ECOSISTEMAS Y RECURSOS AGROPECUARIOS
Ecosist. Recur. Agropec. 10(3): e3756, 2023
https://doi.org/10.19136/era.a10n3.3756

Management of an urban lagoon. Study case: Ilusiones Lagoon, Tabasco, Mexico

Manejo de una laguna urbana. Caso de estudio: Laguna de las Ilusiones, Tabasco, México

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Scientific article
Received: April 27, 2023
Accepted: October 7, 2023

How to cite: Hernández-Ramón JA, Priego-Hernández G, Plesiński KK, Rivera-Trejo F (2023) Management of an urban lagoon. Study case: Ilusiones Lagoon, Tabasco, Mexico. Ecosistemas y Recursos Agropecuarios 10(3): e3756. DOI: 10.19136/era.a10n3.3756

ABSTRACT. As a delta, Tabasco, located in the Mexican southeast, is susceptible to flooding. The city of Villahermosa, the capital of Tabasco, is not an exception. The most recent event occurred in November 2020, when an excess of rain provoked an urban lagoon to exceed its levels. The lagoon discharges at a river by a diversion channel controlled by a culvert. To analyze it, a hydraulic model -HEC RAS V6.0- was used. The precipitation, flow, and level data recorded during 2020 were used to simulate four scenarios: I) one culvert of 1.5 m x 1.75 m (current situation); II) three culverts of 1.5 m x 1.75 m; III) three culverts of 2 m x 2.5 m; and IV) one culvert of 10 m x 2.5 m. The dimensions of the culverts were subject to the available physical space of the discharge channel. It was found that the best performance was achieved with scenario II. This result is contrasting because this alternative is not the largest as might be expected; it is also encouraging because it improves the performance of this lagoon. With this proposal, we reduce the damage by 75.31%, which means 296 homes are protected. Finally, the proposed methodology can guide designers and decision-makers to evaluate hydraulic works in urban lagoons like those presented in this work.
Key words: Urban Lagoon, flood, HEC-RAS, numerical simulation, risk.

RESUMEN. Tabasco, localizado en el sureste mexicano, al ser una planicie es susceptible a las inundaciones. La ciudad de Villahermosa, que es la capital de Tabasco, no es la excepción. El más reciente evento tuvo lugar el pasado noviembre de 2020, cuando se sobrepasó el nivel de esta laguna. Para analizar este evento, se realizó una modelación hidráulica usando el software HEC-RAS V.6.0. Se utilizaron datos medidos de precipitación, caudal y niveles registrados durante el evento de 2020 y se simularon cuatro escenarios de descarga: I) una alcantarilla de 1.5 m x 1.75 m (situación actual); II) tres alcantarillas de 1.5 m x 1.75 m; III) tres alcantarillas de 2 m x 2.5 m; y IV) una alcantarilla de 10 m x 2.5 m. Las dimensiones de las alcantarillas estuvieron sujetas al espacio físico disponible del canal de descarga. Se encontró que el mejor funcionamiento se logró con la Alternativa II. Este resultado es contrastante, debido a que esta alternativa no es la de mayor tamaño como podría esperarse; además, es alentador pues mejora el funcionamiento de esta laguna en particular. Con la propuesta del escenario II, se reduce el daño en un 75.31%, que se traduce en 296 viviendas protegidas. Finalmente, la metodología propuesta es una guía que diseñadores y/o tomadores de decisiones pueden seguir para evaluar trabajos hidráulicos en lagunas urbanas con características similares a las presentadas en este trabajo.
Palabras clave: Laguna Urbana, inundación, HEC RAS, simulación numérica, riesgo.

