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Detection of water quality using simulated satellite data and semi-empirical algorithms in Finland

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Abstract

The aim of the study was to test the feasibility of the band combination of the TERRA MODIS and ENVISAT MERIS instruments for operational monitoring of lakes and coastal waters in Finland. Also simulated LANDSAT TM data were tested. Satellite bands were simulated using airborne measurements with AISA imaging spectrometer. Semi-empirical algorithms with simulated satellite data were tested against field observations using regression analysis. Interpretation of chlorophyll *a*, suspended matter, turbidity and secchi-disk depth was included in the analyses. The data for this study were gathered in campaigns carried out in May and August 1997 and August 1998 both for lakes in southern Finland and coastal waters of the Baltic Sea. The data set included 85 in situ observations for lakes and 107 for coastal waters. Our results show that the band combination to be included in the ENVISAT MERIS instrument enables the interpretation of water quality, including chlorophyll *a* concentration using semi-empirical algorithms both for lakes and coastal waters. MERIS band 9 centred at 705 nm is proven to be of vital importance for the detection of chlorophyll *a* in local surface waters. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Satellite remote sensing of lakes and coastal waters; Monitoring of water quality

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1. Introduction

Reliable, spatially covering and cost-efficient monitoring techniques of lakes and coastal waters are generally growing in importance as a consequence of increasing symptoms of the on-going eutrophication process. Algal blooms, some of them being toxic, are extremely patchy, both temporally and spatially. Consequently, they often remain unobserved using the traditional sampling methods based on temporally sparse sampling at fixed monitoring stations. The problem is obvious in Finland with thousands of lakes, and coastal waters with thousands of islands. Remote sensing offers potentially a significant source of information, and methods are being developed for operational large-scale monitoring of water quality.

Present operative monitoring of lakes and coastal waters in Finland includes several thousands of point samples taken and measured annually. For example in August, when normally the most extensive algal blooms take place both in lakes and coastal waters, over 1200 water quality stations (year 1997) were measured in lakes. This extensive in situ data set enables the calibration of semi-empirical interpretation algorithms of remote sensing data and makes the use of such algorithms a potential alternative for satellite image interpretation in operational monitoring of water quality.

Obviously, the characteristics of the Finnish landscape and water bodies pose a significant demand to the spectral, spatial and temporal resolution of satellite sensors. Present and near future satellite ocean colour sensors are designed mainly for open, oceanic waters (case 1) and their usability for the Baltic Sea and lakes in Scandinavia may be limited.

The objective of this study is to evaluate the potential of data to be provided by satellites TERRA MODIS and ENVISAT MERIS scheduled to be launched in the near future to predict satisfactorily the water quality characteristics (e.g. chlorophyll *a* concentrations) of Finnish surface waters. The simulated satellite data are evaluated against field measurements using simple semi-empirical algorithms. Also the accuracy of the retrieval algorithms is tested for the simulated LANDSAT TM data. This paper considers only the spectral resolution capabilities of tested sensors. The effects of the radiometric and spatial resolution of the sensors in their usability in detection of water quality is ignored.

2. Material and methods

2.1. Field data

The data set has been collected in measurement campaigns carried out in May 1997, August 1997 and August 1998 for several lakes in southern Finland and coastal waters of Gulf of Finland and the archipelago of Turku (Fig. 1). The in situ measurement sites have been selected to represent different types of water bodies from eutrophic waters to oligotrophic and humic waters. Coastal sites are situated in estuaries close to river mouths and also in open sea in the Gulf of Finland. The campaigns were organised in early May during vernal maximum concentration of phytoplankton and in early August when algae blooms most commonly take place both in lakes and the Baltic Sea.

The campaigns included limnological field measurements analysed in the laboratory and airborne measurements using the AISA imaging spectrometer. The data set included 85 observations with chlorophyll *a* measurements for lakes and 107 for coastal waters.

Three stations of the humic lake Keravanjärvi were excluded from the data set, since the optical properties of the lake are highly specific due to absorption [$a_{ah}(400) = 13\text{–}14\ m^{-1}$] caused by dissolved organic matter. The humic lake Pääjärvi [$a_{ah}(400) = 7.2\text{–}7.4\ m^{-1}$] remained in the analysis. Suspended matter was analysed in the laboratory by two methods: first using Whatman GFC and secondly using Nucleopore polycarbonate 0.4-μm filters. Since these two methods give different concentrations, only the data set analysed with the latter method was included in the present study. Thus, analysis of suspended matter does not include measurements completed in August 1998, when Whatman GFC filter was applied. The main characteristics of water stations observed in

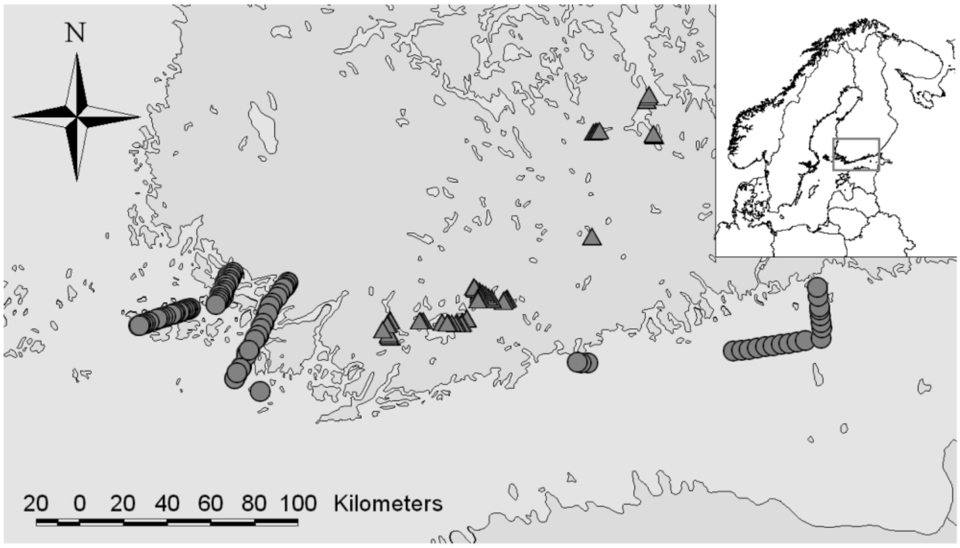

Fig. 1. Location of field and airborne measurement sites; ▲, lake sites; ●, coastal sites.

different campaign are shown in Table 1. More detailed information on field data of the study lakes is provided by Kallio et al. (2001).

