

# The application of spreadsheets for teaching hydrological modeling and climate change impacts on streamflow

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## Abstract

Hydrology teaching currently relies upon educators' background, requiring a change in training future professionals to manage water resources to address climate change, among other issues. In the teaching experience described in this paper, traditional lectures in a postgraduate civil engineering master's degree were replaced by the development and assessment of a lumped hydrological model implemented into an Excel spreadsheet. Although the primary activity evaluated the long-term impacts of climate change on streamflow in a watershed, the students were required to address several specific issues such as calibration and validation processes, goodness-of-fit metrics, uncertainties of parameters, and sensitivity analysis. The learning experience's efficacy was assessed by conducting two surveys comparing the participants' knowledge before and after the exercise. The results revealed that 92.3% of the students considered that their hydrological skills had improved significantly following the exercise. Furthermore, the acquisition of hydrological modeling concepts was satisfactorily appreciated by all the participants, 97.6% of whom considered it useful or highly useful. Using a spreadsheet as a complementary tool in hydrology teaching increases student participation and motivation provided it is a contemporary and appealing issue, and the teacher clearly defines, monitors, and follows up on the class objectives.

## KEYWORDS

civil engineering, conceptual thinking, hydrology education, hydrology modeling, spreadsheet

## 1 | INTRODUCTION

Hydrology studies the water cycle, including surface and groundwater movements. It has evolved to understand the complex water system to predict current and future water resources. However, hydrology teaching relies upon educators' background and their previous experience in planning classes, requiring a change in the approach to training future hydrologists in an interdisciplinary task [35]. Despite efforts to improve hydrology education, practical training still requires much work

[78,80]. The need to adapt hydrology teaching to water requirements and socio-political structures is a crucial factor distinguishing this discipline from similar subjects such as meteorology, which has internationally accepted educational guidelines.

Notwithstanding, the lack of guidelines also has several advantages; thus, the pedagogical process can be adapted to the specific frameworks and resources available at all times. Hydrology education planning should begin by defining its targets. Besides location, climatic conditions, and water resources, future

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hydrological tasks must be considered to provide a complete overview for subsequent generations of hydrologists.

Teaching scientific subjects demands considerable practical training, and hydrology is no exception. In contrast, its study requires practical methods to achieve the appropriate skills. It is not unusual for students to assimilate the complex processes in the water cycle, with a wide range of concepts and spatio-temporal variables, using only theoretical material [44].

The exposition of hydrological processes in a master's class is far from simple. Significant comprehension efforts are required when teaching methodologies focus solely on lectures and audiovisual means. Furthermore, master's classes do not allow several essential aspects of the professional exercise to be considered in depth. Moreover, a lack of clear objectives and assessment, passive learning based on master's classes that do not ensure optimum results, and limited budgets for practical exercises are common in current hydrology teaching [55]. Indeed, the study of technical subjects in engineering often contains complex calculations that are highly time-consuming in sessions devoted to resolving problems. Fortunately, the latter obstacle can be currently avoided using specific, or even, common software that monitors and manages significant amounts of data, allowing students to simulate real situations and put theoretical knowledge into practice [59].

Modeling is a common task in hydrological research and engineering work. Therefore, students must develop the relevant skills throughout the learning period [1]. Moreover, managing a considerable amount of climatic and soil data to analyze watershed behavior following rainfall events is part of this effort [7]. Hydrological models are essential tools for measuring spatio-temporal variability in water cycle processes, contributing to the deeper understanding of concepts, the variables, and their relationships, and data sources within the complex rainfall-runoff process [79], besides assessing streamflow variation due to climate change. The use of models in teaching has significantly increased over the past decades due to significant developments in technology and easy access to computers [64,82]. However, [42] observe two principal problems in implementing hydrological models in an educational framework: their codes and complex use. Indeed, time in university courses can constrain adequate knowledge and the implementation of more complex applications, such as physically based fully distributed models [31]. Conversely, lumped models typically have moderate data requirements and are easily implemented by inexperienced users [37]. Due to these features, models are not only crucial for research and educational purposes [14]. Conceptual models can be

considered the middle ground between black box and physically based models [61], avoiding nontransparent and complex processes that impede the educational objectives and labor preparation discussed above.

The use of technology in teaching and learning has been consolidated in the pedagogical field to the extent that it is a discipline in training specialists at all education levels [82]. Although modeling techniques in the hydrological curriculum remain scarce at the university level [57,78], numerous software packages have implemented hydrological models using different programming languages such as MATLAB [23,42,68] or R [5,9,15,20,40,45,76]. Although these applications are extremely useful in a water management framework, recent studies have focused on applied learning methodologies to improve the acquisition of practical skills and competencies [3,17,26,39,67,70,74]. Jonassen [34] recommended that computer technologies have provided learners with representational power rather than prescribed communication, constraining learning development. Accordingly, spreadsheets can be considered cognitive tools in the learning process [25,34], enabling students to improve their thinking and learning, playing an increasing role effectively in their formation. The potential of spreadsheets in educational settings is unquestionable [4] and is a permanent, relevant topic in educational research in specialized journals, such as [66]. Spreadsheets encourage students to create their own rules for automating operations, manage large amounts of data, assess the sensitivity of model results to individual input parameters, and provide graphical representations of analyses, taking students beyond learning how to use specific software [22]. Indeed, hydrology and hydraulic engineering courses have already been an adequate framework where spreadsheets have been widely used [6,13,16,28,30,43,51,73]. Notwithstanding, spreadsheets for teaching hydrological modeling and climate change impacts have not been implemented in engineering education so far. Nevertheless, active engagement in the learning process may be undermined if the goals are not sufficiently clear from the beginning of the problem statement [55]. Therefore, in addition to the educational feature's conceptual configuration, the teacher's main challenge in ensuring the student body's involvement is to place the students, who are also knowledgeable about the issue and able to use actual data, in a real-world context [59].

This paper describes teaching experience in a postgraduate civil engineering master's degree in water resource management carried out over two consecutive academic years (2019–2020 and 2020–2021). The principal activity was evaluating the long-term impact of climate change (2071–2100) on streamflow in a

watershed (different for each student) in Peninsular Spain. The lumped hydrological Témez model [69] was used due to the low amount of necessary hydrological data [33], its ease of implementation into an Excel spreadsheet [49], and its long history of application in Spanish water resources assessment [41,49,54,83]. Furthermore, during the exercise, students accessed meteorological, streamflow, and climate change databases, calibrated and validated the model, and analyzed the sensitivity of the model parameters. Therefore, the teacher had a less significant role, intervening in the model presentation, defining the exercise goals and steps, and clarifying conceptual and procedural questions throughout the model development. The students undertook the challenge of providing a report on the highly topical issue of climate change and water resources using actual data in their own country. In this context, they were required to analyze hydrological model parameters, implement their relationships, and interpret the results, achieving effective, active involvement in the learning task. To the best of our knowledge, the paper addresses for the first time the use of spreadsheets in hydrological modeling education. The Témez model is introduced in Section 2. The methods and student activities are described in Section 3. Section 4 presents and discusses the results of the educational experience. Finally, Section 5 presents the study conclusions.

