COMPARISON BETWEEN HYDROLOGICAL MODELS: SOIL MOISTURE METHOD AND TÉMEZ, FOR THE CASE STUDY BOSQUE LA PRIMAVERA, MEXICO

MARÍA DEL MAR NAVARRO FARFÁN (1), SONIA TATIANA SÁNCHEZ QUISPE (2)
MARCO ANTONIO MARTÍNEZ CINCO (3), ISRAEL ALEJANDRO GARCÍA LEDESMA (4)

(1,3) Maestría en Ciencias en Ingeniería Ambiental, Universidad Michoacán de San Nicolás de Hidalgo, México
(2,4) Maestría en Ingeniería de Recursos Hídricos, Universidad Michoacán de San Nicolás de Hidalgo, México,
 e-mail (1) mar.farfan@hotmail.com

ABSTRACT

There are several methods for obtaining monthly flows; undoubtedly, the principle of parsimony may be the best solution when considering the use of one method or another. However, it is important to focus on the results obtained and compare the trend presented by the observed and simulated flows through graphs and goodness-of-fit indicators, which are the statistical measure that allows us to consider, or not, a model as appropriate. The case study is La Primavera Forest, in the State of Jalisco, Mexico, which is an area that does not have surface hydrological studies. Although it is not directly affected by water, shares the same geological bed with the metropolitan area of Guadalajara. In the periphery of the study area, five hydrometric stations are located with data at natural regime, which allows them to be used for surface hydrological modeling using the Témez model and Soil Moisture Method. The Soil Moisture Method was selected as the best model because the goodness-of-fit indicators were above the satisfactory value and the closing error in the water balance was low.

Keywords: Hydrological Models, Soil Moisture Method, Témez, Goodness-of-Fit Indicators

1 JUSTIFICATION

As part of the protection and management of a Protected Natural Area (PNA) such as La Primavera Forest (LPF), all the ecological services it can provide should be taken advantage of to the maximum. In order to have a sustainable service, the sustainability of the zone is resources must be considered (SEMARNAT, 2000). The need for this project comes from the lack of updated hydrological studies for the zone. Therefore, it is imperative to carry out a set of multidisciplinary studies in order to know the current situation of the zone, in such a way that the availability of both surface and underground resources can be obtained, thus generating a management model that reproduces the current situation of the water resources system.

2 INTRODUCTION

As can be seen in Figure 1, La Primavera Forest is located on the western of the Guadalajara Metropolitan Area (GMA), which is the second most populated urban nucleus in Mexico with around 4.8 million inhabitants, grouped in the municipalities of Guadalajara, Zapopan, San Pedro Tlaquepaque, Tlajomulco de Zúñiga, Tonalá, El Salto, Ixtlahuacán de los Membrillos and Juanacatlán (ITESO & UNIVA, 2019).
La Primavera Forest was recognized as a PNA by the government of Mexico and as a MAB Biosphere Reserve (Man and the Biosphere Programme) by UNESCO since 2006 (UNESCO, 2019). LPF fulfills an indispensable task to maintain the ecological balance of the Atemajac Valley, in such a way that a good part of the microclimate of the GMA depends on its good state of conservation, which is why it is called "the lung of Guadalajara". Therefore, because the forest is an important source of environmental goods and services due to its high ecological value and the close relationship with the GMA, since the beginning of the 20th century there has been a continuous struggle for the exploitation of the productive resources of the forest, which has accelerated in recent years with the growth of the urban sprawl, leaving the protection zone with a high degree of vulnerability. In addition to this and as shown in Figure 2, the GMA and LPF share the same geological bed, which is formed mainly by rhyolite tuff and rhyolite.

However, when speaking of the vulnerability of the forest, it must be understood that all the natural resources of the area are also affected, as is the case of the water resource, both superficial and underground; added to this, the accelerated growth of the population in urban areas, the inadequate planning of the water infrastructure and the inefficient regulation of contaminants have become some of the causes that affect the supply, distribution and quality of water (Lugo Arias, 2014).