2.2. Remote sensing data

Airborne imaging spectrometer AISA measure-

Table 1
Selected water quality variables of the different measurement campaigns[a]

Campaign	N	Chlorophyll *a* (μg/l) Mean Min/max S.D.	Suspended matter (mg/l) Mean Min/max S.D.	Secchi disk depth, (m) Mean Min/max S.D.	$r_{chl\text{-}susp}$
May 1997	20	8.9	12.5	1.7	0.56
Lakes		2.6/20.0	1.1/23.0	0.5/5.0	
		5.8	7.3	1.6	
August 1997	50	19.6	6.6	2.3	0.84
Lakes		1.3/100.0	0.7/18.0	0.4/7.0	
		22.7	5.3	1.6	
August 1998	15	22.4	6.0	1.3	0.95
Lakes		6.2/70.0	3.0/13.0	0.7/1.8	
		19.7	3.3	0.4	
May 1997	39	4.4	3.4	3.4	0.70
Coastal waters		1.1/15.0	2.0/10.0	1.0/4.9	
		4.1	1.5	1.1	
August 1997	48	3.8	4.1	2.7	0.25
Coastal waters		2.0/7.5	1.6/11.0	0.7/4.2	
		1.4	2.3	0.9	
August 1998	20	7.2	2.8	3.0	0.32
Coastal waters		4.6/11.0	1.4/5.5	2.0/5.0	
		1.9	1.1	0.6	

[a]*Abbreviations: N,* number of observations; $r_{chl\text{-}susp}$, coefficient of correlation between concentrations of chlorophyll *a* and suspended matter. Mean value, minimum and maximum values and standard deviations are shown for each variable.

ments were used to simulate data sets of MERIS, MODIS and TM satellite instruments. AISA data used in the study were radiometrically and geometrically corrected radiances. Atmospheric correction was not applied. The average spectral signatures of AISA data were drawn from nadir angle observations, which were nearest to the sampling stations (Pulliainen et al., 2001). The signatures were calculated by averaging AISA measurements inside a 100×100-m rectangle, Fig. 2.

Since the spectral configuration of the AISA instrument was different in each campaign, measured AISA data were first divided into 255 base bands in order to make the data set more comparable between different campaigns. Satellite data were simulated by averaging AISA base bands, whose spectral range was located inside the spectral range of the satellite bands. The spectral limits of AISA (450–900 nm) and the specific configuration of the AISA instrument in different campaigns did not enable the reproduction of all bands of interest in satellite instruments. TM channels 1–4, MODIS channels 10–16 (10–15 in May 1997) and MERIS channels 3–13 (3–12 in May 1997) were simulated with AISA data. It has

