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# Water Quality and Trophic State Analysis Based on Hyperspectral Remote Sensing Data in the Mecklenburg Lake District, Germany

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**Abstract:** Secchi disc depth and chlorophyll-a content are widely used indicators for the trophic state of lakes. Secchi disc depth and chlorophyll-a are calculated from hyperspectral remote sensing data to estimate the trophic state of 25 lakes. A remote sensing database was established for the Mecklenburg Lake District in 1997 comprising field reflectance and analytical reference data on several distinct dates and airborne hyperspectral data recorded by the Compact Airborne Hyperspectral Imager (casi).

The in situ reflectance spectra were analysed to develop and test a model for hyperspectral determination of the phytopigments chlorophyll-a, phycocyanin, and carotenoids, and Secchi disc depth. For Secchi disc depth the area between a base line and the spectrum from 400 nm to 750 nm was calculated and correlated to the Secchi disc depth measured in situ. Chlorophyll-a concentration was quantified using the reflectance ratio at 705 nm and 678 nm and showed a linear relationship to chlorophyll-a content from laboratory spectro-photometric measurements. The accessory phytopigments carotenoids and phycocyanin were determined from the spectral data using their absorption depths at 485 nm and 624 nm, respectively. The algorithms have then been transferred to the hyperspectral airborne data.

This study presents an application of hyperspectral remote sensing data in the quantitative analysis of several water constituents. From Secchi disc depth and chlorophyll-a concentration trophic state has been analysed for the first time for all lakes in this district.

**Zusammenfassung:** *Analyse von Wasserqualität und Trophie-Status mit hyperspektralen Fernerkundungsdaten in der Mecklenburger Seenplatte.* Sichttiefe und Chlorophyll-Gehalt werden in der Limnologie häufig als Indikatoren für die Einschätzung des Trophie-Status von Seen verwendet. Beide Größen wurden in dieser Studie aus hyperspektralen Fernerkundungsdaten abgeleitet, um den Trophie-Status von 25 Seen zu bestimmen. In der Mecklenburger Seenplatte wurde 1997 eine Fernerkundungs-Datenbasis aufgebaut, die aus in situ-Reflexionsspektren, analytischen Referenzdaten und flugzeuggetragenen Hyperspektraldaten des „Compact Airborne Spectrographic Imager“ (casi) besteht.

Aus den in situ-Reflexionsdaten wurden semiempirische Regressionsmodelle zur quantitativen Bestimmung der Phytopigmente Chlorophyll-a, Phycocyanin und Carotinoide sowie der Sichttiefe erstellt. Für die Sichttiefe wurde die Fläche zwischen einer konstruierten Basislinie und dem Spektrum zwischen 400 nm und 750 nm berechnet. Diese Werte und die in situ gemessene Sichttiefe stehen in negativ-exponentiellem Regressions-Zusammenhang. Die Chlorophyll-a-Konzentration wurde über das Reflexionsverhältnis bei 705 nm und 678 nm quantifiziert und weist eine linearen Beziehnung mit dem Chlorophyll-Gehalt aus spektro-photometrischen Laboranalysen auf. Der Gehalt an akzessorischen Phytopigmenten, Carotinoide und Phycocyanin, wurden aus den Spektren durch ihre Absorptionstiefe bei 485 nm bzw. 624 nm ermittelt. Diese Algorithmen wurden anschließend auf die hyperspektralen Flugzeugdaten übertragen.

Diese Studie zeigt die Anwendbarkeit von Hyperspektraldaten für die quantitative Analyse von gleichzeitig mehreren Wasserinhaltsstoffen. Aus Sichttiefe und Chlorophyll-Gehalt wurde der Trophie-Status aller Seen erstmalig für denselben Zeitpunkt abgeleitet.

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## Introduction

Secchi depth and chlorophyll content are widely used as indicators of trophic state (Carlson 1977, Wetzel 1983, Vollenweider 1989, Schwoerbel 1993). Both are characterised by individual spectral features in the visible (VIS) and near infrared (NIR) wavelength range between 400 nm and 750 nm and thus are detectable by remote sensing methods. The advantage of these methods is the synoptic view that allows the analysis of extensive areas at a given date.

The landscape of the German state Brandenburg is characterised by several lake districts with more than 2000 lakes. Since 1992 the Institute of applied Fresh Water Ecology in Brandenburg has been comprehensively recording and assessing the standing waters of the state. However, the updating of the lake database is starting to pose an immense problem. Water monitoring by means of remote sensing is therefore being investigated to help maintain an overview of the changes of the lakes' ecosystems. This study has been carried out for the Brandenburg part of the Mecklenburg Lake District.

## Study Area

The Mecklenburg Lake District comprises more than 2000 lakes located 70 km northwest of Berlin, about half the distance to the Baltic Sea (Fig. 1). The test area of about 100 km$^2$ focuses on 25 lakes close to the city of Rheinsberg in the southern part of the lake district. The centre longitude and latitude are 12°50' E and 53°09' N.

The landscape is characterised by glacial landforms from the Weichsel ice age which lasted until about 18 000 years before present. The ice sheet propagated from Scandinavia over the Baltic Sea. To the west, the test area is marked by terminal moraines of the Frankfurt stadial. To the east the river *Rhin* now uses a large glacial valley (Krausch et al. 1974, Stackebrandt et al. 1997).

The lakes are formed in former dead ice kettle holes of various sizes, depths, and catchment areas. Lake *Wumm* (Fig. 1-1) for example is up to 38 m deep and does not have any surface supply or drainage. Lake *Bramin* (4) is in filling and its depth does not exceed 3 m. Most of the lakes are interconnected by rivers or canals. The lakes *Prebelow* (13), *Tietzow* (14), *Schlaborn* (15), *Rheinsberg* (16), and *Grienerick* (17) for example are linked to the river *Rhin*. Trophic state varies widely between the lakes. Lake *Wumm*, an oligo- to mesotrophic lake surrounded by forests, rarely exceeds chlorophyll-a contents of 3 µg/l. Secchi disc depth was measured between 6 m and 8.5 m (Arp 1997, Thiemann & Kaufmann 1998). In contrast, the lake *Bramin* reaches Secchi disc depths around 0.3 m and chlorophyll-a concentrations between 60 µg/l and 100 µg/l. All the other lakes vary between those two extremes (see Tab. 1).

