2020, Instituto Mexicano de Tecnología del Agua

DOI: 10.24850/j-tyca-2020-03-01

Articles

Estimating areas vulnerable to flooding in urban zones: Morelia, Michoacán, Mexico

Estimación de áreas vulnerables a inundaciones en zonas urbanas: Morelia, Michoacán, México

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Abstract

We determined areas of Morelia, Michoacán, that are vulnerable to flooding caused by the river Río Grande de Morelia, which crosses the city. A hydrological model in the river's basin and another hydraulic model on the stretch of river that goes through the city were applied.

The hydrological model was carried out with *HEC-HMS* considering the characteristics of the sub-basins such as area, lag time and number of runoff curves. The precipitations were incorporated with hyetographs for September 2013. The model was calibrated based on a gauged hydrograph at the outlet of the basin and adjusting the values of the runoff curve number until an acceptable fit was obtained between the hydrograph calculated by the model and that gauged at the basin's exit. The fit was evaluated with the criteria Nash-Sutcliffe, RMSE and Coefficient of Determination.

With the calibrated hydrological model, an event lasting 24 hours was identified and the precipitations for hyetographs were substituted by those associated with 100- and 500-year return periods estimated with the Gumbel Probability Distribution. Both events were modeled, and hydrographs were obtained.

Hydraulic modeling of the section of the Río Grande River that crosses the city was carried out with *IBER*, using the hydrographs for each return period, channel topography and Manning roughness coefficients.

The results of this last modeling allowed identification of the areas vulnerable to flooding produced by rises associated with the return periods considered.

Keywords: Model, hyetograph, automatic weather station, hydrograph, Gumbel PDF, return periods, recurrence interval.

Resumen

Se determinaron áreas vulnerables a inundaciones en la ciudad de Morelia Michoacán, causadas por el río Grande de Morelia que la cruza; esto, mediante la aplicación de un modelo hidrológico en su cuenca hidrológica y otro hidráulico sobre el río, en su tramo por la ciudad.

La modelación hidrológica se realizó con *HEC-HMS*, considerando las características de las subcuencas como área, tiempo de retraso y valores de curvas de escurrimientos. Las precipitaciones se incorporaron mediante hietogramas para septiembre de 2013. Se calibró el modelo, tomando como base un hidrograma aforado a la salida de la cuenca y adecuando valores de curva número de escurrimientos hasta tener un ajuste aceptable entre el hidrograma calculado por el modelo y el aforado a la salida de la cuenca; el ajuste se evaluó mediante los criterios de Nash-Sutcliffe, RMSE y el coeficiente de determinación.

Con el modelo hidrológico calibrado, se identificó un evento con duración de 24 horas y se sustituyeron las precipitaciones por hietogramas asociados con los periodos de retorno de 100 y 500 años, que se estimaron mediante la función de distribución de probabilidad Gumbel; se modelaron ambos eventos y se obtuvieron hidrogramas.

La modelación hidráulica del río Grande se realizó con *IBER*, retomando los hidrogramas para cada periodo de retorno, topografía del cauce y coeficientes de rugosidad de Manning. Los resultados de esta última modelación permitieron identificar las zonas vulnerables a inundaciones producidas por avenidas asociadas con los periodos de retorno considerados.

Palabras clave: modelo, hietograma, estación meteorológica automática, hidrograma, Gumbel, periodo de retorno.

Received: 05/07/2018

Accepted: 23/08/2019

Introduction

A flood is a rise of water above normal levels of a current or body of water or the accumulation of water over areas that are not normally submerged (WMO, 2011). Generally, extraordinary rainfall is the main cause of floods that endanger lives and material goods (Kidd & Huffman, 2011).

To model the rain-runoff process, we use hydrological models such as Hydrologic Engineering Center-Hydrologic Modeling System (HEC-

HMS) (USACE, 2016), among other techniques. For the transit of floods in channels and flood plains, hydraulic-type models are used (Fuentes-Mariles & Franco, 1999). A bidimensional hydraulic simulation model in channels is the *IBER* model developed by the Institute of River Dynamics and Hydrological Engineering (FLUMEN, 2010) that has the advantage of considering the topography of channels and flood plains on a grid.

In the case of the city of Morelia, the urban population has grown into flood-risk areas (Corona-Morales, 2009). In this city, multiple floods have occurred causing economic losses and destruction of infrastructure (Conagua, 2016). In this study, we determined areas of Morelia that are vulnerable to floods and propose the use of mathematical models.

Methodology

The basin was delimited up to the El Plan Conventional Hydrometric Station using *HEC-GeoHMS* (HEC-GeoHMS, 2017). This program generated a scheme formed by sub-basins, rivers and unions. Also, we determined mainly parameters, such as lag time and value of runoff curve number at the sub-basin level.

