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Articles

Application of hydrological and hydraulic models to quantify surface runoff in the endorheic system of the La Picasa Lagoon basin

Aplicación de modelos hidrológicos e hidráulicos para cuantificación de escurrimientos superficiales del sistema endorreico cuenca Laguna La Picasa

Gabriela Alejandra Ponce[1], ORCID: https://orcid.org/0000-0001-6980-4945

Sebastián Grande[2]

Matías Eder[3], ORCID: https://orcid.org/0000-0003-0624-5781

Alejo Juan Sebastián Testa-Tacchino[4]

Claudio Alejandro Carignano[5], ORCID: https://orcid.org/0000-0002-4212-0014

Andrés Rodriguez[6], ORCID: https://orcid.org/0000-0002-4110-6464

[1]Hydraulics Laboratory, School of Physical and Natural Sciences, Universidad Nacional de Córdoba, Córdoba, Argentina, alejandraponce47@hotmail.com

[2]Hydraulics Laboratory, School of Physical and Natural Sciences, Universidad Nacional de Córdoba, Córdoba, Argentina, sebasgrande@gmail.com

[3]Hydraulics Laboratory, School of Physical and Natural Sciences, Universidad Nacional de Córdoba, Córdoba, Argentina, matiaseder2@gmail.com

[4]Hydraulics Laboratory, School of Physical and Natural Sciences, Universidad Nacional de Córdoba, Córdoba, Argentina, alejo_testa@unc.edu.ar

[5]Hydraulics Laboratory, School of Physical and Natural Sciences, Universidad Nacional de Córdoba, Córdoba, Argentina, ccarignano@hotmail.com

[6]Hydraulics Laboratory, School of Physical and Natural Sciences, Universidad Nacional de Córdoba, Córdoba, Argentina, andres.rodriguez@unc.edu.ar

Corresponding author: Gabriela Alejandra Ponce, alejandraponce47@hotmail.com

Abstract

The basins in the plain present particularities from the approach of the hydrological processes that take place there. They present a predominance of vertical water movements (evapotranspiration-infiltration) over horizontal movements (runoff), showing a strong interrelation between surface and underground water.

The La Picasa Lagoon basin is a naturally depressed humid pampa region with an undulating plain relief with low temporary flooding sectors and permanent lagoons without a defined drainage network. It is an inter-jurisdictional endorheic basin between the provinces of Córdoba, Santa Fe, and Buenos Aires (Argentina) that has suffered recurrent floods between 2014 and 2017 caused by an increase in the average level of the lagoon reaching historical maximums, producing floods, and affecting infrastructure, transport, and agricultural activity. Due to these problems, through the application of hydrological and hydraulic models, the behavior of the La Picasa basin system quantified and evaluated to avoid future floods.

In the present work, a hydrological model applied using the HEC-HMS free tool and a 1D/2D hydraulic model using the HEC-RAS free tool, where the system of channels and reservoirs that make up the system is considered. The flood marks in reservoirs and La Picasa Lagoonanalyzed, and it is defined as regulating the variation of levels in the different reservoirs within permitted ranges. These models are useful for studying future hydrological situations that may occur around the study area.

Keywords: La Picasa Lagoon basin, plain lagoons, hydrological and hydraulic model, HEC-RAS, HEC-HMS.

Resumen

Las cuencas en llanura presentan particularidades desde el enfoque de los procesos hidrológicos que allí se desarrollan. Se caracterizan por presentar un predominio de movimientos verticales (evapotranspiración-infiltración) del agua sobre movimientos horizontales (escurrimientos) mostrando una fuerte interrelación entre el agua superficial y subterránea.

La cuenca Laguna La Picasa se define como una región de la pampa húmeda naturalmente deprimida, con un relieve de llanura ondulado que posee sectores bajos de anegamientos temporarios y lagunas permanentes sin una red de drenaje definida. Es una cuenca endorreica interjurisdiccional entre las provincias de Córdoba, Santa Fe y Buenos Aires (Argentina) que ha sufrido entre los años 2014 y 2017 inundaciones recurrentes causadas por un incremento del nivel medio de la laguna llegando a máximos históricos, produciendo inundaciones y afectando infraestructura, transporte y la actividad agrícola. Debido a estos problemas, mediante la aplicación de modelos hidrológicos e hidráulicos, se cuantifica y evalúa el comportamiento del sistema cuenca Laguna La Picasa, con el fin de evitar futuras inundaciones.

En el presente trabajo se aplica un modelo hidrológico utilizando la herramienta libre HEC-HMS y un modelo hidráulico 1D/2D usando la herramienta libre HEC-RAS, donde se considera el sistema de canales y reservorios que componen el sistema. Se analizan las marcas de inundación en reservorios y en la laguna La Picasa, y se define cómo regular la variación de niveles en los distintos reservorios dentro de rangos permitidos. Estos modelos conforman una herramienta útil para el estudio de futuras situaciones hidrológicas que puedan ocurrir en torno a la zona de estudio.

Palabras clave: cuenca Laguna La Picasa, lagunas de llanura, modelo hidrológico e hidráulico, HEC-RAS, HEC-HMS.

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Introduction

The study of hydrology aims to understand the hydrological cycle, its processes, and interrelations.

Many flows and precipitation measurement methods and techniques have evolved over time; however, other variables such as infiltration, deep percolation and underground flow do not have the same technical advances because of their evaluation and modeling difficulty. The latter are generally estimated indirectly with more significant uncertainty (Cabrera, 2012).

Changes in vegetation cover and land use associated with an expansion of agriculture and livestock influence hydrological processes in small basins and at the regional level (Sahagian, 2000).

Hydrological and hydraulic mathematical models are useful for understanding the functioning and behavior of the components that make up the hydrological cycle. These models help to understand and analyze extreme events (droughts and floods) and the dynamics of rivers and lagoons. They can also predict the availability of water in view of population growth. These models must be calibrated and verified before fully operational (Palacio, García, & García, 2010).

La Picasa lagoon is located in a region characterized by a high-yield livestock farming activity. During the last decades (1998-2017), it underwent changes in its level due to fluctuations in its volume of water due to the influence of rainfall, the land's topography, and the water runoff's speed.

La Picasa lagoon basin is located in the humid pampas in Argentina and has a low potential for runoff and infiltration. In normal and dry hydric periods, the superficial hydric dynamics are endorheic with a flow towards the lowlands and local lagoons. In these storages, the water evaporates and infiltrates. In the periods already mentioned, vertical water transfer processes (precipitation, infiltration, evaporation) predominate over runoff. On the other hand, during humid periods, if water exceeds the capacity of the basins and lagoons, they overflow and concatenate along temporary lines of relatively concentrated surface flow. These lines converge towards the Central Depressed Belt (central zone of the system) and from there towards the East until they drain into La Picasa, the final receptor of the runoff (INA, 2018).

From 1973 to the present, the study area has undergone a humid period with annual mean rainfall above the historical mean value of 900 mm/year (Ministerio de Obras Públicas, Servicios y Vivienda, Universidad Nacional del Litoral, 1999a; Ministerio de Obras Públicas, Servicios y Vivienda, Universidad Nacional del Litoral, 1999b). Consequently, the level of the La Picasa lagoon has gradually increased. It has caused blocks in important communication routes such as National Route No. 7 and the railway, which connect Buenos Aires with the Provinces of the Cuyo Region along the most important bi-oceanic corridor in the country. As the water level increases, it also floods urban areas; it causes blocks of provincial roads and losses of important productive districts.

This work aimed to quantify the impact on surface runoff of the hydraulic works projected in the original design, the works already executed and the protection works projected in Villa Rossi and Leguizamón towns. A hydrological and a hydraulic model applied to carry out the present work.

Initially, in this work, a comparison made between the hydraulic works projected in the original design and the executed works, which surveyed in blueprints according to the construction work. Since differences observed, to evaluate the impact on the general behavior of the system, the original works, and the executed works simulated separately. Then, hydrological and hydraulic models applied to the endorheic basin of La Picasa lagoon, where the parameters calibrated, and various scenarios simulated. An attempt made to understand the system and quantify the surface runoff using the hydrological model. In turn, the flow parameters over the main drainage system of the basin quantified using a hydraulic model. The models calibrated with data on water levels of the La Picasa lagoon, rainfall, and flow rates measured in the field. The free HEC-HMS software for the hydrological model chosen to comply with the requirements and coordinate with the technical team of the Provincial Administration of Water Resources (APRHI).

The hydrological model used to evaluate the response of the basin and the water level in the La Picasa lagoon. It is important to notice that the model includes modifications in the regulation system as well as the management of the combined gravity and pumping systems. On the other

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hand, the hydraulic model simulated the runoff in the system of main channels and reservoirs.

Study area

The study area includes the surface of the La Picasa basin, the lagoon itself as the final receptor, its entrance channels, its pumping system, and its seven interconnected lagoons (reservoirs).

La Picasa lagoon, situated in the south of the Santa Fe province, belongs to an endorheic basin which includes part of the Buenos Aires and Córdoba provinces (Argentina). It is located in a depression 20 km long (East-West) and 10 km wide (North-South). In normal periods, it occupies slightly more than half of the depression, but in recent decades, it has overflowed and has reached more than double the area of the depression (Iriondo, 2010).

The basin presents a landscape of a gently undulating plain with alternate flattened hills and depressed sectors where lagoons and flooded lowlands are located. These geoforms incorporate a large surface storage capacity (INA, 2018). The dynamics of surface runoff present a typical behavior of hydrological systems of plains where the hydrological processes of precipitation, evaporation, and infiltration predominate (Iriondo, 2010).

Within the study area are the localities of Laboulaye, Villa Rossi, Rufino, Aarón Castellano, and Diego de Alvear, among others (Figure 1).

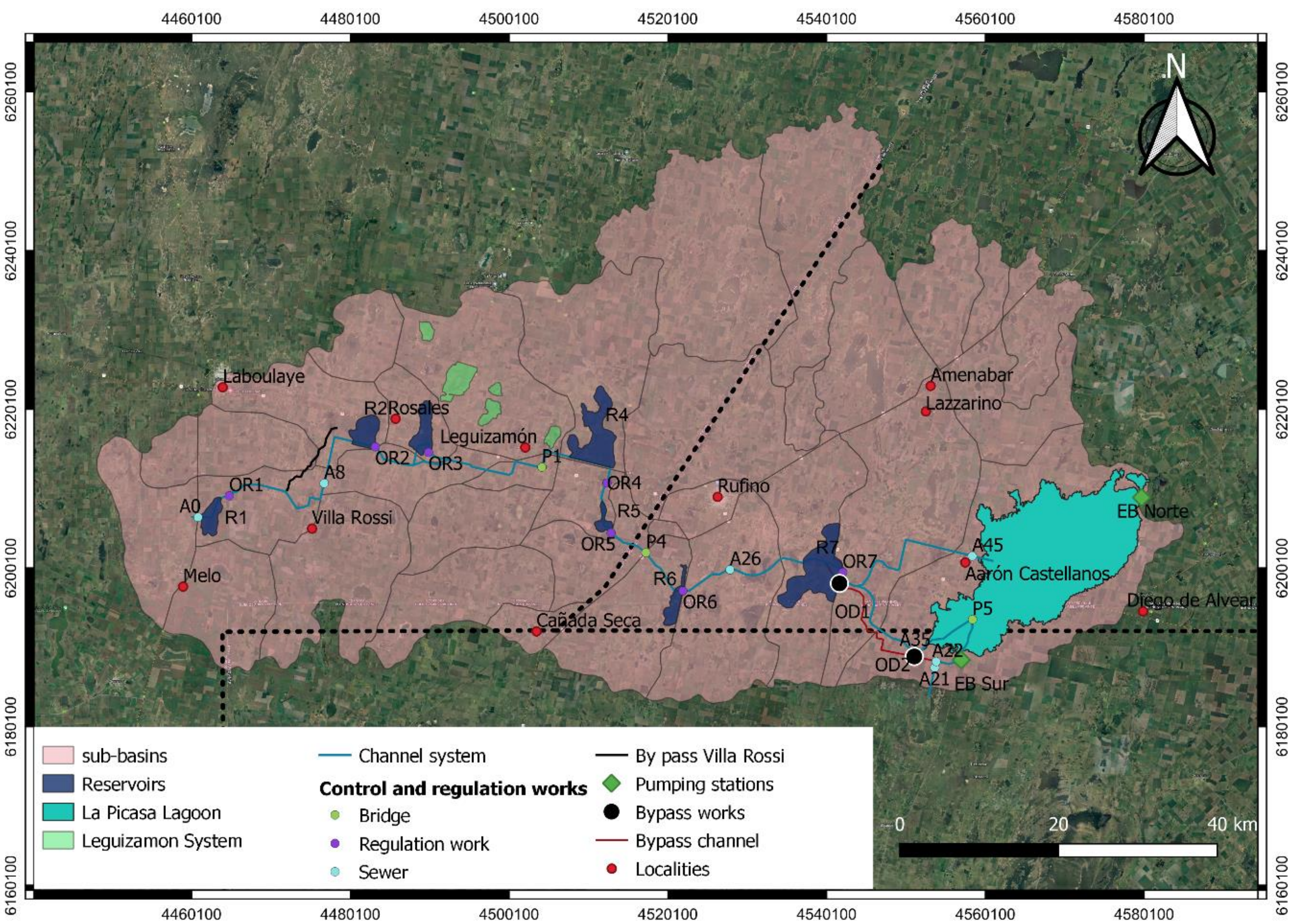

Figure 1. Study area - La Picasa Lagoon.

The surface storage capacity in natural shallows leads to different hydrological responses to the occurrence of rainfall, which strongly depends on the degree of saturation of the substrate of these shallows. Figure 2 shows the topographic depressions in the La Picasa basin with a typical anarchic design. The tributary surface observed with transfers in its divisions with various exit points. These topographic depressions have an area of approximately 1 100 km^2, approximately 18 % of the basin's surface, which has 6 200 km^2.

