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Application of an Object-Oriented Approach Based on the Concepts of System Dynamics in Integrated Water Resources Management

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Abstract

Developing nations are imposing increasing impacts on their bio-resources due in part to their rising population, need to high economic growth, and the incorporation of non-native technologies. Usually, watersheds are the major units which are impacted leading to un-sustainability, specifically from the view point of water resources and hydrological systems. Hydrological systems are generally considered as a set of components which should be regarded interactively related in a watershed scale. The watershed approach is a coordinating framework for integrated water resources management (IWRM) that focuses on public and private sectors' efforts to address the highest priority problems within hydrologically defined geographic areas, taking into consideration both ground and surface water flow in a watershed level. Therefore, watershed modeling lies at the center of water resources planning and management.Relying on a linear causal thinking, most of the hydrological models fail to incorporate socio-economic attributes of a watershed with its hydrological and environmental ones. Based on a systems thinking philosophy, the paper aims to adopt an object-oriented approach based on the concepts of system dynamics (SD) to analyze the dynamics in a hydrological system in a watershed scale. Object-oriented (OO) modeling is a way to organize data into discrete, recognizable entities called objects. These objects could be concrete (such as a river reach) or conceptual (such as a policy decision). Numerous tools can be used for the implementation of an object-oriented modeling approach, and the VENSIM is used in the present paper. The paper adopts the concepts of SD such as stocks and flows to define objects in an OO-SD model. The whole watershed is regarded as a system which comprises of sub-basins as its sub-systems. In the context of an OO-SD modeling, the key concepts within the sub-basins, both physical and conceptual, are addressed as objects using stock and flow variables to represent them. The other characteristics associated to the objects are considered as their attributes represented in terms of stock and flow variables as well. Causal loop diagrams (CLDs) will be applied to visualize the causal relationships among the system objects and attributes. The CLDs also serve as effective means to enhance understanding of physical processes and dynamic mechanisms in the system under study. Although the OO-SD approach has been widely appreciated in the fields of social studies, economics, industrial engineering, and urban planning, the area of water resources has not benefited enough from this modeling approach. The paper aims to show the application of an OO-SD approach in IWRM to model a watershed hydrological system. The application will be illustrated using an example from an Iranian watershed.

Key Words: Conservation, Drought, Drip Irrigation, Water-Saving Technologies

Introduction

It has always been a big challenge to address the consequences of human activities on natural complicated systems. The problem will be more severe among developing nations due in part to their rising populations, developing economies, and facing with new complexities. Usually, watersheds are the major vulnerable units which will influence the sustainability of the ecosystem, specifically from the view point of water resources and the hydrological system. Different types of hydrologic models are in use which can be classified in different categories based on their capabilities, complexity, scale, resolution and preciseness. Management of water resources is concerned with developing, controlling, regulating and beneficial application of water resources. In more details, management goals might be categorized in four major divisions: improvement and development of water supply from water resources, protection and prevention of water pollution, make the best uses of water for recreational, navigation and hydroelectric power generation, reduction of damages due to drought and flood. To achieve these goals in water resources management providing computational models is necessary.

In scientists' and researchers' attitudes mathematical models help to understand the real world phenomena thoroughly. Many of water specialists and decision makers agree with Wurbs (1994) that mathematical models play an important role to provide necessary quantitative information to make the best possible decisions in the real world of water management. Within these models some are used in a watershed scale to accomplish the conversion of precipitation value to runoff discharge.

The watershed approach is a coordinating framework for integrated water resources management (IWRM) that focuses on public and private sectors' efforts to address the highest priority problems within hydrologically defined geographic areas, taking into consideration both ground and surface water flow in a watershed level. Therefore, watershed modeling lies at the center of water resources planning and management.

Watershed models are usually applied to convert the rainfall input to a runoff output. Furthermore, other elements and components (as secondary issues) are also taken into account when analyzing a system. Those models are also used to estimate the amount of water out flowing from the hydrological units.

Watershed models can be mainly categorized to single event and continuous models. Continuous models are grouped into two major classes including models concerning the quality of water and those which address only water (runoff) quantity. A review of hydrological models is presented in Table 1.

