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Rain Transmission Losses Assessment in Arid Environment, Egypt: Numerical and Experimental Study

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Rain Transmission Losses Assessment in Arid Environment, Egypt: Numerical and Experimental Study

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Abstract. In water-scarce regions, Transmission Losses Assessment from rainfall is required for the Numerical and Experimental Study of groundwater recharge. This Study is an attempt to assess Transmission Losses and the infiltration rate at Wadi El-Assiuti, Egypt, field infiltration experiments were conducted to measure the infiltration and porosity at the target area, such as using a double-ring infiltrometer. Determination and Quantify the infiltration rate of the soil is very vital as input parameters of the hydrological modeling, irrigation planning and other natural or man-made Processes. Steady state infiltration rates have been determined in selected sites of Wadi El-Assiuti. Accurate determination of infiltration rates is fundamental for trustworthy prediction of surface runoff and groundwater recharge. Double ring infiltrometer was used to measure infiltration rate at selected sites. An important part of the study was the accurate and consistent measurement of infiltration rates. The infiltration rate was calculated according to the installation and operating instruction for the double ring in ASTM 2003. Final infiltration rates were 18 cm h⁻¹, for the first observation site, 24.2 cm h⁻¹ for the second site and 59 cm h⁻¹ for the third site. The analysis indicated that the soil for the three selected areas is sandy soil. Infiltration rates were taken at 0 to 70 minutes of 10 minutes intervals. The infiltration rate at the third site is high compared to the other two selected sites. After performing the experiments, soil samples have been gathered and analyzed in the laboratory for porosity analysis. The results of this study can therefore be applied in the prediction of saturated hydraulic conductivity of the surface layers and groundwater recharge, and in developing or selecting the most efficient irrigation methods. The results from this work have been also involved in a numerical hydrological model to estimate the Transmission Losses from rainfall at Wadi El-Assiuti using Hydro-BEAM.

Key Words: Transmission Losses, Double ring infiltrometers, hydrological modeling, Wadi El-Assiuti, Hydro-BEAM.

1. Introduction

Not only Transmission losses reduce flood magnitudes but also play a vital role in groundwater recharge in arid areas. Assessment of the transmission losses as well as groundwater recharge for actual runoff events requires extensive data which are generally not available for non-experimental watersheds. The data shortage results in wide uncertainties in hydrological model of flash flood, groundwater recharge and transmission losses.

Recognition of hydrological processes of Wadi system is so important due to the importance of the water resources in the arid regions. In the arid areas, it is renowned that there are many serious problems, for instances, the shortage of water resources which lead to critical effects on the economic activity and human live. Another serious problem is increasing the losses which represent in the evaporation, initial and transmission losses. Despite of the high importance of water in arid and semi-arid regions, hydrological records and data have historically been sorely limited. Moreover,



countries of the arid areas are encountered the problem of overpopulation, So the demand of water for the agricultural and domestic purposes is necessary to overcome such problem. For aforementioned reason Egypt was selected as arid region to apply the Numerical and experimental study, especially in the Wadi system like Wadi EL-Assiuti in the eastern Desert. The hydrological modeling programs are very powerful tools to simulate the transmission losses process in the rainfall-runoff analysis.

The relationship between Wadi flow, transmission losses and groundwater recharge depend on the underlying geology. The alluvium implied the Wadi bed is functional in minimizing evaporation loss through capillary rise (the coarse structure of alluvial deposits minimizes capillary effects). According to reference [1] and [2] 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 promote singularity about the spatial and temporal nature of surface water-groundwater interactions compared to humid basins. Because of transmission losses, the nature of surface water-groundwater interactions can be limited to brief periods during runoff events and to specific areas associated with the runoff production and downstream routing [3]. The rate of loss is linearly related to the volume of surface discharge as mentioned in reference [4] and [5] provided evidence that.

Reference [6] showed that losses are high when the alluvial aquifer is fully saturated, and small once the water table drops below the surface. Reference [7] provided an analysis of groundwater rise due to transmission loss for an experimental reach in Wadi Tabalah, S.W. Saudi Arabia and stated that about average 75% of bed infiltration reaches the water table.

High quality research is needed, specially to investigate spatial rainfall, infiltration and groundwater recharge from ephemeral flows. One reason of this paper focusing on the arid and semiarid regions is to estimate the transmission losses and its effect on both surface and subsurface water. Consequently, one part of this paper is an integrated numerical model based on sporadic precipitation and under conditions of limited data where the watershed modeling was developed by using GIS tool. Furthermore, surface runoff and stream routing modeling based on using the Kinematic wave approximation, the initial losses modeling estimated by applying SCS method and transmission losses modeling estimated with applying Walter's Equation [4], and groundwater modeling based on the linear storage model.

2- Experimental and Methodology

2.1 Location and importance the study area

The area under interest is Wadi El-Assiuti. Wadi El-Assiuti is located in the middle of the Egyptian Eastern Desert as shown in figure 1. Wadi El-Assiuti as a watershed basin is located directly East of the River Nile between longitudes $31^{\circ}12'$ & $32^{\circ}30'$ E, and latitudes $27^{\circ}00'$ & $27^{\circ}48'$ N. This basin is considered a sub-basin of the whole River Nile basin.

