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Estimating the Available Water in the Watershed using System Dynamics Hydrological Model (Case Study: Ilam Watershed)

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Abstract
Hydrological models provide water managers with the available amount of water in the watershed. In this paper, we firstly developed a system dynamics model to calculate the available amount of water in the watershed. Then, we defined two scenarios one of which is the development scenario describing how land use changes can affect water availability in the watershed. Next, we divided the watershed into upstream and downstream assuming that these two sub-watersheds have different physical features including soil type and land cover to find out how the available water changes. The system dynamics model includes three main components of the hydrologic processes: rainfall-runoff model, snow accumulation, and groundwater. The model calculates runoff at the outlet of a watershed and sub-watersheds with monthly time step. We applied the developed model to the Ilam watershed to demonstrate the capability of the model in estimating runoff volume and available water. We calibrated model coefficients based on minimizing the model's error in estimating the out flow of the watershed. The error was measured using the Nash-Sutcliff efficiency coefficient, the Pierson correlation coefficient, and the standard error. Specific tests such as the dimensional analysis test, and extreme conditions test were utilized to assess the structural accuracy of the system dynamics model. Results showed the appropriate accordance of the model's output with the observed data by a value of the Nash-Sutcliff coefficient (E_{ns}) close to 1, the rather high data correlation coefficient (R), and also a low standard error for the model's calibration and verification periods.
Keywords: Available Water, System Dynamics Hydrological Model, Development Scenario, Ilam Watershed.

Introduction

Improving and developing water resources is dependent on the level of knowledge stakeholders benefit from. Acquiring such knowledge requires estimating the hydrological components of the watershed. Regarding integrated water resources management (IWRM), high-priority difficulties in the watershed include supplying water for water consumers (i.e. Industries, Households, Government, and etc.), water demand management, ecosystem conservation plan, and water quality management. To achieve IWRM goals, it is necessary to take advantage of

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computational models. Estimating and managing runoff in the watershed have always been one of the issues of concern to model-makers and water resource planners. Developing mathematical models helps to understand the hydrological process in the watershed (Ward, 1968). These models play an important role in providing insights necessary to make an accurate decision and plan in managing water resources.

Hydrological models can be classified into varied categories based on complexity, uncertainty, resolution, and accuracy. There is generally two kinds of the hydrological model regarding resolution which can be defined as lumped or distributed. Lumped models make use of one set of parameter values for a watershed to estimate the runoff. On the other hand, distributed models are more realistic and can consider the spatial variability of parameters by dividing the watershed into smaller zones having similar physical and hydrological characteristics (Ghashghaei et al., 2012).

If we know every physical rule of every process of a hydrologic system and access to prohibitive data sets, we will be able to benefit from a comprehensive simulation model can be developed to accurately estimate all desired outputs. Nevertheless, practical limitations often prevent from having access to extensive quantities of input data. The appropriate utilization of such system depends upon the goal of the study and the level of required information. In some cases, a detailed calculation of water movement through all components of the hydrologic system is required (e.g. evaluating the efficiency of water in agriculture). Therefore, evapotranspiration, infiltration, percolation and other processes should be estimated over a long period. However, such a detailed model having high cost of memory usage and computational considerations may not be essential for another hydrologic study (e.g. estimating the runoff volume or pick flow in the watershed for events). In addition, there would be no need to dedicate lots of time and investment to acquiring such data sets if the purpose of modeling and the level of complexity are determined carefully. Conceptual models involve various simplified concepts of the physical processes of runoff formation (Carpenter and Georgakakos, 2006). Calibrating such models for a certain watershed is of paramount significance due to the iterative process determining the rather accurate value of parameters. Therefore, it is important to take advantage of a reliable model benefiting from a number of compatible processes and parameters helping to reach the required accuracy.

Generally system dynamics (SD) can be used as a well-suited framework to couple and translate the existing models into system dynamics format. This approach is a modeling method established by Forrester (1958) to analyze complex nonlinear dynamic systems by identifying and involving the relevant variables that form the model structure and its behavior (Kelly et al., 2013). Using this approach, distinct models can be translated, evaluated, improved, and finally, coupled into a system dynamics format by linking and routing back the feedbacks. This methodology assists to better understand complex feedback systems by realizing how changing the dominance of the feedback loops over time generates the dynamic behavior of the system. Applying system dynamics (SD) in the development of conceptual models and hydrological models can considerably help to simulate hydrological processes within the watershed as well as help to take into consideration impacts of economic, social and political development (Sterman, 2000; Ahmad and Simonovic, 2000; Ahmad and Simonovic, 2004; Deckers et al., 2010). These models have been used as the powerful tool for modeling and analyzing various types of water and environmental issues. Aboelata (1986), used SD modeling to integrate five sub-models including agricultural, domestic, industrial, navigation and energy production to make provision for water resource planning in Egypt. There are also many studies showing that how SD can improve realization capacity of an interactive management of water resources for specific problems (Feng and Huang, 2008; Yang et al., 2008; Madani and Mariño, 2009). Modeling urban water systems, operation of water facilities, flood management, water allocation, water quality modeling, and climate change are some popular topics modelers paid studious attention to develop system dynamics model in order to either provide action plans and management scenarios or enlighten the behavior of the system causes such problems (Winz et al., 2009; Gastélum et al., 2009; Gastélum et al., 2010; Ahmad and Prashar, 2010; Xi and Kim, 2013). Furthermore, hydrologic simulation is also in the center of attention of water resources modelers and planners. They applied SD models to simulate and calculate surface runoff, changes in ground water level, base flow, evaporation, eutrophication modeling, and etc. (Tisdale, 1996; Wang et al., 2005; Elshorbagy and Ormsbee, 2006; Ghashghaei et al., 2012). Focusing on internally generated dynamic behavior of a system, emphasizing on understanding patterns of behavior generated by systems' structures instead of focusing on point precise predictions, high level of generality and scale robustness which is allowing to cope with a wide range of variables in the model (Radzicki, 2009), and providing a user friendly graphical environment to develop the model are specific features makes SD highly beneficial in modeling integrated dynamic systems and assessing diverse scenarios. SD models may be developed using lots of software including Stella (http://www.iseesystems.com), Vensim (http://www.vensim.com), or Powersim (http://www.powersim.com). These programs use numerical methods (e.g. Euler and Runge-Kutta) to solve nonlinear equations (Ford, 2011). We used Vensim software to translate and couple the hydrologic and economic models.