We analyzed meteorological information available from the Conventional Meteorological Stations (CMS), consisting of a set of

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instruments placed outdoors to measure weather variations, and from Automatic Meteorological Stations (AMS) that are made up of a group of sensors that record and transmit weather information automatically.

With the register of rainfall in September of 2013 from the AMS, we constructed an adimensional hyetograph and used it as the basis for generating hyetographs with the CMS. In turn, with the historic register from the CMS, we analyzed 24-hour maximums and estimated precipitations for 100- and 500-year return periods (*Tr*) with the Gumbel Probability Distribution function.

Analysis of the hydrometric information consisted of reviewing the historic record of gauges of the El Plan Conventional Hydrometric Station (CHS) with which a hydrograph was generated.

Hydrological modeling was carried out with *HEC-HMS* (2017), using the scheme of the basin. The following values were fed into *HEC-HMS*: areas, number of runoff curve values and lag time. Hydrological simulation was carried out in two parts. The first part was to calibrate the model using the hydrograph observed in the El Plan CHS as the base. In the second part, 24-hour maximum events were modeled for the return periods of 100 and 500 years.

We used *IBER* for hydraulic modeling. An uneven grid was used with channel geometry information, Manning coefficient, and hydrographs for each channel of Río Grande tributaries. With the results of the hydraulic model, we identified areas vulnerable to flooding.

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Results

The hydrological basin up to the El Plan CHS, code 12588 (19°49’10’’ N and 101°00’40’’ W), is in the northwestern part of the state of Michoacán and covers an area of 1,578.36 km². The basin was divided into 14 sub-basins as shown in Figure 1.

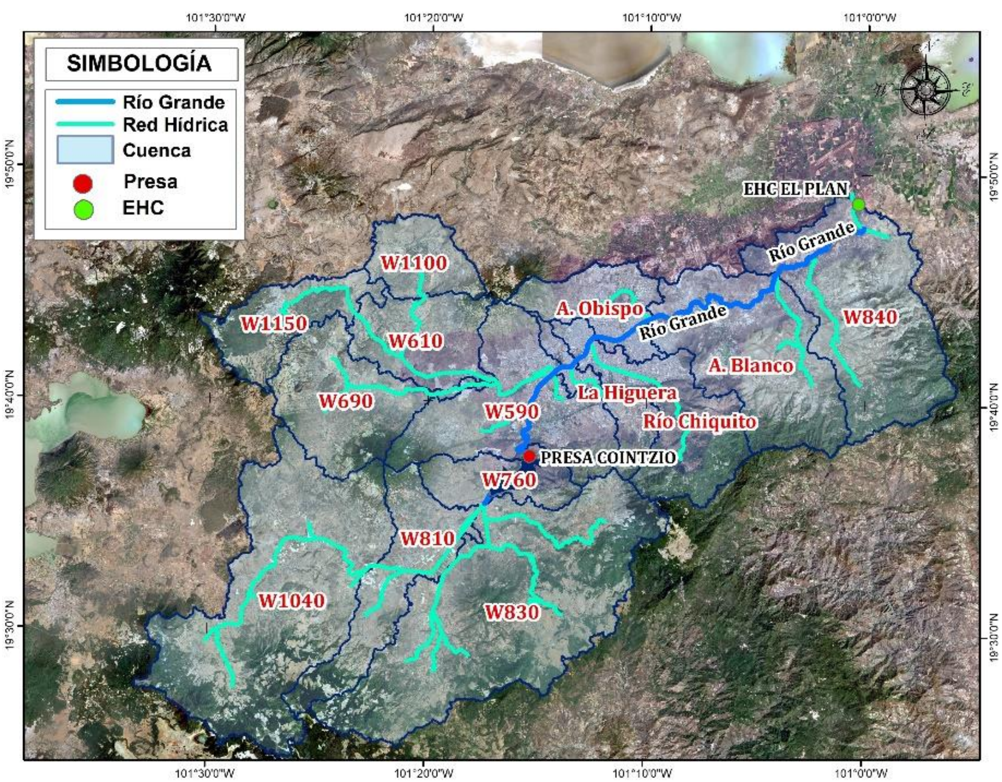

Figure 1. Location of the sub-basins.

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The hydrography in Morelia is mainly made up of the Río Grande, into which flow tributaries such as Itzícuaro River, Chiquito River, the La Higuera stream and the El Obispo stream. In the upper part of the Río Grande is the Cointzio Dam (19°37’48” N and 101°15’27” W).

Concentration times were calculated with the Kirpich formula (Conagua, 2011), and lag times were calculated considering 60% of the concentration time (USACE, 2016).