3 METHODS

It can be said that hydrological models are simplified representations, from which it is possible to study the cause-effect relationship of precipitation on a basin (Navarro Avargonzález, 2017). This is useful in understanding the physical, ecological and hydrological processes that take place within a specific zone,
generally represented by a basin, at the point of departure of which is a hydrometric station with records of volumetric flows for a specific period of years. These models simulate the precipitation-runoff process for a specific period of time, for which it is required to have some components of the hydrological cycle (such as precipitation, temperature, and evapotranspiration). The results of runoff from a basin produced by the models are presented and compared with the circulating volumes recorded in a hydrometric station, considering the same period of time, in order to determine graphically and numerically the similarity between them.

3.1 Data Management
It is important to consider that the processes used clearly depend on the quality and quantity of data entered into the model; due to this, data management has to be an important part of the work, since if there is no adequate series of data (both meteorological and hydrometric), an error will be introduced into the system. For the selection of meteorological stations to be used, the spatial characteristics of the station must be known (such as longitude and latitude), the data recording history of the stations to be used (years in service and effective), the percentage of gaps in their series, etc. In order to avoid an error in the meteorological and hydrometric series, homogeneity tests are required (such as Sequences and Helmert), as well as proof of independence (through a correlogram and Anderson limits) (Merlos Villegas, Sánchez Quispe, & Almanza Campos, 2014). The first test is fulfilled if all the values that make up the sample come statistically from the same population; as for the second test, this implies that the probability of occurrence of any data does not depend on the occurrence of some other derived value (Salas, Delleur, Yevjevich, & Lane, 1980).

3.2 Témez Model
The Témez model operates by performing moisture balances between the different water transport processes that take place in a hydrological system during the different phases of the hydrological cycle. The whole process is governed by the principle of continuity and balance of mass and matter, and regulated by specific laws of distribution and transfer between the different terms of the balance, as shown in Figure 3 (Paredes Arquiola, Solera Solera, Andreu Álvarez, & Lerma Elvira, 2014). The model considers the land divided into 2 reservoirs:

- A top reservoir, which is not saturated where water and air coexist, and its water content is assimilable to soil moisture.
- A reservoir or aquifer, which is saturated and functions as underground storage that drains into the surface drainage network.

![Figure 3. Representation of the Témez Model.](image-url)

The Témez model contemplates the adjustment of four parameters: maximum humidity (Hmax), coefficient C, maximum infiltration (Imax) and the parameter α. The parameters Hmax and C regulate the storage of water in the soil, Imax separates surface runoff from underground and the parameter α regulates underground drainage.

Initial simulation conditions, such as initial soil moisture (Ho) and initial storage in the aquifer, must also be defined. The effect of initial values is reduced over time, so in reality, these values are insignificant.
3.3 Soil Moisture Method

The Soil Moisture Method represents basins as 2 reservoirs, plus the potential for snow accumulation.
- In the top layer, it simulates evapotranspiration, runoff, shallow interflow, and changes in soil moisture.
- In the lower layer, the routing of the base flow to the river and change in soil moisture are simulated.

The hydrological model has 9 parameters that influence each of the processes of the water cycle and by means of which, the calibration of the model is carried out:

- **Kc** Crop coefficient
- **Sw** Soil water capacity
- **Dw** Deep water capacity
- **RRF** Runoff resistance factor
- **Ks** Root zone conductivity
- **Kd** Deep zone conductivity
- **f** Preferred flow direction
- **Z1** Initial moisture level in the root zone
- **Z2** Initial moisture level in the deep zone

In general, this hydrological model is spatially continuous with a study area configured as a set of contiguous sub-basins covering the entire extension of the analysis basin. A homogeneous set of climate data (precipitation, temperature, relative humidity, and wind speed) is used in each of these sub-basins, which are divided into different types of land cover and land use (Stockholm Environment Institute, 2009).

The mathematical model of the soil moisture method is a water balance between inputs and outputs; where the difference between inputs and outputs in each of the two reservoirs represents the changes in moisture in the root zone and deep zone respectively. In Figure 4, the scheme of operation of the Soil Moisture Method is shown:

![Figure 4. Representation of the Soil Moisture Method.](image)

3.4 Goodness-of-fit Indicators

The calibration of models is focused on an accuracy criterion, which is based on the quantification of the goodness of fit of the model. For this purpose, different methodologies based on equations for goodness-of-fit are used. These equations are a numerical difference between the response of the simulated model and the volumes observed in the gauged stations (Casas Mas & Paredes Arquiola, 2013).