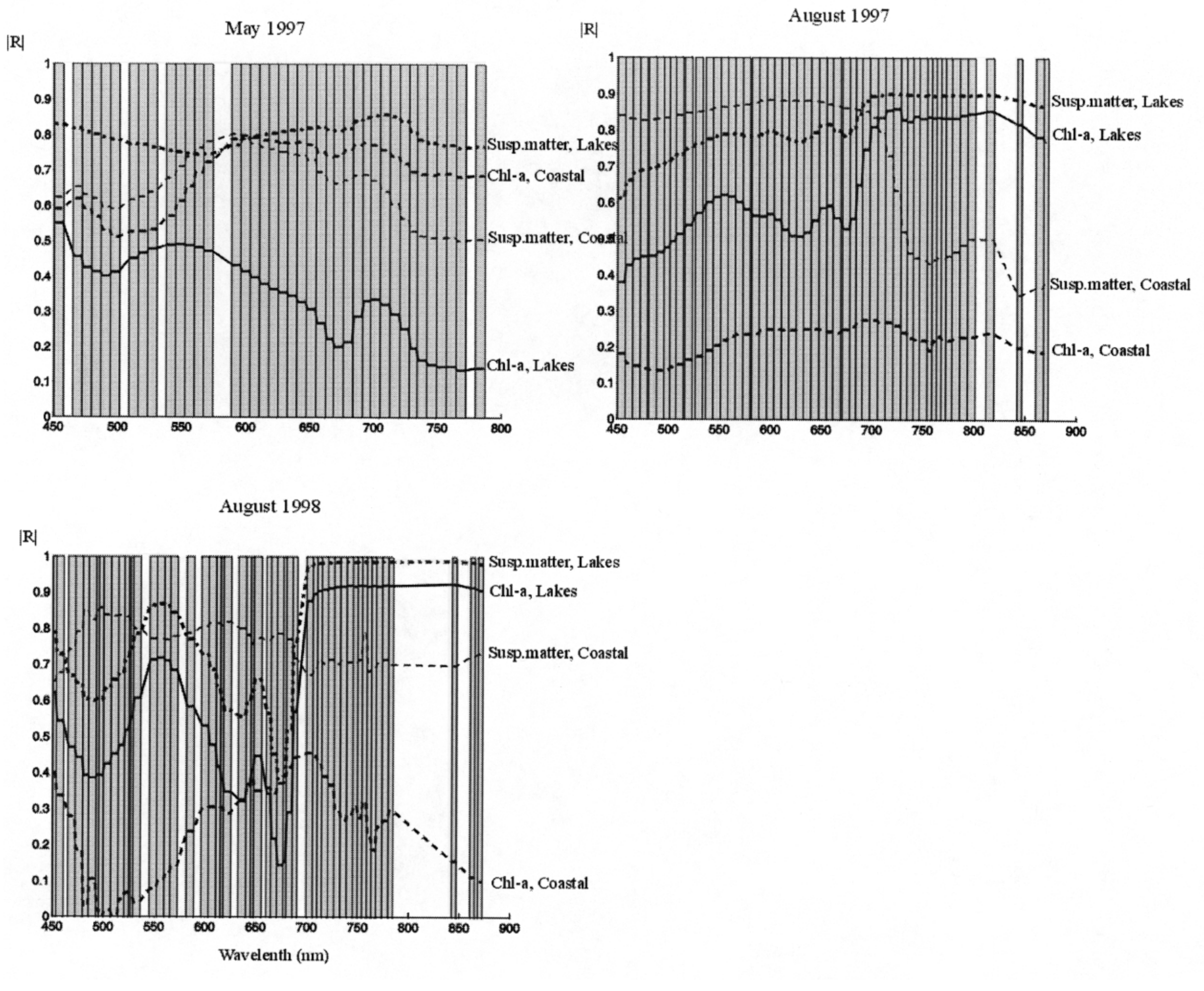

Fig. 2. AISA band configuration in different campaigns (bars) and correlation coefficients (dashed lines) between AISA measurements and chlorophyll *a* and suspended matter.

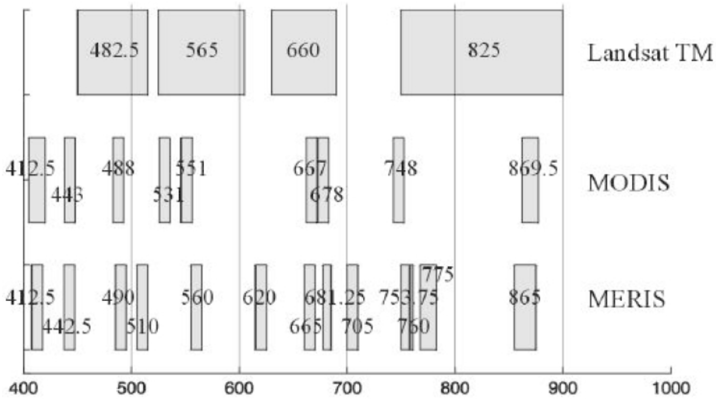

Fig. 3. Spectral range of simulated satellite instruments.

to be noticed that a satellite band was simulated even though AISA band configuration did not cover fully the spectral range of these bands. In Fig. 3 the spectral bands of simulated satellite instruments are shown. The differences in dynamic range, sensitivity and spatial resolution of satellite sensors were ignored in the study.

Fig. 2 depicts the spectral range and location of bands measured with the AISA instrument in each campaign and the correlation between in situ measurements (chlorophyll a and suspended matter) and original AISA bands. A more detailed description of the AISA instrument and measurements is given by Kallio et al. (2001) and Pulliainen et al. (2001).

3. Methods

Interpretation of chlorophyll *a* concentration in turbid inland and coastal waters (case 2) seems feasible using band ratios based on the absorption peak at 670 nm and scattering/fluorescence peak between 685 and 715 nm of phytoplankton (Gitelson et al., 1993). Algorithms for oceanic waters (case 1) with ratios of blue and green reflectance are inappropriate for the detection of chlorophyll *a* in optically complex water bodies (Schalles et al., 1998). In the following, band ratios based on fluorescence peak of chlorophyll *a* at 685–715 nm were tested with simulated MODIS and MERIS bands.

Models for estimating suspended matter, turbidity and secchi disk depth were generated using simple channel ratios and differences. The algorithms evaluated were taken from literature (Dekker, 1993; Gitelson et al., 1993; Abbott and Letelier, 1996; Althuis et al., 1996; Dekker and Hoogenboom, 1997; Carder et al., 1997). In the following, algorithms providing the best fit with these water quality variables are presented.

Althuis et al. (1996) assumes for Dutch coastal waters that the reflectance above 700 nm does not originate from water, and he subtracted reflectance at 750 nm from reflectances in shorter wavelengths in order to reduce sea-surface and atmospheric effects. Since airborne measurements used in this study were not atmospherically corrected and subtraction of radiance close to 750 or 775 nm from radiances in shorter wavelength improved the fit of band ratio algorithms, this technique was applied in the analysis.

The analysis included linear regression, where a water quality variable, in normal or log-transformed form, was predicted with different band combinations. The analysis was completed with different subgroups of the data, i.e. lakes and coastal waters separately and also for the whole data set including lakes and coastal waters. The applied model was in the form:

$$Y = a + b \times X \qquad (1)$$

where Y is the predicted water quality variable, X

is the applied band ratio, and a, b are empirically derived constants.

For each model, the following characteristics are defined:

- location of water stations used in the model (lakes or coastal waters of Finland or the combined data set);
- simulated band combination, which was used in linear regression model;
- coefficient of determination (R^2); and
- root mean squared error of the estimate (rmse), defined as:

$$\text{rmse} = \sqrt{\frac{\Sigma(X_{\text{mod},i} - X_{\text{obs},i})}{(n-k-1)}} \quad (2)$$

  where n is the number of observations, k is the number of independent variables, $(n-k-1)$ is the degree of freedom.
- root mean squared error of the estimate as a percentage of the mean estimate (rmse-%); and
- N is the number of observations.

In some cases logarithmic transformation of the dependent variable increased the goodness of fit for the model. Transformations complicate comparisons of different models by means of coefficient of determination, since the dependent variable is not the same for all models. The standard error of estimate and its relation to the mean response give a better and more comparable picture of the reliability of the models.

The best band combination and possible transformation of the dependent variable in the models was defined by using the data of all campaigns as input data. Since the data set included observations measured in different campaigns which were completed in varying weather conditions in different seasons (May 1997, August 1997 and 1998), a campaign-wise adjustment to the models was tested. This was completed introducing dummy variables for each campaign using a stepwise regression procedure (selection criteria defined as a probability of F, threshold 0.05 was applied in entry and 0.10 in removal of a variable). Dummy variables were estimated for each campaign separately and they produce a campaign-wise adjustment to the bias term of the models. It was assumed that usage of dummy variables could reduce the bias of models caused by varying atmospheric conditions and varying type of water constitutes (for example algae species) in different campaigns in spring and late summer. Usage of such dummy variables can be justified also with practical reasons: if algorithms tested in this study will be used in operative monitoring of water quality in Finland, algorithms would be calibrated for each satellite image or set of images using simultaneous field measurements. When dummy variables were included, the algorithm was in form:

$$Y = a + b \times X + c_i \quad (3)$$

where Y is the estimated water quality variable, X is the applied band ratio, and a, b and c_i are empirically derived constants, c_i is estimated separately for each campaign i.

