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Hydrological simulation of the Teapa river basin

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— Abstract—

In this research, the hydrological simulation of the Teapa River basin was carried out with the hydrological model CEQUEAU from 1980 to 2017. The research objectives are a) to evaluate the efficiency of the CEQUEAU hydrological model to simulate the average daily flows of the Teapa River basin and b) to calibrate and validate the model CEQUEAU at the Teapa hydrometric station. A hydrogeomatic module was used to obtain the input files required by CEQUEAU. The efficiency of the model was evaluated with the Nash-Sutcliffe coefficient of efficiency (*NSE*), the percentage of bias (*PBIAS*), and the coefficient of determination (R2). The results show that CEQUEAU reproduces the hydrological behavior of the Teapa River basin in rainy and dry seasons.

Keywords:

Hydrological modelling; CEQUEAU; Teapa river.

Understanding the hydrological functioning of a region is important for the evaluation, development, and management of its water resources. Hydrological models aim to estimate water resources in a basin. Continuous hydrological modeling is a natural evolution of the event-based design approach in modern hydrology. It improves rainfall-runoff transformation and provides professionals with more effective output hydrological information for risk assessment (Grimaldi *et al*. 2022).

This research aims to: a) evaluate the efficiency of the CEQUEAU hydrological model to simulate the average daily flow rates of the Teapa River basin and b) calibrate and validate the model at the Teapa hydrometric station (CONAGUA Code: 30032).

CEQUEAU is a free hydrological model of distributed parameters; it has been used in different regions (Canada, Morocco, Mexico, Spain, Senegal, etc.) for the hydrological modeling of basins. CEQUEAU can be applied for different purposes, for example: a) obtaining flow rates in non-gapped sites in the basin, b) completing missing hydrometric records in hydrometric stations, c) designing hydraulic infrastructure for flood control, d) drinking water supply, and in general for the evaluation of water resources in a basin.

Bâ *et al*. (2001) used CEQUEAU for the simulation of the average daily flows in the Amacuzac and San Jerónimo rivers in the State of Mexico, Mexico. Bâ *et al*. (2013) simulated with CEQUEAU the average daily flows of the Senegal River in two hydrometric stations (Bakel and Kayes) and the daily water levels in the Manantali reservoir. Llanos and Bâ (2011) evaluated through CEQEAU the hydrological behavior of the basin system of the Nervión and Ibaizabal rivers (Basque Country). Vilchis-Mata *et al*. (2015) implemented the use of precipitation data estimated by remote sensors for the simulation of average daily flows in the Amacuzac River basin (Mexico) with the CEQUEAU model. Kwak *et al*. (2017) used CEQUEAU to simulate the future flow rates and water temperatures of the Fourche River (Quebec) with projected meteorological data in the future. Fniguire *et al*. (2022) used CEQUEAU for the daily simulation of flows in an arid and semi-arid mountainous area in the Ourika River basin, Morocco

METHODOLOGY

The Teapa River is part of the La Sierra River, it is located in the states of Chiapas and Tabasco, Mexico, in the R. H. No. 30 Grijalva-Usumacinta (**Figure 1**). The Teapa River basin drains an area of 424 km^2 to the Teapa hydrometric station (CONAGUA code: 30032). The average annual rainfall in the area under study ranges from 2,500 to 4,000 mm. The predominant climate in the basin is warm-humid.

The CEQUEAU hydrological model was used to carry out daily hydrological simulations in the Teapa River basin for the period from 1980 to 2017. CEQUEAU (Morin *et al*. 1998) was developed at the National Institute of Scientific Research-Water (INRS-EAU) of the University of Québec, Canada. CEQUEAU is a hydrological model of distributed parameters where the basin is divided into a grid of squares. This allows the model to calculate the flows in each table and take into account the spatial and temporal variations of the physiographic characteristics of the basin (Magaña-Hernández *et al*. 2021). The model is structured in two main modules (production and transfer function, **Figure 2**), which together describe the water runoff from when it reaches the surface of the basin until it reaches the exit point (hydrometric station). The production function models the vertical flow of water (rain, evapotranspiration, infiltration, etc.), and calculates the volume of water in the three containers that CEQUEAU considers (soil, aquifer, lakes, and swamps,). On the other hand, the transfer function analyzes the movement of the flow in the drainage network and takes into account the influence of lakes, swamps, and artificial installations such as dams and by-passes, among others (Morin & Paquet, 1995).

