

Learner-centred Approach to Teaching Watershed Hydrology using System Dynamics*

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The use of the system dynamics approach, implemented within an object-oriented simulation environment, is presented as an effective tool for learning watershed hydrology. This approach has the potential to enhance students' understanding of watershed hydrology through experimenting and self-guided learning on their own. The approach could also motivate students to conduct further research in the area and go beyond the material taught in the classroom.

INTRODUCTION

HYDROLOGY is usually defined as a natural science concerned with the occurrence, properties, distribution, and movement of water in the natural and man-made environment. It is an interdisciplinary field that is taught to students in both science (e.g., geography, geology) and engineering (more specifically, civil engineering) courses. From a civil engineering perspective, the most important subsystem of the hydrologic cycle is the watershed system [1]. However, teaching hydrology to engineering students has proved to be a challenging task. Design-oriented students, who expect numbers that can be plugged into formulae or read off a chart, encounter difficulties in digesting certain concepts. According to beginners, fully saturated soil should not accept any further water in the form of infiltration, and most available formulae for estimating evapotranspiration are solely dependent on meteorological conditions; yet, we tell them that available soil moisture influences the rate of evapotranspiration. It is not uncommon to hear engineering students describing hydrology, the science of water, as a 'dry' subject.

Precipitation over a watershed finds its way to the soil by infiltrating through the surface. The soil behaves like a sponge that keeps accepting water at a decreasing rate until it is saturated, after which the infiltration rate remains constant. Water has to accumulate on the surface, contributing to runoff that is the result of overland flow and subsurface interflow (horizontal movement of saturated water). This simple input–output process becomes more sophisticated when understood within the concept of water balance over the watershed. The input (precipitation) has to be in balance with the outputs: water intercepted by the canopy,

infiltrated into soil, evaporated, and ran off as streamflow. A student must understand the details of each process within this balance to master hydrology. Hydrology instructors, facing the common student's attitude of 'write it now and understand it later', need to devise an interesting tool to help students 'understand it later' and change their attitude toward learning. In other words, learners need a learner-centered tool to understand watershed hydrology.

A variety of teaching techniques that are suitable for engineering education, including deductive, facilitative, and inductive instruction, have been discussed in literature [2]. However, the most common technique is still the traditional approach of one-way delivery [3]. In this paper, a system dynamics (SD) approach implemented within an object-oriented (OO) simulation environment is proposed as a 'teach-yourself' tool for watershed hydrology.

WATERSHED HYDROLOGY

The watershed is a natural unit of land upon which water from direct precipitation and snowmelt collects in a channel and flows downhill to a common outlet. The watershed may appear, at first glance, to be a static unit of landscape. However, from a hydrologic standpoint, it is a dynamic area [4]. The natural ecology of the watershed is a dynamically balanced system that can be disturbed by any external force, such as human intervention.

Hydrologically, there are three fundamental watershed functions:

- collection of water;
- storage of various amounts of water for various durations;
- discharge of water as runoff.

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The central role of soil storage in watershed hydrology cannot be overemphasized. Precipitating water accumulates in the soil storage at a certain rate, increasing the soil moisture content. The higher the soil moisture, more water will be available for evaporation from the soil surface and for plant transpiration. When the soil moisture content increases beyond the field capacity, gravity causes the water to start moving downward [5] and accumulate in groundwater storage. In a simplified fashion, when top soil reaches saturation, water ponds on the surface and runoff commences. This means that the higher the moisture content, the lower the infiltration rate.

It is worth mentioning that hydrological processes are simplified here with the purpose of keeping a focussed discussion. However, a detailed description of hydrological processes should be sought in standard textbooks of hydrology [e.g. 4]. These processes are in a state of dynamic balance that is governed by negative feedback loops, as shown in Fig. 1. The positive sign '+' at the head of the arrow indicates that the two variables, at both ends of the arrow, change in the same direction. In other words, an increase in the first variable leads to an increase in the next one. The negative sign '-' means that an increase in the first variable leads to a decrease in the next one, and vice versa. Positive and negative signs shown inside the loop indicate whether the entire loop is positive or negative. Learning how such interconnected and coupled loops affect the system can help increase the understanding of the dynamics of the watershed. More details on causal-loop diagrams can be found in other sources [6 and 7].

SYSTEM DYNAMICS (SD)

The system dynamics (SD) simulation approach is based on understanding complex interrelationships existing between different elements within a system. This is achieved by developing a model that can simulate and quantify the behavior of the system. Execution of the model to simulate the system over time is essential to understanding the dynamics of the system. The major steps that are carried out in the development of an SD model are understanding the system and its boundaries, identifying the key building blocks, representing the physical processes or variables through mathematical relationships, mapping the structure of the model, and conducting numerical simulation.

'Stocks' and 'flows' are the building blocks of an SD model. A simple illustration of stocks and flows is the accumulation of interest in a bank account [7] or the inflow of water into a reservoir. Figure 2 shows a simplified model of a watershed. The double line represents the flow of water from a source, represented by a cloud (or a stock), into the reservoir (another stock). The cloud can be viewed as a stock that is outside the system boundary. The single lines in Fig. 2 connect objects (i.e. processes or coefficients). These are called *connectors*, which show the flow of information inside the model. *Converters* (such as temperature and snow density) can represent any variable as a function of time or any input value or parameter.

