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Determination of algal production in an industrial waste water plume using Landsat TM satellite imagery

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PREFACE

This report constitutes the final report of the project ‘Satellite based mapping of eutrophication effects at forest industry waste water plumes, financed by the Swedish National Space Board and IVL.

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ABSTRACT

This paper describes an experiment with the objective to examine the utility of Landsat TM for estimation of chlorophyll-a, in and close to an outfall plume; in this case a plume from a pulp and paper industry. The principal findings were that the near-infrared band TM4 was independent of the high load of total suspended matterin the plume, but strongly correlated to chlorophyll-a concentrations in the surface water layer. The effect of the industrial effluents on algal production was negligible, or only slightly positive. These results have implications for on-going efforts attempting to identify and rank pollution sources around the Baltic sea and their specific effect on primary production.

1. INTRODUCTION

1.1 Background

In spite of an increasing public awareness of environmental problems as well as industrial reductions in water pollutant loads the situation in coastal waters around Europe have deteriorated rather than recovered during the last decade. Environmental effects seem to accumulate and the state of eutrophication is more alarming than ever. The Baltic sea is a capital example of this. Discharges from eastern Europe as well as an undiminished agricultural use of fertilizers in the western countries around the Baltic sea are the major causes to these problems. The industrial effluents from Sweden and other surrounding western economies have been significantly reduced, but the pulp and paper industry still contributes with 18 % of the phosphorus load and 6 % of the nitrogen load to the Gulf of Bothnia, the northern part of the Baltic sea. Since these effluents originate from a limited number of large industrial sites, reductions in nutrient discharges might be comparatively easy to obtain at these sites, compared to attempts to regulate the use of fertilizers in the entire agricultural community.

The local and regional effects of pulp and paper or other industrial water effluents on primary biological production are not well known. The concentration of phosphorus and nitrogen normally determine the distribution and intensity of algae blooms. However, apart from considerable loads of these nutrients, the pulp and paper effluents also contain metals and persistent organic compounds. These might result in a negative effect on the biological production. The total effect of these factors have not been clarified.

1.2 Objectives

This investigation aims at evaluating the capacity of Landsat TM to monitor chlorophyll-a in and close to industrial effluent plumes, with a pulp and paper industry as case study. The effort is part of a larger research programme aiming to investigate the effects of pulp and paper effluents, and to examine a possible positive or negative gradient in the concentration of chlorophyll-a close to the outfall sites.

1.3 State of the art

Landsat TM is the most suitable sensor for this purpose, since the coastline around the Baltic sea is heterogenous, with archipelagos in several areas. Thus, high geometric resolution is a prerequisite. Additionally, the spatial heterogeneity of phytoplanktion concentrations in near-shore environments accentuates the benefits of high spatial resolution. Spaceborne sensors have frequently been used to measure turbidity, suspended sediments and other water quality parameters (e.g. Alföldi and Munday 1978, Khorram and Cheshire, 1985, Lindell et al. 1986). In ocean waters sensors like the CZCS have also proved capable to estimate chlorophyll-a (Gordon et al. 1980, Smith and Baker 1982, Tassan 1987) However, in inland and coastal waters the influence from suspended sediments and yellow substance have impaired chlorophyll estimation (Möller-Sörensen et al. 1982, Verdin 1985, Tassan 1987).

Landsat TM has in waters with low suspended sediment loads been capable of quantifying chlorophyll-a also at low concentrations, 0-5 μg/l (Kim and Linebaugh 1985, Dwivedi and Narain 1987), using the ratio of TM bands 1/2 corresponding to the ocean chlorophyll algorithm for the CZCS sensor. Several Landsat TM spectral band algorithms have been tested and used, and one of these has been found to be particularly sensitive to chlorophyll-a in coastal and inland waters, i.e, a ratio of TM bands 1 and 3 (Baban 1993, Ekstrand 1992), probably due to a somewhat lower depency on suspended sediment. Forster et al. (1993) presented a promising multiple regression model (bands 1-4) for estimation of chlorophyll-a in a coastal sewage outfall area. In that study however, turbidity and chlorophyll was strongly correlated, which might not be the case here since the plume may have a negative effect on algal production.