Chlorophyll a, turbidity and secchi disk depth were analysed in six campaigns (May 1997 lakes; May 1997 coast; August 1997 lakes; August 1997 coast; August 1998 lakes; August 1998 coast) and data for suspended matter were available from four campaigns, i.e. those organised in 1997.

When assessing the accuracy of the models for different types of water bodies, residuals of the models were plotted against measured values and classified according to the type of water bodies. For the models of chlorophyll a, the water stations were classified according to the concentration of suspended matter and also humic lakes were separated. In cases of secchi disk depth, turbidity and concentration of suspended matter the classification of water stations was based on the measured values of chlorophyll a in each station. The classification does not describe the general trophic stage of the water body. The classes were defined as follows:

- oligotrophic (measured chlorophyll $a = 8$ μg/l);
- mesotrophic ($8 <$ μg/l chlorophyll $a = 25$ μg/l);

- eutrophic (25 μg/l < chlorophyll a = 50 μg/l);
- high-eutrophic (chlorophyll a > 50 μg/l); and
- humic lake (absorption coefficient at 380 nm measured from a filtered water sample $a_{ah}380 > 10\ m^{-1}$, refer to Kallio et al., 2001)

4. Results

4.1. ENVISAT MERIS

Table 2 presents the results from applying the above methods to the ENVISAT spectral bands. The MERIS instrument will include channels for the detection of chlorophyll fluorescence (band 8: 681 nm). However, band ratio L705/L665, i.e. bands number 9 and 7, seem to predict best the chlorophyll concentration. In lakes and coastal waters band combination (L705−L775)/(L665−L775), i.e. bands 7, 9 and 12 explains up to 90% of the variation in chlorophyll concentrations.

Near infrared bands 10 (754 nm) and 13 (865 nm), which are designed mainly for atmospheric correction, contain information of water quality in lakes: correlation between turbidity and bands 10 and 13 is 0.79 and 0.91 (see Fig. 2). Difference of these bands explains 94% of the variation in turbidity in lakes measured in August 1997 and 1998 (63 observations).

4.1.1. Calibration of models in different campaigns

Although no atmospheric correction is applied to the data, observations measured in different campaigns seem to fit quite well into one model (see Table 2). This may be due to the fact that the applied algorithm, for example for chlorophyll a, uses the ratio of MERIS bands 9 and 7 centred at 665 and 705 nm, where the effect of atmospheric scattering is similar in both wavelength and is eliminated in the applied band ratio (Vepsäläinen, 1999).

The model is, however, not unbiased within each campaign and for example, it underestimates the concentration of chlorophyll a in coastal waters measured in May 1997. Calibration of the model in each campaign increases the accuracy. In order to reduce the bias within each campaign, dummy variables were added to the model for each campaign.

Table 3 shows the accuracy of the models demonstrating the inclusion of dummy variables to be statistically significant by applied criteria. The accuracy of models for chlorophyll a, turbidity and secchi disk depth could be improved when dummy variables were introduced. The percent-

Table 2
Accuracy of algorithms for suspended matter (mg/l), turbidity (FNU), secchi disk depth (m) and chlorophyll a (μg/l) in AISA data simulating the MERIS instrument[a]

Variable	Sites	Band combination	R^2	rmse	rmse-%	N
Suspended matter	Lakes 1997	L705−L754	0.81	2.9	34	67
Turbidity	Lakes	L705−L754	0.89	2.1	28	83
Secchi disk depth[b]	Lakes	(L490−L754)/(L620−L754)	0.83	0.7	35	85
Chlorophyll a	Lakes	(L705−L754)/(L665−L754)	0.90	6.5	37	85
Suspended matter	Coast 1997	L705−L775	0.82	0.8	22	87
Turbidity	Coast	L620−L775	0.80	0.6	28	105
Secchi disk depth	Coast	(L510−L754)/(L620−L754)	0.68	0.6	18	107
Chlorophyll a	Coast	(L705−L775)/(L665−L775)	0.77	1.5	31	107
Suspended matter	Lakes and coast 1997	L705−L754	0.84	2.0	35	154
Turbidity	Lakes and coast	L705−L754	0.90	1.6	35	188
Secchi disk depth[b]	Lakes and coast	(L490−L775)/(L620−L775)	0.78	0.8	31	192
Chlorophyll a	Lakes and coast	(L705−L754)/(L665−L754)	0.90	4.6	45	192

[a]*Abbreviations:* R^2, coefficient of determination; rmse, root mean squared error of estimate; rmse-%, relative root mean squared error of estimate; N, number of observations.
[b]Transformed (logarithm) dependent variables.

