Use of LANDSAT 8 images for depth and water quality assessment of El Guájaro reservoir, Colombia

Luis Carlos González-Márquez [a], Franklin M. Torres-Bejarano* [b c], Ana Carolina Torregroza-Espinosa [b], Ivette Renée Hansen-Rodríguez [a] & Hugo B. Rodríguez-Gallegos [d]

[a] *Engineering and Technology Department, Universidad de Occidente, Av. Universidad s/n, 81048, Guasave, Sin., México.* luis.gonzalez@udo.mx, ivrenhr@gmail.com

[b] *Engineering Faculty, Universidad de la Costa CUC, Calle 58 # 55 – 66, Barranquilla, Colombia.* atorregr4@cuc.edu.co

[c] *Environmental Engineering Department, Universidad de Córdoba, Carrera 6 No. 76-103, 230002, Montería, Colombia.* franklintorres@correo.unicordoba.edu.co

[d] *Universidad de Occidente, Blvd. Macario Gaxiola y Carret. Internacional México 15, Los Mochis, Sin., México.* hrodriguez8@icloud.com

* corresponding author

Abstract

The aim of this study was to evaluate the viability of using Landsat 8 spectral images to estimate water quality parameters and depth in El Guájaro Reservoir. On February and March 2015, two samplings were carried out in the reservoir, coinciding with the Landsat 8 images. Turbidity, dissolved oxygen, electrical conductivity, pH and depth were evaluated. Through multiple regression analysis between measured water quality parameters and the reflectance of the pixels corresponding to the sampling stations, statistical models with determination coefficients between 0.6249 and 0.9300 were generated. Results indicate that from a small number of measured parameters we can generate reliable models to estimate the spatial variation of turbidity, dissolved oxygen, pH and depth, as well the temporal variation of electrical conductivity, so models generated from Landsat 8 can be used as a tool to facilitate the environmental, economic and social management of the reservoir.

Keywords: Water quality; remote sensing; statistical models; multispectral analysis.

1 Introduction

Factors such as the climate system, orogenic complexity and biogeographic location have combined exceptionally to allow water resources in Colombia to be plentiful and to model the tropical landscape forming rivers, estuaries, marshes, swamps and lagoons, among others (Minambiente, 2010; Castellanos, 2015). In Colombia, the main institution responsible for monitoring the condition of water resources at the national level is the Institute of Hydrology, Meteorology and Environmental Studies (also known by its acronym in Spanish, IDEAM), which since its creation 20 years ago is in charge of monitoring both the availability of the resource and the water quality. At the same time, regional environmental authorities are responsible for monitoring water bodies belonging to each region. Management that takes place on the water resource is divided into four large groups: planning, administration, follow-up and monitoring, and management of conflicts related to water (IDEAM, 2015). While IDEAM has given guidelines for conducting follow-up activities and monitoring, most of the environmental authorities will not perform these processes. It is important to note that only eight of the 39 environmental authorities have a group or a unit of water resources in their organizational structure, i.e., that in the majority of cases the different functions of the management of water resources are scattered (Minambiente, 2010). Within the national policy for the comprehensive management of the water resource, is stated that in the country there is no periodic, systematic and articulated monitoring of water quality of surface and groundwater sources. In general terms, it is evident that there is an affectation of the water quality resources, with the consequent effect on the availability for different uses, with greater intensity in certain areas and water bodies. Consequently, it is necessary to have available information with greater coverage, continuity and resolution to make a more focused diagnosis in time and space (Minambiente, 2010). In view of the foregoing, in Colombia and especially in the Caribbean region there are difficulties in obtaining basic information on the water quality; further, there is little availability of information and it is generally found widely scattered, as it depends on the different institutions charged with monitoring and controlling the environmental status of the water bodies.

Traditionally, water quality is monitored through spot measurements in situ and analysis of samples in laboratory; this is an expensive and time-consuming practice for its implementation and in most of cases is not suitable for observing spatial and temporal variations in large areas (He et al., 2008). It is difficult to assess through the traditional monitoring the water quality in short periods of time, which is essential for planning, evaluation, and health management of water bodies (Wang & Ma, 2001). Considering that optical properties of water can be altered by variations in the concentration of parameters related to its quality (Pavelsky & Smith, 2009) and that there is no restriction in obtaining and using satellite imagery from the Landsat program, algorithms have been developed that have favored the accessibility and efficiency of monitoring water quality parameters through Remote Sensing (RS) techniques (He et al., 2008; El Saadi et al., 2014). The main benefit of RS via satellites for the evaluation of water quality is the production of synoptic views without the need for costly on-site surveys (Hadjimitsis et al., 2010). However, the estimation of the quality and depth of the water through satellite images has technical drawbacks that have prevented their extensive use. Among the leading is the difficulty in efficiently eliminating the effect of the atmosphere, which has significant impact on data recorded by satellites, such as the loss of information due to dispersion caused by aerosols and atmospheric constituents, and the low signal/noise ratio of sensors; yet, methodologies have been developed to correct the images generated by different sensors (Chavez, 1988; Roy et al., 2014; Doña et al., 2015). RS techniques have had a recent boom in the environmental field and excellent applications have been made for evaluation studies of the water quality. For example, in the development of algorithms to generate estimates of water quality parameters of interest such as the concentrations of chlorophyll a, the transparency or turbidity of the water and the concentration of suspended sediments (Ritchie et al., 2003; Hellweger et al., 2004; Doña et al., 2015; Harvey et al., 2015); as well as for the estimation of parameters of water quality to determine aquaculture areas through the analysis of multispectral and hyperspectral images (Rajitha et al., 2007; Alexandridis et al., 2008; Abd-Elrahman et al., 2011).