The use of the term *feedback* in SD covers any process in which the state of a system influences action, which affects the system, and thereby affects further action. Feedback is one of the

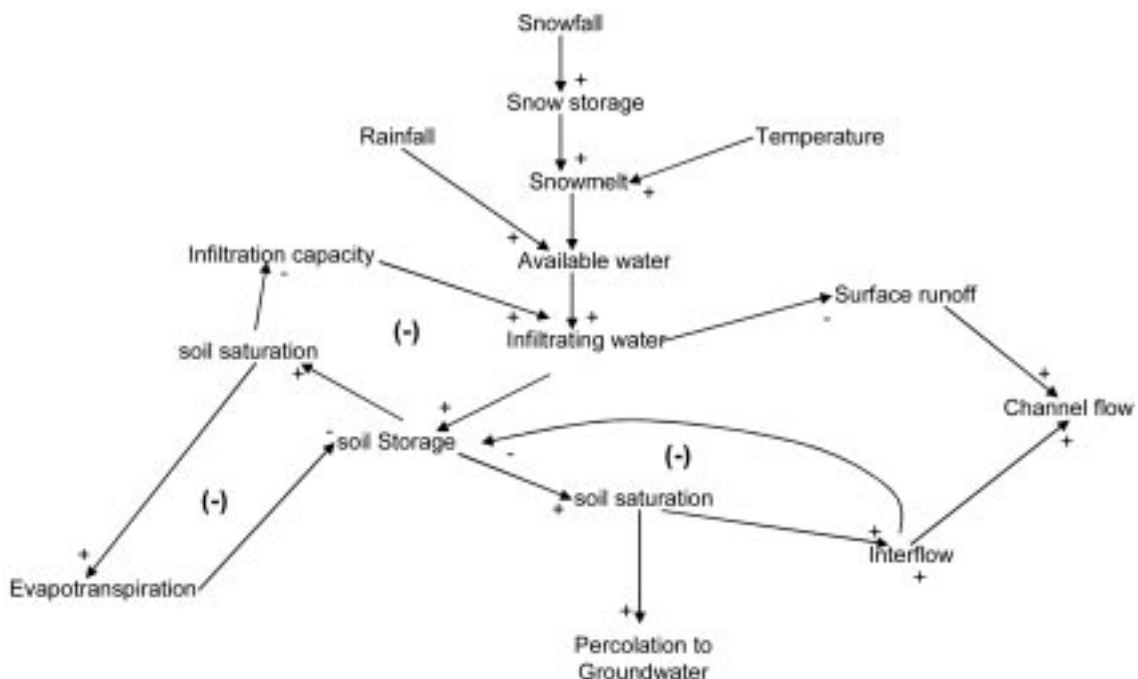


Fig. 1. A simplified causal-loop diagram of the hydrologic processes in a watershed.

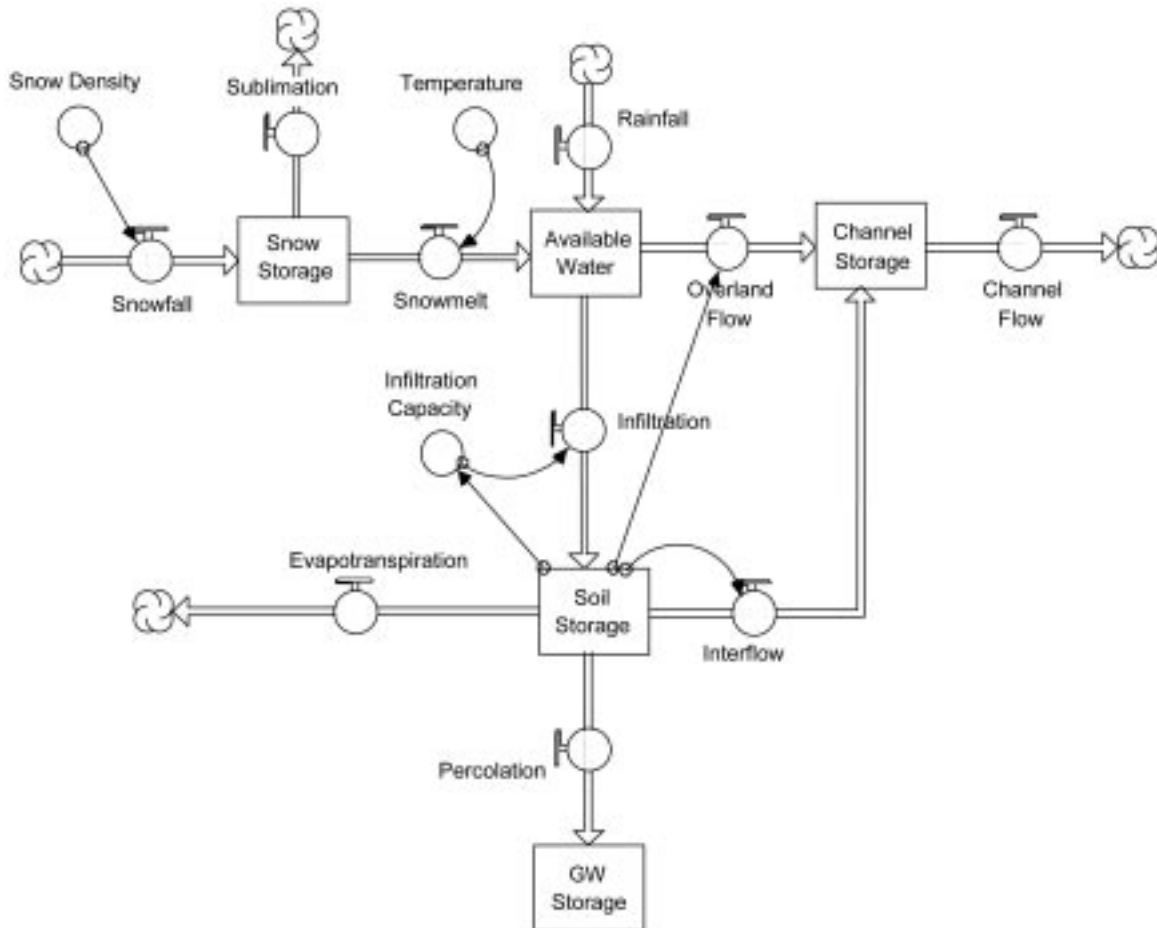


Fig. 2. A simplified object structure of a watershed.

