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Application of a Conceptual Hydrologic Model in Teaching Hydrologic Processes*

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In this study, a hands-on modeling tool is developed for students in civil engineering and earth science disciplines to help them learn the fundamentals of hydrologic processes and basic concepts of model calibration and sensitivity analysis, and practice conceptual thinking in solving and analysis of engineering problems. This modeling tool aims to provide an interdisciplinary application-oriented learning environment that introduces the hydrologic phenomena through the use of a simplified conceptual hydrologic model. The modeling tool was introduced in an upper-level civil engineering course and students were asked to submit their feedback before and after using the modeling tool through the Student Assessment of Learning Gains (SALG) online system to gauge improvement in their learning. The SALG report showed that the hands-on approach significantly added to students' learning and provided them with better understanding of interconnected hydrologic processes. Furthermore, students gained knowledge in areas that are not commonly taught in hydrology lectures (e.g. calibration, sensitivity analysis, etc). Based on the findings, some recommendations are given for further improvements in the use of hydrologic models as interactive tools for teaching complex and interconnected hydrologic concepts and inspiring students towards postgraduate education or future professional career.

Keywords: hydrology education; hydrologic modeling; hands-on laboratory program; conceptual thinking; interdisciplinary application oriented learning environment

1. INTRODUCTION

UNDERSTANDING HYDROLOGIC PROCESSES (i.e. evapotranspiration, infiltration, snowmelt, interflow, etc.) is fundamental to water resources and environmental engineers and scientists. The need for improving existing engineering hydrology curricula has been highlighted in various national and international reports, particularly in two areas: modeling and field observations [1–3]. More recently, two major community initiatives (the Consortium for Universities for the Advancement of Hydrologic Science, Inc., CUAHSI [4]; and the Collaborative Large-Scale Engineering Analysis Network for Environmental Research, CLEANER) have stressed the critical role of observations and simulation models for transforming the future of hydrologic and engineering education. With the increasing availability of hydrologic data over a wide range of scales (e.g., from remote sensing platforms), hydrology education can significantly benefit from the use of simulation models to aid in understanding the complex behavior and significant variability evident in hydrologic observations. In fact, a purely theoretical coverage of hydrology topics can be uninteresting to today's engineering students who are better inspired by hands-on teaching methods.

Hydrologic models [5–6] have been used extensively to study the effect of water resources management scenarios, to enable prediction in ungauged catchments, and to assess the impact of possible future changes in climate and land use. Modeling, in general, is the process of describing a system based on some input variables, model parameters, and initial conditions. Within an educational framework, hydrologic models can provide students and educators with supportive environments for inquiry and discovery-based learning [7]. Recent studies have recommended the use of hands-on teaching techniques in engineering education to inspire students in learning the fundamental concepts and prepare them for their future practical careers [8–10]. Chanson and James [11] used real-life sedimentation and catchment erosion case studies to highlight the importance of sediment transport in design procedure. Hanson et al. [12] presented a learning tool for system modeling using a set of linear reservoirs. Elshorbagy [13] employed the concept of system dynamics for teaching watershed hydrology. Endreny [14] applied numerical methods and programming techniques to explore the Green-Ampt infiltration scheme.

Following on from these efforts, this study tests the use of a simplified conceptual hydrologic model to expose students in engineering and environmental sciences programs to a first-hand experience of hydrologic modeling. The model, described in the following section, is provided in an Excel spreadsheet so that students can easily change the

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parameters and see their effects on the output hydrograph and other intermediate hydrologic processes. Using this step-by-step tool, students learn how hydrologic processes are interconnected and how modeling can be justified based on available observations. This hands-on tool (free copies are available from the authors) is developed for both undergraduate and graduate students to help them learn the fundamentals of hydrologic processes, modeling practices and procedure (e.g. calibration and sensitivity analysis) and also practice conceptual thinking in solving hydrologic engineering problems. In addition to the Excel spreadsheet version, the model is also available in MATLAB with Graphical User Interface (GUI) that is a pervasive element of most modern technical software and represents a convenient tool for student instruction. The modeling-based tool is introduced in an upper-level under-graduate civil engineering course and an assessment survey is conducted to measure the impact on students' learning and conceptualization of hydrologic processes and modeling.

This paper is divided into six sections. After the introduction, the conceptual hydrologic model used in this study is briefly introduced. The third section presents the methodology and approach followed to introduce the model in the classroom. The fourth section is devoted to presenting and discussing the results on assessment of student performance and their response to the modeling tool. In the fifth section, a discussion on perspectives of future work is provided. The paper closes with conclusions and some final remarks.