El Guájaro reservoir presents different problems, which have resulted in changes in its hydro-biological dynamics, one of them being the loss of storage capacity (CRA, 2014). This loss of capacity is mainly due to the decrease in depth of the reservoir by the deposition of sediments from the micro watershed. El Guájaro is a reservoir whose waters have different types of usage: water is extracted for human consumption, for agricultural irrigation and cultured fish, so it is an important source of income for the inhabitants of the region. In order to perform a better environmental, economic and social management of the reservoir, knowledge of the spatial and temporal variation of water quality and its depth is required, so the objective of this study is to generate statistical models that relate water quality parameters in El Guájaro reservoir with spectral records captured in Landsat 8 images.

2 Methodology

The methodology employed on this work is described in the subsequent sections and follows a sequence as illustrated in Figure 1.

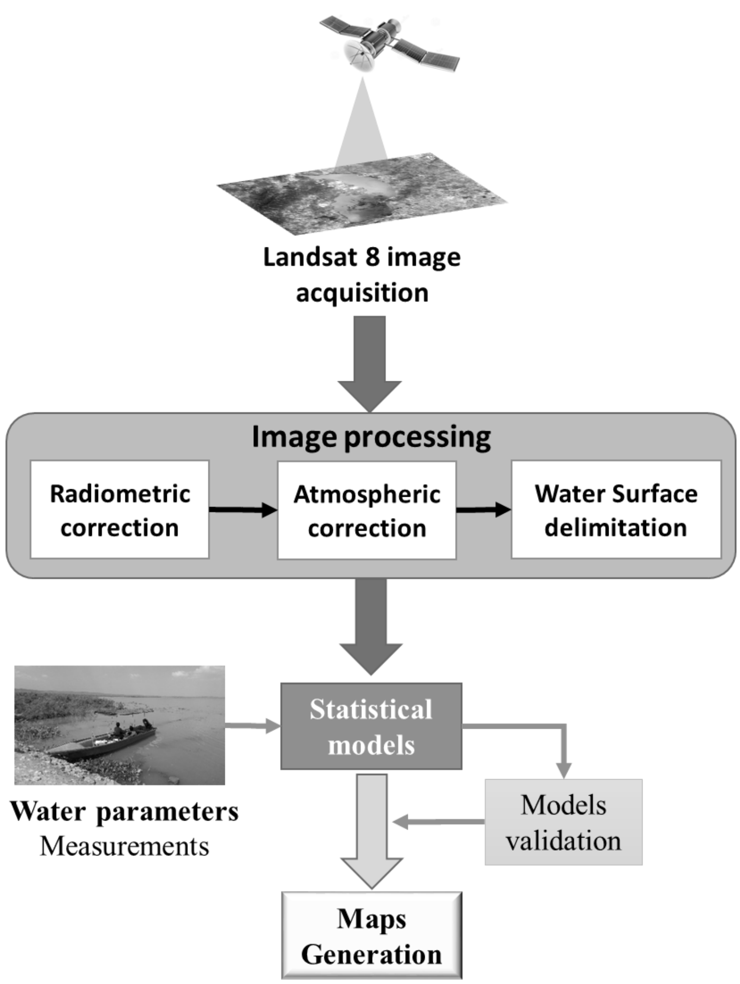

Figure 1. Methodological conceptual diagram

2.1 Study area

El Guájaro reservoir (Figure 2) is located at 10° 25’-10° 38’ N and 75° 00’-75° 08’ W, in the South of the Atlántico Department. Within its area of influence are the municipalities of Luruaco, Repelon, Manatee and Sabanalarga (CRA, 2014).

In its beginnings, the reservoir was capable of storing about 400,000,000 m^3 of water, in an area of 16,000 ha with five meters of average depth. Currently, El Guájaro has an extension of 11,647 ha, a perimeter of 114.28 km and an effective volume of 240,000,000 m^3 (IDEAM, 2015); the reservoir has two sets of gates that connect it with the channel of the dam, allowing to control levels (Torres-Bejarano et al., 2015). El Guájaro basin is confined between latitudes 10°46’51.19”-10°24’06.75” North and longitudes 75°15’11.20”-74°54’13.28” West and has an area of 90,039 hectares (CRA-UNIMAGDALENA, 2012). The region corresponding to El Guájaro area is primarily agricultural; livestock and quarrying are given to a lesser extent. Fishing represents a major line of the economy, occupying the third place among the identified occupations. The three main occupations of the working population are agriculture 22.3%, trade 22.1% and fishing 14.8% (CRA, 2007; CRA, 2014). There are quarries in the middle and North area of El Guájaro, from which is extracted mainly construction material (sand, clay and limestone for cement, gravel and stone), and shrimp farms and irrigation districts (CRA-CARDIQUE, 2002). Economic activities, through the wastewater discharges carried out over the water reservoir in one way or another define the behavior of the parameters of water quality (Torres-Bejarano et al., 2015).