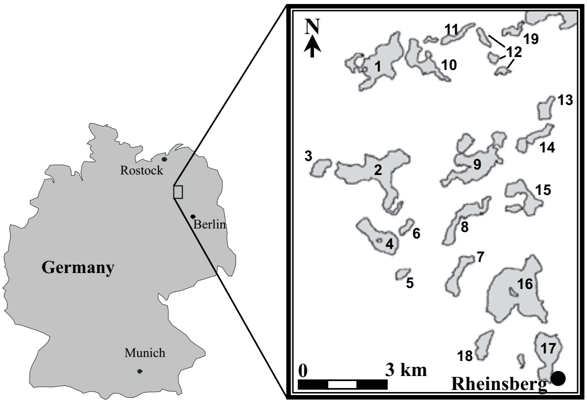

**Fig. 1:** Location of the test area – corresponding lake names and parameters are to be found in Tab. 1.

## Data and Pre-Processing

### *In Situ Reference Data*

Secchi disc depth and water samples for the analysis of chlorophyll-a were taken on four dates in May, June, early September, and end of September 1997 for five selected lakes within the test area. The measurements were taken at two to four different points on each lake. However, the results showed that the differences within each lake were minor in comparison to the lake-to-lake variances.

*Secchi disc depth or Secchi disc transparency* is usually measured with a white disc (diameter 25 cm) which is lowered into the water body on the shaded side of a boat as far as it is just still visible (Wetzel 1983, Schwoerbel 1994). It is influenced by scattering and absorption within the visible wavelength spectrum of all dissolved and particulate compounds, predominantly phytoplankton, re-suspended material, and humic and fulvic substances (Håkanson 1995). Secchi disc depth is a general measure of the underwater supply of light for plants and an important overall indicator of trophic state (Gunkel 1994).

*Chlorophyll-a* is a phytopigment present in all algae species. It is regarded as one main indicator of trophic state (Carlson 1977, Vollenweider 1989, DIN 38 412). The water samples were taken with an integrating water sampler down to the Secchi disc depth 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-a was analysed for all sampling dates in the laboratory using spectro-photometric measurements of the absorption efficiency at 665 nm after extraction in 90 % ethanol according to DIN 38 412 (1986). The results were corrected for phaeopigments after acidification with hydrochloric acid and re-measurement of the absorption efficiency.

The analyses of other phytopigments unfortunately could not have been made available.

**Tab. 1:** Lake parameters.

| No. | Lake Name | max. Depth [m][1] | Shore Development [1][2] | Trophic State (Klapper)[3] | Secchi Depth [m] (9/1/97)[4] | Chlorophyll-a [µg/l] (9/97)[4] | Humic Subst. [mg/l] (9/97)[4] |
|---|---|---|---|---|---|---|---|
| 1 | Wumm | 38.0 | 2.87 | 1.7 | 7.5 | 2.7 | 5.4 |
| 2 | Zechlin | 36.0 | 2.73 | 2.7 | 2.8 | 7.1 | 4.4 |
| 3 | Schwarz | 8.0 | 1.46 | 2.5 | | | |
| 4 | Bramin | 2.5 | 1.98 | 3.0 | 0.5 | 69.9 | 4.3 |
| 5 | Kagar | 3.0 | 1.43 | 3.3 | > 0.3 | 99.8 | 6.0 |
| 6 | Zermitten | 7.0 | 1.56 | 2.5 | | 32.8 | 3.4 |
| 7 | Pätsch | 18.0 | 2.06 | 2.5 | | 5.5 | 4.7 |
| 8 | Dollgow | 11.0 | 2.58 | 2.5 | | 44.0 | 3.6 |
| 9 | Zootzen | 21.0 | 3.08 | 2.3 | 1.5 | 15.7 | 2.3 |
| 10 | Twern | 35.0 | 2.61 | 2.5 | | | |
| 11 | Rochow | | 2.16 | 2.5 | | | |
| 12 | Giesenschlag North<br>Mid<br>South | | 1.69<br>1.36<br>1.90 | 2.3<br>2.3<br>2.3 | | 2.8 | 5.7 |
| 13 | Prebelow | 7.5 | 1.55 | 3.0 | 1.4 | 58.3 | 5.2 |
| 14 | Tietzow | 8.0 | 2.21 | 2.5 | 1.4 | 44.6 | 3.1 |
| 15 | Schlaborn | 9.2 | 2.56 | 2.5 | 1.3 | 35.5 | 2.5 |
| 16 | Rheinsberg | 30.0 | 2.08 | 3.3 | 1.3 | 25.3 | 1.8 |
| 17 | Grienerick | 16.8 | 1.86 | 3.0 | 1.2 | 32.7 | 2.2 |
| 18 | Linow | 20.0 | 1.58 | 2.5 | | 4.2 | 5.0 |
| 19 | Schmidt | | 2.18 | 4.3 | | | |

[1] Geological Maps Scale 1 : 25,000 (1917); Sheets 51/26 & 52/27

[2] Calculated in GIS

[3] Rated and Published in LUA 1996

[4] Field Measurements in September 2–4, 1997

### *In Situ Field Spectrometry*

Along with the in situ reference data, spectral reflectance measurements were taken using a portable spectrometer (FieldSpec FR, ASD Inc.) with an 8-degree fore-optic attachment. The spectra were recorded relative to a white reference panel (Spectralon) to obtain absolute reflectance values. The measurements were directed with the propagation of the sunlight to avoid sunglint and were taken about 50 cm above the water surface most possibly perpendicular to it. The data was resampled to the wavelength range between 400 nm and 850 nm in steps of 1 nm.