Figure 3 presents the structure for performing hydrological modeling with the CEQUEAU model. Table 1 shows the input data for the implementation of the CEQUEAU model in the Teapa River basin. The CEQUEAU model requires a database with hydrometeorological information (flow rates, precipitation, maximum and minimum temperature), and four files in text format to perform the hydrological simulations: physiographic data (* .PHY), basin data (* .BV), hydrometeorological data (*.DHM) and model parameters (*.PAH).

For this study, daily hydrometeorological data (flow rates, precipitation, maximum and minimum temperature) were collected from 1980 to 2017. Precipitation, maximum, and minimum temperature records were obtained from ten climatological stations of the Computerized Climate Database (CLICOM). In addition, hydrometric information on the daily average flows of the Teapa hydrometric station was used (CONAGUA code: 30032).

The input files to CEQUEAU were obtained automatically with a hydrogeomatic module developed in the Idrisi GIS. In the application of the hydrogeomatic module, the following were used: a) the Digital Elevation Model (DEM) of the area under study, b) the land cover map, c) the basin map, and d) the location of ten climatologicalstations and the Teapa hydrometric station.

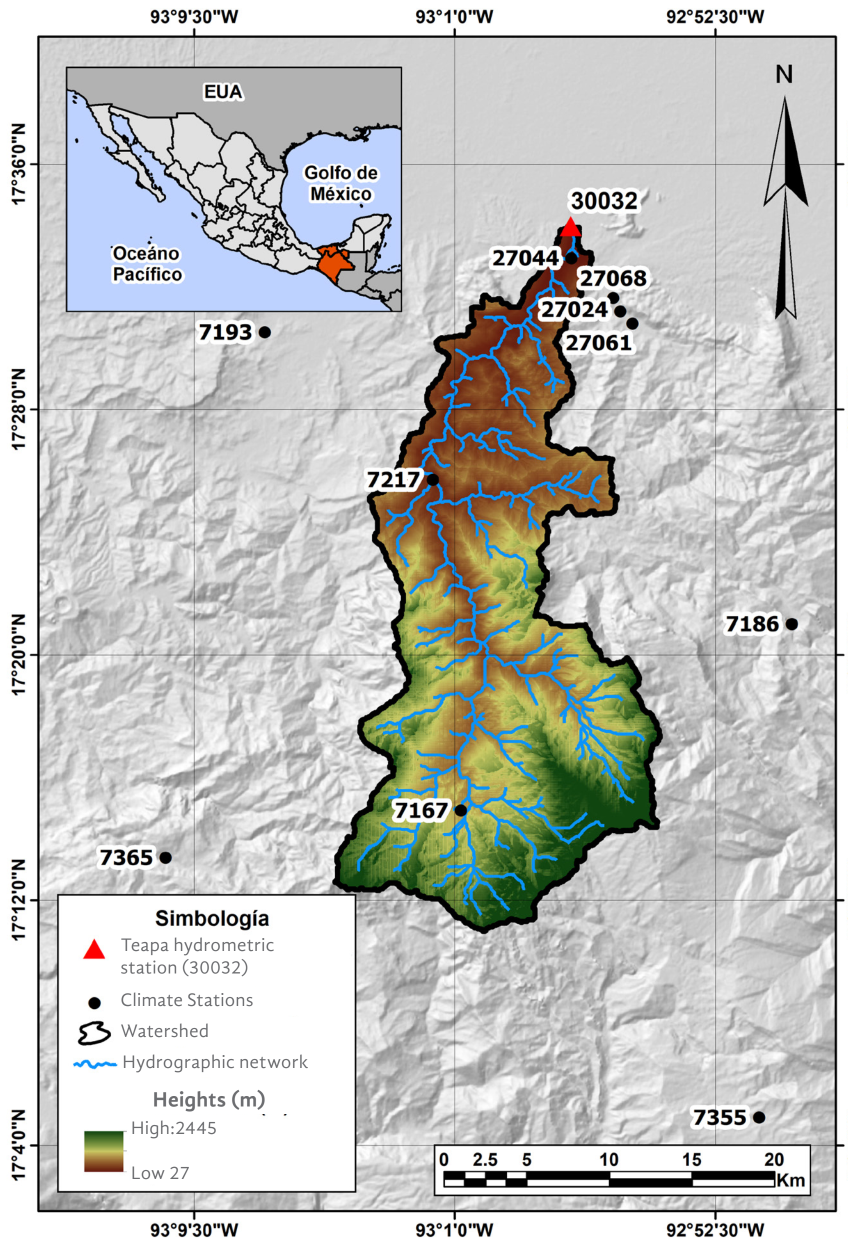

Figure 1. Area under study. Source: Own elaboration

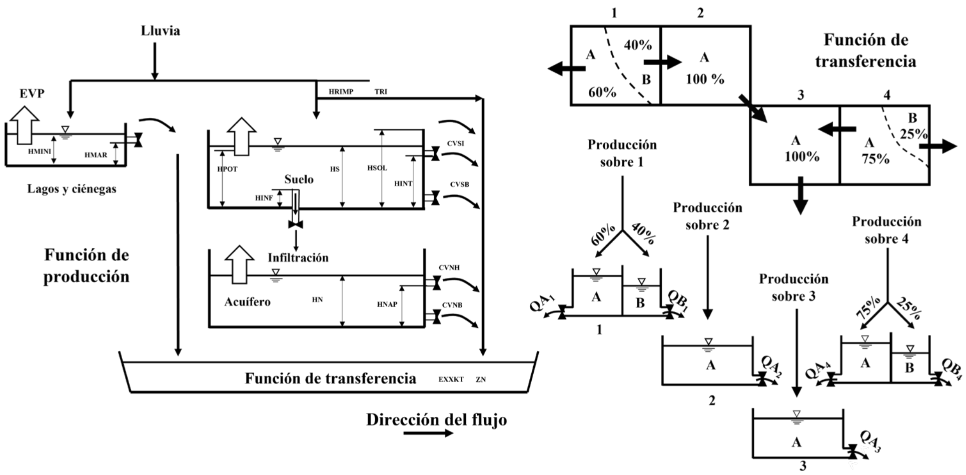

Figure 2. Production and transfer function. Source: Adapted from Morin & Paquet, 1995

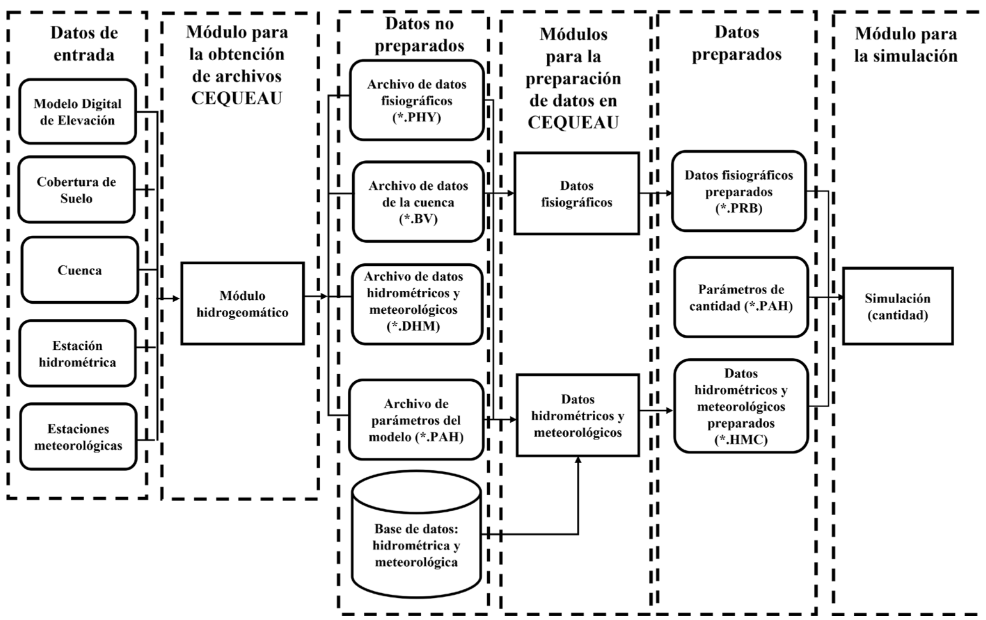

Figure 3. Structure for hydrological modeling with CEQUEAU. Source: Adapted from Morin & Paquet, 1995

