Rainfall Runoff analysis of wadis contributing to the Dead Sea

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Introduction:

Flow simulation in ungauged catchments is presently regarded as one of the most challenging tasks in surface water hydrology. Modeling methods have been widely used for a variety of purposes, but almost all modeling tools have been primarily developed for humid area applications. Arid and semi-arid areas which are defined as areas where water is at its most scarce have particular challenges that have received little attention. The hydrological regime in these areas is extreme and highly variable, and they face great pressures to deliver and manage freshwater resources (Wheater et al. 2008). Due to inaccessibility, rugged and inhospitable terrain, and historical lack of foresight concerning the need to have these areas adequately gauged, their potential is not readily realizable. As predictive tools for water resources, water quality, natural hazard mitigation and water availability assessment are generally data-driven; the lack of adequate hydrometric records poses difficult problems (Ouarda, et al., 2003).

Modeling approach, in general, depends on the required scale of the problem (space-scale and time-scale), the type of catchment, and the modeling task. The tasks for which rainfall-runoff models are used are diverse, and the scale of applications ranges. Typical tasks for hydrological simulation models include:

1. Runoff estimation on ungauged basins;
2. Prediction of effects of catchment change, e.g., land use change, climate change;
3. Coupled hydrology and geochemistry, e.g., nutrients, acid rain
4. Coupled hydrology and meteorology, e.g., Global Climate Models

Hydrologic studies to determine runoff and peak discharge should ideally be based on long- term stationary stream flow records for the area. Such records are seldom available for small drainage areas. It therefore is necessary to estimate peak discharges with hydrologic models based on measurable watershed characteristics (Ostrowski, 1990). A problem common to all models is that they all require some degree of parameter calibration to achieve reliable predictions, in which process the model parameters are adjusted until the observed and simulated watershed responses match as closely as possible. Even physically based models usually require some degree of calibration since it is difficult to estimate values for all of the parameters through field measurements. Problems in hydrologic modeling are accentuated further when it comes to prediction in ungauged watersheds, where sufficiently long streamflow time series for parameter estimation via calibration are typically not available.

At the simplest level, all that is required to reproduce the catchment-scale relationship between storm rainfall and stream response to climatic inputs, is a volumetric loss, to account for processes such as evaporation, soil moisture storage, and groundwater recharge, and a time-distribution function, to represent the various dynamic modes of catchment response. This is the basis of the unit hydrograph method, developed in the 1930s, which, in its basic form, represents the stream response to individual storm events by a non-linear loss function and linear transfer function. The simplicity of the method provides a powerful tool for data analysis. Once a set of assumptions has been adopted (separating fast and slow components of the streamflow hydrograph and allocating rainfall losses); rainfall and streamflow data can be readily analyzed, and a unique model determined.

In this study we introduced an alternative, model independent, approach to streamflow prediction in ungauged basins based on empirical evidence of relationships between watershed structure, climate and watershed response behavior. Synthetic unit hydrographs can readily be generated based on default model parameters, which is particularly helpful in data-scarce situations. However, relatively little work has been done to evaluate the associated uncertainty with these estimates. The essential characteristic of such models (data-based approach) is that they are based primarily on observations and seek to characterize system response from those data. In principle, such models are limited to the range of observed data, and effects such as catchment change cannot be directly represented (Goswami, et al. 2007).

Watershed Description

Figure 1 below shows the location map of the Og watershed .It lies on the northwest shore of the Dead Sea and drains eastwards the Dead Sea through Al Og Wadi, extends from the Mountain plateau Eastern Jerusalem to Jordan River valley at the Dead Sea. The area is about 115 km^2 and built up of several small anticlines and synclines. It descends gently from an altitude of 600-700 m in the west eastwards to sea level in the vicinity borders of the Dead Sea.

