Water Quality Monitoring to Support the European Commission's Water Framework Directive Reporting Requirements

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SUMMARY

The aim of this research is to provide a simple way for water quality monitoring in a set of reservoirs using an earth observation based approach and the assessment of the use of this technique for a monitoring networks in order to meet the requirements and objectives of the Water Framework Directive (WFD) by the Member States. The study carried out was preformed in forty two reservoirs of the Ebro river 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 used 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. These results demonstrate the likeliness of developing a monitoring network based on remote sensing techniques for the implementation of the WFD.

1 Introduction

The European Union 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 to achieve 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. Member States will select the mandatory and recommended Quality Parameters most representative for the surveillance monitoring programs depending on the catchments’ characteristics.

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. Also, the aim of this study is to assess the application of this techniques in the monitoring networks programs required to meet the requirements and objectives of the Water Framework Directive by de Local hydrological Authority. Besides, this remote sensing based approach could be applied to other basins because of the use of standards technologies and infrastructures.

Traditionally, research on the 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. The factors that affect water clarity are very complicated and vary among water bodies. Suspended particles, including algal cells and suspended sediments cause an increase of the water brightness especially for band 1-4 (Brezonik P, 2005)

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, Doxaran et al 2002). Moreover, these techniques show important advantages compared with traditional sampling. Firstly, the continuous geographical coverage of satellite imageries provides 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 an excellent way for monitoring the temporal evolution of water quality, as well. Nevertheless, in spite of these advantages, a subset of *in situ* samples in some “test reservoirs” must be carried 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).

Additionally, management of spatial information is moving from monolith geographic information systems to spatial data infrastructures. Remote sensing systems as a spatial systems have also be immersed in this transformation in order to profit from their advantages .A Spatial Data Infrastructure (SDI) can be defined as the technology, policies, standards, and human resources necessary to acquire, process, store, distribute, and improve utilization of geospatial data (U.S. Federal Register, 1994). There are significant benefits managing the data-management problem from the spatial data infrastructure point of view. Data providers are able to advertise and promote the availability of their data and potentially link to standard online services that relate to their specific data sets and data users can locate all available geospatial and associated data relevant to an area of interest. Additionally, the description of geospatial data with appropriate metadata builds upon and enhances the data management procedures of the geospatial community. Geographic metadata is the description of a particular geographic dataset. Metadata helps to document data (Nebert 2001), find them, determine how best to use then and organize and maintain the investment in data done by the entities participating in the spatial data infrastructure. Advantages of using spatial data infrastructures can apply both inside an organization and among different organizations.

At European level, INSPIRE (http://www.ec-gis.org/inspire/) is an ambitious initiative that intends to trigger the creation of a European spatial information infrastructure that delivers to the users integrated spatial information services. At present, it is a proposal of directive that will enforce European Union member states to develop their own national spatial data infrastructures, in order to built the European SDI on top of the national ones. The process of determining water quality is presented as a use case to provide requirements for an hydrologic SDI, following the principles of INSPIRE.

2 Problem context

The Ebro River Basin Authority is currently developing their own SDI (IDE-Ebro), where data are stored as raster coverages or hydrologic features in compliance with a conceptual data model. Access to the data (both features and raster data) and metadata is achieved by standard web services and, where appropriate, web processing services are planned to be added. Currently, only certain parts of the infrastructure are available: conceptual data model of the hydrologic features managed by the Hydrologic Planning Office of the Ebro River Basin Authority, metadata of the data within the model, access applications for the management of this data, catalogue services and searches, web feature service and gazetteer. The methodology proposed to determine water quality using satellite imagery makes use of the available services and has served to identify different user needs of the system: criteria for searching data, metadata attributes needed, addition, update and retrieval of data requirements (both in terms of models and format). Potential processing services to be included in the Ebro SDI have been identified as well.

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. 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).

3 Geoprocessing Workflow

In order to apply the desired earth observation techniques to analyze water clarity and sediment distribution, adequate geospatial information, such as images or field samples data, must be accessed and processed. A spatial data infrastructure may provide an useful information system architecture for this purpose. Within this architecture spatial data must be organized, standardized metadata must be created and must be available and searchable thought standard catalogue services, and accessible thought standardized web geospatial services (WMS, WCS, WFS, …). OGC and ISO standards are the most indicated for this purpose.

