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Modeling of Rainfall-Runoff Relationship in Semi-Arid Watershed in the Central Region of Jordan

Nidal Hadadin

Associate Professor, Department of Civil Engineering, The University of Jordan, Amman 11942
E-Mail: n.hadadin@ju.edu.jo

ABSTRACT

As a result of quick progression in computer and information technologies, computer modeling has become a vital tool in watershed research and management practices. Stanford Watershed Model (SWM) is an integrated physically based Watershed model that can be used to simulate water flow stream/canal network and overland runoff, interflow and evaporation by considering the interaction between surface water and sub-surface water. The objective of this study is to apply the SWM in order to estimate the rainfall-runoff relationship for Wadi Wala streamflow semi arid area with an average annual rainfall of about 300 mm/yr and a catchment area of 1800 km^2. SWM has been widely accepted as a tool to synthesize a continuous hydrograph of hourly or daily streamflow. Sensitivity analysis, as well as trial and error adjustment techniques were used for the optimization of the number of parameters of the model. Comparing estimated and measured surface runoff for Wala valley indicated that the model is considerably efficient in predicting the total annual surface runoff from rainfall for similar watersheds.

KEYWORDS: Watershed modeling, Watershed hydrology, Rainfall-runoff relationship, SWM, Jordan.

INTRODUCTION

Hydrological models can be classified into two categories: deterministic models and stochastic models. Deterministic hydrological models can be further classified into three main categories on the basis of the spatial representation: empirical models, lumped conceptual models and distributed models. Empirical models, also called black box models, treat watersheds as a single unit where the parameters and the input do not vary spatially within the basin and the basin response is evaluated only at the outlet. The lumped conceptual models, also called grey box models, use physically sound structures and equations together with semi-empirical ones (Refsgaard, 1996).

Several models have been developed to estimate runoff at different comprehension levels and based on different numerical approaches using computer technology. Among these models, some emphasize water quantity, while the others focus on water quality. However, the increasing water resource problems and the recognition that the interactions of different components of hydrologic processes sometimes play an important role require more comprehensive management of water resources. An integrated description of the entire land phase of the hydrological cycle and an integrated description of water quantity, quality and ecology improved tools based on resonance scientific principles and efficient technologies are necessary to predict the relations among different hydrological variables.

It is necessary to estimate the parameters from

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calibration which is perhaps one of the key disadvantages of this type of models from the computational point of view (Yeh et al., 2006). Examples of physics-based watershed models can be found in Van der Kwaak (1999) and Yeh et al. (2006). Many researchers have compared the different categories of models in various conditions (Boyle et al., 2001; Carpernter and Georgakakos, 2006; Koren et al., 2004; Refsgaard and Knudsen, 1996). Their comparison indicated that distributed hydrological models, sometimes even without calibration (Shah et al., 1996), performed better than empirical and conceptual models in their studies.

Watershed models range widely in terms of complexity. Some are nothing more than simple empirical equations; others perform a complex accounting of soil moisture and water in various stages of runoff. Hydrological models are divided broadly into two groups; the deterministic models seek to simulate the physical processes in the catchment involved in the transformation of rainfall to streamflow, whereas stochastic models describe the hydrological time series of several measured variables such as rainfall, evaporation and streamflow, involving probability distribution.

In the past several decades, with the tremendous advance and rapid progress of computer technologies, numerical simulation models have increasingly become important and effective tools for tackling a wide range of environmental and resource management issues. Among these many types of models, watershed hydrologic models that simulate the dynamic behavior of significant flow and storage processes generate water balance information (quantity and associated hydraulic characteristics, source and pathway, residence time,… etc.).

When is it necessary and/or desirable to use a watershed model instead of the simplified statistical and empirical techniques? Watershed models are generally required when an entire hydrograph is desired, when analyzing complex areas or when the past or proposed future watershed response functions are changing. Watershed models are particularly desirable when analyzing the effect of various water management schemes.

The Institute of Hydrology model, essentially a research tool, has several different forms and can be applied over hourly or daily time periods. Although graded as a simple model, it pays particular attention to the complexities of soil moisture storage, which it represents in several layers. In addition to numerous reported studies at the Institute of Hydrology, a modified form of the model was used to investigate the effects of change in land use on East African catchment (Blackie, 1972).