## 2 | THE TÉMEZ MODEL

The hydrological Témez model [69] is a lumped, rainfall-runoff model widely used in Spain for water resource management [11,12,18,19,21,24,32,33,41,46,49,53,54,83], as well as in other countries [52,56,75]. Although a monthly interval is usually considered, the model can be applied to other intervals.

The system is divided into two zones: the nonsaturated zone ( $S$ ), corresponding to soil moisture, and the saturated zone or aquifer ( $G$ ), located below the former, which is considered an underground tank that drains to the surface drainage network. As illustrated in Figure 1, a portion of the precipitation ( $P$ ) is drained and incorporated into the surface drainage network or the aquifer. The remaining precipitation later feeds evapotranspiration ( $ET$ ). Similarly, the excess ( $Ex$ ) is also divided into surface runoff and aquifer storage. The former leaves the watershed at the current time while the latter feeds the aquifer, partly draining at the current time while the remainder is stored in the aquifer and drains later. Water balance is established by inflow ( $P$ ), which is distributed between outflows (actual evapotranspiration [ $ETR$ ],

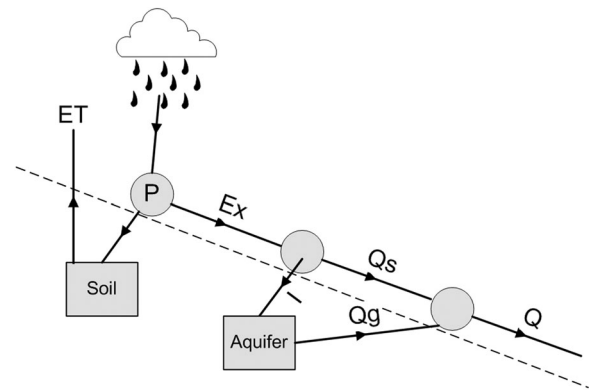


FIGURE 1 The Témez model scheme.

surface runoff [ $Q_s$ ], and underground drainage [ $Q_g$ ], intermediate flows (infiltration [ $I$ ], which is equal to underground recharge [ $R$ ] in the current month), and intermediate storage (soil moisture [ $S$ ] and volume in the aquifer [ $G$ ]) in each  $i$ -month.

The first step is to define the initial soil moisture ( $S_0$ ) and underground storage ( $G_0$ ) conditions. The model considers that one portion of the precipitation (mm) in the  $i$ -month ( $P_i$ ) is stored as soil moisture ( $S_i$ ), and the excess ( $Ex_i$ ) is divided between surface runoff ( $Q_{s_i}$ ) and infiltration to the aquifer ( $I_i$ ).  $Ex_i$  (mm) is calculated using Equations (1) and (2):

$$Ex_i = 0 \quad \text{if } P_i \leq P_0, \quad (1)$$

$$Ex_i = \frac{(P_i - P_0)^2}{P_i + \delta - 2 \cdot P_0} \quad \text{if } P_i > P_0, \quad (2)$$

where:

$$\delta = S_{\max} - S_{i-1} + ETP_i, \quad (3)$$

$$P_0 = C \cdot (S_{\max} - S_{i-1}), \quad (4)$$

where  $S_{\max}$  is the maximum soil water-storage capacity (mm),  $S_{i-1}$  is the soil water-storage (mm) at the beginning of the period ( $i$ ),  $ETP_i$  is the potential evapotranspiration (mm) in the  $i$ -month, and  $C$  is the dimensionless coefficient of the initial excess, which varies between 0.2 and 1.

Soil moisture and evapotranspiration at the end of each month are obtained using Equations (5) and (6):

$$S_i = \max(0; S_{i-1} + P_i - Ex_i - ETP_i), \quad (5)$$

$$ET_i = \min(S_{i-1} + P_i - Ex_i; ETP_i). \quad (6)$$

When there is sufficient  $S_i$ ,  $ET$  rises until it reaches  $ETP$ . Otherwise,  $S_i$  is zero.

Furthermore, the Témez model considers that  $I_i$  depends on the  $EX_i$  and the maximum infiltration ( $I_{\max}$ ), using Equation (7):

$$I_i = I_{\max} \cdot \frac{EX_i}{EX_i + I_{\max}}. \quad (7)$$

$I_i$  (mm) becomes  $R_i$ , as the remaining excess ( $EX_i - I_i$ ) is drained as surface runoff (Equation 8):

$$Qs_i = EX_i - I_i. \quad (8)$$

It is assumed that the time to pass through the non-saturated zone is lower than the simulation interval time.

The release of water from the aquifer is taken into account using a parameter ( $\alpha$  [month<sup>-1</sup>]) that considers the exponential depletion curve, similar to other unicellular models [65]. Thus, the surface flow ( $Q_i$ ) from the aquifer is obtained using Equation (9):

$$Q_i = \alpha \cdot G_i. \quad (9)$$

Applying the mass-balance differential expression in Equation (10) and combining Equations (9) and (10), Equation (11) is obtained:

$$I_i - Q_i = \frac{dG_i}{dt}, \quad (10)$$

$$R_i - \alpha \cdot G_i = \frac{dG_i}{dt}. \quad (11)$$

Additionally,  $R$  can be expressed as Equation (12):

$$R = \text{Sup} \cdot I_i, \quad (12)$$

where  $\text{Sup}$  is the watershed area (km<sup>2</sup>).