All measurements were conducted for the five lakes *Wumm*, *Zechlin*, *Schwarz*, *Bramin*, and *Kagar* (lakes 1–5 in Fig. 1). During the field work in early September, a total of 12 lakes were sampled by in situ reflectance spectrometry including the lakes labeled 1 to 5 and 13 to 17 in Fig. 1. For 15 lakes (including lakes 6, 8, 9, 12, and 18), additional reference information of Secchi disc depth and chlorophyll-a content was collected.

Fig. 2 shows reflectance spectra for different levels of chlorohyll-a concentration. The pure water of lake *Wumm* with negligable chlorophyll-a content shows the lowest reflectance and a continuous decrease of the signal towards longer wavelengths. At high concentrations of phytoplankton the spectra are characterised by chlorophyll-a (Chl-a) absorptions at 435 nm and 678 nm, a distinct green peak due to biomass scattering in between these absorption bands, and a reflectance peak near 700 nm. The 700 nm peak is caused by increasing reflectance at the so-called red edge of plants and narrowed by the increasing absorption of water (Richardson 1996, Thiemann & Kaufmann 1999). The algal pigment phycocyanin (PC) shows an absorption band at 624 nm in most of the reflectance spectra as well as carotenoids at 485 nm at the edge of the green reflectance maximum. At 570 nm the absorption of phycoerythrin (PE) becomes visible in the spectrum of lake *Bramin* taken in June.

### *Airborne Hyperspectral Data*

The *c*ompact *a*irborne *s*pectrographic *i*mager (casi) is mounted on a stabilised airborne platform. Its area array detects the incoming radiation between 400 nm and 900 nm in 512 spatial pixels. The user can choose between a spatial and a spectral mode. In the spectral mode all 288 spectral pixels are used resulting in spectral intervals of 1.8 nm. Due to the limiting read-out frequency there are only 39 so-called look-directions available in the spatial dimension. In this mode with high spectral resolution casi does not cover the ground continuously. In the spatial

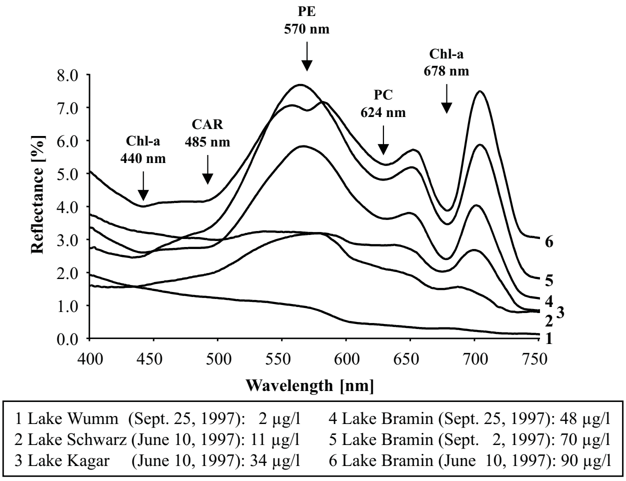

**Fig. 2:** Reflectance spectra measured during field sampling with visible absorption bands (Chl-a: Chlorophyll-a, CAR: Carotinoids, PE: Phycoerythrin, PC: Phycocyanin) and according chlorophyll-a contents from in situ-measurements.

mode full ground coverage is provided and up to 19 non-overlapping spectral bands in variable bandwidths can be defined by the user (itres, 1994). In this study the spatial mode was chosen with 17 bands covering the wavelength range between 430 nm and 716 nm continuously in different bandwidths (Fig. 3). Bands 18 and 19 were defined for later MOMS (Modular Optoelectronic Multispectral Stereo Scanner) simulation purposes. The narrow bands between 670 nm and 716 nm focus on chlorophyll-a absorption and the reflectance peak that is reported to shift due to variations in chlorophyll-a content (Gitelson 1992).

On September 1, 1997 the casi instrument, operated by the Institute for Space Sciences of the Free University of Berlin, was flown over the test site. Three flight lines taking in 25 lakes were recorded from an altitude of 2440 m above ground, resulting in a pixel size of about 3 m × 3 m. The data was calibrated to reflectance and atmospherically corrected using the ATCOR programme for hyperspectral airborne data (Richter 1996) and the empirical line method (Conel et al. 1987) including field reflectance data. The data was geo-coded to a topographic map of the scale 1:25000. About 100 ground control points per flight line have been used. Data was resampled with the nearest neighbor method to preserve radiometry. Finally, a land mask was applied to the entire data set to focus on water bodies only and to avoid any spectral influence of surface floating vegetation.

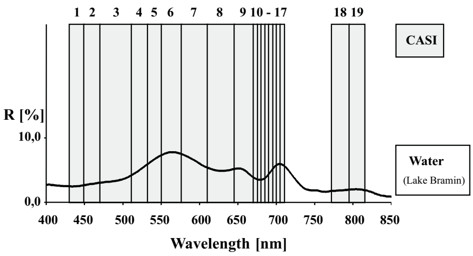

**Fig. 3:** Band settings of casi in comparison with a eutrophic water spectrum.

## Analysis and Results

### *Secchi Disc Depth*

For the determination of Secchi disc depth, the entire wavelength spectrum between 400 nm and 750 nm was used. Fig. 2 shows that the spectra vary in their overall reflectance. This can be due to wave action that can raise the signal by 10–20 % (Wetzel 1983) or to slight variations in the detection angle during the measurements. To account for this and the optical influence of different concentrations of the water constituents present, 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 minimise and thus normalise the area between the base line and the spectrum. This area was calculated 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 baseline may cut the abscissa. From this intersection the abscissa was taken for the further area calculation to circumvent negative values.