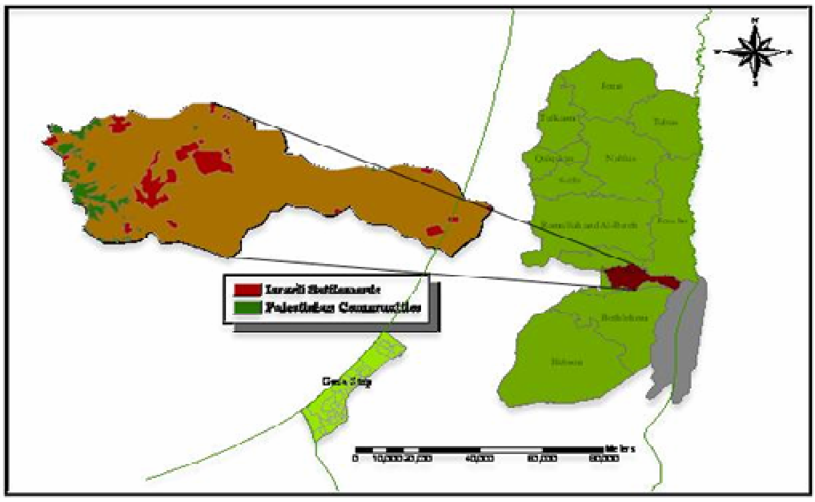


Figure 1: Og Watershed Location

The climate in the Dead Sea Basin varies from annual precipitation in excess of 1,200 mm, to the arid regions of the southern Negev, where annual rainfall averages less than 50 mm. Over the Dead Sea itself, average annual rainfall is about 90 mm and the annual potential evapotranspiration is about 2,000 mm. Actual evaporation ranges from about 1,300 to 1,600 mm. Average temperature is about 40 °C in summer and about 15 °C in winter. Streamflow characteristics change rapidly across the region and closely follow precipitation patterns. The majority of streams flow throughout the rainy season and are dry during the summer. Rainfall decreases eastwards with a high rainfall gradient changes from more than 500 mm to less than 100 mm in the vicinity of the Dead Sea, See figure 2. The Evapotranspiration shown in Figure 3; is a relatively high and increases eastwards. (EXACT, 1998)

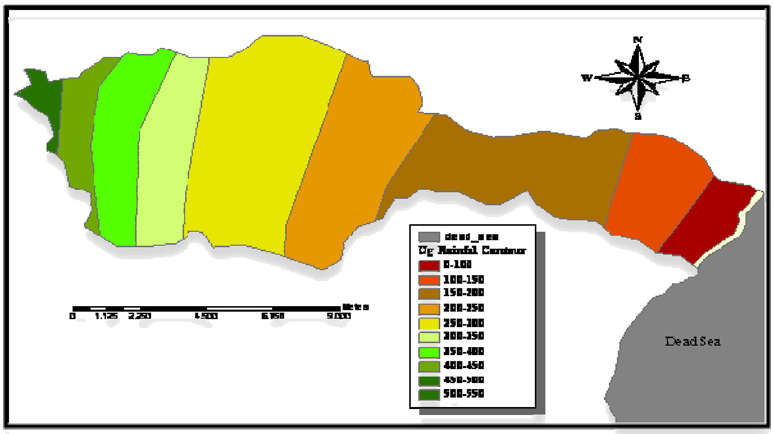


Figure 2: Og Watershed Rainfall Contours

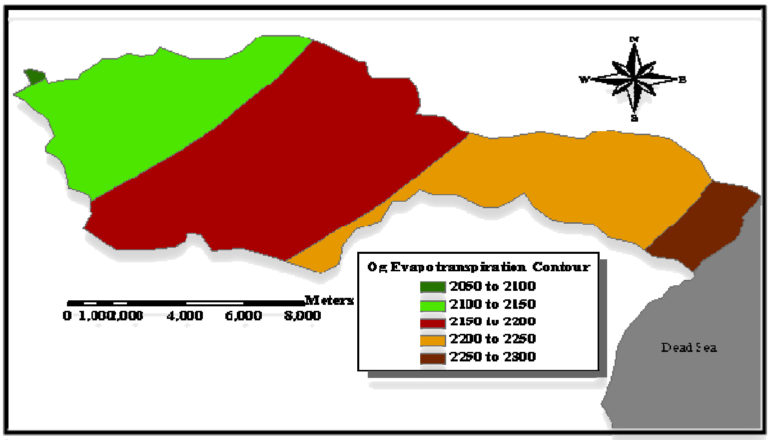


Figure 3: Og Watershed Evapotranspiration

The Land use map of the Watershed was classified into: Palestinian built areas in the vicinity of Jerusalem, Israeli Settlements, arable lands supporting grain, small areas of Forests, and Rough Grazing / subsistence farming. Figure 4 shows land use for the Watershed.