In this paper, we aim to develop a framework that simply translates the hydrologic models into the system dynamics to consider the feedback effects of scenarios on the available water, and to demonstrate how the disaggregation level and the physical features of the watershed affect the outlet flow of the watershed.

The rest of paper begins with an overview of Ilam watershed, followed by presenting the basic concepts of the hydrological model. Next, the hydrologic system dynamics model is described and the model is implemented to analyze two scenarios including the land use change scenario, and the upstream-downstream model. The final conclusion is given in the last section.

Methodology

Case Study: Ilam watershed

The Ilam watershed is 472 km^2 located in the Ilam province in the North West of Iran (Figure 1). This watershed includes three sub-watersheds i.e. Gol Gol, Ama, and Chaviz. The outflow of this watershed is monitored at Ilam's dam station. The average annual air temperature, evaporation, and precipitation are about 16.6 °C, 199.8 cm, and 66 cm, respectively.

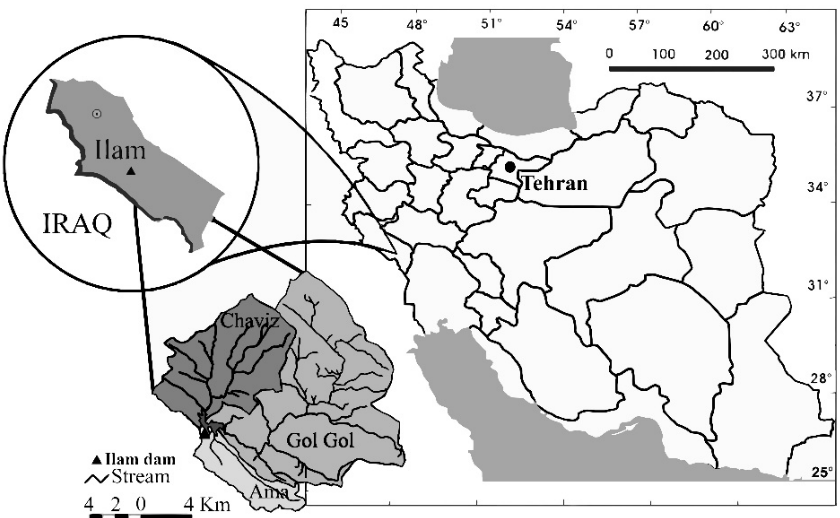

Figure 1. Ilam watershed.

Table 1 shows the monthly precipitation and flow data for the Ilam watershed collected from the research entitled “the long-term study of water quality of Ilam dam” conducted by Mahab (2010). Air temperature and monthly evaporation rate from September to August 2009 were collected from historical data recorded for Ilam station. In addition, 60% of soil in the Ilam watershed is categorized as B for SCS (Soil Conservation Society) hydrological soil group.

Table 1. Input data and observed flow for the Ilam watershed.

Time	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.
Precipitation (mm)	12.8	56.1	57.3	55.5	62.8	70.6	70.7	49.2	4.9	0.3	0.4	0.9
Flow (MCM)	0.46	61.5	70.0	50.0	40.00	65.00	117	50.6	13.3	21.56	20.0	21.56
Evaporation (MCM)	1.37	5.42	4.42	3.37	3.851	5.6	6.82	5.26	0.52	0.02	0.04	0.09
Temperature (°C)	16	9	4	2	2	8	13	17	23	27	27	22

Table 2 indicates the distribution of land use in the study area in 2010. As can be seen, drylands recorded the largest percentage (43.78%), followed by pasture (27.89%). The total Curve Number is 77 which will be used in the SCS method to estimate the runoff volume.

Table 2. Land use distribution in the Ilam watershed.

Number	Land use	Percentage (2010)	CN(2010)
1	Irrigated land	11.83	
2	Drylands	43.78	78.59
3	Scattered Drylands	10.42	
4	Urban	0.15	90
5	Forest	4.64	66.5
6	Pasture	27.89	74
7	Impervious land	1.29	98
Total		100	77

Development of conceptual model

Figure 2 shows the causal loop diagram of the hydrological model indicating key characteristics and elements affecting runoff in the watershed. The meteorological variables including temperature, evaporation and precipitation changes in different areas of the watershed are determined according to the watershed elevation. The temperature affects the formation of the precipitation (rain or snow) and thus can influence the snowmelt process and finally the watershed outflow.

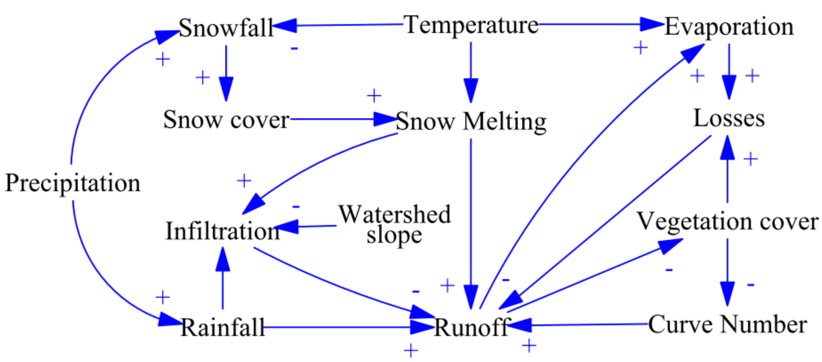

Figure 2. Casual loop diagram of the hydrological model.

As can be seen, an increase in rainfall will heighten the amount of rain or snow according to the temperature. During cold months, when temperature significantly decreases and reaches below zero, snow cover will increase in the watershed. As temperature surges in the highlands, snow starts melting leading to increasing the runoff volume after subtracting losses and infiltration. On the other hand, the increase in rain results in escalating infiltration, evaporation and losses which balances the runoff volume. Moreover, the more increase in the volume of runoff, the more negligible the impact of vegetation cover will be, which ultimately will strengthen the runoff. In this paper, after translating the model structure in VENSIM software, the state variables were calculated based on mathematical relationships explained in detail in the following sections.

Hydrologic model

In this section, the following components of the hydrology processes necessary to estimate runoff volume are represented in detail, and the other processes are omitted or lumped (Carpenter and Georgakakos, 2006). Hydrologic models simulate the hydrological processes within a watershed. They illustrate how the precipitation is converted to rain or snow, surface runoff, interflow, base flow and other components. Figure 3 and 4 indicate the simple Vensim algorithm and conceptual diagram illustrating the required components to estimate runoff volume based on the goal of study.

