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The spatial diversification of lake water quality parameters in Mazurian Lakes in summertime

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ABSTRACT: Lake water quality studies were carried out in the frame of the ESA project and financed by Polish Scientific Committee under the project No 5 T12E 006 24, for test site MAZURY located in north-east Poland in the Masurian Lake District. These investigations were the first in Poland using satellite CHRIS data for the determination of various lake water quality parameters. This test site is included in MEMAMON project (MONitoring of the Mecklenburg and Masurian Lake Districts). The estimations of several water quality parameters retrieved from CHRIS spectral measurements using different methods of image processing were compared with in-situ reference measurements. The values of parameters extracted from CHRIS data showed a very good correlation with lake trophy and with in-situ parameters as: Secchi disk depth, concentration of chlorophyll-a, pheophytin, total suspended matter, total phosphorous and total nitrogen. The detailed interpretation of the spatial variability of different lake water quality parameters brought very interesting results. The analysis of the relationships between limnological and physicochemical indicators showed that the most important influence on water quality in investigated lakes has their altitude above sea level and land use in the direct catchment.

1 INTRODUCTION

Lake water quality studies were carried out in the frame of the ESA project and financed by Polish Scientific Committee under the project No 5 T12E 006 24, for test site MAZURY located in north-east Poland in Mazurian Lake District. These investigations were the first in Poland using satellite CHRIS data for determination of various lake water quality parameters.

The Compact High Resolution Imaging Spectrometer (CHRIS) launched on PROBA platform is a very interesting instrument for various research projects in earth sciences domain. Scanner CHRIS provides superspectral images (18 or 36 spectral bands in spectral region from 410 nm to 1050 nm) in different registration modes (Land/Aerosols,

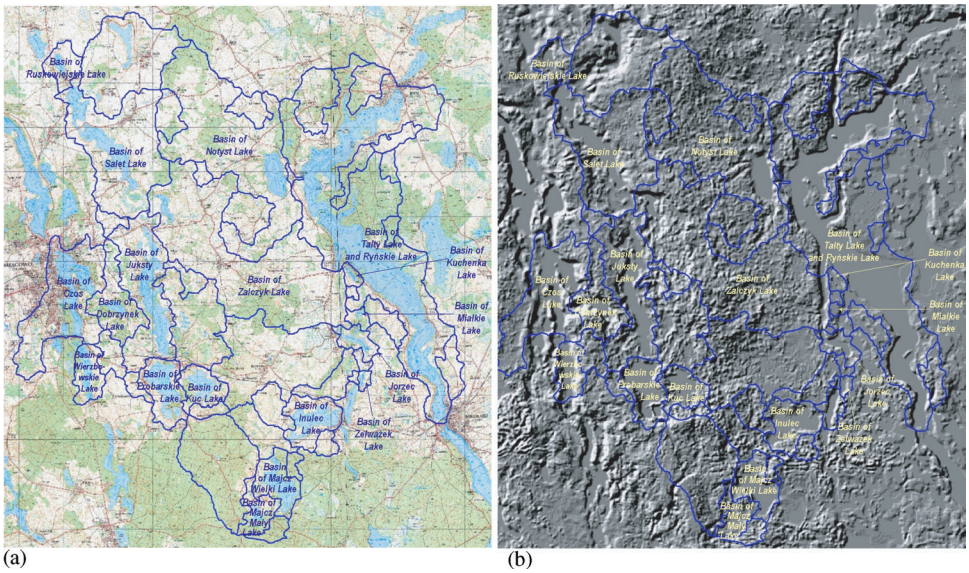
Water, Chlorophyll, etc.) and under different viewing angles. These features give many possibilities for land and water studies, for monitoring of atmospheric aerosols, etc. These are the first satellite superspectral data characterized by high spatial resolution of 18×18 m. The narrow spectral bands of CHRIS instrument are a very good data source for lake water quality monitoring. The optimal dataset for water quality monitoring needs 3–4 CHRIS images registered in specific, narrow, characteristic periods from the limnological point of view.

