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Spatial Distribution of Runoff Discharges Considering Wadi Channel Flow with Upscaling Technique Based on Homogenization

SPATIAL DISTRIBUTION OF RUNOFF DISCHARGES CONSIDERING WADI CHANNEL FLOW WITH UPSCALING TECHNIQUE BASED ON HOMOGENIZATION THEORY

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ABSTRACT

It has been stated that the limitation of the development of arid zone hydrology is the lack of high quality observations. This paper introduces a distributed hydrological model of the Wadi system for flood control and water resources management considering the discontinuous occurrence of flow in both space and time. We provide a homogenization method of upscaling hydrologic parameters related to a distributed runoff model from macroscopic aspects up to megascopic ones. Discharge distribution of the Wadi system can be simulated. Transmission losses and their effects on surface and subsurface flow are evaluated. The conjunctive use of surface and subsurface water is recommended. It is concluded that this model is an applicable methodology for distributed discharge in the arid regions.

Keywords: Homogenization theory, transmission losses, Wadi system and Kinematic wave model

1. INTRODUCTION

Understanding of hydrological processes of Wadi system in the arid regions is so needed due to the importance of the water resources. In the arid regions, there are many problems; the shortage of water resources and increasing the losses. Despite the critical importance of water in arid areas, hydrological data have historically been severely limited. Moreover, those countries of the arid areas are facing the problem of overpopulation, and consequently the demand of water resources for the agricultural and domestic use.

This study proposes a homogenization method of upscaling hydrological parameters related to a distributed runoff model from microscopic aspects up to macroscopic ones. Homogenization is a mathematical method that allow us to upscale differential Equations. The essential idea of homogenization is to average inhomogeneous media in some way in order to capture global properties of the medium.

Wheater et al. (1997) and Telvari et al. (1998) stated that surface water and groundwater interactions depend strongly on the local characteristics of the underlying alluvium and the extent of their connection to, or isolation from, other aquifer systems. Transmission losses in semiarid watersheds raise important distinctions about the spatial and temporal nature of surface water–groundwater interactions compared to humid basins. Ephemeral streams are characterized by much higher flow variability, extended periods of zero surface flow and the general absence of low flows except during the recession periods immediately after moderate to large high flow events (Knighton and Nanson, 1997).

Our main purpose is developing distributed hydrological model to overcome the prescribed struggles for water resources management and flood control in Wadi system due to the deficiency of the water resources and the dangerous of the flood threat. In addition to, studying the interaction between surface and subsurface water.

2. THE TARGET WATERSHED

We aim to study Wadi Assiut watershed (Figure 1) which is located in the Eastern Desert of Egypt. It is located between Long: 32°30′ E & 31°12 W ′ and Lat: 27°48′ N & 27°00 S ′. The total area of Wadi Assiut Catchment is 7293 km2.

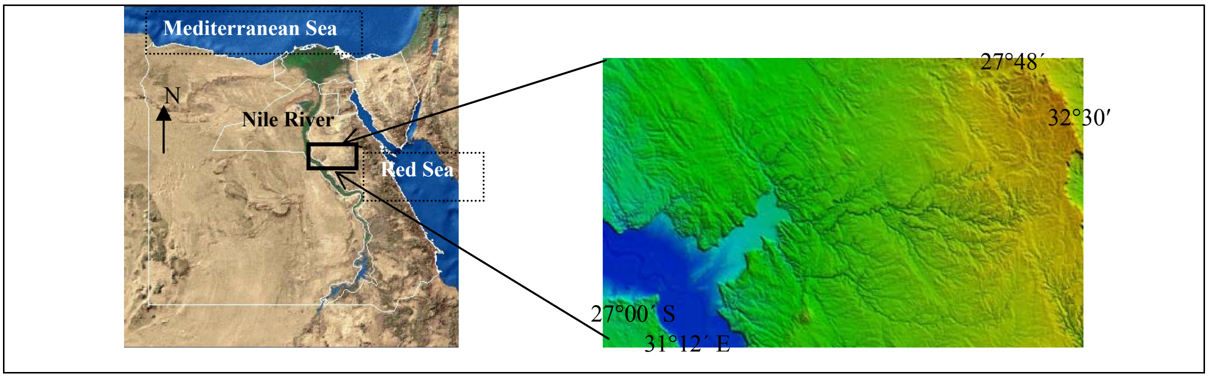


Figure 1 Location map of Wadi Assiut Watershed, Egypt

It is characterized by the features of Wadi System. The establishment of new town there which will be in the near future crowded by populations, thus the hydrological modeling for water resources management and flood threat control is urgently needed and crucial.