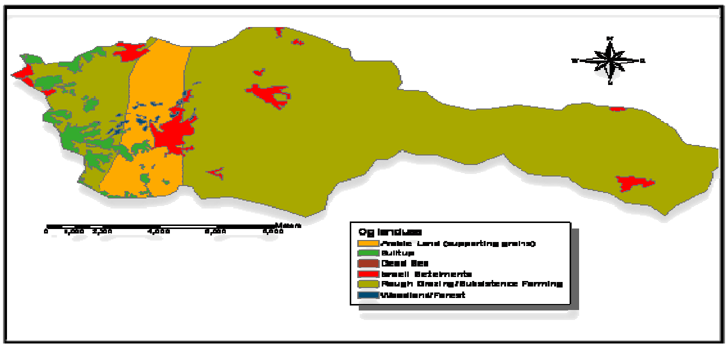


Figure 4: Og Land Use

Figure 5 shows the geology of the Watershed .Cenomanian-Turonian limestones and dolomites are exposed mainly near the fault escarpment facing the Dead Sea.

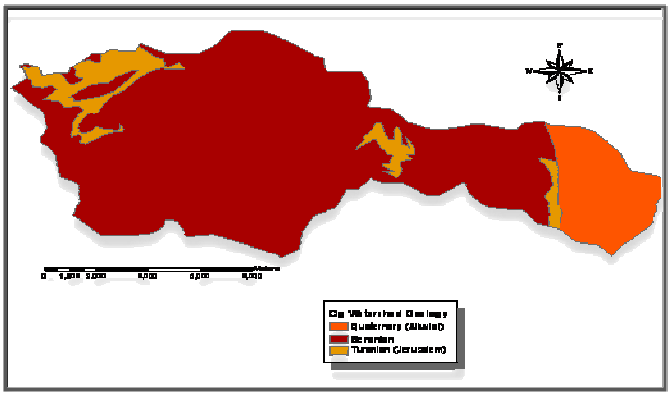


Figure 5: Og Watershed Geology

Soil classifications and characteristics are shown in Figure 6. USDA defined the soil classes according to soil texture as shown in Table 1(USDA, 1986)

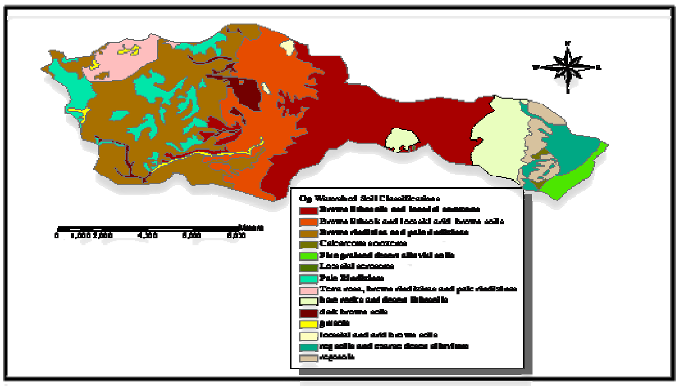


Figure 6: Og Watershed Soil Classification

Table 1: Soil Classes according to Soil Texture

Soil Type	Soil Texture
Regosols	Sandy Loam
Grumusols	Clay
Terra Rosa	Clay
Loessial Seozems	Sandy loam
Brown Rindzianas and Pale Rendinas	Clay loam
Brown lithosols and Loessial Arid Brown Soils	Loamy

The Dimensionless SCS Model

Runoff flow is composed of two main elements: base flow which has its origin in groundwater and surface runoff which is the accumulation of rainfall that drains to the stream. Catchment characteristics that affect baseflow and surface runoff include geology, soil type, vegetation cover, precipitation (magnitude and intensity), drainage area and antecedent moisture conditions (Hammouri et al., 2007). In arid and semi- arid regions, the most important hydrological components during a storm rainfall are the rainfall, runoff and infiltration rates. Since the fact that vegetation cover is not significant in arid regions, evaporation and interception are negligible. Also the surface depression volumes can be neglected since they are comparatively very small. (Sen, 2006)

Runoff is determined primarily by the amount of precipitation and by infiltration characteristics related to soil type, soil moisture, antecedent rainfall, cover type, impervious surfaces, and surface retention. Travel time is determined primarily by slope, length of flow path, depth of flow, and roughness of flow surfaces. Peak discharges are based on the relationship of these parameters and on the total drainage area of the watershed, the location of the development, the effect of any flood control works or other natural or manmade storage, and the time distribution of rainfall during a given storm event. The following information is required to calculate runoff hydrographs for ungauged basins: (City and country of Sacramento Drainage Manual, 1996)

1) Synthetic unit hydrograph: a relationship representing the variation of runoff over time
2) Lag time of the basin : the time required for 50% of the ultimate basin runoff to occur at the basin outlet
3) Unit duration: the duration of the time increment between ordinates of the unit hydrograph
4) Area of the basin