Equation (13) provides the volume in the aquifer at a monthly interval  $\Delta t$  (month), which corresponds to the  $i$ -month to  $i-1$ -month period:

$$G_i = G_{i-1} \cdot e^{-\alpha \cdot \Delta t} + \frac{\text{Sup} \cdot I_i}{\alpha} (1 - e^{-\alpha \cdot \Delta t}). \quad (13)$$

Furthermore,  $Qg_i$  is derived from Equation (14):

$$Qg_i = G_{i-1} - G_i + R_i. \quad (14)$$

Total runoff ( $Q_i$ ) is the sum of surface runoff ( $Qs_i$ ) and underground drainage ( $Qg_i$ ) (Equation 15):

$$Q_i = Qs_i + Qg_i. \quad (15)$$

TABLE 1 The range of Témez model parameters

	$S_{\max}$ (mm)	$C$	$I_{\max}$ (mm)	$\alpha$ (month <sup>-1</sup> )
Minimum	50	0.2	10	0.001
Maximum	250	1	150	0.9

Therefore, the data required to run the model are monthly precipitation and evapotranspiration, calculated with maximum and minimum temperatures. Moreover, the Témez model requires four parameters to be set:  $S_{\max}$ ,  $C$ ,  $I_{\max}$ , and  $\alpha$ . The first two parameters control soil storage, the third surface and underground drainage, and the latter underground drainage. All of the parameters are watershed-specific and subject to calibration. The upper and lower limits of the parameters are given in Table 1.

### 3 | METHODOLOGY

As previously discussed, the Témez model can be easily implemented into an Excel spreadsheet or set up using any programming language. Excel software was used throughout learning the hydrological process because students are more familiar with Excel spreadsheets and their ease of analyzing changes in data and parameters.

#### 3.1 | Participants and equipment

The module was developed as part of the water resources management course in the Civil Engineer master's degree at the Catholic University of San Antonio, Murcia, Spain, over the academic years 2019–2020 and 2020–2021. The numbers of students were 16 and 12, respectively; the average age was 31 years, 18% of the participants were female, and the rest were male. Most of the students (88%) combined work and study. However, none had worked in water management. Therefore, all of them had previously used Excel software either at university or in the workplace. The classes took place in a university computer room with an image projection system and personal, internet-accessible computers with the Windows 7 Professional operating system and Excel 2019 software. Class slides and supporting material were uploaded to the online student platform before the session.

#### 3.2 | Presentation of the issue

First, the Témez model and the parameters and relationships forming its structure were described. The students

were also taught to estimate ET using the Thornthwaite [72] and Hargreaves [29] methods. Therefore, the different steps to develop before considering a model's suitability (calibration, validation, sensitivity, and uncertainty analysis) were explained, in addition to the goodness-of-fit measures to use at each stage and their statistical meanings. Meteorological and streamflow online databases were demonstrated with the download format and the transformations required to work in Excel. Precipitation and temperature were obtained from the 5 × 5 km gridded precipitation data set provided by the Spanish State Meteorology Agency (AEMET) [62] available at <https://swat.tamu.edu/data>. Precipitation data were compared with the Climate Forecast System Reanalysis (CFSR) data set available at <http://globalweather.tamu.edu/>. Finally, climate change data for the assessed scenarios were obtained from the AEMET website at [http://www.aemet.es/es/serviciosclimaticos/cambio\\_climat](http://www.aemet.es/es/serviciosclimaticos/cambio_climat).

Following this introduction, the students were asked to implement the Témez model for a Spanish watershed; the primary objective was to assess the long-term impacts of climate change on streamflow. The exercise consisted of seven tasks, described in the following sections. The complete exercise definition is presented in Appendix 1 (Figure 2).

### 3.3 | Témez model configuration and determination of the initial goodness of fit

Each student was initially assigned a code for a streamflow station in the Spanish official capacity station network

(ROEA) available at [https://ceh.cedex.es/anuarioaforos/afo/estaf-mapa\\_gr\\_cuenca.asp](https://ceh.cedex.es/anuarioaforos/afo/estaf-mapa_gr_cuenca.asp). The code had been examined previously to ensure a minimum of 30 years' streamflow data registered at the gauging station. Next, precipitation and temperature data for each watershed were downloaded from the AEMET website. At this stage, ET was calculated using the Hargreaves method. These data allow the students to prepare the spreadsheet for the Témez model of the watershed, calculate the total monthly runoff ( $Q_i$ ) recorded at the streamflow monitoring stations and compare it with actual data from ROEA. Random values were used for the model parameters and initial conditions

The model's efficiency was evaluated using the Moriasi grading method [48], which is based on the NSE [50], RMSE observations standard deviation ratio [63], and PBIAS [27] values. Each statistical index was allocated a grade (3, 2, 1, or 0) depending on the value obtained within the range illustrated in Table 2. The model was assessed from very good to unsatisfactory according to the classification sum presented in Table 2. In addition to the model's performance according to previous goodness-of-fit tests, observed and calculated monthly flows were compared graphically to better understand the model's ability and confirm the obtained numerical values.

### 3.4 | Model calibration and validation

The second task of the exercise consisted of determining the goodness of fit in both the calibrating and validating stages. One year was considered the warming-up period, 50%–75% of the remaining years were used for calibration and the rest for validation. The evolutionary algorithm in Excel's Solver

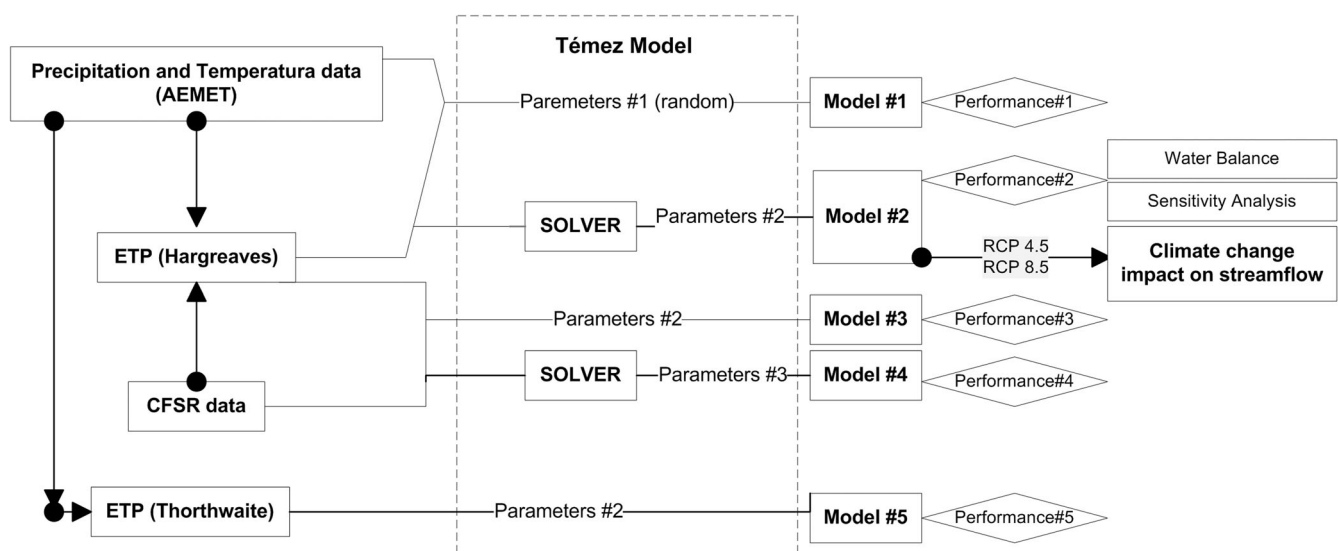


FIGURE 2 The conceptual structure of the educational experience.