Table 1- A review of hydrological models

Hydrological models	Capabilities/ Facilities
HEC- 1:	Computing the runoff from rainfall for a single precipitation, economic analysis of flood damage, optimizing flood control systems
TR-20:	Computing the direct runoff hydrographs of a rainfall, modeling complex watersheds with multiple sub areas, channel reaches, and reservoirs
MIKE SHE:	Computing snowmelt, canopy interception and evapo-transpiration, overland flow, saturated zone flow and unsaturated subsurface flow
SWM-IV:	Computing water budget for different hydrological processes such as interception, infiltration, evapo-transpiration, overland flow and channel routing
SWMM:	Single event or continuous simulation, simulating the quality of storm water runoff both hydrologically and hydraulically
HSPF:	Computing Hydrographs and Pollutographs of streams, simulating interception soil moisture, surface runoff, interflow, base flow, snow pack depth and water content, snowmelt, evapo-transpiration, groundwater recharge, assessing the effects of land-use change, reservoir operations, point or non point source treatment alternatives and flow diversions
SWAT:	Assessing the impacts of management actions on hydrology, water quality and sediment generation on an ungaged watershed
Storm Drain:	Analyzing complete storm sewer network in the case of steady state or transient flow condition
GSSHA:	Analyzing surface runoff, channel hydraulics, groundwater interaction, water quality and sediment transport

Though addressing different aspects of water resources problems, the prevalent hydrological modeling approaches are seldom capable enough to take into account interactions among the components of system under study. In addition, there are socio-economic mechanisms that influence hydrological processes which cannot be normally captured through the traditional engineering modeling tools due to their reliance on a linear thinking philosophy.

Based on a systems thinking philosophy, this paper aims to adopt an object-oriented approach based on the concepts of SD to analyze the dynamics in a hydrological system in a watershed scale. SD is a methodology which is capable of considering all interactions between elements of a system. Software packages based on SD have been extensively used in the fields of simulating businesses, organizational systems, simple engineering and scientific systems. SD models are built using three principal elements (stocks, flows, and converters), and emphasizes on understanding the feedback structure of systems.

The Systemic Approach

Water Resources problems are complicated due to their role in the society context, so a kind of tool is needed to be capable of dealing with complexities.

SD modeling is one of the simulation techniques which extend our findings of natural and water resources systems. This methodology allows the modeler to learn about the behavior of the system through considering primary, major parts and principal relationships between different parts of the system.

The Knowledge of system analysis has shown to be more helpful since water resources problems have been becoming more and more complicated.

This approach has been initiated since 1950, when a group of different specialists on various fields gathered together to solve their problem on water resources planning at Harvard University (Nandalal, 2003).

1. The Methodology of Object Oriented (OO) Modeling

OO modeling is a way of organizing systems, whether they are natural or artificial. It is a way to organize data into discrete, recognizable entities called objects. These objects could be concrete (such as a river reach) or conceptual (such as a policy decision).

In every system to benefit this method, the first job is identifying different key parts and primary components of the system. In the OO methodology systems are considered as a set of collaborative objects.

The Objects capable of changing their states spontaneously are called "Active Objects" (Aboelata, 1998). According to his definition each object is distinguished from the others by its properties. He categorized objects into three forms:

Actor: an object that can affect other objects but is never affected by any object, (in SD it is known as the external or exogenous variable).

Server: an object that can never affect but is affected by other objects,

Agent: an object that can affect and be affected by other objects, (the last two definitions correspond to the internal or indigenous variables in SD).

Each object sends its response function to the object in connection with through connectors.

2. Different Kinds of Object Oriented Methodologies

As many other modeling approaches, OO has an especial language for analyzing and designing different systems and a modeler chooses a language to study and analyze the issue based on the problem under investigation and his/her preferences.

The Unified modeling language (UML) is used for OO modeling. Indeed, it is a kind of graphical explanation (notation) for identification, realization and documentation of a system. Using the UML will help complex systems and their complicated processes to be more easily understood (Bednář, 2004).

This approach requires 3 kinds of diagrams to be constructed:

1. The "Class and Package diagrams" consisting of different variables and functions. Functions, indeed, define the relation between variables of a class. They are also known as data members and member functions. Objects are recognizable when a class is used in a case of a real component in a system, which will form a static state of the system.
2. A "Dynamic structure" demonstrates the behaviors of different components in a system. These structures are known as sequential or collaborative diagrams (Ichikawa, et al., 2000, Bednář, 2004).
3. Finally a "Functional structure" which is a representation of objects variation over the time (Tisdale, 1996).