At the day of satellite overpasses in-situ measurements of several water quality parameters (temperature, Secchi disk depth, chlorophyll-a concentration, total suspended matter, turbidity, total phosphorous, etc.) were made. The estimations of water quality parameters retrieved from CHRIS spectral measurements using different methods of image processing were compared with in-situ reference measurements. The values of parameters extracted from CHRIS data showed a very good correlation with lake trophy and with in-situ parameters as: Secchi disk depth, total suspended matter, concentration of chlorophyll-a, pheophytin, total phosphorous and total nitrogen.

2 TEST SITE "MAZURY"

The test site "Mazury" is a part of Masurian Lake District delimited by following geographic coordinates: north-west corner (53°56' N, 21°22' E) and south-east corner (53°48' N, 21°34' E). It is a typical Lakeland with the reservoirs variable in size, depth and trophy. The lakes concerned by research activity are both large 600–1100 ha (lakes Talty and Ryńskie), medium 100-330 ha (Inulec, Notyst, Salet, Czos, Wierzbowskie, Probarskie, Kuc and Majcz Wielki), small – about 40 ha (Jorzec, Glebokie) and very small – 5-15 ha (Mialkie, Kuchenka). The ratios of the catchment surface to the lake surface or lake volume show an influence of the closest surroundings of lake on its water. The lakes under investigation are quite different from a morphometrical point of view and their mean depth goes from 1.0 m for Mialkie Lake to 14.0 m for Taltowisko, Talty and Ryńskie Lakes. The deepest lakes, more than 30 m depth, are Ryńskie, Talty, Czos, Glebokie and Probarskie. The shallowest, less than 10 m depth, are Inulec, Zelwazek, Kuchenka and Mialkie. Ten of the investigated lakes can be treated as shallow lakes with polimictic regime of vertical water exchange. These are the lakes of mean depth not exceeding 10 meters and of maximum depth less than 20 meters. These are: Inulec, Jorzec, Notyst, Salet, Mialkie, Zelwazek, Kuchenka, Wierzbowskie, Majcz Wielki and Lawki. Eight lakes have a maximum depth of more than 20m and they can be considered as dimictic lakes. These are four largest lakes in the analyzed group – Talty, Ryńskie, Juksty and Taltowisko, and four smaller lakes – Kuc, Probarskie, Glebokie and Czos. The catchments of these reservoirs are characterized by hilly relief, formed in postglacial materials: loams, sands and loamy sands. The lowest point of the test site is located on the Talty lake border – 116 m ASL, the highest point – 186.5 m ASL.

Because of the quite complicated system of water supply and outflow characteristics for lakelands the differences of the level of water table for particular lakes can indicate their hydrological isolation or their connection by streams, rivers and water-bearing layers as well to the larger area of water supply than direct catchment area.



(a) (b)

Figure 1. The lake catchment areas on the topographic map and shaded digital elevation model.

The land use in the catchments of the test area is typically agricultural: fertilized arable fields and grasslands - mainly meadows. The forested areas are also present but not preponderant. The most important percentage of agricultural uses is noted for the catchments of the lakes Zelwazek and Juksty (respectively 100 and 96%), the least – for the catchments of the lakes Mialkie and Czos (about 60%). The lake Czos is exceptional among the others because 28% of its catchment surface is covered by built-up areas of Mragowo town. The most important percentage of forest areas is noted for the catchments of Mialkie and Majcz Wielki lakes (40 and 36% respectively).

