Hydrodynamic Modeling for the Sustainable Management of the Guájaro Hydrosystem, Colombia

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Abstract The Guájaro reservoir is the most important water body located at the north of Colombia. It is supplied by an artificial channel (*Canal del Dique*) through a two floodgates system. As a result of excess nutrients and other pollution loads from the drainage basin in recent decades, the Guájaro reservoir suffers eutrophication and other pollution problems; however it still continues being exploited. For this reason, it is necessary to regulate the hydraulic structures that supply this water body, as they play an important role in managing levels, and these in turn for water supply and environmental purposes. The present work is carried out as a sustainability management alternative of the reservoir. The implementation of a two-dimensional hydrodynamic model and its calibration is achieved using time series of the free surface levels, and comparing the measured velocities and those estimated by the model for two different climatic periods, to assist the operation of the *Canal del Dique-Guájaro* hydrosystem. The corresponding comparisons showed a good behavior between measured and simulated data. Based on the

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quantitative results of the Nash-Sutcliffe reliability method, the results are considered quite satisfactory for estimating and predicting the amount of water flowing in and out of the reservoir through the channel reservoir hydrosystem.

1   Introduction

Currently, a widespread concern in relation to global environmental degradation is going on. Phenomena such as global warming, caused mainly by industrial development and unsustainable population growth, make it necessary to have tools that help us understand these phenomena and evaluate scenarios in case of emergency events, in order to make effective accurate and realistic decisions (Torres-Bejarano et al. 2013).

When solving problems related to water resources, both a spatial representation of the system and the understanding of such problems are needed. In this regard, the hydrodynamic models can represent the characteristics and behavior of system relations, supported on the associated predictive analytics capabilities, which are most useful in the planning and management of complex problems in aquatic resources. The Integrated Water Resources Management (IWRM) nowadays is a prerequisite for environmental preservation and economic development. However, the implementation of proposed actions is significantly hampered due to insufficient necessary data, and the lack of interactions between hydrological and ecological components (Dimitriou and Zacharias 2006). According to McIntosh et al. (2007), a variety of software and modeling technologies are emerging in the form of "support tools" to better handle the problems of use of scientific knowledge in environmental research and planning activities. These technologies are motivated by legitimate concerns about the inefficiency of conventional research methods and of ensuring that science can be effective and easily transferred to management applications, particularly with regard to water resources.

Therefore, the objective of this work is to implement a hydrodynamic numerical model to contribute to the sustainable management of water resources in the Guájaro reservoir, Colombia, considering primarily the management of water levels.

For that reason, the model Environmental Fluid Dynamics Code (EFDC) was chosen for its friendliness to the pre-processing of data and its processing capacity, high performance computing and numerical robustness, plus, it has been applied and successfully implemented in several case studies worldwide. In the last two decades, it has become one of the most used and technically defensible hydrodynamic models in the world. It has been applied in more than 100 water bodies and for environmental water resource management (Kim et al. 1998; Moustafa and Hamrik 2000; Ji et al. 2001; Park et al. 2005; Luo and Li 2009).

2 Materials and Methods

The methodology used in this work includes the implementation of the numerical model EFDC Explorer 7.1 (commercial distribution) version for simulations of hydrodynamic variables in the Guájaro reservoir; the model calibration using a statistical method to evaluate the model's predictive capacity (Molnar 2011); and an indicator of goodness-of-fit as the Nash-Sutcliffe efficiency coefficient (Nash and Sutcliffe 1970).

Within the procedures carried out are: measurements of reservoir hydrodynamics using an Acoustic Doppler Current Profiler (ADCP), with a frequency range of 600 kHz which continuously recorded the magnitude and direction of water velocities. Depths were determined with a bathymetric Sounder Garmin GPSMAP 441S. For hydrometeorology, data from monitoring stations from the Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IDEAM for its acronym in Spanish) were used. From Repelon (code 29035200) and El Limon (code 29035120) stations, located at Latitude: 10.5, Longitude: −75.116667, and Latitude: 10.416667, Longitude: −75.066667, respectively, wind velocity, wind direction, humidity, temperature and precipitation parameters were obtained.

