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Chlorophyll retrieval with MERIS Case-2-Regional in perialpine lakes

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Abstract

Semi-analytical remote sensing applications for eutrophic waters are not applicable to oligo- and mesotrophic lakes in the perialpine area, since they are insensitive to chlorophyll concentration variations between 1-10 mg/m\textsuperscript{3}. The neural network based Case-2-Regional algorithm for MERIS was developed to fill this gap, along with the ICOL adjacency effect correction algorithm. The algorithms are applied to a collection of 239 satellite images from 2003-2008, and the results are compared to experimental and official water quality data collected in six perialpine lakes in the same period. It is shown that remote sensing estimates can provide an adequate supplementary data source to in situ data series of the top 5 m water layer, provided that a sufficient number of matchups for a site specific maximum temporal offset is available.

1. Introduction

The glacial lake basins around the Alps are essential fresh water resources for Central Europe. Their ecological state vitally affects their value as drinking water reservoirs, for irrigation, fishery or recreation. For this reason, the European Commission (EC) has adopted the Water Framework Directive (WFD, Directive 2000/60/EC), which defines water quality
categories as well as monitoring parameters for the appropriate assignment of these categories.

The Directive applies to all countries of the European Union (EU) and the European Economic Area (EEA), but not to Switzerland, where some of the feeder rivers of Europe’s largest river systems (i.e. Danube, Po, Rhine, and Rhone) originate. However, due to its position in the Central Alps, Switzerland shares a long tradition of international water protection directives; with Austria and Germany on Lake Constance (since 1961), with France on Lake Geneva (1962) and with Italy on Lake Lugano and Lake Maggiore (1972). Consequently, the countries involved are experienced in the practice of water quality monitoring and most water bodies in and around Switzerland are considered to be of very good quality, although Switzerland’s water protection laws are less consistent than the WFD and do not contain a mandatory definition of water quality monitoring requirements (Rey & Müller, 2007). Number and type of parameters, sites and intervals applied in such programs vary strongly among perialpine lakes. Chlorophyll-\(a\) concentrations (CHL) are however widely measured as an indicator for eutrophication and primary production. Ongoing efforts in reducing nutrient loads to these lakes trigger large interest in measuring biologic productivity on high-resolution temporal and spatial scales. Development of novel, reliable remote sensing techniques could thus provide a significant improvement in water quality and lake condition monitoring.

Various methods were developed to estimate the constituents of inland waters from remote sensing data, based on physical relations known from radiative transfer theory (Mobley, 1994). Most of them are based on absorption and scattering properties of CHL, total suspended matter (TSM) and gelbstoff (Y). Simple, semi-analytical methods for the retrieval of CHL apply band ratios of the secondary CHL absorption maximum at around 675 nm and adjacent spectral bands that are not affected by CHL absorption, such as the near-infrared (NIR) reflectance peak near MERIS’ 709 nm band (Gons et al., 2002; Gons et al., 2005),
MODIS’ 748 nm and SeaWiFS’ 765 nm band (Dall’Olmo et al., 2005) or a combination of 
MERIS’ 709 nm and 754 nm bands (Gitelson et al., 2007; Gitelson et al., 2008). They are 
applicable to in situ measured or atmospherically corrected surface reflectances of eutrophic 
waters containing 10-200 mg/m$^3$. However, CHL in perialpine lakes varies only between 1 
and 20 mg/m$^3$, and surface reflectances rarely display the needed NIR reflectance peak 
(Giardino et al., 2007; Odermatt et al., 2008a).

More complex, physically based inversion methods for simultaneous retrieval of CHL, 
TSM and Y were originally developed for airborne scanners (Hoogenboom et al., 1998; Heege 
& Fischer, 2004). When applied to satellite sensors of lower spectral resolution, such as 
Landsat-TM5 and SPOT-HRV, such methods are adequate for the quantification of TSM by 
its strong scattering signal (Dekker et al., 2001). However, only more recent sensors were 
found to provide sufficient spectroradiometric properties for the estimation of low CHL 
concentrations in inland waters, for example Hyperion (Giardino et al., 2007) or MERIS 
(Odermatt et al., 2008a) in Lakes Garda and Constance, respectively. However, constant 
gelbstoff (Y) absorption had to be assumed in both studies, as its variation was not 
distinguishable from oligotrophic lakes’ CHL patterns with those instruments.