The Lambert model, developed in the former Dee and Clwyd River Authority essentially for small upland catchments, was the forerunner of DISPRIN for the Dee Research program and has proven to be simpler to operate in practice (Lambert, 1969).

HYSIM, developed by Manley and used in the Directorate of Operations of the Seven Trent Water Authority, is one of a suite of programs for hydrological analysis and provision of information for design and operational purposes (Manley, 1975).

It operates mainly on daily values of areal rainfall and potential evaporation and produces daily values of streamflow, but the time period can be flexible. It may be used for the extension of flow data records and data validation, real time flow forecasting and flood studies and modeling of groundwater. It has also simulated successfully daily and monthly flows on ungaged catchments.

The Boughton model for small-or medium-sized catchments was originally developed in Australia for assessing water yield from catchments in dry regions (Boughton, 1966). Hence, its immediate concern was with quick runoff. Murray (1970) modified the model to include a delayed response interflow and baseflow and applied it to the Brenig catchment in North Wales as part of the study program carried out by the Water Research Association in the late 1960s. The model operates on daily rainfall and evaporation to produce daily runoff (Singh, 1995).

By the early 1970's Crawford and Linsley had founded Hydrocomp, and SWM was expanded and refined to create the Hydrocomp Simulation Program (HSP), which included nonpoint load and water quality simulation. The water quality code was based on work by (Lombardo, 1973). This program was used efficacy of quantity/quality simulation programming running on large basins.

Stanford Watershed Model (SWM)

SWM has been widely accepted as a tool to synthesize a continuous hydrograph of hourly or daily streamflow. A great variety of data is fed into the Stanford Watershed Model, which is usually programmed to produce daily river flow. Provision is made for dealing with snowmelt and, incorporating particular impervious areas the model can be applied to urban studies (Crawford and Linsely, 1966). This model was applied on Wadi Wala (Catchment area 1800km^2), which has good records of precipitation and runoff data. SWM was used to simulate portions of the hydrologic cycle, hourly and daily precipitation, daily temperature, daily surface runoff and characteristics of the watershed area, and several hydrologic parameters are required as input data to the simulation model. The aforesaid data is available in the Water Authority of Jordan (WAJ). The output of the model is the daily and monthly runoff. This information is very essential as input data for hydraulic structure design.

Study Area

The study area is located in a semi-arid zone, which is considered a dry area, with about 100-300 mm average annual rainfall as shown in Fig (1). The runoff is basically generated by thunderstorm (flash) floods which are generally characterized by infrequent, high intensity and short-duration floods and happens only in winter seasons.

Wadi Mujib is the largest tributary on the eastern side of the Dead Sea with a total drainage area of 6,600 km^2, including the Wadi Wala catchment as shown in Fig. 2. The climate is semi-arid to arid, with cold, rainy winters and hot, dry summers that often marked by drought. The average annual precipitation is 154 mm and ranges from 300 mm in the northwestern part of the watershed to 50 mm or less in the southeastern corner. Most of the precipitation occurs in the rainy season from October to April. The average annual potential (pan) evaporation is 2,200 mm (Dead Sea Water Mass Balance Model, 2011).

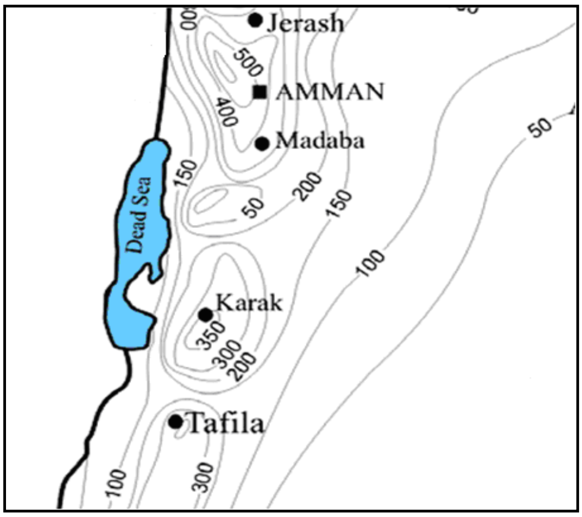

Figure (1): Average distribution of long-term (1938-2005) rainfall in Jordan (after WAJ and Meteorological Department)