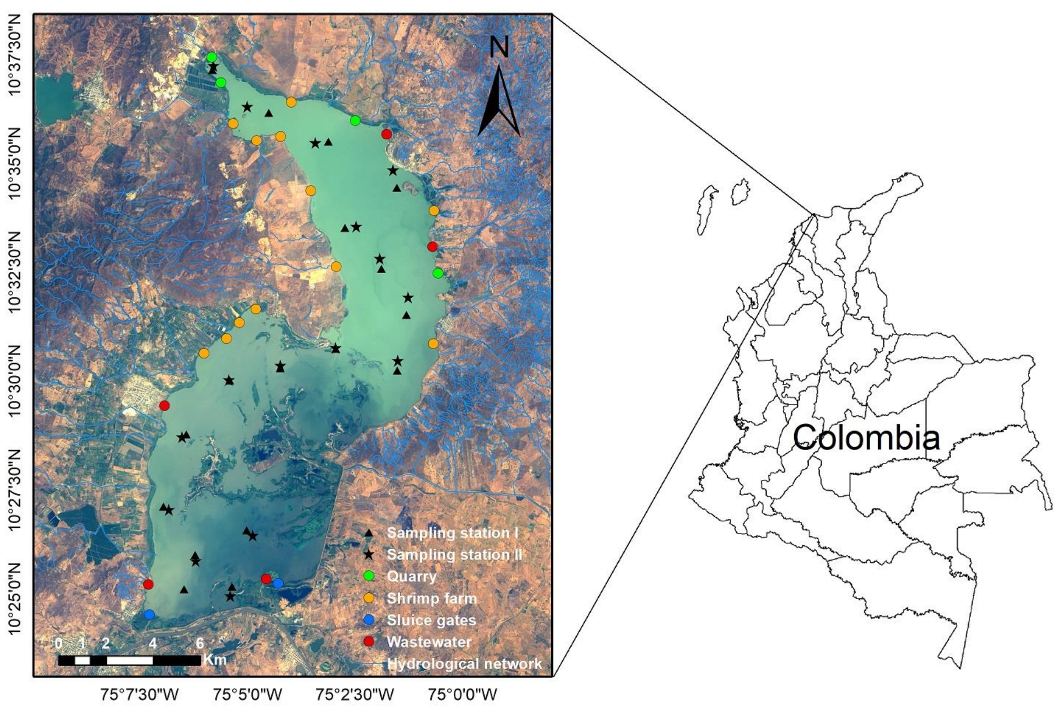

Figure 2. Location of El Guájaro reservoir and sampling sites, over a Landsat 8 image

2.2 Sampling and analysis of water quality parameters

Two subsequent campaigns were conducted before the start of the rainy season, during the days February 28 (sample I) and March 16, 2015 (sample II). The sampling sites were selected considering that they were distributed and extended over all the water surface of the reservoir, except where there was surface aquatic vegetation (Figure 2). Water temperature, electrical conductivity (EC), Dissolved Oxygen (DO) and pH were measured in the field through a (YSI brand, model 6600) multi-parametric computer; turbidity was evaluated with a portable turbidimeter (HACH, model 2100Q) and the depth of the water with a GPSMAP bathymetric echo sounder (Garmin, model 441s). The campaigns were planned so that the water characterization coincided with the day in which Landsat 8 would take the image in this area. In the estimation of the water quality parameters through satellite imagery, it is recommended that the in situ characterization or the collection of samples is made preferably the same day of the acquisition of the satellite image or with a difference of ± 1 day, in order to minimize errors and obtain a better calibration of the algorithms generated to estimate the water quality (Kloiber et al., 2002; Brezonik et al., 2005; Bonansea et al., 2015).

2.3 Landsat 8 images acquisition and processing

Two Landsat 8 images (path, 9; row, 53) were used, obtained the same day that in-situ measurements of water quality in El Guájaro reservoir were realized. The images were downloaded from the US Geological Survey (USGS) database through the Global Visualization Viewer (http://glovis.usgs.gov/). The cloudiness in both analyzed images, on February 28 and March 16, was 3%. The satellite images were level 1 GeoTIFF type. Landsat 8 is a satellite that aims at monitoring the Earth's surface, through the recording of multispectral images, to generate information that may lead to the environmental protection and sustainability of the planet; it is fitted with two sensors, the Operational Land Imager (OLI) multispectral sensor and the Thermal Infrared Sensor (TIRS). Unlike previous Landsat (TM and ETM) satellites, Landsat 8 has a high (12-bit) radiometric resolution, which gives it a significant improvement to detect changes in the Earth's surface (Roy et al., 2014). The images have eleven spectral bands with different spatial resolutions. Bands b1 (coast/aerosol), b2 (blue), b3 (green), b4 (red), b5 (near infrared, NIR), b6 and b7 (short wave infrared bands SWIR1, and SWIR2) as well as band b9 (cirrus) have a 30 m resolution, band b8 (panchromatic) has a 15 m resolution and bands b10 and b11 (TIR-1 and TIR-2) 100 m of resolution, but are resampled to 30 m.

Processing of Landsat 8 images consisted of making radiometric and atmospheric corrections. The radiometric correction transforms the relative values of pixels, or digital numbers, to absolute measurements of radiation per unit of wavelength of light or to reflectance. The atmospheric correction eliminates the atmospheric effects and thus transforms the radiometric values into radiation or reflectance of the surface. This allows field measurements or biophysical parameters to be estimated and compared in time and space (Chavez, 1988). In this paper, the atmospheric correction was applied to the bands in the visible spectrum (blue, green and red), the NIR band and the bands SWIR1 and SWIR2 using the dark object subtraction method (Chavez, 1988). This method assumes that in the image some darker objects have reflectance values close to zero; however, due to dispersion and atmospheric absorption, values of reflectance different from zero are recorded in the pixels where such objects are located. These values should be subtracted from the various spectral bands of the image. The software used to process the images was Exelis Visual Information Solutions (ENVI, version 5.2).

2.4 Delimitation of the water surface

The surface of El Guájaro reservoir water was delimited by applying the Normalized Differential Water Index (NDWI), which is an index used to mark off the water from the soil in satellite images (McFeeters, 1996; Khattab & Merkel, 2013). NDWI values range from -1 to 1, where values greater that zero indicate surfaces covered with water and values equal to or less than zero refer to surfaces not covered by water.

$$NDWI = (b3 - NIR)/(b3 + NIR) \quad (1)$$

In Equation (1) b3 is the green band of the visible spectrum and NIR is the near infrared band (b5)

Delimitation of the reservoir water surface through the NDWI was conducted in ENVI. A mask was generated in which pixels corresponding to the surface of the water were assigned a value of one and non-corresponding pixels (soil, vegetation, etc.) a value of zero. The generated mask was multiplied by previously processed Landsat 8 images (with radiometric and atmospheric correction).