3 METHODOLOGY OF DETERMINATION OF SPATIAL DISTRIBUTION OF WATER QUALITY PARAMETERS

During the years 2002–2005 the eighteen lakes located on the test area Mazury were analyzed in the framework of the KBN Project No. 5T12E00624. The water samples were collected during the summertime: in June and August of 2003 year, in August and September of 2004 and also in August of 2005. In the bigger lakes (Talty, Rynskie, Juksty) the samples were collected from 3–4 places along the transect going from littoral to maximal depth, for the remaining lakes the samples were collected from the point located over the maximal depth. The samples of water were taken from the epilimnion layer not deeper than 0.5 m. The in-situ measurements carried out simultaneously with satellite registration of CHRIS/PROBA images consisted of measurements of oxygen content, water temperature, Secchi disk depth and taking a sample of water for further analysis in laboratory. The geographic coordinates of each sample point were measured with a GPS receiver. The measurements of oxygen content and water temperature were

done with oxygen sounder WTT. The following indicators are determined: chlorophyll-a concentration and pheophytin by the acetone method, suspended matter concentration by the filtration method, total phosphorus concentration by extraction in perchloric acid and by the colorimetric method, total nitrogen concentration by extraction in sulfuric acid and by the colorimetric method, mineral phosphorus (from filtered samples using WhatmanGF/C filter) concentration by the colorimetric method, and nitrate concentration by the colorimetric method.

Ten sets of CHRIS/PROBA images were acquired for the Mazury test site during the period of 2003–2005 years. Unfortunately, in the first years of the project implementation there were quite embarrassing weather conditions making the acquisitions of cloudless images difficult. The satellite observations were planned during spring, summer and autumn months but due to important cloudiness most of the research could be possible only using summer images. In ''Water'' mode, CHRIS spectrometer acquires the images in 18 very narrow spectral bands well adapted for water quality parameters analysis.

As a result of research works some mathematical formulas describing relationships between several physicochemical water parameters and spectral luminance were elaborated. A high coefficient of determination (R^2) was noted for these empirical formulas. The formulas presented below are issued from CHRIS data registered on 4th August 2004. The formulas have permitted a retrieval of Secchi disk depth, total suspended matter, concentration of chlorophyll-a, pheophytin, total phosphorus and total nitrogen as follows:

- Secchi disk depth : $SDD = 0.0038 \cdot \exp[0.234 \cdot [(Ch_{410nm} + \ldots + Ch_{651nm})/(10 \cdot Ch680nm)]]$, $R^2 = 0.95$,
- total suspended matter : $SM = 10^{-05} \cdot \exp[31.284 \cdot (Ch_{680nm}/Ch_{530nm})]$, $R^2 = 0.92$,
- chlorophyll-a concentration :
- $Chl\text{-}a = 1307.7 \cdot (Ch_{706nm}/Ch_{561nm})^2 - 988.72 \cdot (Ch_{706nm}/Ch_{561nm}) + 189.32$, $R^2 = 0.89$,
- pheophytin concentration : $Pheo = 3 \cdot 10^{-23} \cdot (Ch_{622nm})^{5.3552}$, $R^2 = 0.81$,
- total phosphorus concentration : $TP = -242.52 \cdot \ln(Ch_{561nm}/Ch_{680nm}) + 208.36$, $R^2 = 0.64$,
- total nitrogen concentration : $TN = 0.1143 \cdot \exp(0.0001 \cdot Ch_{706nm})$, $R^2 = 0.92$.

The spatial variability of Secchi disk depth, total suspended matter, concentration of chlorophyll-a, pheophytin, total phosphorus and total nitrogen were established for other measurement days using the same algorithms. A typical spatial variability of these particular hydrobiological parameters for examined lakes was presented using the satellite observations from 4th August 2004. Their detailed interpretation is presented in the next paragraph.

4 SPATIAL DISTRIBUTION OF SECCHI DISK DEPTH

The water transparency is a main water quality parameter. The values of Secchi disk depth (SDD) are strongly correlated with suspended matter content thus their spatial variability differs slightly from the characteristics of this parameter. Very low values of SDD, lower than 1.5 m, shown in violet and dark-blue in Figure 2, are characteristic for the lakes:

– Zalczyk (the lowest value of SDD < 1 m) – the catchment of this lake is characterized by the agricultural land use with the animal farms;
– Kuchenka, which is a shallow reservoir with agricultural catchment; a large leisure and recreation center is situated very close to the border of the lake;
– Juksty northern part – a visible influence of agricultural activity and farms on water quality;
– Taltowisko – the catchment has rather an agricultural function but water transparency is also influenced by shipping, sailing and by water mass movement from large lakes contaminated by liquid municipal wastes of Gizycko town via Masurian Channel;
– Talty northern part, where is a visible influence of Ryn's town wastes, water transported from Masurian Channel, tourism and agriculture to a lesser extent;

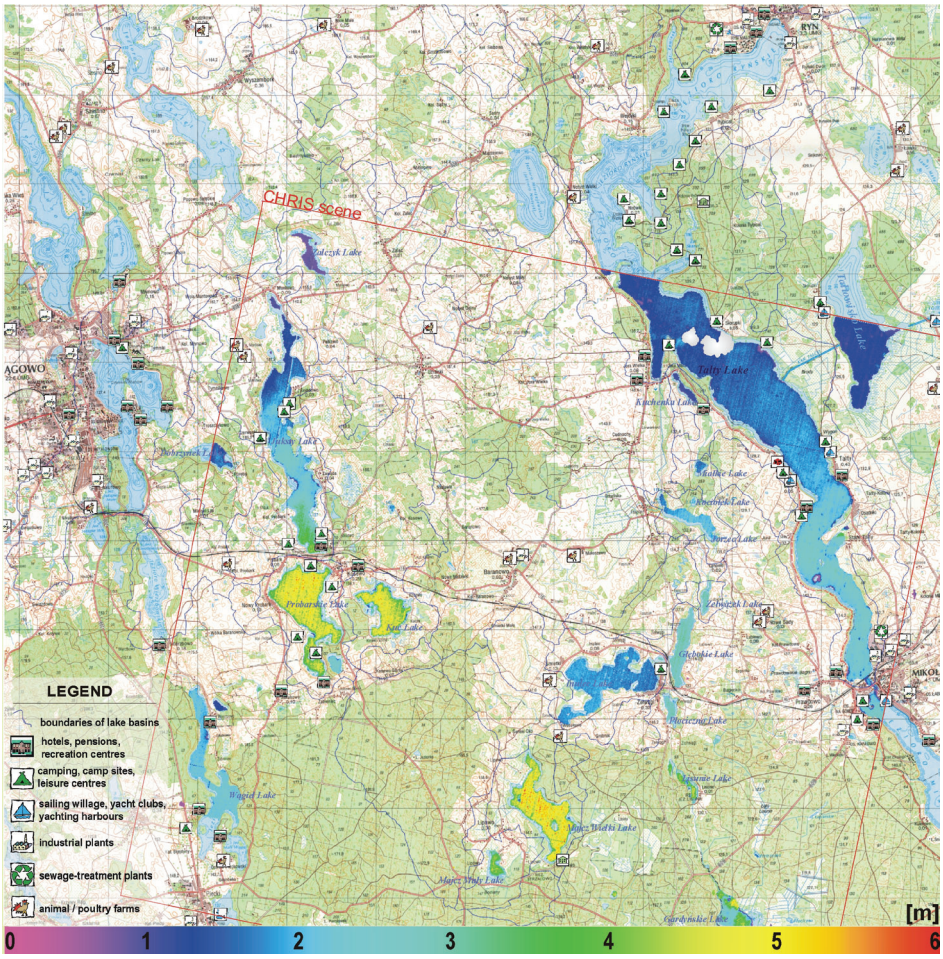


Figure 2. Spatial distribution of Secchi disk depth [m] ($R^2 = 0.95$) for the registration on 4th August 2004 calculated from CHRIS / PROBA data.

- Mialkie, which is a little and shallow reservoir, covered with developing vegetation and the suspended matter coming from the mortification of vegetation influences the water transparency;
- Northern bay of lake Jorzec – clearly visible influence of stream coming from agricultural catchment.