INTRODUCTION

Urban lagoons are water bodies formed by freshwater ecosystems that can be created by natural or artificial conditions. These ecosystems are often affected by water channel diversions, stormwater discharges, or constructions within the water body (Gianello *et al.* 2019). These alterations generate changes in the morphology of the systems, reducing their size and depth (Walsh *et al.* 2005) and decreasing flora and fauna (Paul and Meyer 2008). The lagoons are a refuge and habitat for innumerable species of flora and fauna (Jerez-Ramírez *et al.* 2023); serve as livelihood and/or recreational areas for the surrounding communities (Giang *et al.* 2023); and work as a storing and regulating system for extreme events such as floods (Amoako and Inkoom 2018). The frequency of urban floodings has increased mainly due to three aspects: a) poorly planned urban developments, b) clogging of drains due to the accumulation of solid waste, and c) alteration of the rainfall regime due to climate change (Gupta and Nair 2011, Suriya and Mudgal 2012, Tingsanchali 2012). In particular, the latter cannot be avoided; however, applying the results of numerical flood modeling techniques to know the water surface levels and discharges on old or new infrastructure, can implement actions to mitigate the risk and minimize damage (Gutiérrez-García *et al.* 2022, Plesiński *et al.* 2022). In recent years, the numerical models have improved their graphical interface, allowing a more detailed visualization of the results (Rangari *et al.* 2019). Another advantage is their compatibility with geographic information systems, enabling accurate export of water surface elevations to generate risk maps (Halwatura and Najim 2013). The truth is that the quality of the results depends on the data quality, and in flood modeling, the topography is the key (Liu *et al.* 2019). Although there is a wide variety of numerical models for simulating floods, HEC-RAS V6.0 was chosen in this work (Brunner 2020). Developed by the U.S. Hydrologic Engineering Center, it has proven its effectiveness in different areas of hydraulics (Rangari *et al.* 2019, Namara *et al.* 2022, Rivera-Trejo *et al.* 2022). This research analyzed the lagoon regulation basin. The lagoon receives heavy rains and discharges it into a river through a diversion channel controlled by a culvert with one gate. This lagoon overflowed due to heavy rains on November 2, 2020, flooding the surrounding communities. This study's objective was to recreate a flooding case numerically and model with HEC-RAS three possible culvert sizes that would reduce the flooding effects.

MATERIALS AND METHODS

Study Zone

It is considered a regulatory basin generated by Ilusiones Lagoon, located in the north-central zone of Villahermosa, Tabasco, Mexico. The geographical coordinates are 17° 59' and 18° 01' N and 92° 56' and 92° 55' O (Zequeira and Castillo 2015). The Ilusiones Lagoon, in addition to serving as a regulation zone, has significant cultural and environmental value for the city of Villahermosa (Hansen *et al.* 2007, Flores *et al.* 2018), and it was declared as a protected natural area (Ricardez *et al.* 2016). Its surface area is 259.2 ha, including a perimeter ring of 10 m from the elevation of 6.40 masl, considered the overflow elevation. Figure 1 shows the location map of the study area and a panoramic picture of the lagoon.

Infrastructure

The excess water in the lagoon is currently controlled by a discharge channel connected with a culvert to the Carrizal River and regulated by a rectangular gate (Figure 2). During the flood season, the gate is opened, and the lagoon begins to discharge from 6.40 masl. The entrance is kept open until the lagoon drops to 6.30 masl. The National Water Commission (CONAGUA) estimated that the lagoon would deteriorate below this level. During the dry season, the gate is closed, and the lagoon is maintained at a minimum level of 6.30 masl.

Numerical modeling of hydraulic conditions in HEC-RAS V 6.0

The HEC-RAS V.6.0 numerical model was used in the two-dimensional version (2D) to understand the hydraulic operation of the lagoon-channel-

E. ISSN: 2007-901X

Ecosist. Recur. Agropec. 10(3): e3756, 2023
https://doi.org/10.19136/era.a10n3.3756