An inversion technique based on neural networks (NN) is used in the MERIS ground 
segment to simultaneously retrieve case II water constituents. Current MERIS level 2 standard 
products (algal_2, yellow_subs, total_susp) are processed with such a sensor-specific NN 
algorithm (Doerffer & Schiller, 2007). Between January 2007 and June 2008, the European 
Space Agency (ESA) funded the “Development of MERIS Lake Water Algorithms” (MERIS 
Lakes) project on the elaboration and validation of an inland water NN for BEAM (Fomferra 
& Brockmann, 2006). The project led to three plug-in algorithms based on the MERIS Case-2 
Core Module: Case-2 Regional (C2R), Boreal Lakes and Eutrophic Lakes (Doerffer &
Schiller, 2008a) and a dedicated atmospheric correction (Doerffer & Schiller, 2008b). At about the same time the Improved Contrast between Ocean and Land (ICOL) processor became available, which accounts for the correction of adjacency effects (Santer & Zagolski, 2009; Odermatt et al., 2008b). The corresponding validation campaign concludes that [1] atmospherically corrected and in situ measured reflectances agree well in the green and red spectral region, but worse in the blue region, [2] ICOL has a positive or neutral effect, and [3] the accuracy is sufficient for TSM and CHL, but still not for Y (Koponen et al., 2008; Ruiz-Verdu et al., 2008).

Against the background of this recent progress, the applicability of the current C2R CHL product for the support of water quality monitoring in perialpine lakes is tested in this study.

In section 2, a collection of MERIS images of the alpine region in the years 2003–2008 is described, along with several field campaigns including in situ reflectance measurements coinciding MERIS overpasses and water quality monitoring datasets acquired by local authorities. Section 3 contains an overview of the automatic processing environment applied to the satellite imagery (Odermatt et al., 2008a), which was adapted for the use with BEAM’s command line routines. The same processing environment accounts for the comparison with reflectances and concentrations measured in field campaigns and for water quality monitoring concentrations. Results of all three types of matchups are discussed in section 4. Conclusions are given in section 5.

We specifically address the following questions: [1] Are the C2R and ICOL appropriate for the routine processing of CHL products, [2] what is the spatio-temporal validity of the findings, and [3] how does ICOL affect the outcome of the C2R processing for perialpine lakes.
2. Data

2.1 MERIS images

239 MERIS full resolution (FR) level 1B quarter and full scenes were used in this investigation. The data were originally collected for other experiments on Lake Constance (2003-2007), Garda, and Maggiore (2003-2008), which are covered by 121, 150 and 185 images, respectively. The study includes 7 lakes, which were chosen for their regional relevance and are therefore regularly monitored. This ensures the availability of CHL monitoring reference data along with experimental spectroradiometric reference data. The lakes have a size adequate for the 300 m spatial resolution of MERIS FR (Figure 1). Partial coverage, inappropriate atmospheric conditions or sun glint affected geometries may occur especially over lakes that the data was not originally chosen for, leading to the lowest temporal coverage for Lake Geneva (86). The temporal coverage in winter is lower than in summer (Figure 2), since the images were chosen mainly to observe phytoplankton growth, and clouds and fog reduce the availability of data in the winter half year.

2.2 Field campaign data

35 spectroradiometric measurements with coinciding MERIS images were used in this study. They were converted to remote sensing reflectance $R_{rs}$ (i.e. the ratio between the water leaving radiance and the incoming irradiance flux) for comparison with the C2R calculated reflectance. The field campaign data represent 5 lakes and were gathered on 8 field campaigns in the years 2005-2008. No spectroradiometric measurements are available for Lake Biel and Lake Zug.