Some models are Also constructed based on programming languages such as FORTRAN, C ++ and Java. These are called procedure oriented languages. When objects and their attributes and relations are defined in a system dynamic context, Object Oriented modeling based on SD will then be established. Besides all characteristics which are possessed by different kinds of OO modeling, a more understandable view of a system and interactions will be provided in this method.

3. An Object Oriented Approach Based on the System Dynamics concepts (OO-SD)

Since hydrological systems are generally considered to be interactively related in a watershed scale, an OO approach in combination with SD has been adopted to reflect the dynamic nature of different attributes of each object in a system.

In the context of an OO-SD modeling, the key concepts within a basin, both physical and conceptual, are addressed as objects using stock and flow variables to represent them. The attributes of objects are also represented in terms of stock and flow variables as well.

Causal loop diagrams (CLDs) will be applied to visualize the causal relationships among the system objects and attributes. The CLDs also serve as effective means to enhance understanding of physical processes and dynamic mechanisms in the system under study.

AN OO modeling based on SD in water Resources Systems

The OO methodology has been introduced since 1990s; however, its different varieties have been being developed till now (Kiker, 2001). Although they are different in implementation, all the methodologies are underpinned by a common main idea.

Tisdale (1996) represented the hydrologic systems of south Florida using an OO analysis. In this work, he clarified the objects and interactions of different components within the hydrologic system, though, no model was run.

Aboelata (1998) has introduced an OO modeling in his thesis. He has considered five water use sectors, consisting of agriculture, industry, domestic, navigation, and power generation, in his model, which is a flexible planning tool for the Egypt's water resources system. Above mentioned sectors have been modeled separately and then were integrated into a single model. He has divided surface water into three classes: Rivers, lakes, and control structures. Every class is divided into different divisions, e.g. for the case of surface water the other classes are introduced and the attributes of each class and the relations between different objects are defined.

Belkhouche et al (1999) presented an OO water quality software system using C language programming. In their model, a framework was shown to develop a software system to analyze water quality of river ecosystems.

Using an OO design approach and the C^{++} programming language, Wang et al (2005) defined hydrologic processes in a watershed scale.

Elshorbagy (2006) has applied an OO modeling in a system dynamic context to manage the water quality in Kentucky in the US. Martinez (2008) applied an OO programming using java language to model shallow water table environments.

An illustration of the Object Oriented modeling Methodology

To show the capabilities and application of OO- SD in IWRM, a hydrological model using OO- SD will be developed for analyzing the rainfall- runoff mechanism in Mehran Basin in the southern part of Iran. This modeling procedure aims to achieve the following objectives:

1. identification of major elements of the system
2. determining the classes and ascertaining the attributes of each class
3. Instantiation (Tisdale,1996) and clarifying the relationships between different objects
4. Simulation of the process

In this illustration, the whole watershed is regarded as a system which comprises of sub-basins as its sub-systems, and hydrological processes such as rainfall, runoff, infiltration and evaporation. As other entities, objects are characterized with different attributes.

Components and elements of a system are embedded in a class structure. In a watershed system, there are crucial entities which are active to convert the rainfall to runoff. In this illustration the key components are chosen as objects represented by Stocks and flows (Elshorbagy & Ormsbee, 2006). The classes in a watershed system can then be defined as: Sub basin, Inflow of rainfall, Outflow, infiltration, and Evaporation.

To instantiate these classes and construct the objects of model, attributes of each class are assigned. In the present paper, the attributes of one object (sub basin) is allotted and for the other objects which are similar, the inheritance rule will be applied. In the following steps the research focuses on elucidation of the main model, clarifying the object structure of a sub basin, and finally illustrating its functionality using an example.

Water cycle or hydrological cycle is a set of motions and cycling processes which occur in three different layers of the earth consisting of: atmosphere, lithosphere, and hydrosphere. Although water cycling forms a closed cycle considering the world as a whole, in a watershed it is not a closed system. Thus, to meet the principle of mass balance some part of the water flowing through a watershed should be considered as the basin storage volume ($I – O= \Delta S$, where I and O represent inflow and outflow respectively and ΔS is the amount of water stored in the system). This principle underpins the hydrological model introduced in this research.

