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Hydrology and Earth System Sciences Discussions

An educational model for ensemble streamflow simulation and uncertainty analysis

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Abstract

This paper presents a hands-on modeling toolbox, HBV-Ensemble, designed as a complement to theoretical hydrology lectures, to teach hydrological processes and their uncertainties. The HBV-Ensemble can be used for in-class lab practices and homework assignments, and assessment of students' understanding of hydrological processes. Using this model, students can gain more insights into how hydrological processes (e.g., precipitation, snowmelt and snow accumulation, soil moisture, evapotranspiration and runoff generation) are interconnected. The model includes a MATLAB Graphical User Interface (GUI) and an ensemble simulation scheme that can be used for not only hydrological processes, but also for teaching uncertainty analysis, parameter estimation, ensemble simulation and model sensitivity.

1 Introduction

Rainfall-runoff models have been used to describe nonlinear hydrological processes, predict extreme events and assess the impacts of potential changes in future climates and/or land use. Numerous physical, conceptual, statistical/metric, or hybrid metric conceptual models have been developed for modeling rainfall-runoff processes (e.g., Singh and Woolhiser, 2002; Beven, 2001; Bergström, 1995; Wheater et al., 1993). Given the frequency and significance of hydrologic extremes on human livelihood and society, educating students on various aspects of the hydrological cycle is very important. However, reliable rainfall-runoff modeling and flood management entails a strong background in the hydrological cycle and modeling, which students may not have.

The National Research Council has also stressed the need for an improve hydrology curriculum, specifically in the areas of hydrologic modeling and data analysis (e.g., NRC, 2000, 1991; Wagener et al., 2012). In a report by the Consortium for Universities for the Advancement of Hydrologic Science (CUAHSI) the potential role of hydrologic

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models in transforming the way hydrology is taught and communicated to students is emphasized (CUAHSI, 2007).

Recent research on engineering and science education suggests that students acquire a better knowledge of hydrological processes and their uncertainties when exposed to novel educational techniques (e.g., student centered methods) as a complement to traditional lecture-driven classes (Ngambeki et al., 2012). Wagener et al. (2010) argue that the changing demands on hydrology offers an unprecedented opportunity to advance hydrology education. Recent advances in simulation models and graphical user interface developments provide opportunities for improving existing hydrology curriculum.

Hydrologic models can be used to teach complex hydrological processes by providing tools for hands-on project-based learning. Ngambeki et al. (2012) review recent theoretical developments in engineering and science education research that are relevant to teaching hydrological processes. In a recent study, AghaKouchak and Habib (2010) introduced HBV-EDU which is a hands-on modeling tool developed for students to help them learn the fundamentals of hydrological processes, parameter estimation and model calibration. HBV-EDU provides an application-oriented learning environment that introduces the interconnected hydrological processes through the use of a simplified conceptual hydrologic model. Using HBV-EDU, students can practice conceptual thinking in solving hydrology problems. Using a detailed course survey, AghaKouchak and Habib (2010) showed that students were more inspired by hands-on application-oriented teaching methods (e.g., using models) than by purely theoretical lecture driven classes. Seibert and Vis (2012) presented the HBV-light which is also a user-friendly conceptual model, especially useful for hydrology education. The model includes different functionalities such as automatic calibration and batch simulations designed for teaching advanced hydrology classes and research projects.

Like HBV-EDU, most hydrologic models used for both teaching and research are deterministic, providing the best simulation based on estimated parameters (e.g., Beven, 2001; Young, 2002; Sorooshian and AghaKouchak, 2011). However, quantification of

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uncertainties associated with hydrologic models are fundamental for risk assessment and decision making. To accomplish this, ensemble streamflow simulation can be used for uncertainty analysis, risk assessment and probabilistic analysis of flood forecasts (Wood et al., 2002; Georgakakos et al., 2004; Vrugt et al., 2008). For example, using ensemble streamflow simulations, one can derive the probability of the water level exceeding above a certain extreme threshold. Also, the effect of the uncertainty in hydrological processes and global climate studies has been highlighted in numerous studies (Bell and Moore, 2000; Goodrich et al., 1995; AghaKouchak et al., 2010; Obled et al., 1994).