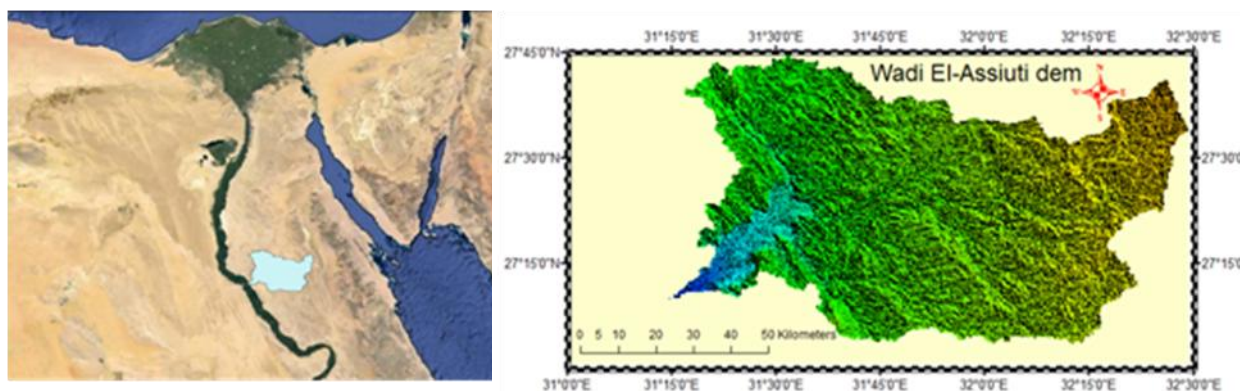


Figure 1. Location map of Wadi El-Assiuti watershed

The total area of Wadi El-Assiuti Catchment is 6051.40 km², the perimeter is 532.722 Km and the length of the main channel is 160.154 km. Most of its area is a desert except some part of urbanization, and very small areas of agricultures which are sealed to Assiut city along the River Nile. Therefore, studying this area is important due to the spread of populations and consequently the need of water resources for agricultural, domestic and manufactory purposes.

Wadi El-Assiuti area has been submitted for development improvements over the past centuries, where many of the former studies were applied and many of projects were established. Wadi El-Assiuti represents the arid conditions, its drainage system is ephemeral streams, also the rainfall is very rare in space and time. Currently, the establishing of new town, which will be in the near future crowded by populations, triggers the importance of hydrological models for water resources management and flood threat control.

2.2 The double ring infiltrometer measurement evaluation

Two different methods of measurements are commonly used with the ring-infiltrometers: constant-head and falling-head. Numerical modeling suggests that constant-head measurements give an overestimate compared to falling-head measurements for coarser textured soils and falling-head measurements tend to underestimate the actual infiltration rate [8].

Field measurements of infiltration rate using a double ring infiltrometer at three observation sites have been conducted at Wadi El-Assiuti as shown in figure 2. Two field trips were conducted for measuring infiltration rate using a double ring infiltrometer. The infiltration rate was calculated according to the installation and operating instruction for the double ring in [9]. In general, the infiltration rate curve acted as theory predicted with high initial infiltration rates and slow approach to the steady state infiltration state.



Figure 2. Double ring infiltrometer observation sites (1, 2 and 3) at Wadi El- Assiuti

2.3 Physical model (rainfall simulator)

The runoff was measured using a rainfall simulator at three observation sites at Wadi El-Assiuti as shown in figure 3. All experiments were performed with a portable rainfall simulator as depicted in figure 4. Portable rainfall simulators have been widely used for various purposes [10] because they make it possible to gather data under controlled conditions over relatively short periods of time [11]. During our field observations at Wadi El-Assiuti, the soil infiltration rate is estimated from the rate of advance of the wetting front, separating wet and dry soil. The relationship between the soil infiltration rate and the progress of the advancing area wetted by water at a constant flow rate is described as follows: Initially, the soil infiltration rate is very high and a small area of the slope can absorb all of the supplied water. With soil infiltration rate decreasing in the previously wetted soil