Fig. 4 shows the regression between the spectral coefficient (SpCoef) and Secchi disc depth (SD) as measured with the Secchi disc.

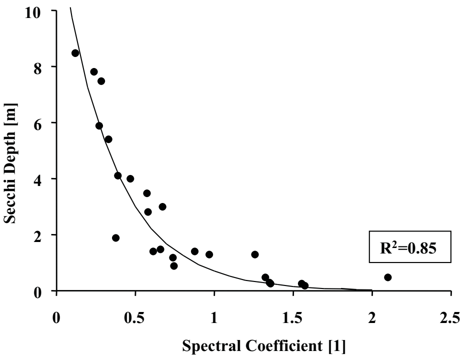

**Fig. 4:** Negative-exponential regression between spectral coefficient calculated from field spectra and Secchi depth as measured during field campaigns.

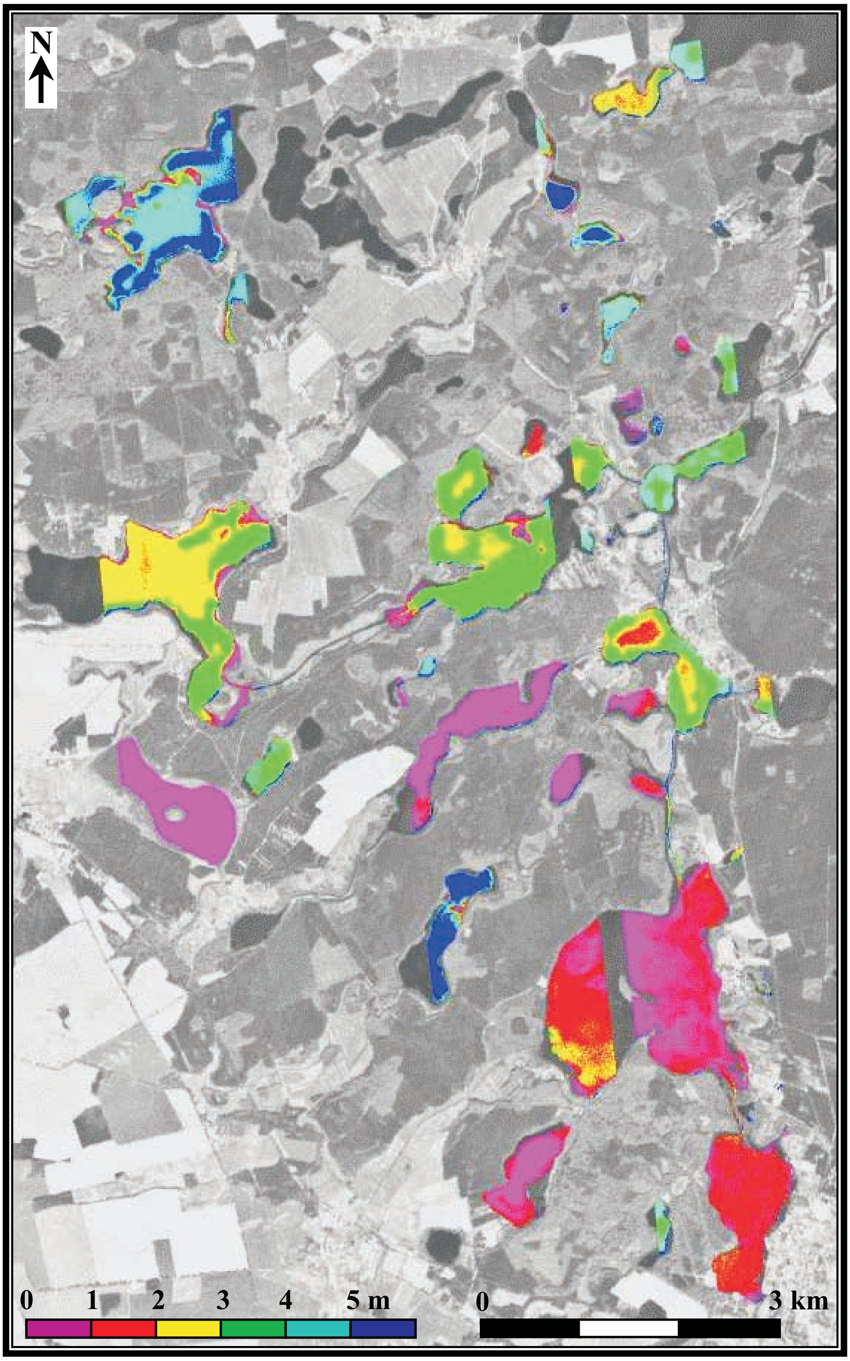

**Fig. 5:** Secchi depth as retrieved from the three casi flight lines by spectral coefficients and regression – panchromatic IRS-1C scene as underlay.

There is a high correlation with an $R^2 = 0.85$ described by the exponential regression Equation 1:

$$SD = 13.07 \cdot e^{-2.94 \cdot SpCoef} \qquad \text{(Eq. 1)}$$

Therefore, low spectral coefficients correspond to high Secchi disc depths, and high spectral coefficients can be assigned to low Secchi disc depths. The approach considers the spectral characteristics of all optical water constituents (phytopigments, suspended matter, humic substances): phytopigments as well as suspended matter especially increase the signal in between the two proposed local minima, the minimum in the blue would stay fixed and the one in the near infrared would only rise slightly with increasing content of water constituents. The area between the base line and the spectrum increases especially in the green wavelength region, and so will the area to be calculated resulting in a lower Secchi disc depth calculated from the negative exponential regression equation (Eq. 1). Increasing content of humic substances with increasing absorption in the blue wavelength range will reduce the first local minimum. With the base line fit to this lower first minimum the included area to be calculated will increase and therefore also the spectral coefficient. Different water types would only need a special adaption of the regression parameters.