2.1 Model Description

The EFDC Model was originally developed at the Virginia Institute of Marine Science and later sponsored by the US Environmental Protection Agency (USEPA). The EFDC model is a fully dynamic 2D and 3D tool, adaptable to the necessary characteristics of water bodies studies (Hamrick 1992). It is a hydrodynamic and water quality model that can be applied to any surface water body, including lakes and rivers. The characteristics of physical, chemical and ecological processes can be simulated by numerical functions. The EFDC was developed with a structure characterized by a model built with cells of finite elements; the possibility of wetting and drying in the contour processing; allowing exchange of heat with the atmosphere; and simulation of water quality (Wang et al. 2013). It is a package of multi-dimensional hydrodynamic modeling, capable of simulating a diverse range of environmental and transport problems. The model solves 3-D vertically hydrostatic, free surface, turbulent averaged equations of momentum for a variable density fluid.

The EFDC is a comprehensive and flexible tool designed for the EFDC modelling system, which was optimized by Dynamic Solutions-International (DSI), who developed a user interface that makes friendly the model implementation, from the data pre-processing to the results post-processing.

The model solves the momentum equations, (1) and (2), the continuity Eq. (3), the state Eq. (4), the transport equations for salinity and temperature (5) and (6),

and the turbulence intensity and the longitudinal turbulence scale, Eqs. (7) and (8). The model uses the sigma coordinate on the vertical and Cartesian or curvilinear orthogonal coordinates in the horizontal axes:

$$\partial_t(Hmu) + \partial_x(m_yHuu) + \partial_y(m_xHvu) + \partial_z(mwu) - (mf + v\partial_xm_y - u\partial_xm_x)Hv$$
$$= -m_yH\partial_x(g\varsigma + \rho) - m_y(\partial_xh - z\partial_xH)\partial_yp + \partial_z(mH^{-1}A_v\partial_vu) + Q_u \tag{1}$$

$$\partial_t(mHv) + \partial_x(m_yHuv) + \partial_y(m_xHvv) + \partial_z(mwv) + (mf + v\partial_xm_y - u\partial_xm_x)Hu$$
$$= -m_xH\partial_y(g\varsigma + \rho) - m_x(\partial_yh - z\partial_yH)\partial_zp + \partial_z(mH^{-1}A_v\partial_zv) + Q_v \tag{2}$$

$$\partial_t(m\varsigma) + \partial_x(m_yHu) + \partial_y(m_xHv) + \partial_z(mw) = 0 \tag{3}$$

$$\rho(P,T,S) = \frac{\rho_0}{\left(1 - \frac{P}{k_P}\right)} \tag{4}$$

$$\partial_t(mHS) + \partial_x(m_yHuS) + \partial_y(m_xHvS) + \partial_z(mwS) = \partial_z(mH^{-1}A_b\partial_zS) + Q_s \tag{5}$$

$$\partial_t(mHT) + \partial_x(m_yHuT) + \partial_y(m_xHvT) + \partial_z(mwT) = \partial_z(mH^{-1}A_b\partial_zT) + Q_T \tag{6}$$

$$\partial_t(mHq^2) + \partial_x(m_yHuq^2) + \partial_y(m_xHvq^2) + \partial_z(mwq^2) = \partial_z(mH^{-1}A_v\partial_zq^2) + Q_p$$
$$+ 2mH^{-1}A_v(\partial_zu)^2 + (\partial_zv)^2 + mgE_1E_2lA_b\partial_zb - 2mH(B_1l)^{-1}q^3 \tag{7}$$

$$\partial_t(mHq^2l) + \partial_x(m_yHuq^2l) + \partial_y(m_xHvq^2l) + \partial_z(mwq^2l) = \partial_z(mH^{-1}A_v\partial_zq^2l)$$
$$+ Q_l + mH^{-1}E_1A_v\left[(\partial_zu)^2 + (\partial_zv)^2\right] + mgE_1E_3lA_b\partial_zb - mHB_l^{-1}q^3\left[1 + E_2(kL)^2l^3\right] \tag{8}$$