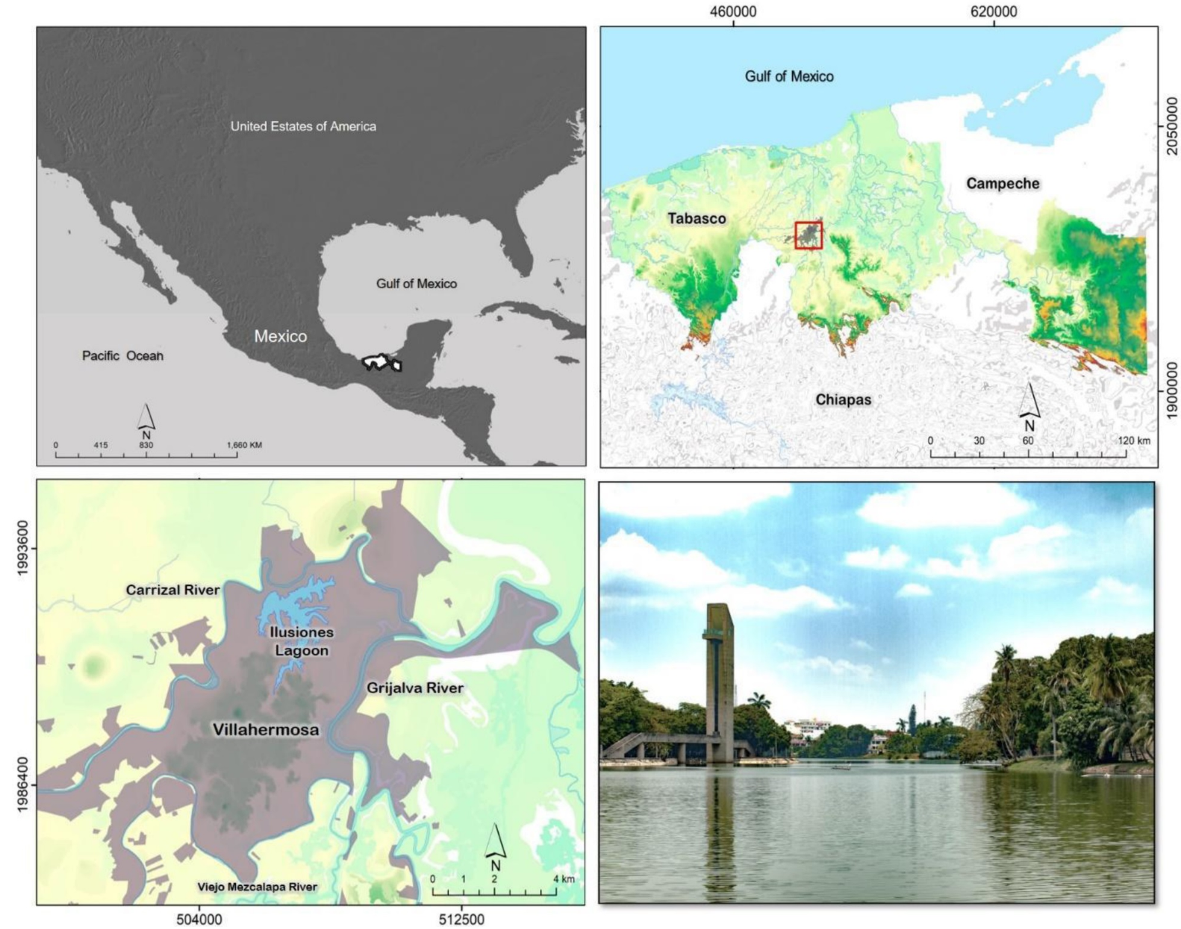

Figure 1. Location of the Ilusiones Lagoon and panoramic picture.

Figure 2. Discharge channel to the Carrizal river and its culvert with regulating gate.

river system. The first step was constructing the Digital Elevation Model (DEM); the initial and border conditions were later added to the model. HEC-RAS employs two basic modules: Ras Mapper and HEC-RAS editor. Next, the operation of each one is described in more detail.

Digital Elevation Model generation

The Digital Elevation Model (DEM) is a visual and mathematical representation of the topographic values referenced to the sea level. The DEM used here was generated from high-resolution terrain maps (5 m) from the GRID version of the National Statistics and Geography Institute of Mexico (INEGI 2020). These maps were processed with the QGIS software (QGIS Development Team 2022) and delimited the area occupied by the Ilusiones Lagoon sub-basin. The DEMs do not represent the water bodies accurately due to the signal with which they have created bounced off on the water's surface. Therefore, these areas appear without depth and must be corrected using field data. A bathymetric survey of the Ilusiones Lagoon conducted in September 2018 was used; it was made by the Water National Commission (CONAGUA).

The 2D hydraulic model generated in HEC-RAS V 6.0

Once the DEM was ready, the next step was to create the project in HEC-RAS. The module RAS Mapper was used to do it. In this module, the two-dimensional geometry is made, and the area, mesh size cells (10 m x 10 m), refinement zones, land cover (Manning's n), and soil type (permeability) are assigned. Later, the HEC-RAS geometry editor entered the control structures' geometry and the boundary conditions. The boundary conditions were: water surface level (masl) and flow (m^3s^{-1}) of the Carrizal River; and water surface level (masl) and precipitation (mm) records over the Lagoon from October 29 to November 12, 2020. During this time, the most intense rainfall was recorded, with 455 mm in 12 h, 600 mm in 24 h, and an accumulative rainfall of 780 mm in 5 d (Figure 3). The historical average precipitation records for October and November for the zone are 298.55 mm and 192.86 mm, respectively (SMN 2022), which means that in 5 d, it rained 1.5 times the accumulated precipitation of two months. In agreement with Gutierrez-Lopez (2022), this event can be categorized as catastrophic.

Calibration

The calibration of this type of model represents a significant challenge (Beleño de Oliveira *et al.* 2019) because the only data available during the 2020 event was a water level mark in the lagoon (7.4 masl). The model was calibrated with this value; however, to obtain results that are as representative as possible, a recommendation is to rely on the literature and enter as much good-quality data as possible (Dottori *et al.* 2013). In this work, in addition to the water level mark, were also considered high-resolution topographic data (INEGI), field bathymetry (CONAGUA), land cover (INEGI), soil maps (INEGI), precipitation records (SMN), and level and flow records of the Carrizal River (CONAGUA).