Figure 3. Rainfall simulator observation sites at Wadi El- Assiuti

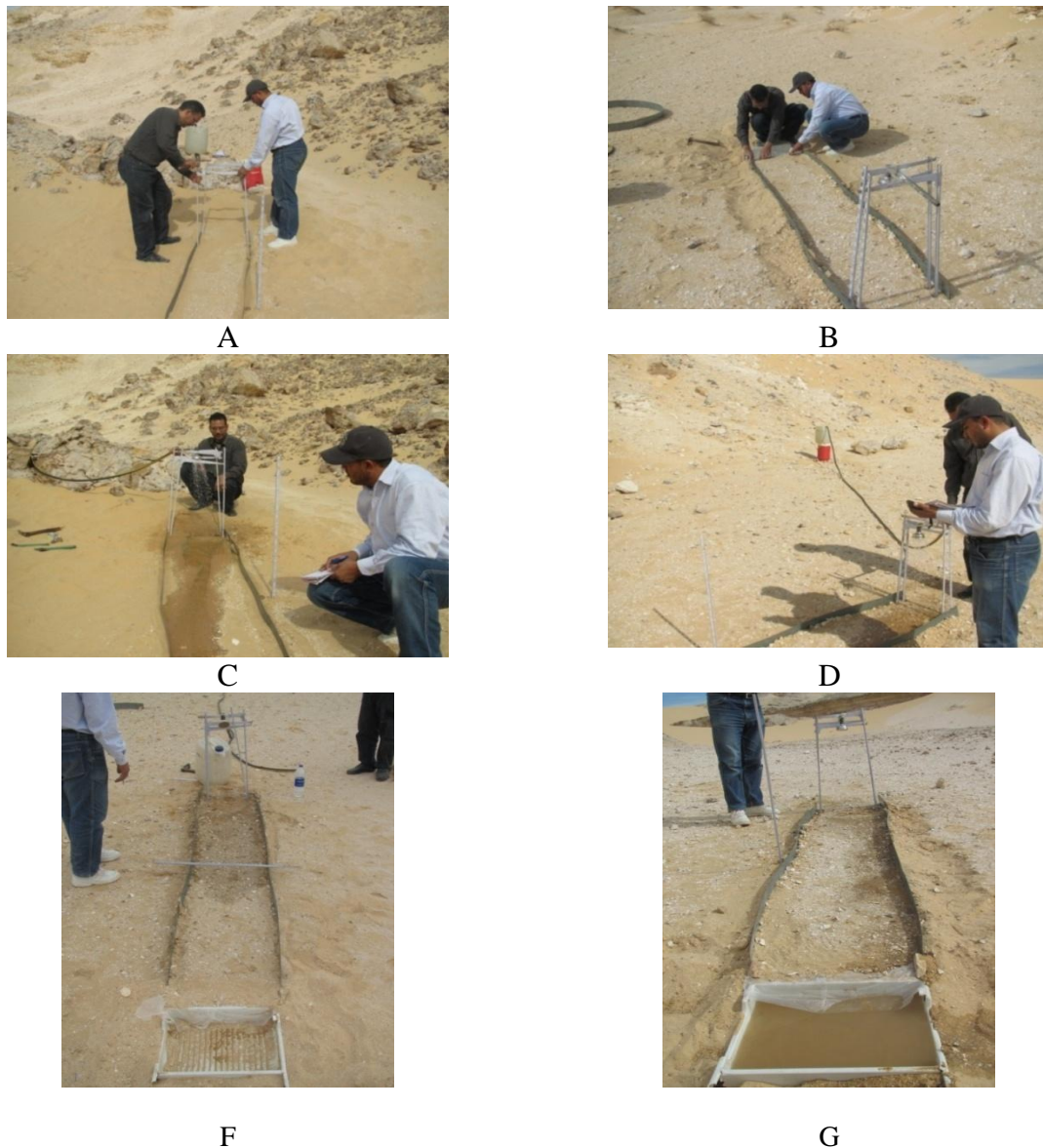


Figure 4. (A, B, C, D, F and G) Field observations of infiltration experiments, runoff was measured using a rainfall simulator at Wadi El-Assiuti.

zone, the same water flow cannot be totally absorbed within the same soil surface area. Thus, the water flow advances over the surface and the wetted area increases gradually. The soil infiltration rate keeps decreasing with time until it reaches its steady value when the area wetted by the constant flow rate no longer expands but also remains constant. The advancing process of the in-flow water over the soil surface indicates that the water supply is sufficient to penetrate the soil in the wetted area [12].

2.4 The porosity analysis

The porosity together with the depth of the alluvium determines the maximum volume that can be absorbed by the alluvium as shown in figure 5. With regard to influence the infiltration rates porosity does not have as much weight as the other parameters. The final infiltration rate is not influenced by the porosity but by the initial infiltration rates. Low values for porosity will reduce the initial infiltration rates whereas large values will increase the initial infiltration rates. Together with the antecedent moisture index Antec, porosity is used to calculate the initial moisture content.