In the northern perialpine region, MERIS coinciding spectroradiometric measurements were taken during 4 campaigns in 2007; in Lake Constance (14 and 20 April, henceforth
addressed as con070414 and con070420), Lake Geneva (gen070910) and Lake Zurich (zur070815). Lake Geneva and Lake Constance are the two largest freshwater reservoirs in Western Europe, while Lake Zurich is the most important drinking water storage for the city of Zurich. Lake Constance is considered oligotrophic, Lake Geneva and Lake Zurich are mesotrophic. In situ CHL concentrations were only measured on the Lake Constance field campaign. All field campaigns took place within 3 hours of MERIS image acquisition.

RAMSES ARC and ACC instruments were used to measure downwelling irradiance as well as upwelling radiance and irradiance below the water surface (Koponen et al., 2008).

Field campaigns in the southern perialpine region were carried out on Lake Garda and Lake Maggiore. The two lakes are the largest of Italy, situated in the northern part of the country, which accounts for 80% of Italy’s total freshwater storage. Both are in an oligotrophic state, although Lake Garda tends to mesotrophic conditions (Premazzi et al., 2003). Lake Garda was visited on two field campaigns (gar050726, gar080506), making available three in situ spectroradiometric measurements. Lake Maggiore field campaigns cover the northern half of the lake with 6 R\textsubscript{m} measurements (mag060710), and its southern half with another 12 measurements (mag080803). Half of the measurements in Lake Maggiore were taken in littoral sites, at only a few hundred meters from the shore and thus at a critical distance for MERIS’ spatial resolution. The measurements were done within 5 hours of the acquisition of a MERIS image. Underwater downwelling irradiance and upwelling radiance were measured with an ASD-FR.

Both RAMSES and ASD-FR underwater measurements were corrected for the emersion factor to derive reflectance values that are comparable to C2R results. Self-shading was not accounted for, as they are minimal in clear waters (Leathers et al., 2004).
2.3 CHL monitoring data

A heterogeneous collection of water quality monitoring data was used for the long time validation of the C2R CHL product with meaningful, official water quality monitoring estimates. However, French, German, Italian and Swiss agencies and commissions responsible for their acquisition are manifold, and the different measurement methods and standards may lead to variations in the comparability with remote sensing estimates (Table 1).

The HPLC method applied to vertical composite water samples as in the monitoring program of Lake Biel, Lake Constance and Lake Zurich gives a precise laboratory measurement of constituent concentrations in a sample. In Lake Zurich, such samples are taken at 0, 1, 2.5 and 5 m depth and thus represent vertical variations in the top water layer; in case of Lake Biel and Lake Constance the water samples are taken as a vertical mixture of the topmost water layer, i.e. 20 m and 15 m, respectively. In Lake Garda, CHL is derived from spectrophotometer measurements of water samples of the top 1 m water layer (ISO 10260-E, 1992). Finally, submersible fluorescence probes such as the SCUFA used in Lake Zug and the CTD90 used in Lake Geneva allow the depth profiling of CHL and other limnic parameters in the field.

3. Processing chain

Four BEAM routines are used in a processing chain for the automatic calculation of the C2R water constituent products. The BEAM tools are controlled by IDL routines, which account for the definition of parameters in the BEAM processor xml files, but also for the post processing of geometrically corrected L2 subsets (Figure 3).

3.1 Preprocessing
In a first step, BEAM’s smile correction *meris-smile.bat* (version 1.1.101) is applied to the original L1B data. This command line algorithm is identical to the MERIS smile correction used in L2 products. It applies an irradiance correction to all bands, which accounts for the difference between actual and nominal wavelengths of the solar irradiance in each channel. A reflectance correction is also applied, based on spectral interpolation of reflectances in two adjacent bands. The default for water targets is to apply the reflectance correction to all bands apart from 8, 11, 14 and 15 (Fomferra & Brockmann, 2006).

The smile corrected L1B data are processed with ICOL (version 1.0.4) as implemented in BEAM’s *gpt.bat* command line routine. ICOL calculates top of atmosphere (TOA) reflectance and applies a regular Rayleigh correction as done in the MERIS atmospheric correction over land of the MERIS ground segment (Santer et al., 1999). This is done for the entire image, while the rest of the procedure is only applied to water pixels within 30 km of land surface areas. Rayleigh and aerosol adjacency effects are corrected by means of a look-up-table simulated with a primary scattering model (Santer & Schmichtig, 2000). MERIS bands 12 and 13 are thereby used for the estimation of aerosol type and optical thickness (AOT). The reduction of the surface reflectance caused Rayleigh and aerosol scattering over adjacent land is also accounted for. Finally, the adjacency effect corrected TOA reflectance is converted back into at-sensor radiances for all 15 bands, creating an L1C product according to ESA definitions (Santer & Zagolski, 2009).