Scenarios

Four scenarios were simulated, and the boundary conditions used came from the 2020 flood event. Each scenario describes the lagoon's hydraulic operation and discharge to the river through different culvert designs. The scenarios were: I) Current conditions with a 1.5 m x 1.75 m culvert (Figure 4a); II) Three culverts of 1.5 m x 1.75 m (Figure 4b); III) Three culverts of 2 m x 2.5 m (Figure 4c); and IV) One large culvert of 10 m x 2.5 m (Figure 4d). The dimensions of the culverts were subject to the physical space available in the diversion channel. To assess the risk, a range from 0.20 m to 0.75 m was used, taking into account that adverse effects were observed starting at a water level of 0.20 m, in accordance with the findings of Gutierrez-Lopez (2022).

RESULTS

The results were analyzed with the RAS Mapper module. We obtained the characteristics of the hydraulic model, the water surface levels in the lagoon, the discharge flows over the Carrizal River,

E. ISSN: 2007-901X

Ecosist. Recur. Agropec. 10(3): e3756, 2023
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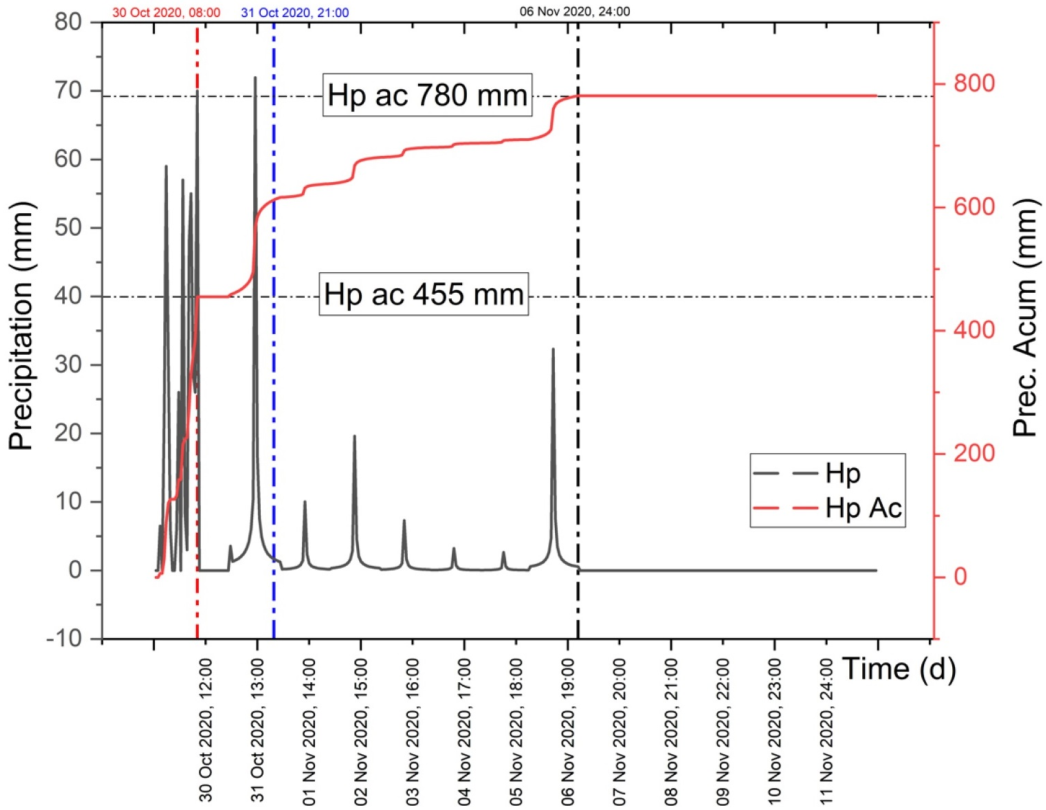

Figure 3. Rain hietograms from October 30 to November 12, 2020.

