in the spatial mode with 17 spectral bands (6–25-nm spectral resolution; Fig. 2) and full ground coverage at an altitude of about 3000 m resulting in a spatial resolution of $3 \times 3$ m. HyMap is a whisk-broom scanner with 128 bands between 430 and 2500 nm. It supplied data sets on three dates in 1998 and 1999 from an altitude of about 4500 m with $10 \times 10$ m pixel size and about 15 nm bandwidth and spectral intervals. Only the first 23 bands between 400 and 750 nm relevant for the determination of water constituents were used in this study (Fig. 2). All flight lines are marked in Fig. 1.

4. Preprocessing of the airborne data

4.1. Atmospheric correction

All airborne data sets have been atmospherically corrected using the ATCOR program for airborne data (Richter, 1996). The radiative transfer in ATCOR is based on the MODTRAN-2 code. This program corrects at-sensor radiance images (selected spectra, see Fig. 3a) for the solar illuminance, the Rayleigh and aerosol scattering. Input parameters are flight altitude, ground elevation above sea level, zenith and azimuth angles of the sun, flight direction, and day of the year, as well as standard atmosphere, aerosol

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**Table 1**

<table>
<thead>
<tr>
<th>Secchi depth</th>
<th>Chlorophyll-a</th>
<th>In situ reflectance</th>
<th>Airborne campaigns</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 15/16, 1997</td>
<td>May 15/16, 1997</td>
<td>May 15/16, 1997</td>
<td>casi: September 1, 1997</td>
</tr>
<tr>
<td>May 5/6, 1999</td>
<td>May 5/6, 1999</td>
<td>September 2/4, 1998</td>
<td></td>
</tr>
</tbody>
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**Fig. 2.** Band settings of casi and HyMap in comparison with a eutrophic water spectrum.
type, and visibility. Output is a ground reflectance image (selected spectra, see Fig. 3b). ATCOR corrects also for the additional atmospheric signal due to scan angle variations and for the adjacency effect which is of particular relevance for water bodies. The ATCOR program has been adapted for the specific band settings of the casi and HyMap sensors. The casi data also were corrected with the empirical line method for fine tuning (Conel et al., 1987) because the atmospheric correction is not accurate enough for low reflecting targets and, in this case, for Lake Wumm reflectance values of 0 were calculated for several visible bands (Fig. 3b). For the empirical line correction, a very bright and very low reflecting area is selected for which ground reflectance spectra had been collected. In this case, only water spectra with highest and lowest reflectance were used as input (Fig. 3d). The mean spectrum of each of the two areas in the scene were correlated with the in situ reference spectra. The gain and offset values for each band correspond to the inverse solar radiance distribution (in our case, almost 1 because of the good atmospheric correction in advance) and the remaining atmospheric scattering. This transformation then was applied to the entire scene (Fig. 3c).

4.2. Geometric correction

Both the casi and HyMap scanners were flown mounted on a stabilizing platform during calm weather conditions. Therefore, pitch, roll, and yaw distortions only played a minor role and were not corrected for. For rough matching to topographic maps, geocoding was conducted via pass points with a first-order polynomial transformation and nearest-neighborhood interpolation using maps of the scale 1:25,000 as reference. The mean standard error of the residuals of all points was less than six pixels. The overlay onto an IRS-1C/PAN satellite scene shows good agreement (grey background in Figs. 5 and 6) with about 80% of the lake pixels with a position accuracy of less than 1 pixel and maximum error of 10 pixels.

5. Methods of data analysis

5.1. Analysis of field spectra regarding Secchi disk transparency and chlorophyll concentration

For the determination of Secchi disk transparency, the wavelength spectrum between 400 and 750 nm was used. A base line was fitted to each spectrum touching the two local minima at short visible wavelengths (mostly near 430 nm) and at longer VIS/NIR wavelengths (in most cases, around 750 nm; in clear waters, around 600 nm) to minimize and thus normalize the area between the base line and the spectrum (Fig. 4a) (Thiemann, 2000; Thiemann, Wieneke, & Kaufmann, 2001). This area was
calculated and divided by the number of spectral bands to get one mean value for each spectrum. The resulting value is called the Spectral Coefficient (SpCoef). In the special case of very clear water with continuously decreasing reflectance along with increasing wavelength, the base line may cut the abscissa. From this intersection the abscissa was taken as base line for the further area calculation to circumvent negative values.