TABLE 2 The hydrological model classification criteria

Goodness of Fit	NSE	PBIAS (%)	RSR	Grading	Classification sum
Very good (V)	$0.75 < \text{NSE} \leq 1.00$	$\text{PBIAS} < \pm 10$	$0.00 < \text{RSR} \leq 0.50$	3	$7 < E \leq 9$
Good (G)	$0.65 < \text{NSE} \leq 0.75$	$\pm 10 \leq \text{PBIAS} < \pm 15$	$0.50 < \text{RSR} \leq 0.60$	2	$5 < E \leq 7$
Satisfactory (S)	$0.50 < \text{NSE} \leq 0.65$	$\pm 5 \leq \text{PBIAS} < \pm 25$	$0.60 < \text{RSR} \leq 0.70$	1	$3 < E \leq 4$
Unsatisfactory (U)	$\text{NSE} \leq 0.50$	$\text{PBIAS} \geq \pm 25$	$\text{RSR} \leq 0.70$	Unsatisfactory	Unsatisfactory

tool was used in the optimization problem to minimize the differences between observed and simulated flows.

As in the previous task, statistical indices and classification criteria were assessed, in addition to a graphical comparison between observed and simulated flows. A simulated rather than a calibrated flow curve was added to provide a comparison with the initial stage.

### 3.5 | Water balance and hydrograph

After validating the model, the students verified the average annual water balance of the watershed, drawing a scheme of the different fluxes and storages according to the previous results. Similarly, both simulated and validated average annual runoff were depicted and compared. Furthermore, an average monthly hydrograph was obtained, as well as the remaining parameters assessed in the Téméz model, to determine the variability in the studied period.

### 3.6 | Precipitation data uncertainty

During this activity, participants analyzed the uncertainty related to precipitation input data. In this case, CFSR precipitation data were used (<https://globalweather.tamu.edu/>), and both precipitation databases were compared. Furthermore, the goodness-of-fit was assessed using CFSR data with previously validated parameters. Finally, the model was calibrated and validated again using CFSR precipitation data, and the models' statistics and classification were compared.

### 3.7 | ETP assessment uncertainty

As in the previous task, students addressed model uncertainty in the calculation of one of the main parameters (ETP) instead of the validity of the data. First, ETP was obtained using the Thornthwaite method [71], and the results were cross-checked with the Hargreaves values used in previous activities. Next, the model's performance was again assessed

using Thornthwaite values with the validated parameters initially obtained.

### 3.8 | Model parameter sensitivity

The sensitivity of the Téméz model's parameters was carried out at this stage using the relative error between the observed and simulated runoff volumes (REV), defined in Equation 16:

$$\text{REV} = \frac{M_t - O_t}{O_t} \cdot 100, \quad (16)$$

where  $M_t$  is the total simulated runoff, and  $O_t$  is the total observed runoff. The range of values for the four parameters is presented in Table 1. A minimum of 10 iterations were made for each parameter to analyze its influence on the changes in REV.

### 3.9 | Climate change impacts

Based on the initial calibrated model, climate change data for the Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 were used to evaluate the impact of these climate change scenarios on the water resources in the watershed. Initially, a comparison was made between historical (1971–2000) and predicted (2071–2100) average precipitation and maximum and minimum temperatures. Next, the model was run using both RCP datasets in the 2071–2100 period. Finally, the streamflow results were compared to historical values.

An example of the spreadsheet used, containing all the worksheets developed in this paper has been made available to the community at Zenodo (<https://doi.org/10.5281/zenodo.6424526>).

### 3.10 | The report

The students delivered a final report, in which they provided a justified response for each of the above

activities and established the findings and conclusions obtained throughout the process. The Excel file they had supported was also joined to the report.

### 3.11 | The survey

Following the report delivery, a survey of all students was conducted. The survey consisted of 16 questions. The first seven related to their previous knowledge of the issues addressed during the activity: Excel, hydrological models in general, and the Temez model in particular, meteorological databases, calibration, validation, uncertainty and sensitivity analyses, and climate change impacts on water resources. The four possible answers to each question ranged from extensive knowledge to none. The remaining nine questions considered experience and educational targets. The students were asked about the issues described above from the perspective of improvement following the activities. Thus, the possible responses, in this case, varied from a substantial improvement to virtually no change. Therefore, two questions were added at the end of the questionnaire. These included a global evaluation of the educational methodology and the usefulness of spreadsheets for developing hydrological models and understanding modeling concepts.

The survey questions are included in Appendix 2.

## 4 | RESULTS AND DISCUSSION

Although meteorological databases were initially the only data source used to set the model, we realized that this widely available information was new to the students. All of

them were civil engineering graduates, and some had previously worked on hydrological tasks. However, none were aware of the existence of historical and satellite meteorological or streamflow data series that could be easily (in most cases) downloaded from institutional or research organizations. To present a sufficiently representative result, the conventional data created in class preparation may have diminished the analytical intention, ignoring the study and purpose of the data themselves, as well as their sources, both traditional and emerging. Although CFSR products have been researched intensively for more than a decade [65,81], their usefulness is rarely explained in graduate degrees.

Almost 82% of the participating students considered their previous knowledge of Excel to be moderate to high. However, when preparing the Temez model spreadsheet, many students encountered problems using basic tools such as the conditional function, and some did not know how to lock the cell reference. The survey revealed that the use of Excel had improved significantly during the activities in 93% of the students, indicating clear underuse of this software. The 21st-century graduate curricula should pay more attention to global and international labor market requirements, and lecture-based classrooms must be coupled with hardware and software learning [8] to prepare students for employment [58].