2. MODEL CONCEPT

It was some 160 years ago that the first hydrologic model for runoff prediction was introduced based on an empirical relation between rainfall intensity and peak flow [15–16]. Since then, a multitude of hydrologic models with various degrees of assumption and simplification have been developed to simulate various rainfall-runoff processes, many of which are still not fully understood. Depending on the assumptions used by the modeler, a model can give reasonable results for a specific situation which it is calibrated for; however, the same model may not work in other cases. Hydrologic models can be categorized into three different groups [17]:

(1) Physically-based models that are based on solving governing equations such as conservation of mass and momentum equations. Parameters and state variables may be either directly measured in the field or reasonably assumed based on site characteristics;
(2) conceptual models that use simple mathematical equations to describe the main hydrologic processes such as evapotranspiration, surface storage, percolation, snowmelt, baseflow, and runoff. The advantage of this approach is that the model is much simpler from a mathematical point of view. The processes are estimated with simple equations rather than solving governing partial differential equations. To replace the partial differential equations with simple statements, a variety of different model parameters are introduced into the model that may have little physical meaning;
(3) empirical models that are based on analyzing observed input (e.g. rainfall) and output (e.g. discharge) and linking them through statistical or other similar techniques. Empirical models are normally mathematically simpler than their physical and conceptual counterparts, and reasonably good results can be quickly obtained by using techniques such as regression and neural networks. The SCS method [18] is a very well-known example of an empirical model that is frequently used for runoff prediction.

In the current study, a conceptual model based on the HBV model concepts is presented for hydrology educational purposes. The HBV model is selected mainly because of its conceptual approach in which the hydrologic processes are simplified to algebraic functions and thus, the required calculations can be easily conducted in an Excel spreadsheet. The HBV model was originally developed by the water balance section of the Swedish Meteorological and Hydrological Institute (SMHI) to predict the inflow of hydropower plants in the 1970s [19–20].

The HBV model is available as a community model in various versions that vary in their complexity and utility features. The principal model structure and process representations presented here, is based on the modified version of the HBV model, developed at the Institute of Hydraulic Engineering, University of Stuttgart, Germany [21–24].

HBV can be used as a fully-distributed or a semi-distributed model by dividing the catchment into sub-basins; however, in the current study a simplified spatially-lumped version of the model is used for teaching purposes. In a lumped model, it is assumed that the study area (watershed) is one single unit (zone) and the parameters do not change spatially across the watershed. The HBV model consists of four main modules:

(1) Snowmelt and snow accumulation module;
(2) Soil moisture and effective precipitation module;
(3) Evapotranspiration module;
(4) Runoff response module.

Figure 1 illustrates the general processes of the simplified educational version of the HBV model. The model can run at a daily or monthly time step; the required input data include time series of precipitation and temperature observations at each time step, and long-term estimates of mean

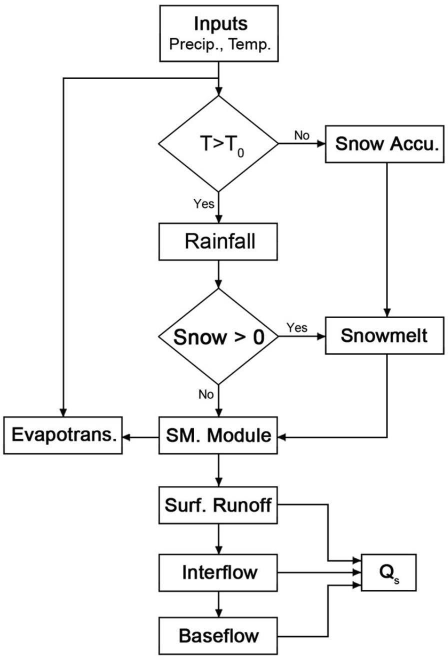

Fig. 1. General processes of educational version of HBV model.

monthly temperature and potential evapotranspiration rates. As shown, the model includes a module that processes the input precipitation either as rainfall or snow, based on the input temperature at each time step. The rainfall and snowmelt (if it exists) are then processed in the soil moisture module where the effective rainfall that contributes to the surface runoff is evaluated. The remaining part of the rainfall contributes to the soil moisture storage which itself can be evaporated as long as there is enough water content in the subsurface. The main output of the model is discharge runoff at the outlet of the watershed, which has three components: surface runoff, interflow (contribution from near surface flow) and baseflow (contribution from groundwater flow). The model has a number of parameters that need to be calibrated based on available observations. In the following, the details of each module are briefly described.

2.1 Snowmelt and snow accumulation

Snowmelt and accumulation are assumed to be directly proportional to the temperature. The first model parameter is the threshold temperature, T_t; for temperatures above T_t snow melts and below T_t it accumulates. Setting the initial T_t temperature to zero degrees Celsius (32 degrees Fahrenheit) is a reasonable initial assumption. If a precipitation event occurs when the temperature is below T_t then precipitation accumulates as snow, otherwise the input precipitation is assumed to be rainfall (i.e. liquid). As long as the temperature remains below the threshold temperature, the input precipitation does not contribute to runoff. However, as soon as the temperature exceeds the threshold, both snowmelt and precipitation start to contribute to runoff. In this model Equation 1 is used to estimate the snowmelt rate as water equivalent:

$$S_m = DD \cdot (T - T_t) \tag{1}$$

Where S_m is snowmelt rate as water equivalent [LT^{-1}]; DD is degree-day factor [$L\theta^{-1}T^{-1}$]; T is mean daily air temperature [θ]; T_t is threshold temperature for snow melt initiation [θ].