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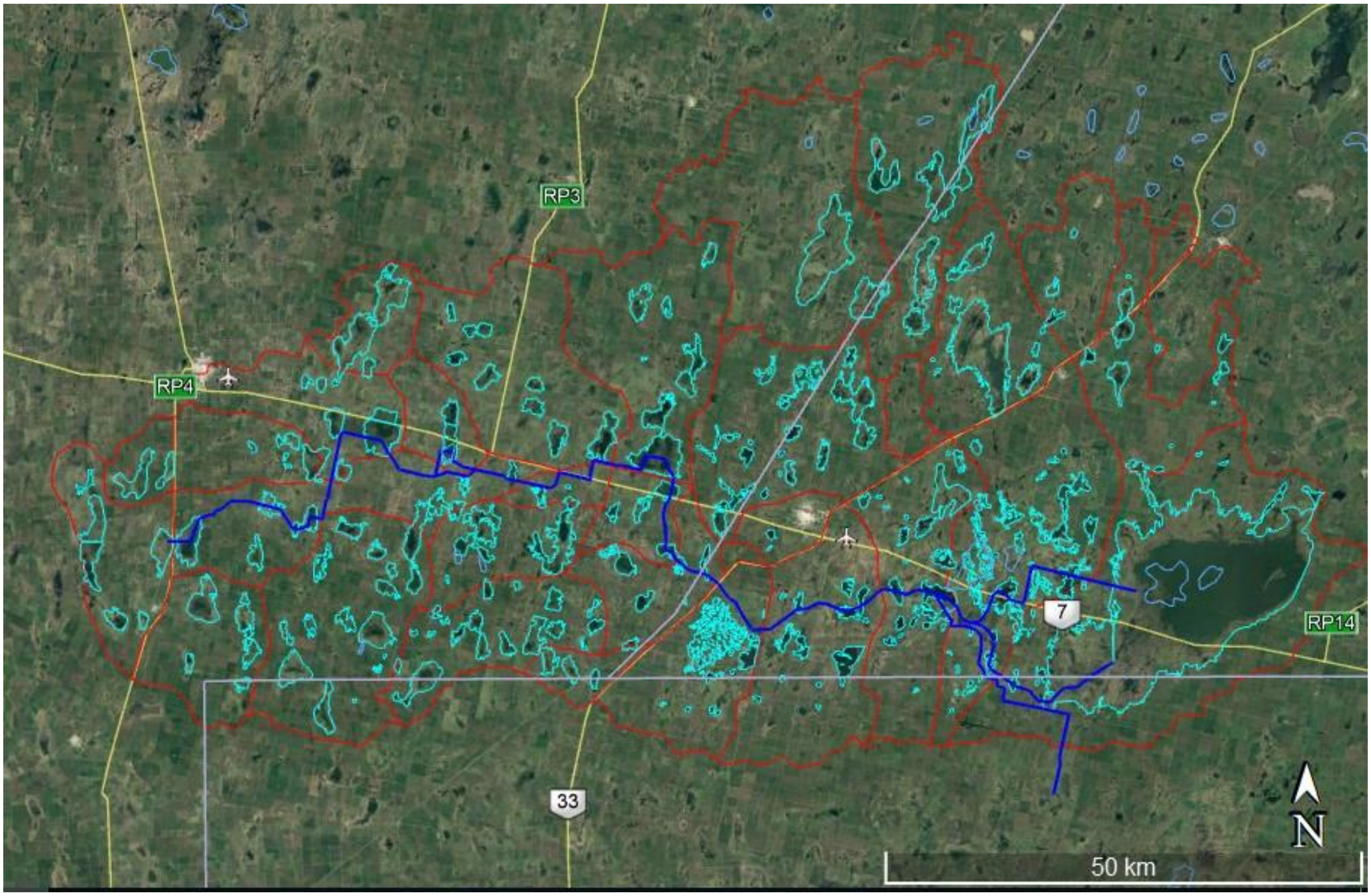

Figure 2. Water depressions in La Picasa basin.

The fundamental hydrological characteristic of this system is the predominance of vertical movements of water over horizontal movements. In this context, it is important to mention evaporation, evapotranspiration, infiltration, exchanges between the unsaturated zone and the water table, and variations in surface and underground storage.

This system can defined as a plain or non-typical hydrological system (NTHS).

The hydro-geomorphological information taken from the studies carried out by Carignano (Carignano, 1999; Carignano, Kröhling, Degiovanni, & Cioccale, 2014), where it observed that the type of soil that predominated in the study area was mollisol ranging from sandy loam to loamy textures with drainage problems due to topography, and elevated groundwater conditions (Carignano, 1999; Carignano *et al*., 2014). A Central Depressed Strip (CDS) can identified in the system's central zone. It runs longitudinally close to the south of the railway between Laboulaye and Aarón Castellanos stations (Iriondo, 2010).

The FDC has a flat-concave shape, with numerous closed shallows and a general slope of approximately 0.00030 m/m towards the East. La Picasa lagoon is at the eastern end of the FDC. The high and low areas of the landscape have well-drained deep soils, while the lower areas have fine soils with difficult drainage (INA, 2018). Because of FDC morphological, edaphological and climatic characteristics (Carignano *et al*., 2014), a hierarchical natural river network has not developed in the system. However, in recent decades, channels that link lowlands and lagoons have built, mainly on the central strip between Rufino town and La Picasa lagoon.

Description of the hydraulic works included in the system

The federal state and the provinces not only planned but carried out several hydraulic works to allow better drainage toward the La Picasa lagoon and to control its levels in wet periods. The system consists of La Picasa lagoon and seven regulation lagoons west of the former. The system also includes a) interconnection channels among them, which are laid out both in the Provinces of Córdoba and Santa Fe, b) a discharge system composed of two pumping stations (EBSouth and EBNorth), and c) channels that lead the waters from La Picasa lagoon to the Salado River in the province of Buenos Aires.

The objectives of the planned hydraulic works were, first, to enable the evacuation of excess rainfall through a combined system of gravity and pumping to regulate the variation of La Picasa lagoon levels within a range established by the management policies about water surpluses. Second, to improve the evacuation capacity of the FDC by means of a series of channeling works and regulation devices to better the transit through existing roads. These works divided into the following modules (INA, 2018):

Module I. Internal canalization works. The canal system links natural shallows, as shown in Figure 1. Its trace follows the trajectory of the higher hierarchical surface runoff along the Central Depressed Strip.

Module II. Regulation works. They consist of seven (7) reservoirs located in natural depressions of the land. These reservoirs function as regulation lagoons, which connected by the canalization system described in Module I. Their discharge controlled by hydraulic structures called regulation works (OR) that have manually operated adjustable gates and downstream protection mats to prevent local erosion processes. These works aim to attenuate the peak flood flows and enlarge the water surface to increase the evaporation areas (Figure 1).

Module III. Bypass and protection work. They comprise two (2) pumping stations (EBSur and EBNorte) and two (2) bypass channels (D1 and D2). These works aim to control the lagoon's water level and the flows that enter and leave the La Picasa lagoon. Below the 105.80 m IGM elevation, the only significant discharge pathway from the lagoon is evaporation (Figure 1).

The diversion channel D1 is born inside the regulation lagoon N ° 7 and connects with the Horquetas channel that leads the runoff to the Salado River basin (Province of Buenos Aires). The entrance to the diversion channel controlled by the Diversion Work (OD1), which regulates the entrance of water to the canal through gates.

The diversion channel D2 is located approximately 3 km upstream from the Horquetas channel. The purpose of D2 is to carry out a second control flow. These works made it possible to control the water levels in the canal and to divert the surpluses back to La Picasa lagoon.

The North pumping station is located in the northeast sector of the lagoon and is composed of five pumps of 1 m^3/s capacity and 6 m of loading head for a maximum evacuation of 5 m^3/s. The station pumps water towards a channel that leads the runoff through a series of natural shallows to the El Chañar lagoon, near the town of Teodelina, the head of the Salado River basin.

The South pumping station is located south of the La Picasa lagoon and is identical to the North pumping station. Its operation is as follows: if the flow derived by gravity towards the Salado River basin is less than 5 m^3/s. If the level of the La Picasa lagoon is higher than 98.50 m IGM, the station pumps to complete the 5 m^3/s towards the Salado River basin. If the flow-entering reservoir 7 is greater than 5 m^3/s, only 5 m^3/s are derived, and the rest enters the lagoon through the canalization system.

Module IV - Protection works. Since the initial drainage system did not have sufficient capacity to conduct the flows produced by the basin, floodings in the area were unavoidable, affecting an important agricultural area and rural roads. The protection works are located near the town of Villa Rossi in Córdoba (By Pass Villa Rossi). Their objective is to improve the runoff capacity in the area and reduce the town's vulnerability. Other protection and regulation work included in this module is the system of canals and reservoirs located in the town of Leguizamón (Figure 1).

Materials and methods

Background data

Figure 3 shows the positions of the measuring stations, which provided the information used in the hydrological and the hydraulic model. All stations measure precipitation; however, only the Marcos Juárez and Pergamino stations measure evapotranspiration.

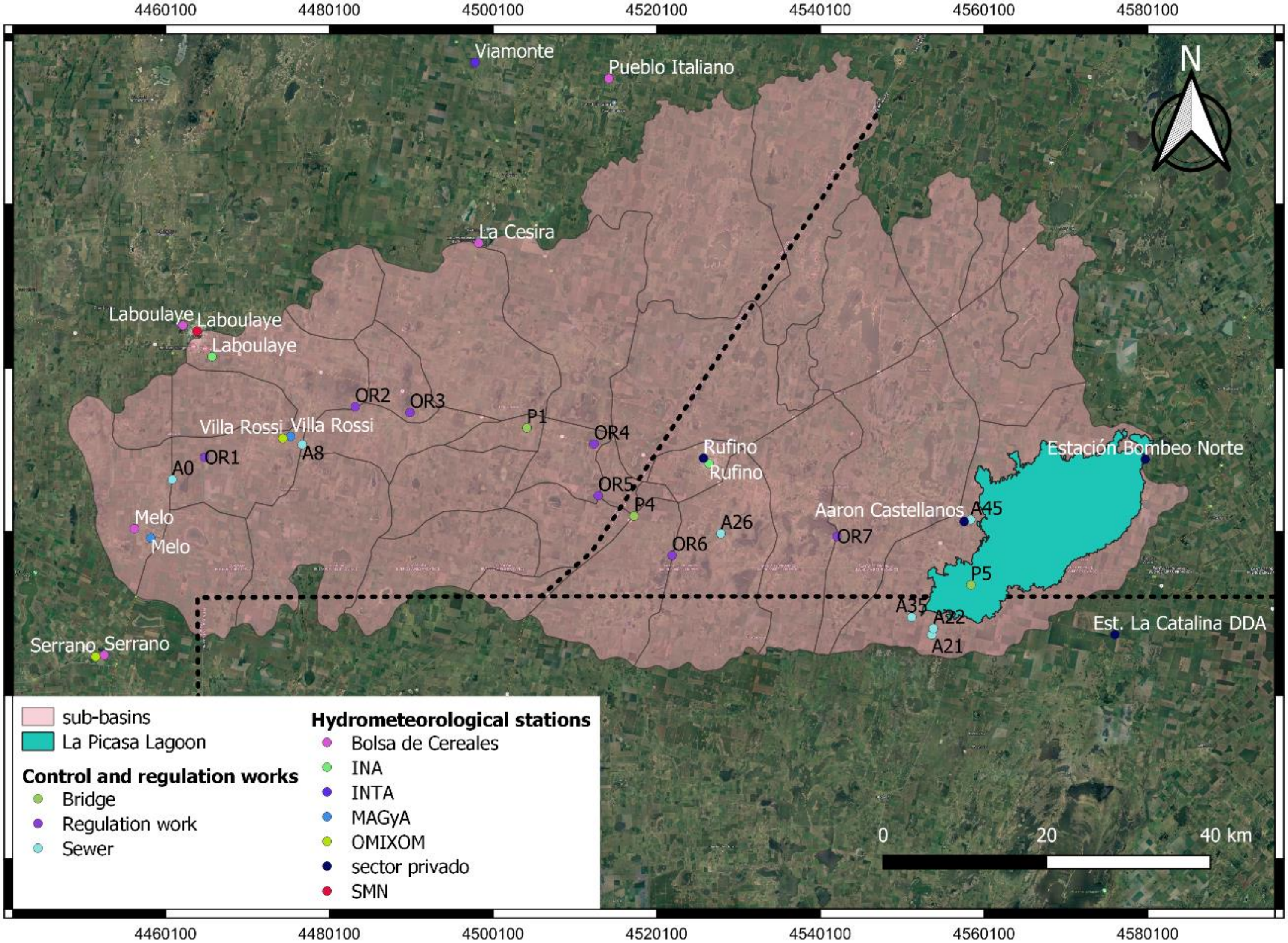

Figure 3. Hydrometeorological stations and gauging points are located in the study area.

In general, precipitation is the only source of moisture for the soil. Since precipitation varies in time and space, it is necessary to ensure reliable data because the accuracy of the proposed models depends on the quality of data. The daily rainfall data are obtained from pluviometric records with time series ranging from 1 to 20 years with a low-density spatial distribution.

Evapotranspiration ET is the total amount of water lost in the atmosphere through evaporation and transpiration. In this work, it considered that ET varies in time; however, in each reservoir, it is spatially uniform. To study ET, it considered that the precipitation captured to some degree by the vegetation where it partially evaporates. The rest of the precipitation reaches the soil and then partly evaporates from the moist soil. Once the soil is saturated, the water runs off into bodies of water from where the water also evaporates. The daily ET data obtained by applying the Thornthwaite method based on the daily temperature series at the Rufino stations.

The flow gauging points are located at the outlet of each reservoir, which is part of the system of regulation, diversion, and crossing works such as sewers and bridges associated with the La Picasa lagoon. Instead of taking these measurements daily, they taken once or twice a month. Capacity data have collected and measured since 1998 by Gustavo Villauria and Alfredo Raparo for the province of Santa Fe. These data are included in the project "Flow monitoring - internal works in La Picasa lagoon basin".

The water levels of the La Picasa lagoon used to calibrate the hydrological model have a daily temporal variation and assumed valid for the entire body of water. The data collected covers the study period from 2007 to 2017.