where the u and v terms are the velocity components at the horizontal curvilinear-orthogonal coordinates (x and y); m_x and m_y are the square roots of the diagonal components; $H = h + \zeta$ is the sum of the depth below the free surface displacement relative to the undisturbed physical vertical coordinate origin, $z^* = 0$; p is the physical pressure in excess of the reference density; f is the Coriolis parameter; A_v and A_b, are the terms of the vertical turbulent diffusion and vertical diffusion or eddy viscosity; Q_u and Q_v, representing the additional forces or sources and sinks including: turbulent diffusion and horizontal pulse, vegetation resistance and Reynolds stress wave; ρ represents the density; T and S, temperature and salinity, respectively; Q_S and Q_T, include the dissemination of horizontal scale of sub-mesh, and thermal sources and sinks, respectively; q is the diffusion of turbulent intensity; l is the turbulent length scale; and E_1, E_2, E_3, B_1 are empirical constants.
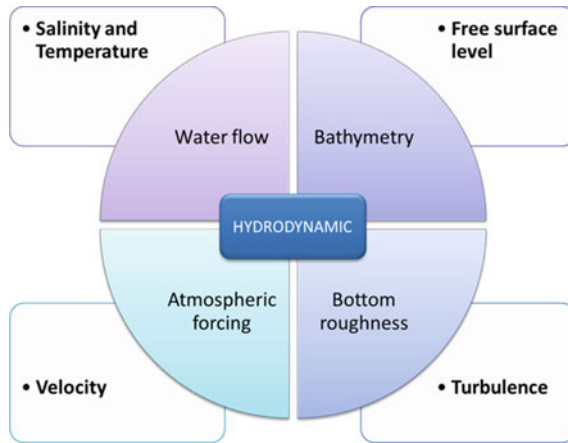
Fig. 1 Structure of the EFDC hydrodynamic model

Figure 1 shows the structure that uses the EFDC model for hydrodynamic surface water.

2.2 Model Calibration

The purpose of the model calibration is to reproduce the mass water movement for known conditions by varying the physical parameters within rationally suitable values (Palacio et al. 2010). To calibrate the model, a total time of 15 days were simulated for two scenarios. The elevations and the corresponding area to the maximum level for that period were used; also outflows and inflows for dry and rainy season, respectively, were determined. To verify the goodness of fit, the root mean square error (RMSE) and the Nash-Sutcliffe efficiency coefficient (Ceff) were used. The error in the model predictions is quantified in terms of units of the calculated variable by RMSE which is expressed in Eq. (9), followed by the efficiency coefficient using Eq. (10).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (O_i - p_i)^2}{N}} \tag{9}$$

$$Ceff = \frac{\sum_{i=1}^{n} (O_i - p_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O}_i)^2} \tag{10}$$

where O_i and p_i are the reservoir levels; N is the number of samples in the time series; and $\bar{O}_i$ is the value of the time average reservoir levels.

Validation involves assessing the predictive ability of the model. This means checking the model results with observed data and adjusting the parameters until

the results are within acceptable limits of accuracy. The parameter adjusted in this work was the flow rate flowing in/out through the floodgates system.

2.3   Data Requirement

To configure and implement the model, a dataset was required to specify the boundary conditions or model inputs, thus allowing the corresponding simulations to validate the model for the study area. All data obtained by sampling or measuring equipment were processed and digitized in shape files and displayed in thematic maps, according to the projection WGS (Word Geodetic System) 1984 18N. The ADCP measures were processed and filtered; then the required values and their averages in the water column were extracted. It should be stressed that it was necessary to obtain digitized contours of the reservoir for the sampling dates; satellite images of those dates were obtained from the US Geological Survey, http://glovis.usgs.gov/.