The empirical parameter degree-day factor (DD) indicates the decrease of the water-content in the snow cover caused by 1° above the freezing threshold in one day. A relatively wide range of degree-day-factor, from 0.7 to 9 mm°C^{-1}day^{-1}, has been reported in the literature [25–26]. The degree-day factor, DD, can be assumed to be a constant or varying parameter. When rainfall occurs over existing snow, snowmelt increases due to the additional thermal energy available in the slightly warmer rainwater [27]. In the educational version, however, the degree-day factor (DD) is assumed to be a constant. The DD factor is a model parameter that can be measured through field experiment. However, this model parameter can also be estimated via calibration against observed hydrograph as explained later.

2.2. Effective precipitation and soil moisture

Precipitation falling over a watershed is usually partitioned into two components: the first contributes to infiltration into the soil zone, and the second component contributes to surface runoff. The second component, usually known as effective precipitation, is estimated by HBV based on soil moisture content at the time of precipitation. Field capacity (FC) is the parameter that describes maximum soil moisture storage in the subsurface zone. Generally, the higher the amount of soil moisture content at the time or precipitation, the more the contribution from precipitation to runoff production becomes. When the soil moisture content approaches the field capacity, infiltration reduces and the contribution of rainfall to runoff production increases. Equation 2 calculates the effective precipitation as a function of the current soil moisture content:

$$P_{eff} = \left(\frac{SM}{FC}\right)^{\beta}(P + S_m) \tag{2}$$

where P_{eff} is effective precipitation [L], SM is actual soil-moisture [L], FC is maximum soil storage capacity [L], P is depth of daily precipitation [L], β a model parameter (shape coefficient) [–].

For a given soil moisture deficit (measured by the ratio of SM/FC), the parameter β, known as the shape coefficient, controls the amount of liquid water ($P + S_m$) which contributes to runoff. Figure 2 plots the relation between soil moisture, field capacity, shape coefficient β and runoff coefficient which is defined as the ratio of the effective precipitation to the total available water depth

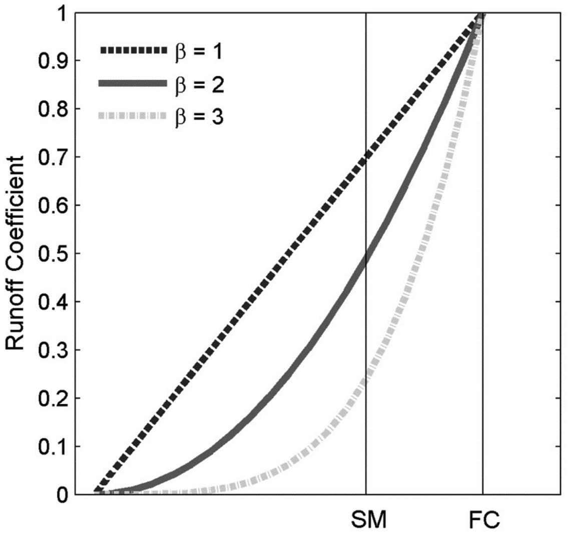

Fig. 2. Relation between soil moisture, field capacity, runoff coefficient and β.

($P_{eff}/(P+S_m)$). The graph shows that for a specific amount of soil moisture, the higher the β, the lower the runoff coefficient. Moreover, as the soil moisture (*SM*) approaches the field capacity (*FC*), the runoff coefficient increases. Both the field capacity, *FC*, and the shape coefficient, β, are used as calibration parameters. It is noted that the runoff coefficient and soil moisture are not constant and they change dynamically over the simulation time steps. An initial value for the soil moisture is required to start the calculations. Using Equation 2 and the initial value of the soil moisture (*SM*), the effective precipitation is calculated. For example, if the runoff coefficient is estimated as 0.7, then 70 percent of the rainfall contributes to the runoff and the rest (30 percent) infiltrates into the subsurface. The initial value of the soil moisture is then updated based on the infiltration and evapotranspiration (see Section 2.3). For the next time step, the new value of the soil moisture is used and the calculations are repeated using the new precipitation.

2.3. Evapotranspiration

To calculate actual evapotranspiration over the watershed, the model user needs to provide as input long-term monthly mean potential evapotranspiration (PE_m, $m = 1$ to 12). Then for each day within the simulation period, the adjusted potential evapotranspiration is calculated by reducing the potential value based on the difference between the mean temperature in the day and the long-term mean monthly temperature:

$$PE_a = (1 + C(T - T_m)).PE_m \tag{3}$$

where: PE_a is adjusted potential evapotranspiration [L], T is mean daily temperature [θ], T_m is long term mean monthly temperature [θ], PE_m is long-term mean monthly potential evapotranspiration [L], C is model parameter [θ^{-1}].