### 3.2 Atmospheric correction and water constituent retrieval

The smile corrected L1B and L1C data are processed with C2R (version 1.3.2, Case 2 core module version 1.0), resulting in two sets of water constituent products, one with and one without ICOL correction (Figure 3). A C2R batch processing routine was therefore
customized as described in the BEAM Lakes Wiki (Peters, 2008). It makes use of an adapted
parameter file that switches C2R’s internal smile correction off. C2R applies a dedicated NN
based atmospheric correction built on more than 200’000 simulations for 15 input neurons,
including radiance reflectance at top of a 50 layer standard atmosphere after Ozone and
Rayleigh correction in 12 visible and NIR bands. Only bands 11, 14 and 15 are excluded. This
helps to avoid the over-correction of visible bands occurring in earlier versions, which were
based on the extrapolation of NIR retrieved atmospheric parameters to shorter wavelengths. 43
neurons are defined as output, consisting of water leaving radiance and downwelling
irradiance (i.e., the terms to derive $R_{rs}$) as well as path scattered radiance for the 12 input
bands, AOT in 4 bands (given at 550 nm hereafter), and a sun glint parameter. The scattering
by ice crystals in cirrus clouds is also accounted for. Performance tests across the entire range
of values of atmospheric parameters included in the NN show that largest inaccuracies occur
for low water leaving reflectances, i.e. at short wavelengths, under hazy conditions and over
absorption dominated, low scattering waters. Therefore, the atmospheric correction was found
to be applicable for atmospheric conditions up to AOT=0.5 under normal circumstances, but
might fail even at AOT=0.2 over very dark water, such as in Finnish lakes (Doerffer &
Schiller, 2008b).

C2R’s water constituent retrieval NN uses the $R_{rs}$ in MERIS bands 1-8 after atmospheric
correction. It was trained with a LUT consisting of more than 80’000 Hydrolight simulations
(Mobley, 1994). Natural variations in IOP and unavoidable errors in input $R_{rs}$ are accounted
for, but fluorescence effects are neglected. A so-called $invNN$ is applied to invert given
directional $R_{rs}$ into concentrations, and a $forwNN$ models $R_{rs}$ for given concentrations and
geometries. The $invNN$ provides a first guess of instant concentrations. They fed in the
$forwNN$ together with the acquisition geometry, producing an $R_{rs}$ spectrum to verify the
inversion procedure. The difference in these $R_{rs}$ is minimized by means of a Levenberg-Marquardt algorithm until an accuracy threshold is met, or up to a maximum of 10 iterations.

The L2 products calculated in this way include CHL, TSM and $Y$, but also the minimum irradiance attenuation coefficient and the signal depth $z_{90}$. Furthermore, retrieval quality flags are set according to failures in meeting quality check thresholds for both atmospheric correction and water constituent retrieval (Doerffer & Schiller, 2008a).

3.3 Post processing

The optical closure of in situ $R_{rs}$ measurements and corresponding C2R $R_{rs}$ pixel spectra is quantified by means of the absolute and relative spectral Root Mean Square Error (RMSE) of MERIS channels 1-9:

$$ RMSE = \sqrt{\frac{\sum_{i=1}^{N} (\bar{X}_i - \hat{X}_i)^2}{N - 1}} $$

(1)

$$ Rel. RMSE = \frac{RMSE}{\sqrt{\frac{1}{N} \sum_{i=1}^{N} \bar{X}_i}} \cdot 100 $$

(2)

where $N$ is the number of bands (i.e. 9) and $\bar{X}_i$ and $\hat{X}_i$ are the remote sensing reflectances measured in situ and retrieved by C2R, respectively.