3. CHARACTERISTICS OF WADI SYSTEM

The arid regions are characterized by the expanding populations, increasing per capita water use, and limited water resources and so on. Rainfall is characterized by extremely high spatiotemporal variability. The most obvious characteristics in the ephemeral streams are the initial, transmission losses and the discontinuous occurrence of flow in both space and time.

3.1 Initial and Transmission Losses

Initial losses occur in the sub-basins before runoff reaches the stream networks, whereas transmission losses occur as water is channeled through the valley network. Initial losses are related largely to infiltration, surface soil type, land use activities, evapotranspiration, interception, and surface depression storage. Transmission losses are important not only with respect to their effect on stage flow reduction, but also to their effect as recharge to groundwater of underground alluvial aquifers. It was suggested that two sources of transmission loss could be occurring, direct losses to the bed, limited by available storage, and losses through the banks during flood events as shown in Figure 2A.

3.2 Surface and Subsurface Water Interactions

Surface water–groundwater interactions in semiarid drainages are controlled by transmission losses. In contrast to humid basins, the coupling between stream channels and underlying aquifers in semiarid regions often promotes infiltration of water through the channel bed, i.e. channel transmission losses (Stephens, 1996; Goodrich et al., 1997). The balance between distributed infiltration from rainfall and Wadi bed infiltration is obviously dependant on local conditions, but soil moisture observations from S.W. Saudi Arabia imply that, at least for frequent events, distributed infiltration of catchment soils is limited, and that increased near surface soil moisture levels are subsequently depleted by evaporation.

4. METHODOLOGY AND MODEL COMPONENTS

Due to the severe problems of Wadi system in the arid areas, it is recommended to develop the distributed hydrological models, including surface water/groundwater interactions in the active Wadi channel, sediment transport and evaporation processes. These are challenging studies, with particularly challenging logistical problems, and require the full range of advanced hydrological experimental methods and approaches to be applied.

A distributed hydrological model in the Wadi system is proposed. This model is based on the modification of Hydro-BEAM (Hydrological Basin Environmental Assessment Model), it was first developed by Kojiri et al. (1998). which has been chosen for simulation the surface runoff model and estimation of the transmission losses.

Thus, our approach is an integrated numerical model (Figure 2B) based on sporadic precipitation and under conditions of data deficiency where we developed the watershed modeling by using GIS tool, surface runoff and stream routing modeling based on using the Kinematic wave approximation, the initial and transmission losses modeling were estimated with applying SCS method (1985) (an empirical model for rainfall abstractions suggested by the U.S Soil conservation Service) and Walter's Eq. (1990) respectively, and groundwater modeling based on the linear storage model.

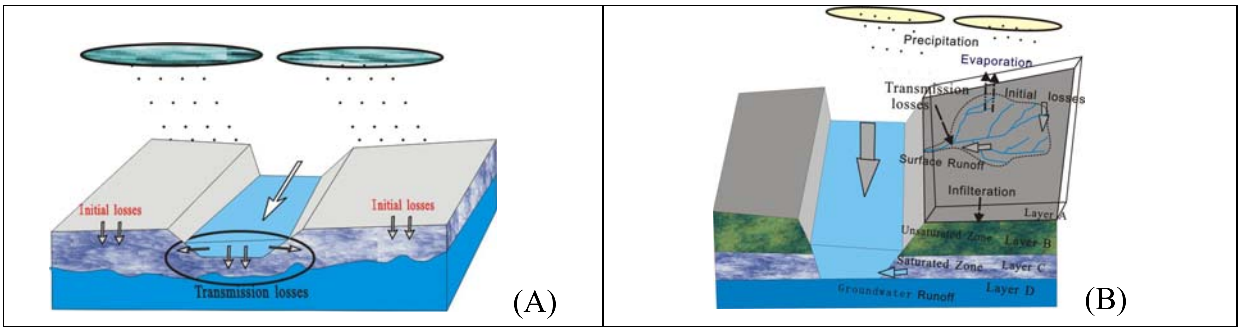


Figure 2 (A) Conceptual model showing transmission and initial losses in the Wadi System, (B) Schematic conceptual model of Wadi system