The regression between the Spectral Coefficient (SpCoef) and Secchi disk transparency (SD) as measured with the Secchi disk was calculated for quantification (Fig. 4b). There is a high correlation with an $R^2=0.85$ (mean standard error: ± 0.87 m) described by the exponential regression (Eq. (1)):

$$SD = 13.07e^{-2.94SpCoef}$$

With increasing concentration of water constituents, the area between the spectrum and the base line and therefore the Spectral Coefficient rise. A strong absorption by Gelb-
stoß, chlorophyll, or carotenoids lowers the first minimum of the spectrum and increases the area between the spectrum and the base line. In the same manner, the area increases with a higher reflectance peak around 700 nm and a higher reflectance in the green with increasing concentration of algal chlorophyll and biomass. In addition, increased mineral suspension and therefore higher scattering results in higher reflectance especially in the range between 450 and 700 nm. This also entails a larger area between base line and spectrum and a higher Spectral Coefficient. Generally speaking, there is an inverse correlation between the Spectral Coefficient and the Secchi disk transparency.

This relationship between the Spectral Coefficient and Secchi disk transparency can also be shown using subsurface irradiance reflectance spectra modeled by the BIOPTI program for inland waters (Hoogenboom, Dekker, & Althuis, 1998). Fig. 4c shows the spectra used with varying program for inland waters (Hoogenboom, Dekker, & Althuis, 1998). Fig. 4c shows the spectra used with varying chlorophyll concentrations from 1 to 10 µg/l in steps of 1 µg/l and from 10 to 90 µg/l in steps of 10 µg/l as modeled by BIOPTI. There, the subsurface irradiance reflectance decreases between 400 and 500 nm, and it increases between 500 and 750 nm with higher respective chlorophyll concentration. For all spectra shown in Fig. 4c, the Spectral Coefficient was calculated and correlated with the Secchi disk transparency that was also calculated by the BIOPTI model. Fig. 4d displays the exponential correlation ($R^2=0.99$) with a similar scaling factor of 16.77 and an exponent factor of 256, which is two orders of magnitude higher than in Eq. (1) due to the lower Spectral Coefficient because of the low values of the subsurface irradiance reflectance. Therefore, the shape of the exponential fitting curve is similar for the in situ and modeled spectra. It is shown in Fig. 4c and d that the base line method for the calculation of the Secchi disk transparency is also valid for subsurface irradiance reflectance spectra.

Depending on the prominent compositions of water constituents in a region, the relationship between the Spectral Coefficient and Secchi disk transparency should be adaptable via new coefficients in the regression equation. The base line also implies a correction for a higher reflectance signal because of spectral reflectance due to higher wave action as well as because of slightly differing angles between water surface and spectrometer due to handheld variances (Thiemann & Kaufmann, 1998).

Chlorophyll-a shows two diagnostic absorption bands centered at 435 and 678 nm. The reflectance peak around 700 nm rises with increasing chlorophyll concentration. This phenomenon is reported in the literature to be caused by (i) fluorescence (Carder & Steward, 1985; Fischer, Doerffer, & Grassel, 1986; Gordon, 1979; Hoge & Swift, 1987; Morel & Prieur, 1977), (ii) abnormal scattering due to the chlorophyll absorption at 675 nm (Morel & Prieur, 1977), or (iii) a combination of the decreasing chlorophyll absorption and the increasing water absorption in this wavelength range (Gitelson & Kondrat’ev, 1991; Kishino, Sugihara, & Okami, 1986; Richardson, 1996; Thiemann, 1999; Thiemann, 2000; Vasilkov & Kopelevich, 1982; Vos, Donze, & Buitveld, 1986). Different semiempirical and semianalytical regression approaches (Dekker, 1993; Gitelson, 1991; Gitelson, Mayo, Yacobi, Parparov, & Berman, 1994) using the chlorophyll absorption band in the red and the near-infrared reflectance peak were tested to determine the chlorophyll concentration from the reflectance spectra (Fig. 4e) (Thiemann, 2000). However, the algorithm as already proposed by Dekker (1993) and Mittenzwey et al. (1988) with modification according to Eq. (2) gave the best correlation coefficient ($R^2=0.89$) and the least mean standard error ($±9.80 \mu g/l$) (Fig. 4f). The wavelengths used here correspond to the most frequent maximum and minimum within the measured field spectra. This linear relationship was applied to derive chlorophyll-a concentration (CHL) from the in situ reflectance data (see also Fig. 4f):