The use of TM band 4 for water quality applications have been limited, mainly due to the high water absorption of light at these wavelengths. However, light is actually reflected from particles in the top layer, and it is a well-known fact that near-infrared radiance is reflected to a much higher degree by chlorophyll, than by sediment. (see e.g. Bartolucci et al. 1977, Clark and James 1939). Althuis and Shimwell (1995) showed that the effect of suspended matter in water, with a range of 1-42 mg/l including very little chlorophyll, had virtually no effect on reflectance above 730 nm.

Some researchers have explored the capacity of wavelengths close to and in the NIR region for chlorophyll estimation during the last few years. These hyperspectral studies reveal a strong relationship between NIR reflectance and surface chlorophyll-a. Some of them found that single NIR bands, e.g. around 705 nm, were the most suitable for chlorophyll estimation (Gitelson 1992, Quibell 1992), others that a NIR/red ratio was more robust (Mittenzwey et al. 1992, Rundquist et al. 1996). Gitelson et al. (1993) showed that the visible spectral regions lost their correlation with chlorophyll when the concentration of suspended matter was high, while wavelengths above 700 nm were still strongly correlated with chlorophyll, The above experiments were conducted either in water tanks or in extremely eutrophicated inland lakes. No references in literature have been found that apply these findings to satellite data, or to coastal waters where the chlorophyll concentration is considerably lower.

2. DATA COLLECTION AND METHODS

The Iggesund pulp and paper industrial site is situated at the Swedish east coast, approximately 300 kilometres north of Stockholm. The submarine outfall pipe is located two kilometres out from the industrial area in a narrow bay. The wastewater plume reaches the sea through yet another bay called Gårdsfjärden. The water passes two narrow sounds and on occasions with easterly winds the water is forced back into the two inner bays.

Figure 1. The plume from the Iggesund pulp and paper industry as viewed with Landsat TM 3,2,1 (R,G,B). The plume can be distinguished out to approximately 12 km from the outfall site.

2.1 Sea water analyses

Surface water samples for laboratory analysis were collected simultaneously with the Landsat TM overpasses of the 4 June 1992 and the 29 of April 1993. Eleven samples were collected at the first occasion and six at the later, at sample sites evenly distributed from the outfall pipe to a distance of 12 km from the pipe, reaching the open sea. The sea water samples were analysed in in-house laboratories for total suspended matter, secchi disk depth, chlorophyll-a, nitrogen and phosphorus concentrations.