The model parameter C is used to improve the model performance when the mean daily temperature deviates considerably from its long-term mean. The soil moisture and the actual evapotranspiration calculations are coupled through the use of the Soil Permanent Wilting Point (*PWP*). Equation 4 shows the relation between soil moisture and actual evapotranspiration.

$$\begin{aligned} E_a &= PE_a\left(\frac{SM}{PWP}\right) && \text{if } SM < PWP \\ E_a &= PE_a && \text{if } SM < PWP \end{aligned} \tag{4}$$

where E_a is actual evapotranspiration [L], *PWP* is soil permanent wilting point [L].

Equation 4 indicates that when the soil moisture is above *PWP*, the actual evapotranspiration occurs at the same rate as potential evapotranspiration. The *PWP* is a soil-moisture limit for evapotranspiration, meaning that when the soil moisture is less than *PWP*, the actual evapotranspiration is less then the adjusted evapotranspiration. In other words, Equation 4 reduces the amount of evapotranspiration due to lack of soil moisture availability below the *PWP*. Figure 3 illustrates the relationship between the actual evapotranspiration and *PWP* described in Equation 4. The graph indicates that when the *PWP* is close to the field capacity, the actual evapotranspiration will be higher, and vice versa. On the basis of the observations, the model parameter *C* and *PWP* can both be estimated via model calibration.

2.4. Runoff response

This module estimates the runoff at the watershed outlet based on the reservoir concept. The system consists of two conceptual reservoirs, one above the other, as schematically depicted in Fig. 4. The first reservoir is introduced to model the near surface flow, whereas the second reservoir is used to simulate the base flow (groundwater contribution). From a temporal viewpoint, the first

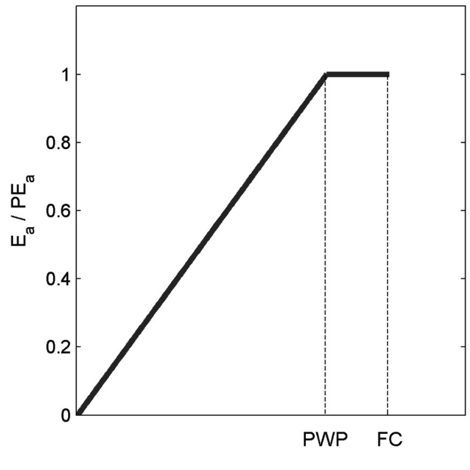

Fig. 3. Relation between the actual evapotranspiration and PWP.

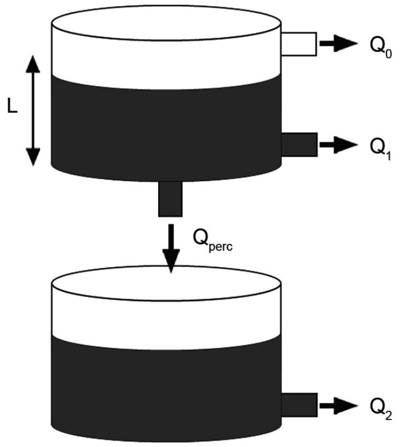

Fig. 4. Conceptual reservoirs used to estimate runoff response.

and second reservoirs simulate fast and slow subsurface processes, respectively. The reservoirs are directly connected to each other through the use of a constant percolation rate (Q_{perc}). As shown in the figure, there are two outlets (Q_0 and Q_1) one in each reservoir. When the water level in the upper reservoir exceeds the threshold value L, runoff occurs quickly from the upper reservoir (Q_0). The flow response of the other two outlets is relatively slower. Recession coefficients K_0, K_1, K_2, represent the response functions of the upper and lower reservoirs. In order to ensure that the runoff process is the fastest, the initial value of K_0 should always be greater than K_1. The response of the third outlet (Q_2) should be slower than the second outlet (Q_1) and thus, K_2 should be less than K_1. The three recession coefficients and the percolation rates are all model parameters and are estimated via calibration. Equation 5 gives the response functions of the outlets shown in Figure 4.

$$\begin{aligned} &Q_0 = K_0(S_u - L).A && \text{if } S_u > L \\ &Q_0 = 0 && \text{if } S_u \leq L \\ &Q_1 = K_1 S_u A && \\ &Q_{perc} = K_{perc} S_u A && \\ &Q_2 = K_2 S_l A && \end{aligned} \qquad (5)$$

where Q_0 is near surface flow [L^3T^{-1}], Q_1 is interflow [L^3T^{-1}], Q_2 is baseflow [L^3T^{-1}], Q_{perc} is percolation [L^3T^{-1}], K_0 is near surface flow storage coefficient [T^{-1}], K_1 is interflow storage coefficient [T^{-1}], K_2 is baseflow storage coefficient [T^{-1}], K_{perc} is percolation storage coefficient [T^{-1}], S_u is upper reservoir water level [L], S_l is lower reservoir water level [L], L is threshold water level [L], A is watershed area [L^2].