The concepts of ensemble simulation and uncertainty analysis are typically covered in hydrology classes only theoretically. We hypothesize that the students would gain a better knowledge of model uncertainty using educational simulation tools and techniques. This study builds upon the previous model (HBV-EDU) and provides an educational software for teaching ensemble simulation and uncertainty analysis. The model (hereafter, HBV-Ensemble) simulates an ensemble of simulated streamflows based on randomly selected parameters that satisfy a certain objective function. We anticipate that the presented model to encourage students to learn more about the fundamentals of hydrology, ensemble simulation and uncertainty analysis. Notice that an ensemble is often described as simulations from different models. In this paper, an ensemble is defined as multiple simulations using different sets of parameters. This definition is similar to methods of quantifying uncertainties of climate models using perturbed physics ensembles (PPE) of climate simulations (e.g., Murphy et al., 2004; Piani et al., 2005).

The paper is organized into five sections. After this introduction, the model concept and methodology are briefly introduced. In the third section, an example application of the model is presented. The fourth section is devoted to model assessment and the students feedback. Finally, the last section summarizes the results and conclusions.

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2 Methodology and model concept

The proposed model is based on the a modified version of HBV hydrologic model (Bergström, 1995). The model is originally developed by the Swedish Meteorological and Hydrological Institute. Various versions of the model are now available that vary in complexity and utility features. The model concept and structure utilized here is based on the modified version presented in Hundecha and Bárdossy (2004) and AghaKouchak and Habib (2010). The HBV-Ensemble consists of five main modules: (1) snowmelt and snow accumulation; (2) soil moisture and effective precipitation; (3) evapotranspiration; (4) runoff response; (5) ensemble simulation. A detailed discussion on the HBV model is provided in this special issue (see Seibert and Vis, 2012) as well as in Hundecha and Bárdossy (2004) and AghaKouchak and Habib (2010). For this reason, only a brief overview of the model is presented here.

In this model, observed precipitation partitions into rainfall and snow based on observed temperature. As long as the temperature remains below the melting threshold snow accumulates, and for temperatures above the melting threshold snow melts (see Seibert and Vis, 2012, for the governing equations). The combination of rainfall and snowmelt will then partitioned into direct (surface) runoff and infiltration based on the soil moisture condition.

In HBV-Ensemble, the actual evapotranspiration is derived based on the long-term monthly potential evapotranspiration, adjusted for temperature deviation from the long-term monthly mean temperature (AghaKouchak and Habib, 2010). The Runoff Response Module of the model includes two conceptual reservoirs where the upper reservoir models the near surface flow and the lower reservoir simulates the base flow (groundwater flow). A constant percolation rate is used to connect the reservoirs. The upper reservoir has two outlets for estimation of the near surface flow and interflow, whereas the lower reservoir has one outlet for simulation of the baseflow. The total surface water (runoff) would then be derived as the sum of the outflows from both reservoirs.

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2.1 Ensemble simulation module

Numerous studies have highlighted that hydrologic models are sensitive to model parameters. Quantification of uncertainties of hydrologic forecasts is fundamental to development of water resources management and adaptation strategies. Several studies have attempted to describe uncertainties of models using perturbed or randomly sampled model parameters. This approach can be used to explore uncertainties of one (or more) model(s) outputs with respect to various choices of parameters.

HBV-Ensemble this study builds upon the previous model (HBV-EDU) and provides an educational software for teaching ensemble simulation and uncertainty analysis. The model (hereafter, HBV-Ensemble) simulates an ensemble of simulated streamflows based on randomly selected parameters that satisfy a certain objective function.

HBV-Ensemble builds upon the previous deterministic version of the model (HBV-EDU). In HBV-Ensemble a range of model parameters will be sampled using the Monte Carlo technique and all simulations that satisfy the objective function will be accepted as one realization in the ensemble output. A common objective function is the Nash-Sutcliffe coefficient (Nash and Sutcliffe, 1970):

$$R_{\mathrm{NS}} = 1 - \frac{\Sigma_{t=1}^{n}\left(Q_{\mathrm{s}}^{t} - Q_{\mathrm{o}}^{t}\right)^{2}}{\Sigma_{t=1}^{n}\left(Q_{\mathrm{o}}^{t} - \overline{Q_{\mathrm{o}}}\right)^{2}} \tag{1}$$

where R_{NS} = Nash-Sutcliffe coefficient (–); Q_{s} = simulated discharge (L3T1); Q_{o} = observed discharge (L3T1); $\overline{O_{\mathrm{o}}}$ = mean observed discharge (L3T1); and n = number of time steps. The model parameters of HBV-Ensemble include: degree-day factor; field capacity; shape coefficient; evapotranspiration adjustment parameter; permanent wilting point; near surface flow, interflow and baseflow constants; percolation storage constant; and threshold water level for near surface flow. For a detailed discussion on the parameters the interested reader is referred to Seibert and Vis (2012) and