The mean standard error for this regression is 0.87 m for all recorded lakes. The more eutrophic lakes (e. g. lake *Bramin*) with low Secchi disc depths thus are provided with a higher percentage error than clear lakes.

This algorithm for the determination of Secchi disc depth from reflectance data was adapted to the 19 casi bands and implemented into the ENVI software (CREASO 1997) to be applied to spatial hyperspectral casi data. The $R^2$ is then reduced to 0.71 and the mean standard error is 1.26 m.

Fig. 5 presents the results for Secchi disc depth from the casi data sets. Secchi disc depth is subdivided into six classes from $< 1$ m to $> 5$ m. Lake *Bramin* (field measurement: 0.5 m) has always been underestimated by far with about 0.03 m. Considering the mean standard error of 0.87 m, a division into classes of 1 m steps seems appropriate and results in the following classification of lakes. The lakes *Zechlin* (2.8 m), *Grienerick* (1.2 m), *Rheinsberg* (1.3 m), and *Schlaborn* (1.3 m) were very well estimated. Lake *Wumm*, even though partly in the greatest and most oligotrophic Secchi disc depth class, might be mainly underestimated. The measured Secchi disc depth at that date was 7.5 m; therefore a general decrease below a value of 5 m in the main basin is hard to assume. The areas in lake *Wumm* with calculated Secchi disc depths less than 4 m can be assigned to shallow water depths where the bottom limits the measurement of the Secchi disc depth.

## *Chlorophyll-a*

Chlorophyll-a shows two diagnostic absorption bands at 435 nm and 678 nm. The reflectance peak around 700 nm is reported to correlate in its height with chlorophyll-a content (GITELSON 1992, GITELSON 1993, DEKKER 1993). A ratio between the reflectance peak and the red absorption has already been proposed by MITTENZWEY et al. (1988) and GITELSON (1992). DEKKER (1993) modified this ratio to 705 nm/675 nm. This relationship was applied here to derive chlorophyll-a content (CHL) from the in situ reflectance data (see Eq. 2). The wavelengths used correspond to the most frequent maximum and minimum within the measured field spectra.

$$CHL = -52.91 + 73.59 \cdot \text{Ratio} \; [705\,\text{nm}/678\,\text{nm}] \qquad \text{(Eq. 2)}$$

Fig. 6 gives the linear relation of chlorophyll-a concentration to the ratio [705 nm/678 nm]. The additional influence of resuspended matter in the more turbid waters could therefore be excluded: the spectral ratio would have been reduced since suspended minerals increase the optical signal rather more in the chlorophyll-a absorption band at 678 nm than at the peak near 705 nm. Thus in the case of additional mi-

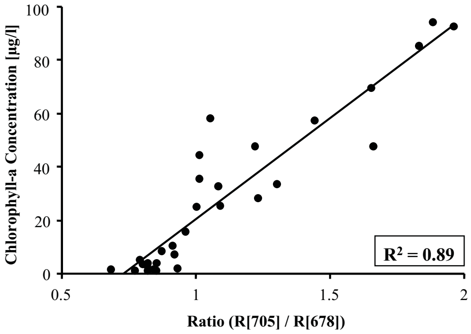

Fig. 6: Linear regression between spectral ratio calculated from field spectra and chlorophyll-a as analysed from field samples.

neral suspension, chlorophyll-a regression would not have been linear.

The mean standard error for predicted CHL is about 10 µg/l ($R^2 = 0.87$). Therefore, only low concentrations show a high percentage error and are often overestimated by this algorithm.

The algorithm was transferred to casi bands 16 (704 nm–710 nm) and 11 (675 nm–681 nm), thereby changing slightly the centre distance to − 54.94 and the gradient factor to 75.63. The $R^2$ decreases slightly to 0.86, and the mean standard error increases to 11.0 µg/l.

The lakes *Wumm*, *Zechlin*, and *Zootzen* show low chlorophyll-a contents as has also been verified during the field research (Fig. 7). Only lake *Wumm* exceeds the mean standard error significantly with derived 17 µg/l compared to 2 µg/l as measured. This fact may be explained by the used wavelength range for the reflectance ratio: at low chlorophyll concentrations the reflectance peak is shifted more towards shorter wavelengths and so the water absorption superimposes the reflectance peak. This makes the reflectance ratio less sensitive at low chlorophyll concentrations. Lake *Bramin* has the hightest chlorophyll-a contents greater than 60 µg/l. Even though the lake is very shallow, a comparison between chlorophyll-a distribution and water depth showed no correlations. An interesting feature is the increasing chlorophyll-a content of the interconnected lakes *Tietzow*, *Schlaborn*, *Rheinsberg*, and *Grienerick* (lakes 14 to 17 – compare Fig. 1) along the direction of flow. Also the southern basin of lake *Tietzow* shows a mixture zone of the northern water body and the waters of lake *Zootzen* entering from the western canal.

### Phycocyanin

Phycocyanin absorption was quantified using the absorption depth at 624 nm against a constructed continuum of the spectrum as it would be without the absorbing substance (CLARK & ROUSH 1984, DEKKER 1993). This continuum was assumed by the turning point within the flank of the green peak at 596 nm and by the maximum between the phycocyanin and chlorophyll-a absorption bands at 642 nm. These wavelength positions were determined by calculation of the first derivative as the most frequently occuring one for this purpose from the measured field spectra. The equation for the absorption depth of phycocyanin ($D_{PC}$) found here is similar to the one used by DEKKER (1993).

$$D_{PC} = \frac{R[596\,\text{nm}] + R[642\,\text{nm}]}{2} - R[624\,\text{nm}] \qquad \text{(Eq. 3)}$$

This algorithm was transferred to the casi data using bands 7 (575 nm to 610 nm), 9 (645 nm to 670 nm), and 8 (609 nm to 645 nm) (THIEMANN 2000). Since no in situ data for phycocyanin was available, phycocyanin could only be mapped qualitatively (Fig. 8a). Lakes with very little or no phycocyanin content coincide as expected with those showing low chlorophyll-a content. The highest content of phycocyanin can be found in lake *Bramin*, corresponding to the highest chlorophyll-a concentrations. Otherwise, lakes like lake *Schmidt* or lake *Dollgow* with high chlorophyll-a concentrations do not agree with higher phycocyanin contents.