most important concepts of SD. A feedback loop is a circle of cause-and-effect. The cause-and-effect in feedback loops always runs from a stock to a flow and then back to a stock again. Feedback loops are relationships that generate *goal-seeking* behaviors. Goal-seeking behaviours enable conditions within a system to remain 'on course'. When deviations do occur, feedback relationships inspire and then direct corrective actions that bring conditions back into line [7]. An example of feedback in watershed hydrology is the reaction to the soil surface becoming saturated, which should affect the amount of water infiltrating into the soil. This is, for example, one of the three negative feedback loops shown in Fig. 1.

Models developed using SD should be calibrated and validated in a way similar to any other modeling approach. The governing equations are represented by the stock-flow model used for modeling different elements in a system and are solved using standard numerical schemes. For example, in the case of a stock, a continuity equation for mass balance is developed considering the inflows and the outflows, whereas a converter carries a functional relationship between different variables that can be represented in a mathematical or a graphical form.

Understanding the concepts of SD and the way

they work is rather difficult unless it is presented within a simulation environment. In this paper, an object-oriented simulation environment, STELLA Software [8], is used as a sophisticated tool to model the watershed as a dynamic system.

Although SD concepts have been applied to a wide variety of applications in the fields of social studies, economics, industrial engineering, and urban planning to the point that a scientific journal (*System Dynamics Review*) is dedicated to publish its applications in different fields, the area of civil engineering in general, and watershed hydrology in particular, has not benefited enough from this modeling approach; neither in research nor in education. A conceptualization of hydrological models using the stock-flow concept has been briefly outlined by Lee [9] who indicated that the SD modeling approach is a candidate to be an excellent tool for teaching hydrological modeling. Lee's one-sentence idea has not been revisited or investigated further.

NUMERICAL EXAMPLE

One can start experimenting with watershed hydrology using a simple object-oriented model, such as the one shown in Fig. 3a as a step-1 model.