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AghaKouchak and Habib (2010). The procedure to generate an ensemble of streamflow simulations is as follows:

1. Select reasonable upper and lower bounds for the model parameters mentioned above based on expert knowledge, available data or literature.
2. Draw random samples of parameters from the above range (e.g., 1000 sets of randomly selected parameters).
3. Run HBV-Ensemble with all parameter combinations obtained from the previous time-step.
4. Accept simulations and parameter sets that satisfy a certain objective function (e.g., Nash-Sutcliffe coefficient above 0.7). Each accepted simulation will then be a member in the final ensemble. Alternatively, one can select the best simulations (e.g., top 100) that lead to a root mean square error below an acceptable threshold.
5. Accept simulations and parameter sets that satisfy a certain objective function (e.g., Nash-Sutcliffe coefficient above 0.7). Each accepted simulation will then be a member in the final ensemble. Alternatively, one can select the best simulations (e.g., top 100) that lead to a root mean square error below an acceptable threshold.
6. Finally, the model gives the best set of parameters using the Generalized Likelihood Uncertainty Estimation (GLUE; Beven and Binley, 1992).

3 Application

Figure 1 illustrates the HBV-Ensemble Graphical User Interface (GUI). In panel A, the user can specify the upper and lower bounds of the parameters (see the first column

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in panel A). The initial values, such as the initial state of soil moisture, can be entered using panel B. Panel C can be used to load the input data. The required input data include precipitation, temperature, long-term monthly evapotranspiration and temperature. Using panel D, the user can select the objective function (e.g., root mean square error, Nash-Sutcliffe coefficient and correlation coefficient). The number of simulations (randomly sampled parameters) can be specified using panel E. Finally, the model performance measures will appear in panel F.

Figure 2 presents an example of the outputs of HBV-Ensemble. In the figure, the solid black line represents the simulated runoff, whereas the solid red line represents th observed runoff. The gray lines show the uncertainty space or ensemble simulation using 1000 simulations. One can see that in this approach, in addition the runoff, estimates of upper and lower bounds (gray lines) provide measures of uncertainty.

It should be noted that the model produces other variables besides runoff, including time series of snow accumulation, soil moisture, evapotranspiration, and upper and lower reservoir water levels. For instance, Fig. 3 displays sample model outputs derived using panel G in Fig. 1.

The presented hydrologic model can be used for both in-class lab practices and homework assignments to test the extent of the students understanding of hydrological processes. An executable version of the model is also available for students who are not familiar with MATLAB, which is used to develop this hands-on toolbox. Having this modeling toolbox, students can easily change the parameters and see the effects on simulated streamflow promptly. The model can also be used for teaching sensitivity analysis by changing one parameter at a time and observing the effect of the parameter on model output. Furthermore, the model can be used for a lab practice or homework on the effects of initial values on streamflow simulation. For example, one can run the model with different initial values of soil moisture and compare the output hydrographs (as shown in Fig. 4). Using this particular exercise, student will find out that the initial values will have a significant impact on the model outputs at the beginning of the

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simulations. However, the effects of the initial values diminish over time in the long-term simulations.

4 Students feedback

The previous version of the model (Excel Spreadsheet version) was used at the University of Louisiana at Lafayette (ULL) in Spring 2009 and students' feedback were reported in AghaKouchak and Habib (2010). The presented model has been administered at the University of California, Irvine (UCI) in Winter Quarters 2011 and 2012 (Watershed Modeling CEE173273). Students learned the fundamentals of the model and used the MATLAB Graphical User Interface (GUI), shown in Fig. 1 for their final project (hydrologic modeling for a watershed in southern California). In the following, the feedback from UCI students who used the MATLAB GUI are presented.

The Watershed Modeling class included theoretical instructions and several homeworks and projects. For the final project, students were asked to simulate the streamflow for San Onofre watershed in Southern California and submit a detailed report. A total of 60 students completed the project from which 56 students participated in an anonymous survey designed to gauge students' learning gains. The survey was administered once the students learned about the processes of HBV and how the model works, but prior to completing the final project. Table 1 summarizes the survey questions. The first ten questions (Q1–Q10) aimed to gauge students' learning gains as a result of using the presented education toolbox. The last four questions (Q11–Q14) aimed to understand which aspects of the this teaching tool contributed to students' learning gains.

