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Articles

Hydrological simulation of the Laja River basin with the WEAP model

Simulación hidrológica de la cuenca del río Laja con el modelo WEAP

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Abstract

The Laja River basin is located between parallels 21° 32' 58", 20° 16'14" N, and meridians - 100° 6' 28'' - 101° 30'44" W. In 2014, the basin was classified with a high degree of pressure on the water resource (Conagua, 2014). It also ranked second as an administrative hydrological region with the highest population density, and it presents strong problems with supply and demand. All the previous reasons motivated this work. The objective was to calibrate, validate and estimate runoff surface, considering the effects of changes in precipitation, Therefore, a Hydrological modeling was performed in WEAP (Water Evaluation and Planning) using the soil moisture method. The information used was on soil use and physical characteristics; crop coefficients; average monthly data on precipitation; average temperatures; relative humidity; and wind speed. The calibration and validation processes were carried out at four points in the basin, for five years on a monthly period. The hydrometric stations were Puente Dolores, Begoña II, Tres Guerras and Pericos. For each station, the coefficient of determination (r^2) and Nash-Sutcliffe efficiency index (NSE) were estimated. The values obtained in the calibration phase were an r^2 of 0.8 to 0.82 and NSE from 0.55 to 0.77. In the validation phase, the values for r^2 range from 0.65 to 0.86 and NSE from 0.57 to 0.75. Climate information was generated with WGEN for 10 years, to generate runoff scenarios, with the RCP8.5 projections, for the period 2012-2022. In conclusion WEAP is a software capable of correctly simulating, with the soil moisture method, the response of the Laja River basin. WEAP correctly simulated flows measured in gauging station with an average absolute error of less than 10 %.

Keywords: hydrological modeling, WEAP, calibration, validation, runoff, Laja River.

Resumen

La cuenca del río Laja se localiza entre los paralelos 21° 32′ 58″, 20° 16′ 14″ N y los meridianos -100° 6′ 28″ -101° 30′ 44″ O; en 2014 fue clasificada con grado de presión alto sobre el recurso hídrico (Conagua, 2014); ocupó el segundo lugar como región hidrológica administrativa con mayor densidad de población, y presentó fuertes problemas con oferta y demanda del recurso, lo que motivó llevar a cabo este trabajo. Se realizó una modelación hidrológica en WEAP (*Water Evaluation and Planning*) con el método de humedad del suelo. El objetivo fue calibrar, validar y estimar escurrimientos superficiales, considerando efectos del cambio en precipitación. Se utilizó información de uso y características físicas de suelo, coeficientes de cultivo y datos mensuales promedios de precipitación, temperaturas medias, humedad relativa, velocidad del viento. Los procesos de calibración y validación se efectuaron en cuatro puntos de la cuenca para un periodo de cinco años por mes en las siguientes estaciones hidrométricas: Puente Dolores, Begoña II, Tres Guerras y Pericos; para cada una de ellas se estimó el coeficiente de determinación (r^2) e índice de eficiencia Nash-Sutcliffe (NSE), y se obtuvieron valores de r^2 de 0.8 a 0.82, y de NSE de 0.55 a 0.77 en calibración, y r^2 de 0.65 a 0.86 y NSE de 0.57 a 0.75 en validación. Se generó información climática con WGEN para 10 años, para generar escurrimientos con las proyecciones del escenario RCP8.5 para el periodo 2012-2022. Se concluye que WEAP es un *software* capaz de simular correctamente la respuesta de la cuenca del río Laja con el método de humedad del suelo. WEAP simuló correctamente los flujos medidos en la estación de medición con un error absoluto medio inferior al 10 %.

Palabras clave: modelación hidrológica, WEAP, calibración, validación, escurrimientos, río Laja.

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Introduction

Water is a precious natural resource, vital for life, development, and the environment. It can be a matter of life and death, depending on how it occurs and how it is managed (Hamlat, Errih, & Guidoum, 2013). Changes in temperature and precipitation affect hydrological processes and water availability for agricultural areas, hydropower, industrial sectors, and people. Climate change will accelerate the hydrological cycle, increasing temperature and evapotranspiration and changing precipitation. Surface flow will be affected by the changes in precipitation intensity, distribution, and frequency (Rochdane, Reichert, Messouli, Babqiqi, & Khebiza, 2012).

Hydrologic modeling has become an indispensable component in water resource research and management. Hydrologic models help to understand the current and past status of water resources in a watershed. They also provide a way to review implications of management decisions; and imposed changes, such as climate change (Johnston & Smakhtin, 2014).

The WEAP (Water Evaluation and Planning) model of the Stockholm Environment Institute (SEI, 2015) analyzes water availability and demand. The model provides a framework to assess sectoral demands, water conservation measures, allocation priorities, aquifer functions, and project costs and benefits Yates, Sieber, Purkey, Huber-Lee, & Galbraith, 2005b). It is especially useful when comparing changes in hydrological

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scenarios (Höllermann, Giertz, & Diekkrüger, 2010; Harma, Johnson & Cohen, 2012). Also, it is used to evaluate adaptation options in urban areas (Bonelli, Vicuña, Meza, Gironás, & Barton, 2014; Yates, Miller, Wilby, & Kaatz, 2015a).

The potential scenarios that can be analyzed are of different types: land use, climate, population growth, or change. Climate scenarios are the most used aspects of a WEAP model. The input the model requires are the changes/variations in temperature and/or precipitation based on projections from climate models and polarized data for the region (CCG, 2009; SEI, 2015).

The WEAP model is used in different parts of the world, for example, the Korean Institute of Construction Technology used WEAP as a tool to assist their long-term water supply planning, surface water quality modeling, and benefit-cost analysis (Choi, Kim, & Lee, 2012). On the other hand, the water plan of California is built upon the application of WEAP. These provided a framework of options for water managers, policymakers, and the public so they can make decisions regarding the future of California's water (Savage *et al*., 2004). Meanwhile, in Guatemala, the model was used to estimate vulnerability to climate change (Magaña, 2005).

WEAP is applied in different places of Mexico. In the Guayalejo-Tamesí river basins, Tamaulipas (Sánchez-Torres-Esqueda, Ospina-Noreña, Gay-García, & Conde, 2011) the impact of climate change was addressed by developing short-, medium-, and long-term scenarios, that

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measure the variability of water availability. In the Grande/Bravo River basin (Sandoval-Solis & McKinney, 2009) a collaborative modeling process was used for water resource planning and to evaluate scenarios. In the Sextín or Oro River watershed, located in central-northeastern Durango, Mexico, the impact of weather patterns, were evaluated on watershed runoff (Esquivel, Nevárez, Velásquez, Sánchez, & Bueno, 2017).

In Mexico, large rivers compose a great number of basins, inhabited by dispersed population groups, that exert strong pressure on scarce resources, such as water resources. The Laja river basin in Guanajuato has these characteristics in its upper region, which impacts its middle and lower region (Torres-Benites, Mejía-Sáenz, Cortés-Becerra, Palacios-Vélez, & Exebio-García, 2005). Water resource planning, in the Laja River Basin, is an immediate necessity. Since, over the years, water resource management is fixed to water supply needs, without prior hydrological analysis of the basin’s behavior. This causes problems in resource availability, especially in the lower regions of the basin, that severely affect the agricultural sector (Palacios-Vélez, & López-López, 2004). The objective of this work was to perform, calibrate, validate, and estimate surface runoff using a hydrological simulation that uses the "Soil Moisture Method". Meanwhile, estimating the effects of climate change with the RCP8.5 scenario projections.