To analyze the mass balance for the hydrological system of a specified basin using SD, it is essential to consider the system key elements which are: precipitation, runoff, evapo-transpiration, interception, infiltration, and surface retention inside the basin. Precipitation creates the total amount of water available on the surface of watershed; and the interaction between the existing surface water and the runoff makes a balancing loop. Moreover, the interaction between existing surface water and infiltration will create a balancing loop.

When the water capacity of soil is saturated, the infiltration rate will then remain at a constant discharge, that means the relative moisture percentage of soil and infiltration will create a balancing mechanism with a goal seeking behaviour.
Interception, on the other hand, causes a delay in the system, while, it will finally lead in the system water loss through evaporation and infiltration. In this paper, all types of water outflow in terms of evapo-transpiration, interception, and surface retention are aggregated into a single variable named as water loss.

In contrast to prevalent models in hydrology, the adopted modelling scheme is capable of incorporating any other mechanisms and parameters and their feedbacks affecting the main process of hydrological cycle through adding relevant sub-systems. That scheme is demonstrated in terms of a causal loop diagram in Fig. 1.

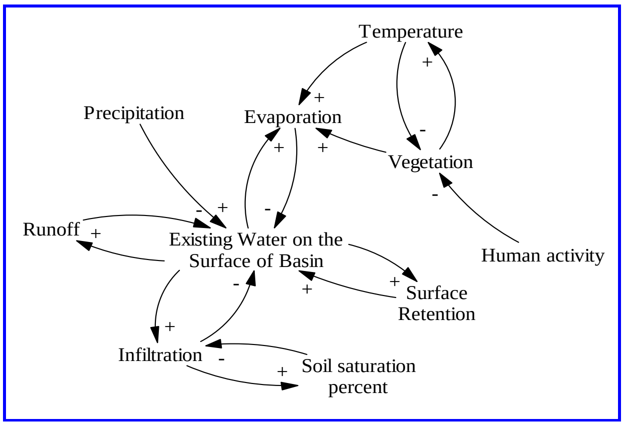

Figure 1- The Casual Loop Diagram of a Sub basin

It is obviously shown that analysing a water resources system in a watershed scale is a challenging task without the help of SD, and it is the capability of a SD methodology which allows for a clear, exact and easy designation of a system at the same time.

To test and examine the structure, behaviour, and functionality of the model, it is run in Vensim. The steps of model development are explained in the following paragraphs.

The process of designing the model structure is presented in 5 stages:

Stocks and Flows define classes composing the system and the relation between these classes is shown by equations. At First, different classes and their associations which are important in this study are introduced and then the objects, relations, and behavior of the system as a whole will be investigated in an example.

1. Here Precipitation is the only source of water available in the basin, and composes the runoff inflowing into Bed River (Fig. 2). As it is shown any new module such as Social, Economic and Political strategies can be added to the system. Indeed, these mechanisms affect the system behavior by altering the runoff (Fig. 2), infiltration (Fig. 5), or evaporation rate (Fig. 6).

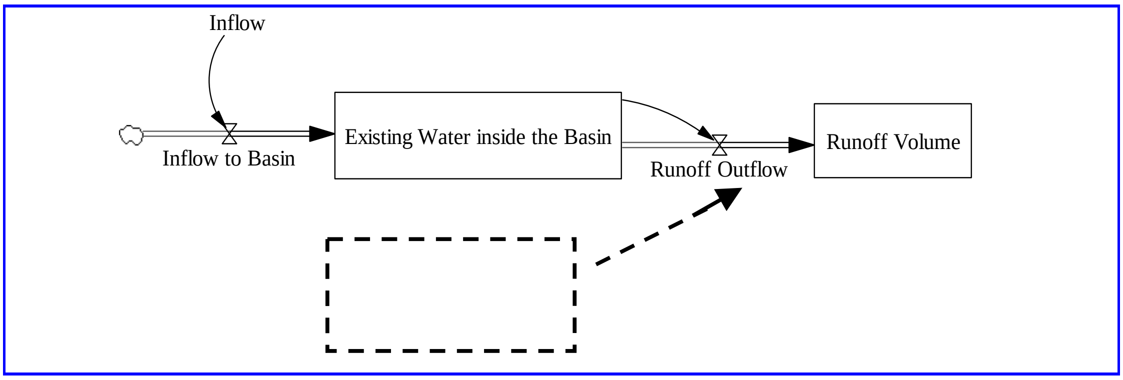

Figure 2- The structure of Rainfall- Runoff and Water Volume

2. To calculate the Runoff coefficient the volume of precipitation is needed. A Co-Flow structure is used to estimate the runoff coefficient (Fig. 3):

