Water quality monitoring based on sediment distribution using satellite imagery

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SUMMARY

The aim of this research is to provide a simple way of monitoring water quality in a set of reservoirs using an earth observation based approach. The study carried out was preformed in forty two reservoirs of the Ebro basin. The proposed methodology is based on the development of an algorithm for the estimation of water quality by means of the Landsat 5 TM bands reflectance. Some band ratios were utilized in the model as well. Trophic State Index (TSI), calculated by means of Secchi Disc Transparency data, was estimated using a forward stepwise multiple regression analysis. A great correlation degree for the TSI values prediction was obtained. The best prediction of the dependent variable was explained by the independent variables TM2 band and TM1/TM2 ratio. The final results showed a highly spatial heterogeneity of water quality among reservoirs along the study area. Moreover, an important spatial heterogeneity was also observed in the water bodies.

KEYWORDS: *Reservoirs water quality, Remote sensing, Trophic State Index (TSI)*

INTRODUCTION

Europe is immersed in a new water policy with an important environmental component. As a consequence of this, the European Commission proposed the Water Framework Directive (WFD), whose main objective is achieving an accurate management of all water bodies. It expects to be reaching a “good status” for them by 2015 (European Parliament, 2000). In order to achieve this, the WFD requires all water bodies to be monitored (Water Directors, 2003)- including Artificial Water Bodies (AWB) or Heavily Modified Water Bodies (HMWB)- and their status report should be taken at regular intervals.

Traditionally, research on quality of water bodies has consisted of assigning quality indicator values to the whole water body by means of sampled sites. However, this is not a good approach for highly heterogeneous water surfaces or for situations where high spatial precision is required. In order to improve the limnological research some remote-sensing-based methodologies has been proposed. Optical properties of water depend on the concentration of suspended sediments, phytoplankton and dissolved organic mater, parameters highly related to water quality. Previous research studied the actual relationship between water properties (i.e. water quality) and satellite data for several types of water bodies and geographical extensions (Wang et al. 2004, Hellweger et al. 2004, Kloiber et al. 2002ab, Vincent et al. 2004). Moreover, these techniques show more important advantages than traditional sampling. Firstly, the continuous geographical coverage of satellite imageries provide a continuous water quality information about the whole water body. Secondly, remote sensing allows us to obtain information about inaccessible places. Finally, historical imageries provide estimation of historical water quality and offer a excellent way to monitoring the water quality temporal evolution, as well. Nevertheless, in spite of this advantages, a subset of *in situ* samples in some “test reservoirs” must be carry out, in order to calibrate the relationship between water properties and satellite imaginary information continuously.

Another factor that must be taken into account is sediment accumulation, since it has an important effect on water quality and on aquatic life of water bodies. Therefore, its study is essential in order to reach the WFD objectives. Additionally, sediment models can provide information about watershed characteristics, for instance erosion degree and consequently global rates of soil loss. Other studies demonstrated that satellite imagery can be used to calibrate or to validate the transportation model of hydrodynamic sediments (Mertes et al. 1993; Hellweger et al. 2004).

In this research, the utility of earth observation techniques applied to water clarity and sediment distribution is illustrated. A simple and replicable methodology is suggested as a contribution to the research, the evaluation and the management of reservoirs at the Ebro basin. Besides, this remote sensing based approach could be applied to other basins.

The Ebro River Basin Authority (Confederación Hidrográfica del Ebro, CHE) is the state organization in charge of physically and administratively managing the hydrographical basin of the Ebro river, the one of the biggest flow in the Iberian Peninsula, through planning (by elaborating and revising a global catchment hydrological plan), managing (by administering and controlling the different water resources in the catchment area) and investing (by projecting and carrying out the public works that may be entrusted to them).

METHODOLOGY

Study Area

The Ebro river basin is located in the Northeast of the Iberian Peninsula (western Europe). This basin limits to the North with the Pyrenees chain, to the Southwest with the Iberian chain and the east with the Coast-Catalonian chain and covers an extension of 85.566 Km^2. This basin currently has over 45 reservoirs with more than $1Hm^3$ of capacity. Beside, its global capacity exceeds 3000 Hm^3. The 42 reservoirs included in this research were extended along the whole basin. In the north slope (which is the highest rainfall area) the number of reservoirs is greater than in the south slope. This scattered distribution together with the high geomorphological heterogeneity gives high limnological diversity to the area.