The processes devoted to perform the earth observation techniques must interact with that other geospatial services of the architecture and must, in turn, facilitate the integration of their final and some intermediary results back in the architecture. Figure 1 shows an overview of this integration and of the workflow of the geoprocesses that are involved, which will be explained in the following paragraphs.

The infrastructure has significant amount of spatial images from the area of interest which are metadated and accessible and, some of them, available through OGC web coverage services. Metadata, which has been created conform to ISO 19115, is available to search through a OGC catalog. In this case our search was oriented to find out available satellite images collected during the *in situ* sample date.

Image search

Many types of satellite imageries could be used for the monitoring of water quality and sediment distribution. In order to compare the usefulness of different sensors the spectral, spatial and temporal resolutions could be used. High spatial resolution is useful for many uses but in this case light energy capture have great limitations and, consequently, spectral and temporal resolution decrease. Landsat TM imageries seem to be appropriate for inland surface water bodies assessments, because of their relative low cost, temporal coverage and spatial resolution. The TM sensor (onboard Landsat 5 satellite) consists of six spectral bands (three in the visible range and 3 in the IR range) with a spatial resolution of 30 meters and a thermal infrared band whit a resolution of 120 meters (web site http://eros.usgs.gov/products/satellite/tm.html). Within the imagery collection available in the catalogue for Landsat TM 5, eight cloud-free or near cloud-free (<20%) were used in this study. In this case the overpass date of each image did not exceed the sampling date 20 days. Important image information necessary for the radiometric correction (gain, bias, sun cenit angle and date) was also integrated in the associated metadata records.

Field sample information from monitoring points

On the other hand, forty five surveillance punctual stations, located inside forty five reservoir were used as data source for in situ information. These data was sampled during the summer of 2004 since 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 and chlorophyll-a concentration were estimated for each reservoir (table 1). GPS was used in order to obtain the correct position inside the reservoir and, subsequently, data and coordinate were introduced into our SDI as punctual feature class and cataloged using the ISO standard.

Radiometric and geometric correction

With the help of the metadata, satellite imageries were properly 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. Compared to soil and vegetation, the fraction of light reflected form water is very small so an accurate absolute radiometric correction is critical (Gordon, 1987) This correction aims at minimizing the variation due to varying solar zenith angles and incident solar radiation assuming Lambertian surface. DN values were calibrated using the calibration coefficients in 1 and consequently through equation 2 this values were converted to apparent reflectance at the same time that the most important atmospheric effects are corrected as well.

$$L_\lambda = Gain_\lambda \cdot DN_\lambda + Bias_\lambda \qquad (1)$$

$$\rho_\lambda = \pi\, d_s^2\, L_\lambda / T_\lambda\, E_{0\lambda} \cos \mu_s \qquad (2)$$

Where $Gain_\lambda$ and $Bias_\lambda$ are calibration coefficients of the TM sensor for each band, ρ_λ is the reflectance value for each band, d_s is the distance form the Earth to the Sun (in astronomic units), $E_{0\lambda}$ is the mean Solar exo-atmospheric irradiance [$Wm^{-2}\ \mu m^{-1}$], μ_s is the zenith solar angle and T_λ is the atmospheric transmittance along the path from the sun to the ground surface for each TM band. As they may be also useful for other purposes, corrected images were again metadated and stored inside the infrastructure database for further uses.

Water body images extraction

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, to eliminate pixels influenced by terrestrial or vegetation information and besides, to use the images in the process to obtain water surface quality maps. To do that, each Landsat image was processed 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. A selection of the reservoir features from the water body features (obtained from the infrastructure WFS) were used, by means of some spatial operations, to make separate individual raster images (one for each reservoir) from the raster scene and relate them with their respective reservoir feature. Additionally this process also allows to eliminate wet places which may be close to the reservoirs that could affect the final results.