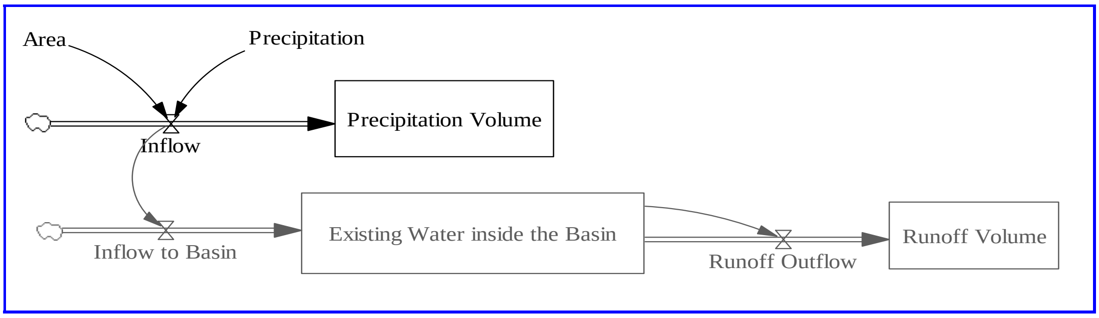

Figure 3- The Co-Flow structure of Precipitation and Inflow to the Basin

3. Runoff coefficient is calculated for each Time Step in this model. C is considered as an Object which is a coefficient to determine the outflow from the Existing water inside the Basin and is a time varying coefficient. The final amount of C clarifies the runoff coefficient. On the other side, the amount of Runoff Coefficient at each time step plays its role in calculating the Evaporation coefficient for each time step which will be explained later (Fig. 4) :

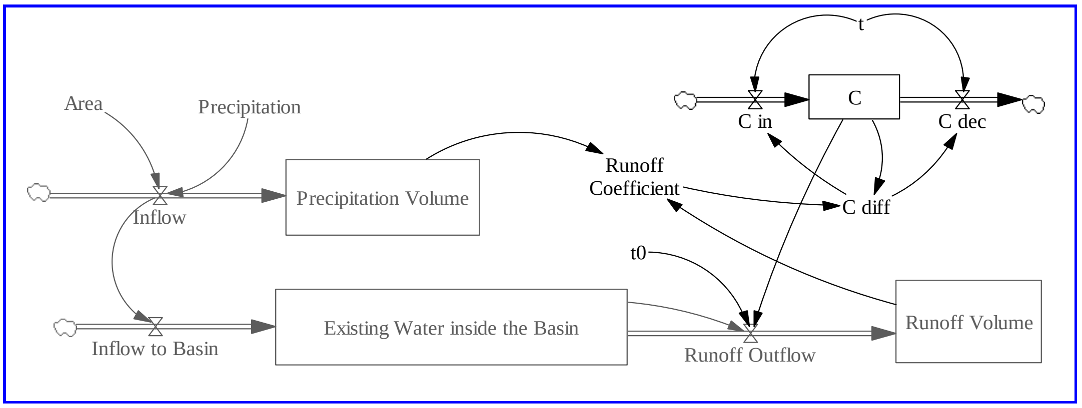

Figure 4- Precipitation- Runoff Coefficient association

4. To calculate the infiltration rate, the amount of water entering the ground is determined according to the saturation condition of soil, as the amount of infiltration associates inversely with the saturation degree. This point is used to identify a lookup function for infiltration which is a dependent variable of saturation degree. Soil Porosity, Maximum water capacity of soil and Soil Water Content are the key factors in calculating the soil saturation degree (Fig. 5):