Imageries Data

Several satellite imageries could be used for water quality and sediment distribution. Nonetheless, Landsat TM imageries seem to be more appropriate for inland surface water bodies assessments, because of their relative low cost, temporal coverage and spatial resolution. Eight cloud-free or near cloud-free (<20%) Landat images (TM 5 sensor) were selected from the study area. The overpass date of each image did not exceed the sampling date 20 days.

Water Quality Reference Data and Images Processing

In situ quality data were acquired from the The Ebro River Basin Authority (CHE). Those data came from a limnological study carried out at forty five reservoirs of the Ebro basin during the summer of 2004. Summer periods are stated to be the best ones for water properties estimation by means of remote sensing techniques (Steadelmann et al 2001). In this sampling, trophic state indicative parameters as Secchi disc transparency, chlorophyll-a concentration and Total Solid Dissolved were estimated for each reservoir.

Satellite imageries were georreferenced into UTM coordinates (zone 30N) and resampled by using nearest neighbor. Subsequently, according to Chuvieco (Chuvieco, 1996) those scenes were radiometrically corrected and calibrated by converting raw digital numbers (DN) observed by a sensor into physical units of reflectance. This correction aims at minimizing the variation due to varying solar zenith angles and incident solar radiation assuming Lambertian surface. DN values are converted into reflectance values for each band using the equation:

$$\rho_\lambda = \pi\, d_s^2\, (\alpha_\lambda+\beta_\lambda DN_\lambda) / E_{0\lambda} \cos \mu_s$$

Where ρ_λ is the reflectance value for each band, d_s is the distance form the Earth to the Sun (in astronomic units), α_λ and β_λ are calibration coefficients of the TM sensor for each band, $E_{0\lambda}$ is the mean Solar exo-atmospheric irradiance [Wm^{-2} μm^{-1}] and μ_s is the zenith solar angle.

The spectral response of water is significantly different from the terrestrial response. Therefore it is important to obtain "water-only" spectral bands from original imaginaries. This procedure allows us to:

- Work with less information.
- Eliminate terrestrial or vegetation influenced pixels

Besides, these images were used to obtain water surface quality maps.
In order to do that, each Landsat image was performed to differentiate water bodies from terrestrial areas by means of an unsupervised classification using ten classes (Kloiber et al. 2002a). Once the water classes were identified, the resultant categorical images were used as a binary mask to take out terrestrial zones from the originals scenes. Each sampled reservoirs were identified and separated into individual images.

In order to obtain optical properties of water, spectral signatures were collected by using from 50 to 500 pixels around sampling point depending on reservoir size and therefore, the mean of the reflectance value was extracted from each seven bands.

Subsequently, this spectral signatures will be related with measured water parameters. In order to obtain quality indicative values, Secchi disc depth data (SD) were transformed into Trophic State Index (TSI) appliying the Carlson's approach (Carlson, 1977). The carlson's approach utilizes the following equation:

$$TSI\ (SD) = 10 \cdot [6 - \mathrm{Ln}\ SD / \mathrm{Ln}\ 2]$$

Trophic state based on chlorophyll was not taken into account because the overpass date of the available satellite imageries was significantly different from the sampling date. In order to obtain a good predictive relation between clorophyll measurement and satellite imageries data, the satellite overpass and the sample date should be obtained very closely in time, around ±1-2 days (Standelmann et al 2001). In contracts, transparency is more stable in time and consequently it can be used with a greater range of days.

Statistical model development

The final step consists of the developent of the algorithm which is able to predict clarity values from spectral features of the satellite imageries. When the needing of a continuous dependent variable from a number of independent variables is required, a regression analysis must be carried out, in this case a multiple lineal regression. Standard multiple regression allows us to discover how well each independent variables (spectral values) predicts the dependent variable (TSI value).