2.5 Statistical analysis

Differences between the parameters evaluated in sampling I and sampling II were evaluated statistically by Student's t test ($p < 0.05$). To determine the statistical models, the results of water quality from sampling II were used as dependent variables and the reflectance data of different combinations of spectral bands of the processed Landsat 8 images as independent variables. The normality of the data was evaluated prior to the determination of the models through the Shapiro-Wilk test, using the Real Statistics Resource Pack software (Zaiontz, 2015). When a series of data did not show normal distribution, it was normalized using decimal logarithm. The models were generated and validated with the information generated in sampling II and sampling I, respectively. The models were generated through the stepwise linear regression technique and validation was performed through simple linear regression analysis, using Matlab version 2015.

2.6 Maps Generation

Once the models were generated for each water quality parameter and for depth, the Band Math tool of ENVI was used to apply the statistical models and transform the reflectance of each pixel of the reservoir into values of EC, Turbidity, pH, DO and depth. Maps of the spatial distribution of the water quality and depth parameters in El Guájaro reservoir were generated with ArcMap 10.2.

3 Results and discussion

3.1 Characterization in situ

The water quality parameters and depth of the water in the reservoir, evaluated in sampling I and sampling II are given in Table 1. With the exception of DO, analyzed parameters did not show significant differences ($p<0.05$) between the two samplings. The evaluated parameters were compared with the values recommended by the Colombian legislation in Decree 1594, regarding the characteristics of superficial, ground, marine and estuarine waters, including wastewater and determination for each use (Ministry of Agriculture, 1984). EC presented average values of 0.98 mS/cm in sampling I and 1.06 mS/cm in sampling II, being the North of the reservoir area, which presented the highest values of EC (1.82 mS/cm). In both surveys, in all sampling sites, turbidity presented higher values than those recommended in Decree 1594, for water for human and domestic consumption. PH of water also had values higher than those recommended for human and domestic consumption, but only at sites located in the northern part of the reservoir; for flora and fauna preservation, the pH was within the recommended values. During sampling I, DO presented values conducive to the preservation of flora and fauna, although during sampling II values were lower than those recommended in the Decree, in all the analyzed sites.

Table 1. Results of the evaluation of water quality parameters and depth in El Guájaro, during sampling I (February 28, 2015) and sampling II (March 16, 2015)

Parameters	**Sampling I (No. sites = 17)**			**Sampling II (No. sites = 16)**		
	Min	**Avg.**	**Max**	**Min**	**Avg.**	**Max**
EC (mS/cm)	0.45	0.98	1.61	0.54	1.06	1.82
Turbidity (NTU)	14.70	41.02	85.60	13.50	54.29	117.00
pH	8.00	8.41	8.81	8.18	8.51	8.80
DO (mg/L)	4.08	4.84	6.10	2.98	3.49	3.81
Depth (m)	1.00	1.85	2.80	0.60	1.76	2.70

3.2 Statistical models of water quality and depth

Statistical models that were significant ($p<0.05$) and that best fitted the EC, turbidity, pH, DO and depth parameters evaluated in situ in sampling II, as well as the coefficients of determination (R^2) and the Root Mean Squared Error (RMSE) are given in Table 2. Regression analysis showed good correlations ($R^2>0.6419$) between the reflectance of the Landsat 8 spectral bands and the water quality parameters and depth measured in the reservoir (Table 2). Parameters measured in-situ versus estimates are shown in Figure 3.

The water turbidity presented an R^2 of 0.6419, relating significantly with the sum of bands b4 and b5. Turbidity causes light to disperse and be absorbed rather than transmitted in a straight line in the water column. Water turbidity can be caused by the presence of suspended and dissolved matter. Previous studies indicate that turbid waters have high reflectance in bands b4 and b5 (Wu et al., 2009; Khattab & Merkel, 2013), which is consistent with findings in this study. EC was linked to the b2-b3 ratio between b4-b6, presenting an R^2 of 0.6994. The variation of EC in a water body is related to changes in the concentration of total dissolved solids in the water. The increase in the salinity of the water causes changes in the amount of radiation reflected in the visible and infrared spectrum bands (Khattab & Merkel, 2013; Theologou et al., 2015). Further, pH was related to bands b3, b4, b5, and b6 with R^2 of 0.8153. pH is the negative logarithm of the concentration of H^+ ions and has also been linked with the band b6 (Theologou et al., 2015). DO was related to bands b1, b3, b4, b5, and b7 with R^2 of 0.930. DO can be an indicator of the water pollution caused by the decomposition of organic compounds, as well as of primary productivity. The depth of the water was related to bands b1, b3, and b4 with an R^2 of 0.9217.

Table 2. Statistical models generated from the Landsat 8 image of March 16, 2015, to estimate EC, turbidity, pH, DO y depth in El Guájaro reservoir, as well as R^2 and RMSE values

Parameter	Equation	R^2	RMSE
EC	$\mathrm{EC} = -6.6166 * \left(\frac{\mathrm{b2} - \mathrm{b3}}{\mathrm{b4} - \mathrm{b6}}\right) - 0.12025$	0.699	0.223
Turbidity	$\mathrm{Log(Turbidity)} = 10.26 * (\mathrm{b4} + \mathrm{b5}) - 0.18359$	0.642	0.111
pH	$pH = 11.987 + 422850000 * (\mathrm{B3})^{10} - 1263600000 * (\mathrm{B4})^{10} - 0.62664 * \left(\frac{1}{B5}\right) + 0.052596 * \left(\frac{1}{B6}\right) + 0.016603 * \left(\frac{1}{B5}\right)^2$	0.815	0.088
Depth	$Depth = -0.54525 + 443420000 * (B1)^8 + 92125 * (B3)^5 - 186970 * (B4)^5 - 2088700000 * (B3)^{10}$	0.922	0.213
DO	$OD = 37.182 + 223510000 * (B1)^8 + 72725 * (B3)^5 - 122280 * (B4)^5 - 3.5878 * \left(\frac{1}{B5}\right) - 1325.5 * (B7) + 85.887 * \left(\frac{B7}{B5}\right) - 1794000000 * (B3)^{10} + 0.086922 * \left(\frac{1}{B5}\right)^2$	0.930	0.085