Low values of SDD, marked in blue color in Figure 2, can be seen on:

- central part of the Talty lake, where agriculture and tourism influence is important;
- on the north-west part of the Juksty lake, where direct influence of agricultural activity is strong;
- lake Inulec, for which the catchment is small, typically agricultural with animal farms;
- lake Jorzec, where agricultural activity dominates on a relatively small catchment area.

The medium values of the SDD, shown in light blue and celadon green in Figure 2, are visible for:

- Glebokie lake, which is a gully lake with a relatively large water volume comparing with its medium catchment area;
- Zelwazek lake, which is a very small reservoir supplied with water of lake Glebokie;
- southern part of Talty lake, which is a deep part of the gully lake with a narrow, elongated, partially forested catchment area;
- central part of Juksty lake, which catchment has a mixed character (forested and agricultural) in this area.

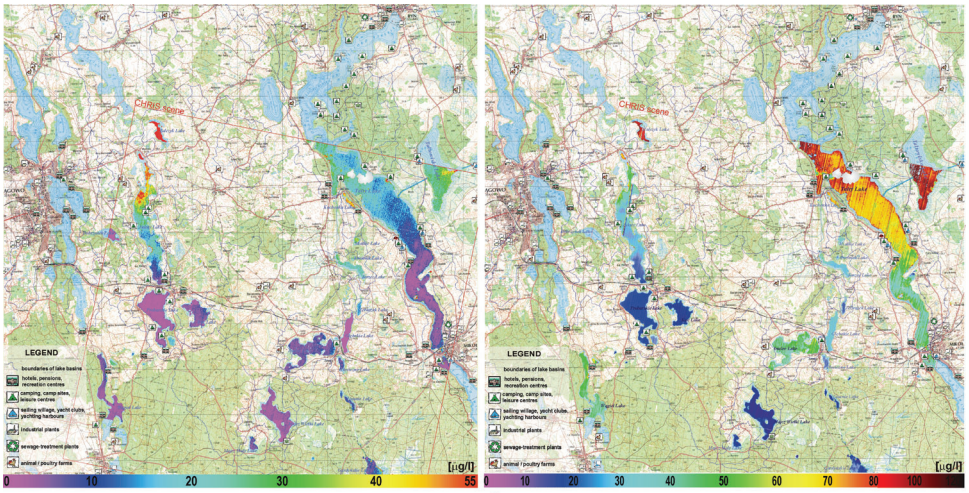
High values of SDD, shown in green and yellow in Figure 2, can be seen on:

- lake Majcz Wielki, which catchment is a typically forested catchment; the reduced values of SDD in the coastal zone result from mortification of rushes vegetation;
- lake Probarskie, quite deep lake with narrow catchment; slightly reduced values of SDD in the coastal zone result from mortification of rushes vegetation, influence of Probark village and near camping areas;
- lake Kuc, located in forested catchment; Slightly reduced values of SDD are noted only in coastal zone because of rushes vegetation mortification.
- southern part of Juksty lake, which catchment is a forested one.

The spatial variability of total suspended matter is similar to the SDD distribution. Greater lake water transparency means less content of suspended matter and vice versa.

5 SPATIAL DISTRIBUTION OF CHLOROPHYLL-A CONCENTRATION

The content of the chlorophyll-a is an indicator of actual, current production of phytoplancton, it means an indicator of the occurrence of live organisms of plankton in the lakes. The highest values of the chlorophyll-a concentration, shown in yellow and green in Figure 3a, are noted for:



a. b.

Figure 3. Spatial variability of a. chlorophyll-a and b. pheophytin concentration [μg/l] ($R^2 = 0.89$) and ($R^2 = 0.81$) respectively on 4th August 2004 calculated from CHRIS/PROBA measurements.