As might be expected, the noncalibrating model provided unsatisfactory results in individual statistics and the proposed grading method. At this stage, students may not realize how far they are from attaining the objective of the hydrological model's performance. Nevertheless, the differences with satisfactory values are beyond a reasonable doubt. The chart comparing observed and simulated (but noncalibrated) streamflow with random parameters (Figure 3) helped to understand the inconsistency of the results and the invalidity of the

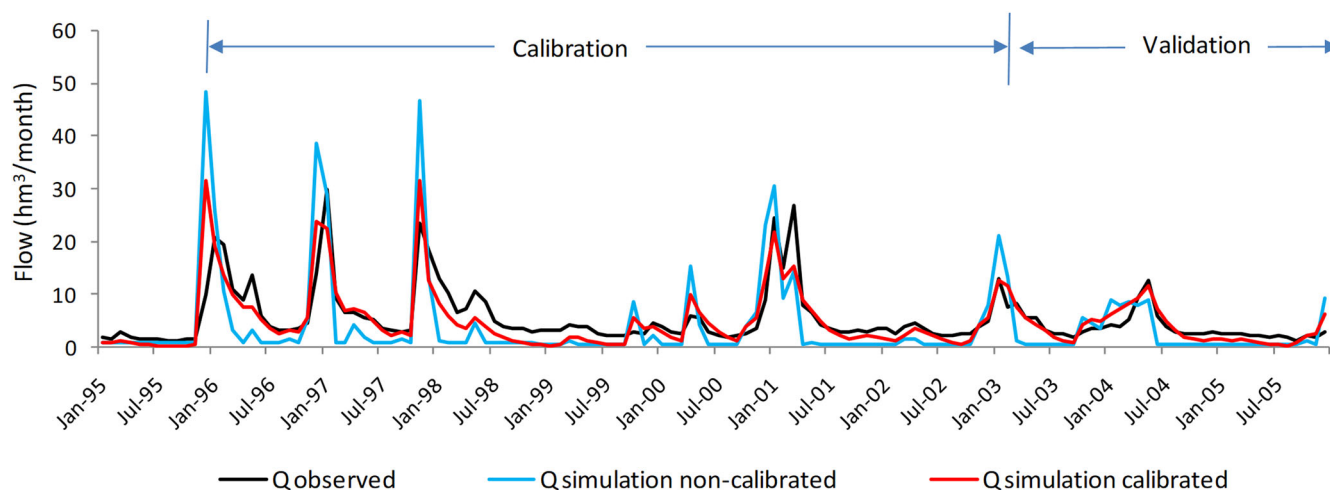


FIGURE 3 Comparison between observed flow rates and those simulated by the Temez model.

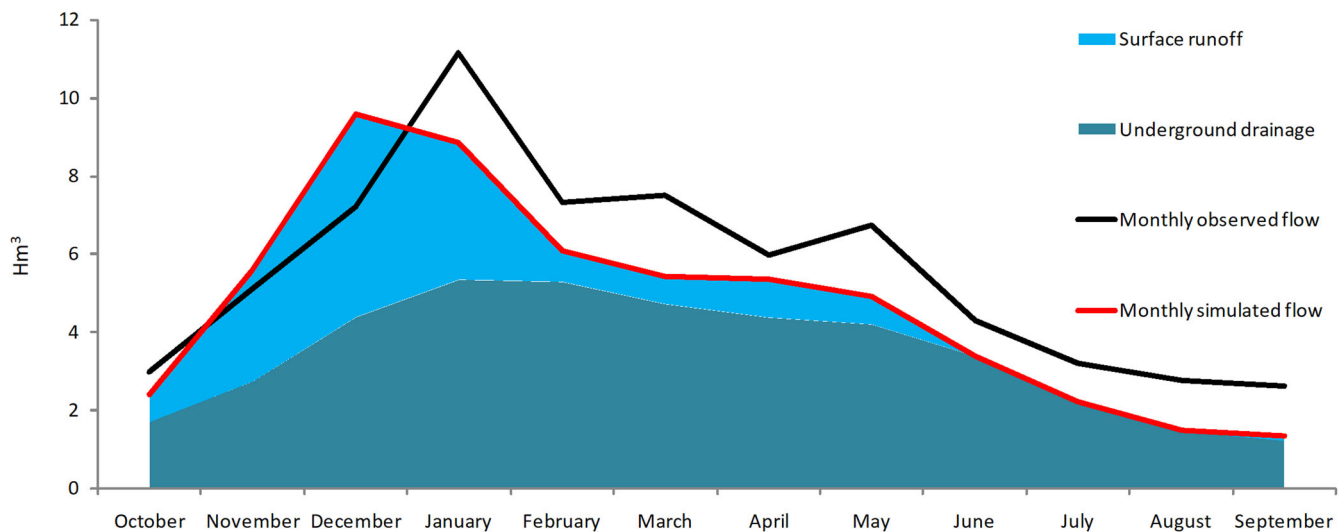


FIGURE 4 Average monthly hydrograph.

TABLE 3 Physical and statistical characteristics of the watershed ( $P_{av}$ : average yearly precipitation,  $A$ : drainage area,  $H$ : basin relief,  $S$ : slope,  $C_v$ : coefficient of variation,  $C_s$ : coefficient of skewness, IR: intermittency ratio).

Physical characteristics				Statistical characteristics							
	$P_{av}$	$A$	$H$	$S$	Average	Min	Max	St. Dev.	$C_v$	$C_s$	IR (%)
River basin	(mm/year)	(km <sup>2</sup> )	(m)	(m/m)	(hm <sup>3</sup> /month)	(hm <sup>3</sup> /month)	(hm <sup>3</sup> /month)	(hm <sup>3</sup> /month)			
Anchuricas	607	233	797.6	0.0221							
Stage	Calibration				5.24	0.26	31.44	5.86	1.12	1.05	0.0
	Validation				4.01	0.21	12.64	3.50	0.87	1.12	0.0
	Observed				5.55	1.40	29.90	5.22	0.94	1.09	0.0

model. Graphical information can be used to interpret and support statistical values and reveal differences between calibrated and noncalibrated models, as shown in Figure 3. Using the Solver tool to optimize the square disparity between observed and simulated flows had the desired impact on goodness-of-fit tests and the comparison chart. Aside from largely reducing the differences between observed and simulated streamflow, and although the grading method did not bring satisfactory results in many students' models, the statistics significantly improved regarding the random parameters model, especially PBIAS. This is easily correlated graphically with the model's performance using actual values in the studied period (Figure 3). Although the highest peaks tended to be far from the observed flow, the trend was more comparable for the calibrated model than for the noncalibrated model.

The average monthly hydrograph presented in Figure 4 allows the months with marked disparities to be analyzed. Spring is the rainiest season in peninsular Spain and when peak flows are more concentrated.

However, as demonstrated in Figures 3 and 4, the Temez model underestimated extremes, resulting in lower streamflow than observed. Conversely, the model overestimated drought periods during the summer season and at the beginning of autumn. Students can efficiently conduct this analysis by critically observing the graphics, aided by statistical measures (Table 3) as shown by [10] and appropriate teacher guidance. Furthermore, after adding surface and underground water to the hydrograph chart, students can assess their relative contribution to the flow in the control section and the importance of aquifers in the watershed.