Figure 5 presents students' responses on their learning gains using a five-point ranking scale where: 1 = *no gains*; 2 = *a little gain*; 3 = *moderate gain*; 4 = *good gain*; and 5 = *great gain*. Figure 5 displays the mean and confidence intervals (here defined as ±3× the standard error) of student responses for each question. Figure 5 indicates that this educational software had a positive impact on students understanding and

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knowledge of hydrological processes. Notice that the students were asked to evaluate their learning gains as a result of their work with this education toolbox in the class (see Table 1). However, the authors acknowledge that evaluating students' responses and associating them to only the model and not a combination of instruction and model may not be possible.

5 Conclusions

This study presents a modeling tool, HBV-Ensemble, designed for teaching hydrological processes through hands-on watershed modeling practices. The HBV-Ensemble can be used for in-class lab practices and homework assignments, and for assessment of students' understanding of hydrological processes. Using this model, students can gain more insights on how hydrological processes (e.g., precipitation, evapotranspiration, snowmelt, snow accumulation, soil moisture, and runoff) are interconnected.

An earlier version of this model, developed in Excel spreadsheet is presented in AghaKouchak and Habib (2010). The current version includes a MATLAB Graphical User Interface (GUI) and an ensemble simulation scheme that can be used for teaching uncertainty analysis, parameter estimation and model sensitivity to parameters and initial conditions. An executable version of HBV-Ensemble is available for students who are not familiar with MATLAB.

This modeling toolbox has been used in an upper level watershed modeling class at the University of California, Irvine, and the students' feedback have been positive as shown in Fig. 5. One attractive feature of HBV-Ensemble is that students can change model parameters and investigate their effects on simulated streamflow. HBV-Ensemble offers an educational tool that can students in understanding complex and interconnected hydrological processes. Along with theoretical concepts, HBV-Ensemble equip students with critical practical skills students needed for their future careers in hydrology. Instructors, students and interested readers can request a free copy of HBV-Ensemble for educational purposes.

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Table 1. Survey questions.

	As a result of your work with this education toolbox in the class, what gains did you make in each of the followings?
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 and ensemble simulation
Q7	Sensitivity analysis
Q8	Differences between empirical and physically-based parameters
Q9	Enthusiasm for the subject of hydrologic modeling and analysis
Q10	Confidence in performing hydrologic modeling
	How each of the following aspects and attributes of the developed teaching tool contributed to your learning gains?
Q11	The use of a practical case study with actual data
Q12	The use of hands-on calculations in the lecture
Q13	The fact that you could change the model parameters and see their effects
Q14	The requirement of a hydrologic modeling project using this hands-on toolbox.

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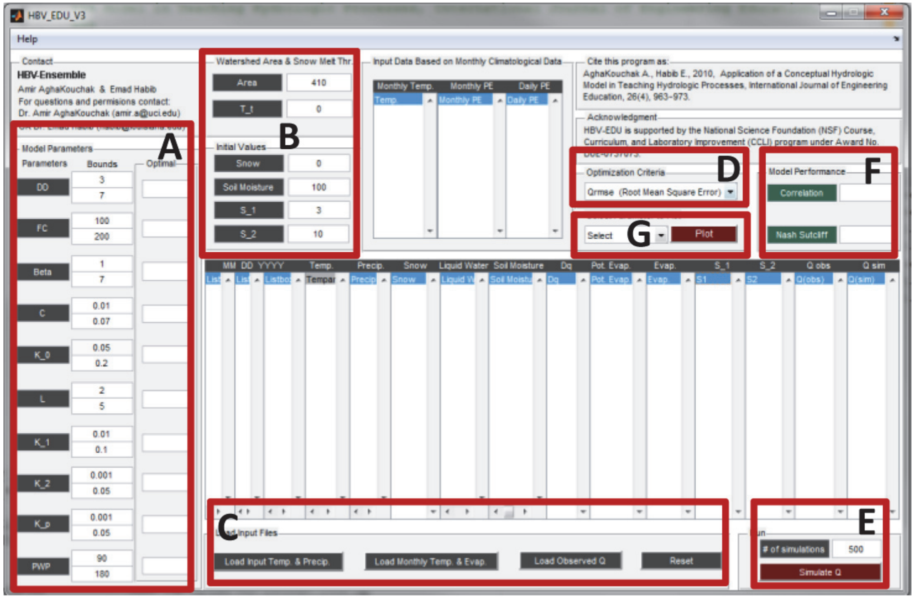