We provide a homogenization method of upscaling hydrologic parameters related to a distributed runoff model from macroscopic aspects up to megascopic ones. A surface flow direction prescribed through a flow routing map is significant to replace the discontinuous flow in the lumped model cell to the homogenized equivalent flow for the simplicity of calculations in the complicated Wadi system based on the conservation of water balance. Where the homogenized parameters (equivalent roughness coefficient n^* and equivalent hydraulic conductivity k^*) are equivalently derived from the mathematically formulated descriptions based on the conservation of surface and subsurface water quantities (Hamaguchi et. al., 2007).

The original Hydro-BEAM model that uses for the humid conditions can be adopted for simulation of Wadi system in the arid area as described in the following sections. Initial and transmission losses are evaluated. The watershed to be investigated is divided into an array of unit mesh cells. A mesh cell can be arranged as a combination of a surface layer and several subsurface layers. The following description considers Hydro-BEAM calibrated with four subsurface layers, labeled A, B, C and D. A-Layer is calibrated using Kinematic wave model for the overland flow evaluation and the other C-D layers (subsurface layers) are calculated by the linear storage model.

4.1 Watershed Modeling

The watershed basin delineation and stream network determination are achieved using the digital elevation map (DEM) as input to Arcview GIS (Figure 3A), in addition to geomorphologic features can be calculated. We considered some points in the watershed modeling: i) Determination of the watershed boundary location, ii) Division of the watershed into a regular grid of mesh cells (2 km), iii) Determination of a flow routing network based on mesh cell elevation as given by a DEM.

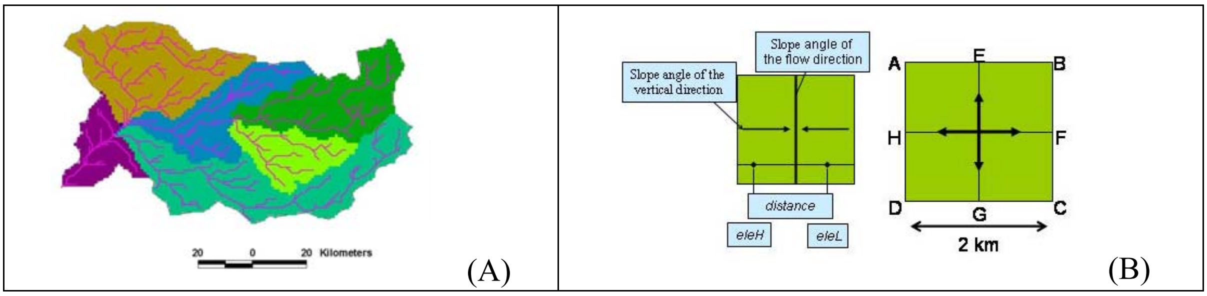


Figure 3 (A) Watershed delineation and stream network determination of Wadi Assiut, (B) Schematic diagram of the flow direction determination

There are two types of ***flow routing system***; 4 directions and 8 directions to determine drainage of flow water direction. Hydro-BEAM was originally developed to use a 4-direction flow routing map. Flow direction from any given mesh cell can be estimated using the DEM elevations of the corners of each mesh cell as declared in Figure 3B. Hydro-BEAM is set to use *five categories of land use types*. The land use distribution data (GLCC; Global Land Cover Characterization) are reclassified into 5 types.The five categories of land use types are; *mountains and forests, paddy field (rice field), desert, urban and water*.