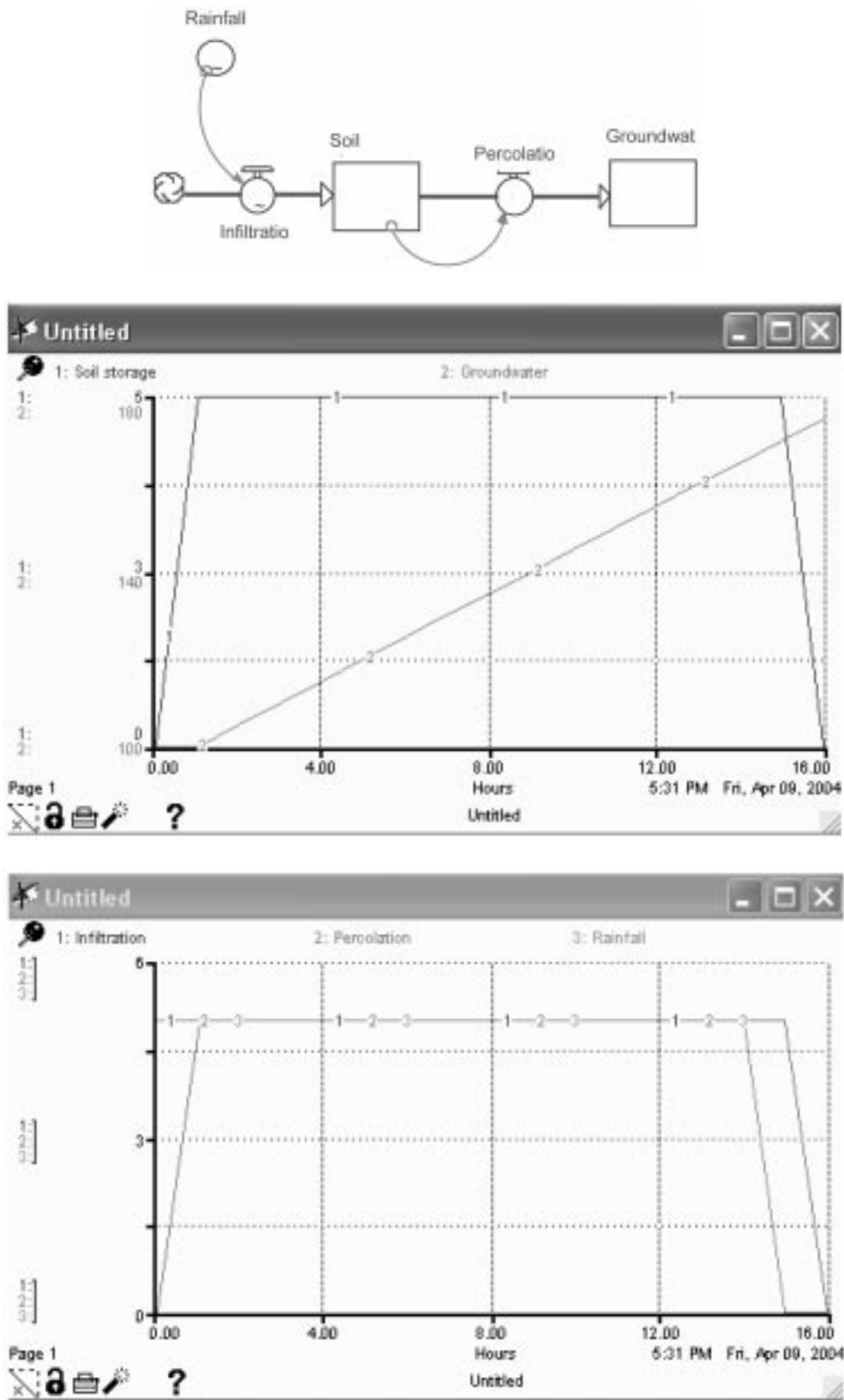


Fig. 3. Step-1 SD model: (a) object structure, (b) resulting soil and groundwater storages, and (c) infiltration and percolation.

The first intuitive model is an object of rainfall that is infiltrating as inflow into the soil storage. The infiltrating water will continue its journey downward through a process called percolation (outflow

from soil moisture stock) to a deeper storage that is called hereafter the groundwater storage. For this example, a heavy and constant storm of 5 cm/hr of rainfall is assumed for 14 hours (i.e. rainfall at

hour 15 = zero). Running this simple model, with a time step of 1 hr, using STELLA software, the results are as follows (Figs 3b and 3c): infiltrating water passes through the soil storage (after 1 hr, which is the time lag due to the numerical simulation) and accumulates linearly into the groundwater. In this example, initial storage values in the soil and groundwater are assumed zero and 100 cm, respectively. A glance at Fig. 3 could reveal that such results are unreasonable; groundwater storage is receiving all infiltrating water whereas the topsoil is keeping nothing beyond the first 5 cm of water. It is meant here to present the outputs that are produced by STELLA software.

The experimenting learner may easily observe, based on basic knowledge, that the water infiltrating into the soil should follow a certain behaviour in time depending on the amount of water (moisture) available within the soil matrix. More than one conceptual infiltration models are available in literature [1, 4]. In this paper, the simple Horton model, provided as Equation 1, is used:

$$f_t = f_c + (f_o - f_c)e^{-kt} \quad (1)$$

where,

f_t is the infiltration capacity (cm/hr) at time t ,
 f_o is the initial infiltration capacity (cm/hr),
 f_c is the final capacity (cm/hr),
 k is empirical constant (hr^{-1}).

Accordingly, three objects (f_o , f_c , k) are added and connected, in a step-2 model, to govern the infiltration process in the model (Fig. 4a). The model is executed to simulate the modified system. Results are shown as Figs 4b and c. Infiltration and percolation decrease exponentially due to the effect of the accumulative moisture, but the fact that soil storage does not keep water beyond the 5-cm threshold and groundwater storage increases exponentially are counter-intuitive. The question of the soil depth and its porosity (pore space that can be filled with water) poses itself since these two variables govern the amount of water that can be held within the soil matrix before water starts percolating to a deeper storage.

A step-3 model should include both depth and porosity (Fig. 5a) to correct and adjust the behaviour of the model. In this example, soil depth is assumed to be 50 cm with 50% porosity. Intuitively, soil will be saturated when all voids are filled with water (i.e. 25 cm of water). Hydrologically, water should start percolating before full saturation (at field capacity), but for simplicity in this example, it is assumed that the soil matrix will be able to retain all water until saturation. An IF-statement is included in the percolation object to allow downward movement of water only after full saturation of top soil. The results of this model are shown in Figs 5b and c. As expected, more reasonable results are obtained. Water accumulates in soil storage until the saturation point is

reached, at which time the groundwater starts receiving water (Fig. 5b). Infiltration decreases exponentially, whereas percolation starts later and increases for some time until it pursues the same recession curve as infiltration (Fig. 5c).

The model can be further enhanced as a step-4 model to address the water balance question. The soil matrix can take a certain amount of water at a certain rate, so what happens to excessive rainfall? Water must start ponding on the surface, forming what is known as runoff (rainfall minus infiltration). Also, another outflow could potentially deplete the stock of water in the soil; that is evapotranspiration (evaporation from land plus transpiration from vegetation). When evapotranspiration consumes some of the water from the soil storage, more room can become available for additional water to infiltrate, which in turn affects both percolation and runoff. Therefore, two more objects namely, 'runoff' and 'evapotranspiration' are added to the model and properly connected as shown in Fig. 6a. Arbitrarily selected hourly values of evaporation, ranging from 0.2–0.7 cm/hr, are applied for exemplification. Final results of the model are presented in Figs 6b, c and d. This last model can be considered a simple watershed model that helps students experiment with it, changes values of parameters, runs different scenarios, and simulates different conditions to deepen understanding of watershed processes. Figure 6d shows that runoff increases as a result of the decreasing infiltration shown in Fig. 6c.

FROM SIMPLICITY TO SOPHISTICATION

In this section, a real case study is summarized and presented to show the capabilities of the SD approach within an OO simulation environment to simulate a real situation. This case study focuses on the simulation of a reconstructed experimental watershed near Fort McMurray, Alberta, Canada. The mining of oilsands near Fort McMurray, Alberta, involves the stripping of the saline-sodic overburden to gain access to the oil-bearing formation. The overburden is placed in large mined out pits and surface dumps and is re-contoured before being capped with a mandated 1-m soil cover. Syncrude Canada Ltd is conducting large-scale cover experiments at the Mildred Lake mine in order to assess the performance of different reclamation strategies.