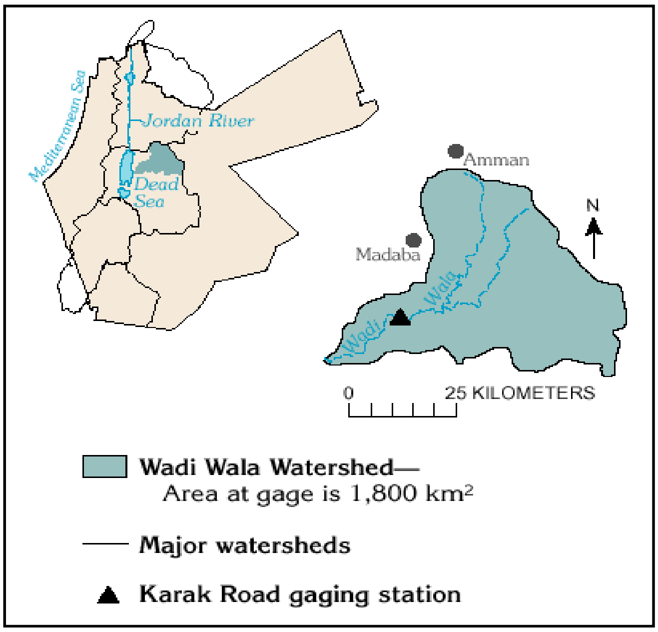

Figure (2): Catchment area of Wala streamflow

Available Data

Meteorological Data

1) Rainfall Data

All the rainfall stations have been registered and named by the agencies concerned in accordance with the drainage systems. There are 12 rainfall stations in Wala watershed. Most of these stations have been operating for periods up to 20 years. The rainfall records for these stations consist of a few thousands of autographic charts. The personnel of Water Authority of Jordan (WAJ) reduced the mass curves on the recording charts to monthly abstracts presenting the data as hourly precipitation.

2) Evaporation Data

WAJ and the Meteorological Department have operated 4 evaporation stations in the area. 10 evaporation pans of US Weather Bureau class–A have been installed and observed in and around the study area since 1960.

3) Other Meteorological Data

Other meteorological data such as air temperature (daily maximum and minimum) and sunshine hours are observed at the meteorological stations operated by the Meteorological Department since 1962.

Hydrological Data

1) Existing Water Level/ Discharge Record:

Water level and discharge stations at four gaging stations: Wala stream at Kings Highway (Wala at upstream), Wala stream at weir (Wala at downstream), Swaqa at Desert Highway and Wadi Mujib at Kings Highway, are operated by WAJ.

2) Baseflow

Springs and groundwater runoff maintain perennial baseflow in the Wala stream. Its value decreases sometimes because of infiltration into deep aquifer.

3) Runoff Coefficient

Flood runoff feature in the basin is small, since most of the rainfall evaporates. According to WAJ, runoff ratio ranges from 4% in the desert area to 15% in the northern and western parts of the study area.

Present Approach

Crawford and Linsley (1966) designed a digital computer program to simulate portions of the hydrologic cycle for an entire watershed. This program has been widely accepted as a tool to synthesize a continuous hydrograph of a daily streamflow at a watershed outlet. Hourly and daily precipitation, daily temperature and a variety of watershed parameters are the input data. By the early 1970's the developers of SWM expanded and refined SWM to create the Hydrocomp Simulation Program (HSP), which also included general nonpoint source loadings and water quality simulation capabilities.

Incoming rainfall is distributed among interceptions, impervious areas such as lakes and streams and water destined to be infiltrated or to appear in the upper zone of the soil as surface runoff or interflow, both contributing to the channel inflow. Infiltration and upper zone water eventually percolate to lower zone storage and to groundwater storage. The lower zone is responsible for long-term infiltration and groundwater storage later released as baseflow to the stream. The total streamflow is a combination of overland flow, groundwater and interflow. Hydrologic fundamentals are used at each point to transform the input data into a hydrograph of streamflow at the basin outlet.