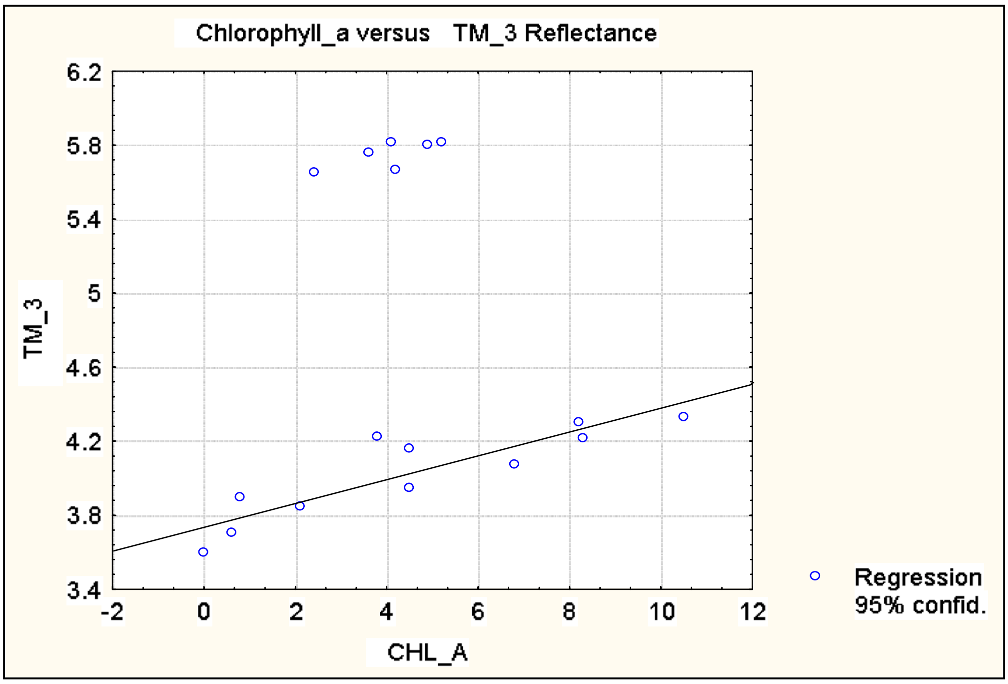
2.2 Analysis of Landsat TM data

The Landsat TM scene from 1992 was purchased geometrically precision corrected which meant that inflight calibration data from the lamp on board the spacecraft was used to correct for gain decay. This was not possible for the scene from 1993, due to problems with data transfer between the ESA station in Fucino, and the Swedish distributor, Satimage. Thus, this scene had been radiometrically corrected based on pre-launch data. When calculating reflectance values for this scene constants for gain decay and exoatmospheric irradiance presented by Epema (1990) were used. Mean reflectance values for five by five pixel windows covering each sample site were calculated. Simple and multiple regression analyses were used to determine the relationships between satellite data and water quality parameters.

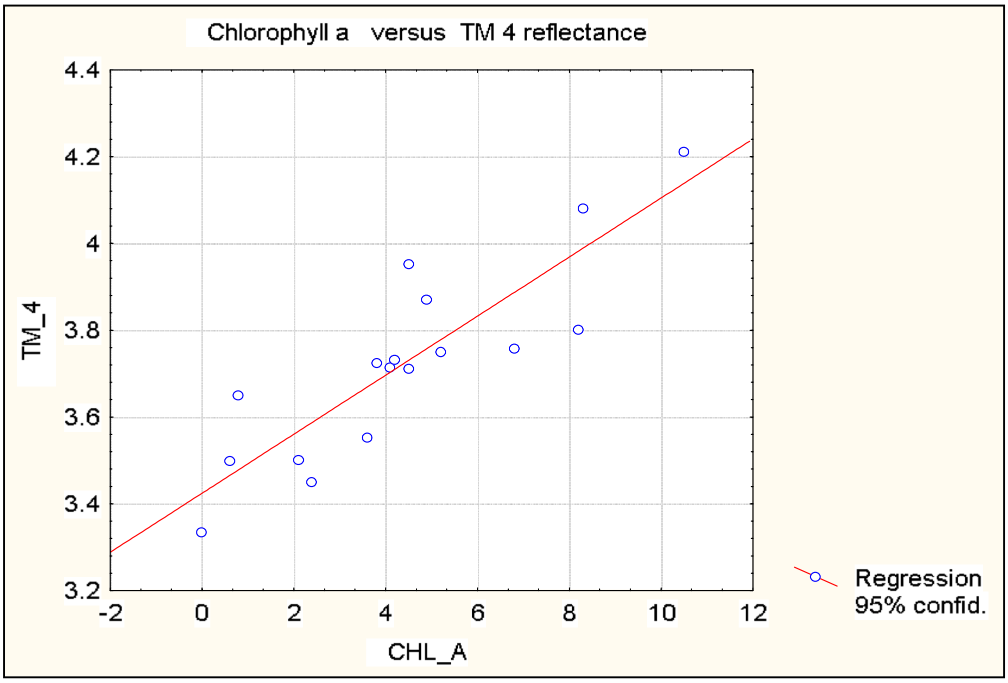
3. Results

Regression analysis of the revealed that the chlorophyll concentration on June 4 1992 was strongly correlated to total suspended matter (r=0.85), secchi disk depth (r=0.87) and phosphorus concentration (r=0.94) in and around the effluent plume. Iggesund is the only contributor of suspended material and nutrients to these bays, no other outfall sites or river outlets exist. This means that the algal production at this occasion seems to be related to the density of the plume and its phosphorus content. The relationship with nitrogen concentration was not statistically significant. Landsat TM bands 3 and 4 were strongly correlated with chlorophyll, while the correlation for TM bands 1 and 2 as well as the earlier used ratios of TM bands 1/3 and 1/2 were not statistically significant. In Figure 2 the relationships between chlorophyll-a and the reflectance of the red and near-infrared spectral bands as well as algorithms proposed in recent studies (see introduction) are presented.