- Zalczyk lake, which catchment is agricultural and where the animal farms are an important source of nutrients in the catchment;
- Kuchenka lake – shallow and small reservoir, influenced by an intensive tourism and agriculture;
- Talty lake – yellow area in the bay is a place of liquid waste dump from former agricultural holding; yellow area in the strait and a smudge towards north it is a region of liquid waste effluence from wastewater treatment plant in Mikolajki town;

The medium values of the chlorophyll-a, shown in blue-green and blue colors in Figure 3a are noted for:

- major part of the Talty lake; it results from the influence of water transfer from polluted lake Niegocin via Masurian Channel, influence of agricultural activity of Talty village and tourism sites of Talty and Stare Sady villages;
- whole area of the Mialkie lake. This is a shallow reservoir with luxuriant vegetation;
- whole area of the lake Jorzec; influence of agricultural activity from southern side of the lake.
- whole area of Zelwazek lake; it is an after-effect of liquid waste deposition from part of Mikolajki town and its biggest hotel;
- whole Inulec lake which catchment is agricultural and draining ditches located on the western side of the lake transport water from fields and farms in Wesolowo village.
- northern part of Juksty lake situated in catchment characterized by important slopes and existence of animal farms.

Low values of chlorophyll-a concentration, shown in purple and dark-blue in Figure 3a, can be seen on the southern part of Juksty lake, where the catchment surrounding the deeper parts of the lake is afforested, on areas of Probarskie, Kuc and Glebokie lakes where the lakes are deep and direct catchments are narrow (Probarskie, Glebokie) or covered by forests (Kuc).

6 SPATIAL DISTRIBUTION OF PHEOPHYTIN CONCENTRATION

The pheophytin is an indicator of dead organic matter content in the lakes and jointly with chlorophyll is a very important indicator of the hydrobiological quality of the lake water. The lakes with very high pheophytin content, shown in red and yellow in Figure 3b, on the test site are:

- lake Zalczyk- in typically agricultural catchment, with animal farms as an additional source of nutrients;
- lake Taltowisko - with clear influence of agricultural activity in the catchment (very intensive use of fertilizers in the seventies of 20th century), of shipment and sailing, and water transfer from great polluted lakes near Gizycko town via Masurian Channel;
- northern and central part of Talty lake, influenced by wastewater coming from Ryn town, water coming by Masurian Channel;
- northern part of Kuchenka lake; in this case 3 elements influence high pheophytin concentration: close neighborhood of leisure center, agricultural activity and shallowness of the lake.
- the bay of Juksty lake where the most important factors are agriculture and animal husbandry.

The lakes of high pheophytin concentration, marked in green in Figure 3b, are: southern part of Talty lake, northern part of Juksty lake and lake Inulec. In these cases the most important influencing factors are agriculture and animal farms.

The lakes of medium pheophytin content, shown in light blue and celadon colors in Figure 3b, are:

- southern parts of Talty lake; these are the areas with reduced productivity, having narrow and forested catchment, protecting reservoir from disadvantageous impact of adjacent terrains.
- lake Glebokie being the deep lake situated in narrow direct catchment;
- lake Jorzec where an moderate impact of agriculture is visible on the small surface of the catchment;
- lake Mialkie where reduced phytoplankton productivity is observed due to succession of vascular plants.
- central part of Juksty lake where the catchment is partially forested.

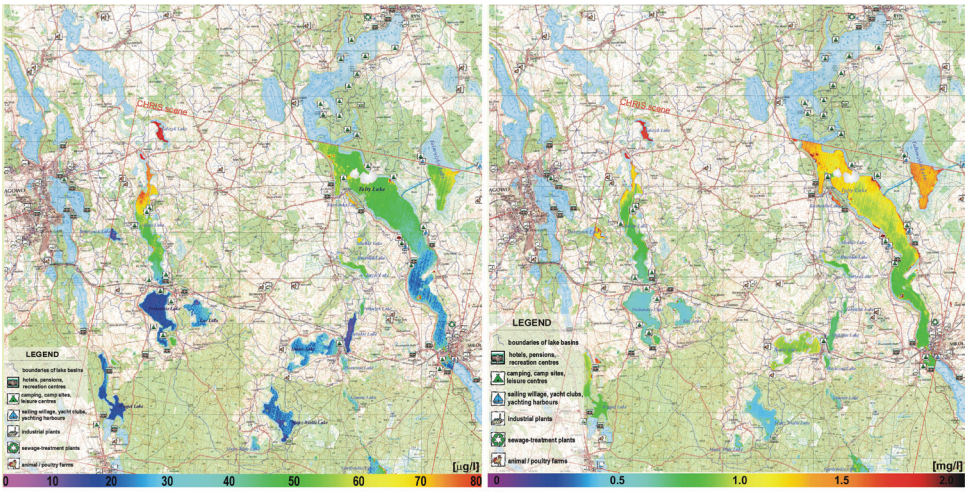
The lakes characterized by low pheophytin content, shown in blue, are very deep and have narrow catchments (Probarskie lake); or lakes situated in forested catchments (Majcz Wielki, Kuc). The lake Zelwazek is also a reservoir having low content of dead