Once the water constituent concentrations are calculated, the subsequent post processing steps make use of two tables for the creation of map products and point wise comparison with in situ data. The lake parameter table contains geographic information for each lake to be extracted from the MERIS L2 images, i.e. name, altitude, pixel size, geographical coordinate subset boundaries in each direction and UTM zone. This information is used for geometric correction and image clipping by means of the BEAM tool `mapproj.bat`. The DIMAP format
lake clippings are then illustrated with legend and color table templates according to the variation of concentrations expected in each lake and saved as JPEG.

The second table with site parameters contains local CHL monitoring time series along with site name, acquisition method and latitude and longitude coordinates. It enables the extraction of spatio-temporal matchups between in situ CHL measurements and corresponding MERIS pixels. Where cloud free matchup pixels are found, the values of acquisition date, L1B flags, C2R flags, viewing zenith angle, C2R’s chi square, AOT, CHL, TSM, Y and z90 are extracted and simple statistics such as $R^2$ and RMSEs are calculated. Corresponding values extracted from a 3x3 neighborhood instead of a single pixel do not consistently lead to improved results. Channel 13 quick looks of each MERIS image are automatically generated and manually searched for cirrus and contrail contaminations that were not identified by the MERIS flags. About 10 images per reference site were blacklisted and excluded from processing in this way. Additional criteria for data exclusion in the automatic process were sunglint suspect geometries (i.e. above 10° east in summer or 20° east in winter), C2R’s error indicating retrieval flags (i.e. $ATC_{OOR}$ and $RAD_{ERR}$) and unrealistic CHL levels (i.e. below 0.1 mg/m³). The latter two may differ between ICOL corrected and uncorrected data, causing differences in the number of matchups available.

4. Results

4.1 Field campaign $R_{rs}$ matchups

The comparison between 35 spectroradiometric measurements and corresponding image derived $R_{rs}$ spectra for ICOL corrected and uncorrected MERIS data allows for a direct validation of the performance of ICOL and the C2R atmospheric correction. A qualitative evaluation of four cases can be given (Figure 4): [1] In situations with AOT around 0.05, the
effect of ICOL is small, even for narrow basins such as Lake Zurich (zur070815). [2] When AOT increases to moderate values such as 0.14 over the eastern bay of Lake Constance on 13 April 2007, ICOL significantly improves the retrieved reflectance spectrum. [3] Underestimations of adjacency effects by ICOL were found for Lake Maggiore, where relatively low water reflectance leads to at-sensor radiances as small as the noise of MERIS (Guanter et al., 2009) and the surrounding topography further increases the intensity of adjacency effects (Candiani et al., 2007). [4] The retrieval for Lake Geneva on 10 September 2007 is carried out for a similar AOT (0.13) as in example 2. However, the shape of the Lake Geneva reflectance spectra with a secondary maximum in the 681 nm chlorophyll fluorescence band and an inflection point around 500 nm is generally not well reproduced, possibly due to the neglect of fluorescence and SIOP variations that C2R’s forward simulations do not account for, respectively.

The optical closure according to equations 1 and 2 was calculated for both adjacency effect corrected and uncorrected data. In 32 of 35 cases, both absolute and relative RMSEs decrease when ICOL is applied (Figure 5). But through normalization of the RMSEs, higher relative inaccuracies for darker waters such as Lake Maggiore become visible. In the case of gen060910 and mag080803, the application of ICOL reduces the average relative RMSEs from 55% and 54%, respectively, to 24% for both lakes. Only for mag060710, the average relative RMSE is not sufficiently improved (57% to 43%), displaying case [3] in Figure 4. Among brighter waters, the relative RMSEs for Lakes Zurich and Constance decrease to an average of 12% and 19%, respectively, whereas the spectral fits for Lake Garda are not improved by ICOL. The relative RMSEs for ICOL corrected data of Lake Constance, Lake Garda, Lake Geneva and Lake Zurich are more or less in the range of the 10-21% calculated for the visible spectral range in a previous experiment on Lake Garda, where a customized
atmospheric correction using actual AOT measurements was applied to a single Hyperion image (Giardino et al., 2007).