The topobathymetric information of the system includes a) previous digital models of elevation of the seven reservoirs. These digital elevation models based on field tasks in La Picasa lagoon; b) H-V and H-A curves for each reservoir included in the system and layout of the main system of channels.

Hydrological model

The objective of the hydrological model is to study and analyze the present system associated with the La Picasa lagoon basin. This study attempts to calibrate the model's parameters with data observed in the field. The hydrological response of the system evaluated by taking into account the hydraulic works projected in the original design, the hydraulic works already built, and the modifications made to the regulation works in reservoirs 2 and 4. Finally, the water levels of the La Picasa lagoon calculated as a function of the different handlings of the pumping system. A daytime step used for the model from 2007 to 2017.

To develop the model, the HEC HMS (Hydrologic Engineering Center's Hydrologic Modeling System) program used and applied for ten years, from 2007 to 2017. During this period, a significant increase in the water level of the La Picasa lagoon observed.

Figure 4 shows the basin model scheme composed of 29 sub-basins that make up the main system, seven sub-basins called external contributions to the La Picasa system, 27 transits, and eight reservoirs.

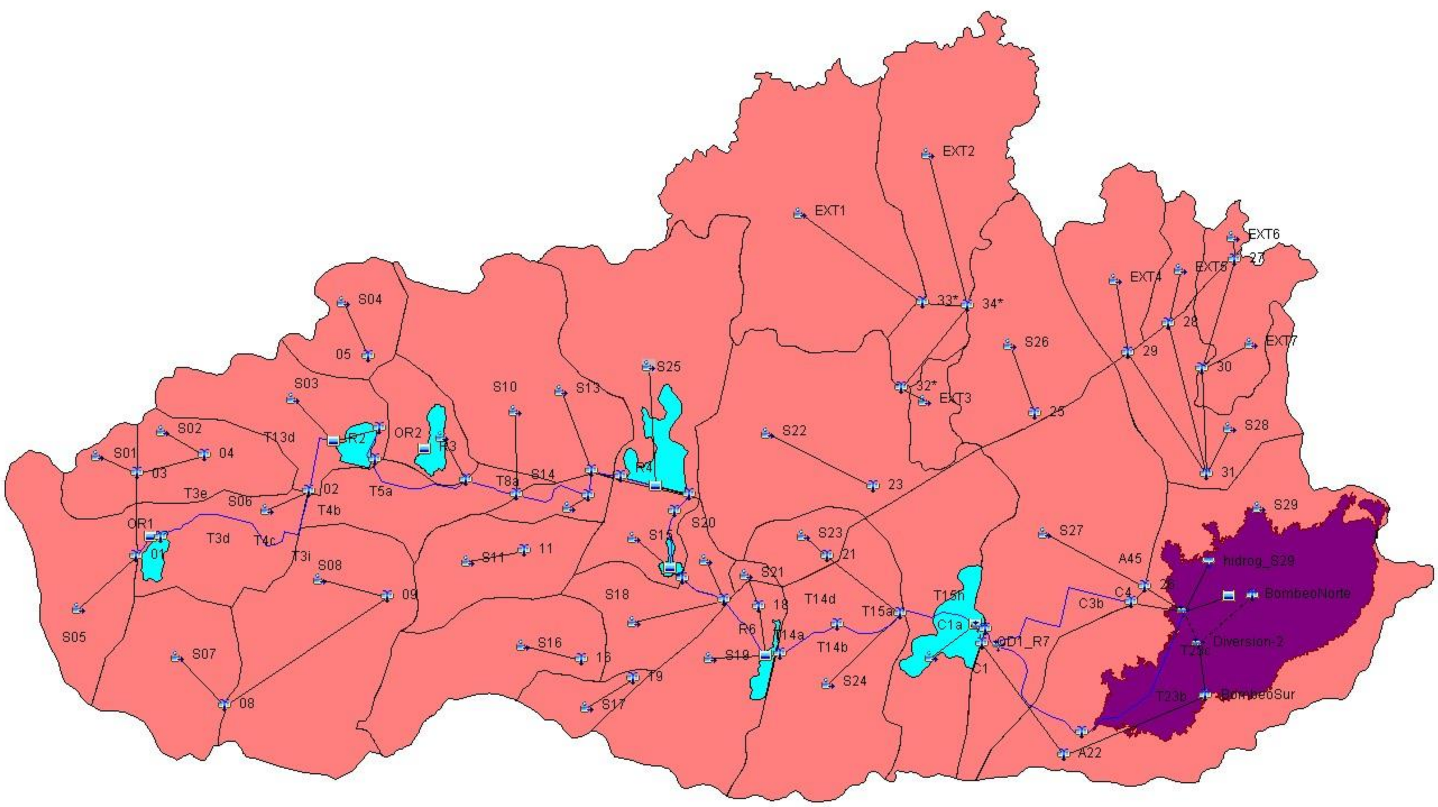

Figure 4. Basin model scheme in HEC-HMS.

The main basins considered to delimit the 29 sub-basins, which were artificially interconnected through channels that flow into La Picasa lagoon, natural depressions, and civil engineering works such as sewers, routes, and bridges (Figure 5).

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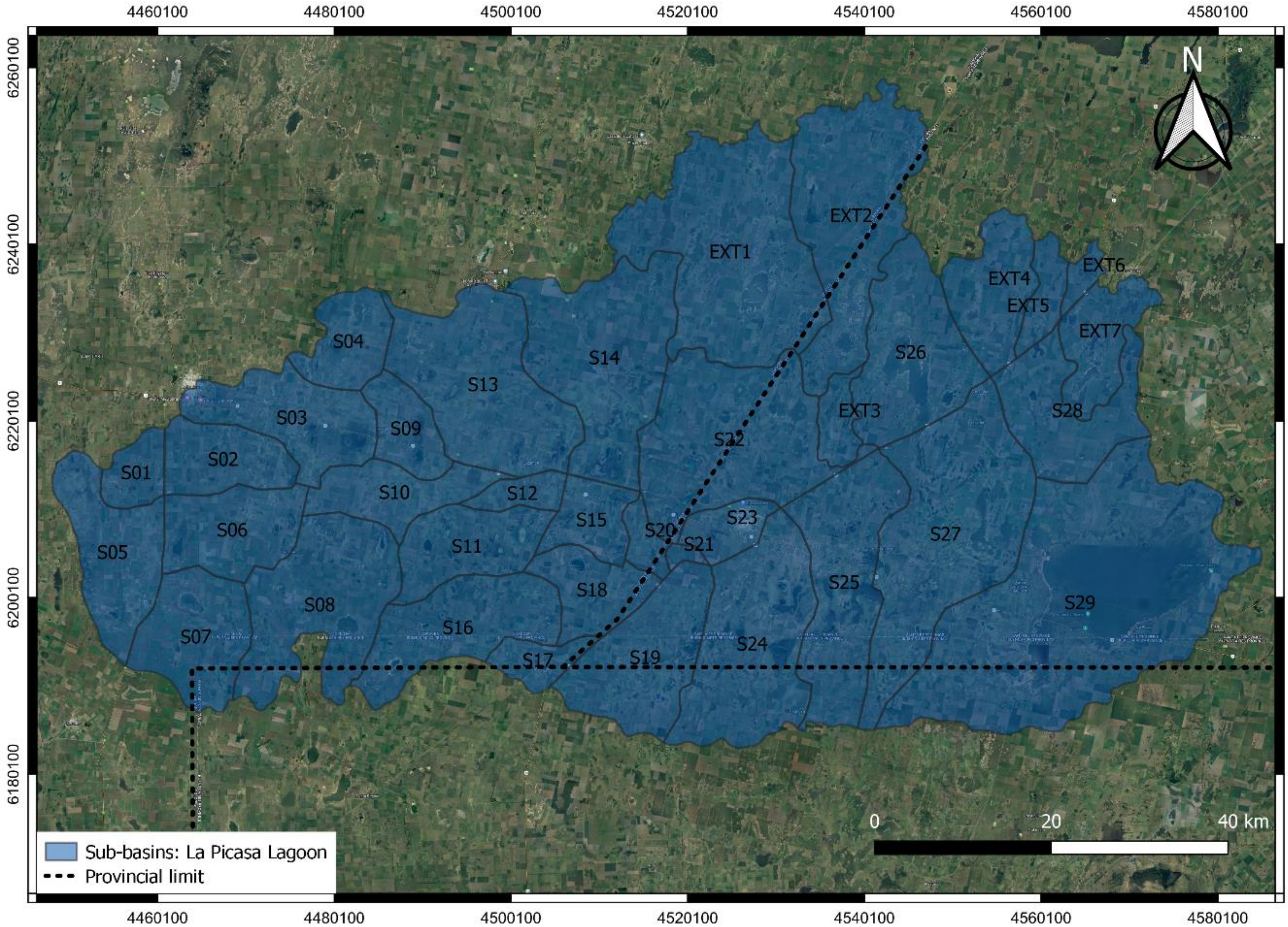

Figure 5. Sub-basin delimitation.

The losses method used was the SMA (Soil Moisture Accounting). It is a continuous method that uses three layers to represent the dynamics of water movement on the ground. The SMA simulates the movement and storage of water in the vegetation cover, soil surface, soil profile, and aquifers. In the SMA. Water flow considered in speed (mm / h) that goes through from the soil surface to the first soil layer and from the latter to the first aquifer. In this work, the water flow was determined according to use, with a predominance of agro-livestock (Ministerio de Agricultura y Ganadería de la Provincia de Córdoba, 2019), and of the type of soil, in terms of permeability (Universidad Nacional de Córdoba, 2019) (Figure 6).

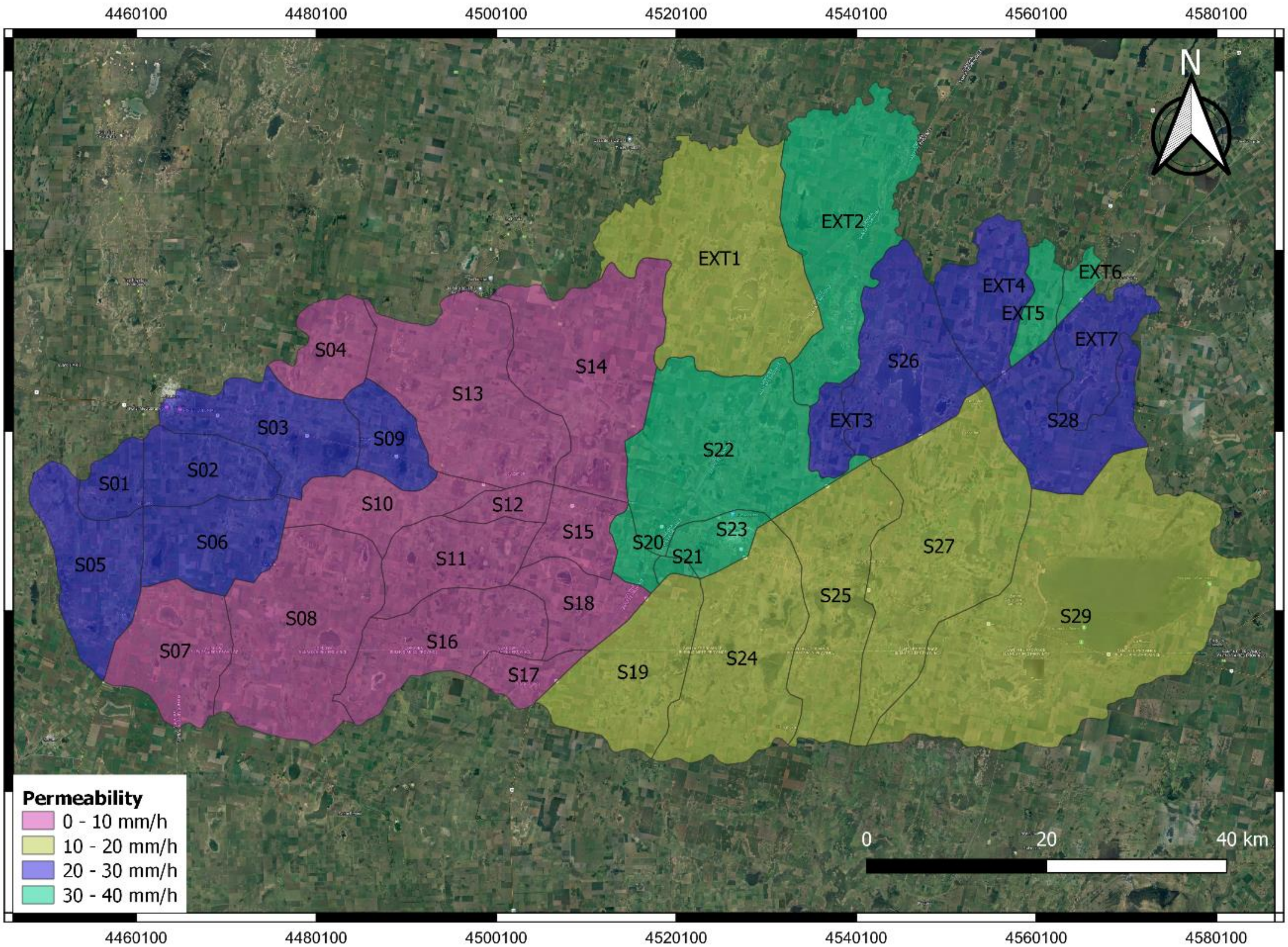

Figure 6. Classification in sub-basins according to permeability in mm/h.

The Muskingum method developed by McCarthy (1938) used to study channel flow routing. The method based on the principle that a flood wave moving in a river dampened due to friction at the bottom and on the margins. Another delay caused by natural storage in the flood bed (Llamas, 1993). The parameters defined according to each channel's geometric characteristics and longitudinal slopes.

The Puls method applied for the storage routing in the reservoirs (CEWRC-HEC, 1990). The reservoirs modeled about the parameters defined by the geometry of the water bodies. In addition, direct entry (rainfall) and exit (evapotranspiration) on each lagoon body quantified.

The underground runoff to La Picasa lagoon established by examining the use and type of soil, contour lines, and the system of main channels. The direct underground contribution attributed to the sub-basin, including the lagoon (Figure 7).