One of the three experimental covers shown in Fig. 7 is used for the case study presented in this section to show the utility of the SD-OO approach in modeling the hydrologic performance of the 'D3' cover. An SD model was constructed for the cover to simulate the watershed processes. Details of the modeling are not included in this paper but can be found in [10].

Figure 8 shows the object structure of the model needed to simulate the cover under consideration, with the purpose of showing the extent of the

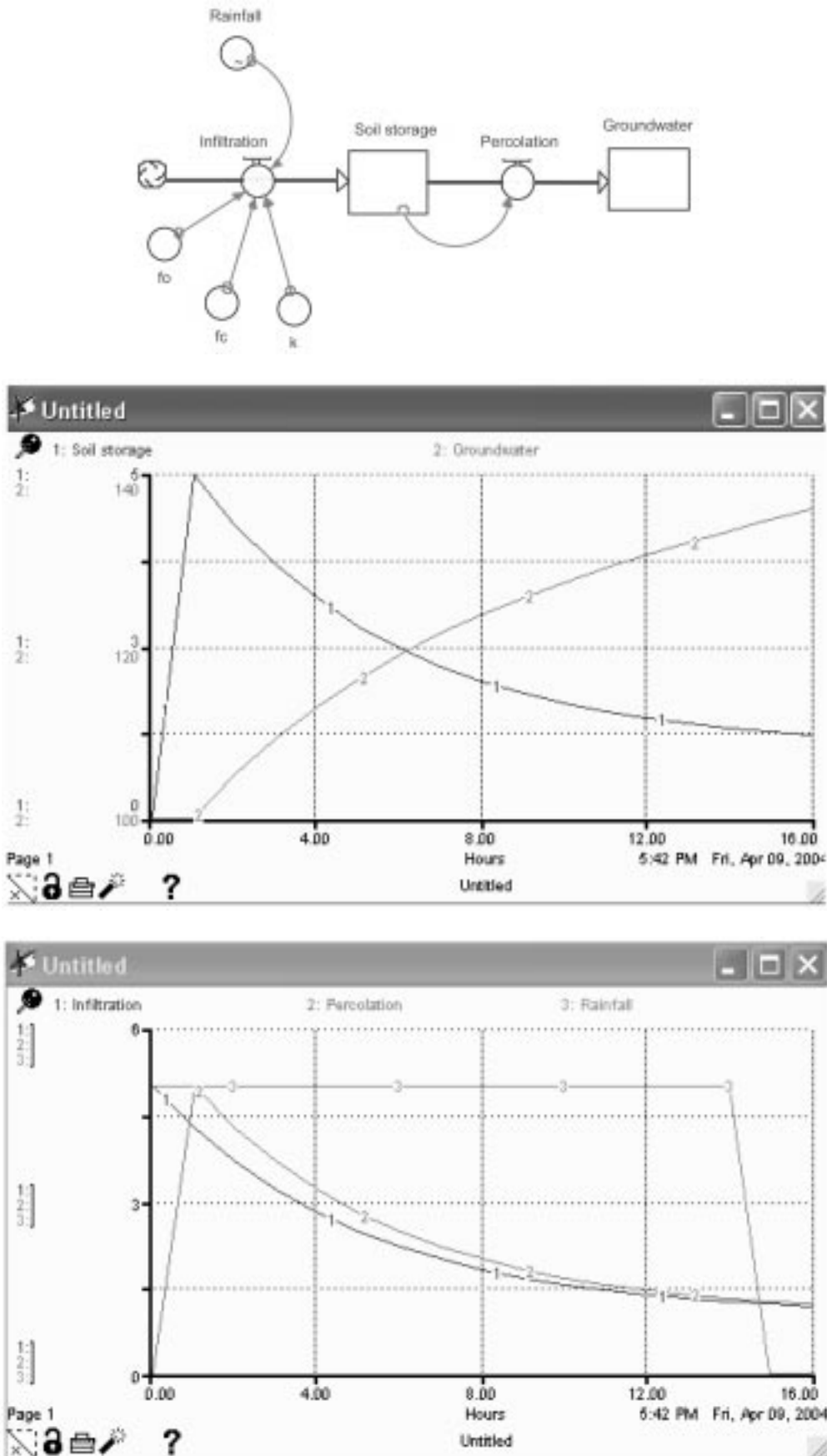


Fig. 4. Step-2 SD model: (a) object structure, (b) resulting soil and groundwater storages, and (c) infiltration and percolation.