Model Structure

SWM is made up of a sequence of computation routines for each process in the hydrologic cycle (interception, infiltration, routing,… and so on). All the moisture originally stored in the watershed or input as precipitation during any time period is balanced in the continuity equation. The Stanford Water Model utilizes a hydrologic watershed routing technique to translate the channel inflow to the watershed outlet. The change in storage in each zone is calculated as the difference between the volume of inflow and that of outflow.

Rainfall Analysis

S.W.M program required hourly rainfall depth, daily streamflow daily maximum and minimum temperature (F^o) as input data in order to simulate the synthetic streamflow. Hydrologic simulation combines the physical characteristics of the watershed and the observed meteorological data series to produce the simulated hydrologic response. SWM simulates runoff from four components: surface runoff from impervious areas directly connected to the channel network, surface runoff from pervious areas, and interflow from pervious areas, and groundwater flow. Because the historic streamflow is not divided into these four units, the relative relationship among these components must be inferred from the examination of many events over several years of continuous simulation.

A complete hydrologic calibration involves a successive examination of the four characteristics of the watershed hydrology, these are: annual water balance, seasonal and monthly flow volumes, baseflow, and storm events.

Simulated and observed values for reach characteristic are examined and critical parameters are adjusted to attain acceptable levels of agreement. The annual water balance specifies the ultimate destination of incoming precipitation and is indicated as: Precipitation - Actual Evapotranspiration - Deep Percolation - Soil Moisture = Runoff

SWM requires input precipitation and potential evapotranspiration (PET), which effectively "drive" the hydrology of the watershed; actual evapotranspiration is calculated by the model from the input potential and ambient soil moisture conditions. Thus, both inputs must be accurate and representative of the watershed conditions; it is often necessary to adjust the input data derived from neighboring stations that may be some distance away in order to reflect conditions on the watershed.

Trial and Adjustment Parameters

There are some parameters for Wala watershed, which were determined from a topographic map scale (1:100,000). These parameters are shown in shown in Table 1.

Table (1): Topographic map parameters

Watershed drainage area	**AREA**
Average ground slope of overland flow	OFSS
Length of overland flow	OFSL
Drainage density	D
Fractional stream and lake surface area	FWTR
Impervious fraction of the watershed	FIMP
Elevation of catchment above thermometer	ELDIF
Channel capacity	CHCAP
Mean length of overland flow	OFSL

Model verification is not complete without comprehensive sensitivity analysis. Once the calibrated parameters are arrived at by a best fit procedure, sensitivity analysis is performed by holding all parameters constant but one and perturbation the last one such that the variation of the objective function (measure of fit between the observed storm hydrograph and the fitted model) can be examined.

If small perturbations of the parameter produce large changes in the objective function, the system is said to be sensitive to that parameter. This gives a measure of how accurate that parameter must be estimated if the model is to be used in the prediction. If the objective function is not sensitive to the perturbed parameter, then the parameter does not need be accurately estimated in the prediction. If the system is extremely insensitive to the perturbed parameter, the parameter and its associated system components may be redundant and could be deleted from the model.

The results of the sensitivity analysis of the Stanford Watershed Model (SWM) on monthly simulated runoff rates are shown in Table (2).

The successful operation of the Stanford Digital Computer Model relies to a considerable extent on the skilled experience and personal judgment of its operator. Without denying the power and advantages of using engineering judgment and acquired skills, it is likely that the adjustment of the large number of parameters of a more complex model by subjective trial and error procedures is impracticable.

Finding a set of “best fit” parameter values for a given physical system with given input and output data is a frequently met problem in many fields of activity.

The effects of increasing various watershed parameters and coefficients on runoff volume are shown in Table (3).