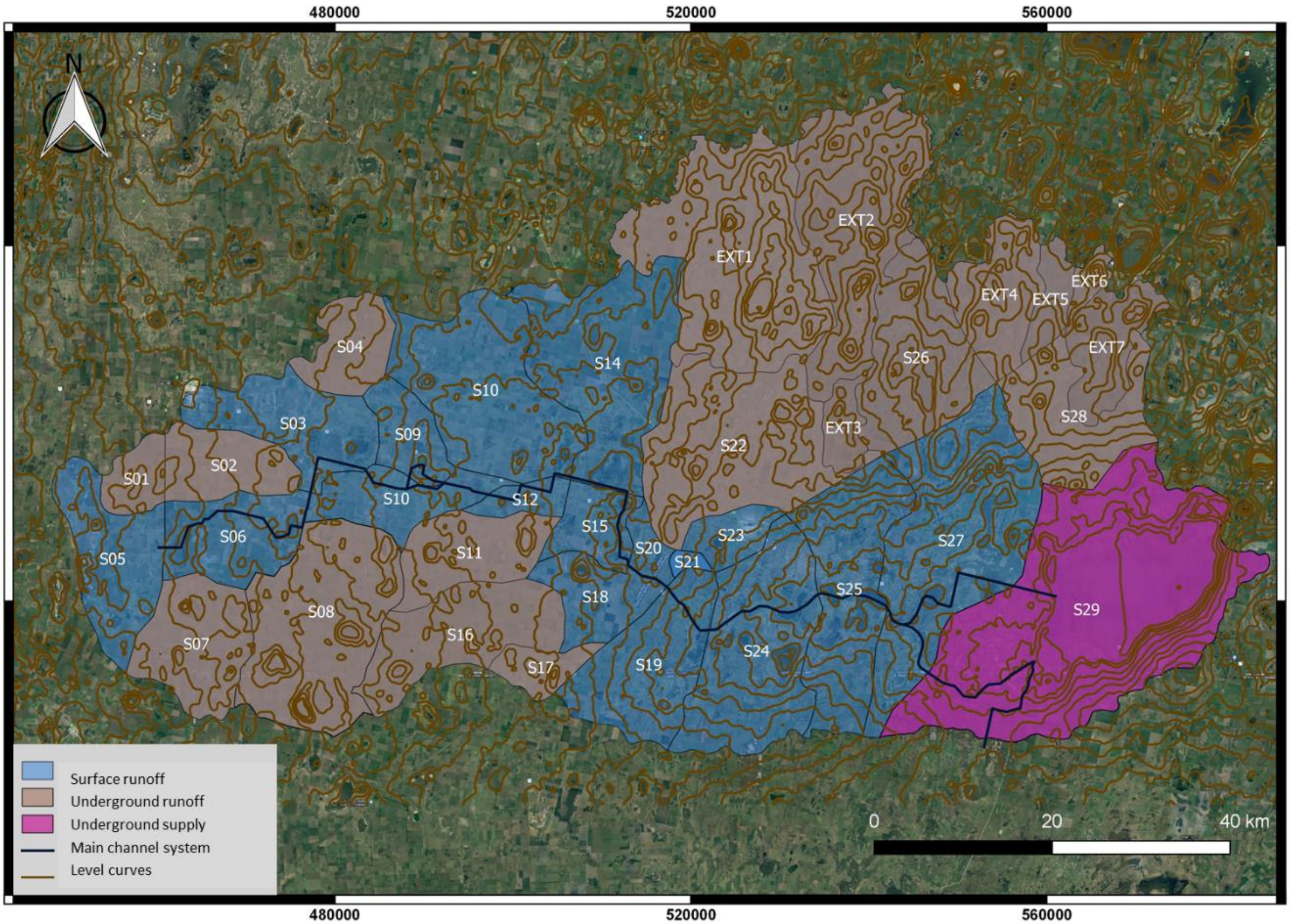

Figure 7. Sub-basins with underground and superficial contributions.

The balances disaggregated for each lagoon body independently according to either the natural runoff from the depressions or interconnections to be determined. These structures varied in the simulations by establishing different interconnections from one lagoon body to another to evaluate different scenarios.

Calibration of the hydrological model

To calibrate the hydrological model, results compared with observed data on water levels and gauged flows in control sections located along the La Picasa lagoon system (Figure 1). The four study periods were as follows: 1st period, from March to November 2007; 2nd period, from March to June 2010; 3rd period, from March to December 2012; and 4th period, from January to December 2016.

The surface storage, storage in the first and second aquifers, infiltration speed, and delay times defined for each sub-basin were the parameters adjusted for the calibration. The calibration procedure consisted of iterative simulations where the parameters above varied until the model results and the observations made in the field were close enough.

It should be noted that the infiltration speed is associated with the maximum flow of water that goes through from one level to the next, and the delay times refer to the intervals that elapse for the stored water to flow laterally so that the channel is fed as a base flow.

Simulated scenarios

Once the parameters of the sub-basins calibrated, nine scenarios simulated. The design of hydraulic works varied in compliance with original blueprints (E1) and works (E2 and E3). Alternatives were proposed with threshold elevations in reservoirs 2 and 4 (E4), and different options were considered regarding the management of the pumping system (E5, E6, E7, E8, and E9):

Scenario 1-E1: Drafts according to the original design of reservoirs and main canal system without diversion work in Villa Rossi.

Scenario 2-E2: Blueprints as built without the diversion work in Villa Rossi.

Scenario 3-E3: Blueprints as-built, adding reservoir 3 with its entrance and exit channels, the Villa Rossi diversion work, and modifications to the entrance of reservoir 2.

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Scenario 4-E4: Based on E3, threshold levels modified in reservoirs 2 and 4 by increasing their elevation.

Scenario 5-E5: North and South pumpings were not considered.

Scenario 6-E6: Maximum pumping capacity proposed in the South and North pumping stations.

Scenario 7-E7: Optimal pumping sought to maintain the lagoon level according to project considerations.

Scenario 8-E8: Based on E3, a maximum capacity of 5 m^3/s added to the South pumping station.

Scenario 9-E9: Based on E4, a maximum capacity of 5 m^3/s added to the South pumping station.

Hydraulic model

The objective of the hydraulic model is to study and analyze the system of main channels and reservoirs. Different scenarios proposed for each reservoir's floodplain areas, water levels, and velocities.

The HEC-RAS (Hydrologic Engineering Center-River Analysis System) computer program used to implement the hydraulic model. The model applied to data from December 17 to March 25, 2016, when the lagoon exceeded the maximum project level. This computational tool allows one-dimensional 1D, two-dimensional 2D hydraulic calculations, or a combination of 1D and 2D models. HEC-RAS allows using either Saint-Venant equations or diffusive wave equations (2D) to solve two-dimensional models.

In this work, a combined 1D/2D model made. 1D components were used for the channel system because the flow is mainly one-dimensional in these elements. On the other hand, in the reservoirs where the flow is two-dimensional, 2D calculation meshes used.

The main advantage of using a combined 1D and 2D model compared to a 2D model is the decrease in both computational cost and calculation time. In all simulations, the 2D diffusive wave equationsused under the assumption that the gravimetric pressure gradient and friction are dominant terms.

To assign heights to the cells of the two-dimensional areas, a digital terrain elevation model (DEM) made from topographic information collected from previous measurements and surveyed in the field of the different reservoirs. This information complemented with the DEM MERIT to expand the domain of calculation of 2D areas.

Figure 8 presents the hydraulic model diagram comprising ten one-dimensional channels and eight two-dimensional calculation meshes. The approximate size of 2D cells was 30 x 30 m, and the complete model included 779 000 cells.

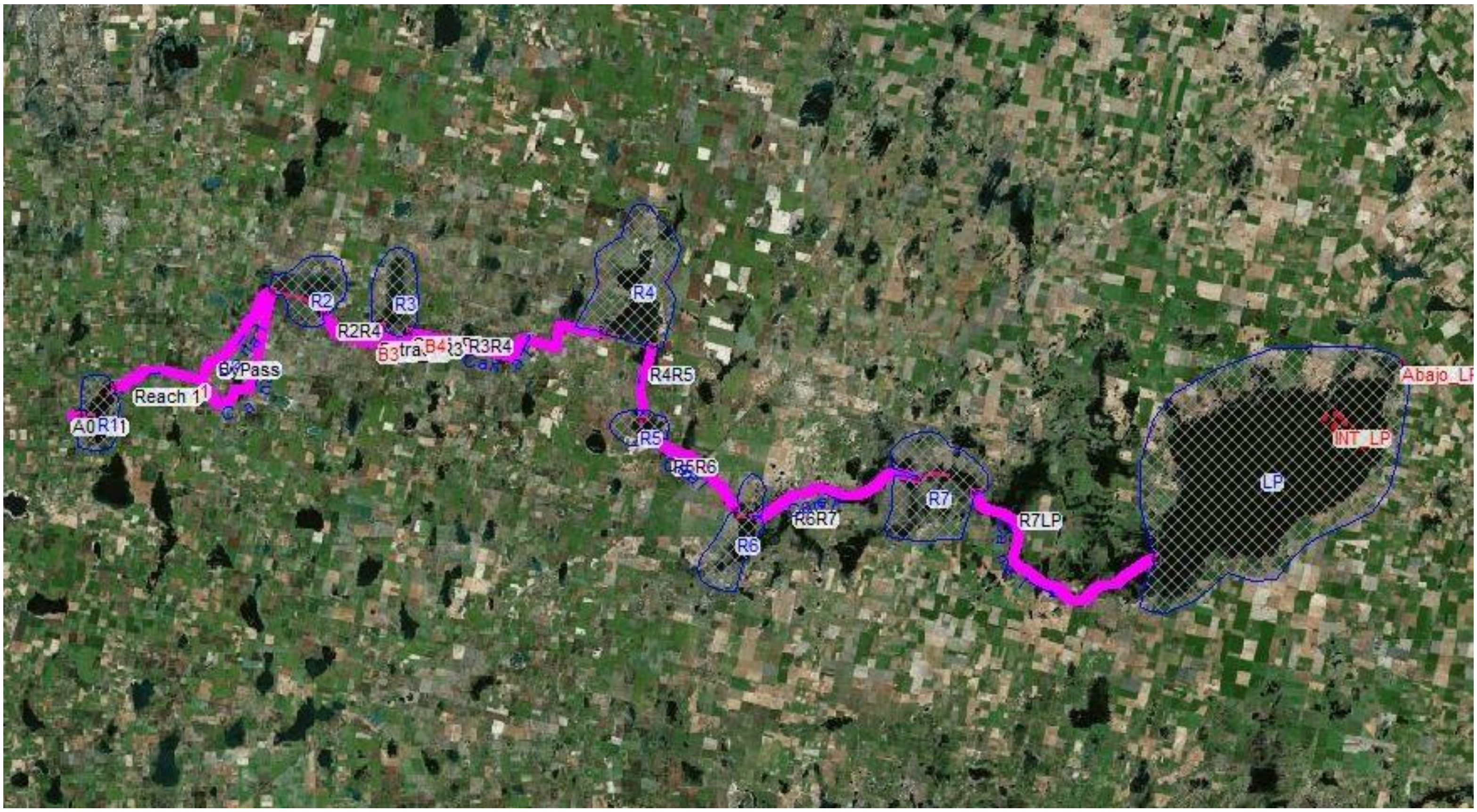

Figure 8. 1D and 2D geometry configuration in La Picasa lagoon system.

The configuration before the execution of the quasi 2D model involved the definition of the mesh size (Δx) and the computation time step (Δt), which allowed to obtain both numerical precision and minimal calculation time.

The mesh size allowed the model to be appropriately suited to the terrain and define all obstructions correctly. The computation time step related to the Courant number, obtained from the space, speed, and time relationship.

The boundary conditions were the flows obtained from the hydrological model. Hydrographsintroduced at the upstream ends of the system, and a normal depth condition defined downstream. In addition, the outlet hydrographs at the closing points of the sub-basins introduced as lateral flows.

Hydraulic model calibration

For the calibration of the hydraulic model, the flood area obtained for scenarios 1 and 2 for reservoirs 2 and 4compared with the flooded areas mapped from satellite images. To evaluate the latter area, the Modified Normalized Differential Water Index (MNDWI) from Landsat 7 and eight satellite images was used (Universidad Nacional de Córdoba, 2019).

Simulated scenarios

The hydraulic model applied in four scenarios, which depend on the original hydraulic works design, the plans according to the works, and alternatives with raising thresholds in reservoirs:

Scenario 1-E1: Channel line according to work, with regulation, works according to the original design, without diversion work in the town of Villa Rossi and design of reservoir 3.

Scenario 2-E2: Blueprints as-built, neither with diversion work in the town of Villa Rossi nor with connection to reservoir 3 (with regulation works according to work).

Scenario 3-E3: Blueprint as-built, and project drawings added for reservoir 3 and the diversion work in the town of Villa Rossi.

Scenario 4-E4: Based on E3, threshold levels modified in reservoirs 2 and 4 and propose their elevation as future works.

Results and discussion

Hydrological model

Model validation and tuning

E3 is a scenario that represents the system in its current state. The results of the model obtained for this scenario are similar to the observed data on water levels in the La Picasa lagoon. The model could simulate the increase in the level measured from 2015 onward, coinciding with an increase in rainfall and surface runoff. Nevertheless, a maximum difference between levels of 70cm occurred in 2012 can be noted in Figure 9.