Spectral signature extraction

The spectral signature was obtained by combining each reservoir image with the respective monitoring point spatial location. Optical properties were computed by using a set of pixels around the monitoring point. The amounts of pixels vary in a range of 50 to 500 depending on the reservoir size. For each of the seven bands, the reflectance value was computed by the mean value in the set of pixels.

Conversion to TSI values

In order to obtain quality indicative values, Secchi disc depth data (SD) associated with the field samples of the monitoring point features, were transformed into Trophic State Index (TSI) by applying the Carlson's approach (Carlson, 1977). The Carlson's approach utilizes the following equation:

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

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 chlorophyll 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). On the contrary, transparency is more stable in time and, consequently, it can be used with a greater range of days.

Geostatistical analysis

The final step consists of the development of an algorithm capable to predict the clarity values from the spectral characteristics of the satellite imageries. A regression analysis must be carried out when a continuous dependent variable must be expressed by a number of independent variables. A multiple lineal regression has been use in this case. Standard multiple regression facilitates to discover how well each independent variable (spectral value) predicts the dependent variable (TSI value).

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

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.

Application of the obtained equation

Once the final model was obtained and evaluated, the obtained equation was extrapolated in the original band data. The resultant imagery contained the continuous information about the TSI value around the reservoir. There, the calculated values were discredited into 10 TSI unit ranges, and exported to a map with a specific color for each range. This representation allows to obtain useful visual information about the general condition of simple reservoirs and the whole basin. Additionally, basic statistic procedures were performed to obtain useful numerical information about final results. Final trophic condition for the whole water body was calculated as the mean of the values of the pixels. These images were metadated and stored inside the infrastructure database for further uses.

These results will let us make decisions about the final report of the individual phisico-chemical status as the WFD show. Two important informations will be essential to reach this objective, the average of the throphic index into the whole reservoir as well as the maximum quartile and the standard deviation.

4 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 2). This result illustrates the predictive performance of the final model.

A TSI map was produced for each reservoir by means of the obtained equation model (Figure 3). 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 figure 4 illustrate the difference of this two distributions. It show that the distribution of reservoir quality using traditional sampling has greater deviation than the results using remote sensing. This mean that the quality values assignment to inland water has to be taken into account the whole surface, specially in heterogeneous one.

- 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.

5 Conclusions and further research

The geoprocessing workflow has demonstrated the availability of using a SDI and remote sensing technique for reach a specific objective, in this case for quantification of water bodies quality. 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.

These results seem to be a powerful step for the Water Framework Directive (WFD) implementation by the hydrological authority. Member States can plan their monitoring programs and select quality elements that measure the quality degree of the water bodies and compare this with its reference status. The approach shown here is a first approximation to evaluate the initial state of this water bodies and calculate the reference chemical values and its integration within an information system architecture recommended by the WFD and Inspire. Furthermore, the applied strategy could be used as a good mechanism to facilitate the automation of the monitoring of these parameters and the reporting of the chemical status of reservoirs and also lakes in supporting the WFD.

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Tables

Table 1: Secchi Disc Transparency (SDT) y chlorophyll-a (Chl-a) values obtained for each reservoir during the summer of 2005