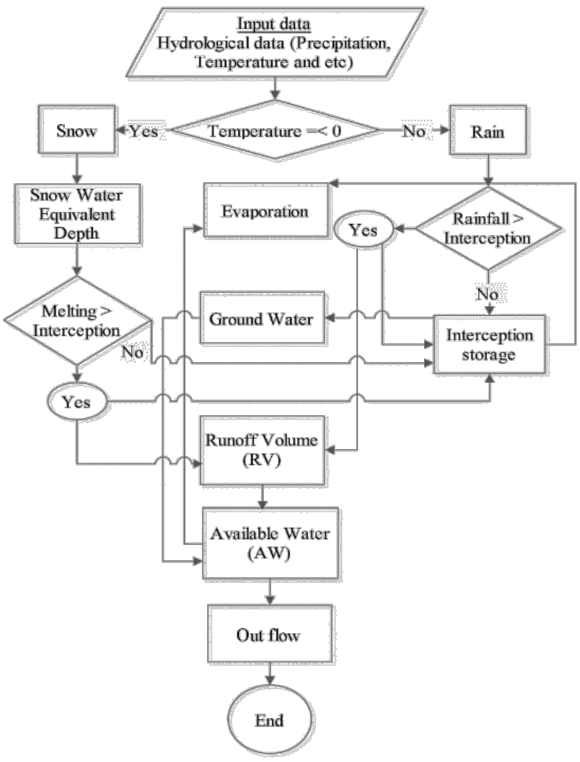

Figure 3. Model Algorithm.

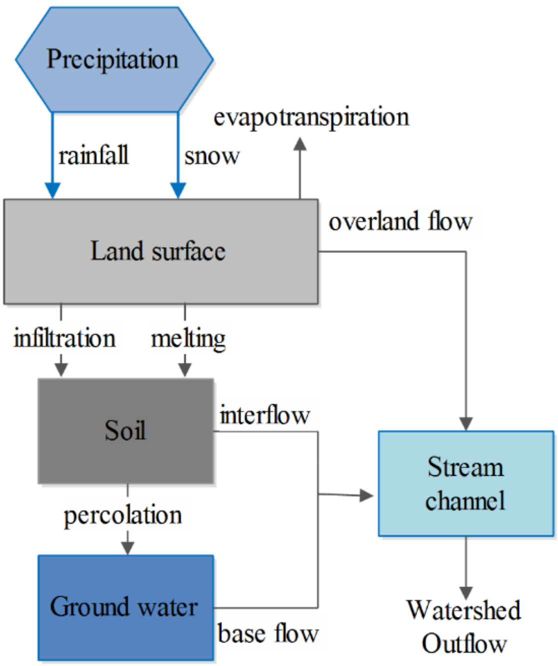

Figure 4. Vensim runoff model.

The processes begin with precipitation which falls on the watershed surface. Depending upon air temperature, precipitation could be either in form of snow or rain (we suppose that if temperature is less than 0 ℃, snow occurs and if it will be higher than 3 ℃, precipitation is in form of rainfall). Most of the water that falls as precipitation returns to the atmosphere through evapotranspiration. Some precipitation falls through the vegetation on the land and joins the precipitation that fell directly onto the surface as overland flow (Scharffenberg and Fleming, 2006). A portion of water might be intercepted, stored, and evaporated. It also infiltrates into the soil's upper layer. The infiltration rate and capacity depend on some physical characteristics of the watershed such as soil type, ground cover, and antecedent moisture. Capillary pressure may cause some infiltrated water to rise to the land surface. It also can be transferred horizontally as interflow, or percolates vertically to the lower layer and finally the aquifer. Some of ground water can be slowly discharged to the stream as base flow. For situation that snow is accumulated, as temperature increases, snow pack starts to melt. The process of converting melted water into the runoff volume is the same as rainfall. All the water flows which are not stored, percolated to the deep aquifer or evaporated join each other at the stream and eventually form the total watershed outflow.

The available water volume as a stock variable named Available Water is calculated based on the general water balance in the watershed (Equation 1). All the variables have the same unit of cubic meter per month.

$$Available\ Water = Base\ flow + Runoff\ \ Volume - Evaporation(E) - Loss\ \ - Out\ flow \tag{1}$$

Rainfall excess as the Runoff Volume and inter flow and ground water flow as the Base flow are the main flows charging the Available Water storage. Equation 2 describes how rainfall and snow melting affect the runoff volume in the model.

$$Runoff\ \ Volume = (Q + Melt\ \ depth) * WA \tag{2}$$

Runoff volume is computed by multiplying rainfall excess (actual accumulated runoff, Q (m/month) and the watershed area (WA) (m2) for a time interval, plus the snow melt volume (m3/month) is calculated by multiplying snow melt depth (m/month) by the watershed area.

SCS curve number method is an event, lumped, empirical, fitted parameter model developed by the United States Department of Agriculture (USDA) Soil Conservation Service (SCS) (Mockus, 2010). It assumes the ratio of actual accumulated surface retention (F=P-Q) to the potential maximum retention (S) is equal to the ratio of actual accumulated runoff (Q) to the potential maximum runoff (P) (Mockus, 2010). All the components of Equation 1 are expressed in meter.

$$\frac{F}{S} = \frac{Q}{P} \tag{3}$$

Equation S1 illustrates the conditions in which no initial abstraction (Ia) occurs. Ia represents a parameter lumped three losses including interception and depression storage assuming a certain portion of precipitation is stored by surface cover and the watershed topography respectively, and eventually, infiltration into the upper soil layer. The resultant Equation 4 will be:

$$Q = \begin{Bmatrix} 0 & \text{for}\, P \le I_a \\ \dfrac{(P - I_a)^2}{P - I_a + S} & \text{for}\, P > I_a \end{Bmatrix} \tag{4}$$

The SCS suggested an empirical equation to approximate Ia as a function of the potential maximum retention S (Ia=0.2S). The potential maximum retention, S, has an inverse relation with the dimensionless parameter Curve Number CN in the range of 0 <= CN <= 100 (Equation 5). The CN for a watershed is calculated based on land use, soil type, and antecedent watershed moisture utilizing tables published by the Boughton (1989). Lower CN results low runoff potential while larger number indicates less permeable soil and more potential runoff.

$$S = \frac{25.400}{CN} - 0.254 \tag{5}$$

For a watershed that have several soil types and land uses, a composite CN can be calculated as:

$$CN_{composite} = \frac{\sum A_i CN_i}{\sum A_i} \quad (6)$$

in which

CN_i= the CN for subdivision i; and A_i = the drainage area of subdivision i (Mockus, 2010).