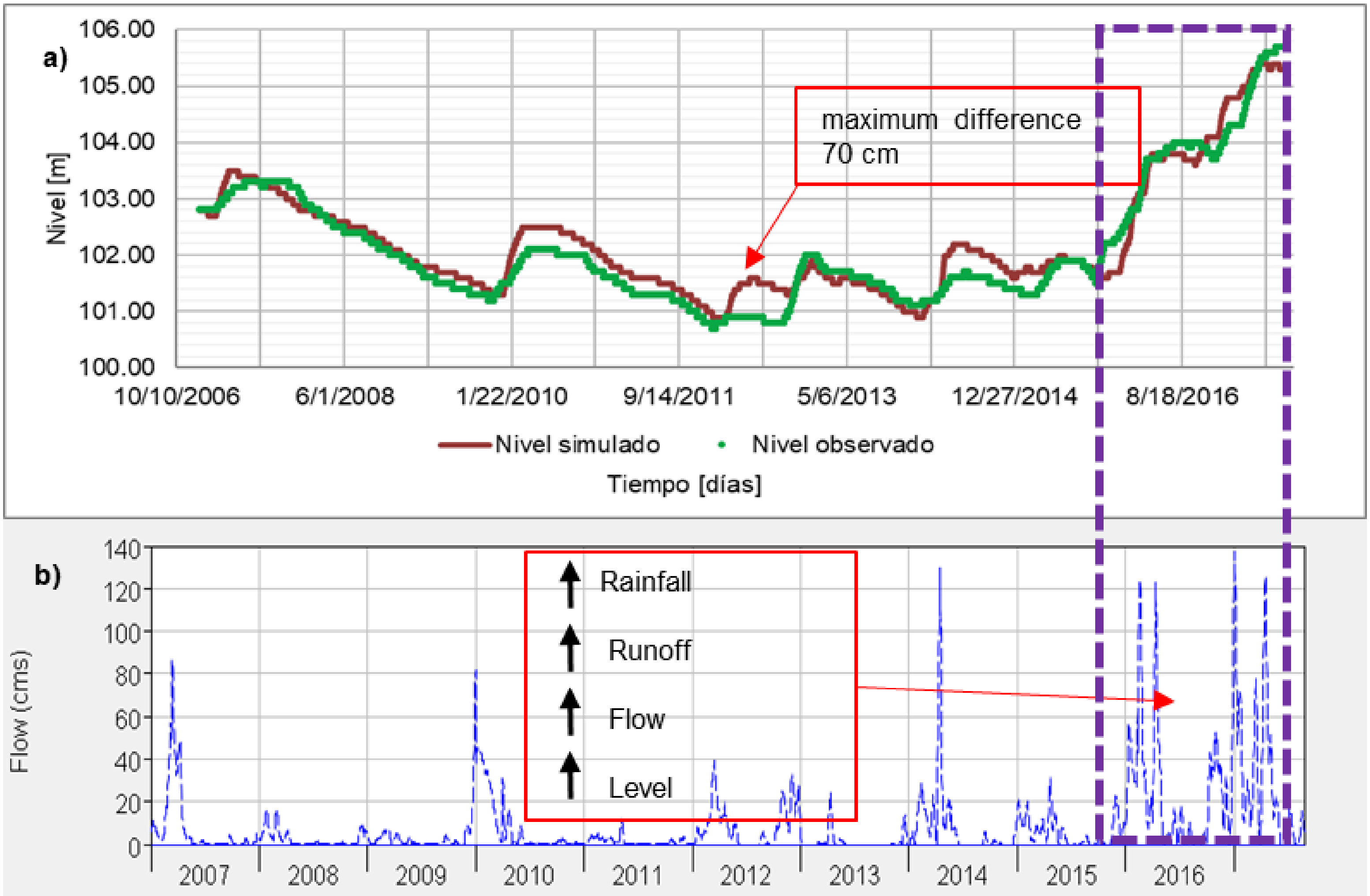

Figure 9. a) Comparison of water levels obtained from the model and water levels observed in La Picasa lagoon (2007-2017); b) Series of flows applied to the hydrological model of La Picasa lagoon (2007-2017).

The Nash-Sutcliffe efficiency coefficient was determined, which categorizes the predictive ability of hydrological models. It calculated from the observed and simulated water levels in La Picasa lagoon by means of the following equation:

$$NSE = 1 - \frac{\sum_{t=1}^{T}\left(h_m^t - h_0^t\right)^2}{\sum_0^t\left(h_0^t - \overline{h_0}\right)^2} \tag{1}$$

Where $h^t{}_m$ refers to the simulated water level, $h^t{}_0$ to the observed water level, and $\overline{h_0}$ to the mean level of the observed data. From Equation (1), a value of NSE = 0.93 was obtained. This value must be compared with the reference scale. It is important to note that when this coefficient exceeds 0.8, it considered an "excellent" fit (Molnar, 2011).

Then, minimum, average, and maximum flows calculated from both the simulated and measured data and compared pairwise. Regulation works OR1, OR2, OR4, OR6, and 0R7, bridges P1, O4, and culvert A26 were the control points used for this comparison.

The model compared and adjusted for scenarios 1, 2, 3, and 4 in the four periods selected in the parameter calibration process. The model adjusted for both wet and dry periods (2015) and a dry period (2010).

Figure 10, Figure 11, and Figure 12 show how the hydrological model calibrated to represent the La Picasa basin system and allows for quantifying surface runoff. Therefore, the model becomes a useful tool for predicting future scenarios.

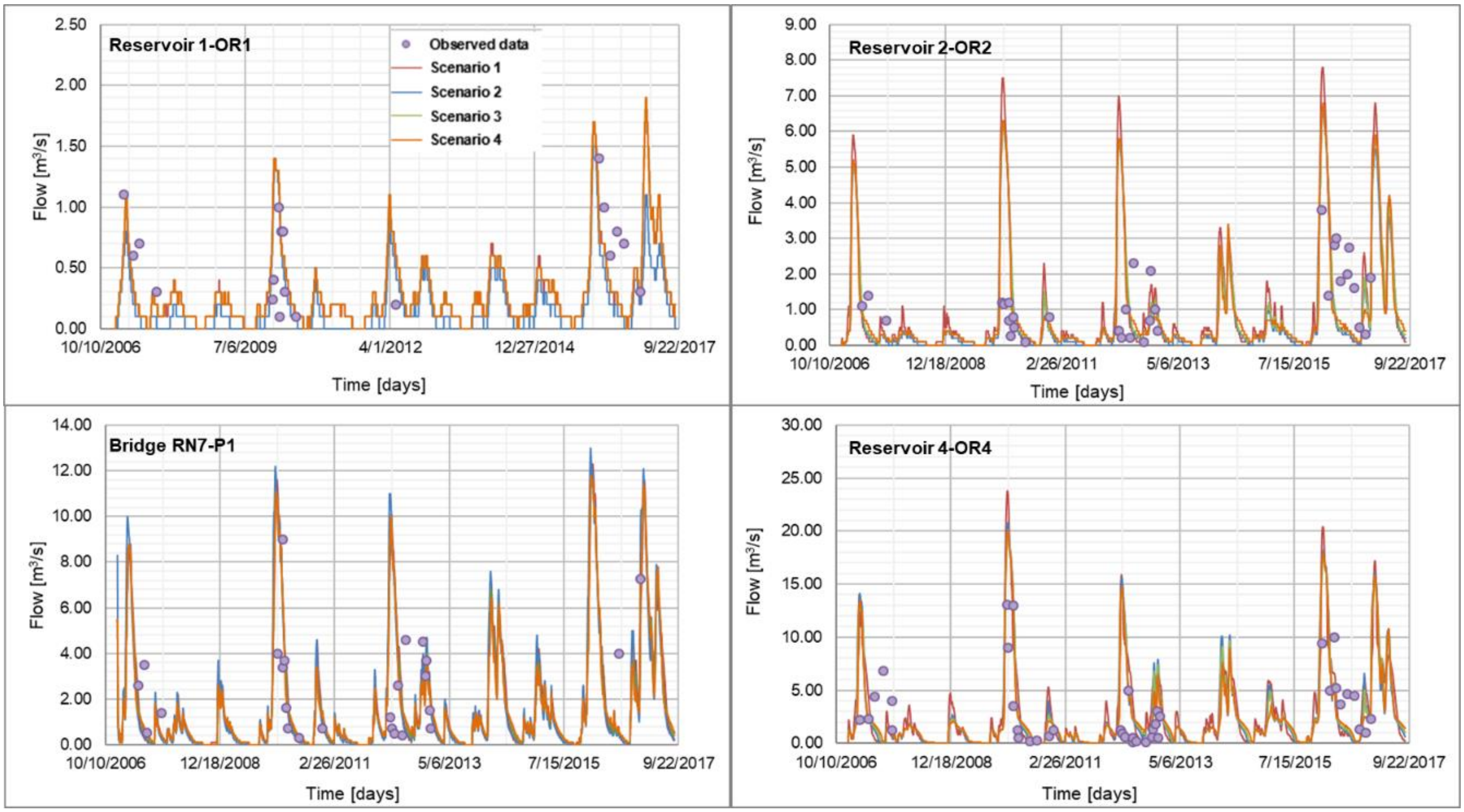

Figure 10. Results of E1, E2, E3, and E4 for the OR1, OR2, P1, and OR4 control sections.

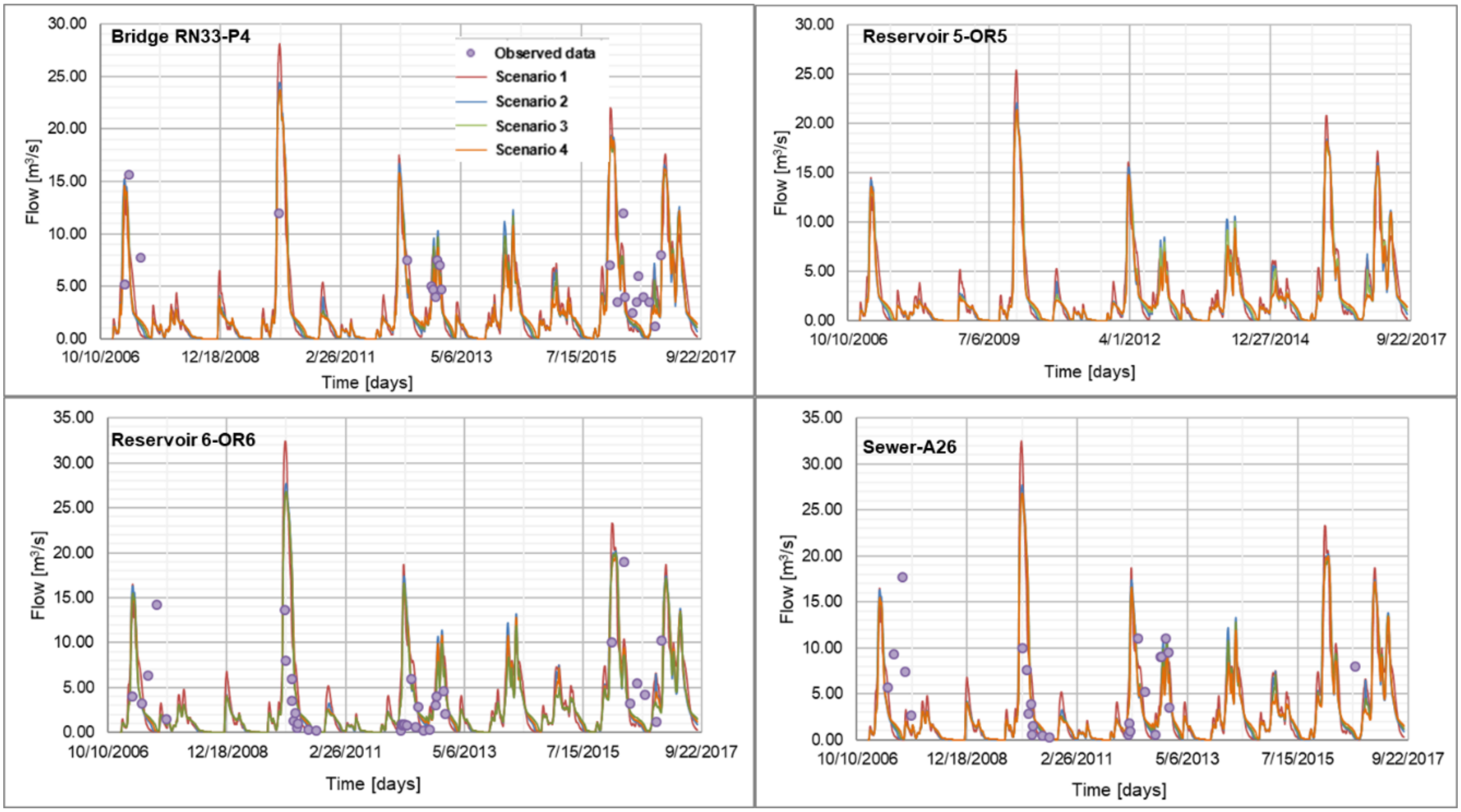

Figure 11. Results of E1, E2, E3, and E4 for the control sections P4, OR5, OR6, and A26.

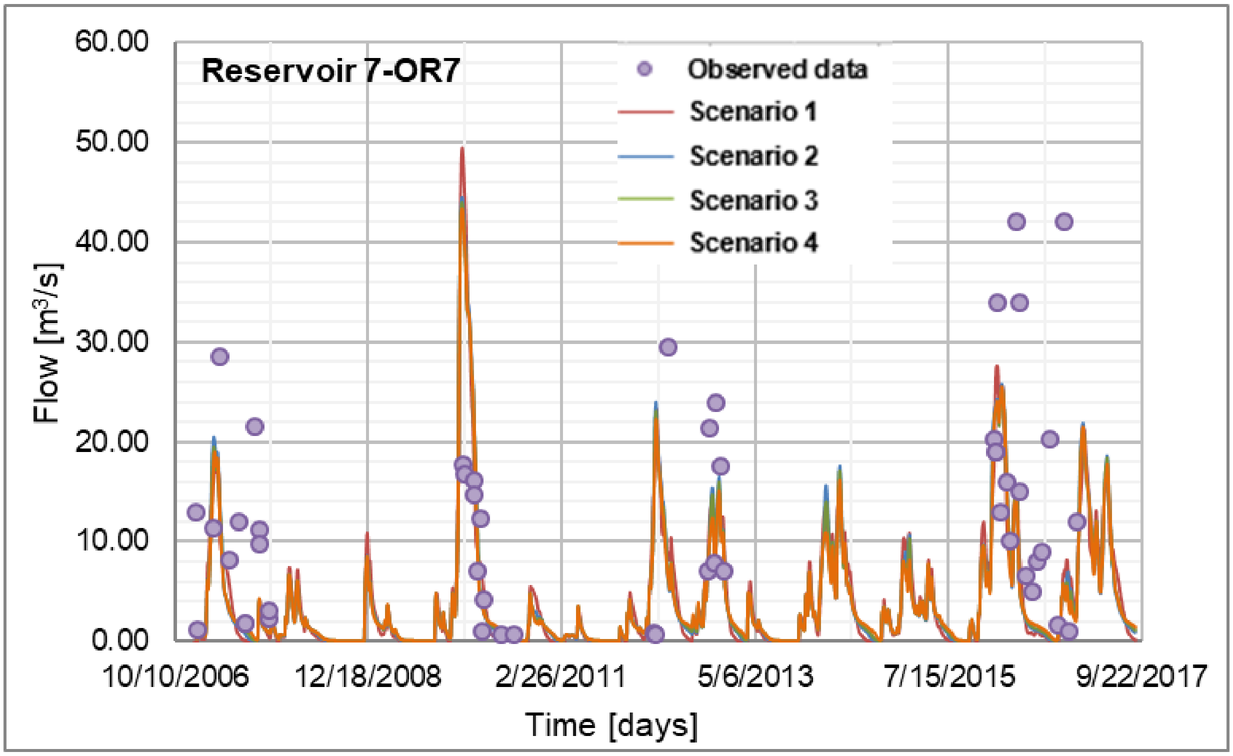

Figure 12. Results of E1, E2, E3, and E4 compared with data observed in the OR7 control section.