Table 3
Accuracy of algorithms for turbidity (FNU), secchi disk depth (m) and chlorophyll *a* (μg/l) with simulated MERIS data when dummy variables were included[a]

Variable	Sites	Band combination	Dummy variable included for	R^2	rmse	rmse-%	*N*
Chlorophyll *a*	Lakes and coast	(L705−L775)/(L665−L775)	May 1997 lakes August 1998 lakes	0.94	3.8	37	192
Chlorophyll *a*	Lakes	(L705−L775)/(L665−L775)	August 1997 lakes	0.93	5.5	31	85
Chlorophyll *a*	Coast	(L705−L775)/(L665−L775)	August 1997 coast	0.79	1.4	30	107
Turbidity	Lakes and coast	L705−L754	August 1998 lakes August 1998 coast August 1997 coast	0.92	1.5	32	188
Turbidity	Lakes	L705−L754	August 1998 lakes	0.89	2.1	27	83
Turbidity	Coast	L620−L775	May 1997 coast	0.81	0.6	28	105
Secchi disk depth[b]	Lakes and coast	(L490−L775)/L620−L775	May 1997 coast August 1997 coast August 1998 coast	0.81	0.8	32	192
Secchi disk depth[b]	Lakes	(L490−L754)/L620−L754	August 1997 lakes	0.84	0.7	34	85

[a]*Abbreviations:* R^2, coefficient of determination; rmse, root mean squared error of estimate; rmse-%, relative root mean squared error of estimate; *N*, number of observations.
[b]Transformed (logarithm) dependent variables.

age error of chlorophyll *a* estimation decreased in lakes from 37 to 31% by introducing dummy variable for August 1997 campaign (see Table 3). In Figs. 4 and 5 measured and estimated chlorophyll *a* values are plotted for lakes and coastal waters using Eq. (3).

4.1.2. Usability of models in different type of water bodies

In Fig. 6 the differences between estimated and measured chlorophyll *a* divided by measured values are plotted against measured chlorophyll *a* in

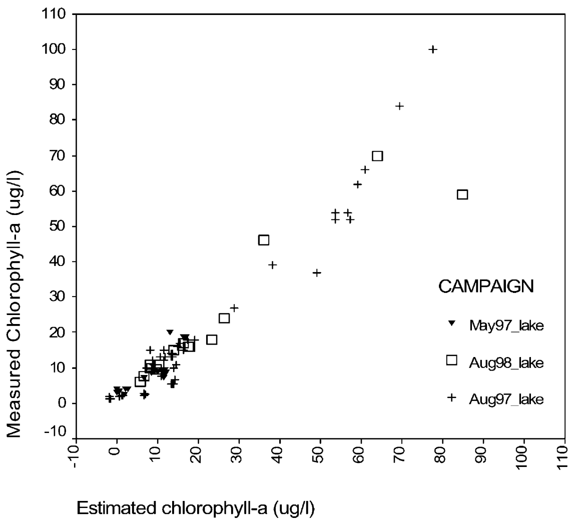

Fig. 4. Measured and estimated concentration of chlorophyll *a* (μg/l) using MERIS bands in lakes. Observations are classified according to the campaign.

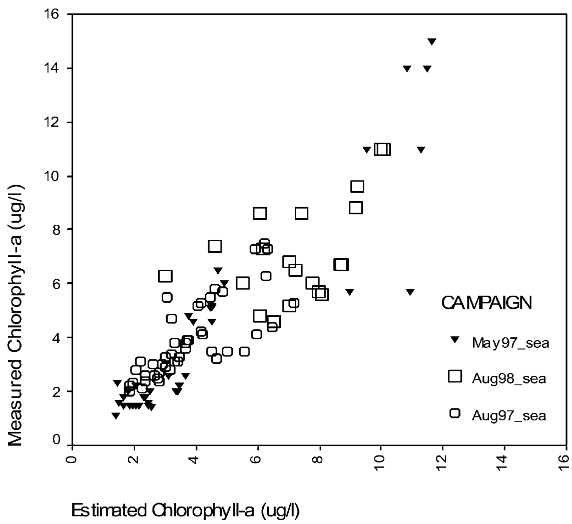

Fig. 5. Measured and estimated concentration of chlorophyll *a* (μg/l) using MERIS in coastal waters. Observations are classified according to the campaign.

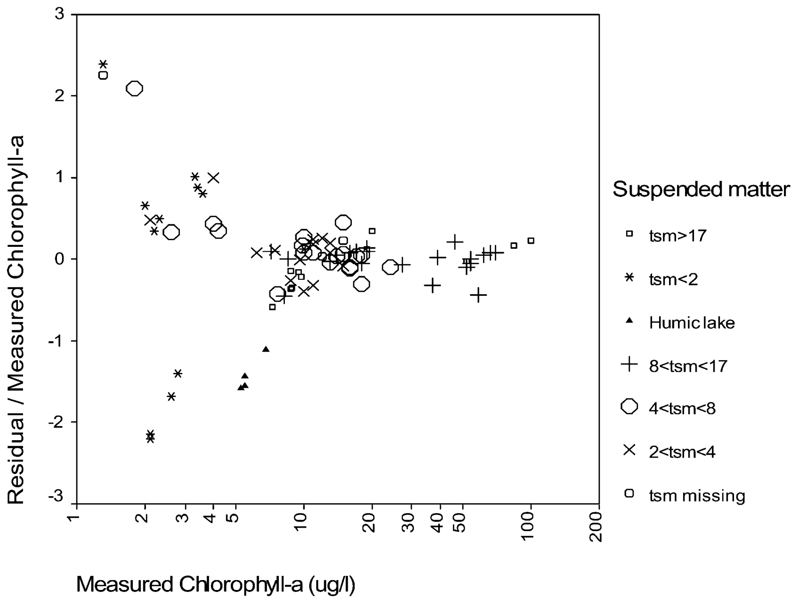

Fig. 6. Relative residuals (residual divided by measured value) of model for chlorophyll *a* in lakes using MERIS bands. Observations are classified according to the concentration of suspended matter. Also humic lakes are separated.

lakes. It can be seen that the relative error of the model is large for a humic lake (Lake Pääjärvi August 1997) and for some lakes (Lakes Päijänne and Puujärvi August 1997 and Lake Iso-Kisko in May 1997), where the chlorophyll *a* concentration is low (below 5 μg/l). No systematic error can be detected caused by concentrations of suspended matter.