Monthly water balance (Figure 5) is also a very intuitive means of understanding the hydrological cycle in the studied watershed. The different components and their values are given in Figure 5, in which precipitation and temperature (maximum and minimum) inputs are turned into evapotranspiration, soil moisture storage, underground water, and surface runoff, resulting in the output streamflow. Using this simple image, the student returns to the initial considerations and maintains vision



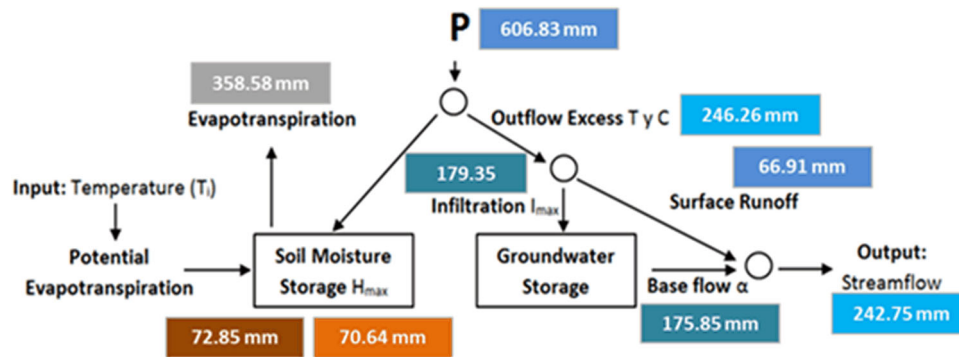


FIGURE 5 Monthly water balance.

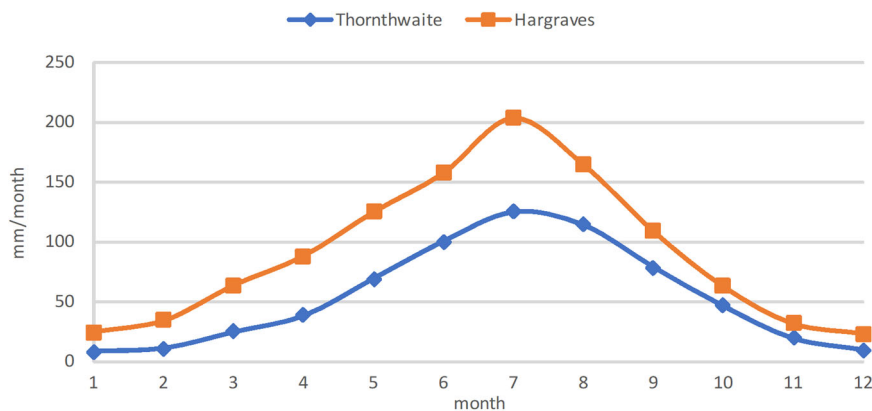


FIGURE 6 Comparison of Thornthwaite and Hargraves ETP (mm).

based on the process. In some senses, they become conscious of the information provided in the spreadsheet and replicated by the model.

Using the CFSR database with previously validated parameters emphasizes the relevance of precipitation data in the model's behavior, resulting in poorer statistical values in all cases and generally unsatisfactory performance. A comparison of AEMET and CFSR precipitation indicates that the CFSR maximum and minimum precipitation extremes are within the range of variation in the AEMET data, which reveal more irregularity throughout the studied period, far more in line with observed streamflow values. Therefore, model performance using CFSR data in calibration was also poor.

Similarly, ETP uncertainty analysis was also carried out considering ETP calculus using the Thornthwaite method, as well as Hargraves. Figure 6 compares the results of both techniques, indicating lower values using the Thornthwaite method. The higher the Hargraves ETP, the greater the difference with Thornthwaite. Virtually all the participants attributed this fact to Hargraves' superior accuracy. Conversely, the simplicity of Thornthwaite relies on the series under study and the

average values obtained. Nevertheless, the latter's lower ETP each month reduced water losses and increased simulated streamflow, achieving close to observed values. This substantially reduced the differences between simulated and observed values and produced satisfactory models in many cases.

Regarding the sensitivity analysis, students obtained a series of REV percentages for the four Temez model parameters (Figure 7), varying within the range shown in Table 1. Besides using a new statistic to assess the model's performance concerning total volume, the results and their graphics provide a valuable tool for differentiating between the more influential parameters and those with less influence on the outcome. Figure 7a demonstrates that  $\alpha$  exerts little influence on the ratio between observed and simulated streamflow in the watershed. A similar result is achieved when  $I_{max}$  is tested, and the REV only differs by 0.01% in the maximum and minimum parameter variation (Figure 7b). Conversely, modifying the  $S_{max}$  and  $C$  values produced approximately 40% and 12% REV, respectively, highlighting the relevance of soil water-storage capacity in the hydrological model's performance, especially in total runoff. Furthermore, participants were able to verify that the