Table 1
Input data for the implementation of the CEQUEAU model in the Teapa River basin

Input data	Format	Period	Spatial Scale	Time scale	Source
Digital Elevation Model (DEM)	Raster		50 m		National Institute of Statistics and Geography (INEGI)
Ground cover	Raster		50 m		National Institute of Statistics and Geography (INEGI)
Teapa River Basin	Raster		50 m		Defined with a Geographic Information System (GIS)
Physiographic data file, watershed data file, hydrometeoro-logical data file, and model parameter file	Ascii				They are obtained with the application of a hydrogeomatic module
Location of climato-logical stations and hydrometric station	Vector				Own elaboration
Precipitation	Ascii	1980-2017		Daily	Computerized Climate Database (CLICOM)
Maximum andminimum temperature	Ascii	1980-2017		Daily	Computerized Climate Database (CLICOM)
Flow	Ascii	1980-2017		Daily	National Surface Water Data Bank (BANDA)

The calibration of the CEQUEAU model was carried out for the period from 1990 to 2017, and the validation from 1980 to 1989 daily. In this study, the calibration was performed by trial and error, manually varying the parameters of the model and trying to adjust the simulated hydrographs with those observed in the Teapa hydrometric station. Calibration is a process by which the parameters of the model are adjusted, the objective is to minimize the difference between the observed and simulated flow rates. Validation consists of testing the parameters obtained in the calibration for another period to know the prediction efficiency of the model.

Three statistics were used to evaluate the efficiency of the model, according to Moriasi *et al.* (2015): the Nash-Sutcliffe coefficient of efficiency (very good $NSE > 0.80$, good $0.70 < NSE \leq 0.80$, satisfactory $0.50 < NSE \leq 0.70$, unsatisfactory NSE ≤ 0.50, equation [1]), the percentage of bias (very good PBIAS < ±5, good ±5 ≤ PBIAS ≤ ±10, satisfactory ± 10 ≤ PBIAS ≤ ±15, unsatisfactory PBIAS ≥ ±15, equation [2])) and the coefficient of determination (very good $R^2 > 0.85$, *good* $0.75 < R^2 \leq 0.85$, satisfactory $0.60 < R^2 \leq 0.75$, unsatisfactory $R^2 \leq 0.60$, *equation* [3]).

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_{Obs_i} - Q_{Cal_i}\right)^2}{\sum_{i=1}^{n}\left(Q_{Obs_i} - \bar{Q}_{Obs}\right)^2} \quad [1]$$

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(Q_{Obs_i} - Q_{Cal_i}\right)}{\sum_{i=1}^{n} Q_{Obs_i}}\right] \times 100 \quad [2]$$

$$R^2 = \left[\frac{\sum_{i=1}^{n}\left(Q_{Obs_i} - \bar{Q}_{Obs}\right)\left(Q_{Cal_i} - \bar{Q}_{Cal}\right)}{\sqrt{\sum_{i=1}^{n}\left(Q_{Obs_i} - \bar{Q}_{Obs}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Q_{Cal_i} - \bar{Q}_{Cal}\right)^2}}\right]^2 \quad [3]$$

where QObsi and QCali = flow rates observed and calculated on day i (m^3/s), $\bar{Q}_{Obs}$ and $\bar{Q}_{Cal}$= average flow rates observed and calculated on n days (m^3/s).

RESULTS

The Idrisi-CEQUEAU module allowed obtaining the physiographic information (soil occupation, altitudes, and flow directions) required by the model, using the information available in digital format. Table 2 shows the parameters obtained in the calibration of the CEQUEAU model in the Teapa River basin from 1990 to 2017. 21 parameters were adjusted in the calibration and used for model validation (1980 to 1989). Table 3 presents the results of the calibration and validation of the model in the Teapa River basin.

Figure 4 presents the hydrographs of the daily interannual flows observed and simulated at the Teapa hydrometric station. In the entire simulation period (1980 to 2017, Figure 4a) the model is very good (*NSE = 0.82* and $R^2 = 0.83$), and the *PBIAS = 1.02* is positive, indicating that the model underestimates the flows, mainly in March to May. In calibration (1990 to 2017, Figure 4c) and validation (1980 to 1989, Figure 4e) the model is good with *NSE values = 0.76*. CEQUEAU underestimates the flow rates in the calibration (*PBIAS = 1.5*) and overestimates them in the validation (*PBIAS = - 1.01*). In the dispersion diagrams (Figure 4b, 4d, and 4f) the good performance of the model is observed, the flow rates are grouped at a line of 45°.