Table (2). The sensitivity analysis of the Stanford Watershed Model (SWM) on monthly runoff rates

SWM parameter		**Sensitivity of the parameter on runoff volume**
Actual upper zone soil moisture storage parameter	UZS	Quite
Nominal lower zone soil storage parameter (LZSN),	LZSN	Medium
Actual lower zone soil storage parameter	LZS	Medium
Infiltration index	CB	Quite
Interception storage volume parameter	SCEP	Quite
Interception storage parameter	EPXM	Medium
Actual evapotranspiration rate parameter (K3)	K3	Quite
Rainfall adjustment parameter	K1	High

Table 3. The effects of increasing various watershed parameters and coefficients on runoff volume

SWM parameter		**Effect of increasing the parameter on runoff volume**
Index of soil surface moisture storage capacity	SUZC	Insignificant
Impervious fraction of the watershed surface draining directly into the stream	FIMP	Increased
Daily baseflow recession adjustment factor	BFNLR	Negligible
Daily interflow recession constant	IFRC	Insignificant
Overland flow coefficient	OFMN	Decreased
Impervious surface flow coefficient	OFNINS	Decreased
Fractional stream and lake surface area	FWTR	Decreased
Index controlling the time distribution and quantities of moisture entering interflow	BIVF	Decreased
Average ground slope of overland flow	OFSS	Increased
Index of the surface capacity to store water as interception and depression storage	BUZC	Decreased
Index of moisture storage in soil profile above water table	LZC	Decreased
Channel capacity	CHCAP	Negligible
Index of infiltration rate	BMIR	Decreased
Daily baseflow recession constant	BFRC	Decreased

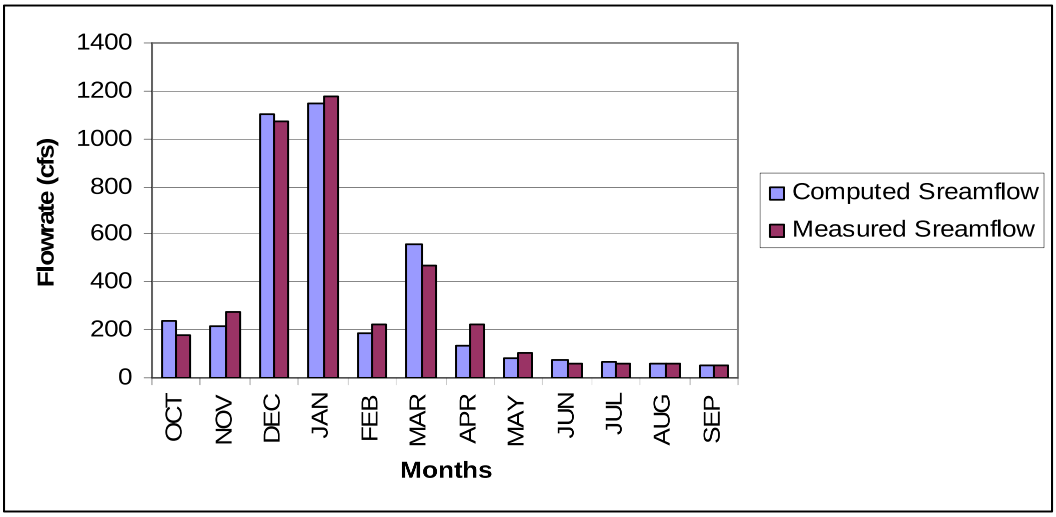

Figure (3): Comparison between monthly totals of synthesized and recorded flowrate for the water year 2003/2004

Output from SWM

Comparison between recorded and synthesized monthly total streamflow is shown in Figures (3) and (4) for the water years 2003/2004 and 1997/1998, respectively.

At first, the SWM is applied on the normal water year 2003/2004. The result shows a good agreement between recorded and synthesized annual streamflow volumes. The summation of annual recorded streamflow is about 3952 SFD and the synthesized stream flow amounts to 3918 SFD, where SFD is 1 ft deep of water over I acre of land. The difference is less than 1%. The sum of the recorded precipitation for the year is about 6.22 in and the synthesized annual evaporation is about 5.55 in. A depth of 0.21 in is discharged as runoff.