Number of runoff curve values were obtained by discretization of the edaphic distribution of the vector maps with which we determined soil texture and unit and sub-units of the predominant soil and then the soil hydrological group (A, B, C or D). Later, with land use and vegetation maps, we determined the number of runoff curve values in function of the condition of the plant cover. Table 1 shows the main characteristics at the sub-basin level.

Table 1. Characteristics at the sub-basin level.

Sub-basin	Area (km^2)	Concentration time (min)	Lag time (min)	Runoff curve number (adimensional)
W1040	260.48	308.51	185.1	77.55
W810	88.00	276.26	165.8	77.74
W830	283.27	274.47	164.7	79.08
W760	45.97	143.31	120.3	79.94

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W1150	60.11	36.68	95.0	78.06
W1100	45.47	83.18	86.0	81.18
W610	68.79	158.25	213.1	81.27
W690	99.49	200.49	22.0	79.05
W590	126.77	355.13	49.9	83.94
W840	32.29	215.64	43.6	79.9
La Higuera	95.19	72.64	123.5	91.27
Río Chiquito	149.39	205.77	282.6	82.7
A. Blanco	54.19	174.35	104.6	83.23
A. Obispo	168.94	471.07	129.4	90.19

The meteorological analysis consisted of identifying the stations near the basin. Six CMS and two AMS were found. To determine the influence of these at the sub-basin level, isohyets were generated for the month of September 2013 (Figure 2).

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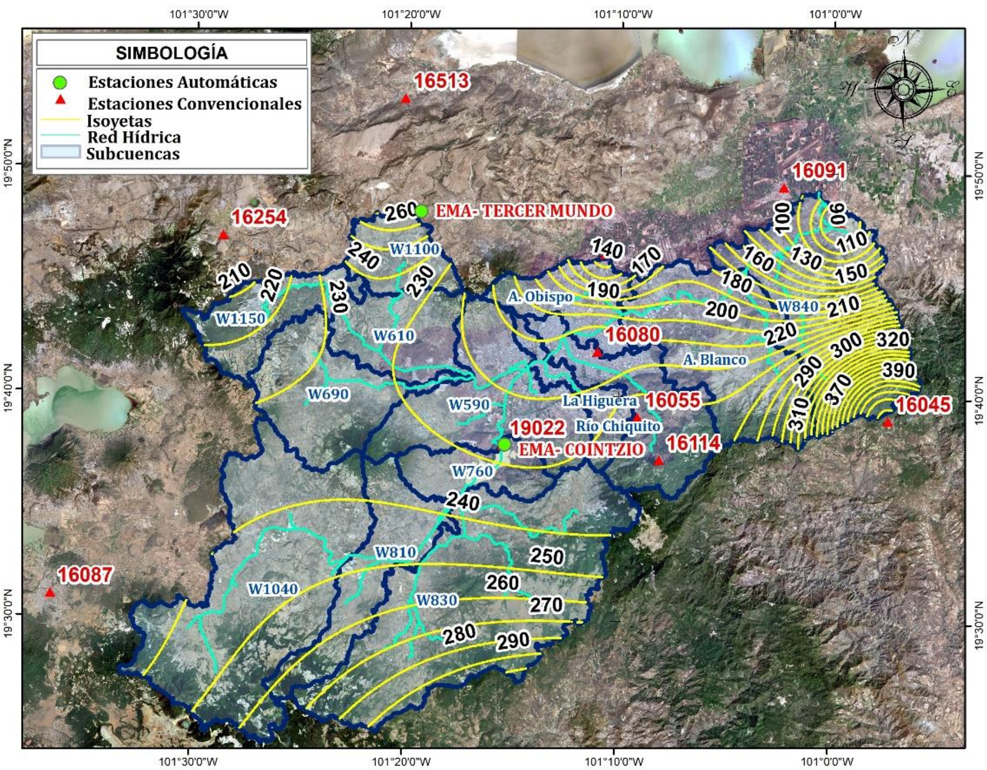

Figure 2. Isohyets for the month of September 2013.

From the isohyet analysis, a station of influence was assigned to each sub-basin. The list is presented in Table 2.

Table 2. Stations selected for each sub-basin.

Sub-basin	Station	Sub-basin	Station
W1040	AMS-Tercer Mundo/16513 El Jacal	W690	AMS -Tercer Mundo/16513 El Jacal
W810	AMS -Tercer Mundo/16513 El Jacal	W590	16105-Quirio

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W830	AMS -Cointzio/16022 Cointzio	W840	16105-Quirio
W760	AMS -Cointzio/16022 Cointzio	La Higuera	AMS -Cointzio/ 16022 Cointzio
W1100	AMS -Tercer Mundo/ 16513 El Jacal	Río Chiquito	16080-Morelia (OBS)
W1150	16254-Teremendo	Arroyo Blanco	16512-El Colegio
W610	AMS -Cointzio/16022 Cointzio	El Obispo	16512-El Colegio

We were not able to access the rainfall data to generate hyetographs with intervals of less than 24 hours. However, using the methodology of López *et al*. (2012) and the register of rainfall in some neighboring AMS outside or inside the basin (that generally report precipitation every 10 min), we assumed that the distribution in 24 hours of the daily values in the CMSs is similar to those of the AMS.