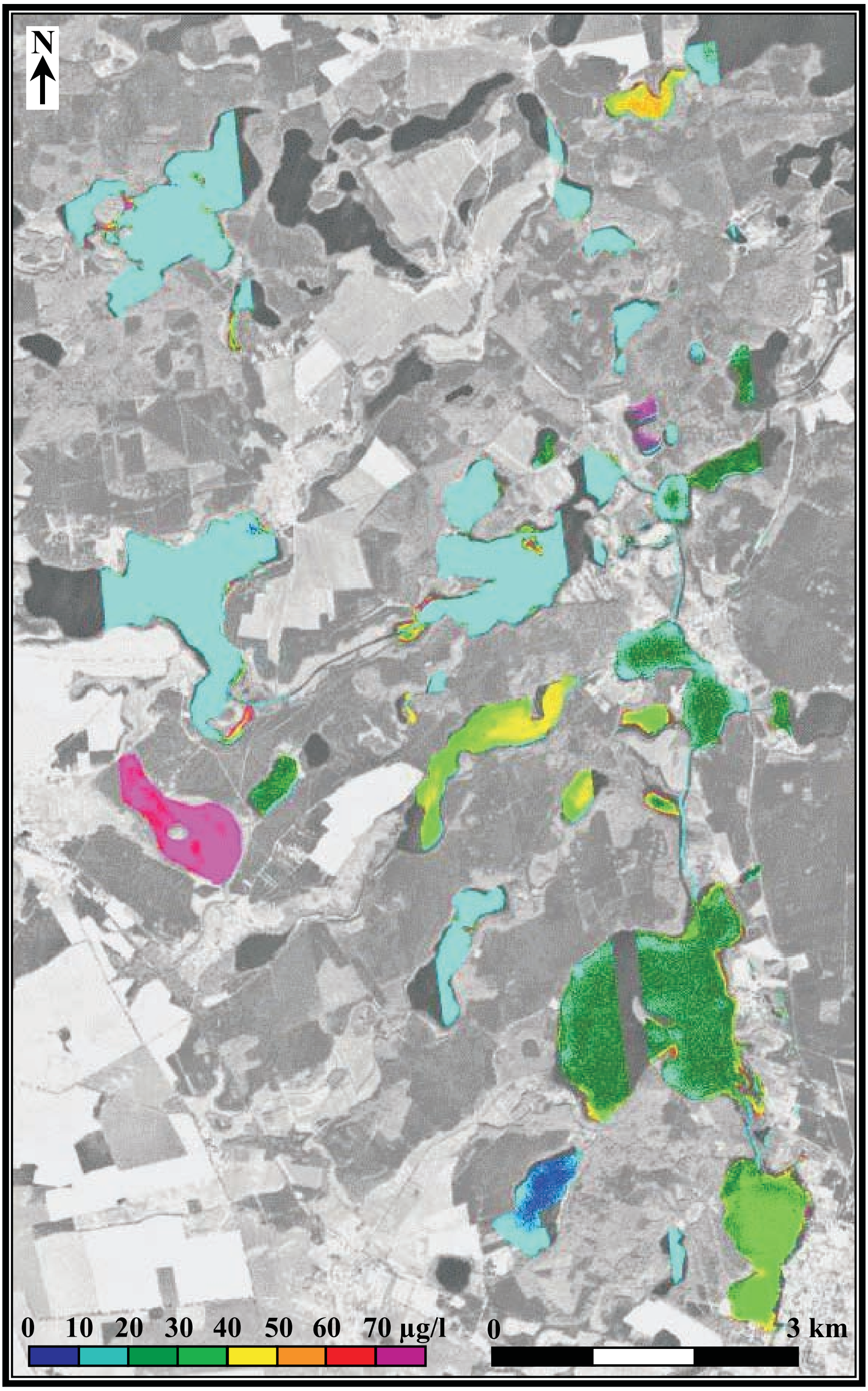

**Fig. 7:** Chlorophyll-a content as retrieved from the three casi flight lines by spectral rationing and regression – panchromatic IRS-1C scene as underlay.