On April 29 1993, the plume was larger and the water in the plume more turbid. Mean secchi disk depth for stations 1-3 (in the plume) was 0.8 metre on this date, compared to 1.3 metre on June 4 1992. Nitrogen, phosphorus and chlorophyll concentrations however, were somewhat lower. The higher level of suspended matter in the plume gave a considerable increase in reflectance for the visible bands at the sample sites located within the plume. Consequently, chlorophyll estimation using visible bands, or algorithms based on visible bands (such as TM bands 1/2 and 1/3), resulted in completely misleading, overestimated figures for the 1993 plume stations (figure 1). This implies that the correlation between the red spectral band (TM band 3) and chlorophyll-a in the earlier image from June 4 1992 depended on a relationship between chlorophyll-a and the density of the plume, meaning that the factors actually governing the visible reflectance were secchi disk depth, turbidity, total suspended matter, etc, rather than chlorophyll-a. Figure 2 displays satellite data in reflectance percentages, which means that differences between the two image dates due to atmosphere or sun elevation should be negligible. Thus, the difference in reflectance levels between the two dates, at the sample sites, depends on turbidity in the water. Insecurities connected with calculation of reflectance values from different years do exist, since a few different sets of constants for sensor gain decay and exoatmospheric irradiance have been presented in literature. Yet, the considerable reflectance differences between visible spectral bands from the two occasions are not believed to be a result of this, since the differences were marginal further out in the Gulf of Bothnia. The differences at the sample sites in or close to the plume, are thus attributed solely to differences in the plumes of the two years.As a consequence, visible bands or algorithms based on visible bands could not be used for chlorophyll estimation within the plume.

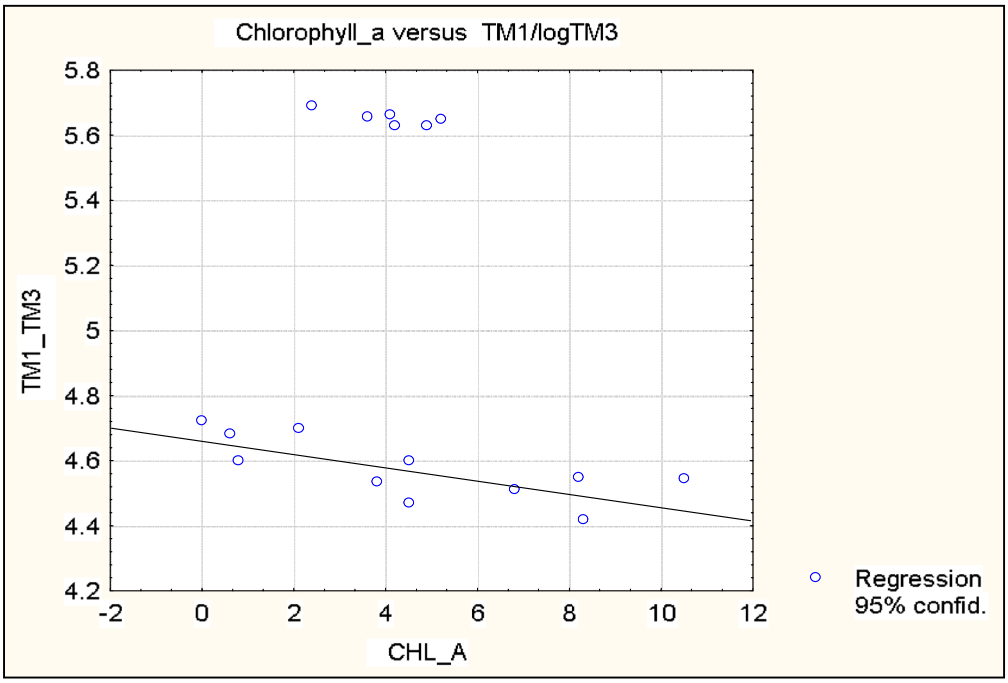


(a)