organic matter because its water comes mainly from Glebokie Lake and there are no local pollution sources in its catchment.

7 SPATIAL DISTRIBUTION OF TOTAL PHOSPHORUS CONCENTRATION

Phosphorus and nitrogen are chemical elements influencing the conditions of the development of plankton organisms and are indicators of lake water quality. In the case of the Masurian lakes it has been observed that phosphorus determines typical, hydrobiological indicators linked to the metabolism of phytoplankton and its quality for the consumer. The highest values of total phosphorus content, shown in orange and yellow in Figure 4a, are noted for the lakes in the catchments characterized by an intensive agricultural activity where the animal farms are known as pollution sources. This is the case in Zalczyk lake and in northern and north–west part of the Juksty lake. High phosphorus concentration is also observed for lake Kuchenka, which is exposed to influence of agricultural activity and intensive tourism. Increased values of the total phosphorus content are observed (in green in Figure 4a) for:

- north eastern part of the Juksty lake, resulting from agriculture influence and animal farms;
- Mialkie lake, where phosphorus concentration is a result of vegetation mortification in this shallow reservoir;
- northern part of the lake Jorzec influenced by agriculture;
- some places on the northern part of the lake Talty border where some sailing and leisure centers exist.



a. b.

Figure 4. Spatial distribution of a. total phosphorus content [μg/l]($R^2 = 0.70$) and b. total nitrogen concentration [mg/l] ($R^2 = 0.95$) in 4th August 2004 year calculated using CHRIS data.

The medium values of the total phosphorus content (in light blue in Figure 4a) are observed for:

- lake Talty where this parameter results from additive influence of tourism, agriculture and water transfer from Masurian Channel and Ryn town;
- lake Jorzec where the influence of agriculture is visible from the south-east side characterized by steep shores;
- lake Zelwazek; here it is an after-effect of wastewater dump from a big hotel in the past years;
- central part of Juksty lake where it is an impact of agriculture from the northern side of the catchment and tourism in the central part of it;
- locally, on the eastern part of lake Inulec where the village Zelwagi is situated.

The low values of the total phosphorus content, in blue and violet in Figure 4a, are observed for:

- southern part of Juksty lake and in Kuc lake, where the catchments are covered by forests protecting lakes from runoff from arable fields;
- lakes Probarskie and Glebokie, where the direct catchments are very narrow and lakes are deep;
- central and southern part of Talty lake and lake Kuc area, both having partially forested catchments. In these lakes a high content of chlorophyll-a and low concentration of total phosphorus is observed. The whole phosphorus is contained in live phytoplankton (organic phosphorus) but its concentration is very low in dissolved form (phosphates) and in seston i.e. in dead phytoplankton.

8 SPATIAL DISTRIBUTION OF TOTAL NITROGEN CONCENTRATION

In the seventies of 20th century, there was a very intensive use of fertilizers on agricultural areas. The consequences of this are still visible on the lakelands. The ecosystems of the lakes being one of the most fragile are still vulnerable by influence of agricultural activity. The return to the prior state is a difficult and long-lasting process. Even now the fatal abuse of fertilizers on agricultural areas is visible.