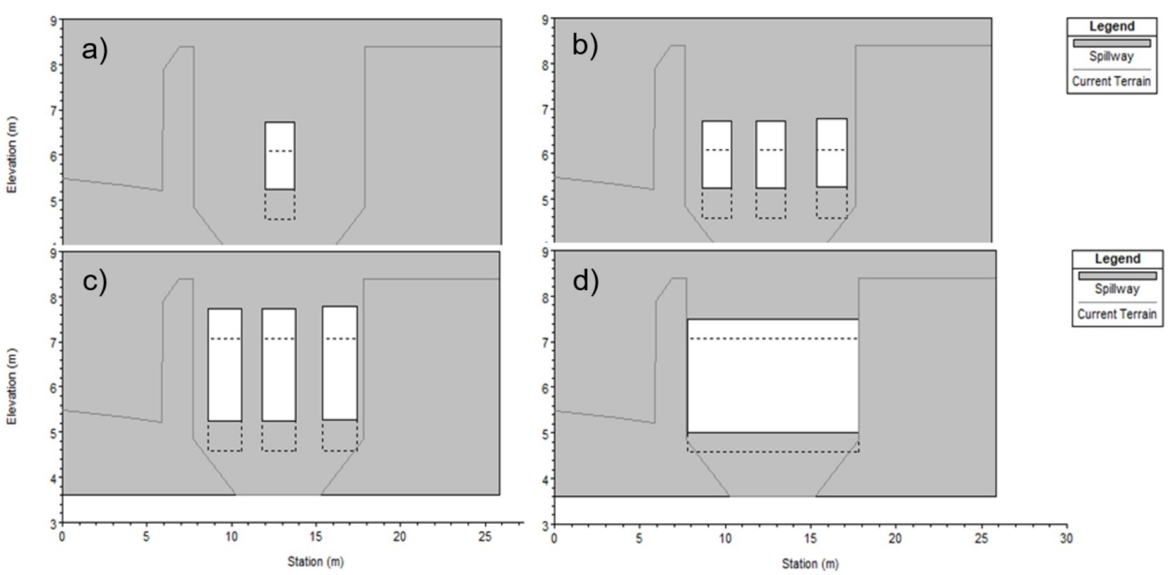

Figure 4. Proposed scenarios: a) current condition, b) three culverts with the same size of the current; c) three culverts with bigger size to the current; and d) One biggest culvert.

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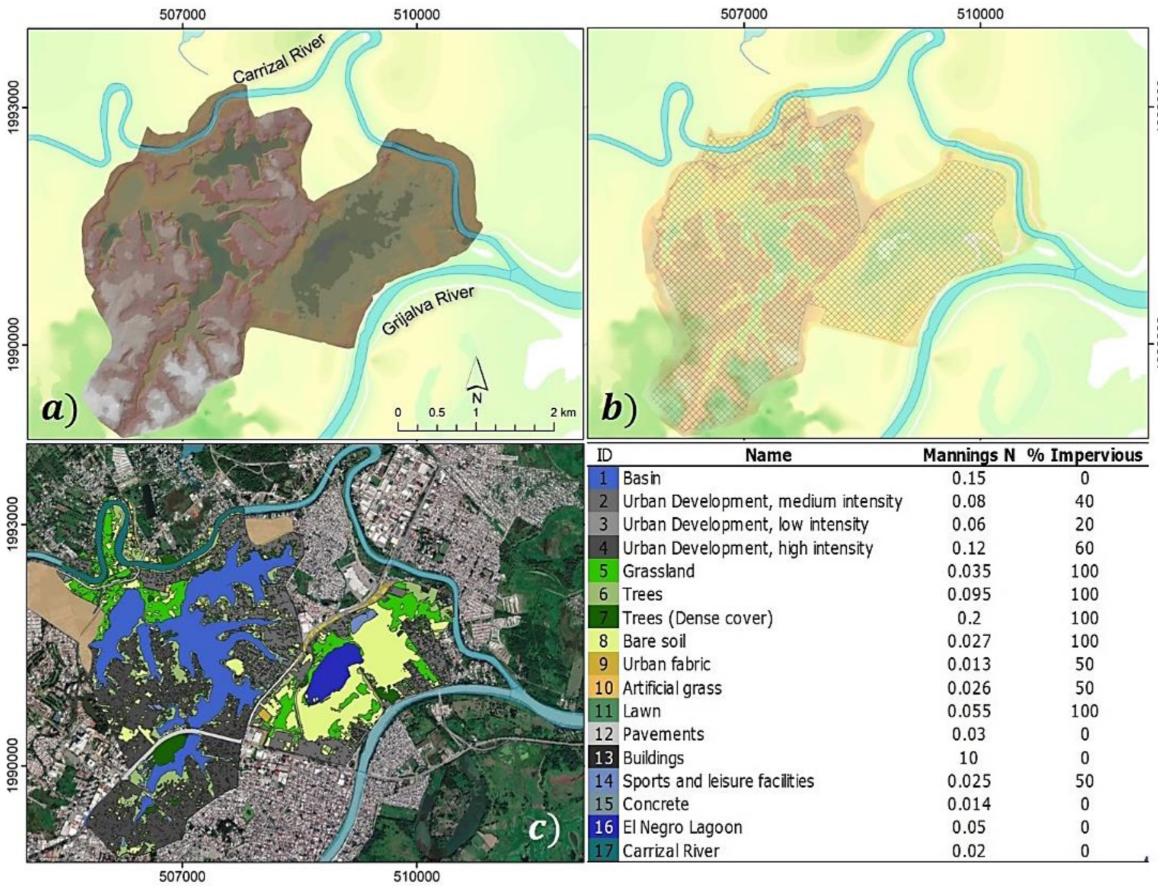