Reservoir	Code	SDT (m)	Chl-a (μg/l)	Date	Reservoir	Code	SDT (m)	Chl-a (μg/l)	Date
ALLOZ	E01	1.18	1.50	23/07/04	MONEVA	E24	5.50	0.10	20/08/04
BARASONA	E02	3.20	3.70	07/08/04	MONTEAGUDO	E25	2.03	17.80	16/08/04
BÚBAL	E03	3.10	14.30	12/08/04	OLIANA	E26	2.20	19.30	03/08/04
CALANDA	E04	2.20	3.60	19/08/04	PENA	E27	3.20	2.80	18/08/04
CAMARASA	E05	2.55	1.20	04/08/04	PEÑA	E28	0.89	11.30	27/07/04
CANELLES	E06	2.40	2.30	05/08/04	RIALB	E29	1.60	5.90	03/08/04
CASPE	E07	1.40	0.40	19/08/04	RIBARROJA	E30	1.40	16.10	21/08/04
CAVALLERS	E08	7.00	0.50	06/08/04	SALLENTE	E31	7.00	0.70	06/08/04
CIURANA	E09	5.20	10.80	17/08/04	SAN BARTOLOMÉ	E32	1.20	8.50	30/07/04
CUEVA FORADADA	E10	2.10	0.60	20/08/04	SANTA ANA	E33	2.55	2.00	04/08/04
EBRO	E11	3.40	3.70	20/07/04	STA. MARÍA BELSUÉ	E34	1.78	8.50	27/07/04
ESCALES	E12	5.50	1.70	06/08/04	SANTOLEA	E35	4.10	0.50	18/08/04
ESTANCA DE ALCAÑIZ	E13	1.20	3.30	19/08/04	SOBRÓN	E36	1.55	6.10	20/07/04
EUGUI	E14	3.70	1.40	22/07/04	SOTONERA	E37	1.61	4.10	30/07/04
GONZÁLEZ-LACASA	E15	2.35	17.60	09/08/04	TALARN-TREMP	E38	5.90	2.60	04/08/04
EL GRADO	E16	4.05	0.90	07/08/04	TERRADETS	E39	0.60	2.90	03/08/04
GUIAMETS	E17	1.70	8.30	20/08/04	LAS TORCAS	E40	2.50	2.20	20/08/04
IRABIA	E18	4.55	1.40	22/07/04	LA TRANQUERA	E41	2.10	18.60	13/08/04
LANUZA	E19	3.60	10.90	10/08/04	ULLIVARRI	E42	5.20	2.00	21/07/04
LLAUSET	E20	8.00	0.70	05/08/04	URRÚNAGA	E43	4.10	1.40	21/07/04
MAIDEVERA	E21	2.50	14.80	12/08/04	VADIELLO	E44	4.41	1.60	29/07/04
MEDIANO	E22	1.70	1.70	07/08/04	YESA	E45	1.95	2.60	26/07/04
MEQUINENZA	E23	2.90	4.70	21/08/04					