Fig. 7 shows measured and estimated concentration of suspended matter. There is no syste-

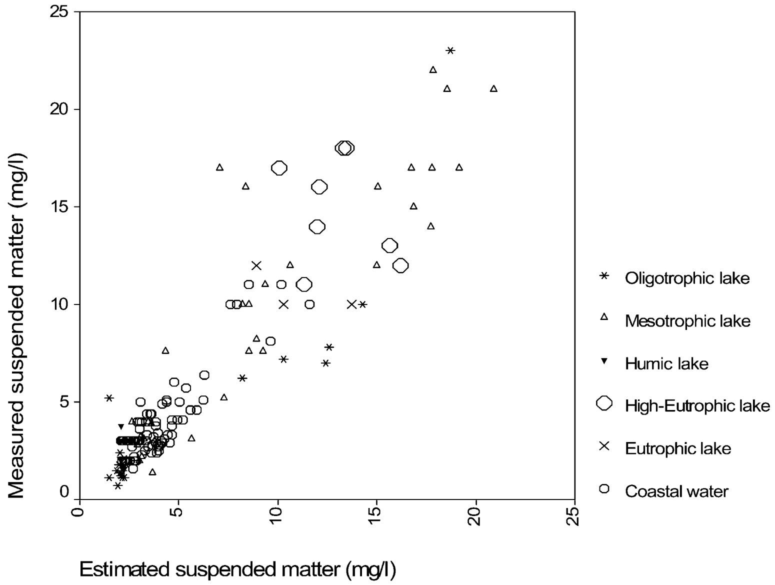

Fig. 7. Measured and estimated concentration of suspended matter (mg/l) using MERIS bands. Observation classified according to the concentration of chlorophyll *a*. Also humic lakes are separated.

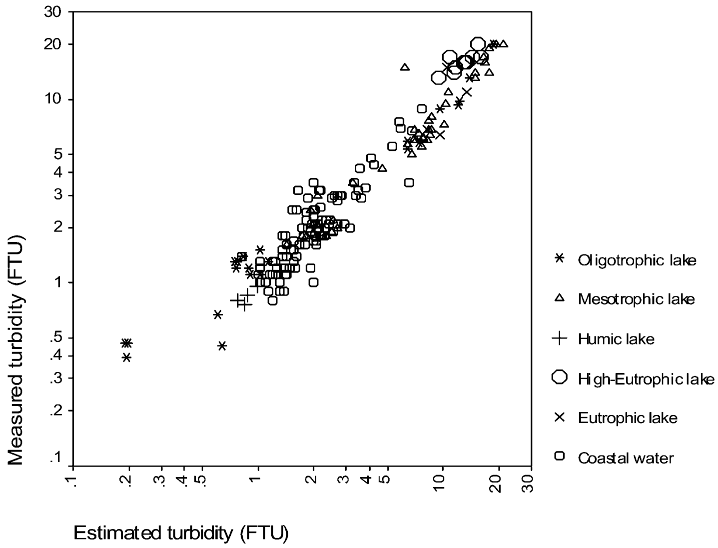

Fig. 8. Measured and estimated turbidity (FNU) using MERIS bands separately for lakes and coastal waters. Observations are classified according to the concentration of chlorophyll a. Also humic lakes are separated.

matic error within different water body types in estimates of suspended matter. However, different levels of suspended matter cannot be detected within lakes classified as eutrophic or high-eutrophic. This is also the case for the humic lake Pääjärvi.

In Fig. 8 the measured and estimated turbidity using separate models for lakes and coastal

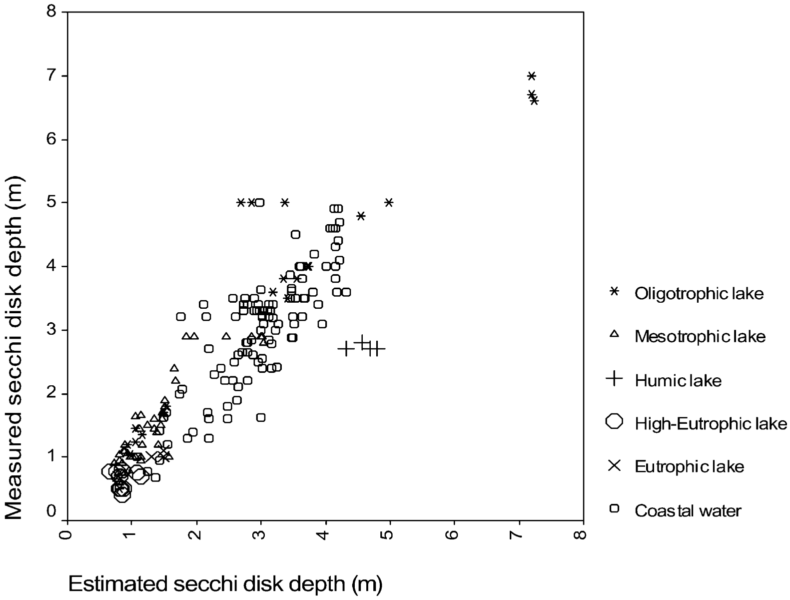

Fig. 9. Measured and estimated secchi disk depth (m) using MERIS bands separately for lakes and coastal waters. Observations are classified according to the concentration of chlorophyll a. Also humic lakes are separated.

waters are plotted. It can be observed that the estimation of turbidity is quite reliable for each type of water body with the exception of high-eutrophic lakes, where turbidity is clearly underestimated. Accuracy of the estimate is 27% for lakes and 28% for coastal waters (Table 3).

Secchi disk depth cannot be estimated for humic lakes using applied algorithm for MERIS (Fig. 9). If the humic lake Pääjärvi (four observations) is omitted from the analysis and a linear model was applied, the rmse values of the model decreased from 0.83 (34%) down to 0.48 m (25%) in lakes.

4.2. TERRA MODIS

The MODIS instrument includes channels for detection of chlorophyll fluorescence. However, the correlation between channel ratio L678/L667 with simulated MODIS data and chlorophyll *a* was low both for lakes and coastal waters in our data set ($r = -0.45$ for lakes and $r = 0.15$ for coastal waters). This was also the case with fluorescence line height calculated with MODIS bands 13, 14 and 15. Thus, other band combinations presented by Althuis et al. (1996) were tested for chlorophyll *a* (see Table 4).

When using the data set where simulation of MODIS band 16 (862–877 nm) was possible, i.e. campaigns August 1997 and 1998, the best fit was found between suspended matter, chlorophyll *a* and turbidity and difference of MODIS near infrared bands 15 and 16 in lakes (see Table 5).