The total simulated runoff, Q_s, can be obtained by summing the first and the second reservoir outflows ($Q_s = Q_0 + Q_1 + Q_2$). While the full HBV model includes other features such as the use of more elaborate discharge transformation functions and the capability of streamflow routing, these features are not included in the educational version of the model since the focus here is more on the main hydrologic processes and understanding their relative significance and interaction with each other.

2.5. Model calibration and evaluation of performance

As mentioned previously, in conceptual models, the mathematical formulation of hydrologic processes is simplified using a number of parameters. Generally, the parameters are categorized into two types:

(1) physically-based parameters that describe a physical property such as field capacity (*FC*), soil permanent wilting point (*PWP*) and degree-day factor (*DD*);
(2) empirical, that have little or no physical basis but are used to describe the processes conceptually. In this model, empirical parameters include the reservoir parameters (K_0, K_1, K_2, K_p and L), the shape coefficient (β) and the parameter C.

In the calibration process, the model parameters are changed iteratively until a satisfactory match is attained between observed and simulated discharge. If the physically-based parameters are known from field measurements or experience, it would be sufficient to calibrate the model using the empirical parameters. Otherwise all the parameters are to be included in the model calibration.

Different statistical criteria such as the root mean square error, peak error, index of agreement, Nash-Sutcliffe coefficient, correlation coefficient and relative accumulated error are often used in model calibration and assessing the model performance (i.e. the agreement between observed and simulated discharge). In this hands-on assignment, only two statistical criteria namely, the Nash-Sutcliffe [28] and Pearson correlation coefficients are used due to their simple interpretation:

$$R_{NS} = 1 - \frac{\sum_{t=1}^{n} (Q_s^t - Q_o^t)^2}{\sum_{t=1}^{n} (Q_o^t - \overline{Q_o})^2} \qquad (6)$$

where R_{NS} is Nash-Sutcliffe coefficient [–], Q_s is simulated discharge [L^3T^{-1}], Q_o is observed discharge [L^3T^{-1}], O_o is mean observed discharge [L^3T^{-1}], n is number of time steps

$$R_P = \frac{\sum_{i=1}^{n} (Q_o^i - \overline{Q}_o) \cdot \sum_{i=1}^{n} (Q_s^i - \overline{Q}_s)}{\sqrt{\sum_{i=1}^{n} (Q_o^i - \overline{Q}_o)^2} \cdot \sqrt{\sum_{i=1}^{n} (Q_s^i - \overline{Q}_s)^2}} \qquad (7)$$

where R_P is Pearson correlation coefficient [–], O_s mean simulated discharge [L^3T^{-1}].

The Nash-Sutcliffe coefficient (R_{NS}), ranging between $-\infty$ and 1 where the closer the model

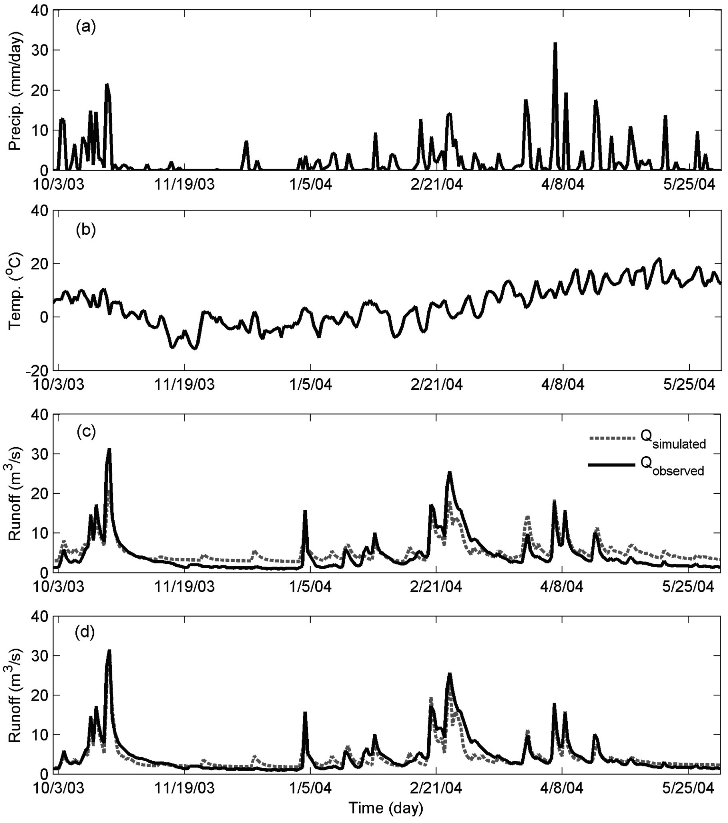

Fig. 5. Input: (a) precipitation; (b) temperature. Simulated and observed runoff: (c) before calibration; (d) after calibration.

efficiency is to 1, the more accurate it is. On the other hand, a negative value means that the mean of the observations is a better predictor than the model being evaluated. Nevertheless, the Pearson correlation coefficient provides a measure of linear association between the model and the corresponding observations. It ranges between –1 to 1 where a value of 1 implies a perfect linear agreement between simulated (Q_S) and observed (Q_o) discharges, while a value close to 0 indicates weak or no linear agreement between Q_s and Q_o.