Illustrations

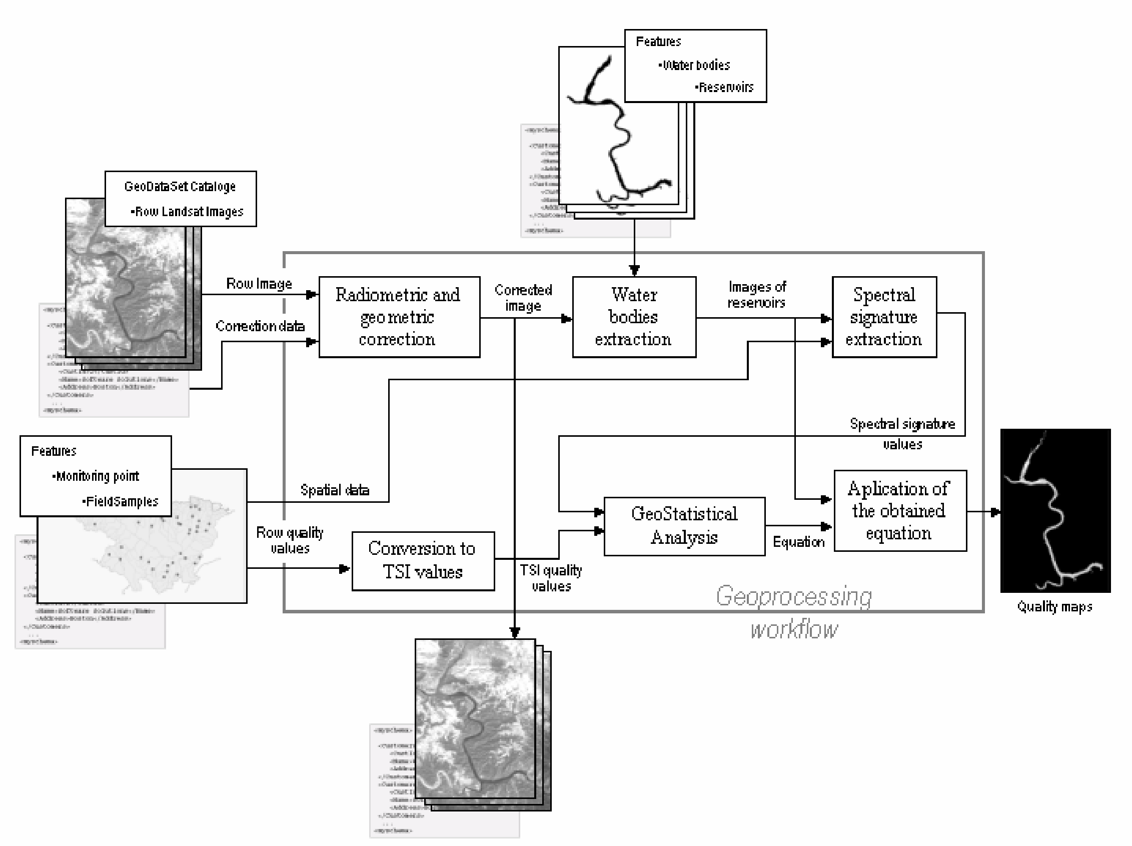

Figure 1: Geoprocesing Workflow applied in order to obtain the final quality maps.

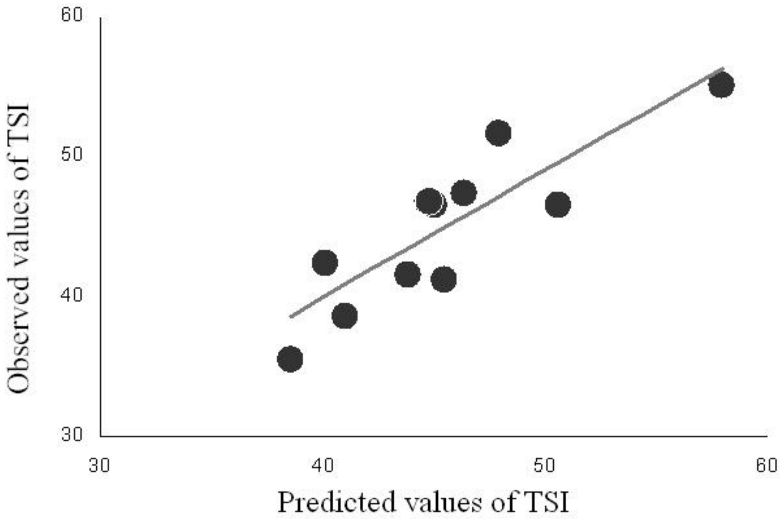

Figure 2: Scatter plot of the predicted values vs the sampling values (observed values) of TSI (Trophic State Index) for test group (N = 11, $r^2 = 0,72$, $p < 0,001$, slope = 0.911).