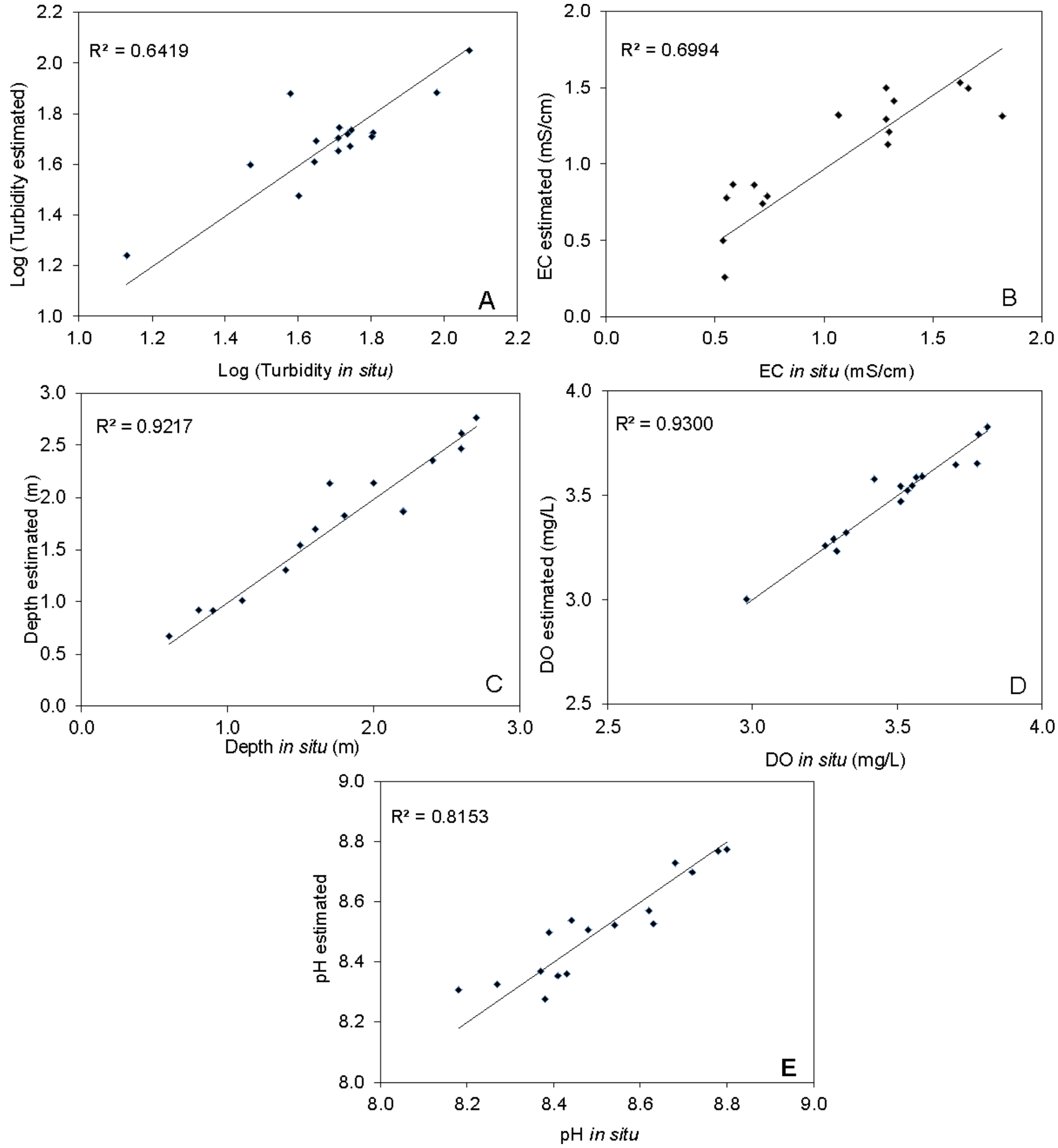

Figure 3. Measurements in situ versus parameters of water quality and depth estimated with models generated from Landsat 8 images of March 16, 2015

The capacity of the statistical models to predict the spatial and temporal variation of EC, turbidity, pH, DO and depth in the reservoir was validated through simple linear regression analysis, using spectral information of the image of February 28, 2015 and the results of the water quality and depth parameters obtained in sampling I. Only turbidity, EC and depth models could be validated (Figure 4).