4.2 Climatic Model

By using the metrological data of NCDC (National Climatic Data Center) , Global Hourly and Monthly data, ***Thornthwaite method*** can be adopted to calculate daily mean potential evapotranspiration as given in equations 1, 2, 3, and 4. The mean air temperature and duration of possible sunshine of each mesh are needed as meteorological data for our model.

$$E_p = 0.553 D_0 \left(\frac{10 T_i}{J} \right)^a \tag{1}$$

$$a = 0.000000675 J^3 - 0.0000771 J^2 + 0.01792 J + 0.049293 \tag{2}$$

$$J = \sum_{i=1}^{12} \left(\frac{T_i}{5} \right)^{1.514} \tag{3}$$

$$E_a = M \times E_p \tag{4}$$

Where, E_a *and* E_p *(mm/d)* are the actual and the potential evapotranspiration; *Ti* (^0C) is the monthly average temperature, *J*: Heat index, D_0 *(h/12h)* is the potential day length and *M* is the reduction coefficient, vapor effective parameter.

4.3 Kinematic Wave Model

The kinematic wave equations as given in eq. 5 are derived from the St. Venant equations by preserving conservation of mass and approximately satisfying conservation of momentum. The momentum of the flow can be approximated with a uniform flow assumption as described by Manning's equation (eq. 6). A finite difference approximation of the kinematic wave model can be used to model watershed runoff on the surface and layer A.

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = r(x,t) \tag{5}$$

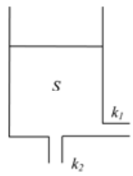
$$q = \alpha h^m \tag{6}$$

Where, *h*: water depth *m, q*: is discharge [m3/m.s], r is rainfall intensity [m/s], *t* is time [s], *x* is distance from the upstream edge, and *α, m* is constant concerning friction

4.4 Linear Storage Model

We used linear storage model (eq. 7 & 8) for groundwater modeling in layers B-D in each mesh, thus the ground water storage can be evaluated in the proposed model.

$$\frac{dS}{dt} = I - O \tag{7}$$



$$O = (k_1 + k_2) \cdot S \tag{8}$$

Where S: is storage amount [m], *I*: is inflow [ms^{-1}], *O*: is outflow [ms^{-1}], k_1, k_2: are coefficient of permeability

4.5 Initial and Transmission Losses Model

The SCS (Soil Conservation Service) method can be adopted to calculate initial losses in Wadi Assiut catchment. The method (SCS. 1985) has been successfully applied to ephemeral watersheds in SW US. Runoff in sub basins occurs after rainfall exceeds an initial abstraction (Ia) value. Rainfall excess, Q, in NRCS method is related to the effective potential retention value, S, as given in eq. 9.

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \tag{9}$$

The initial abstraction is suggested by SCS to be approximately 20 % of the maximum potential retention value. The initial abstraction consists mainly of interception, infiltration prior to runoff, and surface storage, and is related to potential maximum retention as given in eq. 10.

$$I_a = 0.2S \quad (10)$$

S (mm) is the maximum retention parameter as given in eq. 11.

$$S = \frac{25400 - 254CN}{CN} \quad (11)$$

Where, P_e = Accumulated precipitation excess at time t (mm), P = Accumulated rainfall depth at time t (mm), I_a = the initial loss (mm), S = potential maximum retention (mm)

The catchment's capability for rainfall abstraction is inversely proportional to the runoff curve number. For CN = 100, no abstraction is possible, with runoff being equal to total rainfall. On the other hand, for CN = 1 practically all rainfall would be abstracted, with runoff being reduced to zero. The curve number CN value depends on hydrologic soil group and land use cover complex. The hydrologic soil groups are defined by SCS soil scientists as A, B, C, and D are classified based o the soil type and infiltration rate. So, based on the land use, soil type and infiltration rate, the curve number of the land use in the studied area can be estimated.

Transmission losses are important not only in their obvious effect on stage flow reduction, but also as a source of ground water recharge to underlying alluvial aquifers. The variables that are considered useful in estimating the variation in the transmission loss included; 1-the flow volume at the upstream end of the reach, 2-channel antecedent condition, 3-chaneel slope, 4- channel bed material, the duration of the flow, 5- channel width. Walter's (1990) developed an equation to calculate the transmission losses as given in Eq. 12.

$$V_1 = 0.0006225W^{1.216}V_A^{0.507} \quad (12)$$

Where V_1 =transmission loss for the first mile (acre-ft), V_A = upstream flow volume (acre-ft), w=active channel width. The distributed transmission losses can be calculated in the Wadi system using this equation.