3. STUDENT ACTIVITIES

The presented hydrologic model can be easily structured in an Excel spreadsheet or programmed into a MATLAB application. Using Excel spreadsheet is preferred due to the fact that students are more familiar with spreadsheet applications and that they can easily change the parameters and see their effects promptly. The educational version of the HBV model was presented over two laboratory sessions in the spring of 2009 for 24 students participating in an upper-level undergraduate course called Computer Applications for Civil Engineers. The participating students have completed (or about to complete) a parallel course on Engineering Hydrology. After describing the theory behind each module (e.g. snowmelt, soil moisture, evapotranspiration, runoff response), the students were asked to implement the knowledge they gained to perform a real-life hydrologic modeling application. The students were provided with an Excel spreadsheet with the necessary input data along with initial values for the model parameters. For the given input data (see Fig. 5(a) and 5(b)) and some initial values for soil moisture, snow depth, the students were asked to perform the required calculations of the various hydrologic processes described above in order to estimate the discharge. Figure 5(c) display the output discharge (m^3/s) based on the input data (Fig. 5(a) and 5(b)) before model calibration. After a short overview on the concept of model calibration, the students were asked to practice model calibration by changing the model parameters within reasonable bounds to maximize the Nash-Sutcliffe coefficient as an objective function. By taking the shape coefficient (β), reservoir parameters (K_0, K_1, K_2, K_p and L), field capacity (FC), soil permanent wilting point (PWP), degree-day factor (DD) and model parameter C as the calibration parameters, the students used the Excel Solver tool to maximize the objective function (Nash-Sutcliffe coefficient) based on necessary constraints on the model parameters. Figure 5 (c and d) shows an example of the model output discharge before and after the model calibration. Using this example, the students realized the importance of model calibration.

Besides model calibration, the students were also introduced to the concept of sensitivity analysis by changing one model parameter at a time and observing the effect on model output. For example, the students were asked to change the shape coefficient (β) while keeping all the other parameters fixed and observe the absolute error (%) of model output defined as:

$$\left| \frac{\sum_{i=1}^{n} Q_s^i - \sum_{i=1}^{n} Q_o^i}{\sum_{i=1}^{n} Q_o^i} \right| \times 100 \qquad (8)$$

The students were asked to produce a sensitivity plot as shown in Fig. 6(a) in which absolute error (%) is plotted against the parameter β. This is a clear example of a parameter to which the model is quite sensitive as seen in the relatively high variability in the absolute error. The students were also asked to investigate the sensitivity of the degree-day factor (*DD*) by changing its value while keeping the other parameters fixed. As shown in Fig. 6(b), model sensitivity to the parameter *D* is significantly less than that to β. Students were asked to repeat this type of analysis for the rest of the model parameters to gain insight into the sensitivity of model behavior and the simulated processes to different parameters. At the end of the two sessions, an assignment was given to the students to evaluate their learning outcome. The assignment included:

(a) hydrologic modeling analysis and discharge estimation for a given precipitation and temperature input using the HBV model;
(b) a simple calibration exercise using the introduced version of the HBV with different combinations of parameters;
(c) a sensitivity analysis exercise;
(d) several fundamental questions regarding model structure to test the extent of students' understanding of the modeling concepts and the simulations of different hydrologic processes.

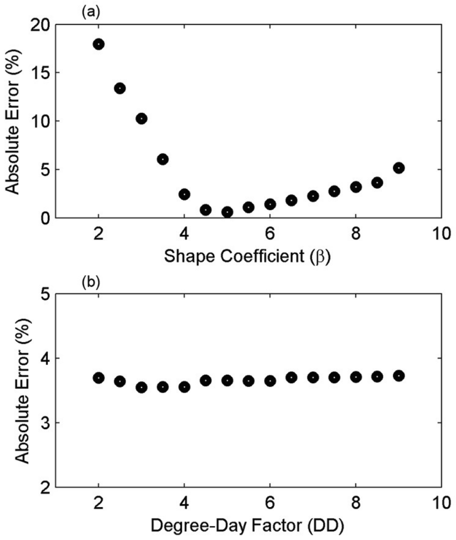

Fig. 6. Sensitivity of model with respect to: (a) shape coefficient (β); (b) degree-day factor (DD).

4. ASSESSMENT METHODS AND RESULTS

The HBV module was introduced to 24 students in an upper-level civil engineering course (Computer Applications) at the University of Louisiana at Lafayette. The module was introduced in two class sessions towards the end of the semester and all of the participating students completed (or are about to complete) a parallel course on Engineering Hydrology. In such a course, the focus is more on empirical hydrologic analysis methods (e.g. SCS curve number method, rational method, etc.) with little information about hydrologic modeling. In order to evaluate improvement in students' learning and their enthusiasm for the subject area of hydrologic modeling and analysis, an online instrument known as Student Assessment of Learning Gains (SALG) ([29]) was used to obtain anonymous feedback from the students after completing the two sessions and the associated practice and homework assignments. The assessment was conducted in three parts before and after introducing the modeling sessions:

(a) the first part focused on gauging students' knowledge and understanding of key hydrologic processes and modeling concepts before and after using the developed modeling program;
(b) the second part focused on assessing the impact of this hands-on approach on students' attitude and enthusiasm for the subject area;
(c) the third part assessed the overall design and features of the module in terms of lecture contents, class activities, and the assigned homework.