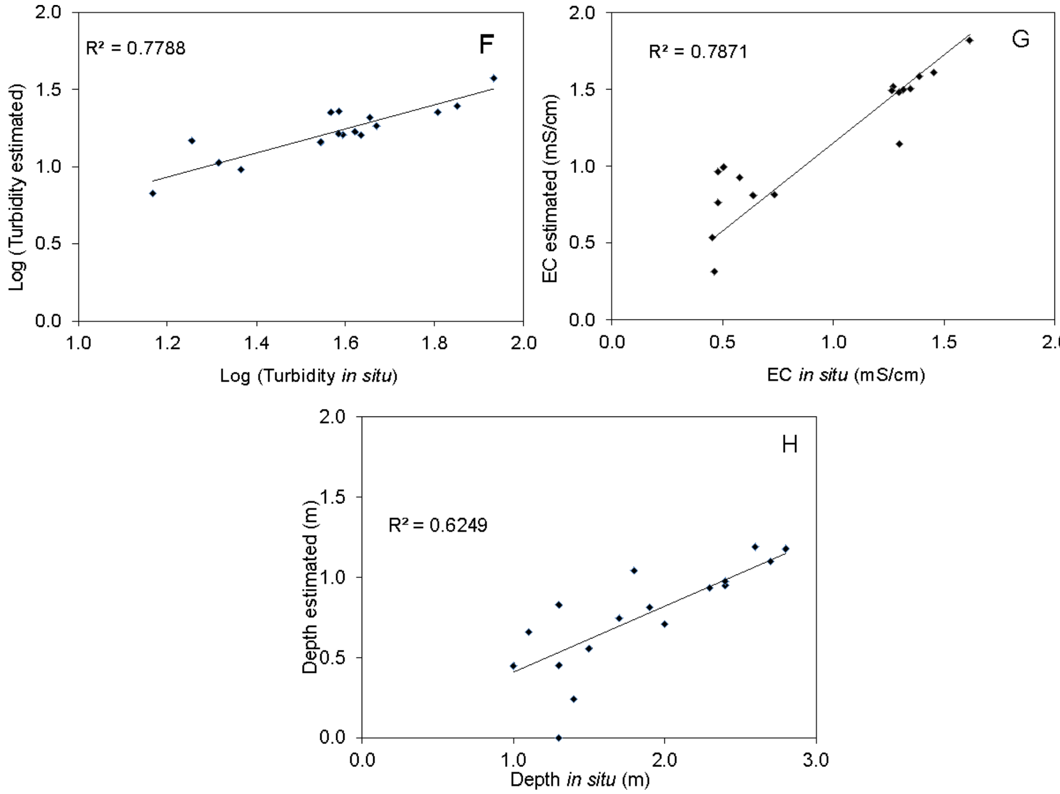

Figure 4. Results of the validation of models through simple linear regression, using spectral information from the image of February 28, 2015 and results from sampling I.

In the validation, EC presented an R^2 of 0.7871, turbidity an R^2 of 0.7788 and depth an R^2 of 0.6249. The EC model predicts the concentration relatively well in space and in time; however, in the validation of the turbidity and depth models it is noted that the values of both parameters are underestimated (Figure 4), so it is not convenient to use them to assess their temporal variation in the reservoir.

3.2 Maps of water quality parameters and depth

Through the application of statistical models to the image of March 16, 2015, turbidity, EC, pH, DO, and depth maps were generated in El Guájaro reservoir (Figure 5). EC presented values lower than 0.25 in the southern part and 2 mS/cm in the North zone. EC is distributed almost evenly in two large areas of the reservoir; a clear gradient is seen with a tendency to increased EC values in the South-North direction, due to the characteristics of the soil under the water body, as in areas where there are dams throughout most of the year, fine texture saline soils are formed as happened in the northern region of the reservoir, as opposed to the South zone which is where the sluicegates that feed the reservoir with water from the Magdalena River are located. The highest turbidity values were in the northern area of the reservoir, with values that reached 117 NTU. As can be seen in Figure 2, one of the main activities carried out in this area is related to the quarrying for the extraction of building material, so there is a significant contribution of sediments, either by surface runoff or by air transport, causing a high content of suspended sediments in this area of the reservoir and the consequent increase in the turbidity. Soils surrounding El Guájaro reservoir, from sandstone and well drained gravels are slightly acidic to neutral. However, in water bodies with intense photosynthesis pH values of almost 9 occur, as was observed in the results of the in-situ measurements and estimates using multispectral analysis, values that probably also are influenced by the oxidation-reduction conditions prevailing in the system due to the degradation of organic matter particles, and the presence of more carbonated waters northward due to the nature of the terrain (CRA 2014).

In general, the average values of DO were found above 4 mg/L in all sectors of the reservoir for sampling I; on the contrary, values observed during the sampling II are slightly under 4 mg/L, the minimum concentration recommended for the preservation of aquatic life (Ministry of Agriculture, 1984).