With the report from two AMS for September 2013 every 10 minutes, the temporal distribution of the precipitation was used to generate a monthly hyetograph for each AMS (dividing the ordinates of the hyetograph observed in the AMS by the total precipitation registered in the same month). These hyetographs were multiplied by the depth of total precipitation reported in the CMS for the same month. In this way, hyetographs in the CMS were obtained.

With the historical register in the CMSs for the period 1986 to 2014, 24-hour maximum precipitations and the Gumbel function (Aparicio,

1992) we obtained the CMS's expected maximums for the 100- and 500-year return periods (Table 3).

Table 3. Maximum precipitations (mm) in 24 hours for the 100- and 500-year return periods.

***Tr* (years)**	**16513 El Jacal**	**16512 El Colegio**	**16254 Teremendo**	**16080 Morelia (OBS)**	**16022 Cointzio**	**16105 Quirio**
100	94.00	86.16	83.06	101.01	85.04	73.23
500	114.47	102.60	99.78	121.55	102.11	86.78

The hydrometric analysis found that the only CHS with available useful information was 12588 El Plan. With its register of gauges in September 2013, the hydrograph in Figure 3 was generated.

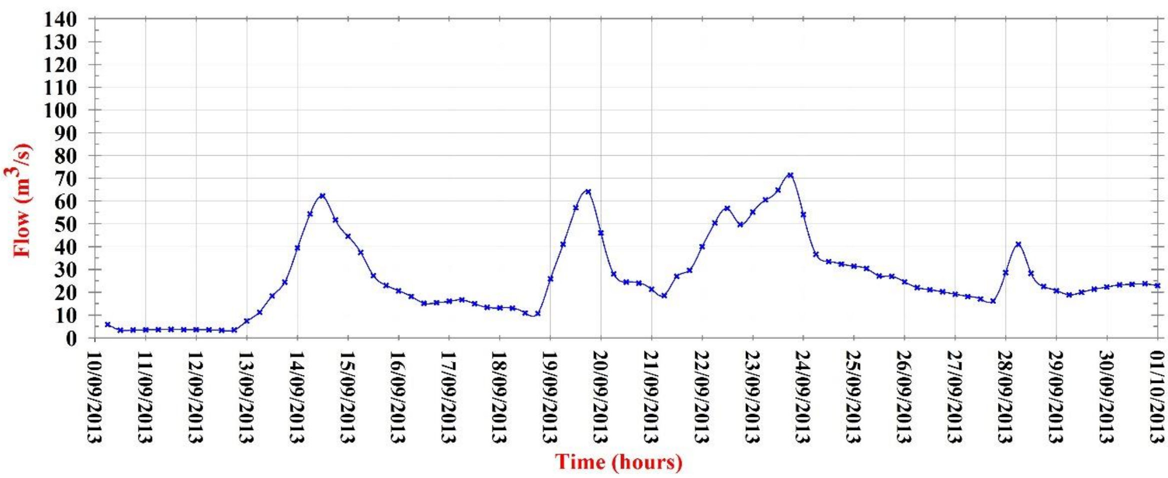

Figure 3. Hydrograph for the month of September 2013 constructed with data from the CHS El Plan.

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Hydrological modeling

Hydrological modeling was carried out in *HEC-HMS* (USACE, 2016). This program used the basin scheme integrated by sub-basins, rivers, unions and the Cointzio dam. The parameters that were fed into the model at the sub-basin level were the values of area, runoff curve number and lag times. Also, the Cointzio dam was integrated as a regulator of maximum rises and the reservoir was considered full.

The September hyetographs were input for the meteorological module, and the model was run for the entire month with 10 min intervals to obtain the simulated hydrograph. When this hydrograph was compared with the observed hydrograph (gauged) in the El Plan CHS, the peaks coincide. However, the model overestimated them. To calibrate the model, number of runoff curve number were fit for each sub-basin until an optimal value was arrived at, taking care that these values did not surpass 15%, relative to the initial proposed value (Table 4).

Table 4. Runoff curve number adjusted at the sub-basin level (adimensional).