Moreover, multiple regression models with spectral ratio have found to be more robust and more reliable than the regression model with single band (Vincent et al 2004). For this reason, different spectral ratio was used in this work (i.e. TM1/TM2; TM1/TM3; TM2/TM3) in order to improve the final algorithm. A forward stepwise selection method was used to determine the best fitting model. The correlation degree between the predictor variables affects the final model, therefore, to avoid collinearity, we chose one of the two variables with high Pearson correlation for further analyses ($r^2 >$ 0,7 and $p<0,001$).

For the evaluation of the predictive performance of the final model, two independent datasets are needed: training dataset to provide de regression model, and a test dataset to evaluate the equation.

Thus, data were randomly divided in two different groups where the bigger one (80% of data) was used as a training group, whereas the second one (20%) was used as a test group. The evaluation method consists of a correlation between the observed quality values in the test group and the predicted quality values using the obtained equation. High correlation value and slope closed to 1 show elevate predictive performance of the final model.

Once the final model was obtained and evaluated, we extrapolated the obtained equation in the original band data. The resultant imagery contained the continuous information about the TSI value around the reservoir. There, the calculated values were discretised into 10 TSI unit ranges, and exported to a map with a specific color for each range.

This representation allows us to obtain useful visual information about general condition of simples reservoirs and of the whole basin. Moreover, basic statistics procedures were performed in order to obtain useful numerical information about the final results. Final trophic condition for the whole water body was calculated as the mean of the values of the pixels.

RESULTS AND DISCUSSION

The best model extracted by the multiple lineal regression analysis, which had an R^2 (adjusted) = 0,5 (N = 31 and p<0.005) is given by the following equation for TSI:

$$TSI = 286,63(TM2) - 2,40\ (TM1/TM2) + 39,31.$$

Where TM1 and TM2 was the reflectivity value of Landast TM band 1 (Blue band) and band 2 (Green band), respectively. The prediction results based on the separate test dataset showed a strong correlation between the observed values of TSI and the predicted values which were calculated through the obtained equation (Figure 1). This result illustrates the predictive performance of the final model.

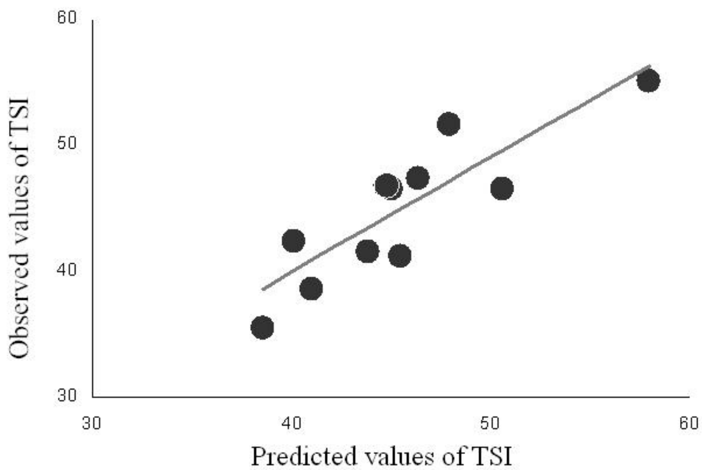

Figure 1: Scatter plot of the predicted values vs the sampling values (observed values) of TSI (Trophic State Index) for test group (N = 11, r^2 = 0,72, p < 0,001, slope = 0.911).

A TSI map was produced for each reservoir by means of the obtained equation model (Figure 2). Tree important results were extracted by visual and statistical analysis of these maps:

- A t-test for paired samples was carried out in order to observe statistical difference between the final TSI value of reservoir obtained though *in situ* sampling method and remote sensing methods. The t-test showed significantly differences between two datasets ($F = -0.752$, $fd = 41$ and $p = 0.009$). This result indicates that the total quality values of reservoirs, calculated using the mean of the pixels values of the whole water body, was significantly different from assigning them the value of a simple sampled point to them.

- The mean of the TSI values for the set of reservoirs was 51.777 with a standard deviation of 5.91 what shows that Ebro basin reservoirs have medium state condition (mesotrophic-eutrophic). In addition, the relatively high standard deviation of the TSI values corroborates the greater diversity of limnological condition in the study area.