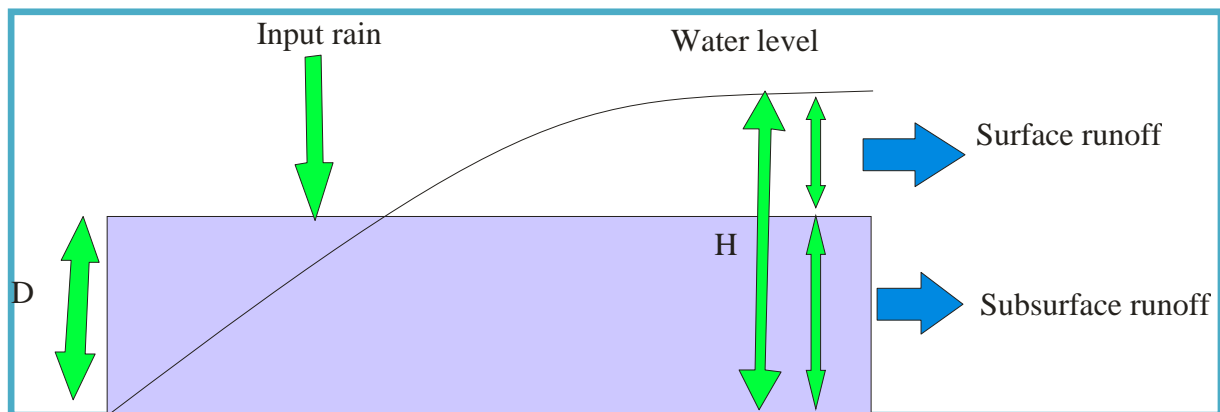


Figure 5. Conceptual model of effective soil depth D is layer depth, H water depth

Effective soil depth = porosity \times soil depth

$$H = h_s + h_a \quad (1)$$

$$q_s = \alpha h_s^m \text{ Surface flow only Manning formula} \quad (2)$$

$$q_a = \alpha h_a \text{ Subsurface flow only Darcy's formula} \quad (3)$$

Where: h_s surface water level, h_a water depth in soil q : discharge per unit length of flow

2.5 Hydro-BEAM model

The Hydrological River Basin Environment Assessment Model (Hydro-BEAM) was originally developed by Kojiri et al. [13] and has been used in many studies as a river basin environment model for assessing water quantity, sediment, reservoir operations, and the impacts of climate change and anthropogenic activity (e.g., [14,15]). However, all of these applications were limited to environments with humid conditions until the model was later modified for flash flood simulations in the arid valleys [17, 18] and semi-arid basins [16].

The most beneficial worthiness of distributed hydrological models such as Hydro-BEAM is their representation of the spatial variations in watershed characteristics and hydrological processes. The watershed under investigation is divided into a number of unit mesh cells (in this study, approximately 5457 mesh cells with a resolution of 1 km). The unit mesh CELL is divided into two pairs of rectangular hill slopes and one river channel. The river channel geometry (depth and width) is related to the upstream area and is tested using Google Earth and DEM data. Vertically, each mesh is represented by a combination of one surface layer and three subsurface layers. The integrated kinematic wave model is used to describe the flow over the surface layer A and throughout the

channel by considering the diverse surface characteristics of the different land use types. The subsurface layers (layers B, C and D) are modeled using the linear storage model. The Natural Resources Conservation Service (NRCS) method is used to calculate the initial losses in the target catchments [19], and a regression formula developed for the arid regions and valleys by Walters [4] is adopted to estimate the instantaneous transmission losses with runoff.

2.6 Hydro-BEAM model calibration

For several reasons, the calibration of rainfall-runoff models in wadi systems is hampered by a lack of data [20, 21]. To our knowledge, no flow rate data have ever been recorded in Wadi El-Assiuti. In this study, model parameterization is performed based on the calibrated model parameters conducted by [18] in Wadi Al-Khouth in Oman. Applying a calibrated hydrological model from another wadi to a wadi under similar conditions has been done by some researchers, such as [22], who transferred the SWAT model calibration in Wadi Girafi in Palestine to all major wadis in the Saini Peninsula and the Eastern Desert in Egypt.

Both Al-Khouth and El-Assiuti wadis had arid conditions with high average potential evapotranspiration values. However, the mean annual rainfall is higher in Wadi Al-Khouth (150mm). Both Al-Khouth and El-Assiuti wadis had very similar land use settings; both of them had areas mainly consist of desert and bare mountain land (comprising 90-95%) of the total area with very few urban and agricultural activities mainly in the downstream regions (5-10%). Therefore, these similarity in land use and climatic conditions could support the application of the Wadi Al-Khouth parameter settings to Wadi El-Assiuti.

3. Results and Discussion

3.1 Double ring infiltrometer measurement

The measured steady state infiltration rates for the selected experiments are presented in table 1

Table 1. Field measurements of double ring infiltrometer at Wadi El-Assiuti, Egypt.

	LOCATION		elevation m	Initial Infiltration rate cm/h	Final Infiltration rate cm/h	Wetting front depth cm
	North	East				
Site1	27°16' 52.1"	31° 22'19.3"	101	24	18	75
Site2	27°27'53.87"	31°31'31.76"	222	60	24.2	98
Site3	27°16'33.34"	31°22'35.15"	88	62.4	59	108