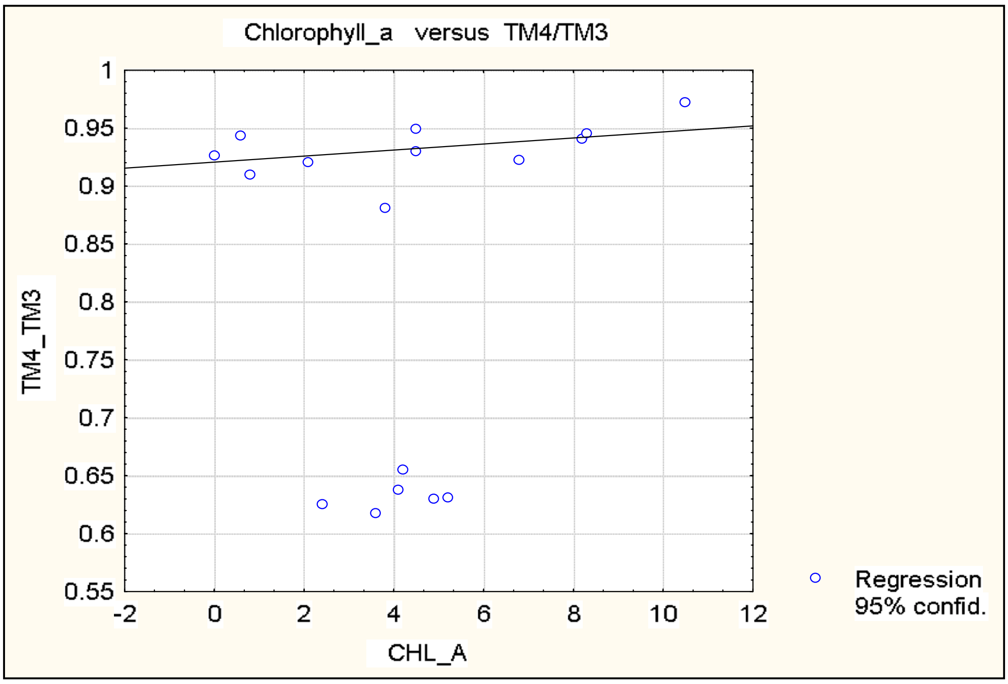


(b)

Figure 2 (a). Chlorophyll-a versus TM band 3. The upper group of sample points are all from the satellite image from 1993, with higher turbidity (b) Chlorophyll-a versus TM band 4. R=0.8647



(a)



(b)

Figure3 (a) Chlorophyll-a versus TM1/logTM3. The upper group of sample points are all from the satellite image from 1993, with higher turbidity (b) Chlorophyll-a versus TM band 4/3. The lower group of sample points are all from the satellite image from 1993.