The dry year 1997/1998 was adopted using the same parameters. The results show that the annual recorded streamflow is 1933 SFD and the synthesized streamflow is about 1963 SFD. The difference is about 1.6%.

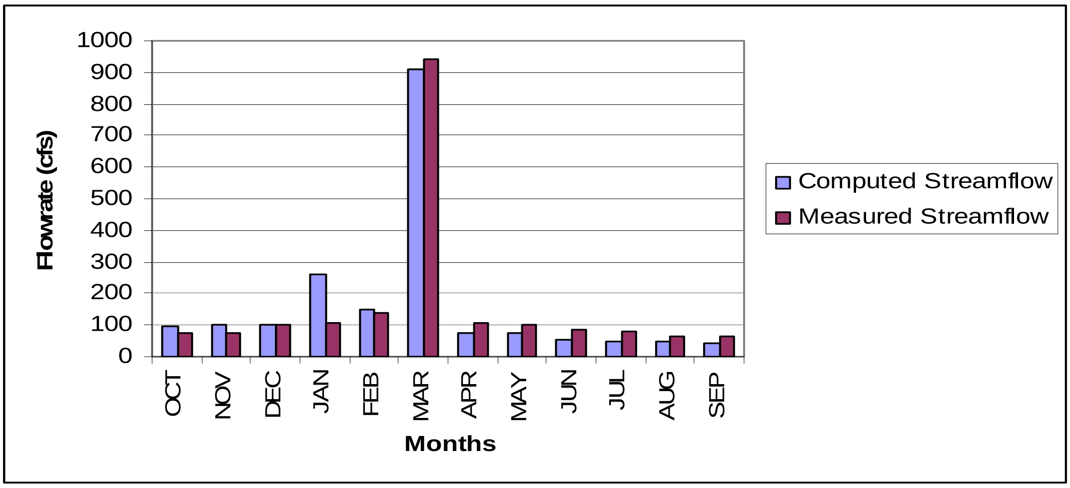

Figure (4): Comparison between monthly totals of synthesized and recorded flowrate for the water year 1997/1998

DISCUSSION AND CONCLUSIONS

Rainfall precipitation is the primary source of water for streamflow runoff. The characteristics of the watershed govern losses within the watershed, and the portion of that precipitation not lost results in surface runoff. Various techniques may be used to relate precipitation to corresponding runoff. These techniques vary in complexity. As a general rule, the shorter the time period of runoff to be simulated, the more complex and sophisticated the model. SWM is one of these complex models. It was applied in this research on Wala Valley Watershed.

The choice of a model is based on the availability of records for a particular watershed. In our study, the relationship between rainfall and runoff is investigated by the aid of a computer program depending on the calibration and optimization of the watershed parameters.

There are some differences between recorded and synthesized streamflows (of course, hydrologic forecasts can not be 100% accurate). There are many sources of forecast errors. The influence of man power plays an important role. The changes due to dam construction on Wala stream cause a heterogeneous catchment area, basic errors in the historic basic data which the values of watershed parameters depend on, disunity in the rainfall pattern and insufficiency in the density in the rainfall station.

This study drew several conclusions, the most important of which are:

1. SWM can be applied to Wala Watershed in order to predict the total annual streamflow and peak flood, since there is good agreement between recorded

and predicted streamflows.

2. It is concluded that SWM will be accurate if it is applied to very small watersheds, where we deal with one rainfall station and one streamflow station and where the variety of characteristics of the watershed (geology, topography, land uses and vegetation cover) is very small.
3. The model can produce results when properly calibrated. The model is difficult to calibrate because of the large number of parameters and the mass of data processing. It was difficult to know the starting values for several parameters, but this should become easier with experience.
4. The data requirements are extensive, both in quantity and in terms of labor necessary for preprocessing.
5. The model is relatively easy to operate in terms of input instructions, file organization and manipulation.
6. The model is best for comprehensive river basin studies requiring analysis of both high and low flows.
7. The model can be used for all sizes of catchment. Where there are data shortages, regional values of the required inputs may be used. The model has been applied to catchments throughout the world and helped with its great flexibility provide hydrological information on problems in civil engineering design and agricultural engineering.

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