For the first part (a), two stages of assessment were performed. In the first assessment stage, held before introducing the learning module, students were asked about their prior knowledge in the following areas: (Q1) Hydrologic modeling in general; (Q2) Water budget analysis; (Q3) Rainfall-runoff processes, their mathematical formulations and the required calculations to estimate the flood resulting from a given precipitation event; (Q4) The effect of evapotranspiration on rainfall-runoff processes, its mathematical formulation and the required calculations; (Q5) The effect of soil moisture on rainfall-runoff processes, its mathematical formulation and the required calculations; (Q6) Model calibration; (Q7) Sensitivity analysis; (Q8) Differences between empirical and physically-based parameters; and (Q9) How much they think that their knowledge in the field of hydrology will help them address real-world problems. The same sets of questions were administered once again to the students after using the HBV learning module.

Figure 7 compares the students' feedback before and after going through the HBV module using a 5-point ranking scale for learning gains, where 1 to 5 are defined as no gains, a little gain, moderate gain, good gain and great gain, respectively. The dark lines are the results of the post-assessment, whereas, the gray lines represent the prior assessment. The graph shows the mean and confidence intervals (±3 times the standard error) based on the defined 5-point ranking scale for each question. The comparison indicates that the introduced learning module had an overall positive impact on student knowledge and understanding of hydrologic processes and their modeling. After going through the modeling sessions, the gain in student knowledge of basic hydrologic processes (Q1 to Q5) increased from moderate (3) to good (4). Their confidence in tackling real-world hydrologic analysis increased by more than one point (from below moderate to good). More noticeably, their familiarity and understanding of modeling concepts and procedure (Q6 to Q8) increased by two points or higher (from little or no gain to around high or above moderate). This indicates the effect of using a hands-on approach where students had the tool to simulate hydrologic processes and their interaction, exercise how a model is constructed and calibrated, and understand the role that model parameters play in changing the end results. This experience, along with the knowledge of fundamental concepts, is an important key for future engineering practitioners. Additionally, the figure shows that exposing the students to this application-oriented lecture significantly increased their confidence to address real-world problems (see Q9 in Fig. 7).

The second set of assessment questions (Q10 to Q15) was administered only after introducing the learning module. These questions focused on evaluating the impact of this approach on student attitudes with regards to: (Q10) Enthusiasm for the subject of hydrologic modeling and analysis; (Q11) Interest in discussing the subject area (of hydrologic modeling and analysis) with peers; (Q12) Interest in taking or planning to take additional classes in this subject; (Q13) Confidence in understanding hydrologic modeling and analysis; (Q14) Confidence in performing hydrologic modeling; (Q15) Comfort level in working with complex ideas in the field of hydrologic modeling and analysis and applying the learning in this class in future. Figure 8 presents the mean and confidence intervals of the defined 5-point ranking scale for the aforementioned questions. The results show that students' feedback to these questions fall within the range of above moderate (3) to slightly above good gain (4).

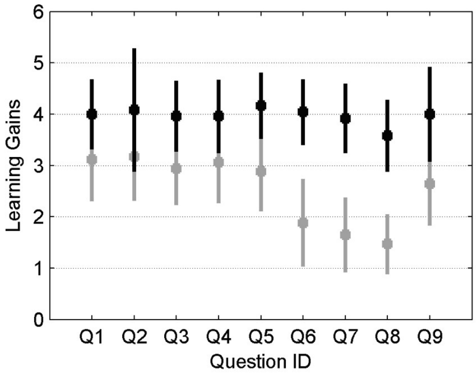

Fig. 7. The mean and confidence intervals of defined 5-point ranking scale for questions Q1 to Q9 in the prior (gray lines) and post (dark lines) assessments.

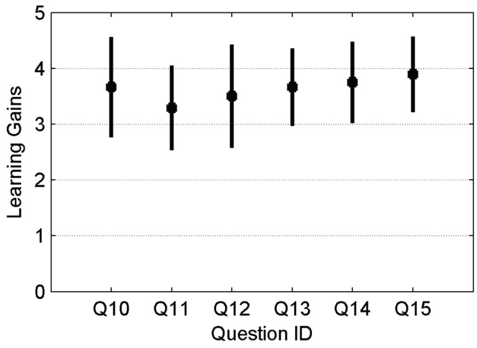

Fig. 8. The mean and confidence intervals of defined 5-point ranking scale for questions Q10 to Q15 (impact on attitudes of students).