Fig. 1. HBV-Ensemble Graphical User Interface (GUI): (A) model parameters; (B) initial values and constants; (C) input data loading tools; (D) objective functions including root mean square error, Nash-Sutcliffe coefficient and correlation coefficient; (E) number of ensemble members; (F) model performance; (G) plotting tools.

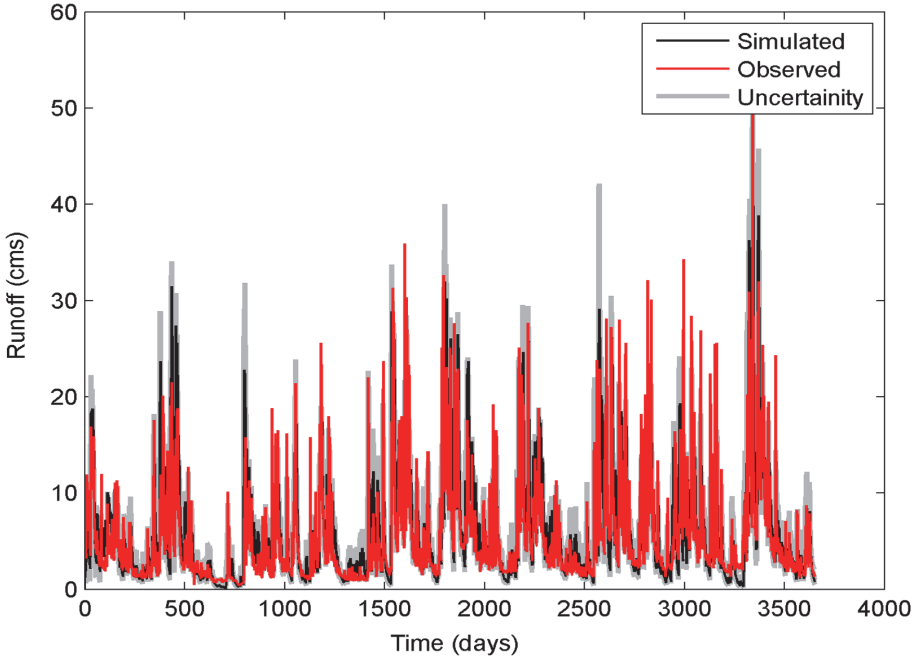

Fig. 2. Runoff ensemble simulation using HBV-Ensemble: simulated runoff (solid black line); observed runoff (solid red line); uncertainty space or ensemble simulation (gray lines).

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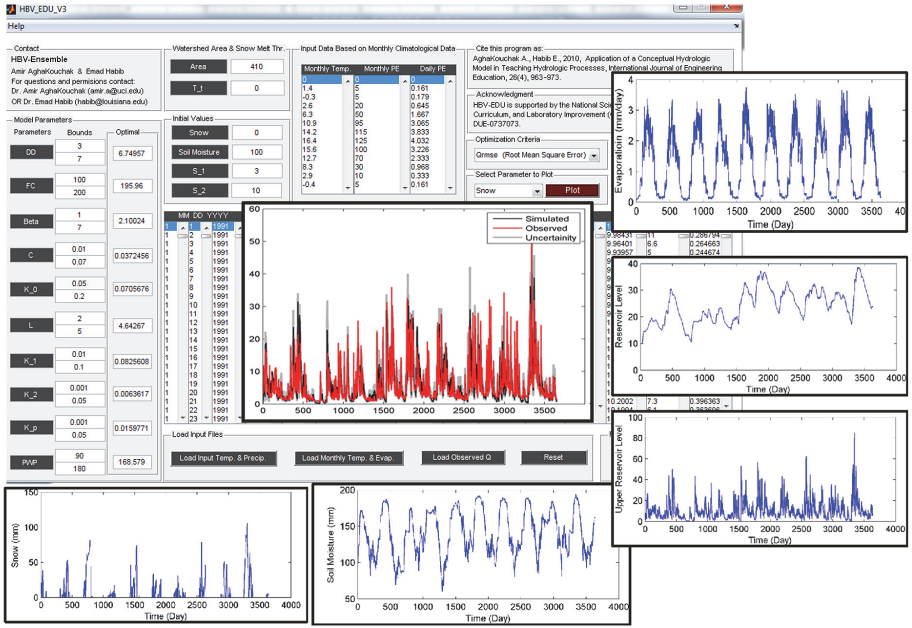

Fig. 3. HBV-Ensemble sample model outputs (snow accumulation, soil moisture, evapotranspiration, and upper and lower reservoir water levels).