5. Results and Application

Hydro-BEAM is a multilayer hydrological model, four layers (A-D); A-Layer is composed of the surface and soil surface layer. kinematic wave model and Manning eq. are used to estimate the surface runoff and roughness coefficient in each mesh. B-D-Layers (subsurface) are evaluated using linear storage model. The flow in each of B and C layers is flowing toward the river, but D-layer is considered as groundwater storage. When storage water content reaches to thickness and becomes saturated state, water content flows into the upper layer of model as returned style. It consists mainly of three main modeling parts; climatic modeling, watershed modeling and the main program modeling. The simulation period is from 1994 to 1995 based on geographical and climatic data where Egypt subjected to a big rainfall event on November 1994. The watershed modeling of Wadi Assiut is achieved based on DEM data by using GIS. The digital topological map of Wadi Assiut is demonstrated as shown in Figure 4A. It is clear that the general slope from NE corner to SW corner.

Land use types can be reclassified from the data of GLCC. The model result of land use distribution can be depicted as mountains, field, desert, city, and water as demonstrated in Figures 4B, 4C, 4D, 4E and 4F respectively. From the distribution maps of land use, it was found that the mountains and forest are limited, and the agricultural field is concentrated at the Southwestern part. Desert is the majority of land use types. The distribution of urban and water are concentrating at the south western side of Wadi Assiut.