### 4.2. Field campaign CHL matchups

The results of the Lake Constance field campaign CHL matchups confirm the moderate correlation for CHL without ICOL (Figure 6) as found in the MERIS Lakes validation study. The correlation coefficient of R=0.74 for the ICOL corrected CHL product is even slightly higher, where the validation study revealed only R=0.32. The absolute and relative RMSEs of ICOL corrected CHL are more than twice that of the uncorrected estimate, since the ICOL correction generally increases the water constituent concentration estimate (Koponen et al., 2008). But when the individual bias in the linear relationship between in situ data and the two C2R estimates is taken into account, the ICOL corrected estimate is again insignificantly better with an RMSE of 0.78 against 0.81 mg/m$^3$. In general, the results confirm the contradictory finding that ICOL significantly improves the retrieval of R$_{rs}$ (Figure 5) but not the determination of water constituents (Koponen et al., 2008).

### 4.3. CHL monitoring matchups

The general comparability of C2R results with 0-5 m depth resolved reference data from official water quality monitoring is demonstrated using the example of Lake Zurich (HPLC reference, Figure 7). Correlation coefficients and absolute RMSEs are higher and the relative RMSEs lower than those found in the field campaign matchups for Lake Constance, which can be explained with the higher range of concentrations occurring in Lake Zurich. The main difference due to ICOL can be expressed by a difference in linear regression similar to the Lake Constance field campaign (Figure 6), only that this time ICOL is closer to the 1:1 line.
Some outliers among the 3-5 days offset matchups can be identified for the occurrence of spatio-temporal variations in the CHL patterns observed by MERIS, but are not discussed individually.

The matchups for Lake Zug in Figure 8 represent an aggregation of low concentration cases and only a few algae bloom events, making the correlation less reliable than for Lake Zurich. Nevertheless, the correlations similar and the linear regression is again considerably steeper for ICOL corrected than for uncorrected data, whereas both are off the 1:1 line in this example. The main differences are due to the strong overestimation of concentrations by C2R for ICOL corrected data, leading to high RMSEs. However, the two maximum values by C2R with ICOL correspond to spring bloom events in April 2005 and 2007, where increased (6-8 mg/m$^3$) CHL concentrations are found at 7-12 m depth, but not in the top 5 m layer averaged for the reference dataset. When comparing to the average of the top 20 m probe profile data, ICOL corrected estimates improve to R=0.84, while it decreases to 0.74 without ICOL.

For Lake Geneva, 98 in situ measurements in 2003-2007 are available for a sampling station in the center of the lake, allowing for the reduction of maximum temporal offset for data matchups to two days. However, the entire investigation period reveals correlations of only R=0.33 without and 0.26 with ICOL. But when only the first 3 of 5 years are analyzed, the correlation without ICOL improves, and the ICOL corrected R=0.89 becomes the highest of all lakes (Figure 9). It is assumed that the SIOPs of Lake Geneva have significantly shifted in 2006-2007. Several indications support this hypothesis, such as the obvious change in phytoplankton variability visible in the CHL reference data (Figure 13), the inability to differentiate AOT, CHL, TSM and Y patterns in some images, the difference between the spectral shape of gen070910 compared to the other reference spectra and the poor retrieval of that spectrum by C2R (Figure 4, type [4]), and finally the observation of exceptional blooms.

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of filamentous Mougeotia algae in 2007 by local limnologists (Rimet et al., 2008; Tadonleke, R., pers. comm.).

In Lake Garda, the sampling station is very close to the inflow of River Sarca in the narrow northern part of the lake. 0-1 days offset would have to be allowed in order to get enough matchups, but cannot account for the temporal variability in this estuary region (R=0.50, n=11). A local comparison with remote sensing estimates is thus impossible unless the temporal agreement of image and in situ sample acquisition can be improved.

In Lake Biel and Lake Constance, water quality monitoring data is measured as HPLC analysis of 20 m composite profiles. A reduced comparability with remote sensing estimates is indicated by matchups for 4 different sites in Lake Constance (Figure 10), where the correlation is only about half of that found for the 0-5 m profile matchups. The largest RMSEs are found for the 4 ICOL corrected matchups of the site BR in the eastern bay of the lake, close to the River Rhine estuary. If removed, the other 3 sites achieve R=0.67 with ICOL. The small number of Lake Biel reference measurements requires a 2-day offset threshold to analyze 12 matchups, which correlate even less (R<0.26).