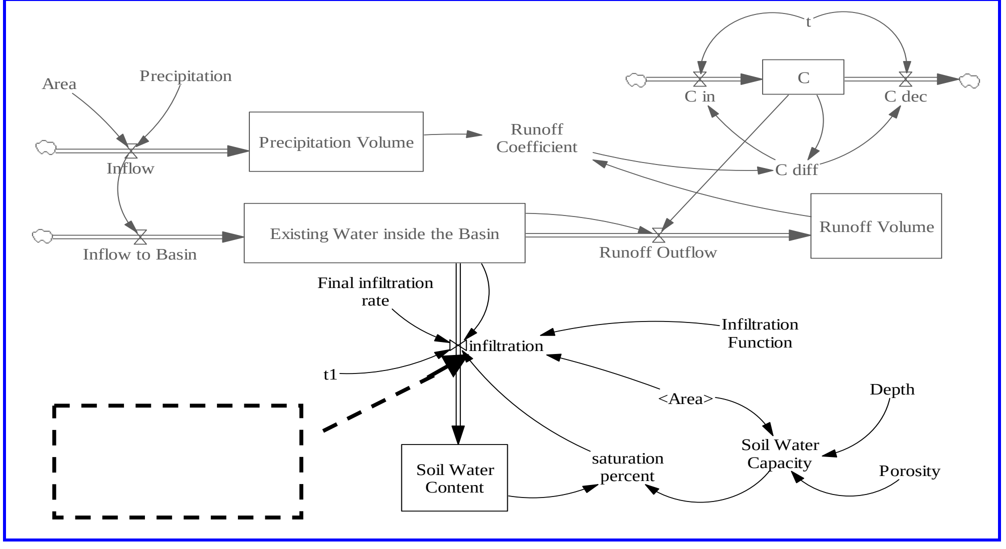

Figure 5- Infiltration in a hydrologic system

5. The amount of evaporation is a fraction of Existing water inside the Basin which is estimated using runoff and infiltration coefficients. The coefficient of evaporation is gained using this equation: "*1- C- Groundwater Coefficient*", Fig. 6.

In the past 5 steps the classes of a sub basin system under investigation were presented to compose the whole structure of the system. In previous steps classes were identified. Using the class structure of a sub basin for the *Mehran River*, the object structure of the problem under investigation will be established. The relation between different classes is determined for the next steps:

The relation between Precipitation and Existing water inside the Basin is indicated by:

Inflow= Precipitation (Time) $\times$ *Area* (M^3*/Second).*

where Precipitation is a time varying variable and is defined using a lookup function of time. So, the accumulative and temporal volume of Existing water inside the Basin is calculated.

Also the relation between runoff and Existing water inside the Basin is under consideration which is written as:

Runoff Outflow= C$\times$*Existing Water inside the Basin/ t0,* (M^3*/Second)*.

where C is considered as a stock and is modified in each step by the following ratio: *(Runoff volume/ Precipitation Volume)*

t_0 is the system delay time i.e. it shows the average time that the surface water takes to pass through the basin outlet .