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Materials and methods

Study basin

The Laja river basin (Figure 1) located between parallels 20°16'14" 21°32' 58" N and meridians -100° 06' 28" -101°30'44" W. It belongs to hydrological region number 12 called "Lerma Santiago". The water resource management belongs to Administrative Hydrological Region VIII "Lerma Santiago Pacifico". According to Campos (1998) classification, the basin is classified as extremely large (11 912 km^2). There are 32 municipalities in the Laja River basin, 9 municipalities have the largest proportion: Dolores Hidalgo (14 %), San Miguel de Allende (13 %), San Felipe (9 %), San Luis de la Paz (8 %), San Diego de la Unión (7 %), El Marqués (6 %), Querétaro (6 %), Celaya (5 %) and Comonfort (5 %). The Laja River is a tributary of the Lerma River. It originates in the San Juan hill, where the river is called the Nuevo Valle de Moreno River. After the river crosses the railroad stations Obregón, Guanajuato, the name changes to the Laja River (DOF, 2003).

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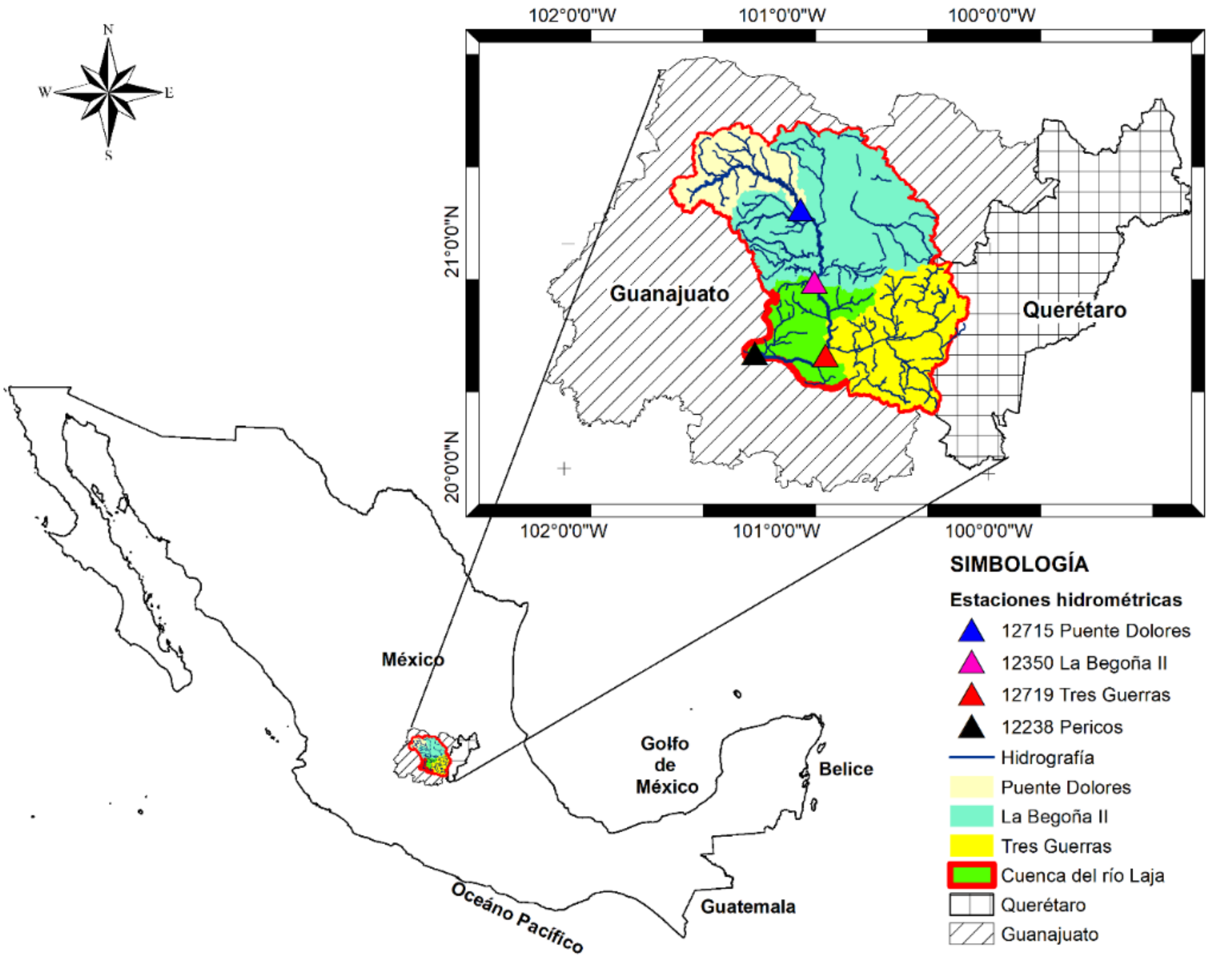

Figure 1. Location of the study area. Own elaboration with information from CONAGUA and INEGI.

Weather

Monthly climatic variables were used from historical series of precipitation and mean monthly temperature recorded at 44 conventional climatological stations, EMCs. They are distributed throughout the basin (Figure 2) (SMN, 2009). Relative humidity and wind speed values were obtained from the network of automatic weather stations, EMAs, of the Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP, 2016). Cloud cover was taken empirically. For the construction of the model, climate information required by WEAP were monthly values.

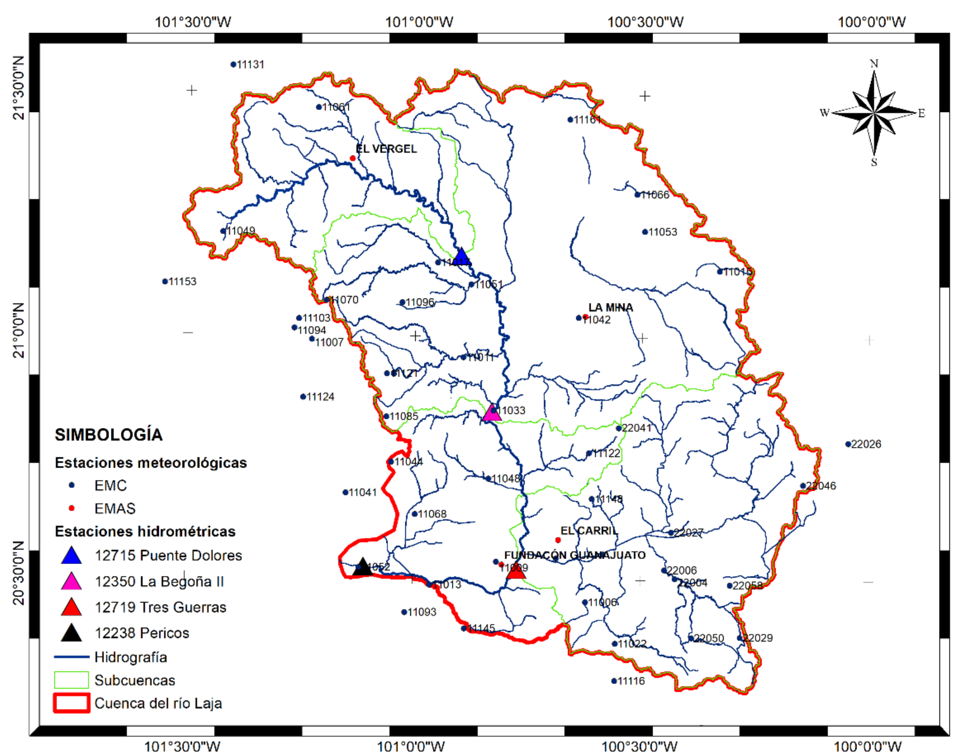

Figure 2. Climatological stations. Own elaboration with information from SMN (2009).