Snow cover

Snow in the watershed is a reliable water stock. Estimating this amount of water as well as its availability can be beneficial for managing water uses including water supply, flood forecasting, and Irrigation of agricultural products. Because Ilam watershed is not at the high altitude, the snow does not play a dominant role in this area. However, to develop a model with an acceptable level of complexity and accuracy, the study of snow is necessary. In this paper, to calculate the snow share, we used the threshold elevation of snowfall to obtain the snow cover area using empirical relationships and temperature indicator. To determine the share of snowfall from total precipitation, we used Chandra's empirical method to calculate the snow cover coefficient due to the unavailability of recorded data for snow. In this method, the ratio of snow water equivalent depth to precipitation is calculated by equation (7).

$$S_n = P_t(1-P_r) \quad (7)$$

Where Sn is snowfall in mm, Pt is the average monthly rainfall in mm, Pr the ratio of total rainfall to precipitation obtained from the following equation.

$$P_r = \frac{(T_{max} - B_s)}{(T_{max} - T_{min})} \quad (8)$$

T_{max} and T_{min} are the maximum and minimum monthly absolute temperature, respectively and BS is temperature at which raindrops are condensed which varies between 1.66 to 2.2 ° C.

The threshold elevation of snowfall

The elevation that is equivalent to the temperature where precipitation will be in the form of snow is called the threshold elevation of snowfall. In this study, the monthly average temperature is used to calculate this elevation. Using this elevation, one can find the snow area in the watershed. Figure 4 shows the relationship between the annual average temperature and altitude in Ilam watershed.

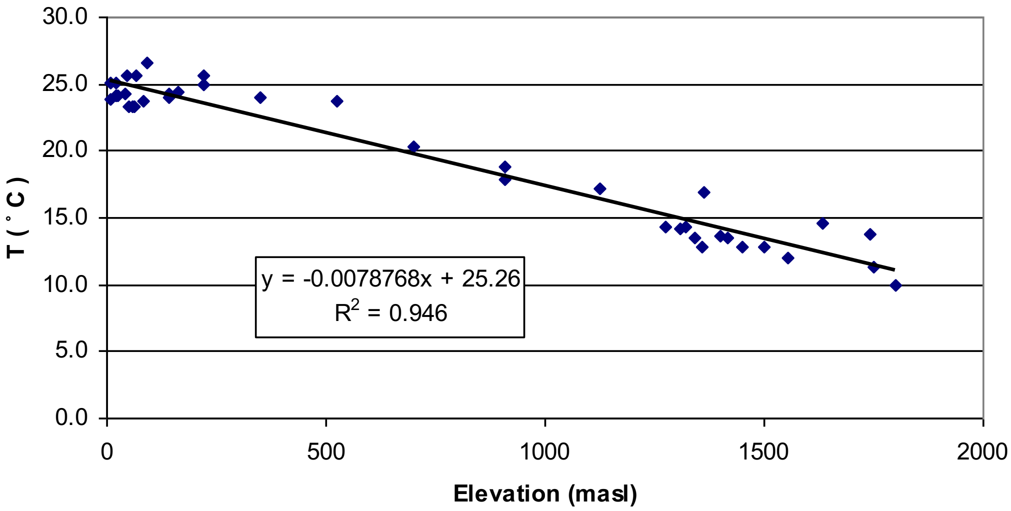

Figure 4. Temperature and altitude Relationship in Ilam watershed.

Snow water equivalent depth and Snow melting

Snow depth is dependent on the snow density (ρ_s), melting density (ρ_m) and snow water equivalent depth (dm) (Equation 9). Snow density varies based on climates. It changes from 50 to 120 kilograms per cubic meter for fresh snow. In cold and dry regions, this value is lower and in hot and humid regions it is higher. Here, we supposed the snow density is 120 kilograms per cubic meter.

$$d_m = \frac{\rho_s S_n}{\rho_m} - Melting\ Water \tag{9}$$

Snowmelt model simulates the process of accumulation and melting. These models classified into lumped and distributed. Lumped models benefit from the mean values of watershed parameters to define hydrological characteristics. While distributed models divides watershed to smaller regions and consider their spatial distribution. In this study, the degree-day method is employed to calculate the amount of melted snow.

$$Melting\ Water = 25.4 \times C\,(1.8(Temperature - Temp + 32) \tag{10}$$

where C is snowmelt coefficient which varies between 0.015 and 0.2, and Temp is a temperature in which snowpack starts melting (Karamouz and Araghinejad, 2005).

To calculate Base flow, we defined a coefficient (bc) representing ground water contribution in the base flow and multiplied Ground water outflow by it (Equation 11). Defining such coefficients are beneficial to calibrate the model outputs. Similar to calculating an outflow of a reservoir, we benefited from concept of water residence time (tg) to estimate the ground water outflow (m3/month) (Equation 12).

$$Base\ flow\ =\ Groundwater\ outflow\ * b_c \tag{11}$$

$$Groundwater\ outflow\ =\ Ground\ Water\ Volume\ / \, t_g \tag{12}$$

Ground water inflow is also computed by using Cp coefficient which is the percentage of water infiltrating into the Ground water storage (Equation 13). The subtracted value of rainfall form rainfall excess (Q) can infiltrate in to ground water.

$$Groundwater\ \ Volume = Groundwater\ inflow - Groundwater\ outflow \tag{13}$$

$$Groundwater\ inflow\ =\ \left(P_r - Q\right) * WA \tag{14}$$

After precipitation, several processes (e.g. interception, surface storage, infiltration, evaporation, and evapotranspiration) cause loss of water due to draining from the basin into the river and flowing downstream. Evaporation (m3/month) is vaporization of water directly from the land surface. As a metrological input, monthly-varying E (m/month) values are specified for the simulation time period. Evapotranspiration loss from the watershed is estimated by multiplying E data and the watershed area (Equation 15). There are also other losses due to environmental conditions and physical characteristics of the watershed when the accumulated rainfall excess begins to run (Equation 16). The coefficient, C0, representing the monthly average percent of runoff which takes part in the watershed outflow was defined to capture the effects of other losses on the model. Furthermore, this coefficient was utilized to calibrate the out flow of the watershed. However, using SCS method to calculate the runoff volume can affect this component due to the initial abstraction concept. Therefore, it is not unexpected that C0 could be 1 after calibration process.

$$ET = \begin{cases} Monthly\ ET * WA & \text{if } Monthly\ ET * WA <= \left(Available\ \ Wate\ / \, te\right) \\ Available\ \ Water\ / \, te & \text{otherwise} \end{cases} \tag{15}$$

$$Loss =\ \left(1\text{-}C_0\right) * Available\ \ Water\ / \, t_l \tag{16}$$

where tl is the average time which takes for complete water losses.