SUB-BASIN	**RUNOFF CURVE NUMBER**		**DIFFERENCE (%)**
	ESTIMATED	**FIT**	

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W1040	77.55	71.53	7.76
W810	77.74	68.51	11.90
W830	79.08	74.42	6.00
W760	79.94	69.09	13.98
W1150	78.06	67.47	13.65
W1100	81.18	76.40	6.16
W610	81.27	71.32	12.83
W690	79.05	74.40	5.99
W590	83.94	79.00	6.36
W840	79.9	73.69	8.00
La Higuera	91.27	80.09	14.41
Río Chiquito	82.7	72.57	13.06
A. Blanco	83.23	73.03	13.14
A. Obispo	90.19	79.14	14.24

To determine the level of fit between the observed hydrograph and the calibrated hydrograph, goodness of fit tests were applied (Table 5). These parameters, mainly Nash-Sutcliffe (Moriasi *et al*., 2007), indicate that the fit of the hydrological model was found with in an acceptable range. Therefore, the calibrated values of runoff curve number for later hydrological modeling of 24-hour events and for 100- and 500-year return periods.

Table 5. Goodness of fit tests.

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Goodness of fit	Value	Score
Nash-Sutcliffe	0.273	Acceptable
RMSE	13.971	---
Coefficient of determination (r^2)	0.743	Acceptable

Figure 4 presents the graphic comparison of the observed, simulated and calibrated hydrographs.

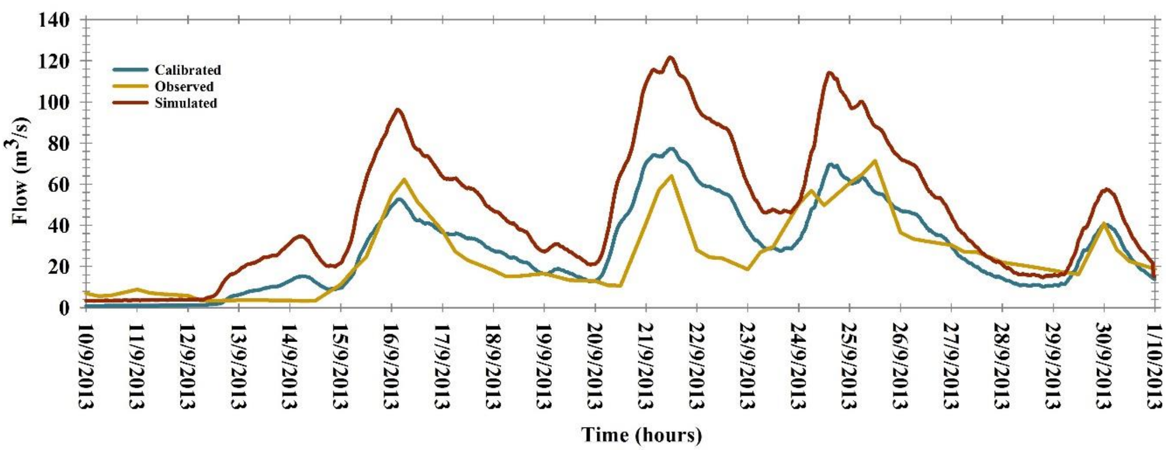

Figure 4. Comparison of observed, simulated and calibrated hydrographs.

With the calibrated hydrological model, an event that lasted 24 hours was detected from September 20 at 12:00 hours to September 21 at 12:00 hours. The adimensional hyetographs corresponding to this event (Figure 5) were multiplied by the precipitation depth associated with the 100- and 500-year return periods.

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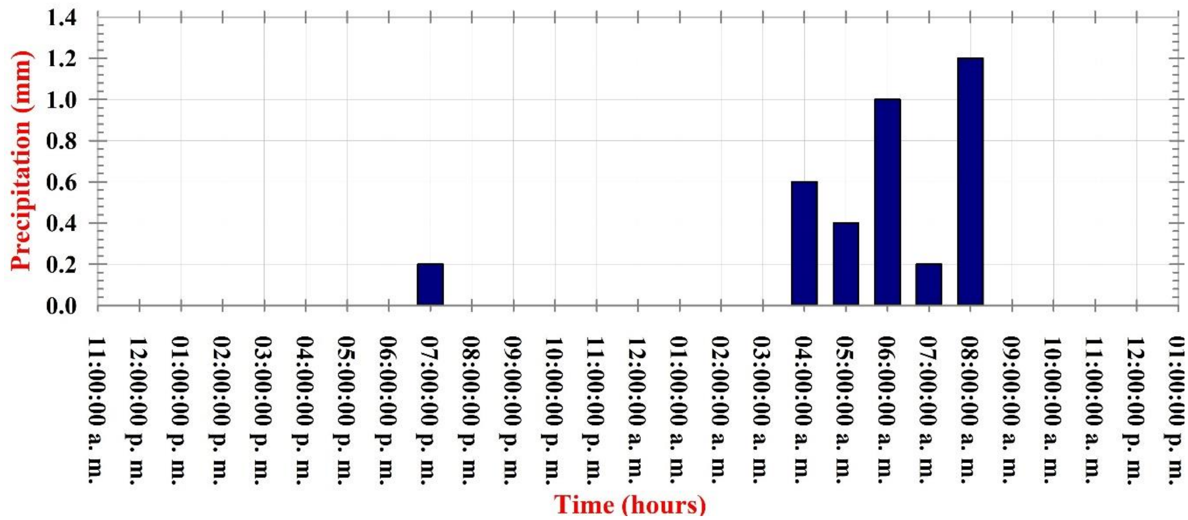

Figure 5. 24-hour hyetograph.