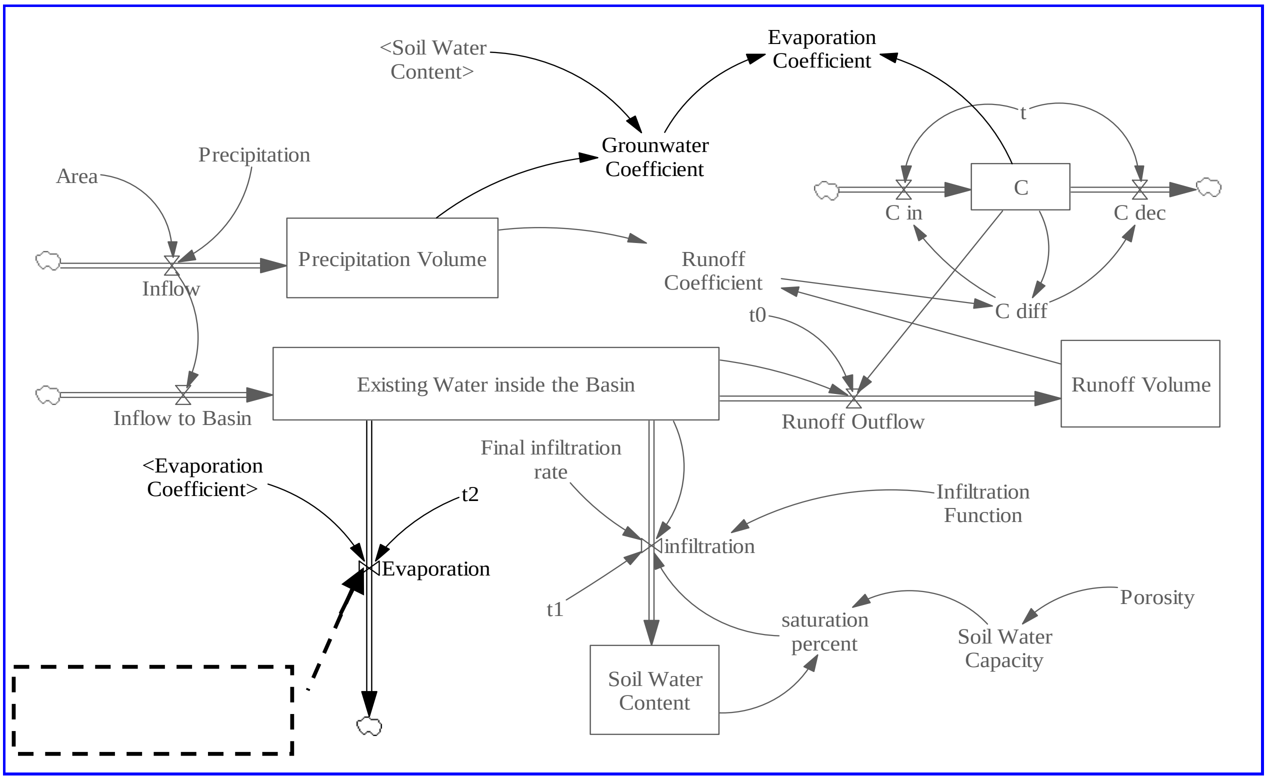

Figure 6- A simplified exhibition of Class structure for a Sub basin

Also for infiltration a conditional statement was used considering the mechanism of infiltration, capillarity and gravity movement of water through the soil. Although the Green Ampt equation is a physical based equation, it is used when the rainfall is monotonous, thus, it has not been applied here. The equation used in the model is similar to that of Horton as follows:

Infiltration= (Final infiltration rate+ Infiltration Function (saturation percentage)/t_1) $\times$ Area, (MM^3/Hour)

Also saturation percent is defined by:

Saturation Percent= (Soil Water Content+ Initial Soil Moisture) / Soil Water Capacity, (Dmnl);

Initial moisture, porosity, and maximum saturation capacity of soil are important elements to achieve the amount of saturation percent which can be written as following:

Saturation percentage= (Soil Water Content+ Initial Soil Moisture)/Soil Water Capacity (Dmnl) and

Soil Water Capacity= Porosity$\times$ Area$\times$ Depth$\times$ Soil Water Potential Capacity (M^3)

The properties of soil are introduced as a lumped parameter in the model.

The evaporation coefficient is a complementary value for runoff and infiltration coefficients, its rate can be written as below:
Evaporation= evaporation coefficient× Existing water inside the basin/t_2, (M^3/Second).

Lag times t_0, t_1 and t_2 are considered for every 3 flows leaving the Existing Water inside the Basin. With respect to saturation condition of the air, delay time for evaporation is assumed equal to the rainfall duration time because during this time the air is supposed to be saturated and the rate of evaporation is considered to be zero.

In this part, a RRM (Rainfall-Runoff Model) is run for a case example in Mehran River in the southern Iran, in Hormozgan Province.

1. Model Verification

The model was verified using the extreme values test. Also the values of parameters and constants were chosen according to the suggested values by hydrological references. The results vary in a logical range.

2. Calibration of the Model

To calibrate this model a set of rainfall- runoff data taken from Dejgan station on Mehran River were used. Calibration of the model parameters was carried on t_0, t_1, and t_2, Final infiltration fate, porosity, and maximum water capacity were achieved for best results of both peak value of runoff and runoff volume. For instance, the amount of t_0 is equal to 1 Hour, t_1= 1 Hour, t_2= 64 Hours, final infiltration rate= 2 mm/Hour, porosity= 0.2 and maximum water capacity of soil= 0.7.