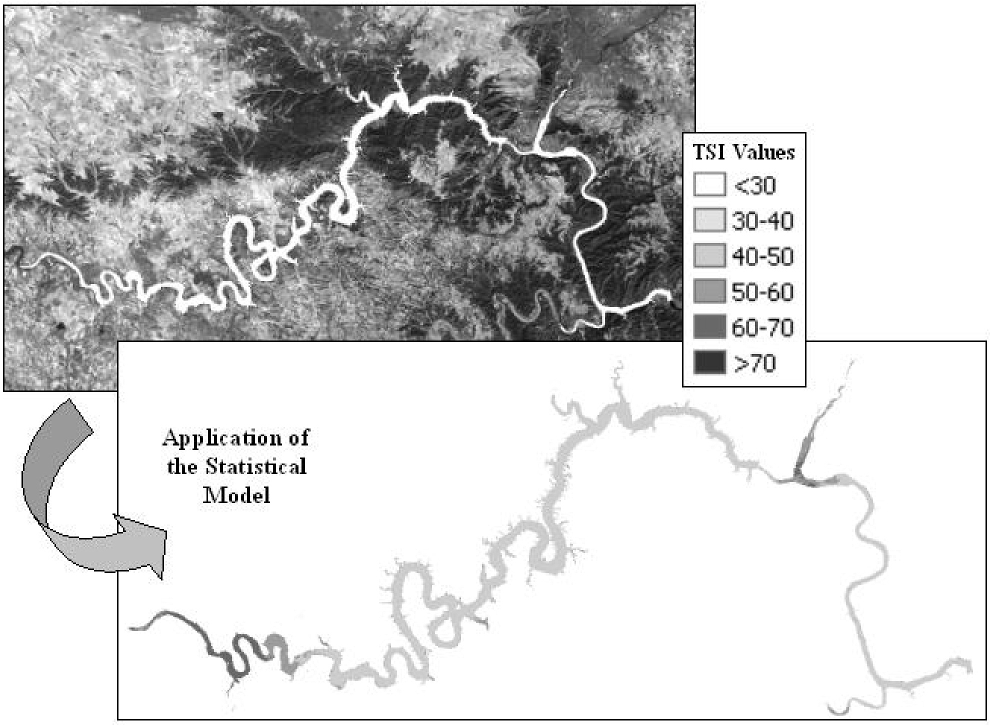

Figure 2: TSI maps for the Mequinenza reservoir and the Ribarroja reservoir calculated from Landsat TM reflectance through the obtained statistical model.

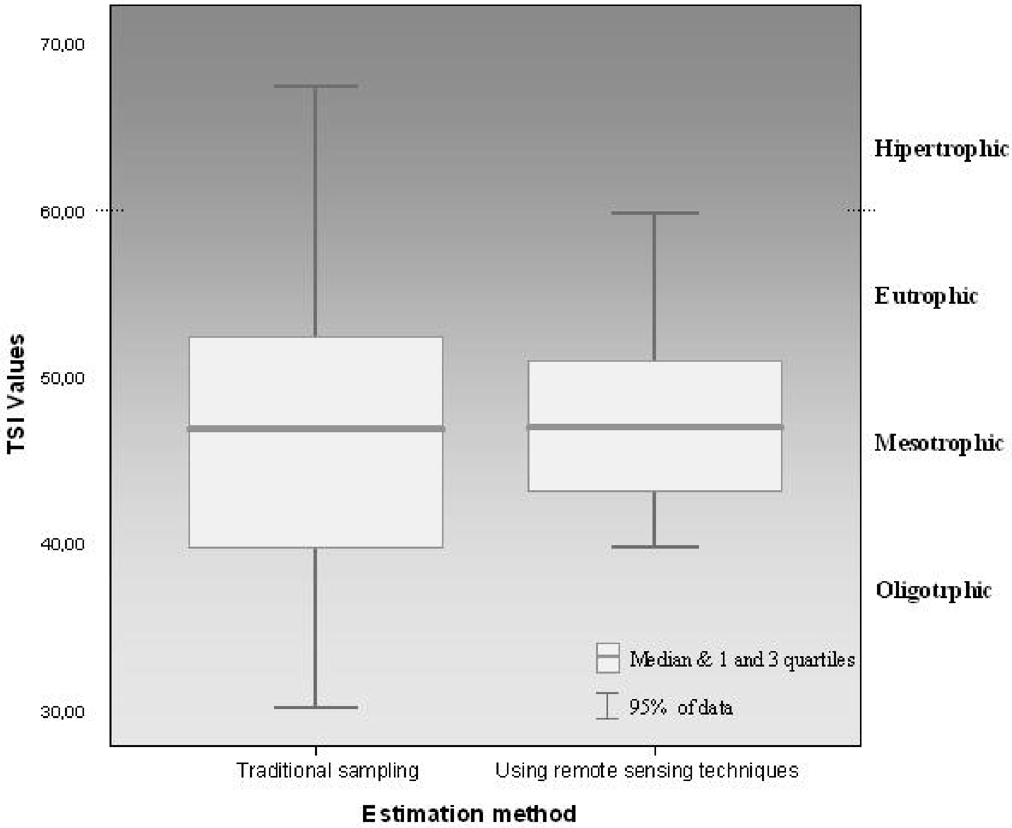

Figure 3: box plot of the two distribution of the water quality results using both traditional sampling and using remote sensing techniques. The t-test applied to these distributions s showed significant differences (F = -0.752, fd = 41 and p = 0.009)

List of illustration.