The SCS (Nayak, et al., 2003, Tekeli, et al., 2006, Shadeed, etal., 2008) dimensionless unit hydrograph (shown in Figure7) is a synthetic unit hydrograph in which direct runoff is expressed by the ratio of discharge q to peak discharge q_p, and time is expressed by the ratio of time t to the time to peak T_p of the unit hydrograph. Given a unit excess rainfall for a certain duration D, the direct runoff hydrograph is converted into a triangular hydrograph having the same peak discharge q_p, time to peak T_p and the volume of direct runoff Q as the original hydrograph by calculating the time base T_b of the triangle. The peak discharge q_p, and the time lag T_{lag} (time difference between the centroid of the unit excess rainfall and q_p), the unit hydrograph can be estimated using the synthetic dimensionless unit hydrograph for a given basin. Once the unit hydrograph is produced, it can be applied to estimate direct runoff via the convolution integral of the excess rainfall hyetograph and unit hydrograph. (Wang, et al., 2008)
The SCS dimensionless curvilinear unit hydrograph (Soil Conservation Service, 1972) has its ordinate values expressed in a dimensionless ratio Q/q_p and its abscissa values as t/T_p, where Q and t are discharge and time respectively (Muzik, et al., 2003).

When this hydrograph is represented by an equivalent triangular hydrograph (see figure 8) having the same percentage of volume in the rising side as the curvilinear hydrograph (37.5% of the total volume) the base time (T_b) is equal, from the geometry of the triangle, to 2.67 times the time of rise ($2.67T_p$) (Viessman et al., 2003).

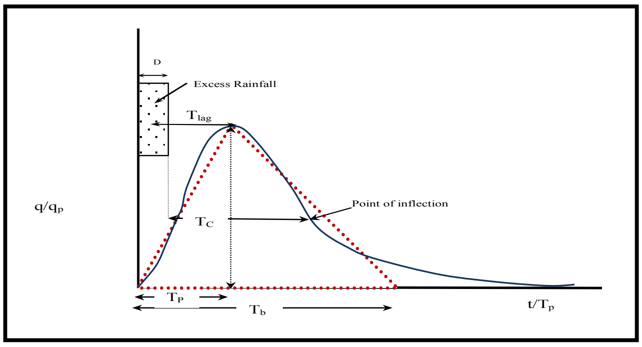
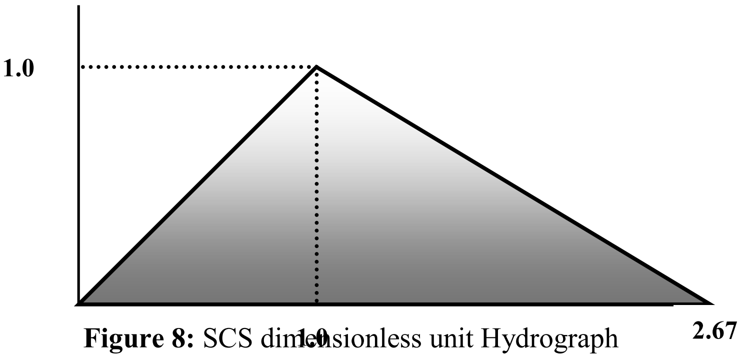


Figure 7: Curvilinear and the equivalent triangular dimensionless runoff hydrograph



$$\frac{Q}{q_p} = \frac{0.749\left(t_p + \frac{D}{2}\right)}{V}$$

$$\frac{t}{T_p} = \frac{t}{t_p + \frac{D}{2}}$$

Figure 8: SCS dimensionless unit Hydrograph

The volume under the triangular hydrograph is

$$V = \frac{1}{2}\, 2.67\, T_p\, q_p$$

Since time to peak is

$$T_p = t_{lag} + \frac{D}{2}$$

Where:

- t_{lag} lag time
- D excess rainfall duration

  The peak discharge

$$q_p = \frac{0{,}749\, V}{\frac{D}{2} + t_{lag}}$$

Where V is the volume under the unit hydrograph
The lag time t_{lag} is a key function for estimating the synthetic unit hydrograph for ungauged watersheds. Since the volume under the unit hydrograph is equal to a unit depth times catchment area, the peak discharge (m^3/s) becomes:

$$q_p = \frac{2.08\, A\, Q}{\frac{D}{2} + t_{lag}}$$

Where:

- A Catchment area (km^2)
- Q Excess unit rainfall (1 cm)

In this expression, the factor 2.08 only applies if the triangular UH has a particular geometry, with 37.5% of its volume in the rising limb and a time of recession equal to 1.67 times the time of rise. This is because the SCS method does not have a unique UH basis; rather, there is a subjective triangular UH that depends on the choice of the CN value (Sen, 2006).