ID	Name	Mannings N	% Impervious
1	Basin	0.15	0
2	Urban Development, medium intensity	0.08	40
3	Urban Development, low intensity	0.06	20
4	Urban Development, high intensity	0.12	60
5	Grassland	0.035	100
6	Trees	0.095	100
7	Trees (Dense cover)	0.2	100
8	Bare soil	0.027	100
9	Urban fabric	0.013	50
10	Artificial grass	0.026	50
11	Lawn	0.055	100
12	Pavements	0.03	0
13	Buildings	10	0
14	Sports and leisure facilities	0.025	50
15	Concrete	0.014	0
16	El Negro Lagoon	0.05	0
17	Carrizal River	0.02	0

Figure 5. Maps developed for the simulation with HEC-RAS: a) Digital Elevation Model, b) The computational mesh, c) The layer for the Manning coefficient and impervious values.

and the risk flood map showing the effect of the proposed works.

Figure 5 presents the main characteristics developed to be used in the hydraulic numerical model. Figure 5a shows the DEM obtained and processed at the study zone; Figure 5b shows the computational mesh used in the simulations; the grid generated included 78875 cells of 10 m by 10 m length; finally, Figure 5c showed a layer with the Manning coefficients and impervious percentage for a specific area.

Figure 6 plotted in the upper part (continuous red line), the lagoon level measured during the event, and (continuous black line) the Carrizal River level. The other continuous lines are the levels on the lagoon under the different scenarios. At the bottom part, (discontinues red line) shows the water flowing through the culvert at a specific time. Values above 0 (positive values) mean the lagoon discharge to the river; otherwise, negative values mean the river discharge to the lagoon. This behavior is impossible to observe during the event because the culvert is submerged. Table 1 summarizes the maximum values.

Finally, a risk map was built with the conditions obtained from the results of scenario II. Flood depth was used to identify the areas of most significant risk. Figure 7a Shows the risk map; in blue is the safe level in the lagoon (6.40 masl). Meanwhile, in yellow and red are the potentially flood-prone areas. With scenario II (Figure 7b), the flooded areas could be reduced by 75.31%, which means 296 homes protected.

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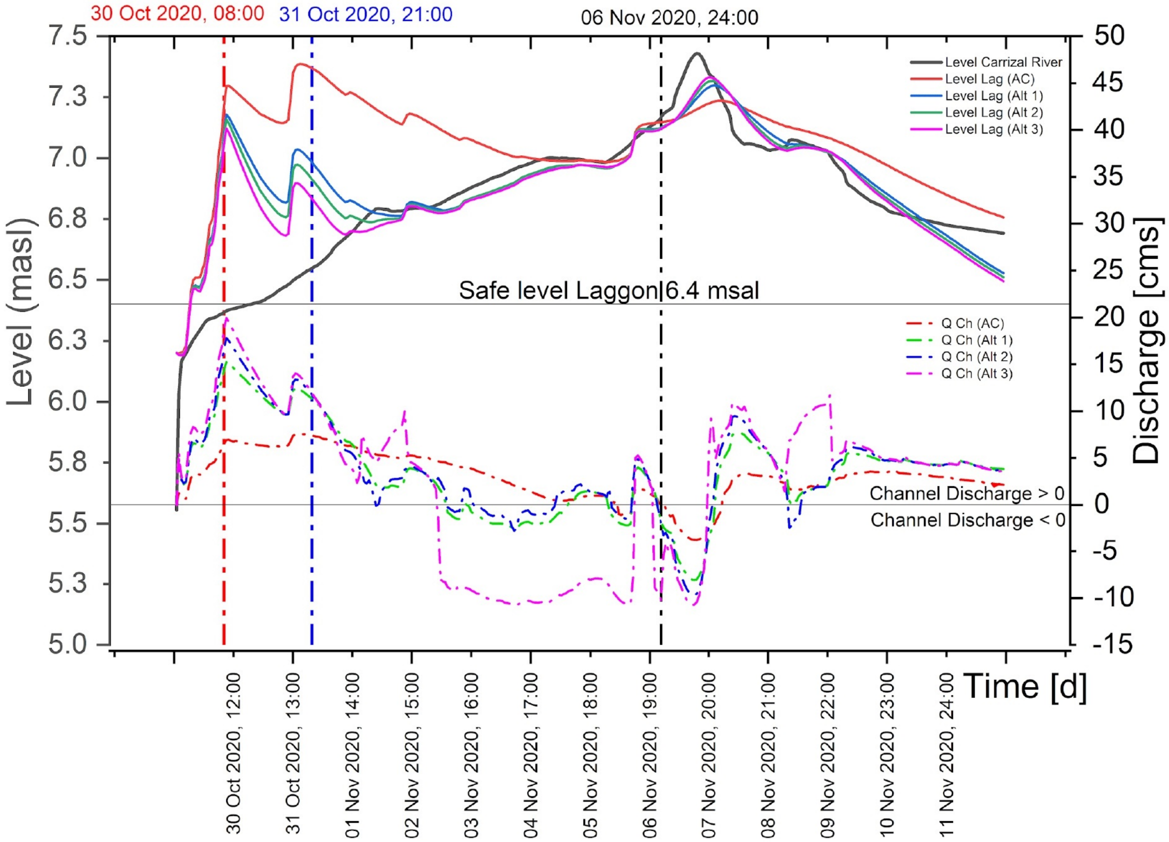