The field measurements of infiltration rate were plotted against time as shown in figures 6. A, B and C. Figure 6 shows temporal changes in infiltration rates measured at different sites at Wadi El-Assiuti. The infiltration rate decreased rapidly at the beginning of the measurement, as well as, it showed marked fluctuations. All infiltration curves showed initial rapid declines, then; the infiltration fluctuated and decreased toward the end of the experiment. The infiltration rates in the last of the experiment were averaged for each plot. The results were as follows: final infiltration rates (basic infiltration) were 18 cm h⁻¹, for the first observation site, 24.2 cmh⁻¹ for the second site and 59 cm h⁻¹ for the third site. An explanation for the third site increase in infiltration rates involves macro pores. Macro pores in the surface soil, formed by soil fauna and the decay of plant roots; it is a common feature of vegetation cover lands. Water can enter macro pores when the surface soil layer is saturated or partially saturated [23]; consequently, the infiltration rate will increase. The increased infiltration rates in the experiment may have reflected a change in water flow paths under such conditions. A higher infiltration rate (59cm h⁻¹) was observed on the third observation site, where there is

agricultural land with vegetation cover. For observation site with lower vegetation cover, the infiltration rate was 18cm h⁻¹ at the first site and 24.2cm h⁻¹ at the second site. These results suggest that dense surface vegetation cover increases the infiltration rate significantly. Agricultural soils usually show wide spatial and temporal changes in pore characteristics due to changes in soil texture, structure, horization, root growth [24].

Infiltration data can be analysed according to a number of infiltration models. One such model is that developed by [25] and can be stated as:

$$I = K t + S t^{\frac{1}{2}} \tag{4}$$

Where *I*, is the cumulative infiltration (cm), *S* is the soil water sorptivity (cm/ h),*K* is the saturated hydraulic conductivity, and *t* is the time (h).

By regressing the cumulative infiltration data collected in the field based on equation 5. One can estimate the values of the parameters *K* and *S*. The infiltration rate *i* (cm h⁻¹) can be computed from equation 5 as follows:

$$i = \frac{dI}{dt} = K + \frac{1}{2} S t^{1/2} \tag{5}$$

The infiltration rate (*i*), can be approximated by *K* as time increases [26].

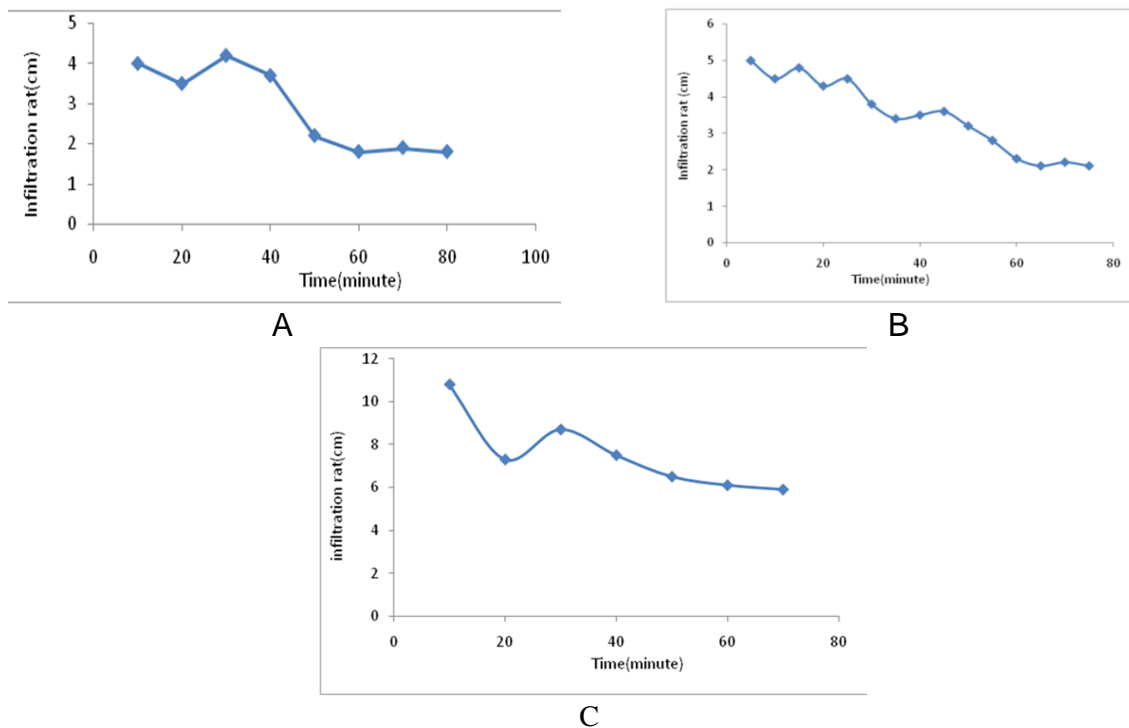


Figure 6. (A, B and C) Infiltration rate curve at observations sits (1, 2 and 3) at Wadi El- Assiuti

Cumulative infiltration and time were recorded for each test. figure 7. (a, b, c) illustrates a linear relationship between the cumulative infiltration and time. In addition it illustrates that the cumulative infiltration increased with time. This occurred because more water accumulated in the soil as the time increase.