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Hydrometry

Three sub-basins and the Laja river basin were bounded by the 4 existing conventional hydrometric stations, EHCs. The hydrometric information was obtained from the National Surface Water Bank (Conagua & IMTA, 2008). The used data is the historical monthly average flows measured in the four existing EHCs, present in the basin (**¡Error! No se encuentra el origen de la referencia.**). Five years of monthly flow data were used to calibrate and validate the model.

Table 1. Hydrometric stations in the basin ((Conagua & IMTA, 2008).

Key	**EHC name**	**Drained area (km^2)**	**Long W**	**Lat. N**
12715	Puente Dolores	1711	-100.90	21.17
12350	La Begoña II	4984	-100.83	20.85
12719	Tres Guerras	5849	-100.77	20.52
12238	Pericos	9651	-101.11	20.53

The Soil Moisture Method, used in the WEAP hydrological model, requires detailed hydrological and climatic parameters. The parameters used were: crop coefficient (Kc) acquired from Allen, Pereira, Raes and Smith (2006) and the vegetation and cropping pattern of DR 085 "La Begoña"; water storage capacity in the root zone (Sw) from different types of soil cover present in the Laja river basin; deep zone water storage capacity (Dw); runoff resistance factor (RRF); root zone conductivity (ks); deep zone conductivity (kd); preferential flow direction (f); initial moisture in the root zone (Z1) and initial moisture in the deep zone (Z2). The values of the parameters were submitted in percentage and absolute values. The adjustments made to the variables were based on the ranges established by the model and from similar studies of the basin hydrological schemes (Flores-López, Galaitsi, Escobar, & Pukey, 2016).

The WEAP model parameter values for the Laja River basin were build using the soil moisture method parameters, present in other studies done in the American continent (Amato, McKinney, Ingol-Blanco, & Teasley, 2006; Flores-López *et al*., 2016; Febrillet-Huertas, José-Clases, Bello, & Chalas, 2014) (Table 2).

Table 2. Parameters used in the hydrological model of the Laja river basin.

CLASS	Kc	Sw (mm)	Dw (mm)	RRF	Kd (mm/ month)	f	Z1 %	Z2 %

Agriculture	1.2	330	330	2	200	0.4	30	30
Forest	0.8	400	400	4	200	0.4	30	30
Waterbodies	0.7	100	100	1	200	0.4	30	30
Shrubland	0.8	100	100	2	200	0.4	30	30
Grassland	0.6	330	330	3	200	0.4	30	30
Jungle	0.7	400	400	4	200	0.4	30	30
Urban area	0.7	100	100	1	200	0.4	30	30

Land use and vegetation

The land use and vegetation information for each sub-basin was obtained from the vector layer series IV of land use and vegetation scale 1:250 000 (INEGI, 2010). The Laja river basin has eight land use classes: agriculture (51.2 %), grassland (21.25 %), forest (11.9 %), jungle (6.23 %), shrubland (6.0 %), urban area (2.3 %), bare soil (0.7 %), waterbodies (0.5 %).

Soil moisture method

The soil moisture method is the most complex method modeled in WEAP. It is based on empirical functions that describe the evapotranspiration behavior, surface runoff, infiltration, baseflow, and the deep seepage of a watershed (SEI, 2015). The model considers the movement of water through two vertical soil layers (Figure 3). The first layer embodies water retained near the surface, which is available to roots. The second layer represents a deeper layer in which water is transfer into the baseflow or groundwater recharge. The main parameters of this model for each layer are the water holding capacity and the saturated hydraulic conductivity (Yates *et al*., 2005b; Yates, Sieber, Purkey, Huber-Lee, & Galbraith, 2005c; SEI, 2015). The model calculates the water balance of a watershed using the inflows, outflows, and storage changes in each layer for each sub-basin.

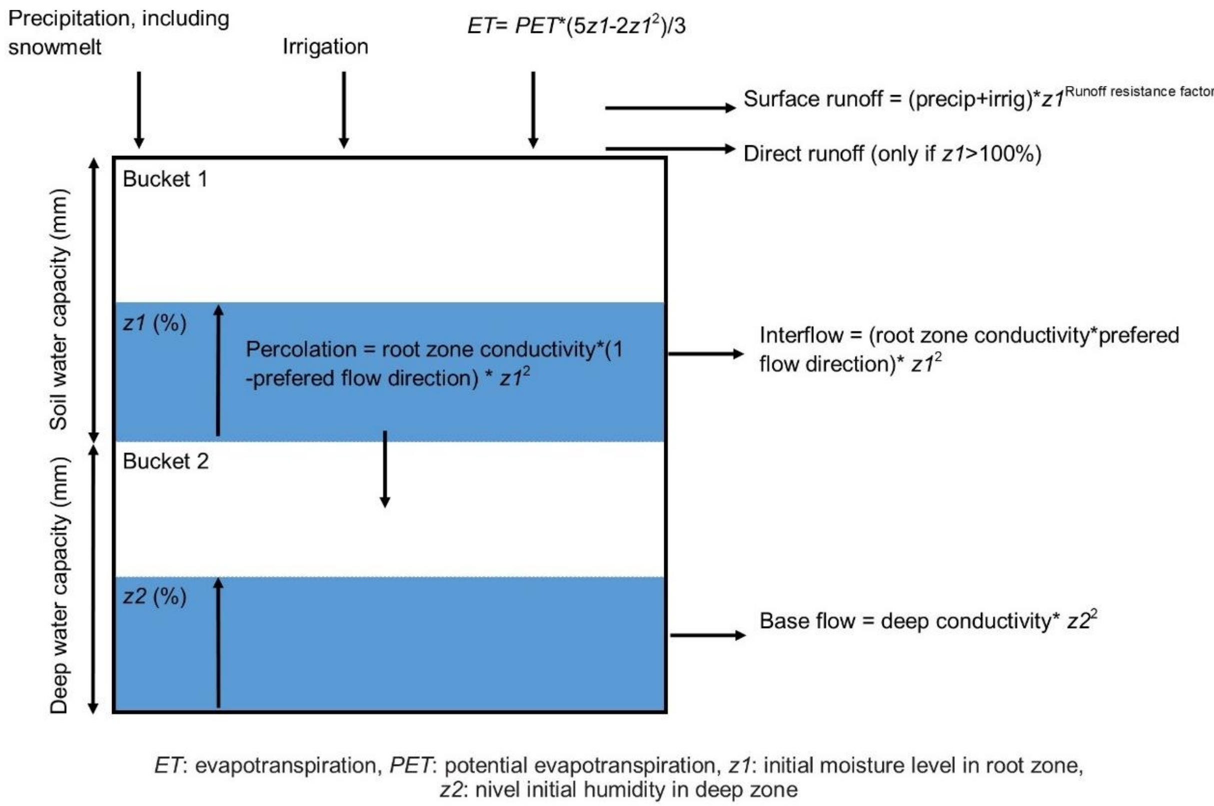

Figure 3. Hydrologic elements modeled in WEAP (CCG, 2009).