4.3. Fusion of CHL time series

The correlation found for 0-5 m monitoring data and C2R CHL estimates are additionally examined by means of their seasonal and interannual variation. The linear gain factors found for the CHL monitoring matchups in Figure 7, Figure 8 and Figure 9 are applied to the C2R estimates, and the standard deviations of the averaged profile data are displayed as error bars of in situ CHL. In Lake Zurich, most images are available for the second half of 2006, where the in situ concentrations show a steady increase. Another cluster is related to the minimum concentrations in summer 2007 and the relative maxima before and after. Both situations are
well reproduced by the C2R estimates, without a significant difference for ICOL corrected (n=39) and uncorrected (n=33) data. A difference in the number of observations occurs because C2R L2 flags ATC_OOR and RAD_ERR are less frequent in the corrected (11) than in the uncorrected (17) data, whereas about half of the flagged non-ICOL CHL concentrations would be in a reasonable range, while the other half is mostly above 20 or below 1 mg/m³. Furthermore, the C2R estimates seem to underestimate low concentrations, while they overestimate higher concentrations. Again, this applies to both types of satellite estimates.

The Lake Zug time series of in situ CHL data consists of relatively constant 2-4 mg/m³ concentrations with annual short periods of increased concentrations in spring and autumn. For the years 2005 and 2007, these events are well reproduced by the C2R estimates, with occasional overestimations by both non-ICOL and ICOL processed CHL. The spring maximum in 2006 measured on 24 April in situ is not confirmed by any valid MERIS observation. A MERIS image acquired on 21 April indicates above average CHL concentrations of 4.3 (non-ICOL) and 4.7 mg/m³, but is not displayed in Figure 12 due to sun glint suspect geometry. The autumn maximum in 2007 is not visible in the in situ data, since no fluorescence probe measurements were taken between 18 July and 29 October. MERIS estimates indicate that this algae growth event has taken place to a similar extent as in the year before.

For the Lake Geneva time series, ICOL results (n=50) are more accurate than non-ICOL (n=49) results, as already found for the correlation of matchups. In the years 2003-2005, only two events of concentrations above 4 mg/m³ are documented by in situ data, while the variations at low concentrations are very volatile. Nevertheless, a good agreement is visible especially in 2004, where all but the first C2R estimates are in the range between the previous and the subsequent in situ measurement. The years 2006 and 2007 introduce increased average
and maximum CHL reference concentrations and an increased seasonal variability. C2R retrieved CHL concentrations cannot account for these changes, although the MERIS images still depict many spatial features as relative concentration differences.

5. Conclusions and discussion

It was shown that both C2R and ICOL are well automatable algorithms, allowing for the supply of relatively accurate CHL products for most of the larger perialpine lakes. The potential for their use for in situ water quality monitoring is considerable, also taking into account the near real-time availability from ESA’s rolling archives. The application of simplified automatic quality checks regarding sun glint suspect and flagged pixels has strongly reduced the number of outliers in the MERIS data, although it lead to the loss of some significant datasets, which could be avoided by means of manual data quality control or an improved C2R flagging system, e.g. for sun glint affected pixels. Extraordinarily complex cases like the strong adjacency effects over Lake Maggiore (Guanter et al., 2009; Candiani et al., 2007) or the change in SIOP in Lake Geneva in the years 2006 and 2007 require further investigation. Especially the changing environmental conditions in Lake Geneva demonstrate that remote sensing means for water constituent estimation will hardly replace in situ measurements in the near future. At the same time, it could strongly improve the current monitoring if in situ observations would include the estimation of the water’s optical properties.