Finally, a third set of questions was administered to gauge the extent to which each of the following aspects and attributes of the developed modeling teaching tool contributed to student learning gains:

- (Q16) The use of a practical case study with actual data;
- (Q17) The overall instructional approach followed in the modeling sessions compared to what students experienced in their prior hydrology courses,
- (Q18) The use of hands-on calculations with the Excel spreadsheet prepared for the lecture; (Q19) The fact that you could change the model parameters in the Excel spreadsheet and see their effects;
- (Q20) The requirement of a hydrologic modeling assignment. Figure 9 shows the mean and con-

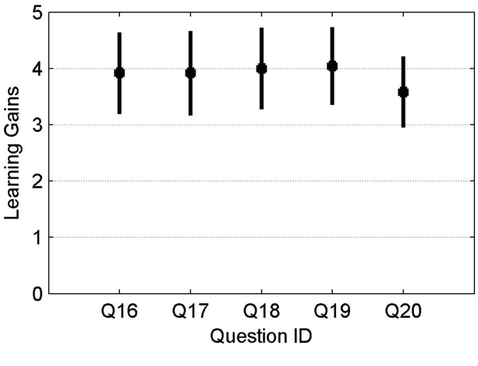

Fig. 9. Mean and confidence intervals of defined 5-point ranking scale for questions Q16–Q20.

fidence intervals of the feedbacks based on the 5-point ranking scale introduced earlier.

As shown, except the assignment (Q20), all other feedbacks are placed around good gain (4). This figure indicates that students are interested in the use of hands-on modeling tools and applying them within practical case studies (see Q16 and Q18). The reason that the assignment was poorly rated (Q20), could perhaps be due to the fact that students were exposed to this learning module for a relatively short time (two sessions) which may not be enough to cover the details of the hydrologic processes that was required for the assignment. It is also expected that exposing the students to similar application-oriented modules for a longer period of time can develop enthusiasm in a future career in the area of hydrology.

5. DISCUSSION

Various areas of possible enhancement to the approach followed in the current study can be highlighted. The learning tool presented was an example of utilizing simulation models in an engineering hydrology curriculum with little overhead to the instructor. Other hydrologic learning modules that are based on physical and spatially-distributed representations are currently being developed by the authors for further evaluations. These models are expected to significantly add to student learning and provide deeper understanding of complex and inter-connected hydrologic processes. However, such models are more computationally demanding and may interfere with the teaching process especially in undergraduate classrooms. Innovative teaching methodologies that are based on interactive visualization and virtual-reality techniques are currently under investigation to facilitate the use of more complex models in hydrology education. Another challenge in using numerical models in hydrologic engineering courses is how to avoid the misperception that hydrologic models can provide an exact representation of what happens in nature. Students need to develop an appreciation of how limitations in data available for model building and validation can contribute to uncertainties in model predictions and subsequent engineering analysis and decisions. These concepts can be presented using simplified uncertainty analysis techniques that are based on Monte-Carlo simulations and re-sampling methods [30]. An example of such methods is the Generalized Likelihood Uncertainty Estimation (GLUE, [5]). The authors are currently implementing this method within a hydrologic teaching context using the MATLAB computing languages. Plans are underway to integrate the different enhancements discussed above in future engineering hydrology courses and assess their impact on student appreciation of capabilities and limitations of hydrologic models as engineering analysis and decision-making tools.

6. CONCLUSIONS

Recent advances in hydrologic numerical simulation models offer unprecedented opportunities for improving existing engineering hydrology curricula. Such models provide teaching tools that can serve two main purposes:

(1) aid engineering students in understanding complex and multi-faceted concepts and processes;
(2) equip them with practical skills that are critically needed for their future careers in hydrology and related fields.

The current study describes the implementation and assessment of a hands-on modeling tool designed for teaching hydrologic processes and other related modeling concepts. The HBV conceptual hydrologic model is selected where the main hydrologic processes are simplified to algebraic functions and, hence, the required calculations can be easily practiced during short lectures and computer laboratory sessions. Using the presented learning tool, different hydrologic processes, such as precipitation, snowmelt and snow accumulation, soil moisture variation, evapotranspiration and runoff generation were introduced to the students. Since the model can be formulated in an Excel spreadsheet format, students had the chance to interact with the model, change its parameters, and observe their effects on the predicted output and the model performance. In order to expose the students to a real-life example and enhance their learning, the students were asked to simulate the runoff output of a watershed based on a set of real input data. Students practiced exercises on model calibration, parameter estimation, sensitivity analysis, and assessment of model performance using statistical measures.

The SALG online system, used to assess the student learning process, showed that the hands-on approach significantly motivated student interest in hydrologic analysis and modeling, which may lead towards increased enthusiasm for a future professional career or graduate study in this field. Results confirmed that students are better inspired by hands-on application-oriented teaching methods than by purely theoretical lecture-driven courses. It is hoped that the presented findings encourage instructors to incorporate application-oriented case studies into the traditional lecture-based engineering hydrology courses. It should be mentioned that instructors and interested readers can request a free copy of MATLAB and EXCEL versions of this hands-on tool for use in engineering hydrology courses in other universities.

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