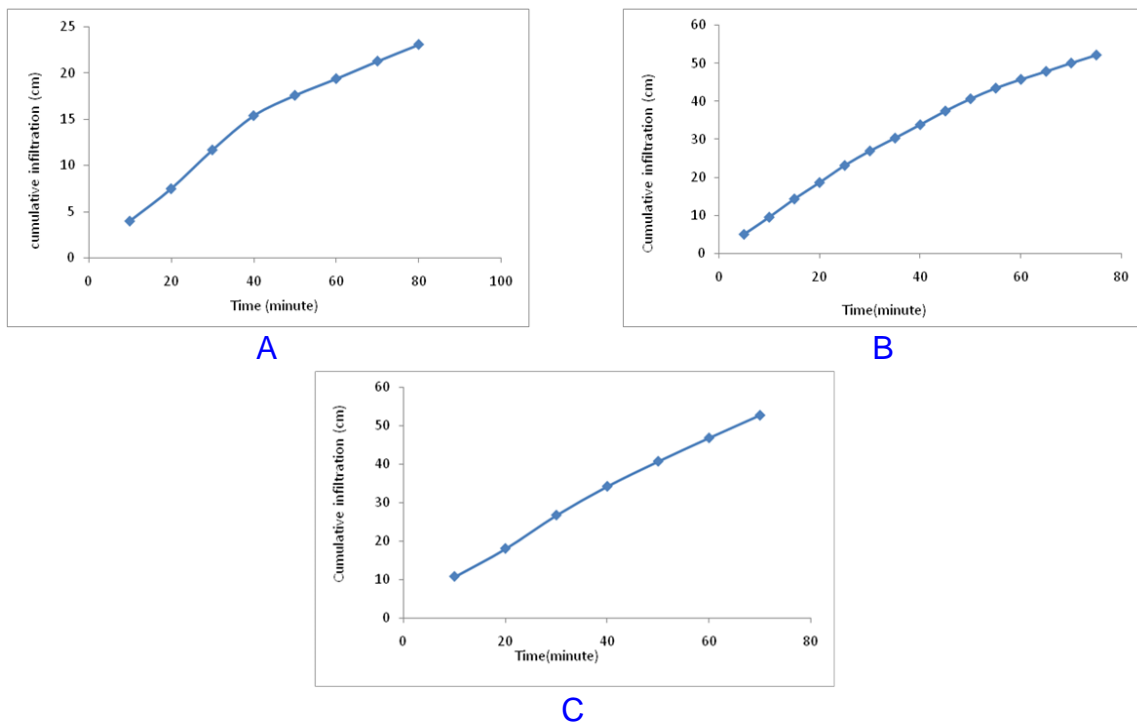


Figure 7. (A, B and C) Cumulative infiltration at observation sites (1, 2 and 3) at Wadi El-Assiuti

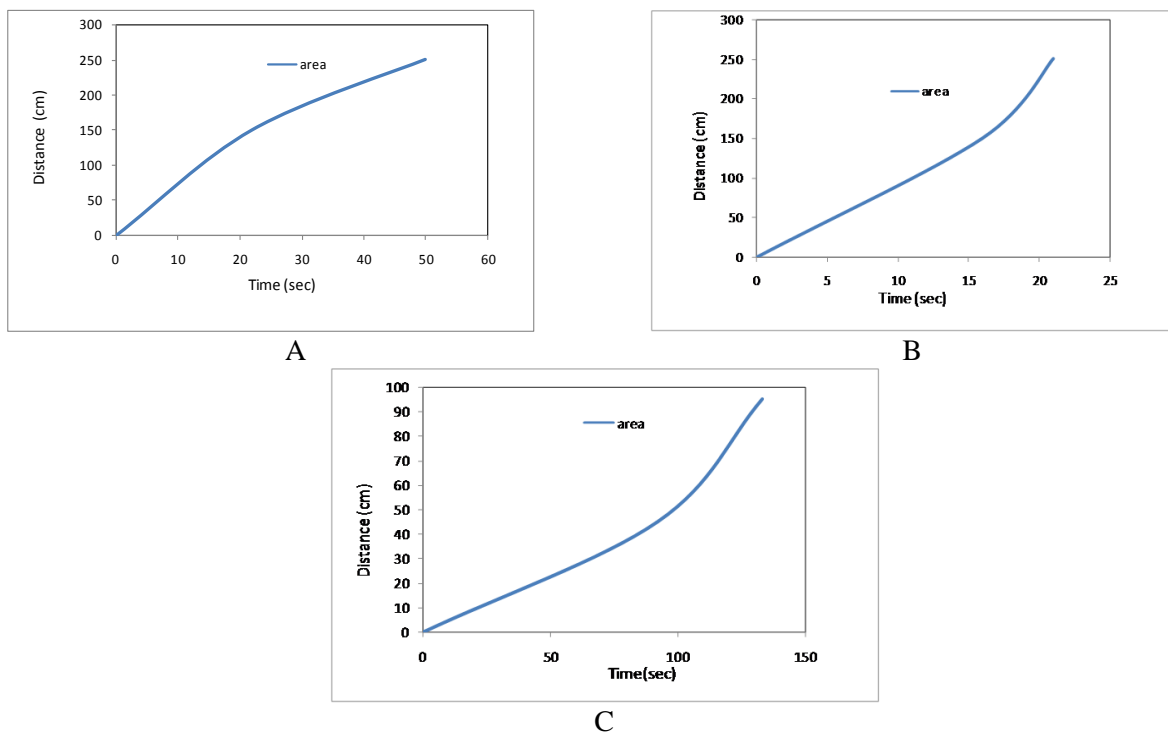


Figure 8. The distance traveled by runoff over time during the experiment of runoff simulator at Wadi El-Assiuti.