The efficiency of Nash-Sutcliffe (NSE) is a quadratic average error that gives greater weight to large errors, which often, but not always happen during periods of high flow (Equation 1).

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{N} (Q_{\text{sim}}(t) - Q_{\text{obs}}(t))^2}{\sum_{i=1}^{N} (Q_{\text{obs}}(t) - Q_{\text{obs}}(t))^2}$$  \[1\]

The efficiency of modified Nash-Sutcliffe (ln NSE) is the logarithmic transformation of the flow (Equation 2), which gives greater weight to errors during low flows; through this logarithmic transformation of the flow, peaks are flattened and lower values are kept more or better at the same level.
The Pearson correlation coefficient (\( r \)) measures the covariance of observed and simulated values without penalty for bias (Equation 3). The Pearson coefficient has the disadvantage that it is a poor statistician to decide whether the observed correlation is statistically significant and/or one observed correlation is significantly stronger than another.

\[
\begin{align*}
    r &= \frac{\sum_{i=1}^{N}(Q_{\text{sim}}(t) - \overline{Q}_{\text{sim}})(Q_{\text{obs}}(t) - \overline{Q}_{\text{obs}})}{\sqrt{\sum_{i=1}^{N}(Q_{\text{sim}}(t) - \overline{Q}_{\text{sim}})^2 \cdot \sum_{i=1}^{N}(Q_{\text{obs}}(t) - \overline{Q}_{\text{obs}})^2}} \quad [3]
\end{align*}
\]

The symmetry coefficient (SC) is a measure of the symmetry of the fit between the mean simulation and the mean observation and is given by Equation 5:

\[
CS = 1 - \left[ \max\left( \frac{\overline{Q}_{\text{sim}}}{\overline{Q}_{\text{obs}}} ; \frac{\overline{Q}_{\text{obs}}}{\overline{Q}_{\text{sim}}} \right) - 1 \right]^2 \quad [4]
\]

For the above equations [1 - 4] \( Q_{\text{sim}}(t) \) and \( Q_{\text{obs}}(t) \) have to be the simulated and observed flows respectively, in the time interval \( t \); \( N \) is the number of months of calibration, and the high slash denotes the mean value. In addition, Table 1 shows the quality of the indicator according to the value obtained in the calibration.

<table>
<thead>
<tr>
<th>QUALITY</th>
<th>NSE / ln NSE / r / SC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Good</td>
<td>0.75 &lt; Coefficient ≤ 1.00</td>
</tr>
<tr>
<td>Good</td>
<td>0.65 &lt; Coefficient ≤ 0.75</td>
</tr>
<tr>
<td>Satisfactory</td>
<td>0.50 &lt; Coefficient ≤ 0.65</td>
</tr>
<tr>
<td>Non-satisfactory</td>
<td>Coefficient ≤ 0.50</td>
</tr>
</tbody>
</table>

Table 1. Quality of the adjustment with the different goodness-of-fit.

### 3.5 Hydric Balance

The term Water Balance was used in 1944 by the meteorologist C. W. Thorthwaite to refer to the accounting between water inflows by precipitation or snowmelt and outflows composed by evapotranspiration, groundwater recharge, and runoff (Campos Aranda, 1998). The study of water balance in hydrology is the application of the principle of mass conservation, usually referenced to the continuity equation. This establishes that, for any volume of water and during any period of time, the difference between the total inputs and outputs of the system are balanced by the change of the volume in storage (Sokolov & Chapman, 1974).

Considering that the water balance presents a diagnosis of the real conditions of the water resource in a particular area, it allows in an integral way to take measures and establish guidelines and strategies for its protection and use, in such a way that its availability is guaranteed both in quantity and quality (Stockholm Environment Institute, 2009).