Once the model adjusted, it was possible to analyze the response of the reservoir system to the rainfall event that occurred during the period of analysis for scenario 3. The buffering or regulation achieved in the reservoir system can see in Figure 13 and Figure 14, where the damping effect in reservoirs R1, R2, R3, and R4 stands out. However, in reservoirs R5, R6, and R7 the inflow was equal to the outlet flow, which means negligible regulation.

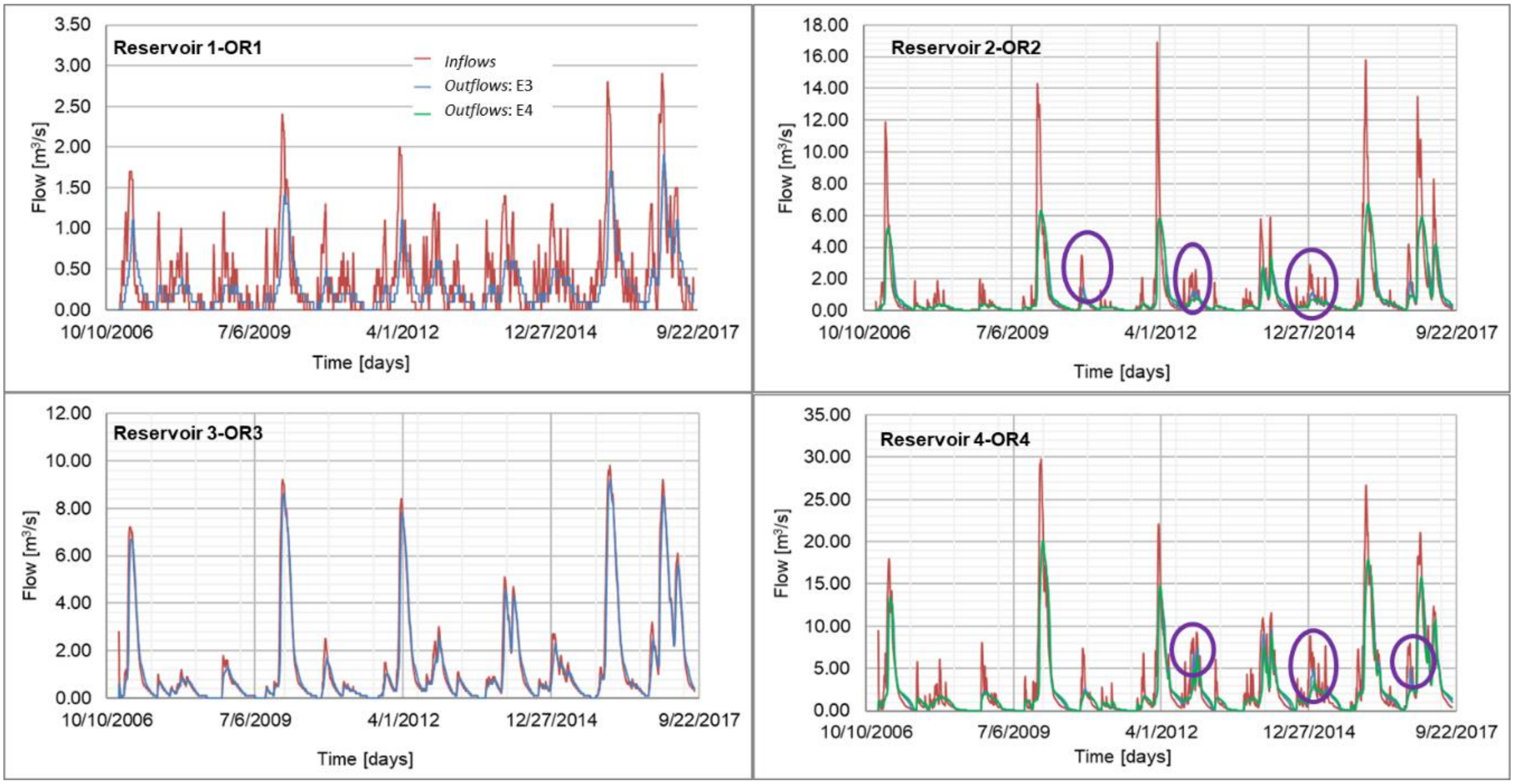

Figure 13. Results for E3 and E4. Comparison between inlet flow and outlet flow in reservoirs R1, R2, R3 and R4.

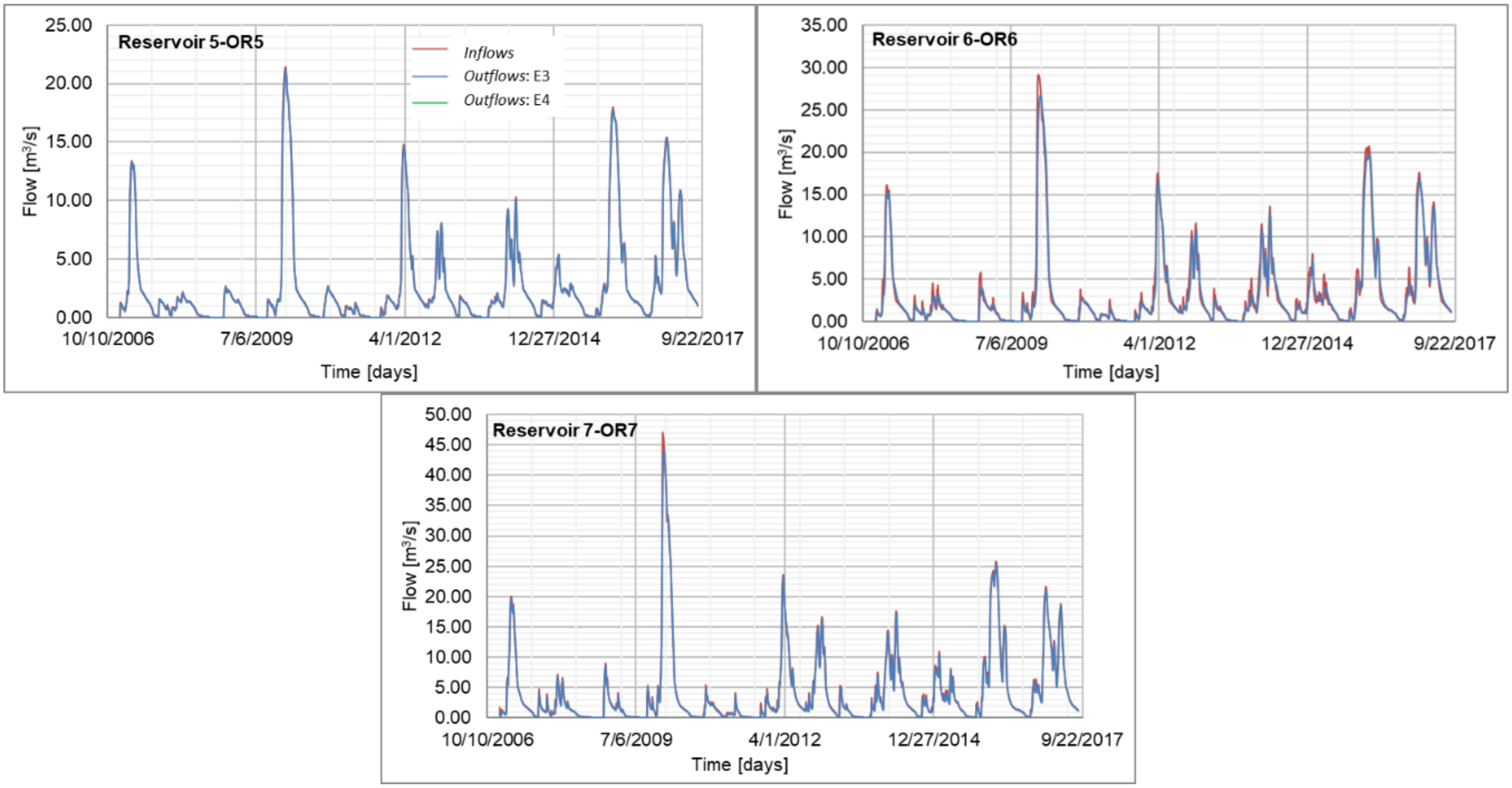

Figure 14. Results for E3 and E4. Comparison between inlet flow and outlet flow in reservoirs R5, R6, and R7.

Finally, scenarios 3 and 4 compared for reservoirs 2 and 4, where only the threshold elevation of these reservoirs differs. A decrease in outflow was observed for scenario 4 (Figure 13 b and d). The alternative of raising the threshold in regulation works (E4) presented an attenuation in outlet hydrographs for medium and minimum flows. An increase of 3 % in the regulation of the average flow observed. For maximum flows, the elevation of the threshold in reservoir 2 did not increase its regulation; in reservoir 4, a decrease of 4 %observed.

The study of these scenarios shows the importance of analyzing the modifications of the discharge works (orifices and landfills) since they will improve the management of surpluses in the main canal system to avoid future flooding in the study area. See figures 13 and 14.

Model application

Water levels in La Picasa lagoon

The hydrological model applied to the nine scenarios proposed. In Figure 15, similarities are observed in the results obtained for scenarios E1, E2, E3, and E4, while since 2012, for scenarios E5, E6, E7, E8, and E9, the curves of the water level begin to separate from the water levels obtained for the first four scenarios. This can related to the start of the pumping operations that took place that year.

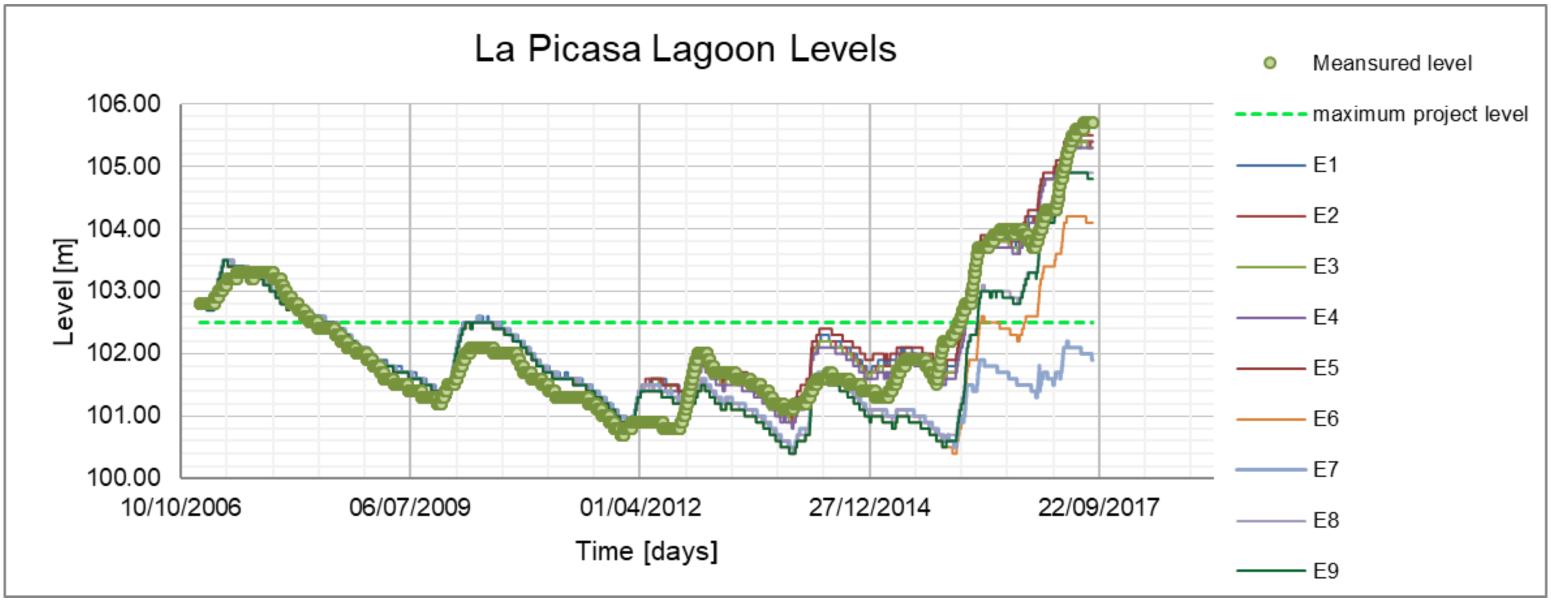

Figure 15. Water level obtained for the nine scenarios proposed (2007-2017).