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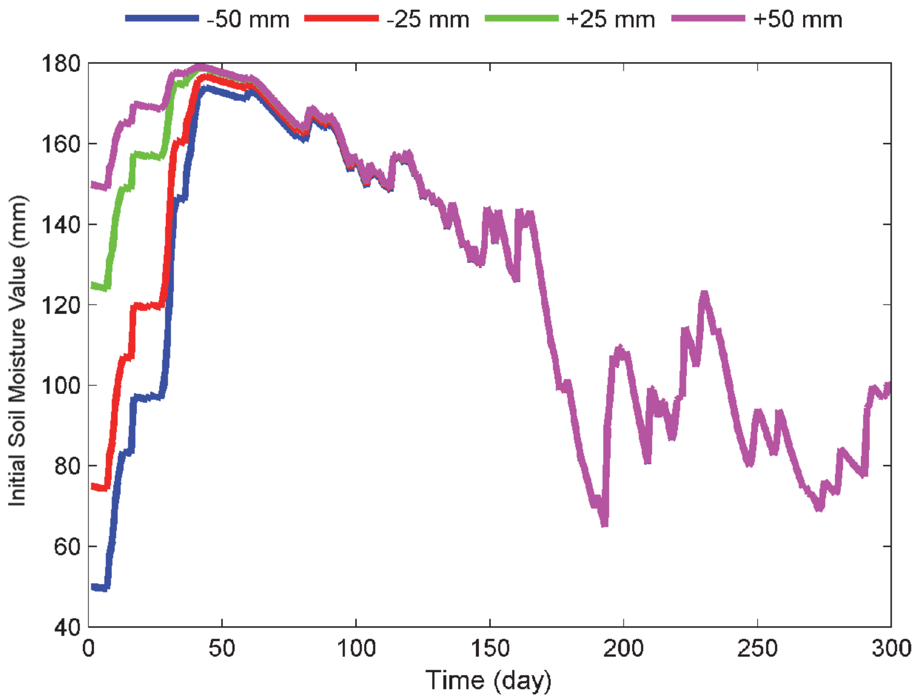

Fig. 4. Investigating the effect of initial value of soil moisture in streamflow simulation.

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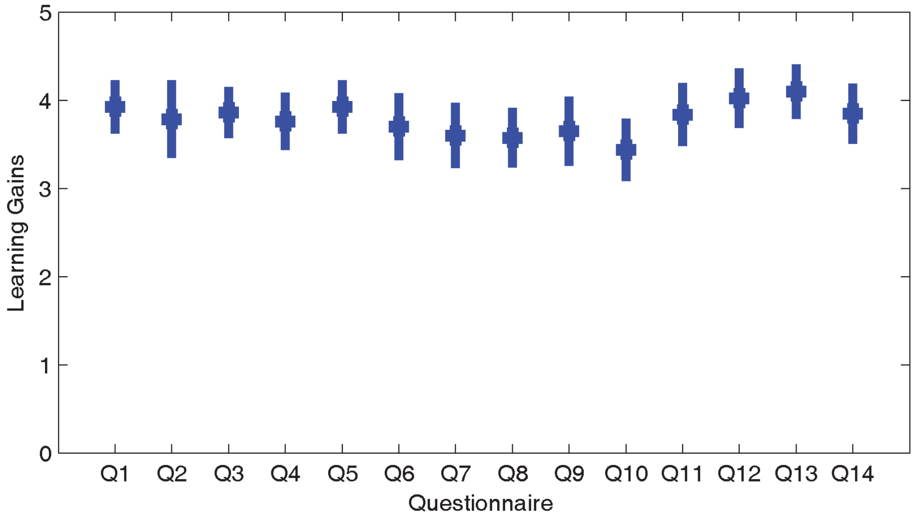

Fig. 5. Students feedback (see Questions 1–15 in Table 1).

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