Figure 5 shows the hydrograms of the daily flows observed and simulated for the years 1980, 1983, and 1999 at the Teapa hydrometric station. According to Moriasi *et al.* (2015), the model is good since $0.70 < NSE \leq 0.80$, for 1980 ($NSE = 0.79$, Figure 5a) and 1983 ($NSE = 0.79$, Figure 5b); and very good for 1999 ($NSE = 0.86$, Figure 5c). In the scatter plots (Figure 5b, 5d, and 5f), the good performance of the model is observed, the flows are grouped at a 45° line between the range of 10 to 90 m^3/s.

Figure 6 shows the hydrographs of the daily flows observed and simulated for the years 2000, 2005, and 2011 at the Teapa hydrometric station. According to Moriasi *et al.* (2015), the model is satisfactory since $0.50 < NSE \leq 0.70$, for 2000 ($NSE = 0.70$, Figure 6a) and 2005 ($NSE = 0.67$, Figure 6c); and good for 2011 ($NSE = 0.74$, Figure 6e) since $0.70 < NSE \leq 0.80$. In the scatter plots (Figure 6b, 6d, and 6f) the good performance of the model is observed, the flows are grouped at a 45° line between the range of 10 to 100 m^3/s.

Table 2

Parameters in the calibration of the CEQUEAU model in the Teapa River basin

No	Parameters	Description	Value
1	CIN	Coefficient of infiltration of the soil container into the aquifer	0.17
2	CVMAR	Emptying coefficient of the lakes and bogs container	0.000
3	CVNB	Emptying coefficient of the aquifer container (bottom hole)	0.018
4	CVNH	Emptying coefficient of the aquifer container (upper hole)	0.033
5	CVSB	Emptying coefficient of the floor container (bottom hole)	0.059
6	CVSI	Emptying coefficient of the floor container (intermediate hole)	0.055
7	HINF	Threshold of infiltration into the aquifer container (mm)	38.5
8	HINT	Intermediate emptying threshold of the floor container (mm)	7
9	HNAP	Upper Emptying Threshold of the Aquifer Container (mm)	140
10	HRIMP	Rain sheet necessary to initiate runoff on impermeable surfaces (mm)	4.5
11	HSOL	Container floor height (mm)	105
12	EVNAP	Percentage of evapotranspiration in the aquifer container (0.0 to 1.0)	0.17
13	HPOT	Threshold of water extraction at potential rate by evapotranspiration (mm)	6.5
14	XAA	Thornthwaite's formula exponent	3.81
15	XIT	Thornthwaite Thermal Index Value	135.9
16	EXXKT	Adjustment parameter of the transfer coefficient	0.002
17	ZN	Basin Concentration Time (Days)	0.675
18	COET	Temperature correction coefficient concerning altitude	0.1
19	COEP	Precipitation correction coefficient concerning altitude (mm/m/year)	1.28
20	XINFMA	Maximum infiltration per day (mm/day)	25.50
21	TRI	Percentage of impermeable surface 0.0 to 1.0)	0.02

Table 3

Calibration and validation of the CEQUEAU model in the Teapa River basin

Description	Q_{Obs} (m^3/s 1)	Q_{Cal} (m^3/s)	L_{Obs} (mm)	L_{Cal} (mm)	*NSE*	*PBIAS*	*R^2*
Simulation (1980 a 2017)	35.1	34.8	2629	2602	0.82	1.02	0.83
Calibration (1990 a 2017)	33.0	32.6	2474	2437	0.76	1.5	0.77
Validation (1980 a 1989)	40.4	40.80	3024	3055	0.76	-1.01	0.78
1980	49.1	43.7	3686	3282	0.79	10.96	0.80
1983	30.8	32.6	2304	2439	0.79	-5.83	0.80
1999	38.3	36.9	2869	2762	0.86	3.72	0.86
2000	35.5	38.5	2231	2893	0.70	-13.24	0.72
2005	20.1	21.7	1501	1625	0.67	-8.24	0.67
2011	41.0	45.0	2807	3366	0.74	-10.54	0.75