As illustrated, the available water is estimated by integrating the difference between the sum of Runoff volume, Base flow, and the sum of Evaporation, Loss, and Out flow as flows draining out.

Most of hydrologic models can be categorized as fitted-parameter models in which model parameters cannot be specified from system properties (Mishra and Singh, 2002). In such model the parameters are approximated by fitting the model with observed values. The current Vensim model estimating the runoff volume and the available water is empirical, so some of its parameters that cannot be measured should be found by calibration.

Results and Discussion

Ilam hydrological Vensim model

The model developed in VENSIM makes use of water balance concept to estimate runoff volume. It includes three main components of the hydrological processes in the watershed: rainfall-runoff model, snow accumulation, and groundwater. The variables and parameters used in the model are described in Table 3. The model computes discharging flow at the outlet point of the watershed based on the following assumptions:

1. The outlet point for the Ilam watershed is assumed to be at the gauging station (Ilam station);
2. The simulation starts in September 2010 and ends in August 2011.
3. The initial amount of available water, snowpack and ground water are assumed to be zero.
4. The snow will be melted if the average temperature is greater than the threshold (0 °C).
5. All look up variables in the model were used to input data time series.
6. The model is run for monthly intervals.

According to the land use data, $CN_{composite}$ is about 77, and so the potential maximum retention will be about 13 cm.

Calibration and validation

After running the model, we calibrated model coefficients based on minimizing the model's error in estimating the out flow of the watershed. The error was measured using the Nash-Sutcliff efficiency coefficient, the Pierson correlation coefficient, and the standard error. Nash-Sutcliff efficiency is defined in equation 17:

$$E_{ns} = 1 - \frac{\sum (C_o - C_m)^2}{\sum (C_o - C_{oave})^2} \tag{17}$$

Where C_o is observed variable and C_m is simulated variable. Nash–Sutcliffe efficiencies can range from −∞ to 1. An efficiency of 1 (E = 1) corresponds to a perfect match of estimated outcomes to the observed data. An efficiency of 0 (E = 0) indicates that the model predictions are as precise as the mean of the observed data (Nash & Sutcliff, 1970). According to Table 3 the appropriate accordance of the model's output with the observed data is indicated by a value of the Nash-Sutcliff coefficient (E_{ns}) close to 1, the data correlation coefficient (R), and also a low standard error for the model's calibration and verification periods. The result indicates an appropriate accuracy of the model. Figure 5 shows observed data and simulation results for runoff flow at the outlet point of the watershed. It can be seen that the correlation between estimated and observed data is acceptable.

Table 3. The results of Nash-Sutcliff coefficient, correlation coefficient, and the standard error.

Criterion	r	S_e	E_{ns}
Outflow	0.9	16	0.74

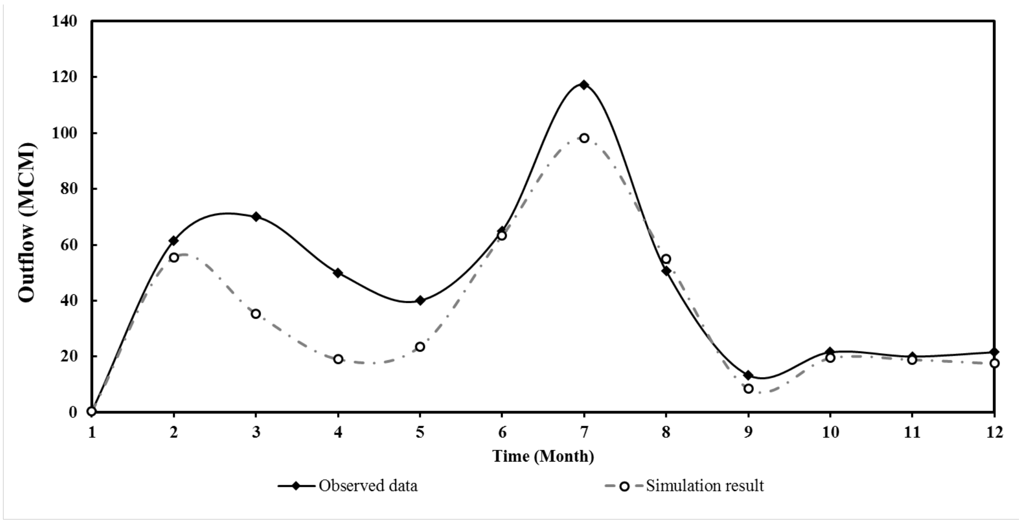

Figure 5. The observed and simulated Outflow of the Ilam watershed.

Specific tests can be utilized to assess the accuracy of a model, based on the system dynamics approach, as described below.

The dimensional analysis test

The unit consistency of each state variable in the model was analyzed by the Units Check order. If there is an inconsistency in units, a unit error will emerge. Although a dimensional error does not affect the numerical calculation and the model's outcomes, it can lead to misunderstanding for complex systems. In this study, there is no unit error in the model.

Extreme conditions test

Every model must cope with extreme circumstances during the simulation period. For this reason, the precipitation was considered as 0. Accordingly, the outflow decreases from the initial amount of 0.46 to about 0 MCM/month (Figure 6).