In the first layer the changes in soil moisture are established by the effective precipitation minus the reference evapotranspiration, surface runoff, infiltration, and percolation. A watershed unit is divided into “N” fractional areas by sub watershed representing different land uses/soil types. Therefore, the water balance is calculated for each fractional area, “j” of “N”. The climate is assumed to be unvarying in each sub-basin, and the water balance is assumed as (SEI, 2015):

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$$Rd_j \frac{dz_{1_j}}{dt} = Pe(t) - PET(t)k_{c,j}(t)\left(\frac{5z_{1,j} - 2{z_1}^2{}_{,j}}{3}\right) - Pe(t){z_{1_j}}^{RRF_j} - f_j k_{s,j} {z_1}^2{}_j - (1 - f_j) k_{s,j} {z_1}^2{}_j \quad (1)$$

Where:

$Rd_j \frac{dz_{1_j}}{dt}$ = change in soil moisture in layer 1 of area j (mm).

$Pe(t)$ = effective precipitation in time t (mm).

$PET(t)$ =potential evapotranspiration for area j at time t.

k_{c_j} = crop coefficient for j area.

$Z_{1,j}$ = relative storage fixed as a fraction of the total effective storage of the root zone layer for j area.

RRF_j = runoff resistance factor (0-1000). Runoff decreases with higher values.

$Pe(t){z_{1_j}}^{RRF_j}$ = surface runoff.

$F_j k_{s,j} {z_1}^2{}_j$ = infiltration of the first layer for the j area.

$(1 - f_j) k_{s,j} {z_1}^2{}_j$ = percolation.

F_j = coefficient related to soil, type of land cover and topography that defines the direction of the flow in layer 1 (0-1).

$K_{s,j}$ = estimated saturated conductivity in root zone (mmh^{-1}).

(t) = time.

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The change in storage of the second layer is calculated with:

$$S_{max}\frac{dz_2}{dt} = \left[\sum_{j=1}^{N}\left(1-f_j\right)k_{s,j}{z_1}^2{}_{,j}\right] - k_{s,2}{z_2}^2 \quad (2)$$

Where:

S_{max}= the deep percolation of storage in the upper layer.

k_{s_2} = the saturated hydraulic conductivity of the lower storage layer for j area is given as a single value for the basin (mm/time).

f_j = coefficient related to soil, the type of land cover and topography that defines the direction of the flow in layer 2 (0-1).

$z_{2,j}$ = is the relative storage fixed as a percentage of the effective storage of the bottom soil layer for j area.

Methodology

Hydrologic modeling

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The watershed and sub-watershed hydrological modeling was delimited using a digital elevation model DEM with a resolution of 15 m, a scale of 1:50 000 (INEGI, 2013). The methodology for the hydrological modeling in WEAP was performed with the steps shown in the diagram of Figure 4.

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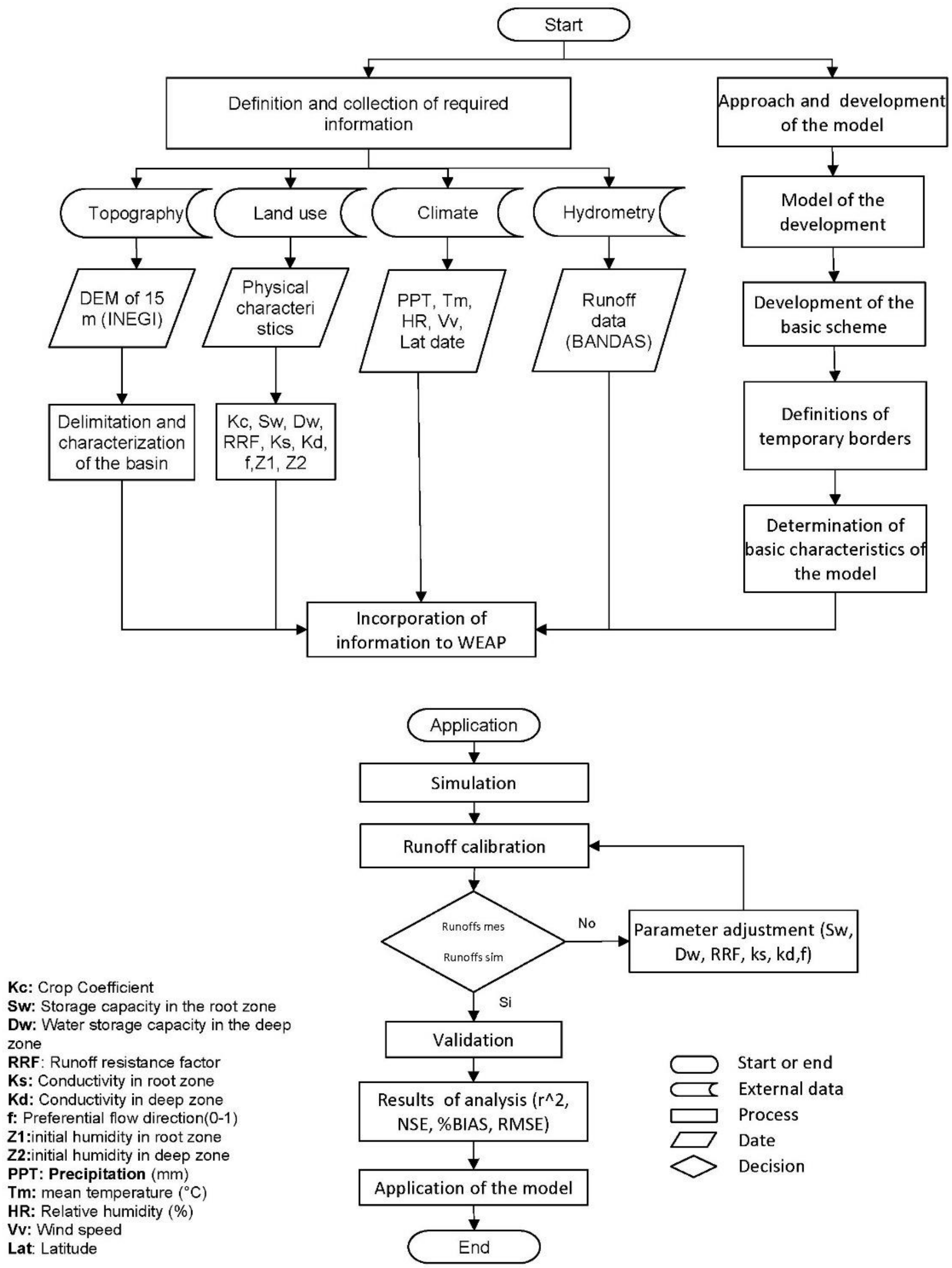

Figure 4. Diagram of the methodology to calibrate and validate the WEAP model in the Laja river basin, Guanajuato, Mexico.

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Construction of the hydrological model of the Laja river basin in WEAP

The model was elaborated with the interaction of natural and anthropogenic elements, which are comprised of parameters. The required parameters and information of the model were defined and afterward submitted into the WEAP model interface. The first simulation was carried out with the required parameters. In the resulting sub-basin and basin model, we spotted if the precipitation peaks in the EMCs and the flows in the EHCs were correctly repeated. The model was calibrated, after it was developed and had acceptable results.

Calibration

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The calibration process consists of adjusting the model parameters until the model output values match the current observed data (Cabrera, 2012).

The calibration compared the runoff measured at the outlet of each sub-basin with the runoff simulated by WEAP. This calibration was performed for the period 1989-1993 because it was the most recent period with a continuous record of data at all hydrometric stations.