Figure 6. Results from the simulation of the 2020 event (September 28 to November 12). In the upper part the levels of the lagoon and the river; at the bottom the channel discharge.

Table 1. Summary of the simulation results.

Simulation	Culverts	Area (m^2)	Discharge Flow (m^3 s^{-1})	WSE (masl)
Scenario I	1	2.175	7.60	7.40
Scenario II	3	6.525	15.24	7.04
Scenario III	3	15.000	17.84	6.97
Scenario IV	1	25.000	20.00	6.90

DISCUSSION

As Beleño *et al.* (2019) said, the simulation of urban floods is a complicated problem due to the available data quality. However, when an adequate calibration is achieved, the results are helpful because they allow knowing and forecasting effects that, by other ways (such as measurement at the time of the event), are difficult or impossible to carry out due to the risk involved. The case analyzed here shows how the system worked during the event of 2020 and some predictions of how it could work under several scenarios. It was found that the best hydraulic performance was not the alternative with the largest regulating culvert but a smaller one due to the backwater when the river has a higher level than the lagoon. For the current conditions -scenario I-, the existing culvert had a maximum discharge of 7.60 m^3 s^{-1} to the river. This caused the lagoon to reach an elevation of 7.40 masl, which exceeds the lagoon overflow level (6.40 masl) by 1 m. Scenario II shows a significant decrease in the lagoon level, reaching 7.04 masl with a maximum discharge flow of 15.24 m^3 s^{-1}. In scenario III, the lagoon level reached 6.97 masl with a