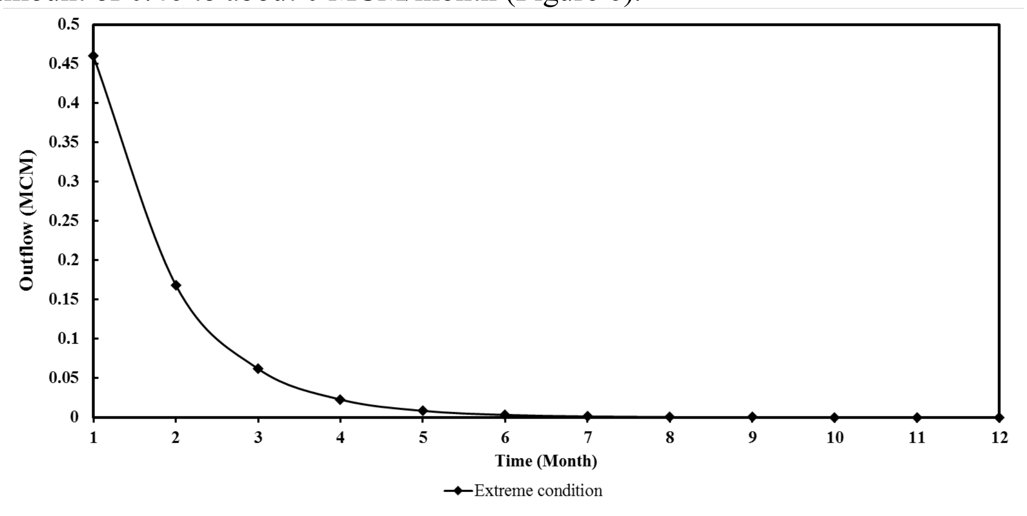

Figure 6. The results of the Outflow under the extreme Condition.

Model parameter

In the system dynamics model, there could be three categories for estimating model parameters. The value of some parameters can be found in the available scientific researches such as T_b (The threshold air temperature below which all precipitation is snow) and T_r (The threshold air temperature above which all precipitation is snow) and there is no need to calibrate them. A number of parameters should be estimated based on the physical characteristic of the watershed including topography, land use, vegetation, ground cover and etc. Although these parameters can be calibrated to heighten the accuracy of the results, in this study, we would prefer not to consider them as calibrating parameters to avoid unnecessarily increasing the level of complexity. Eventually, there are certain number of parameters that must be determined by calibrating process. The value of these parameters are proposed and adjusted by iterative process to minimize the error of the simulation results. In this paper, we aim to illustrate how the hydrologic model can be used to model the water budget in the watershed. For this reason, the level of complexity and the number of parameters are specified so that it satisfies the requirement of the study. Table 4 provides information about the model parameters and their categories. It also indicates the calibrated figures, finally used in the model.

Table 4. Model parameters.

Parameter	Range	Unit	Category	Reference	Calibrated
b_c	(0 - 1)	Dmnl	Calibration	(Ghashgaie et al., 2012)	0.65
C	(0.015 - 0.2)	Dmnl	Calibration	(Karamouz and Araghinejad, 2005)	0.12
C_p	(0 - 1)	Dmnl	Calibration	(Ghashgaie et al., 2012)	0.67
Temp	(0 - 1)	°C	Calibration	(Ghashgaie et al., 2012)	0.1
T_b	(-1 - 1)	°C	Input data	(Ward and Trimble, 2003)	
t_e	No limitation	month	Input data	Estimated from watershed characteristics	
t_g	No limitation	month	Input data	Estimated from watershed characteristics	
t_l	No limitation	month	Input data	Estimated from watershed characteristics	
t_m	No limitation	month	Input data	Estimated from watershed characteristics	
T_r	(1 - 5)	°C	Input data	(Ward and Trimble, 2003)	
CN	(30 – 100)	Dmnl*	Input data	Estimated from watershed characteristics	

Dmnl: Dimensionless

Finally, the system dynamics model was applied to the Ilam watershed to demonstrate how the model estimates runoff volume and available water in the watershed. After verifying the model, we ran the model for the year 2010. Figure 7 shows results of the hydrologic model for three stock variables.

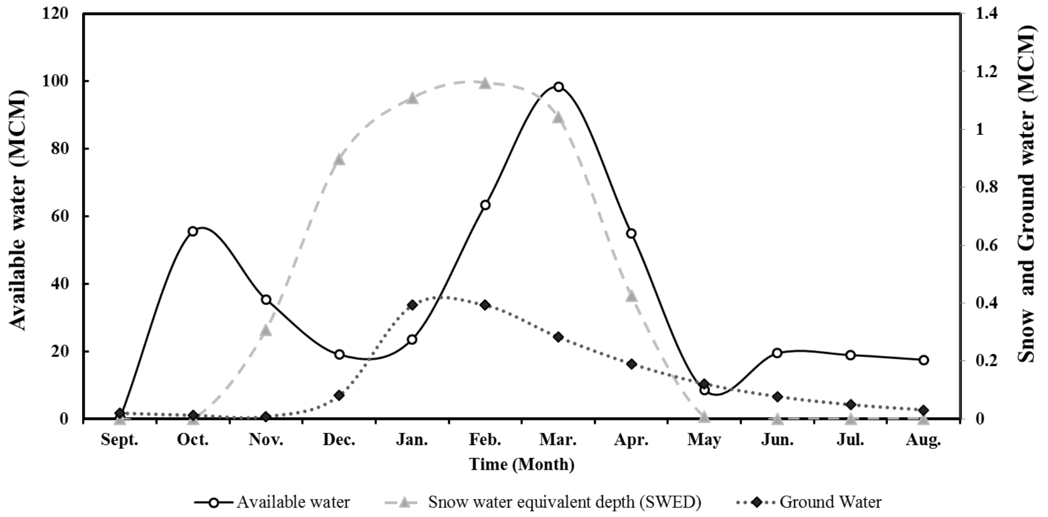

Figure 7. Available water, SWED, and Ground water stock simulation results.

As can be seen, the available water peaks at about 100 MCM in March when precipitation is recorded its highest figure of 70 mm. In summer, both less participation and high rate of evaporation cause this storage to be declined and finally minimized in September. As participation increases and losses decrease, the available water surges and reaches its second peak of about 60 MCM in November. Since temperature is less than 3°C in December and January, precipitation is comprised of snow and rain. As a result, SEWD heightens from November to February and starts melting until May. In December, snowfall occurs causing an increase in SEWD storage. Ground water trend is similar to the SEWD due to the smaller evaporation rate in January and February. For the other months except December the amount of water that can infiltrate into ground water is zero. Therefore, ground water storage draining out gradually until November where charges again.