The lag time (t_{lag}) is computed as follows:

$$t_{lag} = 2.587\ \frac{L^{0.8}\left(\frac{1000}{CN} - 9\right)^{0.7}}{1900\ S^{0.5}}$$

Where:

- t_{lag} lag time (hr)
- L hydraulic watershed length m (length of the longest watercourse)
- CN hydrologic area-weighted curve number
- S average catchment land slope (%)

The major factors that determine CN are the hydrologic soil group (HSG), cover type, treatment, hydrologic condition, and antecedent runoff condition (ARC). Infiltration rates of soils vary widely and are affected by subsurface permeability as well as surface intake rates. Soils are classified into four HSG's (A, B, C, and D) according to their minimum infiltration rate, which is obtained for bare soil after prolonged wetting. ARC is an attempt to account for the variation in CN at a site from storm to storm. CN for the average ARC at a site is the median value as taken from sample rainfall and runoff data.

To determine how the runoff is distributed over time the time of concentration (T_C) was introduced by the SCS method as a time dependent factor. The T_C is defined as the time required for a particle of water to travel from the most remote point in the watershed to the point of collection. Normally rainfall duration equal to or greater than T_C is used .Tc is computed as: (USDA, 1986)

$$T_C = 1.67\ t_{lag}$$

And the SCS assumes the duration of excess unit rainfall as follows:

$$D = 0.133\ T_C$$

I_a is all losses before runoff begins. It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. I_a is highly variable but generally is correlated with soil and cover parameters. Through studies of many small agricultural watersheds, I_a was found to be approximated by the following empirical equation: (USDA, 1986)

$$I_a = 0.2\ S$$

S (cm) is related to the soil and cover conditions of the watershed through the CN by:

$$S = \frac{2540}{CN} - 25.4$$

To estimate the amount of excess rainfall (runoff), the SCS Runoff Curve Number (CN) method uses the following runoff equation: (USDA, 1986)

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

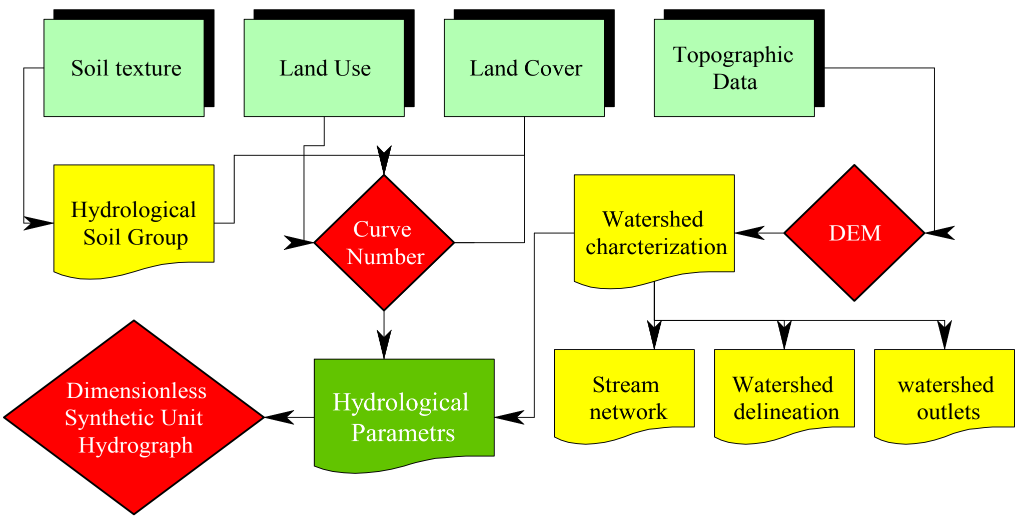
Where:

- Q = runoff (cm)
- P = rainfall (cm)
- S = potential maximum retention after runoff begins (cm)
- I_a = initial abstraction (cm)

The baseflow was assumed to be constant from the beginning of direct runoff until the time of occurrence of peak discharge, and then to increase linearly to the discharge value on the recession limb of the hydrograph corresponding to the cessation of direct runoff (Muzik, et al., 2003)

Input data and Model Application

The following procedure was followed while constructing the dimensionless SCS model; Figure 9 shows the schematic representation of the model.