Bathymetry. Depth information was obtained from measurement campaigns carried out on July 18th, 19th and 20th of 2013 for the dry season and October 27th, 28th and 29th for the rainy season of the same year. Figure 2 shows graphically the
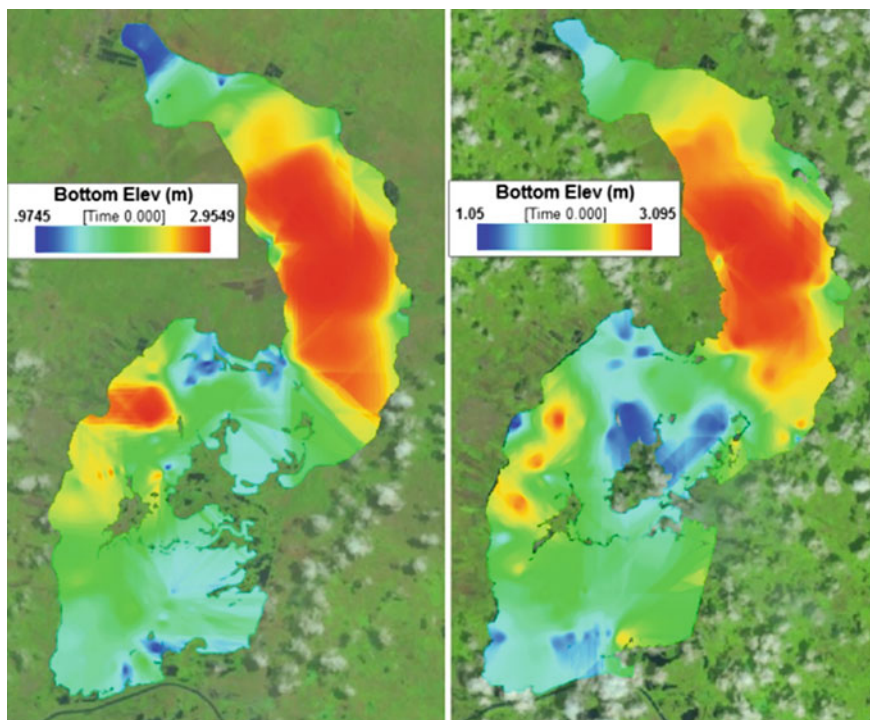
Fig. 2 Bathymetry of Guájaro reservoir; dry season (*left*), rainy season (*right*)
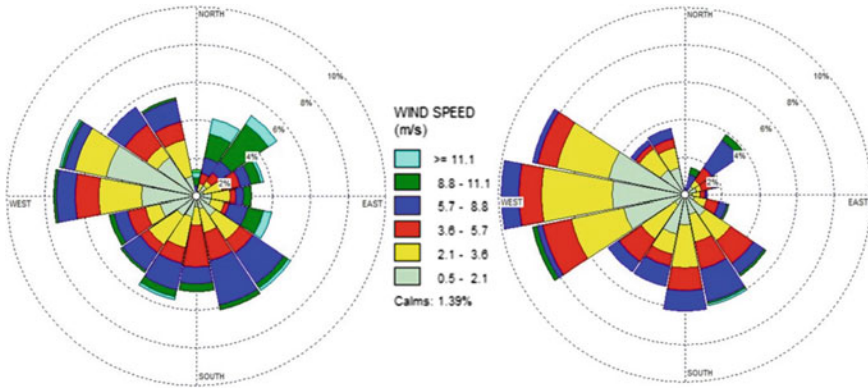
Fig. 3 Wind rose: dry season (*left*); rainy season (*right*)

range of depths of the reservoir in the two selected periods, where the bathymetry covered an area of approximately 12,500 Ha.

Water levels. The corresponding reservoir levels were extracted from the daily measurements records implemented by the environmental authority at the region, The Autonomous Corporation of Atlantic Department (CRA for its acronym in Spanish). These data were compared with the time series calculated by the numerical model, as shown below in Figs. 6 and 8.

Winds. The free surface wind effects were also considered; their magnitudes and directions were obtained from an IDEAM meteorological station, located in the study area (Fig. 3).