4.3. LANDSAT TM

Table 6 represents the best band ratio or band

Table 4
Accuracy of algorithms for suspended matter (mg/l), turbidity (FNU), secchi disk depth (m) and chlorophyll *a* (μg/l) using simulated MODIS data[a]

Variable	Sites	Band combination	Dummy variable included for	R^2	rmse	rmse-%	N
Suspended matter[b]	Lakes 1997	(L531-L748)/(L551–L748)	August 1997 lakes	0.74	4.2	56	67
Turbidity[b]	Lakes	(L488–L748)/(L667–L748)	–	0.84	3.6	54	83
Secchi disk depth	Lakes	(L488–L748)/(L667–L748)	May 1997 lakes	0.83	0.6	32	85
Chlorophyll *a*[b]	Lakes	(L531–L748)/(L551–L748)	May 1997 lakes	0.69	11.6	77	85
Suspended matter	Coast 1997	L667–L748	–	0.78	1.0	25	87
Turbidity	Coast	L667–L748	August 1998 coast	0.80	0.6	28	105
Secchi disk depth	Coast	(L531–L748)/(L667–L748)	–	0.61	0.6	20	107
Chlorophyll *a*[b]	Coast	(L531–L748)/(L667–L748)	August 1998 coast May 1997 coast	0.63	2.1	49	107
Suspended matter[b]	Lakes and coast 1997	(L531–L748)/(L551–L748)	August 1997 coast May 1997 lakes	0.73	3.0	56	154
Turbidity[b]	Lakes and coast	(L488–L748)/(L667–L748)	May 1997 coast August 1997 lakes	0.83	2.6	63	188
Secchi disk depth	Lakes and coast	(L488–L748)/(L667–L748)	May 1997 lakes August 1997 lakes August 1998 coast August 1998 lakes	0.79	0.6	25	192
Chlorophyll *a*[b]	Lakes and coast	(L531–L748)/(L551–L748)	May 1997 lakes May 1997 coast August 1997 lakes August 1997 coast	0.78	7.3	78	192

[a]*Abbreviations:* R^2, coefficient of determination; rmse, root mean squared error of estimate; rmse-%, relative root mean squared error of estimate; N, number of observations.
[b]Transformed (logarithm) dependent variables.

Table 5
Accuracy of algorithms for suspended matter (mg/l), turbidity (FNU) and chlorophyll *a* (μg/l) using simulated MODIS near infrared bands[a]

Variable	Sites	Band combination	Dummy variable included for	R^2	rmse	rmse-%	*N*
Suspended matter	August 1997 lakes August 1998 lakes	L748–L870	–	0.81	2.4	36	47
Turbidity	August 1997 lakes August 1998 lakes	L748–L870	August 1997 lakes	0.94	1.3	21	63
Chlorophyll *a*	August 1997 lakes August 1998 lakes	L748–L870	–	0.74	11.2	55	65

[a]*Abbreviations:* R^2, coefficient of determination; rmse, root mean squared error of estimate; rmse-%, relative root mean squared error of estimate; *N*, number of observations.

difference algorithms, which were tested with simulated TM data. Interpretation of chlorophyll *a* was not tested with TM bands.

5. Discussion

When comparing the spectral resolution of the TM, MODIS and MERIS instruments, MERIS seems to provide the best band combination to map water quality of lakes and coastal waters in Finland if simple semi-empirical algorithms are used (Fig. 10). With all tested water quality variables, the simulated MERIS data proved to be most useful with respect to the detection of variables important for monitoring of eutrophication. MERIS band 9 centred at 705 nm seems to be of vital importance in detection of chlorophyll *a* and suspended matter in this study. The relation between MERIS bands 9 and 7 can be used successfully for estimation of chlorophyll *a* and the difference between bands 9 and 12 predicts the concentration of suspended matter.

The rms errors of models for chlorophyll *a*, suspended matter and turbidity were over 50% for lakes using MODIS bands. Corresponding errors with TM bands in estimation of suspended matter and turbidity were over 40%. The retrieval error of secchi disk depth was 32% with MODIS bands and 34% with TM bands. If humic lake

Table 6
The accuracy of algorithms for suspended matter (mg/l), turbidity (FNU) and secchi disk depth (m) using simulated LANDSAT TM data

Variable	Sites	Band combination	Dummy variable included for	R^2	rmse	rmse-%	*N*
Suspended matter[a]	Lakes 1997	(tm1–tm4)/(tm3–tm4)	–	0.73	3.8	52	67
Turbidity[a]	Lakes	(tm1–tm4)/(tm3–tm4)	August 1997 lakes	0.88	3.1	44	83
Secchi disk depth	Lakes	(tm1–tm4)/(tm3–tm4)	May 1997 lakes	0.81	0.7	34	85
Suspended matter	Coast 1997	tm3–tm4	August 1997 coast	0.80	0.9	24	87
Turbidity	Coast	tm3–tm4	May 1997 coast	0.79	0.6	29	105
Secchi disk depth	Coast	(tm2–tm4)/(tm3–tm4)	–	0.48	0.7	23	107
Suspended matter	Lakes and coast 1997	tm3–tm4	August 1997 lakes	0.72	2.7	47	154
Turbidity[a]	Lakes and coast	tm1/(tm1 + tm2 + tm3)	August 1997 coast August 1998 lakes August 1998 coast	0.85	2.1	52	188
Secchi disk depth	Lakes and coast	tm1/(tm1 + tm2 + tm3)	May 1997 lakes August 1997 lakes August 1998 coast	0.71	0.7	29	192

[a]Transformed (logarithm) dependent variables.