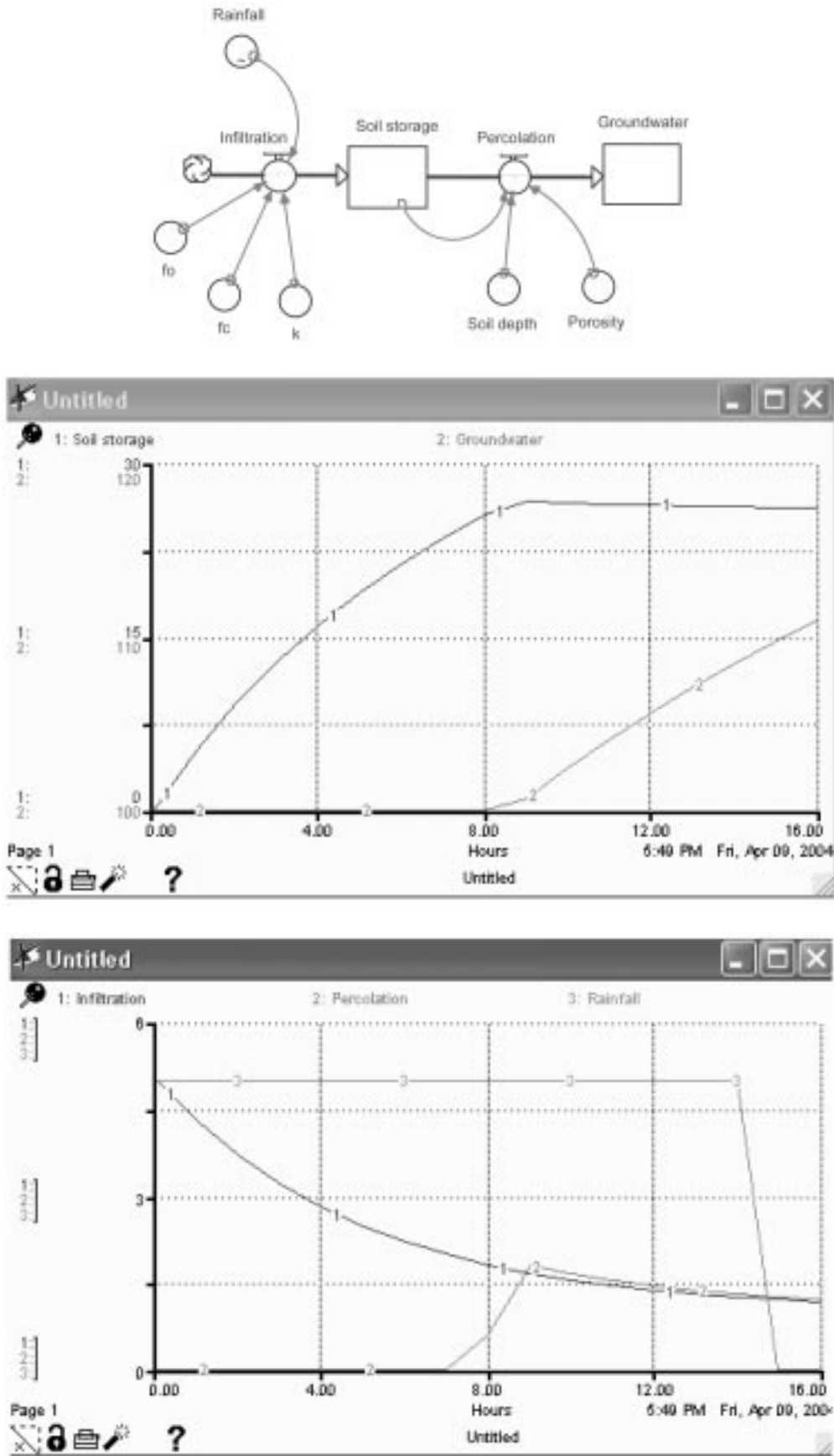


Fig. 5. Step-3 SD model: (a) object structure, (b) resulting soil and groundwater storages, and (c) infiltration and percolation.

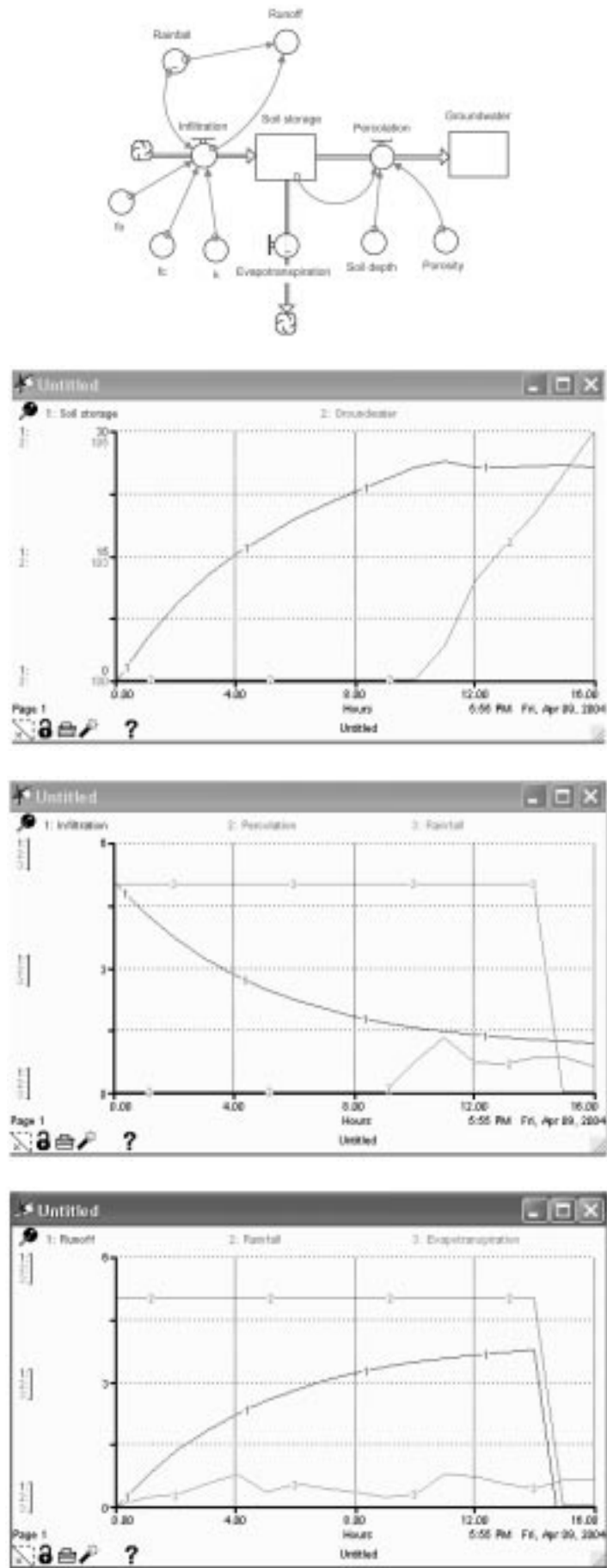


Fig. 6. Step-4 SD model: (a) object structure, (b) resulting soil and groundwater storages, (c) infiltration and percolation, and (d) runoff and evapotranspiration.