The increased nitrogen concentration, shown in red, orange and dark yellow in Figure 4b, can be observed for:

- Kuchenka lake; it results from agriculture and tourism activity in close neighborhood of this shallow reservoir;
- Northern part of Talty lake, where an ineffective wastewater treatment of Ryn town is clearly visible. Also the shipment and agricultural activity in the catchment should not be neglected;
- Taltowisko lake- which is influenced by agriculture, shipment and wastewater transfer from lake Niegocin (Gizycko town) via Masurian Channel;
- North-east part of Juksty lake and lake Zalczyk – probably endangered by intensive animal husbandry on the industrial farms situated in the catchment.

High total nitrogen concentration (yellow and green colors in Figure 4b) are observed for:

- central part of the Talty lake, with reduced influence of agriculture and shipment;
- lake Inulec; shallow lake influenced by farms;
- north-east bays of Juksty lake and north-west bay of Jorzec lake, where the influence of agriculture is visible in the catchment having steep slopes of the terrain.

Medium values of the total nitrogen concentration (green and celadon colors in Figure 4b) are observed for the major part of Jorzec lake, in central and southern part of Juksty lake, on southern part of Talty lake and in lakes: Zelwazek and Glebokie. These are quite deep gully lakes influenced by agriculture but having small catchments. Medium values of the total nitrogen concentration are also observed for Mialkie lake which is a shallow lake rich in vascular plants.

The low concentration of nitrogen is characteristic for Probarskie lake, which is situated in agricultural catchment having a small surface comparing with lake volume. Also a little nitrogen concentration is observed for the lakes Kuc and Majcz Wielki. Their catchments are forested and protect reservoirs from superficial runoff from agricultural parcels.

9 CONCLUSIONS

After the experiments we can conclude that CHRIS / PROBA data are a very interesting source of remotely sensed data for monitoring lake water quality. The results and empirical formulas achieved, showing the relationships between radiance registered by CHRIS sensors and the values of some physicochemical parameters measured *in-situ* have a strong coefficient of determination. These relationships permitted to retrieve a spatial variability (spatial distribution) of particular indicators of water quality, which show after detailed analysis and interpretation an important influence of land use on the areas of the direct catchments on the water quality in reservoirs. The lakes in forested catchments are characterized by a better water quality than the lakes in agricultural ones. In this second case an essential role in the trophy state modification plays the size of the catchment and the terrain relief. In the case of parts of catchments having strong slopes an increase of chlorophyll-a content, nitrogen and total suspended matter in coastal zones was observed. The spatial variability of the most of hydrobiological indicators shows an influence of the former lakes pollution coming from municipal liquid wastes, from towns and villages without waste treatment plants. Current tourism activities, campings, leisure centers and sailors villages also show their influence on water quality. For the small lakes the recreation and tourism activity can provoke worse trophy conditions, as seen on the example of Kuchenka lake.

The analysis of the relationships between limnological and physicochemical indicators showed that the most important influence on water quality in the investigated lakes has their altitude above sea level and land use in the direct catchment. The lakes isolated have the best water quality. It was observed that the bigger is the catchment in relation to lake volume, the higher is the productivity of lake. The mean depth of the lake and degree of forestation in catchment show less important impact on water quality. It seems that the lakes near forests produce live phytoplankton longer than the reservoirs

with agricultural influence. For these lakes dead matter of algae coming from spring algal bloom dominates during summer period. The analysis showed a dominant role of nitrogen in modification of lakes parameters. It was observed that the concentration of total nitrogen plays a dominant role in phytoplankton biomass production and has an impact on physical water parameters like transparency and concentration of suspended matter. The phosphorus total content being a standard and widely used indicator of lake trophy state does not influence directly on phytoplankton production but on the hydrobiological indicators linked to its metabolism.

These conclusions must be confirmed in the future by next investigations confirming the fact of dominant role of nitrogen in the analyzed lakes. Nevertheless, the results show an important role of nitrogen in water quality modification.