3.2 Physical model (rainfall simulator) results

During the first experiment water flows 150 cm distance from the upstream to the downstream point after 22 sec then 250 cm after 50 sec. in the second experiment runoff flows about 150 cm distance in 16 sec, then 250 cm in 21 sec. In addition the third experiment water travels 45 cm in 92 sec then 95 cm in 133 sec as shown in figure 8.

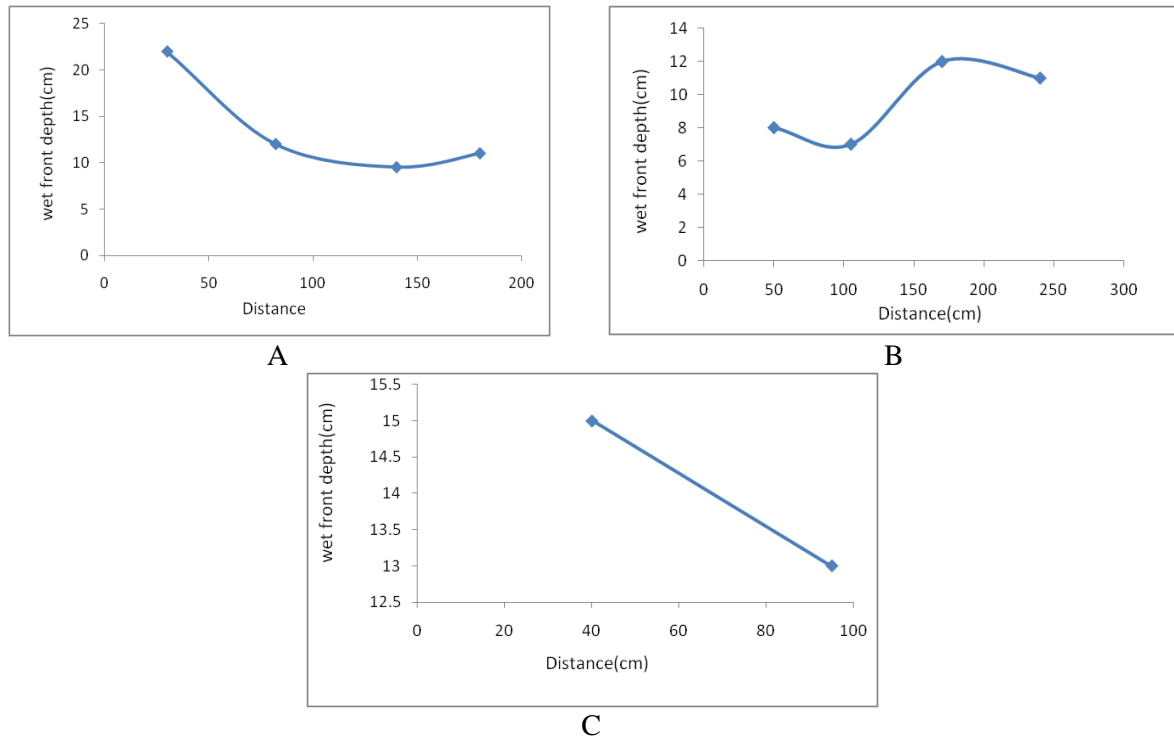


Figure 9. Wet front depth over distance during the experiment of runoff simulator at Wadi El-Assiuti.

Additionally, wetting depth after 162 sec of rainfall in the first experiment reached a depth of more than 22 cm, in the second experiment the wetting front was 12 cm after 145 sec. In the third experiment the wetting depth was 15 cm after 133 sec. so the distance against the wet front was plot as shown in figure 9. Additionally transmission losses are calculated and listed in

Table 2. Rainfall simulator results

	Volume of water in (rain) cm ³	Volume of water out (runoff) cm ³	Transmission losses cm ³	Transmission losses %	slope
site 1	38278.2	0	38278.2	100	8.53
site 2	20496	10744.5	9751.5	47.58	3.43
site 3	31894.2	0	31894.2	100	

3.3 The porosity results

Geomorphology of the region controls the alluvium material of the channel, and transmission losses depend primarily on the bed and over-bank materials. Actually, the coarse materials have a high porosity which enables significant transmission losses. This high porosity leads to a high hydraulic

conductivity which plays one of the main roles in the transmission losses phenomenon. Reference [27] demonstrated that transmission losses are influenced by the quantity and texture of the channel alluvium. The increase in porosity of the soil increased percolation of water hence water runoff was reduced. The measured porosity at different observation sites at Wadi El- Assiuti was shown in figure 10, and then listed in table 3.