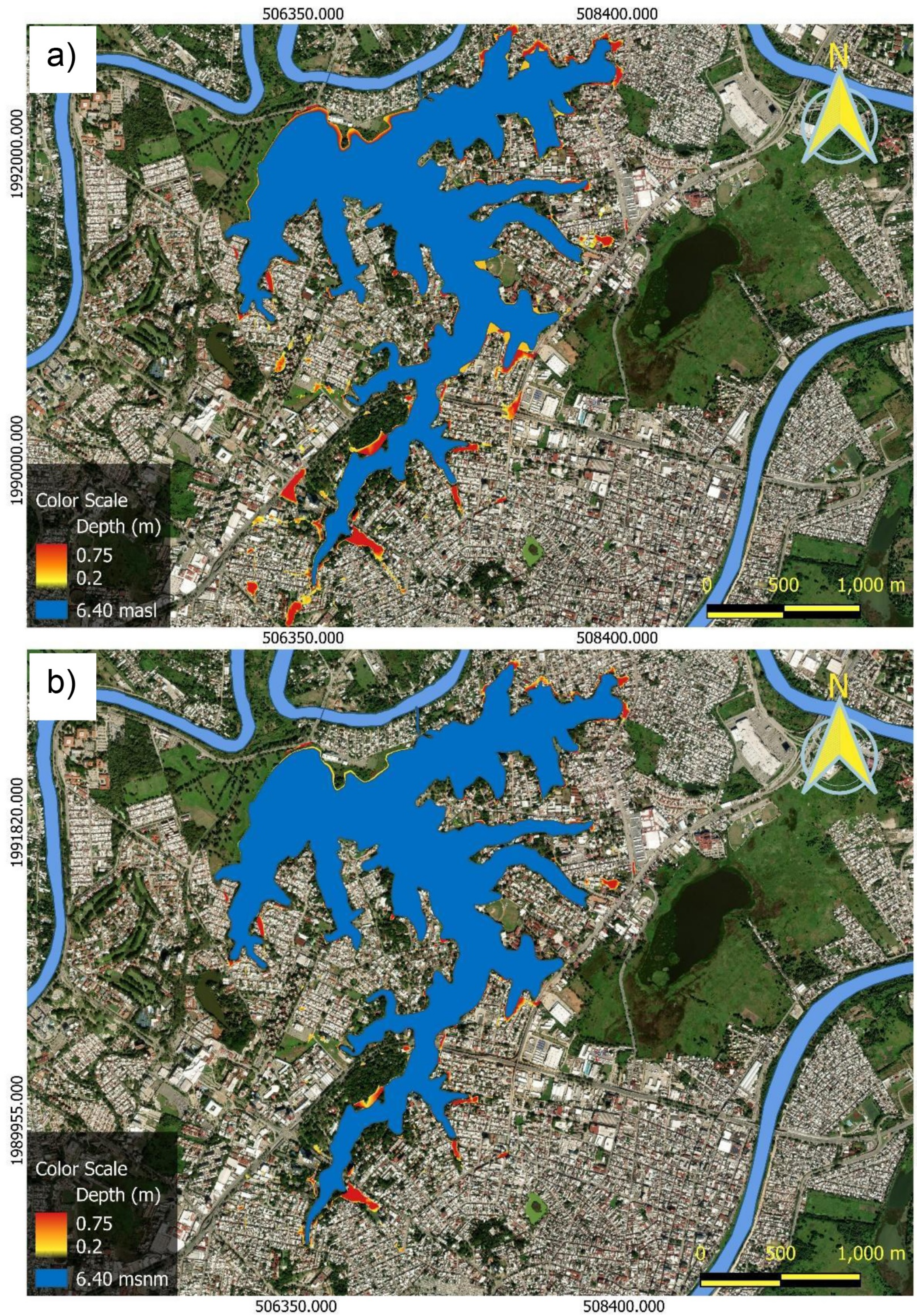

Figure 7. Risk map of the Ilusiones lagoon. a) current conditions, and b) with scenario II (The best results).

E. ISSN: 2007-901X

maximum discharge of 17.84 m^3 s^{-1}. Finally, in scenario IV, the lagoon level reached 6.90 masl and a maximum discharge of 20.00 m^3 s^{-1}. Although scenario IV shows the highest discharge and the lowest level in the lagoon, this value is only 0.14 m lower than scenario II; however, due to the dimensions of the proposed work, it would imply a higher construction cost. In addition, as shown in Figure 6, a larger size allows a greater flow of backflow from the river to the lagoon (negative discharge).

After knowing how the system works, as Mel *et al.* (2020) comment, it is possible to reduce the damages with a gate control. For example, from the results shown, it is possible to establish a management operation of the gates. Because the level on the lagoon doesn't have to exceed 6.40 masl, the gates must be kept open as long as the level of the Carrizal River is below 6.40 masl; once this level has been exceeded, the gates must be closed. It has to be closed until the level at the Carrizal River is lower than the level of the lagoon. This operation avoids the largest flooding in the neighborhoods around the lagoon. However, it has to be careful with the effect of the level on the Carrizal River because, as Moreira *et al.* (2021) said, the levels' analyses need optimization routines for every condition predicted.

Furthermore, the operations gates can be combined with a pumping station (currently nonexistent) to extract water from the lagoon to the river. It should operate when the Carrizal River's level is above the lagoon's, and it continues receiving water and increasing its level. Today, it is feasible to apply this criterion because we have results and information about how the system works. To understand the urban flooding surrounding of the Ilusiones lagoon, this paper demonstrates the effectiveness of numerical simulation as a valuable tool to analyze urban flooding, its origins, impact, and possible strategies to mitigate it through modification of hydraulic infrastructures and operation rules.

CONCLUSIONS

Through a 2D numerical simulation, the hydraulic operation of a regulation pond formed by the Ilusiones Lagoon in Tabasco, Mexico, was analyzed. It was found that under current operating conditions -one culvert- it is insufficient to deal with heavy rainfall such as the one recorded in October-November 2020. Consequently, four scenarios were modeled, considering different numbers and sizes of culverts. All these dimensions are in function of the available area of construction. It has been found that the best performance is obtained by adding two culverts with the same size as the current. This result is contrasting because this alternative was not the largest area as might be expected. The reason is that we obtain the largest discharges with the largest culvert, and when a backflow is presented, the lagoon rises quickly, and overpassing is the safety level. With the proposal used in scenario II, it is possible to reduce the affected area by flooding in 75.31%, which means 296 homes are protected. Finally, in addition to our encouraging results for managing this lagoon, a practical methodology has been presented for designers and decision-makers to evaluate hydraulic works in urban lagoons with similar characteristics to those shown in this work.

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