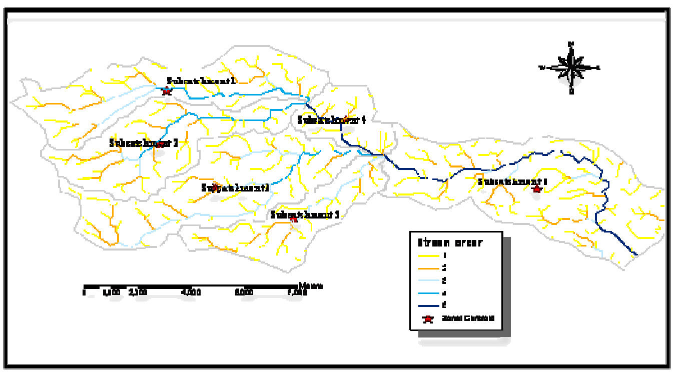


Figure 9: Schematic Representation of the SCS method

(1) Watershed characterization

The first step was preparing the Digital elevation model (DEM) for the Watershed from a contour map of 10 m interval using ArcGIS 3D analyst extension. The watershed was then characterized using the GIS tools.

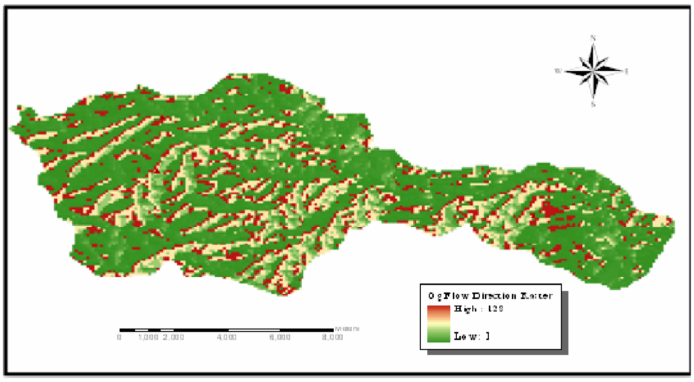


Figure 9: Og Watershed TIN 3D Data

Processing the data available with GIS tools flow direction and accumulation were computed and shown in Figures 10 and 11.

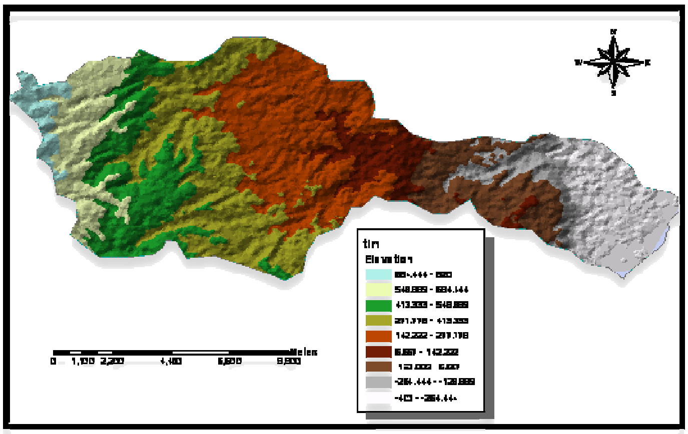


Figure 10: Og Flow Direction

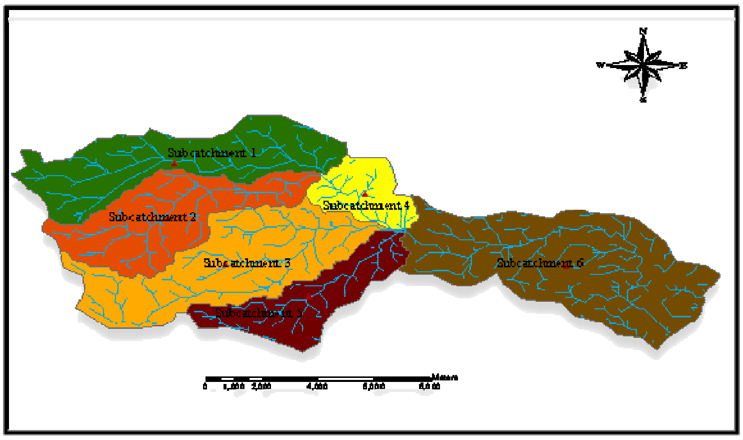


Figure 11: Og Flow Accumulation

The stream network was then delineated and stream order was identified using flow direction and flow accumulation rasters as shown in Figure 12. The catchments was then delineated and divided into sub-watersheds as shown in Figure 13.