3 Model Adaptation

3.1 Study Zone Description

The Guájaro reservoir is considered a strategic ecoregion, located at north Colombia (Fig. 4) at 10°42′ N and 75°6′ W, a few km from the Caribbean Sea. This water body covers an area of 16,000 Ha, a volume of 400 Mm^3; it drains 12,000 Ha by an irrigation district, and has two sets of floodgates that communicate with the *Canal del Dique* channel; these allow the control of the reservoir levels (Uninorte 2009). Today the floodgates have an operation protocol that establishes the actions required according to the hydrological season presented.
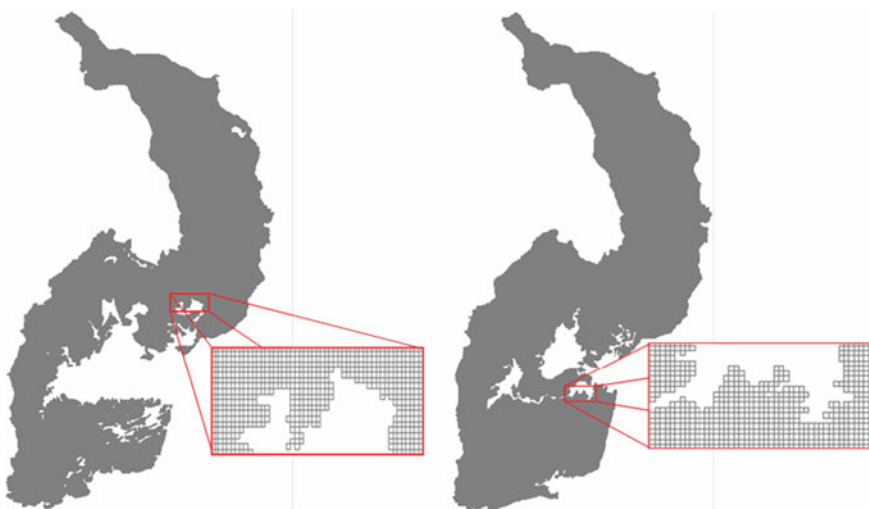
Fig. 4 Study zone location

Fig. 5 Computational grid for dry season (*left*) and rainy season (*right*)

3.2 Computational Grid Configuration

A mesh with $\Delta X = \Delta Y = 30$ m was used, for the dry season 320 elements in the horizontal direction and 600 in the vertical direction, for a total of 201,736 elements, of which 84,589 are active cells; and for the rainy season 334 elements in the horizontal and 600 direction in the vertical direction, for a total of 201,736 elements with 84,594 active cells (Fig. 5). The time step used in each simulation was 2 s, generating results every 2 h.
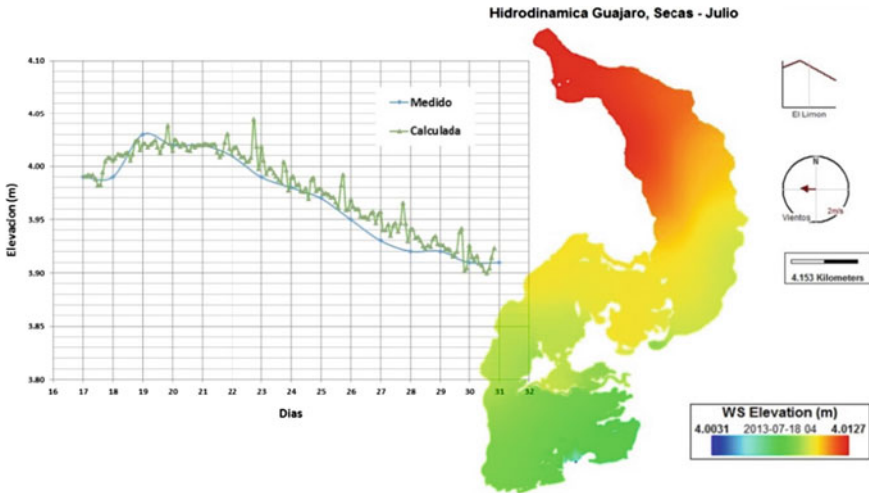
Fig. 6 Behavior of measured and simulated reservoir levels for dry season

4 Results and Discussion

4.1 Dry Season Simulation

The climatological measurements reported for this period show that the Guájaro reservoir reached a maximum level of 4.03 m, and according to the water balance, a minimum level of 3.91 m. Figure 6 shows the variation of the reservoir levels. Likewise, the behavior of reservoir levels obtained with the applied numerical model is illustrated.