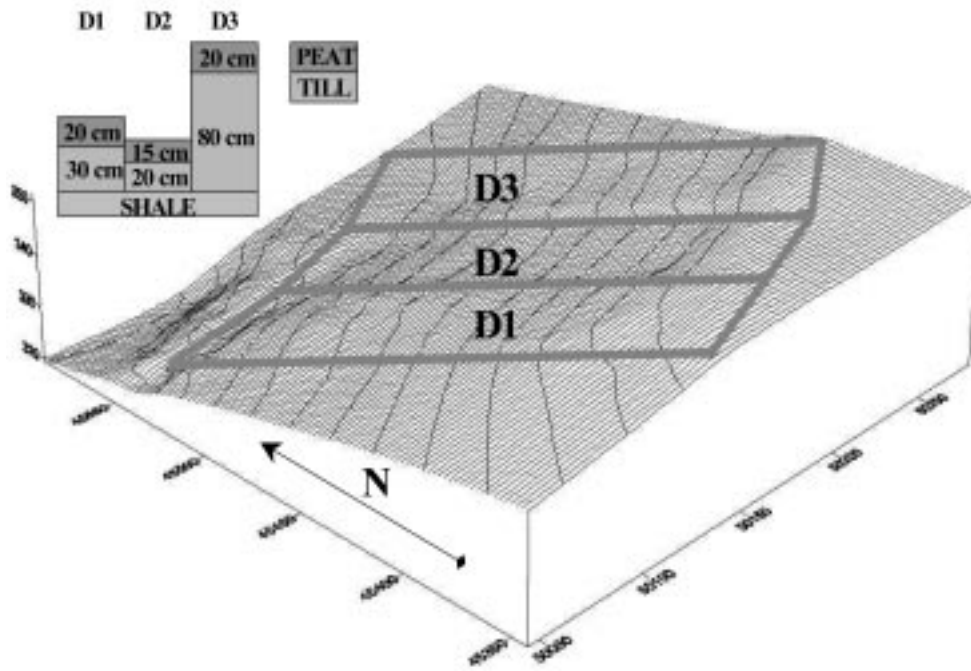


Fig. 7. The prototype cover site [10].

model. In spite of the apparent sophistication of the model, it is based on the same simple concepts discussed earlier. Starting simple, and adding more objects as needed, leads to a model that can address an important issue of the hydrologic performance of a reclamation strategy. An example of the model outputs, which is given as Fig. 9, presents simulated and observed moisture content within the upper peat layer. Such a graph

reminds students that a simulation exercise is nothing more than our perception of the reality but not the reality itself. At this point, a reasonable and fruitful discussion with the students on the limitations of models and modeling exercise can be conducted. Students will be able to digest why modeling in general, and hydrologic models in particular, are only a simplified representation of the reality.

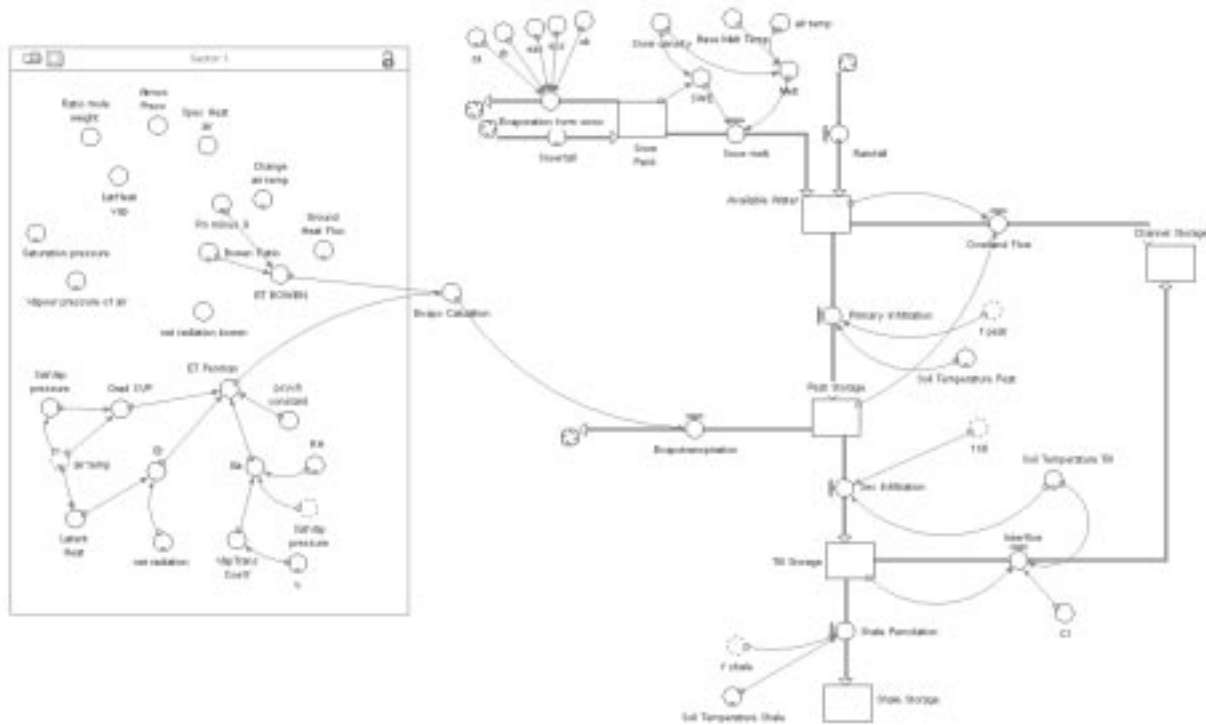


Fig. 8. Object structure of the real case study.