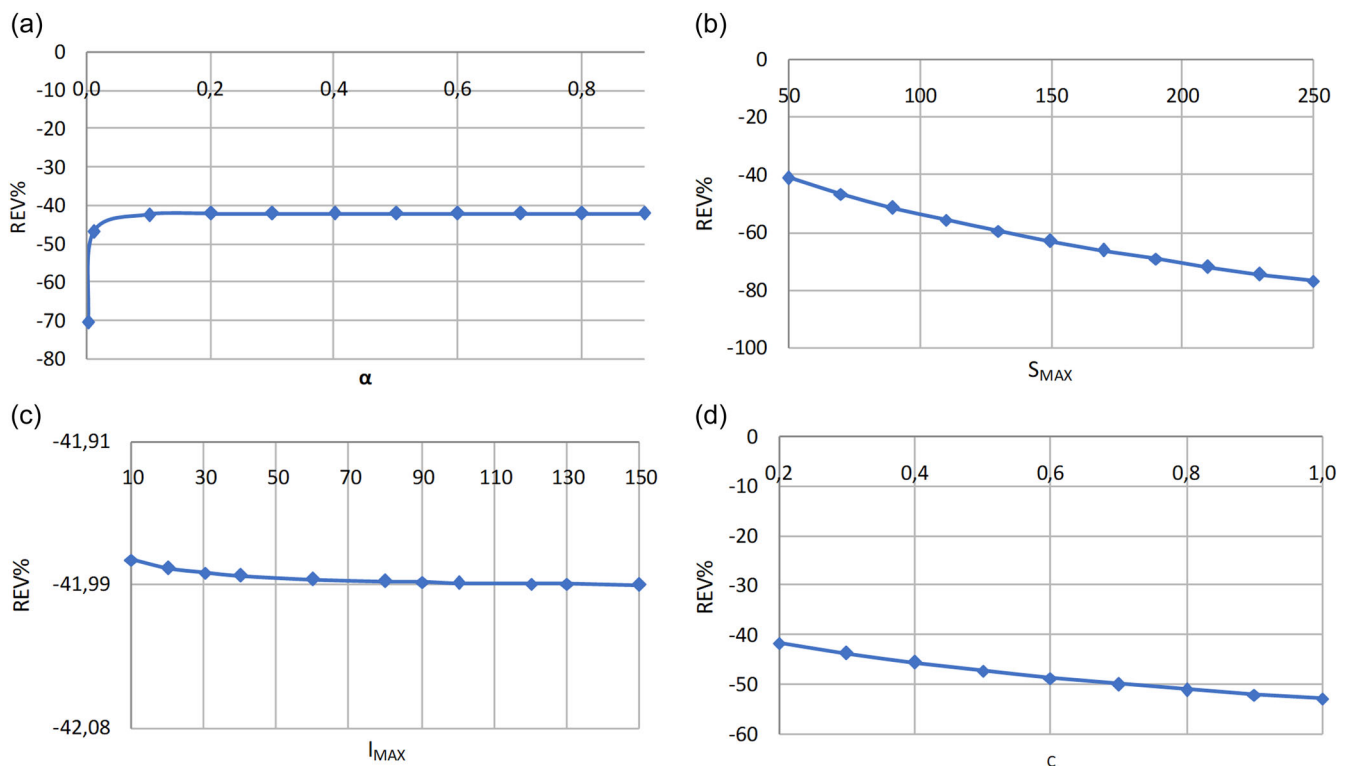


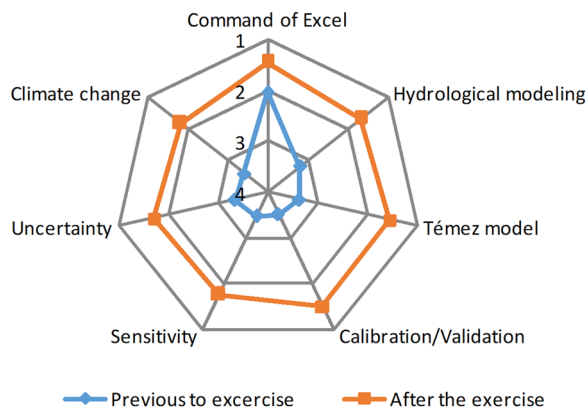
FIGURE 7 Sensitivity analyses of REV for the Temez model parameters. REV, runoff volumes.

sensitivity analysis and the change in the four parameters did not improve the hydrological model's performance compared to using the Solver optimization.

Finally, the validated model was run using RCP 4.5 and RCP 8.5 data for the 2071–2100 period, and the results were compared with the historical period (1971–2000). Although predicted meteorological variables depend on the watershed's location, the main conclusions did not differ substantially. An increase in temperature of 4 and 7°C in RCP4.5 and RCP8.5, respectively, is expected. Annual precipitation decreases significantly in the Iberian Peninsula, especially during the summer months and the further south the watershed is located. Therefore, extremes due to stormy events occur more frequently. However, the total runoff volume did not follow a homogeneous trend in the studied watersheds, although the changes in RCP 8.5 are remarkable when compared with RCP 4.5.

After delivering the report and the spreadsheet, the students were asked to undertake a survey on their improvements in the different issues developed by the methodology. Previous knowledge and improvement were ranked from one to four: (1) high knowledge, (2) moderate knowledge, (3) low knowledge, and (4) no knowledge before the exercise; (1) high improvement, (2) moderate improvement, (3) low improvement, and (4) no improvement during the exercise. As illustrated in Figure 8,

all the subjects had improved significantly, on average, from 3.19 (low knowledge) to 1.64 (high-moderate improvement). As previously discussed, all the students believed that command of Excel was controlled moderately. However, although the exercise included basic functions, the common perception was of significant improvement, achieving the best result of all the issues (1.45). The use of spreadsheets in engineering should be a standard and powerful tool for automating relatively complex calculations and processes efficiently. Excel and other spreadsheets are well-known software among students. However, performance is sometimes reduced to basic operations, so extensive use in classes is needed. The remaining survey questions focused on hydrological modeling and subsequent stages in the process. Values from 3.2 to 3.5 reveal that these issues were almost unknown to the participants. Calibration, validation, and sensitivity analysis represented the highest percentage of students with no knowledge (63%). A similar result (61.5%) was obtained regarding the effects of climate change in a watershed. Climate change is a crucial topic, not only in the research field but also in social and media environments [36,38,60,77]. Future hydrologists must have sufficient theoretical and practical preparation for current and future water management challenges to overcome problems such as water resource security, droughts, or floods. Moreover, active and engaging teaching methods must be applied [47]. These techniques must accompany hydrological modeling,



**FIGURE 8** Comparison of knowledge before and after the exercises.

from data collection to interpretation and evaluating uncertainty. During the described activities, students were able to implement a lumped model into a spreadsheet, optimize the differences between simulated and observed streamflow problems, assess the hydrological model's validity using different goodness-of-fit methods, and test the sensitivity and uncertainty of different parameters. Thus, analyzing the effects of climate change in the studied watershed involved a rigorous understanding of the final comparison between historical and long-term forecasting. This is also reflected in students' views on improving knowledge of the specific tasks carried out, as illustrated in Figure 8. Uncertainty, sensitivity, and climate change were the issues with the highest ratings: 1.70, 1.78, and 1.81, respectively. The results for uncertainty and sensitivity analysis were expected because they are not included in the civil engineering syllabus. However, the climate change result was not anticipated. The most significant differences in knowledge before and after the activities were observed in specific modeling tasks such as calibration and validation, sensitivity analyses, and the Téméz model.

Regarding the teaching method and its usefulness in furthering the learning process, 50% of the participants considered it very useful, 42.3% moderately useful, and 7.7% slightly useful, supporting its implementation in subsequent courses. All the students satisfactorily appreciated the use of spreadsheets for building hydrological models and understanding modeling concepts, with 97.6% considering it useful or highly useful.