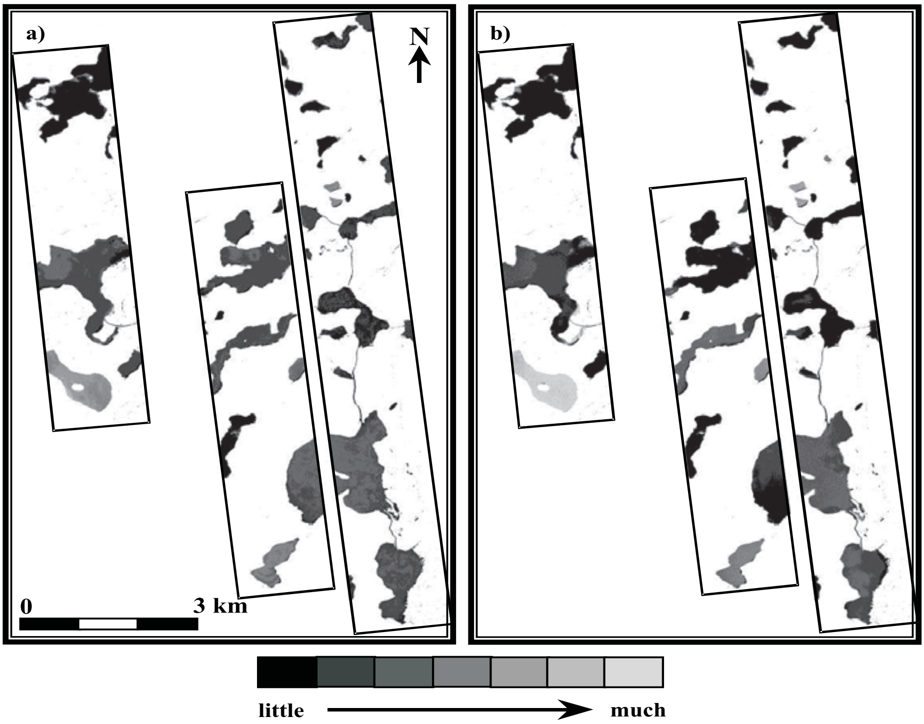

**Fig. 8:** Qualitative map a) of the phycocyanin content and b) of the carotenoid content as retrieved using absorption depth from the three casi flight lines.

### *Carotenoids*

Those carotenoids absorbing at 485 nm could be quantified using the absorption depth underneath the constructed continuum between the turning points at 467 nm and 526 nm. Since carotenoids absorb at different wavelengths in the shorter visible wavelength range, one should have in mind that this approach only records part of this group of phytopigments. The absorption depth for carotenoids ($D_{CAR}$) is calculated following Equation 4 (THIEMANN 2000):

$$D_{CAR} = \frac{R[467\,\text{nm}] + R[526\,\text{nm}]}{2} - R[485\,\text{nm}] \qquad \text{(Eq. 4)}$$

For mapping carotenoids qualitatively from the casi data, the algorithm was applied to bands 2 (449 nm to 469 nm), 4 (510 nm to 532 nm), and 3 (469 nm to 510 nm). The results for carotenoids displayed in Fig. 8b show a similar pattern as phycocyanin content with lowest contents in lakes *Wumm*, *Zechlin*, *Giesenschlag*, *Schmidt*, *Zootzen*, and *Pätsch*. The contents in lake *Bramin* seem to be higher than the ones for phycocyanin in relation to the other lakes. In lake *Zechlin* similar patterns for carotenoids and phycocyanin are visible, but differ from the chlorophyll-a distribution (Fig. 7). Further, different patterns appear in lakes *Zootzen*, *Schlaborn*, *Rheinsberg*, and *Grienerick* when comparing Figs. 8a and b. This is an indicator that different algal species occur within the test area.

## Interpretation Regarding Trophic State

### *Trophic State Index after* C*ARLSON*

The trophic state index (TSI) for lakes (CARLSON 1977) yields continuous values scaled between 0 and 100 based either on Secchi disc depth, chlorophyll-a concentration, or total phosphorus content. A TSI between 40 and 50 can be assigned to mesotrophic state, whereas values of more than 80 correspond to hypertrophic conditions. The TSI permits the comparison of the trophic state of lakes where only one or another parameter was measured. The trophic state index TSI using Secchi disc depth ($TSI_{SD}$) is calculated following Equation 5. A Secchi disc depth of 2 m results in a $TSI_{SD}$ of 50. The TSI using chlorophyll-a concentrations ($TSI_{CHL}$) includes a regression between Secchi disc depth and chlorophyll-a content where numerous midlatitude lakes were considered (see Eq. 6). To get a $TSI_{CHL}$ of 50 a chlorophyll-a content of 7.25 µg/l is assumed.

$$TSI_{SD} = 10 \cdot \left(6 - \frac{\ln[SD]}{\ln 2}\right) \qquad \text{(Eq. 5)}$$

$$TSI_{SD} = 10 \cdot \left(6 - \frac{2.04 - 0.68 \ln[Chl - a]}{\ln 2}\right) \qquad \text{(Eq. 6)}$$

Both Secchi disc depth and chlorophyll-a, as quantified from the airborne hyperspectral data, were used as inputs for the TSI. Regarding Secchi disc depth the trophic state index could be well determined for mesotrophic lakes. The eutrophic lake *Bramin* was overestimated with this method. However, a eutrophic lake could be classified very well by the estimations based on chlorophyll-a, whereas the more clear lakes are then overestimated. This can be explained by the mean errors which have a much higher percentage on low values resulting from Equations 1 and 2. $TSI_{SD}$ is more sensitive at low Secchi disc depths, while $TSI_{CHL}$ is more sensitive at low chlorophyll-a contents. In this case, high values of Secchi disc depth corresponding to low nutrient lakes show the best results in trophic classification using the TSI. Both methods are complementary in their accuracy (THIEMANN & KAUFMANN 1998). Therefore, the TSI-results calculated from Secchi disc depth and chlorophyll-a have been averaged to take account for the complementary accuracies within oligo- and eutrophic waters. Thus, a more detailed discrimination of trophic state has been achieved (Fig. 9). In contrast to the maps of chlorophyll-a (Fig. 7) and Secchi disc depth (Fig. 5), respectively, lake *Wumm* is distinguishable from lake *Zechlin* and lake *Dollgow* from lake *Bramin*. The phenomenon of decreasing water quality along the river *Rhin* is also visible in the merge of $TSI_{SD}$ and $TSI_{CHL}$. Lake *Bramin* is classified as highly eutrophic corresponding to its state of infilling.