The hydrological model was run for the 24-hour events and the hydrographs were obtained for each sub-basin that, in turn, correspond to the tributary channels that contribute runoff to the Río Grande in its passage through the city (Figures 5 and 7).

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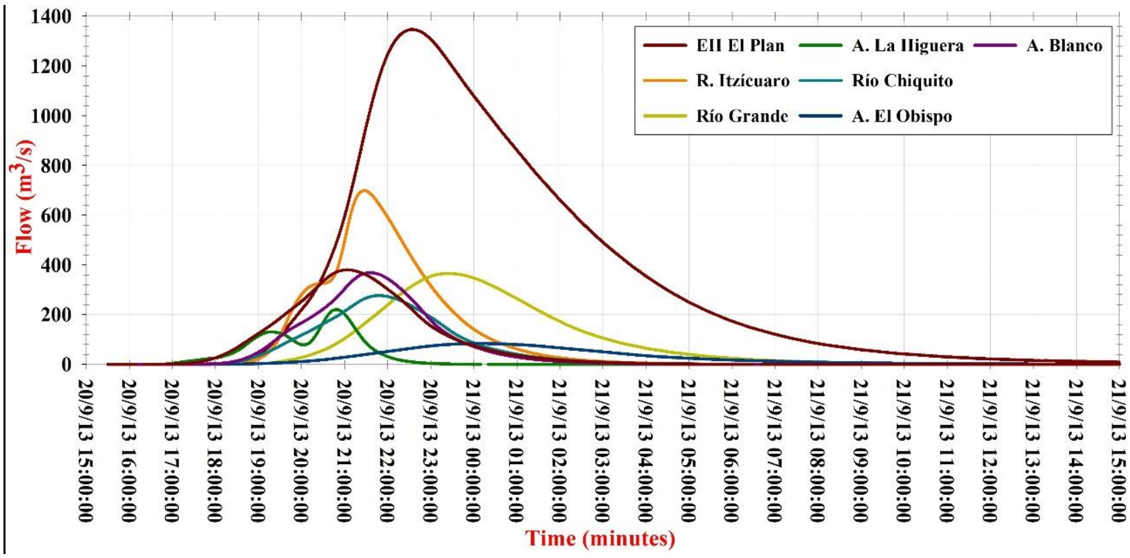

Figure 6. Hydrographs for the 100-year return period.

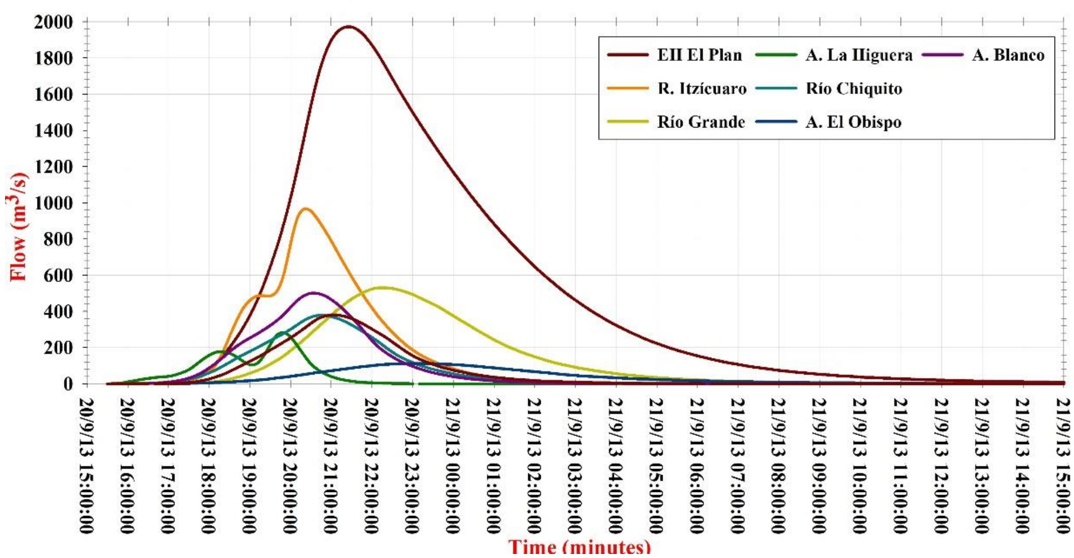

Figure 7. Hydrographs for the 500-year return period.