In terms of purposeful water quality monitoring, reliability and significance of remote sensing estimates cannot substitute in situ estimates, as they are strongly depending on atmospheric conditions and do not represent identical quantities, regarding area representation and penetration depth. Nevertheless, this study showed that the combination of in situ and
spaceborne inland water CHL monitoring can improve our knowledge of the current state of our freshwater reservoirs with both temporally and spatially improved resolution. Depth resolved data are thereby clearly more suitable for comparison (R=0.71 to 0.89 and rel. RMSEs between 30% and 69% with ICOL) with remote sensing estimates than 15 or 20 m composite samples (ICOL R<0.58). The signal depth \( z_{90} \) calculated by the C2R algorithm in the present study (not shown) was between 5 to 12 m for all lakes. Vertically resolved in situ measurements of the topmost 5-12 m are accordingly the most suitable reference datasets when it comes to combining in situ and remotely sensed water quality estimates (Lindell et al., 1999). Temporal offsets up to 5 days turned out to be adequate for the majority of matchups in Lake Zug and Lake Zurich, whereas a very high temporal agreement is required in estuary sites such as BR in Lake Constance or the Lake Garda site. Regarding other water constituents, it is known from the outcome of the MERIS Lakes validation campaign and was confirmed by our estimates, that the TSM estimates by C2R are even more accurate than CHL, while the Y product is faulty, probably due to atmospheric correction issues at short wavelengths (Koponen et al., 2008).

The role of the ICOL adjacency effect correction in the processing of MERIS data is consistently positive as far as the retrieval of accurate \( R_{es} \) by C2R is concerned. It also increases the correlation coefficient for CHL comparisons in 5 out of 6 examples, but not to a comparable extent. This finding confirms the conclusions of the MERIS Lakes validation study (Koponen et al., 2008), but lacks a simple explanation since the inversion criteria of the NN are relatively intransparent. However, C2R was originally developed for use without ICOL, and adjacency effects remained unconsidered in the forward NN, among other parameters. The reflectance inversion is therefore an approximation, in which neglected optical effects may be erroneously compensated by other parameters. In the present study, the
correlation between adjacency effect corrected and uncorrected Y estimates (e.g. \( R=0.38 \) for Lake Zurich matchups) is considerably lower than in the case of CHL and TSM (\( R=0.70 \) and 0.67, respectively). C2R’s Y was also found to be the most inaccurately retrieved constituent in the MERIS Lakes validation study (Koponen et al., 2008). Average values without adjacency effect correction are twice to three times lower than found in previous studies (Odermatt et al., 2008; Heege & Fischer, 2004) or when ICOL is applied. Therefore, we assume that Y buffers a large portion of the inaccuracy of \( R_{rs} \) derived without ICOL, while the CHL retrieval suffers only minor damages in relation to other error sources and the limited comparability of in situ and remote sensing measurements.

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<table>
<thead>
<tr>
<th>Lake</th>
<th>Directive</th>
<th>Executing institution</th>
<th>Method</th>
<th>Interval</th>
<th>Timeframe</th>
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<tbody>
<tr>
<td>Biel</td>
<td>Cantonal</td>
<td>Bernese Cant. Water Protection and Waste Management Office</td>
<td>HPLC (15 m)</td>
<td>30 d</td>
<td>2003-2008</td>
</tr>
<tr>
<td>Constance</td>
<td>IGKB¹</td>
<td>Institute for Lake Research, Langenargen (Germany)</td>
<td>HPLC (20 m)</td>
<td>14-30 d</td>
<td>2003-2007</td>
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<tr>
<td>Garda</td>
<td>WFD</td>
<td>APPA Trento (Italy)</td>
<td>Spectrophotometer (0-1 m)</td>
<td>30 d</td>
<td>2003-2008</td>
</tr>
<tr>
<td>Geneva</td>
<td>CIPEL</td>
<td>INRA, Thonon Les Bains (France)</td>
<td>Fluorescence probe (1-5 m)</td>
<td>14-30 d</td>
<td>2003-2007</td>
</tr>
<tr>
<td>Zug</td>
<td>Cantonal</td>
<td>Zug Cant. Environmental Protection Office</td>
<td>Fluorescence probe (1-5 m)</td>
<td>30 d</td>
<td>2005-2007</td>
</tr>
<tr>
<td>Zurich</td>
<td>Cantonal</td>
<td>Zurich Municipal Water Utility</td>
<td>HPLC profile (0-5 m)</td>
<td>30 d</td>
<td>2006-2008</td>
</tr>
</tbody>
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¹ International Commission for the Protection of Lake Constance
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