Regarding the water body hydrodynamics, the depth averaged velocities were compared with those obtained by the numerical model. This comparison of measured and calculated velocity vectors is shown in Fig. 7.

4.2 Rainy Season Simulation

The measured free surface levels corresponding to the simulated period show that the Guájaro reservoir was 4.08 m above the sea level, and according to the floodgates operations the reservoir reached a maximum level of 4.16 m above the sea level. Likewise, the numerically calculated level behavior is illustrated in Fig. 8.

Figure 9 shows the measured and calculated velocity vectors for the rainy season. For this period, a good correspondence between those measured and calculated is also found.
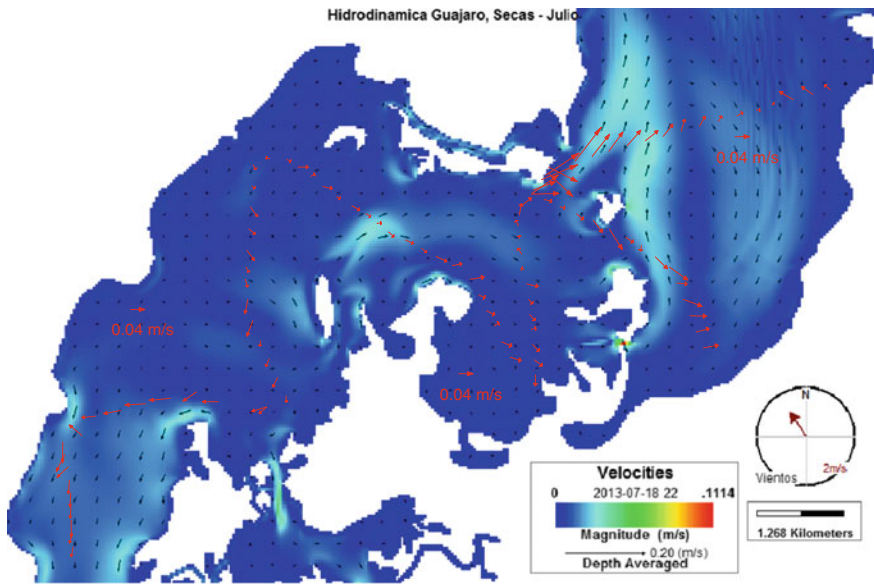
Fig. 7 Measured (*red*) and simulated (*black*) velocity vectors for dry season
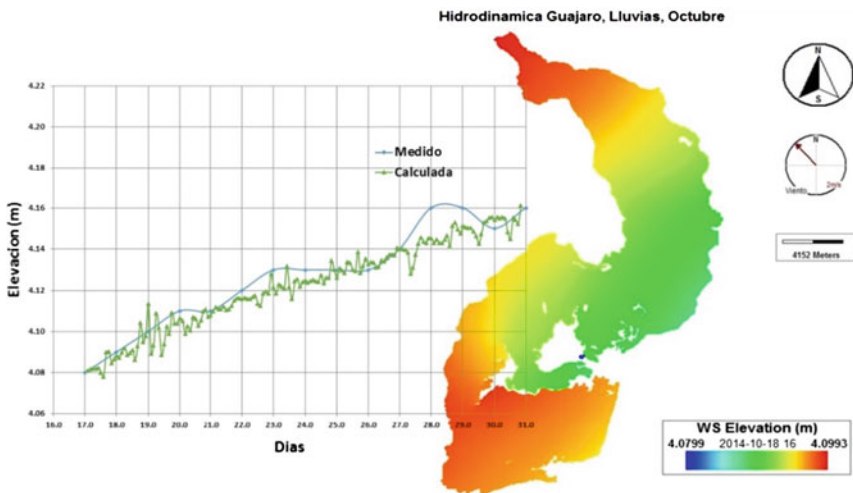