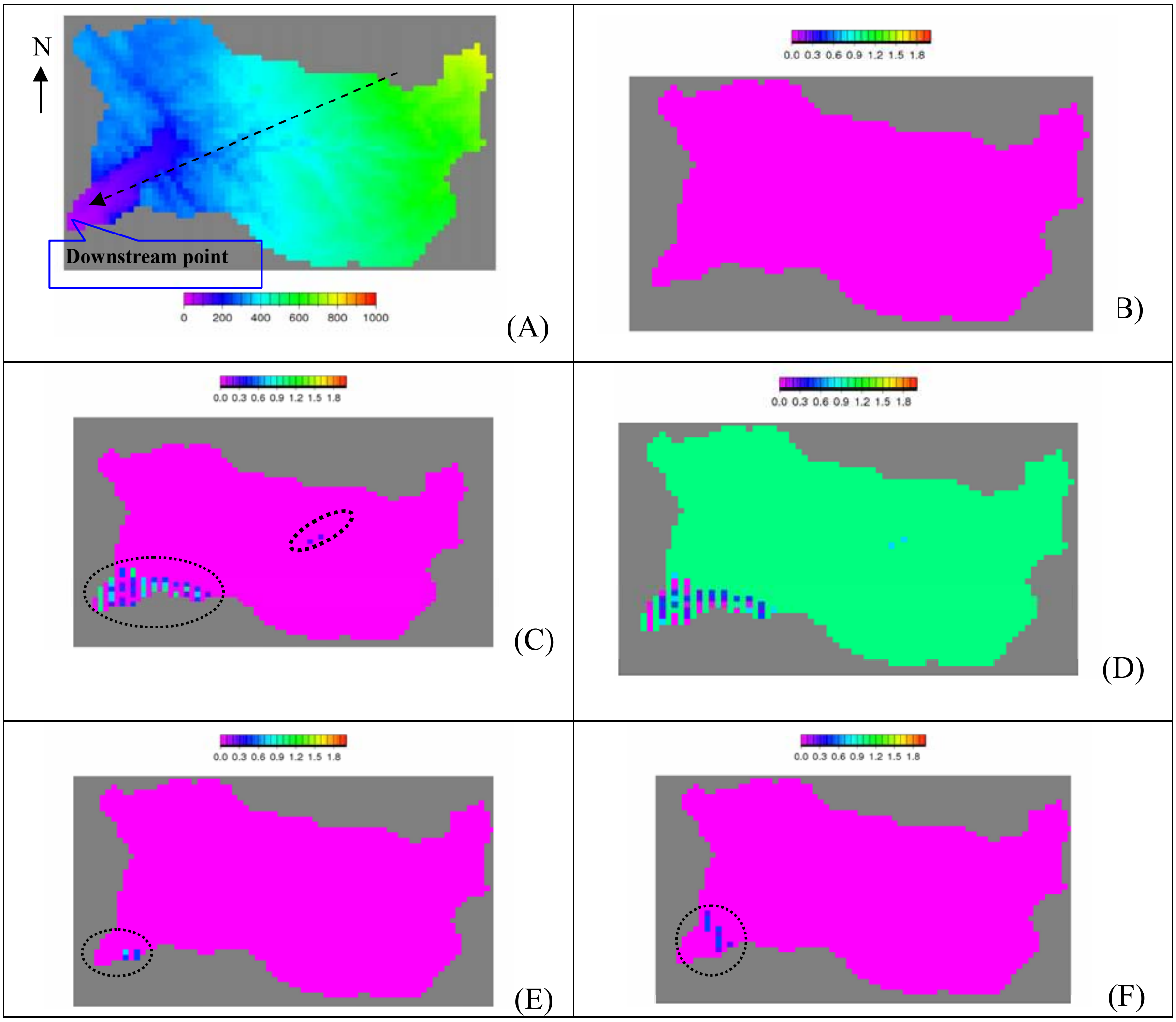


Figure 4 Modeled topographical map of Wadi Assiut watershed (A), distribution map of mountains (B), distribution map of filed and paddy field (C), distribution map of desert (D), distribution map of city (E), and distribution map of water (F).

The surface flow discharge can be demonstrated in Wadi Assiut watershed using the climatic data of the two years (1994-1995), where the daily and hourly output results can be obtained using Hydro-BEAM. However the lack of observed data, the simulated results are reasonable and satisfied due to good agreement between discharge hydrograph and rainfall hyetograph as shown in Figure 5A. The maximum peak of the runoff in Wadi assiut is 85m3/s and the rainfall maximum peak is about 12.7mm/hr.

The simulation of hourly discharge also is accomplished as the maximum peak of is 49 m3/s as shown in Figure 5B. The results of daily and hourly simulations (simulation period is November 2-5, 1995) are completely coincide in their curve shape, thus the behaviors of the Wadi system can be declared using the proposed model.

From the distribution map of surface runoff, we noticed that the discontinuous flow is perfectly depicted as shown in Figure 6A, so the most import characteristics (the discontinuous surface flow) in the ephemeral streams is successfully evaluated.

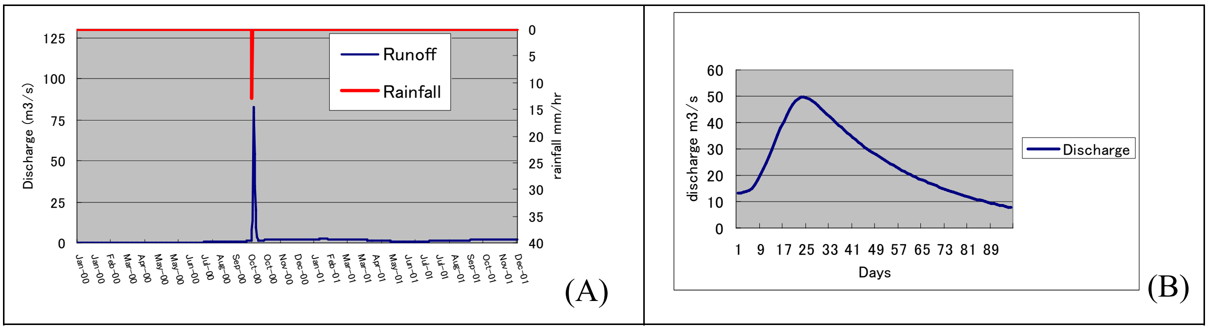


Figure 5 Daily discharge simulation hydrograph and rainfall hyetograph (A), Hydrograph of hourly discharge simulation (B)

The merit of our model is evaluation the interaction between surface and subsurface water due to its importance in the arid regions. So, based on the linear storage model, the equivalent ground water storage can be investigated.