Scenario 1: Effects of land use change on the available water

With the burgeoning population of industries in the Ilam watershed, it is predictable that economic growth can cause the distribution of land use to change rapidly. For this reason, we defined a scenario supposing that drylands in the watershed will turn into the urban area by 15 percent until 2020. This variation will affect the watershed cover, thus will change CN. Table 5 indicates the distribution of land use in 2010 and 2020.

Table 5. Land use distribution in the Ilam watershed.

Number	Land use	Percentage (1995)	CN (2010)	Percentage (2020)	CN (2020)
1	Irrigated land	11.83		11.83	
2	Drylands	43.78	78.59	28.78	78
3	Scattered Drylands	10.42		10.42	
4	Urban	0.15	90	15.15	90
5	Forest	4.64	66.5	4.64	66.5
6	Pasture	27.89	74	27.89	74
7	Impervious land	1.29	98	1.29	98
Total		100	77	100	79

According to the table, drylands has the largest percentage of land use (28.78%), followed by pasture (27.89%). The total Curve Number of the watershed increased by about 2.5% and reaches 79. Figure 8 shows results of outflow for both status quo and the development scenario.

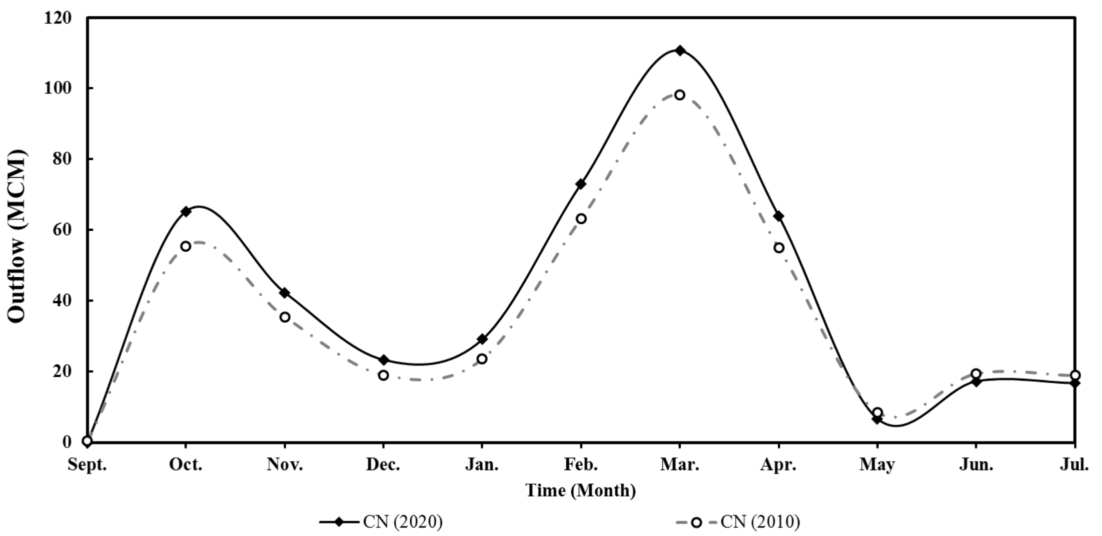

Figure 8. Outflow of the watershed under both status quo and the development scenario.

As can be seen, the amount of outflow will heighten when the CN increases. Since there is an inverse relationship between the Curve number and the potential maximum retention, S, as CN increases by about 2%, the S decreased from about 75 mm to 63mm. The amount of outflow surges for most of the months and will approximately be unchanged in last three months in 2010 and 2020. The peak flow increased from 98 to 110 MCM in March, and the minimum flow stayed unchanged. Therefore, it is evident that changing land use causes escalating the runoff volume in the watershed.

Scenario 2: Effects of spatial level on the available water

Considering the watershed as an entity (Scenario 1) can omit important details when estimating available water. This approach may be subject to the lumping of some spatial characteristics of the watershed. For instance, less available water in some sub-watersheds is balanced with abundance in other sub-watersheds. To consider the spatial distribution of the economic sectors, we divide the watershed into upstream and downstream sub-watersheds. The hypsographical curve, which determines the relationship between altitude and the cumulative surface area of a watershed, is used. After separating the two sub-watersheds, the system dynamics model is applied to estimate available water and outflow in each sub-watershed. Here, we assume that the two sub-watersheds have different physical features including soil type and land cover so as to have either more or less available water. For example, one sub-watershed can have soil and ground cover (CN curve number) where a larger percent of rainfall converts to runoff compared to the other sub-watershed. The process of estimating the available water, runoff volume, base flow, evapotranspiration, and other components of the hydrologic model is similar to the main process described in the previous sections except for the CN curve number. In the upstream, the runoff volume is calculated using the SCS method having larger CN than the downstream. The downstream has an additional inflow variable to its Available water stock accounting for the outlet flow of the upstream sub-watershed into the downstream sub-watershed. Figure 9, shows the model for the upstream and downstream sub-watersheds.