Validation

Refsgaard and Knudsen (1996) define model validation as "the process of demonstrating that the model is capable of making predictions at a specific location for periods outside the calibration period". In this study, the validation was performed with hydrometric information from five years (2001-2005 for the Begoña II, Tres Guerras, and Pericos EHCs and 1984-1988 for the Puente Dolores EHC). The data correspond to the five years with the most recent information available. To measure, in the calibration and validation, the predictive efficiency of the hydrological modeling, the most frequent indicators are Coefficient of Determination (r^2), Mean Absolute Error (MAE), Percentage Bias (%BIAS), and Nash-Sutcliffe Efficiency Coefficient (NSE) (Ahmed, 2012).

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Results and discussion

The hydrological model was developed, calibrated, and validated for the sub-basins and basin of the Laja River; with precipitation information from the EMCs and from four conventional hydrometric gauging stations. The parameters that presented greater sensitivity and that were adjusted within the model are soil moisture-holding capacity (SWC), root zone conductivity (RZC), flow resistance factor (RRF), and preferential flow direction (PFD). These parameters characterize the soil and its horizons and, it is information that is scarce in our country.

The result obtained in the modeling is affected by the quality of the underlying data.

The error obtained between simulated, and the measured flows is less than 10 % on average.

Calibration

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The goodness-of-fit tests applied during calibration to the results of the hydrologic model of the Laja river showed a good correlation between the flows simulated by the WEAP model and those observed in the EHCs Puente Dolores, La Begoña II, Tres Guerras and Pericos (Figure 5). The Nash-Sutcliffe statistical indices = 0.55, 0.6, 0.77 and 0.74 and r^2 of 0.82, 0.88, 0.81, 0.8 respectively show this correlation (Table 3).

Table 3. Goodness-of-fit measures for the calibration in the Laja river sub-basins and basin.

Test	**EHC Puente Dolores**		**EHC Begoña II**		**EHC Tres Guerras**		**EHC Pericos**	
	V	**C**	**V**	**C**	**V**	**C**	**V**	**C**
r^2	0.82	J	0.88	B	0.81	J	0.78	J
NSE	0.55	B	0.64	M.B	0.77	M.B.	0.74	M.B.
PBIAS	-125.28	S.E.	26.5	Sub.E.	-57.01	S.E.	-77.34	S.E.
MAE	5.2	N.A.	11.2	N.A.	12.22	N.A.	17.55	N.A.

EHC= Conventional hydrometric station, V= Value, C= Classification, J=Fair, B=Good, M.B.= Very Good, E=Excellent, J=Fair N.A.=Not Applicable, S.E.=Overestimation, Sub.E=Underestimation.

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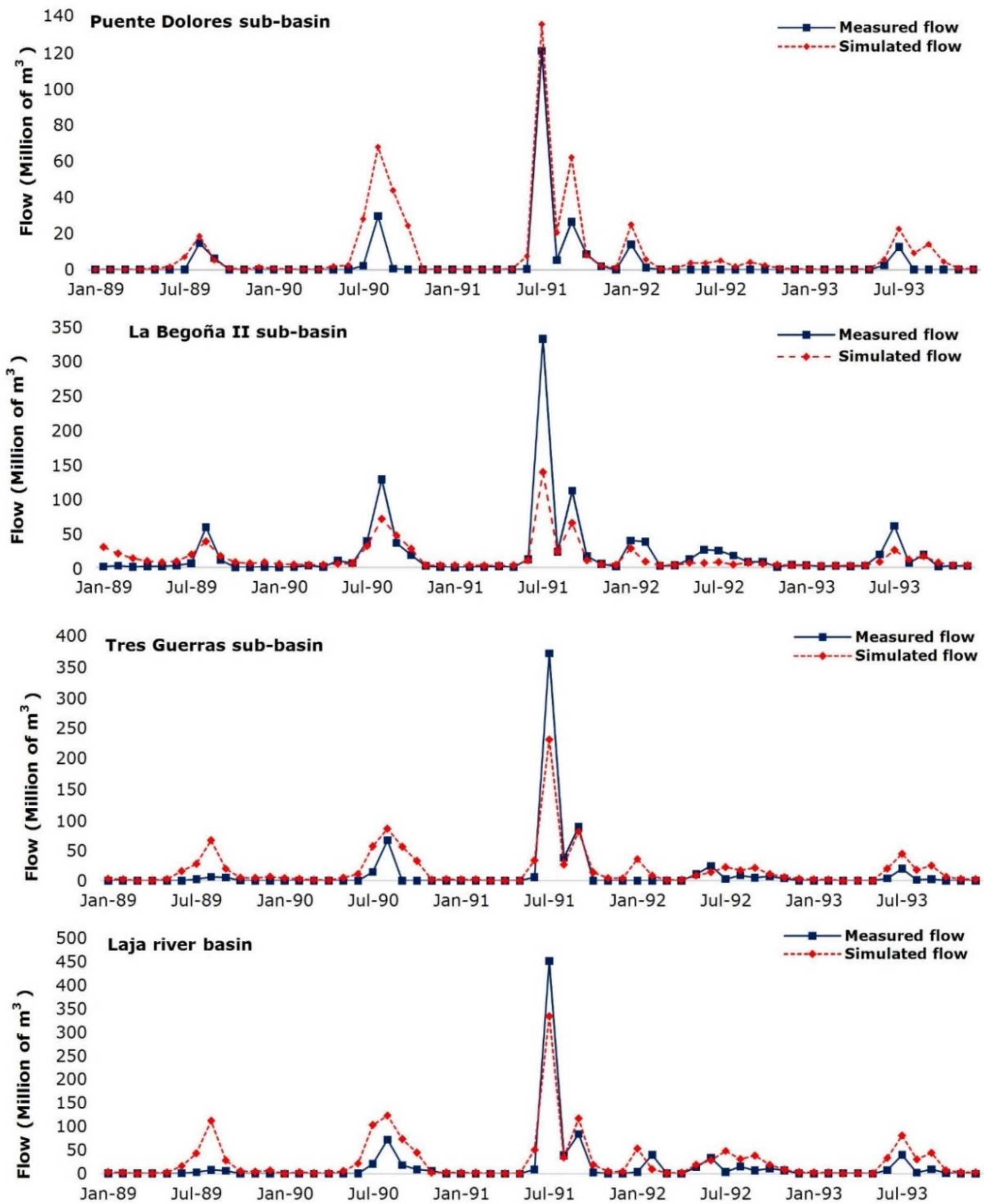

Figure 5. Measured and simulated flow in the WEAP calibration process in the Laja river sub-basins and basin.

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The classification of Molnar (2011), NSE values less than 0.2 indicates that the fit is insufficient; between 0.2 and 0.4 is satisfactory; between 0.4 and 0.6 is good; between 0.6 and 0.8 is very good; and greater than 0.8 is excellent. The coefficient of determination was classified based on Andersen, Refsgaard and Jensen (2001).

The results in the calibration display that the model overestimates small flows but underestimates large flows in all sub-basins and at the general level. The MAE deviation increased depending on the location of the hydrometric stations in the basin. The smallest error occurred at Puente Dolores EHC, located in the upper part of the basin, and the largest error at the Pericos EHC set at the outlet of the basin.