Campos Aranda (1998) mentions that the runoff of a stream can be considered the most important component of the hydrological cycle. The hydric balance shows the inputs and outputs of water in a given system and can be considered as shown in Equation 5:

\[
P + Q_{\text{in}} = ETR + \Delta S + Q_{\text{out}} \quad [5]
\]

Where \( P \) is precipitation (hm\(^3\)); \( Q_{\text{in}} \) is water flow into the basin (hm\(^3\)); \( ETR \) is evapotranspiration (the sum of evaporation from soil, water surfaces and, plants, expressed in hm\(^3\)); \( \Delta S \) is the change in water storage (hm\(^3\)), and \( Q_{\text{out}} \) is the flow of water (hm\(^3\)) out of the basin under consideration (Cogliati, Ostertag, Caso, Finessi, & Groch, 2018).

### 4 RESULTS

The five basins generated with the hydrometric stations (12607, 14011, 14015, 14018 and 14020) shown in Figure 5 were considered for modeling.
Likewise, to validate them, some characteristics shown in Table 2 were considered, such as the results of the tests of persistence and homogeneity of the annual series, as well as the amount of data available, the trend and the presence of any jump that might show the existence of some work in the area that altered the behavior of the runoff series, in addition to the runoff coefficient and the relative module. Thus, it is possible to determine whether the series can be used for the simulation with a hydrological model of precipitation-runoff - runoff; in this way, it is possible to determine whether the series can be used for the simulation with a hydrological model of precipitation - runoff.

Table 2. Characteristics of hydrometric stations used in surface modeling.

<table>
<thead>
<tr>
<th>H. S.</th>
<th>CONSISTENCY</th>
<th>YEARS WITH INFORMATION</th>
<th>RELATIVE MODULE l/s·km²</th>
<th>RUNOFF COEFFICIENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>12607</td>
<td>Homogeneous and non-persistent</td>
<td>27</td>
<td>9.34</td>
<td>0.32</td>
</tr>
<tr>
<td>14011</td>
<td>Homogeneous and non-persistent</td>
<td>48</td>
<td>5.94</td>
<td>0.19</td>
</tr>
<tr>
<td>14015</td>
<td>Non-homogeneous and persistent</td>
<td>47</td>
<td>6.02</td>
<td>0.19</td>
</tr>
<tr>
<td>14018</td>
<td>Homogeneous and persistent</td>
<td>22</td>
<td>2.85</td>
<td>0.09</td>
</tr>
<tr>
<td>14020</td>
<td>Homogeneous and non-persistent</td>
<td>16</td>
<td>14.3</td>
<td>0.47</td>
</tr>
</tbody>
</table>

4.1 Témez Model Results

The Témez model is used to calibrate the basins presented in table 2 and, given that Témez is a model of two reservoirs with a simplified system, when comparing the simulated volumes with those observed, the series has an appropriate behavior and trend in the graphs (Figures 6 and 7). However, for basins 14015 (Figure 8), 14018 (Figure 9) and 14020 (Figure 10), the behavior of the simulated volumes are above those observed, which demonstrates the need to improve calibration with another model due to the excess water present in the system.
Similarly, the goodness-of-fit indicators show acceptable results (Table 3) in three (12607, 14011 and 14018) of the five basins, but only two (12607 and 14011) present values established as good.

Table 3. Results of the goodness-of-fit indicators obtained from the simulation with the Témez model.

<table>
<thead>
<tr>
<th>WATERSHED</th>
<th>GOODNESS-OF-FIT INDICATORS</th>
<th>AVERAGE INDICATOR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NSE</td>
<td>Ln NSE</td>
</tr>
<tr>
<td>12607</td>
<td>0.77</td>
<td>0.86</td>
</tr>
<tr>
<td>14011</td>
<td>0.56</td>
<td>0.78</td>
</tr>
<tr>
<td>14015</td>
<td>-0.62</td>
<td>-0.08</td>
</tr>
<tr>
<td>14018</td>
<td>-0.01</td>
<td>0.59</td>
</tr>
<tr>
<td>14020</td>
<td>0.11</td>
<td>0.35</td>
</tr>
</tbody>
</table>
According to geological data available (Servicio Geológico Mexicano, 2000), the study area is conformed mainly by materials of volcanic origin and, therefore, porous. For this reason, it is known that the basins have an important underground recharge, which forces us to improve the modeling obtained with Témez.