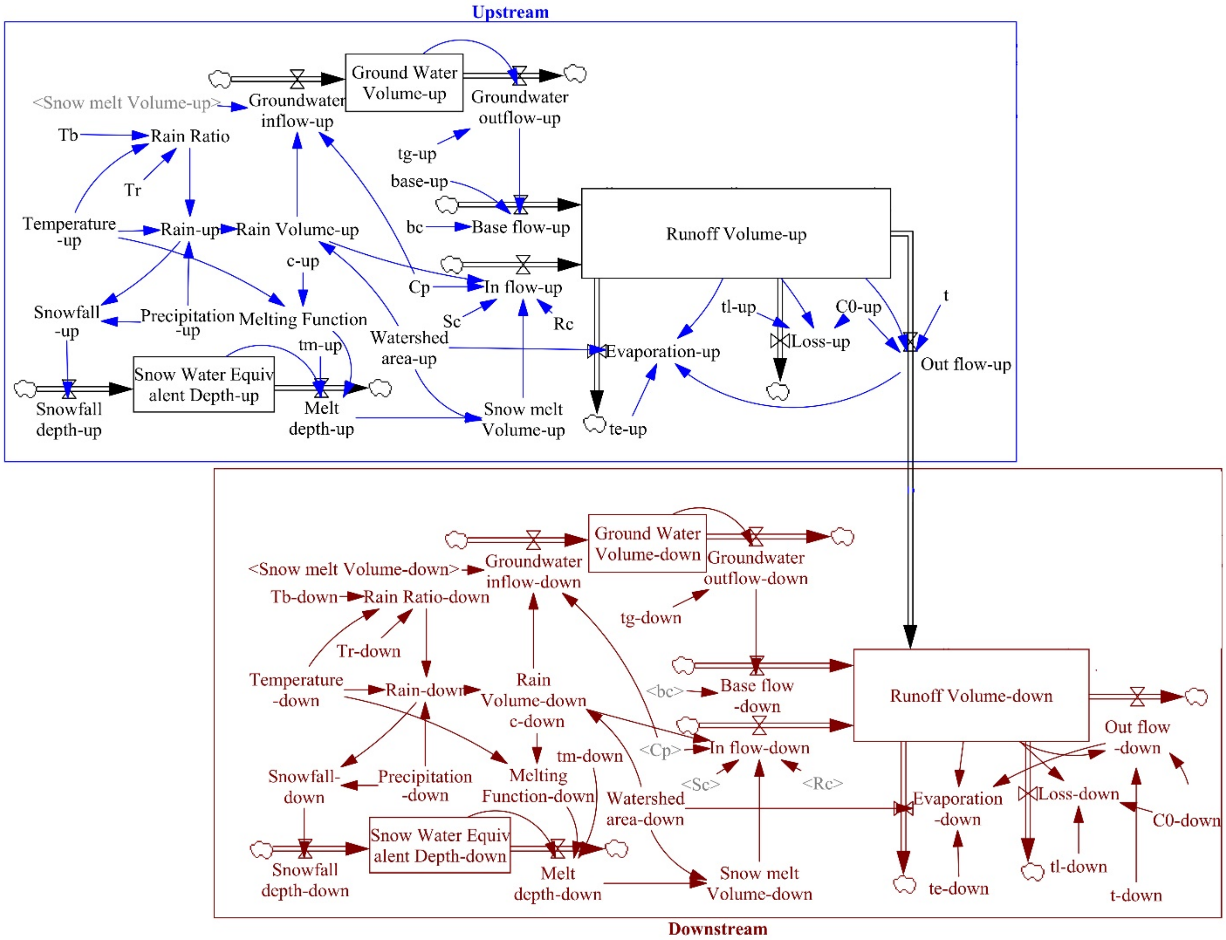

Figure 9. The hydrologic system dynamics model for the upstream-downstream scenario.

To apply the model for this scenario and demonstrate that the upstream has a higher potential runoff, its CN curve number is assumed to be 89 and for downstream CN is considered to be 79. The coupled model is solved with monthly time step, with results shown in Figure 10.

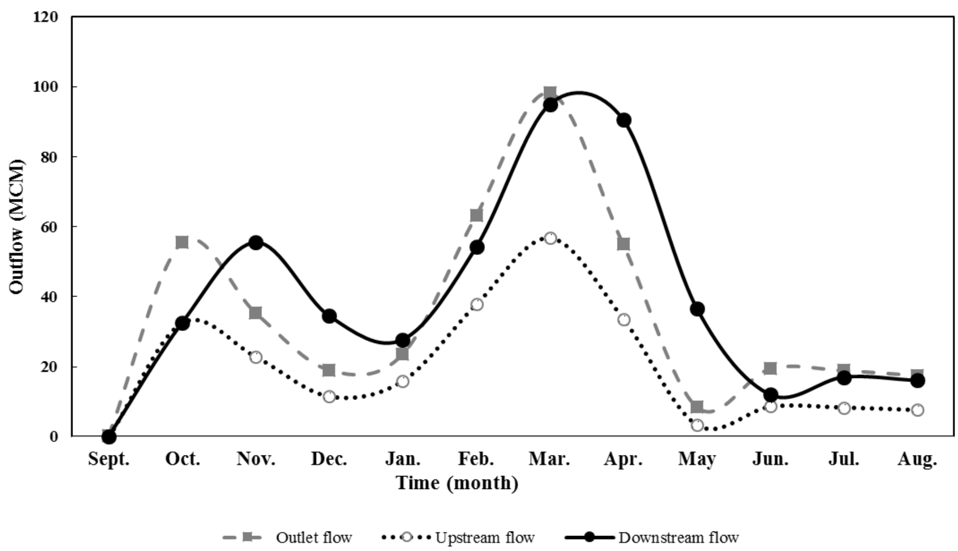

Figure 10. The results of hydrologic model for the upstream-downstream flow.

In the downstream sub-watershed, the Available water stock is fed by the outflow from upstream and the runoff volume obtained from precipitation in the downstream sub-watershed.

As can be seen, assuming all other factors equal, there is a slight shift between the downstream flow and the outlet flow. This is because we modeled two sub-watersheds as two linear reservoirs. Therefore, dividing the watershed into two sub-watersheds and distributing sectors between them in this particular way allows outflow to be more accurately estimated. The upstream outflow is higher than the half of outlet flow. The reason is the larger CN that leads to having more potential of outflow in this sub-watershed.

Conclusion

Since water is the key component of economic growth, managing this valuable resource is of paramount significance for decision makers as well as people. Estimating the amount of water, which could be available for varied water uses is the first step towards achieving sustainable water resources management. In this paper, we developed a simple hydrological model to, firstly, provide a framework enabling us to calculate runoff volume and available water in the watershed. Next, we defined a scenario considering the land use of the watershed will change from 2010 to 2020. We suppose that the rate of change for drylands is 15%, and it will turn into the urban district.

We used SCS curve number method to calculate runoff volume obtained by computing the volume of water that is intercepted, stored, and infiltrated, and subtracting it from the precipitation. Then, the available water is estimated by integrating the difference of runoff volume, base flow as flows pouring in, and evaporation, losses, and outflow as flows draining out the stock variable. After developing the framework, we calibrated and verified the model using a couple of tests indicating that the model benefits from an appropriate level of accuracy.

Under the development scenario, we had an increase in the runoff volume for almost all months. That is because of surging CN and decreasing the maximum potential retention parameter. The peak flow increased by 12% from 98 to 110 MCM in March. However, the amount of changes was negligible in the summer.

Scenario 2 revealed that dividing the watershed into upstream and downstream having different physical features in sub-watersheds can cause model to be more realistic. To wrap up, results show that vegetation cover degradation by changing the land use can create substantial differences in runoff volume. This could lead to increasing the intensity of flood in the watershed and finally enhance the risk of development in the future.

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