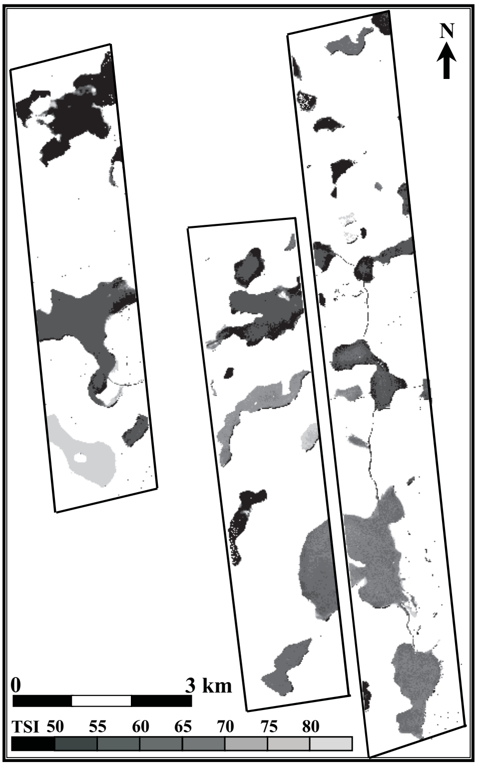

**Fig. 9:** Trophic State Index after CARLSON (1977) as mean after Secchi depth ($TSI_{SD}$) and chlorophyll-a ($TSI_{CHL}$).

### *Quality Classes after* KLAPPER

The determination of quality classes after KLAPPER (1992) is based on 17 different criteria divided into oxygene rate, nutrient rate, and production rate. Of these 17 criteria, chlorophyll-a content and Secchi disc depth are considered to be of major importance since they are the easiest to determine in practice. Tab. 2 shows how chlorophyll-a content and Secchi disc depth are assigned to the quality classes. The approach after Klapper was also used by the Institute for applied Fresh Water Ecology to rate the Brandenburg lakes, so the remote sensing results (Fig. 10) could be compared to the existing data (see Tab. 1). The lakes *Pätsch* and *Giesenschlag* and partly lake *Wumm* have been rated as mesotrophic (THIEMANN 2000). Most of the lakes like *Zechlin*, *Zootzen*, and *Prebelow* through *Grienerick* have been ranked in the eutrophic class, and lakes *Bramin* and *Dollgow* can be found in the polytrophic class. Only lake *Schmidt* reaches hypertrophic state using this database. Therefore, the ranking does not exactly fit the one in Tab. 1 since there were only two parameters and one date to be included instead of a mean over the entire bioproductive phase. However, even though the classes are spread over a larger scale, the internal ranking with lowest and highest trophic state is preserved.

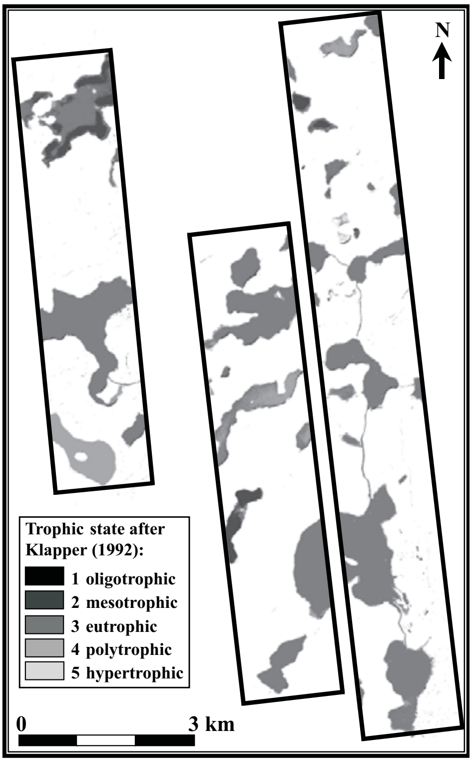

**Fig. 10:** Trophic state after KLAPPER (1992) as mean from Secchi depth and chlorophyll-a.

Both models for determination of trophic state generally show the same tendency with the lowest ranking for lakes *Wumm*, *Giesenschlag*, and *Pätsch*, and with highest for lakes *Bramin*, *Dollgow*, and *Schmidt*. Both lakes *Bramin* and *Dollgow* are rated in much higher classes using the remote sensing analysis than when using in situ measurements. Therefore, it should be clarified in further multi-temporal evaluations whether this is due to a unique seasonal incident or due to long-term changes in water quality.

## Conclusion

This study presents methods and results for the analysis of water constituents using hyperspectral field and airborne data. The point measurements of the high spectral resolution field spectrometer were used to set up the algorithms for a hyperspectral ana-

**Tab. 2:** Quality classes after KLAPPER (1992).

| Criteria | 1 oligotrophic | 2 mesotrophic | 3 eutrophic | 4 polythrophic | 5 hypertrophic |
|---|---|---|---|---|---|
| **Chlorophyll-a [µg/l] (mean April–September)** | ≤ 3 | ≤ 10 | 10–40 | 40–60 | > 60 |
| **Secchi depth [m]** | ≥ 6 | ≥ 4 | ≥ 1 | ≥ 0.5 | < 0.5 |

lysis and were also used for atmospheric correction of the casi as ground reference.

The airborne hyperspectral casi data provides information on Secchi disc depth and chlorophyll-a, and thus on trophic state. The Secchi disc depth and chlorophyll-a content figures calculated from the casi data have almost the same correlation coefficients and mean standard errors as the field data, but offer the great advantage of a simultaneous spatial overview of numerous lakes. The further potential of hyperspectral data to quantify humic substances is under investigation. As for the phytopigments, carotenoids and phycocyanin, approaches for their quantification using their absorption bands have been developed and applied to the casi data. The results remain qualitative because of the lack of reference data. However, they already give a differetiated spatial overview. In the same way the quantification of phycoerythrin using the absorption at 570 nm (see Fig. 2) also seems to be possible if present in the waters.

The resulting algorithms may be transferred to other lake systems in Northern Germany. By the application of models for trophic state it could be shown that mapping of trophic state is possible using remote sensing data. It is an advantageous tool to support the more intensive in situ measurements more effective over space and time.

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