QObs = observed flow rates; QCal = calculated flow rates; LObs = observerd rain level; LCal = calculated rain level

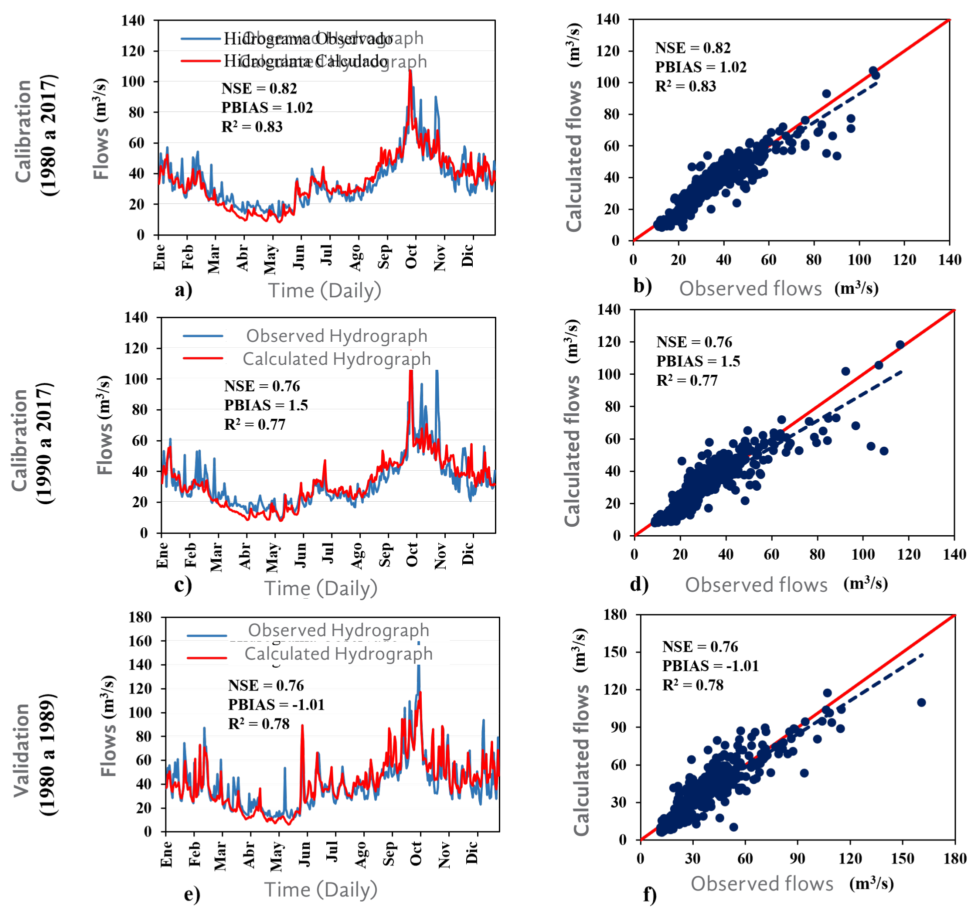

Figure 4. Interannual daily flows observed and simulated at the Teapa hydrometric station: simulation period (1980 to 2017), calibration (1990 to 2017), and validation (1980 to 1989)