The observed and estimated runoff Hydrographs are shown in figure 8:

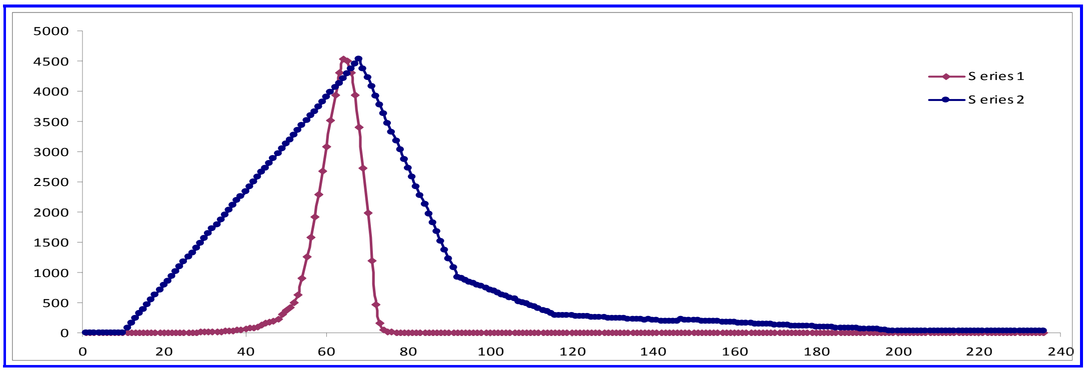

Figure 8- Estimated (Series 1) and Observed (Series 2) Runoff Hydrographs, M^3 /S

Moreover, the rate of infiltration was achieved as is demonstrated in Fig. 9. It is clearly shown that the variation of infiltration during the time follows the general pattern of infiltration of water through the soil.

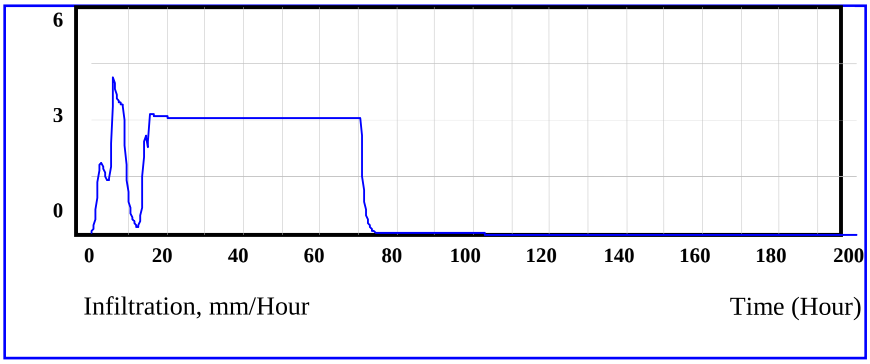

Figure 9 - Infiltration amount, Mm^3 /Hour

Results and discussion

The value of peak flow estimated by the model follows the same as that of the observed data. Also the amount of runoff observed volume is 110 MCM, while that of achieved by the model equals to 203 MCM.

The purpose of presenting such a model is not comparing its capabilities with other programs and environments capable of computing runoff from rainfall events; rather, it is intended to introduce a dynamic paradigm of hydrological modeling capable of incorporation of feedback mechanisms, which can be applicable in integrated watershed management. For instance, it is possible to add any managerial module to such flexible models, while this is not possible in the case of other computer models such as HEC- HMS, MIKE- SHE and SWAT. With the rapid evolution of human ability to change the environment to get the most benefits, this kind of modeling always seems to be as an open model due to its flexibility. In addition, the sufficiency of required data has always been a matter of issue for other computer models to predict the outcomes of different situations. Moreover, OO- SD allows for direct awareness of human different activities impacts on nature and will provide a platform to design strategies to manage the consequences of such improvident behavior of human beings. For instance, the results of changing the land use from agriculture to industry, deforestation and so on affects the vegetation after more or less 1 year, which can be considered when allotting a delay time for such a situation. The aim of this research was only to verify and demonstrate the capability of an OO- SD approach as a suitable methodology to investigate different strategies and select appropriate decisions by adding any artificial modules as a result of human activity in nature.

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