## 5 | CONCLUSIONS

Hydrology teaching demands a shift in approaches to training future professionals to manage water resources to cope with climate change challenges in an increasingly technological society. Modeling allows the student body

to acquire key competencies and knowledge based on actual data using specialized software, replicating standard conditions. This paper discussed the teaching experience in a postgraduate civil engineering master's degree, evaluating the long-term impact of climate change on streamflow in a watershed using the lumped Téméz model implemented into an Excel spreadsheet. To achieve this final objective, the students were required to address several specific tasks to develop a hydrological model, such as calibration and validation processes, goodness-of-fit metrics, uncertainties of parameters, and sensitivity analysis. Repeated calculations and their results were immediate, so students were prone to analyze them and interpret their implications. Furthermore, statistical libraries and optimization algorithms included allowed for first hydrological modeling in an intuitive and easy way. It was observed that using a spreadsheet as a complementary tool in hydrology teaching substantially increases student participation and motivation, provided the issue is contemporary and appealing, and the teacher clearly defines, monitors, and follows up on the class objectives. The common use and basic knowledge of Excel spreadsheets by students enabled their implementation within the course schedule with no need for previous remarks or complicated users' manuals. The results obtained in the survey support this finding since 92.3% of the students considered the learning experience to be positive. All the participants satisfactorily appreciated the acquisition of hydrological modeling concepts, 97.6% considering it useful or highly useful. Indeed, knowledge of the specific hydrological skills related to the subject's competencies also improved significantly. Furthermore, during the exercise development, the common perception about the use of spreadsheets was greater control of Excel's built-in functions.

Future work could adapt this methodology to other subjects in which spreadsheets can easily be implemented in graduate and post-graduate civil engineering course planning. In addition, statistical and data analysis software, such as MATLAB, R, or SPSS, could be progressively incorporated into the academic curriculum to enable civil engineers to adjust to the current labor market, as well as focus on self-learning.

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## DATA AVAILABILITY STATEMENT

An example of the Excel spreadsheet developed in this study is openly available in Zenodo at <https://doi.org/10.1090/542.2022.5>

5281/zenodo.6424526. Detailed instructions on how to use them are also provided.

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## APPENDIX 1: EXERCISE WATER RESOURCES ASSESSMENT

Perform a preliminary water resource analysis for the assigned watershed, using the precipitation, evapotranspiration, and streamflow data available in the different databases described in the classes. This requires creating an Excel spreadsheet using the Témez model to assess water resources in the watershed. Use 50%–75% of the available data series for the calibration stage and the remainder for the validation process. Consider one year for the warming-up period.

The following information is required:

1. Determine the ETP using the Hargreaves method and assess the goodness-of-fit in calibration and validation according to Moriasi et al. [48] criteria (NSE, PBIAS, RSR, and  $R^2$ ). Use random values for both the model parameters and initial conditions.
2. Determine the goodness-of-fit of the calibrated model using the Solver tool in Excel. Use the evolutionary algorithm.
3. Obtain the yearly average water balance of the watershed and graphically depict the annual average value of each flux and storage. In addition, compare the observed and simulated flows. Plot the average monthly hydrograph.
4. Analyze the uncertainty regarding input precipitation data. Use CFSR data (<https://globalweather.tamu.edu/>).
  - a. Compare the precipitation data.
  - b. Assess the goodness-of-fit using the parameter values obtained in 2.
  - c. Use the CFSR data to calibrate and validate the model and provide the goodness of fit.
5. Analyze the uncertainty associated with the ETP calculation method.
  - a. Calculate ETP using the Thornthwaite method and compare this with the values obtained using Hargreaves.
  - b. Analyze the model's goodness of fit using the parameter values obtained in 2.
6. Assess the sensitivity of the model parameters using the relative error between observed and simulated REV, defined by the following equation:

$$\text{REV} = \frac{M_t - O_t}{O_t} \cdot 100,$$

where  $M_t$  is the total simulated runoff and  $O_t$  is the total observed runoff.

7. Use the provided climate change data for RCP 4.5 and RCP 8.5 to assess the impact of climate change on the water resources in the watershed.
8. Write a summary report that provides responses to the exercise and attach the used Excel file.

## APPENDIX 2: SURVEY

1. What level of knowledge of using Excel spreadsheets did you have before undertaking this exercise?
  1. High
  2. Moderate
  3. Low
  4. None

2. What level of knowledge about hydrological modeling did you have before undertaking this exercise?
  1. High
  2. Moderate
  3. Low
  4. None
3. What level of knowledge about using the rain-runoff Témez model, including its formulae and calculations, to assess the streamflow in a watershed did you have before undertaking this exercise?
  1. High
  2. Moderate
  3. Low
  4. None
4. What level of knowledge about the calibration, validation, and goodness-of-fit tests of a hydrological model did you have before undertaking this exercise?
  1. High
  2. Moderate
  3. Low
  4. None
5. What level of knowledge about the sensitivity analysis of the model parameters did you have before undertaking this exercise?
  1. High
  2. Moderate
  3. Low
  4. None
6. What level of knowledge about uncertainty regarding input data did you have before undertaking this exercise?
  1. High
  2. Moderate
  3. Low
  4. None
7. What level of knowledge about climate change analysis in a watershed did you have before undertaking this exercise?
  1. High
  2. Moderate
  3. Low
  4. None
8. Has your knowledge of using Excel spreadsheets improved after undertaking this exercise?
  1. Considerably
  2. Moderately
  3. A little
  4. No improvement
9. Has your knowledge about hydrological modeling improved after undertaking this exercise?
  1. Considerably
  2. Moderately
  3. A little
  4. No improvement
10. Has your knowledge about the rain-runoff Témez model, including its formulae and calculations, to assess the streamflow in a watershed improved after undertaking this exercise?
  1. Considerably
  2. Moderately
  3. A little
  4. No improvement
11. Has your knowledge about calibrating, validating, and testing the goodness-of-fit of a hydrological model improved after undertaking this exercise?
  1. Considerably
  2. Moderately
  3. A little
  4. No improvement
12. Has your knowledge about analyzing the sensitivity of model parameters improved after undertaking this exercise?
  1. Considerably
  2. Moderately
  3. A little
  4. No improvement
13. Has your knowledge about uncertainty regarding input data improved after undertaking this exercise?
  1. Considerably
  2. Moderately
  3. A little
  4. No improvement
14. Has your knowledge about climate change analysis in a watershed improved after undertaking this exercise?
  1. Considerably
  2. Moderately
  3. A little
  4. No improvement
15. How useful was the learning method used to achieve the subject's goals?
  1. Very useful
  2. Moderately useful
  3. Little useful
  4. Useless
16. How useful was the Excel spreadsheet in implementing the hydrological model and understanding modeling concepts?
  1. Very useful
  2. Moderately useful
  3. Little useful
  4. Useless