- High spatial heterogeneity inside reservoirs was also observed. The quality values of the studied reservoirs have a significantly high average standard deviation (7.27). The visual analysis of the TSI maps shows this event as well. Principally, the higher change degree takes place in reservoir tails where an increase of the turbidity is observed. This increase of turbidity allows us the delimitation of sediment plumes which were caused by the erosion dynamics in the watershed.

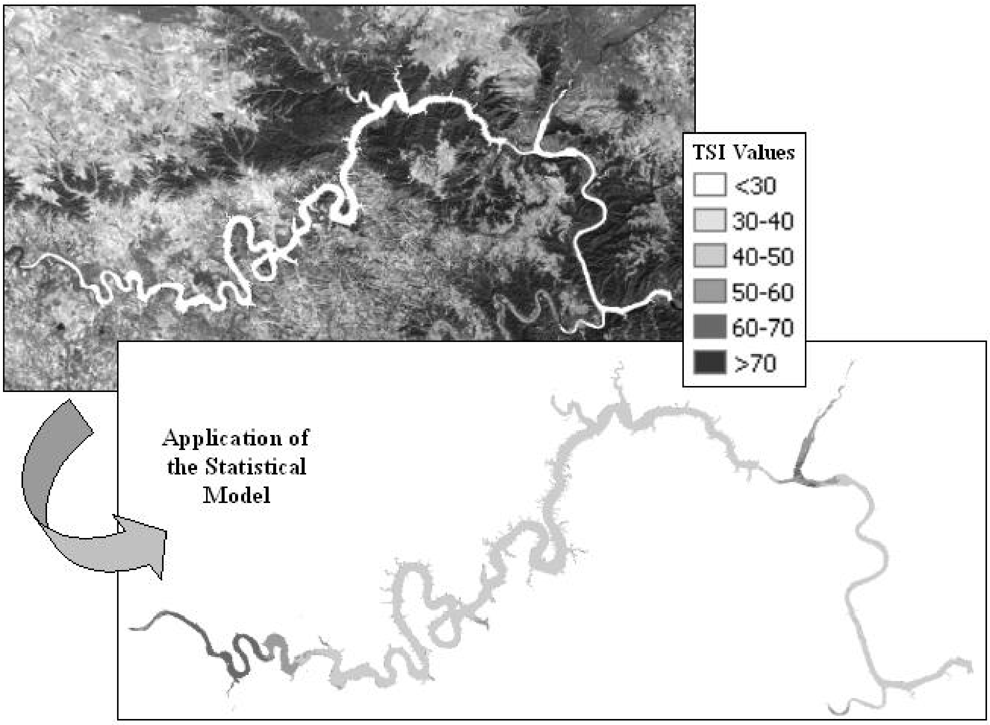

Figure 2: TSI maps for the Mequinenza reservoir and the Ribarroja reservoir calculated from Landsat TM reflectance through statistical model.

CONCLUSIONS AND FURTHER RESEARCH

This study presented an algorithm for quantification of the trophic state index based on Secchi disk transparency by applying Landsat TM data. By using this algorithm we were able to research the spatial variation of water clarity. Secchi disc depth was correlated with visible bands of Landsat 5 TM specially with green band and the ratio between blue band and green band.

The assignation of a water quality value for individual reservoirs by means of traditional methods was found significantly different from a remote sensing technique-based approach. Owing to the great spatial heterogeneity which was found on the studied water bodies, it can be stated that not only do remote sensing techniques provide a better water quality indicator, but also an indicator of the variability.

Quality maps showed elevated spatial heterogeneity among reservoirs. This spatial heterogeneity can be also observed in a reservoir. This fact justifies the application of remote sensing techniques as a complement for traditional methods. In addition, this spatial variation provides the delineations of sediment plumes and, at the same time, sediment transportation model research could be carried out. Thus, turbidity representation permits obtaining useful visual information about water sediment load, for instance the sediment transport model evolution through time can be obtained by this method.

In spite of the overpass date of Landsat scenes was not very closely in time with sampling date, correlation among spectral values and water parameters was reasonably high. Nevertheless, future research should contemplate this issue in order to improve results. Beside, another important quality parameters as chlorophyll concentration could be used. Further seasonal development is necessary in order to estimate water quality and sediment hydrodynamic model, along an annual cycle.

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