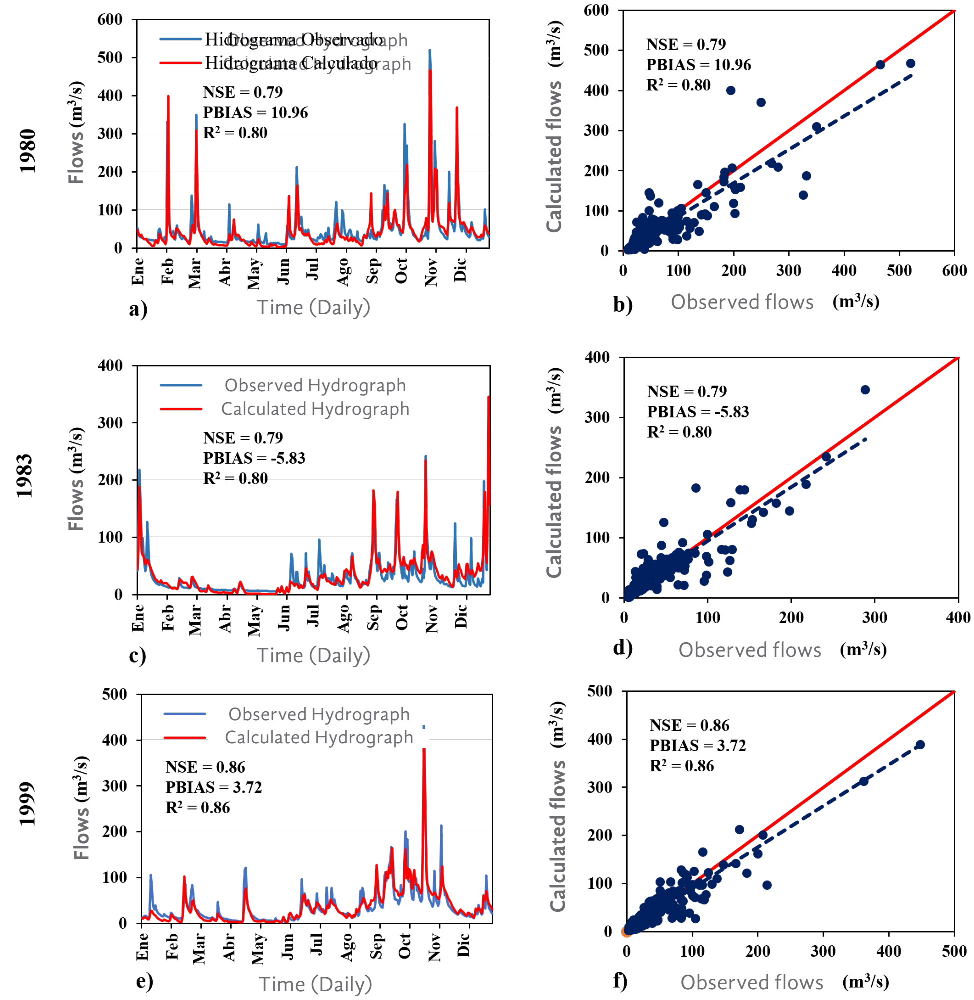

Figure 5. Daily flow rates observed and simulated at the Teapa hydrometric station for the years: 1980, 1983 and 1999