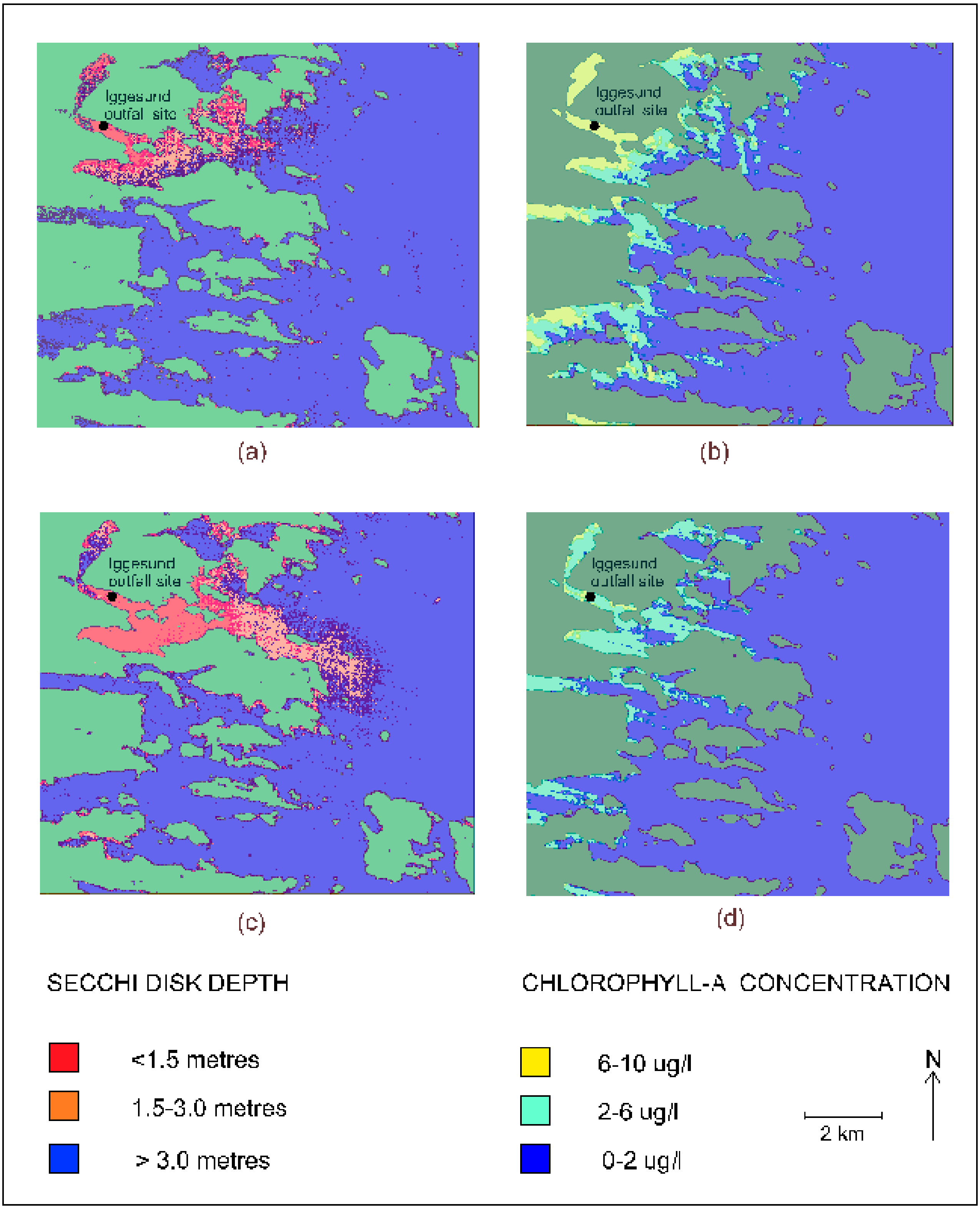


Figure 4. Landsat TM estimates of secchi disk depths and chlorophyll-a in the Iggesund area (a) Secchi disk depth 4 June 1992. (b) Chlorophyll-a concentration 4 June 1992. Secchi disk depth 29 April 1993. (d) Chlorophyll-a concentration 29 April 1993.

For TM band 4 however, suspended non-algal material in the plume did not significantly affect the reflectance. The reflectance values for 1993 fitted very well into the chlorophyll regression model from 1992. TM band 4 reflectance, although not sensitive to secchi disk depth, was highly correlated to chlorophyll-a and revealed a strong discrimination power for both occasions.

The number of sites presented in figures 2 and 3. is not high, but the data originates from two different occasions which strengthens the implications found. The chlorophyll prediction standard error for the sample sites from both years were 1.4 µg/l. This figure would have been somewhat higher if a verification set of sample points not used in the regression model would have been available. Naturally, TM band 4 can only be used to map the chlorophyll concentration in the top layer of the water, perhaps only at 0-5 cm depth, and this may also be part of the reason to the insensitivity to total suspended matter in the plume.

4. Conclusions

The results implicate that TM band 4 may be used to estimate surface water chlorophyll-a in coastal waters. This is in accordance with recent hyperspectral field measurements presented in international journals. Additionally, the study implies that the near-infrared spectral band can be used for chlorophyll-a mapping also in and adjacent to effluent plumes. The reflectance of the visible bands proved to be strongly dependent on total suspended matter in the plume. This fact obstructed all attempts to use the visible bands, or algorithms including any of the visible bands, for chlorophyll-a estimation.

For the two occasions monitored, chlorophyll-a concentrations displayed a gradient that was positively correlated to the plume. However, surrounding coastal bays with no industrial plume also displayed increasing chlorophyll-a concentrations in the inner parts of the bays (Figure 4). Thus, the effect of these pulp & paper mill effluents on algal production seems to be negligible, or only slightly positive.

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