Hydraulic modeling

Hydraulic modeling was carried out in *IBER* software (FLUMEN, 2017), using the channel topography obtained directly in the field, and *LIDAR* (Conagua, 2016) topography was used for the flood plains.

The hydraulic model replicated the topography using a triangular-cell grid. The channel area was assigned a cell size of 5 meters, and the plains a cell size of 10 meters. The Manning roughness coefficients were also defined: 0.18 for the channel and 0.032 in the flood channels. The flow of each current was assigned using the corresponding hydrograph for the 100- and 500-year return periods.

The model transited the floods and estimated the depth and maximum peaks reached by the water in the channel area and river edges. With these results, which can be expected for the modeled return periods, the areas vulnerable to flooding are evident (Figure 8 and Figure 9). These areas correspond to highly populated neighborhoods such as the residential area San Lorenzo Itzcuaro, Amplificación del Club Campestre la Huerta, Molino de Parras, Profesor Jesús Romero Flores and the Cuauhtémoc sports complex.

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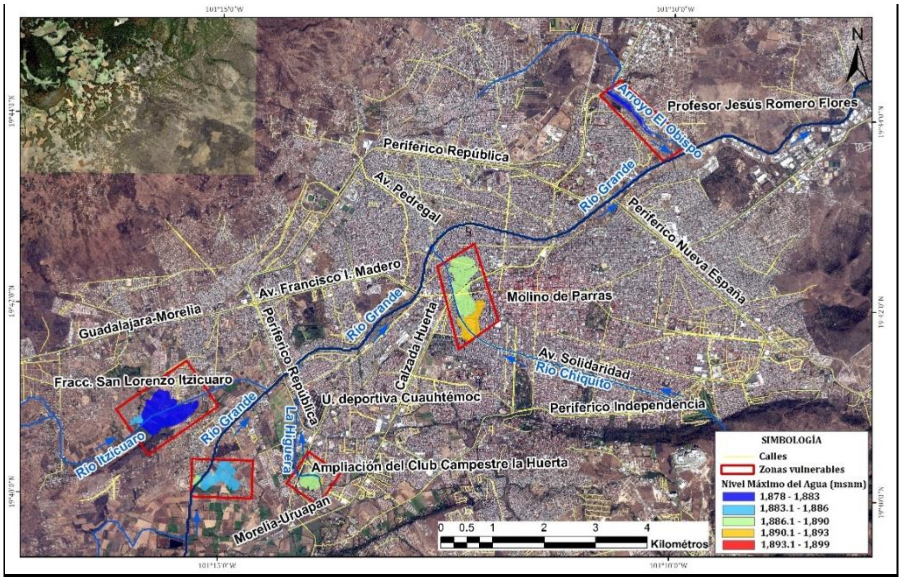

Figure 8. Visualization of hydraulic simulation. Altitude (m), *Tr* = 100 years.

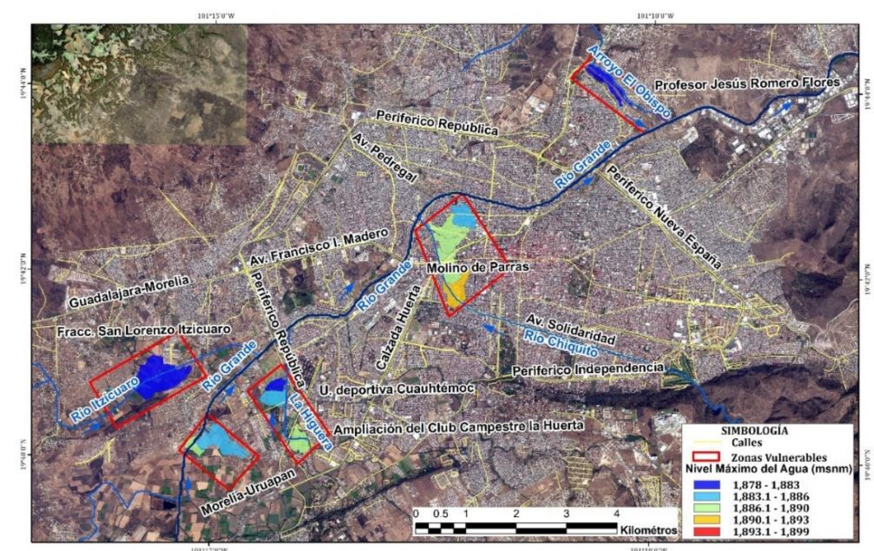

Figure 9. Visualization of hydraulic simulation. Altitude (m), *Tr* = 500 years.