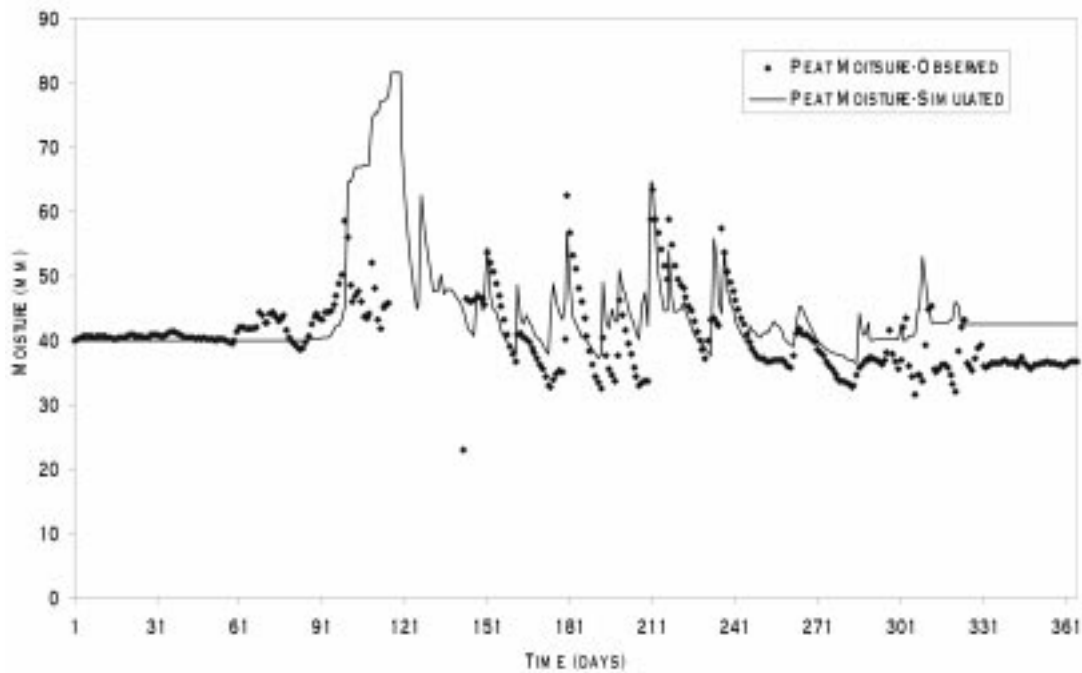


Fig. 9. Observed and simulated soil moisture in the upper peat layer.

DISCUSSION AND FINAL REMARKS

The system dynamics (SD) simulation approach presented in this paper proves to be a viable teaching alternative for watershed hydrology as a learner-centered tool. Personal experience of its efficacy, which was obtained by using it with undergraduate engineering summer students, supports this claim. Not only does it enhance the understanding of the subject, but it also raises the level of the student's interest in it. This impressive and powerful tool encourages the learner to experiment with different parameter values and scenarios, which in turn deepens the students' understanding of hydrology. The fact that STELLA is a generic shell stimulates students to use it with other systems in disciplines other than hydrology. The SD approach helps students learn the basics and increases their level of interest in research (i.e., going beyond what is taught in classroom).

The introduction of the SD approach to teaching hydrology is expected to cause lecturing behaviour and style to become more active through having students experiment with the step-wise simulation [3]. Time devoted to explaining the SD approach could significantly decrease time spent on stimulating students' self-study.

The transmissive style of lecturing is no longer supported by research, which has found that learning through memorisation and reproduction does not result in knowledge that can be used to reason and solve problems in new situations [11]. Different learning methods result in different levels of retention of content material. Biggs describes the

contribution of different learning methods to the student's retention level in a chart, which shows that lectures and reading result in 5% and 10% retention respectively, while 'practice by doing' and 'teaching others' [2, 12] result in retention levels of 75% and 90%. 'Teaching yourself' should be considered part of 'teaching others'. In this regard, the SD approach can play a significant role as an effective tool for 'practice by doing' and 'teaching yourself'.

Perceived control over one's learning is strongly related to and a major contributor to self-efficacy for engineering students [13]. It raises levels of confidence, motivation, and feelings of responsibility towards learning. The SD approach is presented in this paper as an appropriate tool that helps engineering students develop these qualities. The often-missing balance between 'know it to get a good mark' and 'master it for future use' can be achieved by being innovative in using different tools that make engineering education enjoyable.

CONCLUSIONS

With increasing challenges of teaching watershed hydrology and processes to engineering students come calls for adopting more 'teach-yourself' and learner-centered strategies. The adoption of the system dynamics approach, implemented within an object-oriented simulation environment, could be one of these promising strategies. System dynamics simulation, along with its inherent

capabilities for accounting for feedback loops and counter-intuitive behaviour, is a viable option for teaching and learning many natural and man-made systems, including hydrologic systems. The step-wise approach to building and simulating a system has been presented in this paper and shown

to be effective by starting simply and ending with a highly sophisticated system.

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