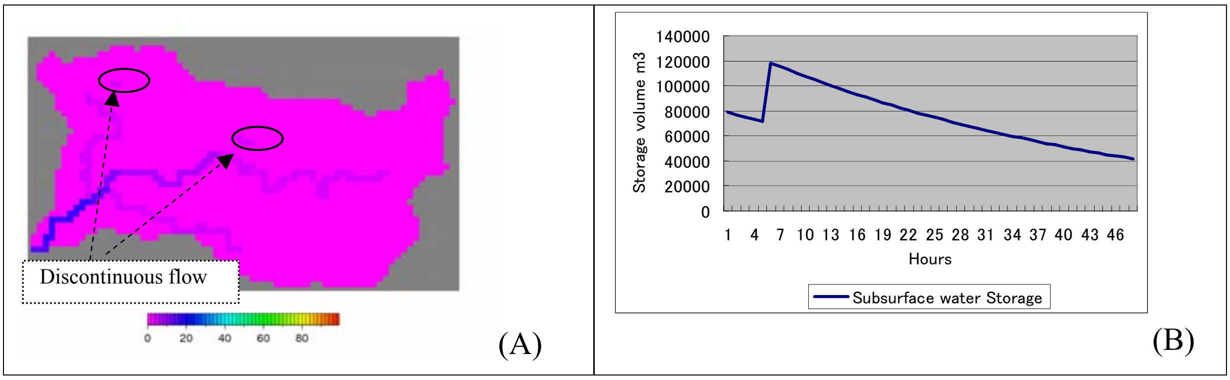


Figure 6 Distributed map showing the discontinuously surface flow (A), hydrograph of subsurface water equivalent storage (B)

It is declared that the subsurface water storage is affected by the flood where the hydrograph of subsurface water storage increased during flood event and then gradually decreased during the recession of the flood as depicted in Figure 6B.

Quantification of transmission loss is important, but it raises a number of difficulties. Walters (1990) provided evidence that the rate of loss is linearly related to the volume of surface discharge. They are evaluated by using Walter's equation and the balance method (the difference between inflow and out flow in each mesh). A good agreement between the results of transmission losses using the two methods is found as shown in Figure 7A. The maximum peak of transmission losses is 13m3/s by using Walter's method and 15m3/s by using balance method. It is deduced that the transmission losses contribute to the ground water as the main recharge for the subsurface water in the Wadi system. We noticed that the linear relationship between the transmission losses and discharge hydrographs as shown in Figure 7B, Moreover, you can see that the transmission losses curve at the recession of the flood is approximately equal to runoff.

Because of our main targets in this research are water resources management and flood control, the conjunctive use of surface and subsurface water can be used for the real application. A lot of surface water infiltrated as the main resource of recharge to the subsurface due to the transmission losses. This subsurface water can be utilized for domestic and agriculture use.

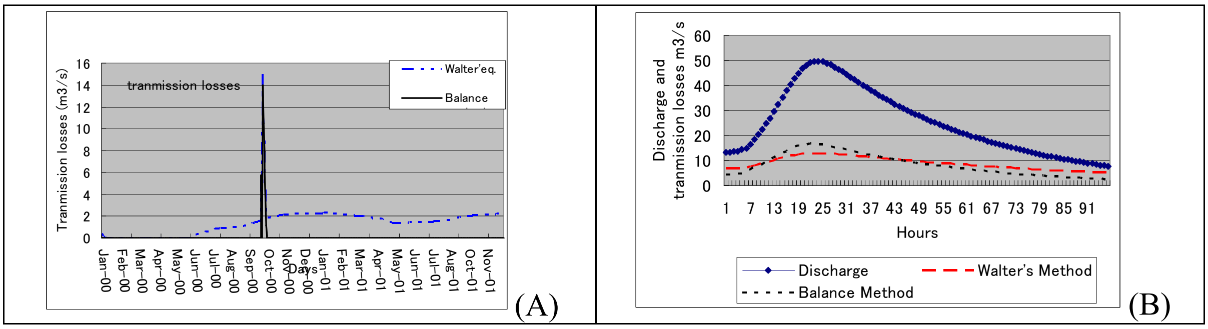


Figure 7 Transmission losses simulation (Walter's Eq. and Balance method) (A), comparing of discharge and transmission losses (Walter's Eq. and Balance method) (B)