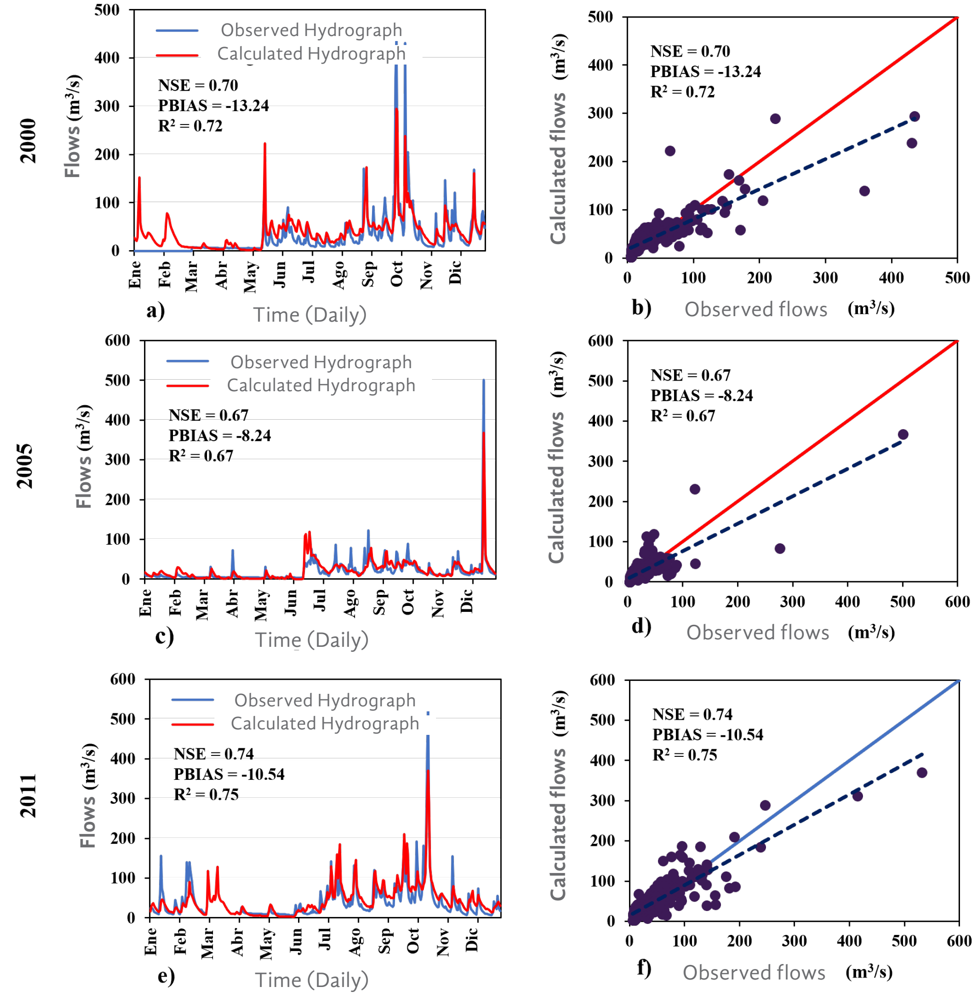

Figure 6. Daily flow rates observed and simulated at the Teapa hydrometric station: 2000, 2005 and 2011

DISCUSSION

CEQUEAU is a hydrological model for accessible and free use. This has been used in different climatic regions. The results presented in this research show that the CEQUEAU model is capable of reproducing the rainfall-runoff process of the Teapa River basin, and they are compared with other studies carried out in Mexico and other countries.

Díaz-Mercado *et al.* (2015), Torres *et al.* (2018) and Magaña-Hernández *et al*. (2021) conducted studies in the same climate region with the CEQUEAU model. Díaz-Mercado *et al.* (2015) simulated the average daily flows of the La Sierra River to the Pueblo Nuevo hydrometric station (CONAGUA code: 30032) from 1968 to 1998, obtaining NSE values of 0.83 to 0.88 for the interannual daily flows. Magaña-Hernández *et al.* (2022) applied CEQUEAU for the estimation of flows in non-volumed sites in the Tacotalpa river basin, calibrated and validated the model in the Tapijulapa hydrometric station (CONAGUA code: 30093) and Oxolotán (CONAGUA code: 30111), with NSE values of 0.94 and 0.97 in the calibration and *NSE* values of 0.89 in the validation. Torres *et al*. (2018) performed the hydrological simulation of the Teapa River basin with the MIKE-SHE model. Model calibration was from 1998 to 2000, and validation from 2003 to 2005. The NSE in the calibration is between 0.40 and 0.64, and in the validation 0.35 and 0.46 for the daily flows in the Teapa hydrometric station. In this study, two climatological stations and the Teapa hydrometric station were used for the calibration and validation of the model.

In our research, the CEQUEAU model was used to simulate the daily flows of the Teapa River basin. Ten climatological stations were used in the hydrological simulation, which are inside and outside the basin under study. Therefore, the spatial distribution of rainfall can be better determined. The *NSE* was 0.76 in calibration (1900 to 2017) and 0.76 in validation (1980 to 1989).

CONCLUSIONS

In the research, the hydrological model of distributed parameters CEQUEAU was used to evaluate the efficiency in the simulation of the daily average flows of the Teapa River basin for the period from 1980 to 2017. The CEQUEAU model was calibrated from 1990 to 2017 and validated from 1980 to 1989 at the Teapa hydrometric station. The three statistics used to measure the efficiency of the model indicate that it is good.

Finally, the results obtained in the hydrological simulation of the Teapa River basin using the CEQUEAU model, represent the hydrological behavior of the basin in times of rain and drought.

For future research, it is important to carry out hydrological simulations on a smaller time scale, in basins where there are records of rainfall at short intervals since this is fundamental for hydrological forecasting and disaster warning. An alternative is the use of estimated precipitation by meteorological satellite that provides real-time data at different time scales and globally. However, there are uncertainties in satellite rainfall estimates, as they determine rainfall indirectly. Therefore, it is necessary to validate these estimates with ground rainfall measurements to use it in hydrological applications.

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