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Discussion

In the analysis, precipitations were distributed using the hyetographs of the AMS applied to the CMS; in recent years radar (Méndez-Antonio, Magaña, Caetano, Da-Silveira, & Domínguez, 2009; Méndez-Antonio, Domínguez-Mora, Magaña-Rueda, & Carrizosa-Elizondo, 2006; Magaña-Hernández, Bâ, & Guerra-Cobián, 2013) and satellites (Zubieta, Getirana, Espinoza, Lavado, & Aragón, 2017; Zubieta, Laqui, & Lavado, 2018) have been implemented. Although it is certain that these technologies will be used in the future, we decided not to use them, and we implemented one suggested by López *et al*. (2012).

The vulnerable areas determined in this study correspond to 100- and 500-year return periods. Corona-Morales (2009) reported what was published in the Risks Atlas of Morelia (Figure 10). In this report, a model of water depth distributed every 25 cm was carried out by analysis of peaks and identification of areas flooded in 2003. It should be noted that in this study the rain-runoff model was not used. But, because the storm was observed and the affected areas were identified, it was possible to consider problems derived from stagnating water resulting from

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obstruction by garbage. Evidently, most of the areas do not coincide with those determined in our study.

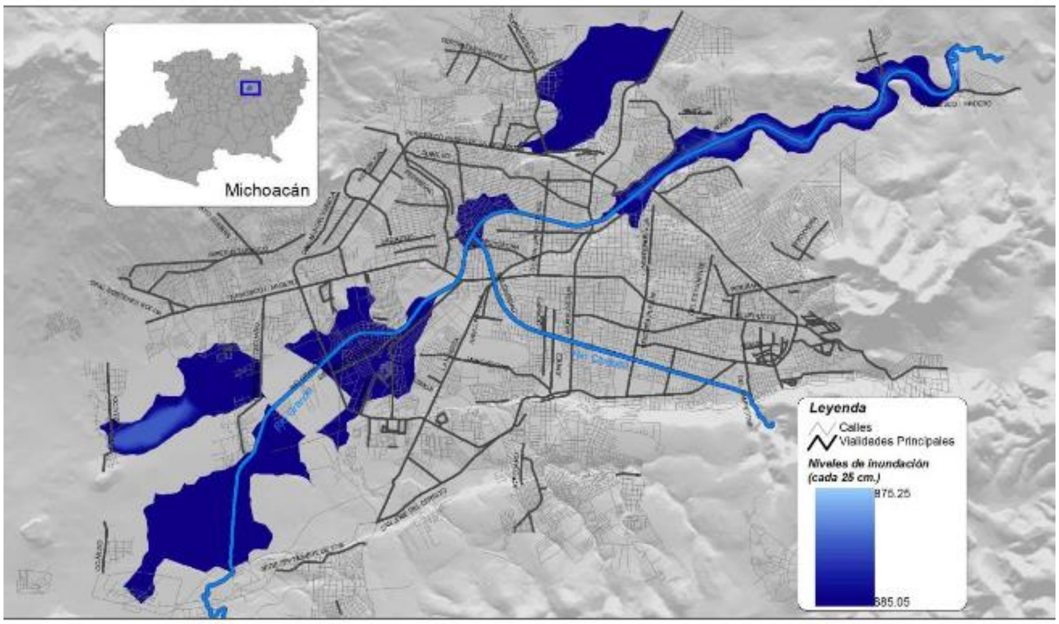

Figure 10. Model of water depth distribution every 25 cm. *Risk Atlas of Morelia*. Source: Corona-Morales (2009).

Another study by Roblero-Hidalgo (2018) defined areas vulnerable to flooding using a rain-runoff model for a continuous event from January 2013 to January 2014. Given that in our study we used return periods, the flooded areas coincide, but the estimates for the return periods cover more extensive areas.

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Conclusions

The methodology proposed for identification of areas vulnerable to flooding contemplated the use of models. One was hydrological in *HEC-HMS*, which used as input hyetographs generated from information registered in the AMS and CMS, sub-basin scheme, runoff number curve values and lag times. This model was calibrated on the basis of a hydrograph gauged in the El Plan CHS and goodness of fit tests. According to the Nash-Sutcliffe criterion, it was an acceptable model.

The other model was hydraulic in *IBER*, for which hydrographs and a topographic grid were input. With this model, areas of the city of Morelia, Michoacán, that are vulnerable to flooding were identified for the 100- and 500-year return periods.

The models used, *HEC-HMS* and *IBER*, are highly powerful and robust for estimation of the rain-runoff process and transit of rises in the urban channels. However, they require specific information that is difficult to access in Mexico.

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