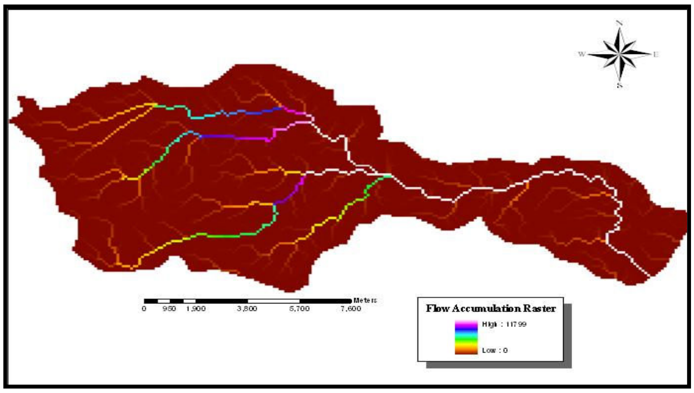


Figure 12: Stream Network

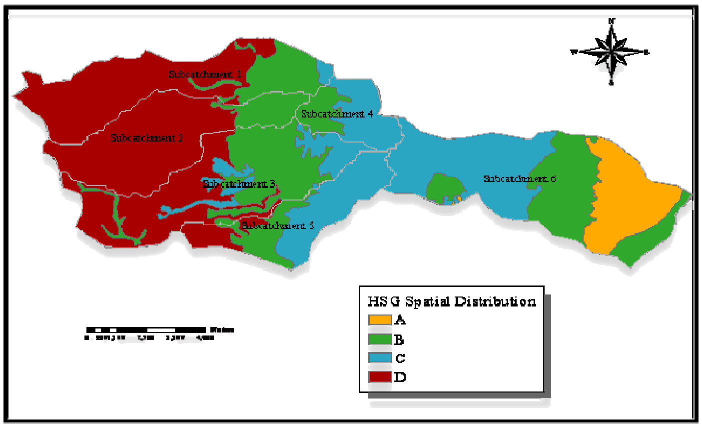


Figure 13: Og Sub-Watersheds Delineation

(2) Curve Number Calculation

According to the soil texture and classifications, the soils were classified into the USDA hydrologic soil groups (HSG's). Soils are classified into HSG's to indicate the minimum rate of infiltration obtained for bare soil after prolonged wetting. The HSG's, which are A, B, C, arid D, are used in determining runoff curve numbers .The infiltration rate is the rate at which water enters the soil at the soil surface controlled by surface conditions. HSG also indicates the transmission rate at which the water moves within the soil which is controlled by the soil profile. The four groups are defined by SCS soil scientists as follows (USDA, 1986):

Group A soils have low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sand or gravel and have a high rate of water transmission.

Group B soils have moderate infiltration rate when thoroughly wetted and consist chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.

Group C soils have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine texture. These soils have a low rate of water transmission.

Group D soils have high runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very low rate of water transmission.

As a result the soil Hydrological groups are classified according to its texture (USDA, 1986) as shown in table 2

Table 2: Hydrological Soil Groups (HSG's) Classifications

HSG	Soil Texture
A	Sand, Loamy Sand, or Sandy Loam
B	Silt Loam or Loam
C	Sandy Clay Loam
D	Clay loam , Silt Clay Loam, Sandy Clay, Silt Clay, or Clay

Soil data for the Og catchment was processed and the HSG's were identified as shown in Figure 14

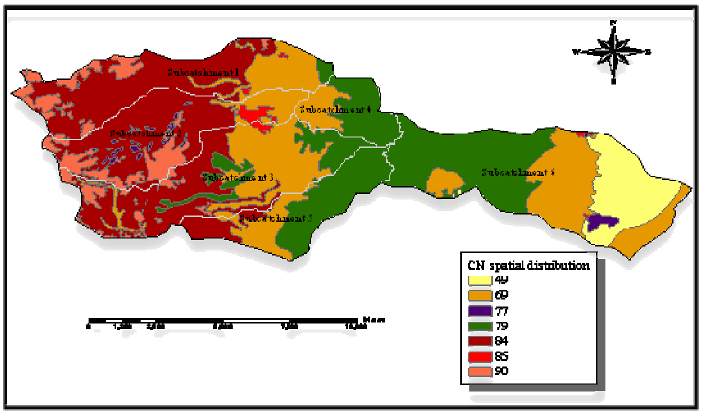


Figure 14: Og Watershed HSG's

According to HSG's and land use the weighted curve numbers were calculated and are represented in Figure 15.