Validation

The goodness-of-fit measures validated the process using data from the EMCs for the period precipitation of 1984-1988 (Puente Dolores sub-basin) and 2001-2005 (La Begoña II, Tres Guerras and Pericos). The coefficient of determination obtained ranged between 0.65 and 0.86 in the hydrometric stations. The Nash-Sutcliffe coefficient in the hydrometric

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stations is very good based on the classification of Molnar (2011). The PBIAS was mainly negative, which indicates an overestimation of the model (Table 4).

Table 4. Goodness-of-fit measures for validation in the Laja river sub-basins and basin.

Test	EHC Puente Dolores		EHC Begoña II		EHC Tres Guerras		EHC Pericos	
	V	C	V	C	V	C	V	C
r^2	0.65	P	0.86	B	0.79	J	0.71	J
NSE	0.64	M.B.	0.62	M.B.	0.75	M.B.	0.57	M.B.
PBIAS	-22.23	S.E.	26.1	Sub.E.	-31.84	S.E.	-89.79	S.E.
MAE	3.67	N.A.	11.0	N.A.	10.88	N.A.	16.67	N.A.

EHC= Conventional hydrometric station, V= Value, C= Classification, J=Fair, B=Good, M.B.= Very Good, E=Excellent, J=Fair N.A.=Not Applicable, S.E.=Overestimation, Sub.E=Underestimation.

The results of the validation process for the Laja River sub-basins and basin (Figure 6) show the same behavior as in the calibration. In general, the model overestimates, but not in peak flows.

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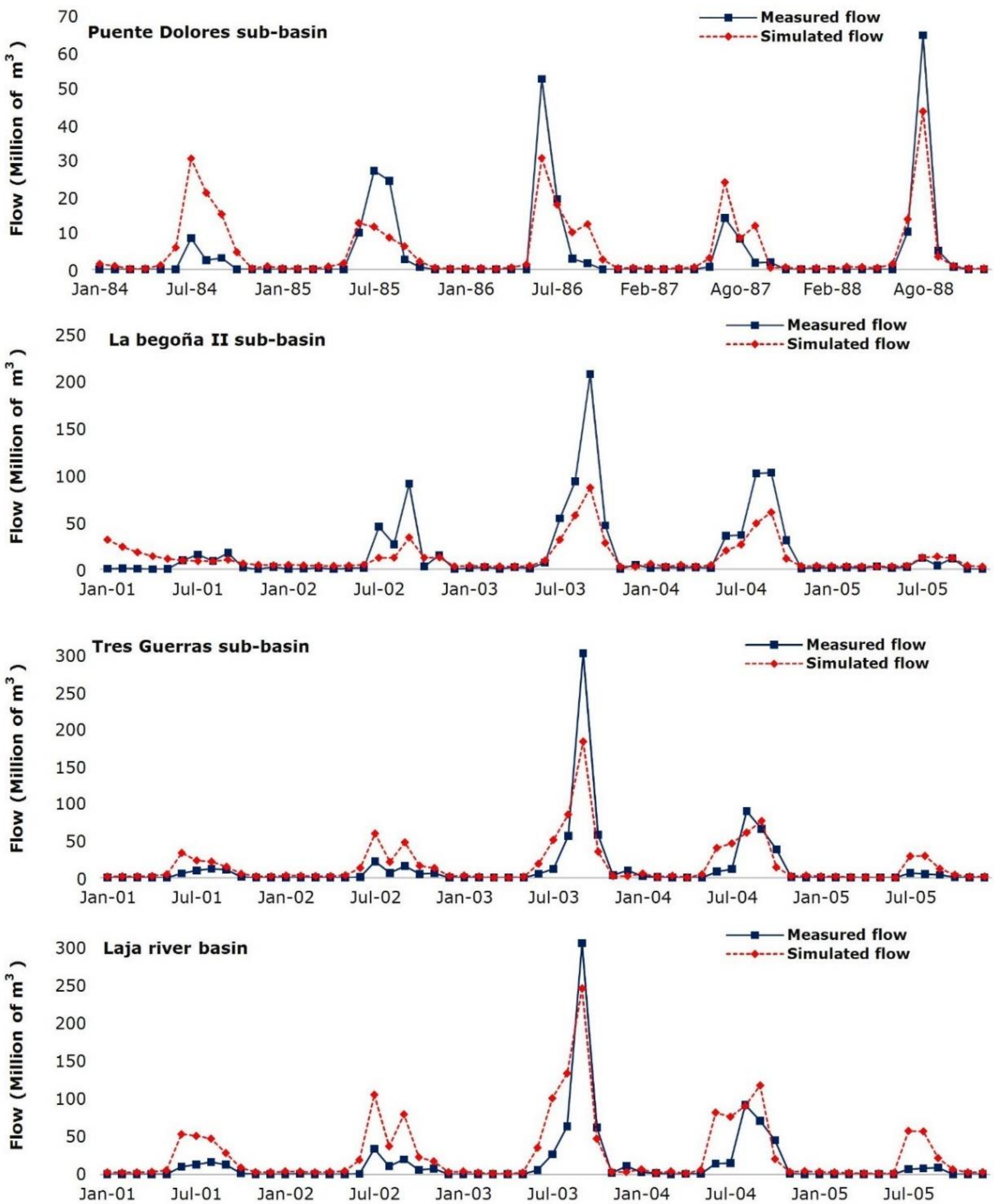

Figure 6. Observed and simulated flow in the WEAP validation process in the Laja river sub-basins and basin.

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Climate change scenario

The modeled runoff corresponds to the projections of scenario RCP8.5. Time series for the Laja river basin was generated from the climatic variables of temperatures and precipitation. The modeling process was performed, and the runoff behavior at the control points was observed.

The evaluation of the RCP8.5 scenario required the use of the stochastic weather generator *WGEN*, developed by the Agricultural Research Service of the United States Department of Agriculture (Richardson & Wright 1984). It uses monthly and annual statistics to generate daily synthetic time series of precipitation, minimum temperature, maximum temperature, and solar radiation. This weather generator is included in the *Weatherman* module present in the *Decision Support System for Agrotechnology Transfer (DSSAT)* (Hoogenboom *et al*., 2017).

A climate scenario was carried out for the period 2012-2022, based on 30 years of data. The generated daily climate variables were precipitation, minimum temperature, maximum temperature, and solar radiation. Subsequently, necessary processes were implemented to obtain monthly variables.

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Scenarios were generated for each sub-basin. The information generated from the calibrated model substituted the climatic data, which allowed the runoff to be estimated based on the estimated precipitation (Figure 7). The RCP8.5 scenario only includes climate change without modifying the land use.