The results of scenario 7 show the water levels that should have been achieved during 2007-2017 to maintain the lagoon at its maximum level of 102.50 m, according to the project. To keep a stable level, it was necessary to consider a series of flows as discharged flows, which added to the pumping of the South and North stations; 5 m^3/s for the period 01/04/2012 to 31/08/2015; 12.20 m^3/s for the period 01/09/2015 to 28/01/2016, and 35 m^3/s for the period from 01/29/2016 to 08/25/2017.

As seen in figure 15, between 2016 and 2017, there was a large increase in the lagoon level, which caused flooding in surrounding areas.

In this context, a pumping station becomes important because if a maximum pumping of 5 m^3/s is considered, the level of the lagoon drops approximately 1 m (E4 and E9).

Table 1 shows the comparison between scenario 1 and scenario 3, where the former based on the original design, and the latter based on the executive plans.

Table 1. Compare mean and maximum discharge flow rates in OR1, OR2, OR3, OR4, OR5, P4, OR6, and OR7 - E1 and E3.

Regulation works	E1 Q medium (m^3/s)	E3 Q medium (m^3/s)	Difference (%)	E1 Qmáx (m^3/s)	E3 Qmáx (m^3/s)	Difference (%)
OR1	0.29	0.29	1	1.36	1.37	1
OR2	0.94	0.85	-9	5.87	5.29	-10
OR3	1.38	1.30	-6	7.81	7.48	-4
OR4	2.70	2.51	-7	17.25	13.16	-24
OR5	2.79	2.60	-7	18.40	13.45	-27
P4	3.05	2.86	-6	20.03	17.67	-12
OR6	3.34	3.15	-6	21.64	17.28	-20
OR7	4.19	4.11	-2	30.47	22.91	-25

Table 1 presents an increase in the regulation of average and maximum flows in the reservoirs, except in reservoir 1. Therefore, the modification of the regulation works was successful. A comparison between scenarios 3 and 4 in the capacity section located in the provincial limit between Córdoba and Santa Fe P4 shows an increase of 2 % in the regulation of the average flow. In contrast, a decrease in regulation obtained for the maximum flows (Table 2). Therefore, the elevation of thresholds favors attenuation of average flows, but this is not the case for the maximum ones.

Table 2. Comparison of maximum and average discharge flow rates in OR2, OR4, and P4 – E3 and E4.

Regulation works	**E3** ***Q*** **medium** **(m^3/s)**	**E4** ***Q*** **medium** **(m^3/s)**	**Difference** **(%)**	**E3** **Qmáx** **(m^3/s)**	**E4** **Qmáx** **(m^3/s)**	**Difference** **(%)**
OR2	0.85	0.82	-3	5.29	5.31	0
OR4	2.51	2.45	-3	13.67	13.67	4
P4	2.86	2.80	-2	17.67	17.81	1

Hydraulic model

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Validation and adjustment of the model

The results obtained in reservoirs 2 and 4 were compared with the flooded areas obtained from an analysis of satellite images and indices obtained from them. The images of the flood spot correspond to March 16, 2016, while the envelope of the maximum surface flooded corresponds to the study period 2007-2017.

The indices analyzed were the Normalized Differential Water Index (NDWI) and the Modified Normalized Differential Water Index (MNDWI) (Xu, 2006). For the present work, this index used since it was considered that its images gave a better delimitation of the flooded areas. A comparison with the natural color band combination also carried out (bands 4, 3, 2 for Landsat 8, and 3, 2, 1 for Landsat 5 and Landsat 7).

Figure 16, Figure 17, Figure 18, and Figure 9 show how the flood patches simulated with HEC-RAS fit the patches obtained with the MNDWI index for the 4 scenarios. The analysis of these results shows that the validation and adjustment of the model can considered acceptable given the size of the study area and the bathymetry achieved. For the model results in the four scenarios, a slightly larger spot is observed in reservoir

2 compared to the envelope of the maximum flooded area, which is presented in red.

- Scenario 1

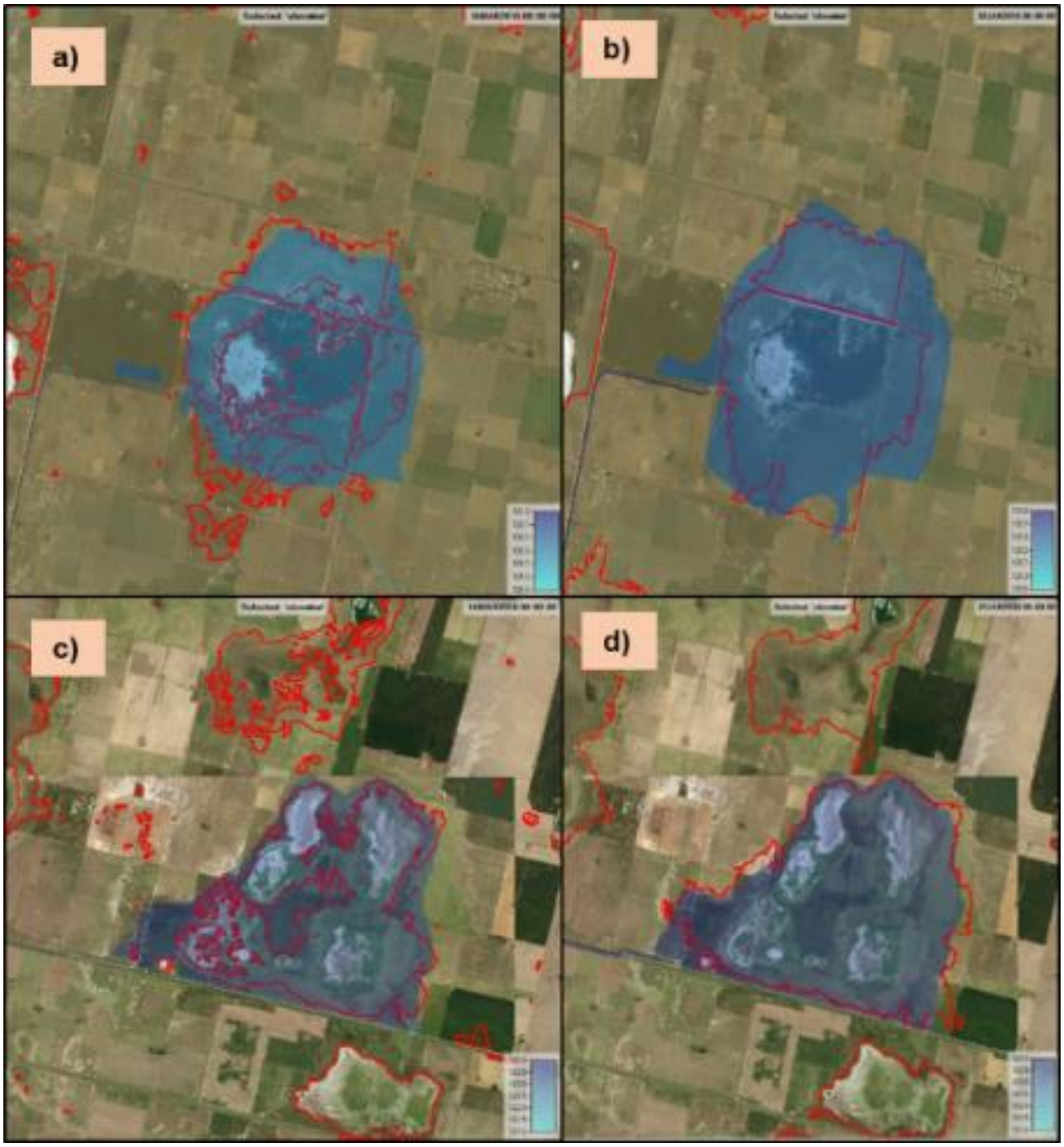

Figure 16. Results of the level obtained for scenario 1: a) reservoir 2-03/16/2016; b) reservoir 2 for maximum level; c) Reservoir 4-03/16/2016; d) reservoir 4 for maximum level.

- Scenario 2

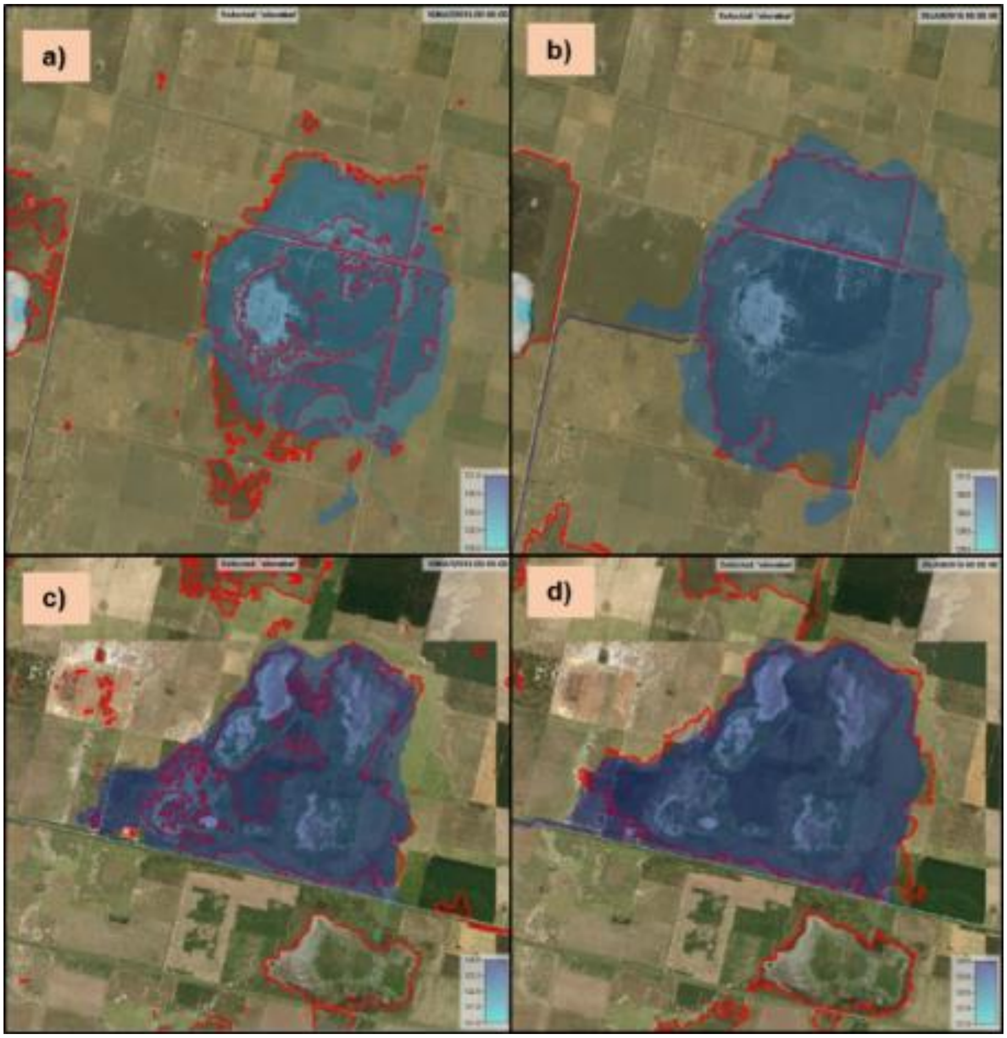

Figure 17. Level results obtained for scenario 2: a) Reservoir 2-03/16/2016; b) reservoir 2 for maximum level; c) Reservoir 4-03/16/2016; d) reservoir 4 for maximum level.

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- Scenario 3

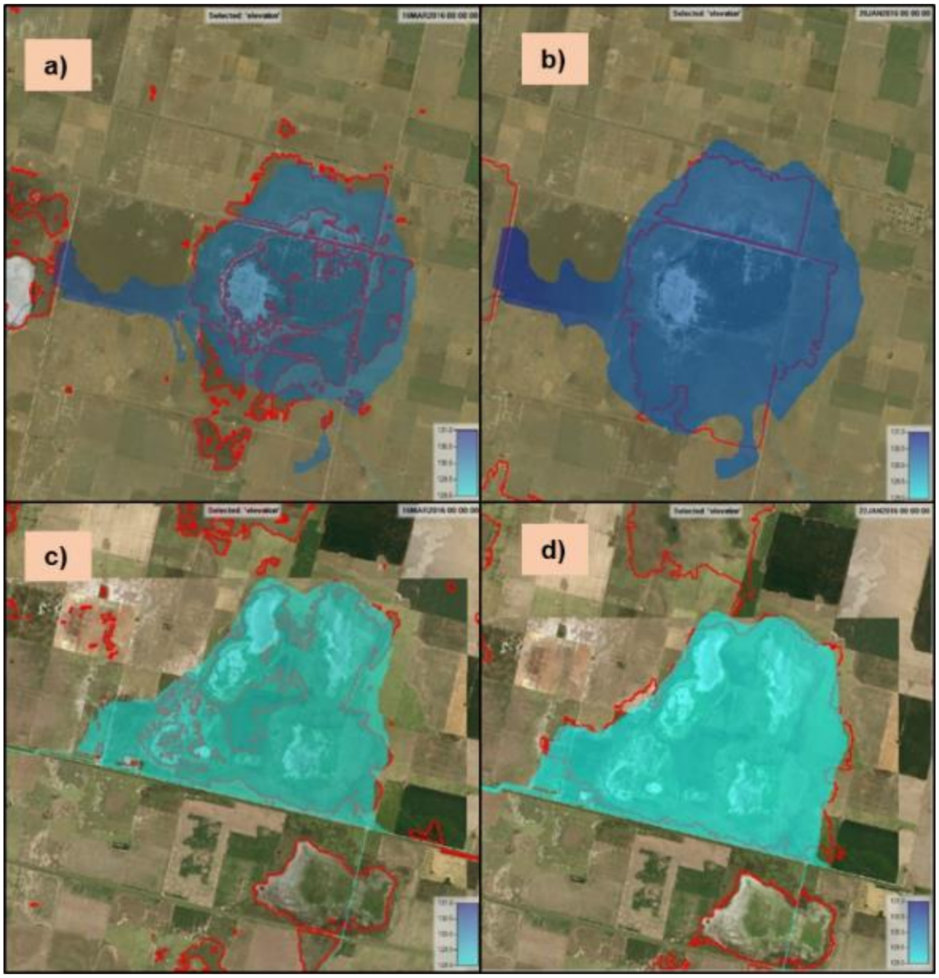

Figure 18. Results obtained for scenario 3: a) level in reservoir 2 for date 03/16/2016; b) level of reservoir 2 for maximum level; c) level in reservoir 4 for date 03/16/2016; d) level of reservoir 4 for maximum level.