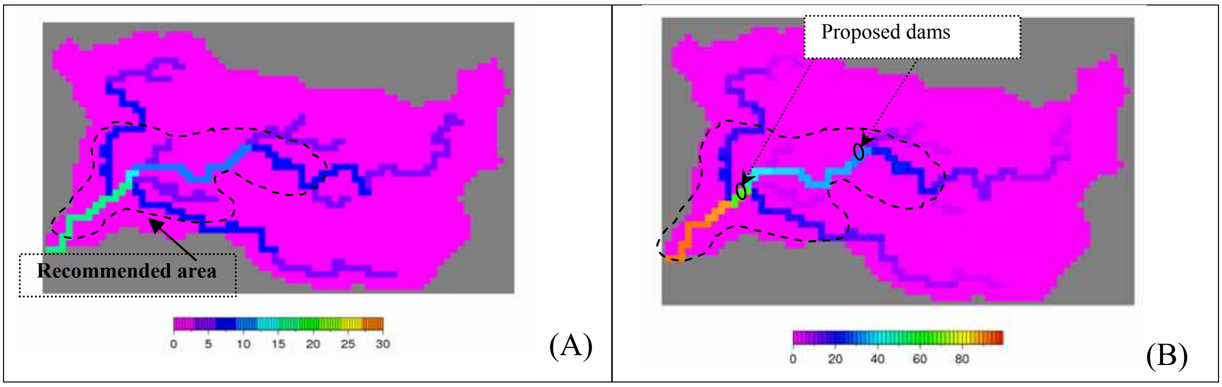


Figure 8 Distribution map of transmission losses (A), distributed map showing the maximum surface runoff (B)

Constructing the pumping wells in the middle and western parts of Wadi Assiut is recommended as declared in Figure 8A. The surface water during the flood event or the rainy season can be used for the agriculture purposes. We propose for the flood control and water resources management to establish two dams along the main channel of Wadi Assiut due to the maximum discharge during the flood at the two locations as shown in Figure 8B. They will be useful for protection the people from any flood threat and to increase the recharge to the subsurface water which can be used for the long term for people needs.

6. Conclusion

Hydro-BEAM has been chosen as distributed model for the Wadi System modeling. Modifications of Hydro-BEAM have been made to simulate the surface runoff in the ephemeral streams and to estimate the transmission losses which are the main source of the recharge to subsurface water. The runoff simulation is successfully achieved in the Wadi system. The maximum peak of the runoff in Wadi Assiut is $85m^3/s$ for the simulation period from (1994-1995). The rainfall maximum peak is about 12.7mm/hr. The simulation of hourly discharge also is accomplished where the maximum peak of discharge is 49 m3/s, the simulation period is November 2-5, 1994. The behaviors of the Wadi system can be declared using the proposed model as depicted in our simulation.

The transmission losses can be evaluated using two methods; Walter's eq. and the balance method and the results are reasonable due to their agreement. It is concluded that transmission losses participate as the main source of recharge to the subsurface. It is noticed that it is affected by the volume of surface runoff as evidence that the rate of losses is linearly related to the volume of surface discharge.

The novelty of this research is that the proposed model shows the discontinuously surface flow of the Wadi system, in addition to the distribution of the equivalent subsurface water storage. The conjunctive use of surface and subsurface water can be used in the real application for flood control and water resources management in Wadi Assiut. It is recommended that the western and the middle parts of Wadi Assiut can be utilized for pumping of subsurface water and establishment the dams to protect the people from the flood thread and increase the water resources to overcome the problem of the water shortage.

It is concluded that the proposed model is considered an applicable methodology in larger areas and consequently, a vital contribution to estimate the distributed surface discharge and equivalent of subsurface water storage regionally not only in Wadi Assiut, Egypt but also in other arid regions. Much more researches are recommended for the Wadi system modeling based on the observed data. The regional application of the Wadi system model is our future target.

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