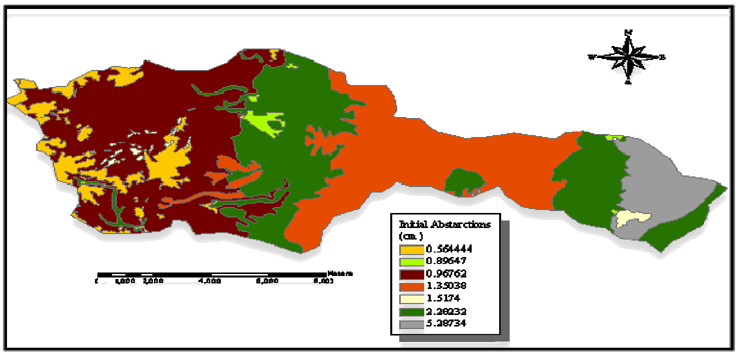


Figure 15: Og Catchment Weighted CN Spatial Distribution

(3) Hydrological Parameters Calculations

The sub-watershed parameters (Area, average slope, lag time, slope and length of the longest flow path were calculated by the means of GIS tools and stored in the sub-watershed attribute table, the results were summarized in Table 3.

Table 3: Sub- Catchment Hydrologic Parameters Summary

Sub watershed	Area (km^2)	Slope (%)	t_{lag} (hr)	L (m)	CN
Sub catchments 1	24.91	13.7549	1.30	9533	81
Sub catchments 2	21.53	16.6509	0.97	8033	83
Sub catchments 3	29.81	14.4178	1.72	12399	78
Sub catchments 4	8.018	12.2257	0.81	4036	76
Sub catchments 5	14.29	13.7924	1.11	6704	77
Sub catchments 6	39.4	13.1162	2.83	15287	68

The unit hydrograph parameters for 1 cm excess rainfall were calculated and summarized in Table 4

Table 4: 1 cm excess rainfall unit hydrograph parameters

Sub catchment	Area (km2)	t_{lag} (hr)	T_C (hr)	D (hr)	T_p (hr)	T_b (hr)	q_p (m^3/S)	V (MCM)
Sub catchments 1	24.91	1.3	2.17	0.29	1.44	3.86	35.872	0.249
Sub catchments 2	21.53	0.97	1.62	0.22	1.08	2.88	41.553	0.215
Sub catchments 3	29.81	1.72	2.87	0.38	1.91	5.10	32.446	0.298
Sub catchments 4	8.018	0.81	1.35	0.18	0.90	2.40	18.531	0.080
Sub catchments 5	14.29	1.11	1.85	0.25	1.23	3.29	24.101	0.143
Sub catchments 6	39.4	2.83	4.73	0.63	3.14	8.40	26.064	0.394

The initial abstraction and maximum retention were calculated and their spatial distributions are represented in Figures 16 & 17 respectively

Figure 16: Initial Abstraction Spatial Distribution

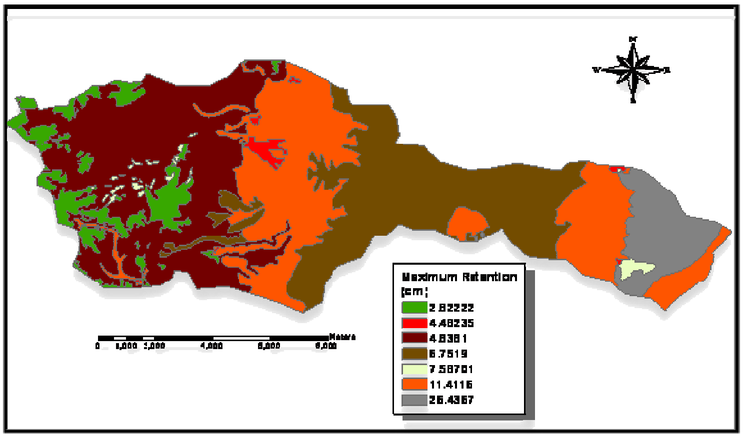


Figure 17: Maximum Retention Spatial Distribution

Conclusion:

The hydrologic parameters determination is required for hydrologic modeling. Those parameters vary spatially and temporally. The GIS techniques were very powerful and efficient that combined with the SCS model made the preliminary runoff estimate more reliable.

The absence of runoff events measures since the catchment is ungauged was a significant challenge. The results obtained from the conceptual model in this study are preliminary, and the model will be calibrated against the observed and measured runoff events in the following steps.

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