- Scenario 4

Figure 19. Level results obtained for scenario 4: a) reservoir 2- 03/16/2016: b) reservoir 2 for maximum level; c) reservoir 4- 03/16/2016; d) reservoir 4 for maximum level.

Figure 20 compares the results obtained for scenario 2 of the floodplain of the lagoon (maximum level) and the envelope of the maximum floods according to the MNDWI index.

Figure 20. Comparison of the maximum level obtained with HEC-RAS and the maximum flood envelope (defined according to the MNDWI index) for scenario 2.

Figure 21 compares water levels obtained with HEC-HMS, those of HEC-RAS, and the observed water level. The error concerning the observed level of less than 1 ‰ for HMS and 0.3 ‰ for the RAS. These errors considered acceptable, especially considering the magnitude of the study area involved. Therefore, the hydraulic model considered calibrated and adjusted applied to the four scenarios under study.

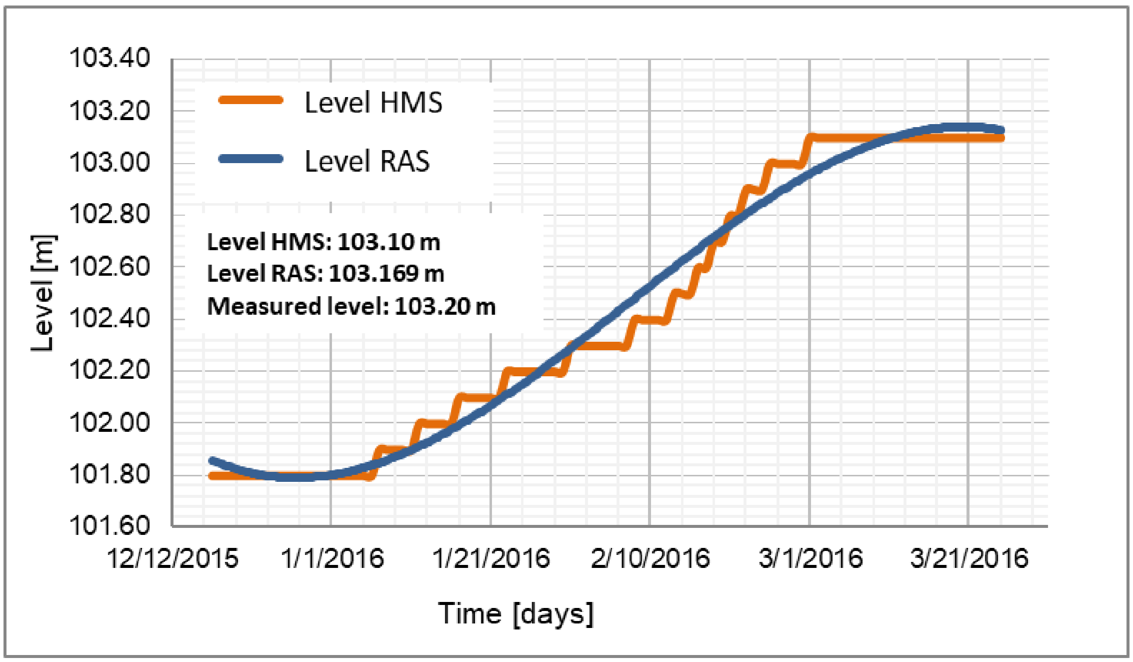

Figure 21. Evolution of levels in La Picasa lagoon with HEC-HMS and HEC-RAS models for scenario 2.

Model application: flow patterns

Figure 22 and Figure 23 show velocities and flow directions derived for scenario 1 at the beginning, at the end of the modeling, and for the maximum level of the lagoon. The color scale in the figure's ranges from blue to red for low to high velocities.

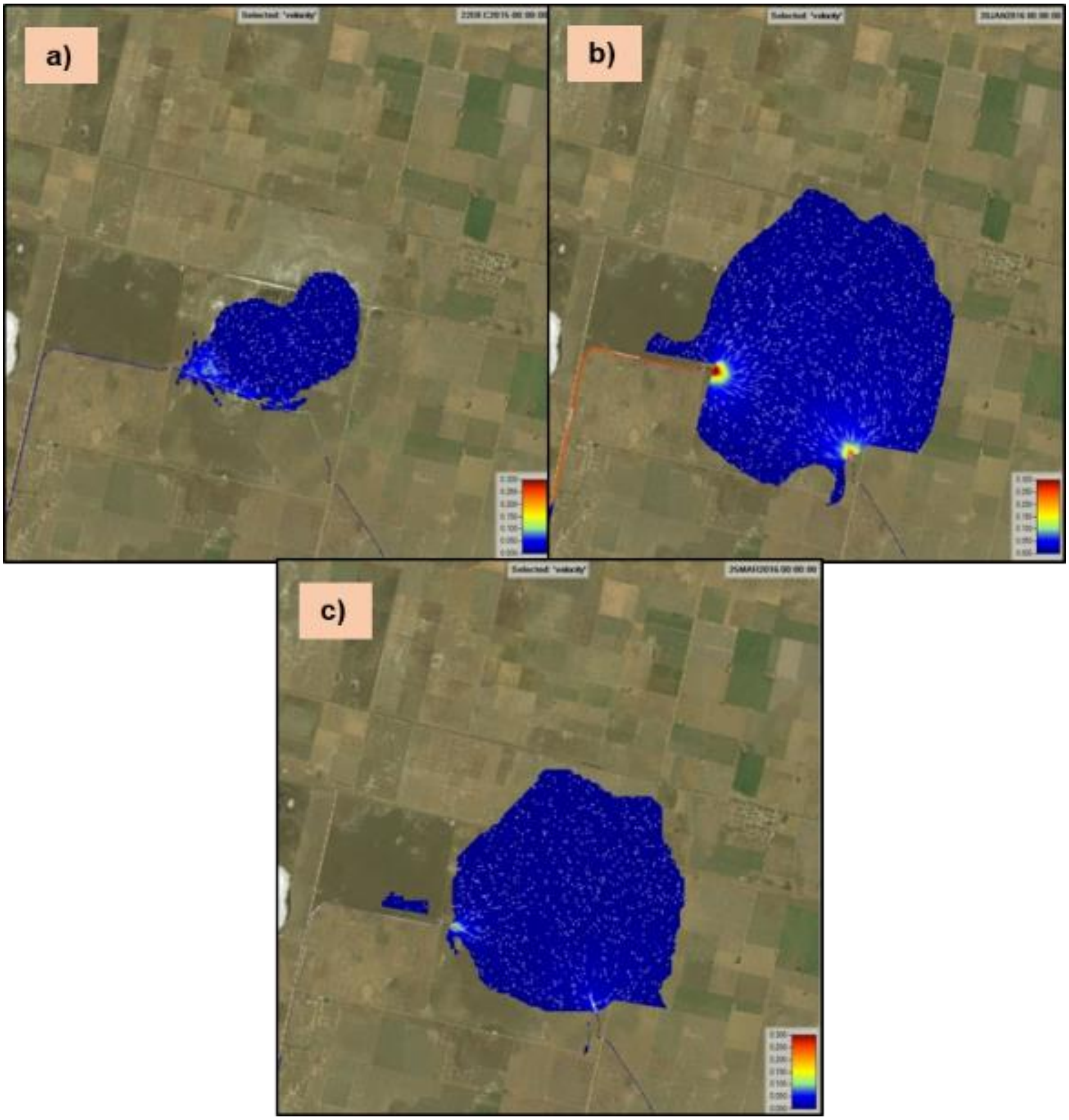

Figure 22. Simulation results for scenario 1 in reservoir 2: a) at the beginning of the modeling; b) for the maximum level; c) at the end of the simulation.

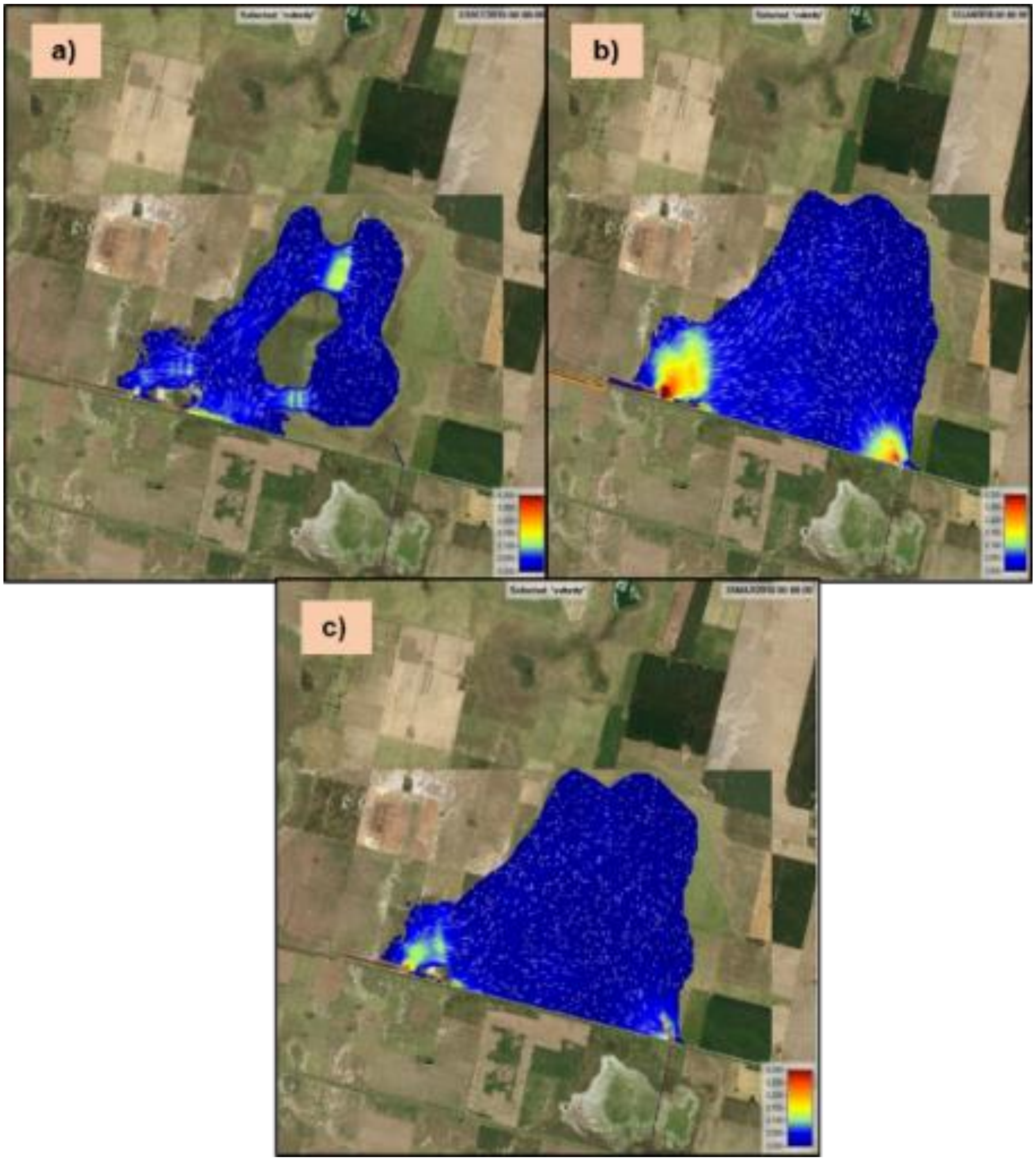

Figure 23. Velocity results in reservoir 4 for scenario 1: a) at the beginning of the simulation; b) for the maximum level; c) at the end of the simulation.

For reservoir 2, when an overflow of the channel arose, the flow directed towards the vessel with velocities less than 0.3 m/s. In the maximum level condition, the flow did not exceed speeds of 0.5 m/s and headed towards the outlet of the reservoir. For reservoir 4, at the beginning of the simulation, the flow was also oriented towards the deepest section of the reservoir, with velocities less than 0.3 m/s. The flow reached higher velocities for the maximum level condition, although it was always less than 1 m/s.

Similar behavior found for other simulated scenarios where no significant differences observed, and average speeds kept below 0.5 m/s.

Conclusions

The hydrological model presents variability caused by several natural and artificial factors such as surface and underground storage or the connections made in the canal systems for water inlets or outlets to and from La Picasa lagoon. The water volumes discharged into the La Picasa lagoon directly influence the water levels and cause large floods in the area. Among the scenarios proposed, there is one that considers hydraulic works according to executive plans. This scenario shows a good fit with maximum differences between simulated and observed water levels of only 70cm, representing an error lower than 1 %.

The flood patches for reservoirs with greater storage obtained in the hydraulic model. When these results compared with flooded areas from the MNDWI index, no significant differences are found.

The representative flow vectors gave evidence of the direction of circulation between the inlet and outlet of reservoirs. The model also enabled obtaining an order of magnitude of the speeds achieved. This model can considered a significant step toward an improved analysis and a predictive and prospective tool for hydraulic situations that may arise.

The results obtained could further improved by carrying out a detailed topobathymetry of the basin system or the reservoirs in particular if each of them evaluated separately.

It becomes important to emphasize the relevance of operating the pumping system efficiently to keep the levels of the lagoon below the established maximum levels.

It is also important to stress the relevance of the modifications in reservoir discharge works, which allowed greater damping of the flows before their arrival at the La Picasa lagoon.

The integration of resources can prevent eventual economic losses, and information and knowledge focused on analyzing the system's operation to reduce the consequences of floods. Efforts oriented in this direction can result in great economic benefits.

The hydrological and hydraulic models applied in this work show the behavior of the La Picasa lagoon system. This work also stresses the importance of these models as useful tools needed for management and planning in the environmental field, especially when it comes to works designed to keep an ecosystem in order.

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