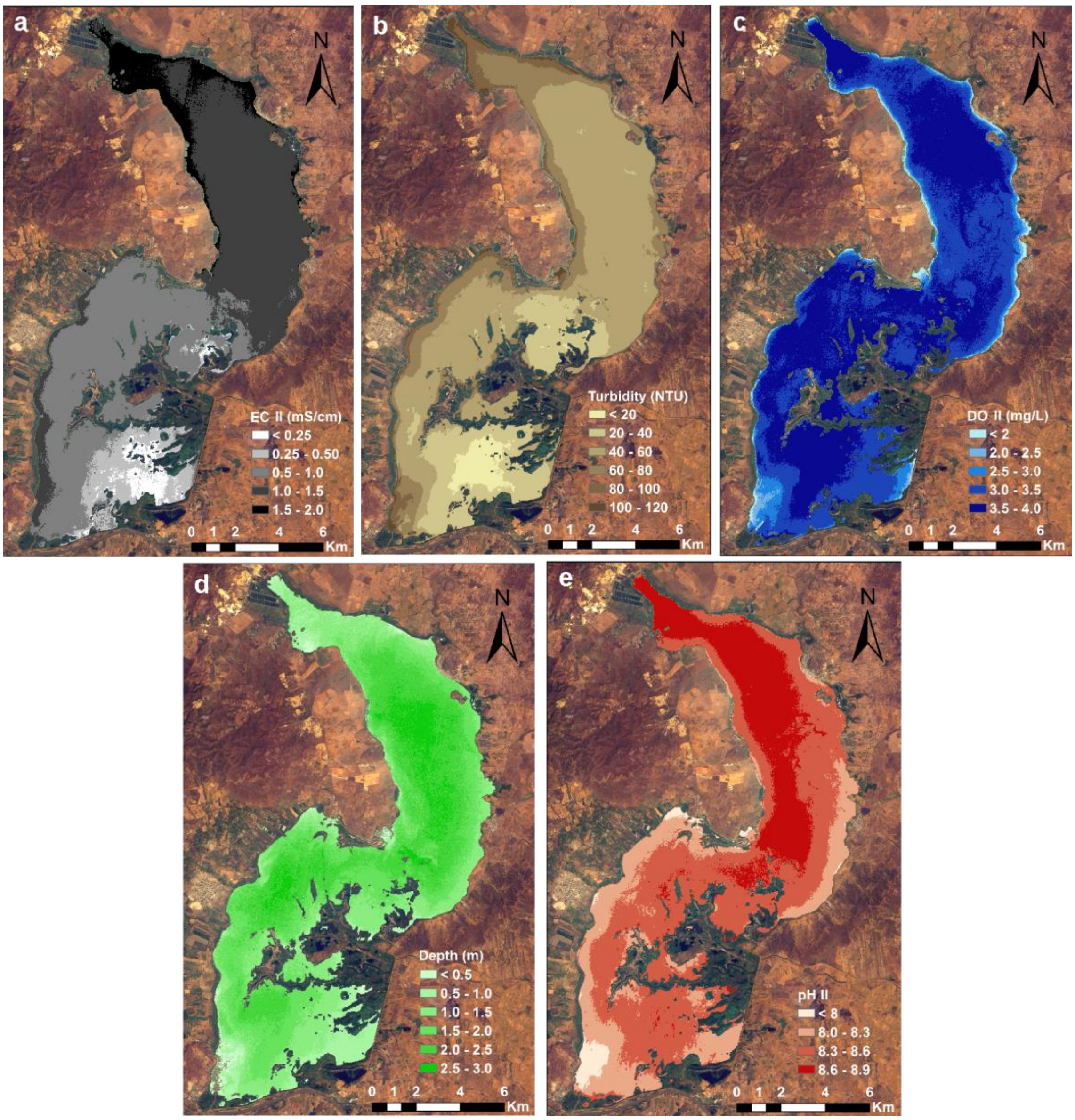

Figure 5. Results of validation of models, through simple linear regression analysis, using spectral information of the image of February 28, 2015 and results of sampling I.

4 Conclusions

Models generated from Landsat 8 images can be a very useful tool for monitoring water quality parameters and depth of water in El Guájaro reservoir. The validation of EC model generated in this research indicates that it can be used to evaluate the temporal and spatial variation of such parameter, in periods with weather conditions similar to those used for the generation of model. Non-validation of the generated models in estimating the temporal variation of turbidity, pH, DO and depth, do not limit their usefulness to evaluate the spatial variation from a small number of parameters evaluated on-site.

Distribution patterns of water quality parameters and depth of water in the reservoir, and the possible relationship of parameters such as EC and turbidity with anthropogenic activities carried out in the area of influence of El Guájaro could be identified through the generated models. Therefore, the models generated from Landsat 8 images to estimate the spatial and temporal variation of water quality in El Guájaro reservoir are a tool that can facilitate the environmental, economic and social management of the reservoir.

References

Abd-Elrahman A., Croxton M., Pande-Chettri R., Toor G. S., Smith S., and Hill J., “In situ estimation of water quality parameters in freshwater aquaculture ponds using hyperspectral imaging system,” ISPRS J. Photogramm. Remote Sens., vol. 66, no. 4, pp. 463–472, Jul. 2011. http://dx.doi.org/10.1016/j.isprsjprs.2011.02.005

Alexandridis T. K., Topaloglou C. A., Lazaridou E. and Zalidis G. C., “The performance of satellite images in mapping aquacultures,” Ocean Coast. Manag., vol. 51, no. 8–9, pp. 638–644, Jan. 2008. doi:10.1016/j.ocecoaman.2008.06.002.

Bonansea M., Rodriguez M. C., Pinotti, L. and Ferrero S., “Using multi-temporal Landsat imagery and linear mixed models for assessing water quality parameters in Río Tercero reservoir (Argentina),” Remote Sens. Environ., vol. 158, pp. 28–41, Mar. 2015. http://dx.doi.org/10.1016/j.rse.2014.10.032.

Brezonik P., Menken K. D. and Bauer M., “Landsat-based Remote Sensing of Lake Water Quality Characteristics, Including Chlorophyll and Colored Dissolved Organic Matter (CDOM),” Lake Reserv. Manag., vol. 21, no. 4, pp. 373–382, Dec. 2005.

Castellanos C., “Humedales, riqueza a conservar,” Revista Ambiental el Reto, 2015. [Online]. Available: http://elretoambiental.webnode.es/news/informe-especial-humedales-riqueza-a-conservar/. [Accessed: 14-Sep-2015].

Chavez P. S., “An improved dark-object subtraction technique for atmospheric scattering correction of multispectral data,” Remote Sens. Environ., vol. 24, no. 3, pp. 459–479, Apr. 1988. http://dx.doi.org/10.1016/0034-4257(88)90019-3.

CRA, “Diagnóstico inicial para el ordenamiento del embalse del Guájaro y la Ciénaga de Luruaco,” Barranquilla, 2014.

CRA, “Documentación del estado de las cuencas hidrográficas en el Departamento del Atlántico,” 2007.

CRA-CARDIQUE, “No TitlePlan de manejo ambiental del complejo de ciénagas El Totumo, Guájaro y El Jobo en la Ecoregión Estratégica del Canal Del Dique,” 2002.

CRA-UNIMAGDALENA, “Actualización del manual de operaciones del hidrosistema al cual pertenece el embalse el Guájaro y llevar a cabo el diseño de las estructuras y sistemas para disminuir la vulnerabilidad de la zona ante eventos climatológicos extremos,” 2012.