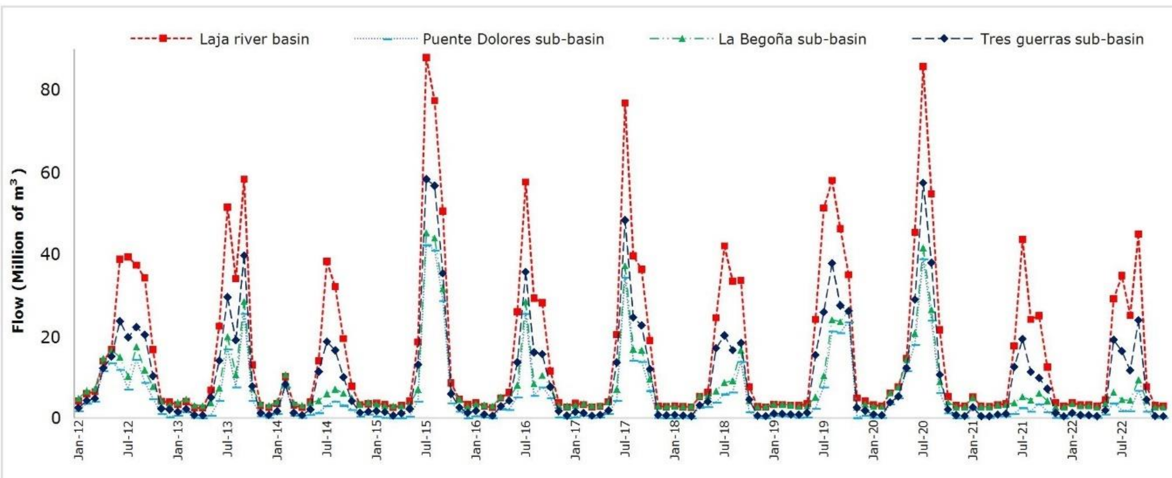

Figure 7. Flows obtained from the scenario with precipitation change.

The average simulated annual runoff obtained with the RCP8.5 scenario projections in the Laja river basin is 184.26 hm^3 for the period 2012- 2022. Palacios-Vélez and López-López (2004) mention that the arithmetic mean of Laja river basin runoff is 183.982 hm^3. This data confirms what Bolongaro-Crevenna *et al*. (2016) argue, that the RCP8.5 scenario estimates minimal changes in the total amount of precipitation.

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Conclusions

Hydrological models are a suitable tool to simulate the processes occurring in a basin. The results obtained from them facilitate decision-making and implementation of public policies that seek the efficient use and development of water resources.

The result obtained from the application of the WEAP tool for the Laja river basin indicates that the soil moisture method accurately reproduces the response of the basin. As proven with the NSE, PBIAS and r^2 efficiency indices.

The model was calibrated and validated for five years in each of the sub-basins of the Laja river basin. In contrast with the measured flow, the model calculates higher flows, but not at peak flows where WEAP underestimates the flows.

It is essential to mention that one of the advantages of WEAP, being a conceptual-physical model, is the amount of data required for its input. It demands fewer data in comparison with other hydrological models. However, the variation range of the values of the parameters that integrate the model is not defined.

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Referencias

Ahmed, F. (2012). A hydrologic model of kemptville basin calibration and extended validation. *Water Resources Management*, 26(9), 2583-2604. DOI:10.1007/s11269-012-0034-0

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (2006). *Estudio FAO riego y drenaje 56. Evapotranspiración del cultivo (guías para la determinación de los requerimientos de agua de los cultivos).* Roma, Italia: Food and Agriculture Organization of the United Nations. Recuperado de http://www.fao.org/3/a-x0490s.pdf

Amato, C. C., McKinney, D. C., Ingol-Blanco, E., & Teasley, R. L. (2006). *WEAP hydrology model applied: the Rio Conchos Basin.* Center for Research in Water Resources, University of Texas at Austin, USA. Recuperado de https://repositories.lib.utexas.edu/bitstream/handle/2152/7025/crwr_onlinereport06-12.pdf?sequence=2

Andersen, J., Refsgaard, J. C., & Jensen, K. H. (2001). Distributed hydrological modelling of the Senegal River Basin-model construction and validation. *Journal of Hydrology*, 247(3-4), 200-214. DOI:

10.1016/S0022-1694(01)00384-5

Bolongaro-Crevenna, A., Márquez-García, A. Z., Torres-Rodríguez, V., Origel-Gutiérrez, G., Márquez-García, E., Aldeco-Ramírez, J., Díaz-Flores, M. A., Fernández-Bringas, L. M., Gómez Mendoza, L., Galván-Ortiz, L. M., Gómez-Millán, D. G., Ávila-Flores, B., Solares-Hernández, H., Montes-León, M. A. L., Márquez-García, L. I., Márquez-Hernández, A. C., Adriana-Pérez, E., Verónica Pérez-Flores, E. V., García-Díaz, B. E., & Arzate-Ramírez, S. G. (2016). Diagnóstico de la vulnerabilidad ante el cambio climático del destino turístico de San Miguel de Allende, Guanajuato. En: Bolongaro-Crevenna, R. A. (coord.). *Estudio de vulnerabilidad al cambio climático en diez destinos turísticos seleccionados* (Informe Técnico Proyecto 238980). Ciudad de México, México: Academia Nacional de Investigación y Desarrollo, Fondo Sectorial para la Investigación en Desarrollo y la Innovación Tecnológica en Turismo Conacyt-Sectur. Recuperado de http://www.sectur.gob.mx/wp-content/uploads/2018/01/6_San-Miguel-de-Allende.pdf

Bonelli, S., Vicuña, S., Meza, F. J., Gironás, J., & Barton, J. (2014). Incorporating climate change adaptation strategies in urban water supply planning: The case of central Chile. *Journal of Water and Climate Change*, 5(3), 357-376.DOI: 10.2166/wcc.2014.037

Cabrera, J. (2012). *Calibración de modelos hidrológicos*. Lima, Perú: Universidad Nacional de Ingeniería Civil, Instituto para la Mitigación de los Efectos del Fenómeno El Niño.

Campos, D. F. (1998). *Procesos del ciclo hidrológico.* San Luis Potosí, México: Editorial Universitaria Potosina, Universidad Autónoma de San Luis Potosí.

CCG, Centro de Cambio Global. (2009). *Guía metodológica: modelación hidrológica y de recursos hídricos con el modelo WEAP.* Santiago/Chile, Boston/EUA: Universidad Católica de Chile, Stockholm Environment Institute. Recuperado de http://www.weap21.org/downloads/Guia_modelacion_WEAP_Espanol.pdf

Choi, S. J., Kim, J. H., & Lee, D. R. (2012). Decision of the water shortage mitigation policy using multi-criteria decision analysis. *KSCE Journal of Civil Engineering*, 16(2), 247-253. DOI: 10.1007/s12205-012-0008-z

Conagua, Comisión Nacional del Agua. (2014). *Estadísticas del agua en México.* México. Recuperado de http://www.conagua.gob.mx/CONAGUA07/Publicaciones/Publicaciones/EAM2014.pdf

Conagua & IMTA, Comisión Nacional del Agua & Instituto Mexicano de Tecnología del Agua. (2008). *Banco Nacional de Datos de Aguas Superficiales (BANDAS)*. Recuperado de https://app.conagua.gob.mx/bandas/

DOF, Diario Oficial de la Federación. (2003). *Acuerdo por el que se dan a conocer las denominaciones y la ubicación geográfica de las diecinueve cuencas localizadas en la zona hidrológica denominada río*

Lerma-Chapala, así como la disponibilidad media anual de las aguas superficiales en las cuencas que comprende dicha zona hidrológica. México, DF, México: Secretaría del Medio Ambiente y Recursos Naturales.