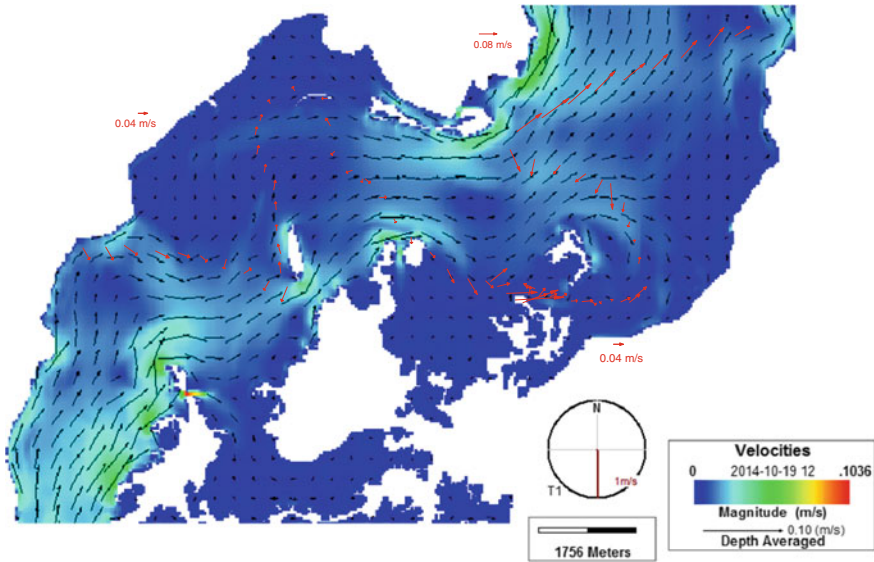**Fig. 8** Behavior of measured and simulated reservoir levels for rainy season

Fig. 9 Measured (*red*) and simulated (*black*) velocity vectors for rainy season

4.3 Calibration Results

In this work, to calibrate the EFDC model, theoretical flows were initially estimated using the difference in water levels and the reservoir surface for each corresponding level. With these values, sequential tests have been conducted by modifying this hydraulic parameter.

As early mentioned, the model results were evaluated using the RMSE y *Ceff* statistical method, to prove if predicted (simulated) water levels results were consistent with the observed values; for dry season (Fig. 6) RMSE = 0.016 and *Ceff* = 0.87263, for rain season (Fig. 8) RMSE = 0.018 and *Ceff* = 0.92709. This show an excellent adjustment and correlation between simulated and field observed, which means, the model results are consistent with the measurements.

The modeling results show, in general, a good agreement with the measurements. The model reproduces quite well the main features of the water movement forced by wind in the Guajaro reservoir. In addition, the results indicate that input and output tributaries (watershed streams, agricultural areas, etc.) play a less important role in the hydrodynamic behavior of the reservoir, while the wind strongly affects velocity fields and circulation patterns.

5   Conclusions

This work shows the EFDC model calibration and validation process for the Guájaro reservoir. This process was carried out comparing the measurements for the two seasons with the calculated or simulated values. The goodness of fit estimators *Ceff* and *RMSE* allow to better estimate the model's capacity to simulate scenarios.

The model has been applied to study the flow exchange through the hydraulic structures (floodgates) that control the water levels of this reservoir; their operation allows the exchange of water within the Canal del Dique-Guájaro hydrosystem. Minimum water levels occur in the dry season, requiring actions to counter the water volume deficit; whereas water levels rise in the rainy season, likewise requiring actions to control the excess volume and levels. Accordingly, the selected model was calibrated and validated for both seasons, proving its ability to simulate and represent the hydrodynamic behavior for these climatic periods.

Given the results obtained in the hydrodynamic calibration and validation processes, this model can be implemented to estimate the possible levels in a water body, considering the climatic factor of occurrence. Finally, the hydrodynamic numerical modeling proves to be an important and useful contribution in the integrated water management and decision making.

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