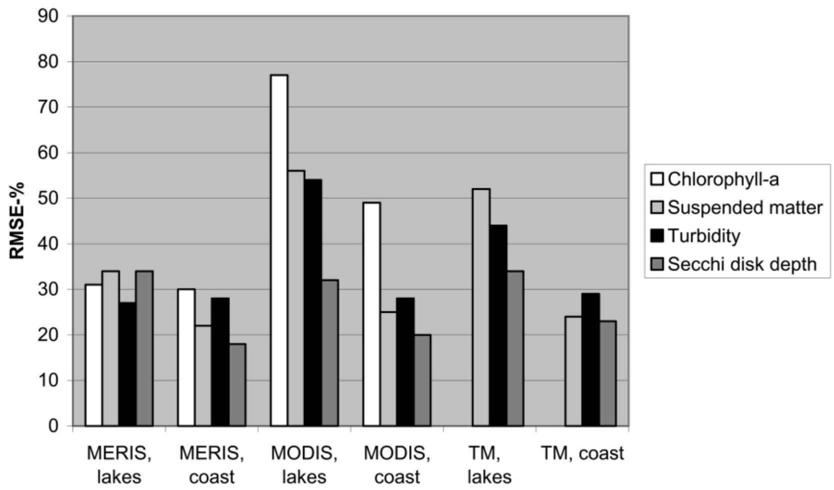

Fig. 10. The relative accuracy of algorithms for chlorophyll *a*, suspended matter, turbidity and secchi disk depth using simulated MERIS, MODIS and TM data.

Pääjärvi was excluded from the analysis corresponding figures were 28% for MODIS and 30% for TM bands. Retrieval error of suspended matter, turbidity and secchi disk depth for coastal waters was between 20 and 30% with both MODIS and TM bands.

Subtraction of band in near infrared region from bands in shorter wavelengths improved the fit of applied algorithms. It was assumed that this technique reduces the atmospheric and surface effects from airborne measurements. However, infrared bands correlated also with water quality parameters: MODIS bands 8 and 9 (centred at 748 and 870 nm) explained 94% of the variation in turbidity and 81% of suspended matter. The data set in the analysis was measured in August 1997 and 1998 when concentrations of chlorophyll *a* were high and most of the suspended matter was explained by chlorophyll *a* ($r = 0.84$ in 1997; $r = 0.95$ in 1998). This indicates that the usage of near infrared bands in atmospheric correction in turbid inland and coastal waters is problematic.

Water quality of the humic lake Pääjärvi [$a_{ah}(400) = 7.2–7.4\ m^{-1}$] could not be interpreted using applied band ratios; especially if bands below 600 nm were used. Also in retrieval of chlorophyll *a* with MERIS bands, the relative error of estimate was high for lake Pääjärvi. These results suggest that if tested algorithms shall be used in monitoring of water quality in lakes, humic lakes need to be separated and interpreted using specific models developed for this type of water bodies. Also oligotrophic lakes may need to be interpreted separately.

Detection of water quality using satellite remote sensing, in spite of its potential, has in Finnish conditions several problems that need to be addressed before the methods can be adopted into operational use:

- These water bodies contain highly varying concentrations of optically active components: phytoplankton, suspended inorganic matter, dissolved and particulate organic matter. These concentrations may vary independently of each other. Surface waters in Finland are characterised by high concentrations of dissolved organic substances due to leaching from peat lands and organic soils. Approximately 30% of the land area in Finland is covered by soils classified as peat land. In addition algae species composition differs seasonally and mass occurrences of algae may occur especially in late summer both in lakes and coastal waters. This means that optical properties of these waters are complex and varying in time.
- Finnish lakes are generally small in size. The total number of lakes and ponds with a sur-

face area exceeding 0.01 ha is 18 8000. There are 56 012 lakes with an area greater than 0.01 km^2 and only three lakes are more than 1000 km^2 in size (Raatikainen and Kuusisto, 1988). In addition, water bodies are further fragmented by islands and by complex shape of lakes. Coastal waters of Baltic Sea in Finland are characterised by thousands of islands.

- Weather conditions in Finland reduce the availability of cloudless satellite images remarkably: for example in August, when the need for monitoring information is highest, the average cloudiness exceeds 65% for the lake district and 55% for the coastal waters of Finland.

Usability of the algorithms has been tested in coastal waters and in 11 lakes in southern Finland in this study. The effects of data corrections ignored in this paper have been discussed by Koponen et al. (2001) and operationalisation of the methods by Pulliainen et al. (2001).

6. Conclusions

Tested semi-empirical algorithms for simulated ENVISAT MERIS data seem to have potential for determining water quality variables of both lakes and coastal waters in Finland. The accuracy of retrieval algorithms tested in this study was approximately 30% for chlorophyll *a*, suspended matter, turbidity and secchi disk depth for lakes and between 20 and 30% for coastal waters.

Usability of TERRA MODIS and LANDSAT TM data with applied algorithms in local conditions is limited since the band configuration of the instruments does not enable interpretation of chlorophyll *a*. The detection of this variable is of vital importance in operative monitoring of water quality, in case the quantity of algae and other symptoms of eutrophication are to be observed. However, these instruments can be used in mapping suspended matter, turbidity and secchi disk depth in coastal waters of the Baltic Sea using tested algorithms. In this study both LANDSAT TM and TERRA MODIS instruments are tested beyond their intended use: TM instrument is designed for land applications and bands 8–16 in MODIS for detection of water quality in oceanic waters.

This paper indicates that in particular the MERIS instrument is spectrally adequate for detection of water quality in Finnish lakes and coastalwaters. However, further research is needed to test the radiometric sensitivity and the impact of coarse spatial resolution of simulated satellite sensors in Finnish lakes and coastal waters, where the effect of adjacent land areas may be significant to the satellite measurement of the waterbody.

Ongoing operational monitoring of lakes and coastal waters in Finland provide the field data needed in the interpretation of satellite images with the method tested in this study. Possibility of acquiring feasible satellite data in the near future is high. Japanese GLI ocean colour instrument planned for launch onboard ADEOS II has corresponding band combination as ENVISAT MERIS between 660 and 710 nm (Morel, 1998). Both ENVISAT and ADEOS II satellites are scheduled for launch in 2000. This means that operational monitoring of water quality can be enhanced spatially and temporally using satellite data together with in situ measurements in the near future.

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