Esquivel, A. G., Nevárez, F. M. M, Velásquez, V. M. A., Sánchez, C. I., & Bueno, H. P. (2017). Hydrological modeling of a basin in Mexico's arid northern region and its response to environmental changes*. Ingeniería Agrícola y Biosistemas*, 9(1), 3-18. DOI: 10.5154/r.inagbi.2016.12.008

Febrillet-Huertas, J. F., José-Clases, S., Bello, L., & Chalas, J. (2014). Simulación de los efectos del cambio climático en los recursos hídricos y estrategias de adaptación, usando el modelo Water Evaluation and Planning (WEAP), en la cuenca de la región Yaque del Norte de la República Dominicana. *Aqua-LAC*, *6*(2), 21-36.DOI: 10.29104/phi-aqualac/2014-v6-2-03

Flores-López, F., Galaitsi, S. E., Escobar, M., & Purkey, D. (2016). Modeling of andean páramo ecosystems' hydrological response to environmental change*. Water*, 8(3), 94. DOI: 10.3390/w8030094

Hamlat, A., Errih, M., & Guidoum, A. (2013). Simulation of water resources management scenarios in western Algeria watersheds using WEAP model. *Arabian Journal of Geosciences*, 6(7), 2225-2236. DOI: 10.1007/s12517-012-0539-0

Harma, K. J., Johnson, M. S., & Cohen, S. J. (2012). Future water supply and demand in the Okanagan Basin, British Columbia: A scenario-based analysis of multiple, interacting stressors. *Water Resources Management*, 26(3), 667-689. DOI: 10.1007/s11269-011-9938-3

Höllermann, B., Giertz, S., & Diekkrüger, B. (2010). Benin 2025-Balancing future water availability and demand using the WEAP 'Water Evaluation and Planning' System. *Water Resources Management*, 24(13), 3591-3613. DOI: 10.1007/s11269-010-9622-z

Hoogenboom, G., Porter, C., Vakhtang, S., Boote, K., Singh, U., White, J., Hunt, L., Ogoshi, R., Lizaso, J. I., Koo, J., Asseng, S., Singels, A., Moreno, L., & Jones, J. (2017). *Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.7 (https://DSSAT.net)*. Gainesville, USA: DSSAT Foundation.

INEGI, Instituto Nacional de Estadística y Geografía. (2013). *Continental - Continuo de elevaciones mexicano, CEM. Versión 3.0.* Aguascalientes, México: Instituto Nacional de Estadística y Geografía. Recuperado de http://www.inegi.org.mx/geo/contenidos/datosrelieve/continental/Descarga.aspx

INEGI, Instituto Nacional de Estadística y Geografía. (2010). *Conjunto de datos vectoriales de la carta de uso de suelo y vegetación, escala 1:250 00 Serie IV (Continuo Nacional)*. Aguascalientes, México: Instituto Nacional de Estadística y Geografía. Recuperado de http://www.inegi.org.mx/geo/contenidos/recnat/usosuelo/Default.aspx.

Tecnología y ciencias del agua, ISSN 2007-2422, 13(2), DOI: 10.24850/j-tyca-2022-02-03

INIFAP, Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias. (2016). *Red Nacional de Estaciones Agrometeorológicas Automatizadas INIFAP*. Ciudad de México: Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias. Recuperado de http://clima.inifap.gob.mx/redinifap/

Johnston, R., & Smakhtin, V. (2014). Hydrological modeling of large river Basins: How much is enough? *Water Resources Management*, 28(10), 2695-2730. DOI: 10.1007/ s11269-014-0637-8

Magaña, V. O. (2005). *Fomento de las capacidades para la etapa II de adaptación al cambio climático en Centroamérica, México y Cuba. Estudio de caso en México: Tlaxcala. Análisis de la vulnerabilidad actual, Informe de Avance de Trabajo* (Vol. 31) (Proyecto RLA/01/G31/A/1G/99). Programa dee las Naciones Unidas para el Desarrollo, Fondo Global del Ambiente. Recuperado de http://www2.inecc.gob.mx/descargas/cclimatico/cc_cmc_regional.pdf

Molnar, P. (2011). *Calibration. Watershed modelling, SS 2011.* Zürich, Switzerland: Institute of Environmental Engineering, Chair of Hydrology and Water Resources Management, ETH.

Palacios-Vélez, E., & López-López, C. (2004). La sobreexplotación de las cuencas hidrológicas: el caso de la cuenca del río de La Laja, Guanajuato. En: Cotler, H. (ed.). *El manejo integral de cuencas en México* (pp. 131-148). México, DF, México: Secretaría de Medio Ambiente y Recursos Naturales, Instituto Nacional de Ecología.

Recuperado de http://www2.inecc.gob.mx/publicaciones2/libros/528/sobreexplotacion.pdf

Refsgaard, J. C., & Knudsen, J. (1996). Operational validation and intercomparison of different types of hydrological models. *Water Resources Research*, 32(7), 2189-2202. DOI: 10.1029/96WR00896

Richardson, C. W., & Wright, D. A. (1984). *WGEN: A model for generating daily weather variables, ARS-8*. Washington, DC, USA: US Department of Agriculture, Agricultural Research Service.

Rochdane, S., Reichert, B., Messouli, M., Babqiqi, A., & Khebiza, M. Y. (2012). Climate change impacts on water supply and demand in Rheraya Watershed (Morocco), with potential adaptation strategies. *Water*, 4(1), 28-44. DOI: 10.3390/w4010028

Sánchez-Torres-Esqueda, G., Ospina-Noreña, J. E., Gay-García, C., & Conde, C. (2011). Vulnerability of water resources to climate change scenarios. Impacts on the irrigation districts in the Guayalejo-Tamesí river basin, Tamaulipas, México. *Atmósfera*, 24(1), 141-155.

Sandoval-Solis, S., & McKinney, D. C. (2009). Hydrological feasibility of environmental flows in the Río Grande/Bravo basin. In: *World Environmental and Water Resources Congress 2009: Great Rivers* (pp. 1-11). DOI: 10.1061/41036(342)497

Savage, M., Rodrigo, D., Lund, J., Munevar, A., Purkey, D., & Bourez, W. (mayo, 2004). Sacramento, California, USA: *California Water and Environmental Modeling Forum Technical Workshop*, Presentation

Summaries, CWEMF.

SMN, Servicio Meteorológico Nacional. (2009). *Red de Estaciones Climatológicas. Climatología mensual.* México, DF, México: Servicio Meteorológico Nacional. Recuperado de http://smn.cna.gob.mx/index.php?option=com_content&view=article&id=42&Itemid=75

SEI, Stockholm Environment Institute. (2015). *Water evaluation and planning system, WEAP.* Boston, USA: Stockholm Environment Institute.

Torres-Benites, E., Mejía-Sáenz, E., Cortés-Becerra, J., Palacios-Vélez, E., & Exebio-García, A. (2005). Adaptación de un modelo de simulación hidrológica a la cuenca del río Laja, Guanajuato, México. *Agrociencia*, 39(5). Recuperado de https://agrociencia-colpos.mx/index.php/agrociencia/article/download/411/411

Yates, D., Miller, K. A., Wilby, R. L., & Kaatz, L. (2015a). Decision-centric adaptation appraisal for water management across Colorado's continental divide. *Climate Risk Management*. DOI: 10.1016/j.crm.2015.06.001

Yates, D., Sieber, J., Purkey, D., Huber-Lee, A., & Galbraith, H. (2005b). WEAP21-A demand, priority, and preference-driven water planning model, part 1: Model characteristics. *Water International*, 30(4), 487-500. DOI: 10.1080/02508060508691893

Yates, D., Sieber, J., Purkey, D., Huber-Lee, A., & Galbraith, H. (2005c). WEAP21-A demand, priority, and preference driven water planning

Tecnología y ciencias del agua, ISSN 2007-2422, 13(2), DOI: 10.24850/j-tyca-2022-02-03

model, part 2: Aiding freshwater ecosystem service evaluation. *Water International*, 30(4), 501-512. DOI: 10.1080/02508060508691894