Doña C., Chang N.B., Caselles V., Sánchez J. M., Camacho A., Delegido J. and Vannah B. W., “Integrated satellite data fusion and mining for monitoring lake water quality status of the Albufera de Valencia in Spain,” J. Environ. Manage., vol. 151, pp. 416–426, Mar. 2015. http://dx.doi.org/10.1016/j.jenvman.2014.12.003

El Saadi A. M., Yousry M. M., and Jahin H. S., “Statistical estimation of Rosetta branch water quality using multi-spectral data,” Water Sci., vol. 28, no. 1, pp. 18–30, 2014. http://dx.doi.org/10.1016/j.wsj.2014.10.001

Hadjimitsis D. G., Hadjimitsis M. G., Toulios L. and Clayton C., "Use of space technology for assisting water quality assessment and monitoring of inland water bodies," Phys. Chem. Earth, Parts A/B/C, vol. 35, no. 1–2, pp. 115–120, Jan. 2010. http://dx.doi.org/10.1016/j.pce.2010.03.033

Harvey E. T., Kratzer S. and Philipson P., "Satellite-based water quality monitoring for improved spatial and temporal retrieval of chlorophyll-*a* in coastal waters," Remote Sens. Environ., vol. 158, pp. 417–430, Mar. 2015. http://dx.doi.org/10.1016/j.rse.2014.11.017

He W., Chen S., Liu X. and Chen J., "Water quality monitoring in a slightly-polluted inland water body through remote sensing—case study of the Guanting Reservoir in Beijing, China," Environ. Sci. Eng., 2008. DOI: 10.1007/s11783-008-0027-7.

Hellweger F. L., Schlosser P., Lall U. and Weissel J. K., "Use of satellite imagery for water quality studies in New York Harbor," Estuar. Coast. Shelf Sci., vol. 61, no. 3, pp. 437–448, Nov. 2004. http://doi:10.1016/j.ecss.2004.06.019

IDEAM, "Estudio Nacional del Agua 2014," Bogotá, D. C., 2015.

Khattab M. F. O. and Merkel B. J., "Application of Landsat 5 and Landsat 7 images data for water quality mapping in Mosul Dam Lake, Northern Iraq," Arab. J. Geosci., vol. 7, no. 9, pp. 3557–3573, Jul. 2013. DOI: 10.1007/s12517-013-1026-y.

Kloiber S. M., Brezonik P. L., Olmanson L. G. and Bauer M. E., "A procedure for regional lake water clarity assessment using Landsat multispectral data," Remote Sens. Environ., vol. 82, no. 1, pp. 38–47, Sep. 2002. PII: S0034-4257(02)00022-6.

McFeeters S. K., "The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features," Int. J. Remote Sens., vol. 17, no. 7, pp. 1425–1432, May 1996. DOI: 10.1080/01431169608948714.

Minambiente, "Política Nacional para la Gestión Integral del Recurso Hídrico," Bogotá, 2010.

Ministry of Agriculture (Ministerio de Agricultura), DECRETO 1594 DE 1984 Usos del agua y Residuos Líquidos. Colombia: Diario Oficial 36700, 1984.

Pavelsky T. M. and Smith L. C., "Remote sensing of suspended sediment concentration, flow velocity, and lake recharge in the Peace-Athabasca Delta, Canada," Water Resources Research, 45(11), W11417. Nov. 2009. http://dx.doi.org/10.1029/2008wr007424.

Rajitha K., Mukherjee C. K., and Vinu Chandran R., "Applications of remote sensing and GIS for sustainable management of shrimp culture in India," Aquac. Eng., vol. 36, no. 1, pp. 1–17, Jan. 2007. http://dx.doi.org/10.1016/j.aquaeng.2006.05.003.

Ritchie J. C., Zimba P. V. and Everitt J. H., "Remote Sensing Techniques to Assess Water Quality," Photogramm. Eng. Remote Sens., vol. 69, no. 6, pp. 695–704, Jun. 2003. DOI: 10.14358/PERS.69.6.695.

Roy D. P., Wulder M. A., Loveland T. R., Woodcock C.E., Allen R. G., Anderson M. C., Helder D., Irons J. R., Johnson D. M., Kennedy R., Scambos T. A., Schaaf C. B., Schott J. R., Sheng Y., Vermote E. F., Belward A. S., Bindschadler R., Cohen W. B., Gao F., Hipple J. D., Hostert P., Huntington J., Justice C. O., Kilic A., Kovalskyy V., Lee Z. P., Lymburner L., Masek J. G., McCorkel J., Shuai Y., Trezza R., Vogelmann J., Wynne R. H., and Zhu Z., "Landsat-8: Science and product vision for terrestrial global change research," Remote Sens. Environ., vol. 145, pp. 154–172, Apr. 2014. http://dx.doi.org/10.1016/j.rse.2014.02.001

Theologou I., Patelaki M. and Karantzalos K., "Can single empirical algorithms accurately predict inland shallow water quality status from high resolution, multi-sensor, multi-temporal satellite data?," ISPRS - Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci., vol. XL–7–W3, no. 1, pp. 1511–1516, Apr. 2015. doi:10.5194/isprsarchives-XL-7-W3-1511-2015.

Torres-Bejarano F., Padilla Coba J., Rodríguez Cuevas C., Ramírez León H. and Cantero Rodelo R., "La modelación hidrodinámica para la gestión hídrica del embalse del Guájaro, Colombia," Rev. Int. Métodos Numér. Cálc. Diseño Ing.2016;32(3):163–172, Jun. 2015. http://dx.doi.org/10.1016/j.rimni.2015.04.001

Wang X. and Ma T., "Application of remote sensing techniques in monitoring and assessing the water quality of Taihu Lake", Bull. Environ. Contam. Toxicol., vol. 67, no. 6, pp. 863 – 870, 2001. DOI: 10.1007/s00128-001-0202-z.

Wu G., de Leeuw J., Skidmore A. K., Liu Y. and Prins H. H. T., “Performance of Landsat TM in ship detection in turbid waters,” Int. J. Appl. Earth Obs. Geoinf., vol. 11, no. 1, pp. 54–61, Feb. 2009. http://dx.doi.org/10.1016/j.jag.2008.07.001

Zaiontz C., “Real Statistics Resource Pack software.” 2015.