As can be seen in Table 3, the best calibrations, considering the mean indicator and the symmetry coefficient, belong to basins 12607, 14011 and 14018, which are migrated to the Soil Moisture Method.

4.2 Soil Moisture Method Results

As shown in Table 4, there are acceptable indicators for basins 12607 and 14011, however, basin 14018 has very low values for Nash-Sutcliffe and the modified Nash-Sutcliff, but the symmetry coefficient is quite good and that helps us to accept the modeling.

<table>
<thead>
<tr>
<th>WATERSHED</th>
<th>GOODNESS-OF-FIT INDICATORS</th>
<th>AVERAGE INDICATOR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NSE</td>
<td>Ln NSE</td>
</tr>
<tr>
<td>12607</td>
<td>0.71</td>
<td>0.56</td>
</tr>
<tr>
<td>14011</td>
<td>0.63</td>
<td>0.66</td>
</tr>
<tr>
<td>14018</td>
<td>0.42</td>
<td>0.16</td>
</tr>
</tbody>
</table>

The 12607 basin has the best calibration in the model and it is appreciated that in the simulated annual volumes (Figure 11) they have a similar behavior to the observed volumes. On the other hand, the monthly average simulated volumes (Figure 12) have a similar tendency to those observed, which allows the value of the adjustment indicators to be high.

The results obtained in the simulation of basin 14011 are quite similar to the behavior of the volumes observed, both in the annual graph (Figure 13) and in the average monthly volumes (Figure 14). Although, for the annual volumes it seems that they were overestimated in the years 1968 - 1972, this is compensated with the previous years, where it is clearly observed that the simulated volumes are below those observed.
As shown in Figure 15, since 1972 there has been an increase in the existing volume, due to the precipitation data entered into the model, which causes the results of the goodness-of-fit indicators of NSE and ln NSE to be very low; even so, it is clearly observed in Figure 16 that the observed and simulated volumes have a similar behavior and the trend is adequate.

4.3 Hydric Balance Results

The water balance is calculated in the three simulated basins with the results obtained with the Soil Moisture Method, as shown in Figure 17, the error is very small and is in the order of five percent for basin 12607 and four percent for basins 14011 and 14018. On the other hand, it is observed that real evapotranspiration is low in basin 14011 compared to basins 12607 and 14018 due to the fact that twenty-seven percent of the total area in the zone is grassland.
5 CONCLUSIONS AND DISCUSSION OF RESULTS

The lack of meteorological and hydrometric information in Mexico is a serious problem. Because of this, it is important to test for the same area, different hydrological models that can adequately represent the conditions and processes necessary for modeling.

It was proposed to use the hydrological model HBV, which is also integrated into the EvalHid software. However, since this model requires daily data to be used, it was discarded.

The mean indicator shown in tables 2 and 3 is the average of the four goodness-of-fit indicators (NSE, InNSE, r, SC) presented in section 3.4: it is considered this way because the best calibration is achieved by pondering all goodness-of-fit indicators with the same weight.

Once the basins that were simulated with the Témez model (12607, 14011, 14018) are determined, it is considered to work for the Soil Moisture Method only with them because this way a clearer comparison is achieved.

The importance of the numerical calibration for both Témez and SMM was based on the symmetry coefficient, because this value preserves the average of the series and because monthly values are worked for long periods, it is required to maintain this characteristic throughout the simulation.

The Témez model has good representation, but, due to the fact that it does not adequately represent the subterranean part, it is discarded and therefore the SMM is used, which clearly considers the subterranean contribution.

The 14018 basin was the only one that is not represented correctly with the Témez model. However, the SMM model improved considerably the graph of monthly average volumes and the indicators of goodness-of-fit (since they are all positive).

The Soil Moisture Method is a malleable model, in the meaning that its calibration is easy because, although it has nine parameters to calibrate, only four are directly related to the surface and underground flow, which are the crop coefficient, soil water capacity, root zone conductivity and the flow resistance factor. In addition, the range of application that the parameters can use is wide.

The result of the balance is acceptable due to the percentage of error represented by the closing of the balance is low.

REFERENCES


©2019, IAHR. Used with permission / ISSN 2521-7119 (Print) - ISSN 2521-716X (Online) - ISSN 2521-7127 (USB)