$$\text{CHL} = -52.91 + 73.59 \text{Ratio}[705 \text{ nm}/678 \text{ nm}]$$  

5.2. Determination of Secchi disk transparency and chlorophyll from hyperspectral airborne data

For each sensor-specific band characteristics, the algorithms were adapted by resampling the field spectra to the resolution of casi and HyMap, respectively (Thiemann et al., 2001). Thus, for Secchi disk transparency, the exponent factor changed for casi to $−3.5$ (HyMap: $−3.5$) and the scaling factor to $13.1$ (HyMap: $8.0$). Regarding the chlorophyll concentration, the center distance was adapted for casi to $−54.9$ (HyMap: $−64.9$) and the gradient factor to $75.6$ (HyMap: $99.9$). These algorithms were implemented into existing image processing software to apply them to the hyperspectral airborne data. The mean standard errors were determined by independent field samples recorded at the same dates as the airborne data as $±1.2$ m (HyMap: $±1.3$ m) for Secchi disk transparency and $±10.2 \mu g/l$ (HyMap: $±10.9 \mu g/l$) for chlorophyll concentration, similar to the results by Dekker (1993).

6. Results

The multitemporal distribution of Secchi disk transparency is displayed in Fig. 5. Some lakes are characterized by permanently high Secchi disk transparencies (Lakes Wumm and Pätsch: more than 5 m; Lake Zechlin: 2–4 m) or low Secchi disk transparencies (Lakes Bramin and Dollgow: less than 1 m). In other lakes, distinct variations over time are visible like in Lake Rheinsberg when comparing its condition in September 1997 (less than 1 m) and September 1998 (more than 2 m) or in the Lake Schwartz (MV) and Vilz in 1998 (more than 2 m) and 1999 (less than 1 m). Sometimes, water mixture zones are clearly to be distinguished where a canal connects two lakes of different Secchi disk transparencies, e.g. in Lake Schlaborn, which is connected to the more
Fig. 5. Multitemporal variations of Secchi disk transparency as retrieved from casi and HyMap data.
Fig. 6. Multitemporal variations of chlorophyll as retrieved from casi and HyMap data.
eutrophic Lake Dollgow to the northwestern end (Fig. 5; September 1997). The permanent calculation of very low Secchi disk transparencies in Lake Wumm and Lake Zootzen can be attributed to low water depths of less than 6 m: There, the algorithm for the determination of Secchi disk transparency (as well as the field measurement) is not valid because the Secchi disk transparency is limited by the lake bottom. It is not possible to determine the actual Secchi disk transparency for these shallow areas.

Fig. 6 shows the chlorophyll concentration varying over space and time. Mesotrophic lakes like the Lakes Wumm, Zootzen, or Zechlin can be identified by low chlorophyll concentrations. Highest concentrations were calculated for the Lakes Bramin, Schmidt, and Dollgow, which can be attributed to their eutrophic state. In September 1997, chlorophyll concentrations increase from Lake Prebelow to Lake Griebenick (no. 13 through 17 in Fig. 1) along the direction of flow of the interconnecting River Rhin. One year later, the situation was reversed with decreasing chlorophyll concentrations. In addition, on the chlorophyll maps, water mixture zones can be distinguished. In the map for September 1998, one can see the mixing of clear Lake Zootzen waters flowing from the West into Lake Tietzow with higher chlorophyll concentrations. The southwestern part of the Tietzow basin thus shows lower chlorophyll levels than the northeastern part. Especially in the scene of May 1999, the patchiness of the chlorophyll concentration is clearly visible in most of the lakes during this spring bloom.

Generally speaking, the chlorophyll concentrations are closely inversely related to Secchi disk transparency: Low chlorophyll concentrations coincide with high Secchi disk transparencies and vice versa. This suggests that the lakes within the test area are dominated by algae as the main optical water constituent affecting water clarity.

7. Conclusions

This study presents algorithms for the quantification of the trophic parameters Secchi disk transparency and chlorophyll-α concentration based on hyperspectral airborne data. Since the algorithms were developed on in situ reflectance data, it is possible to transfer this approach for the Mecklenburg lake district to different spectral bandwidths and sensors. This has been validated by independent in situ reference measurements resulting in mean standard errors of determination of 1.0–1.5 m for Secchi disk transparency and of 10–11 µg/l for chlorophyll-α regarding the casi and HyMap sensors. The multitemporal applicability of the algorithms was demonstrated based on a 3-year database. With the complementary accuracy of Secchi disk transparency and chlorophyll concentration and the additional spatial and synchronous overview of numerous contiguous lakes, this remote sensing approach gives a good overview of changes that can then be recorded more precisely by more extensive in situ measurements (Vetinghoff, 1999).

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