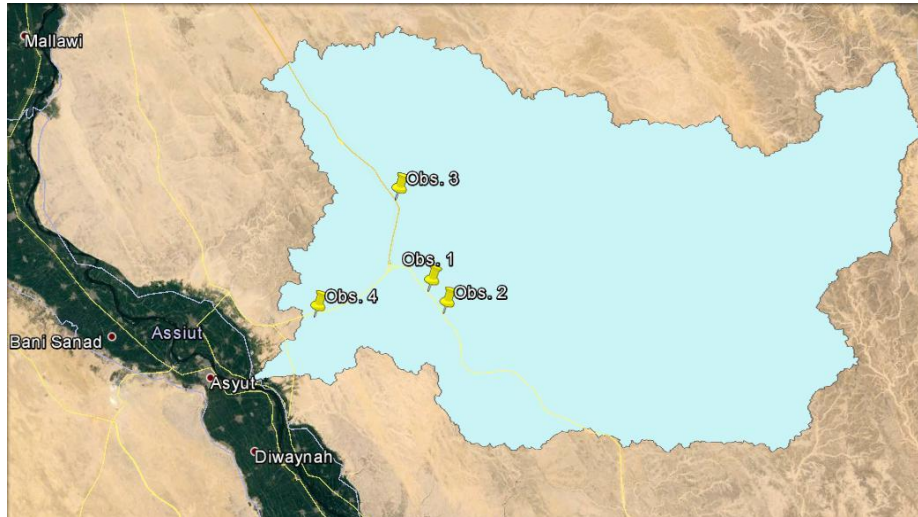


Figure 10. Porosity observation sites at Wadi El- Assiuti

Table 3. Porosity

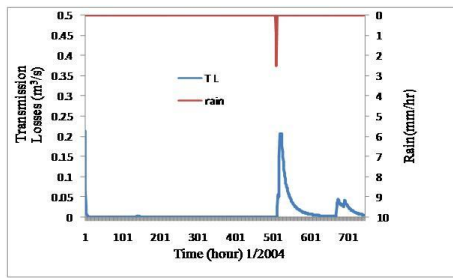
observation site	site		porosity
	North	East	
site 1	27°19' 08.00"	31°35' 02.90"	0.3867
site 2	27°16' 52.90"	31°36' 43.50"	0.4533
site 3	27°27' 53.87"	31°31' 31.76"	0.4267
site 4	27°16' 33.34"	31°22' 35,15"	0.4267

These experimental results of transmission losses and porosity could be very useful for developing the physical models for valley system especially for the parameters calibrations. The measured porosity at different points along the channel bed varied between 0.3867 and 0.4533. Higher porosity increases infiltration and percolation rates and the water-holding capacity of the soil.

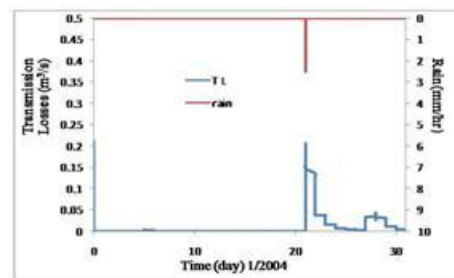
3.4 Hydro-BEAM model results

The flash flood events occurred in January, 2004, February, 2006, January 2008 and January 2010 had severe impacts on many valleys throughout Egypt. The simulation results (Figure 11) described below Highlights the assessment of transmission losses in order to determine its implications for groundwater recharge potential.

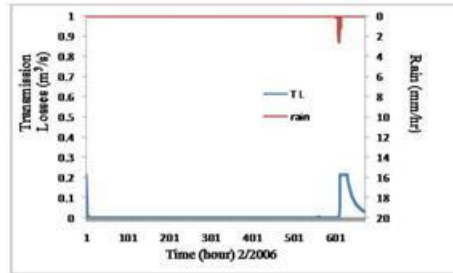
The simulated hydrographs of the selected events show that transmission losses take only a few hours to reach its peak value, before it gradually decrease to return to a zero status (Figure 11). Variations can be noticed in the values of the hydrograph and in the shape of the hydrograph from one event to another due to differences in the rainfall spatial patterns and intensities . The behavior of the hydrograph is directly linked to the pattern of the hyetograph. Even within the same storm, the transmission losses rate can vary between locations due to the spatiotemporal variability of rainfall and the geomorphologic parameters of the upstream catchment.



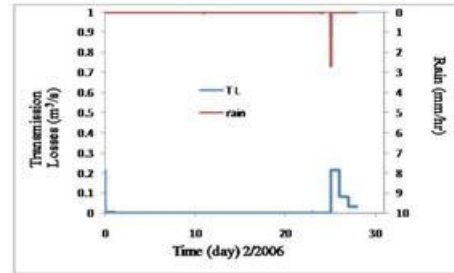
Hourly transmission losses (January, 2004).



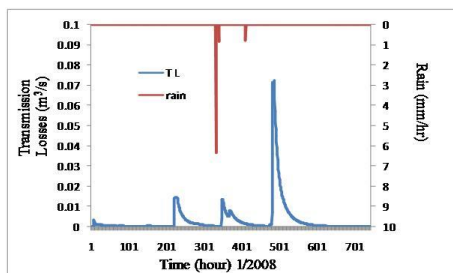
Daily transmission losses (January, 2004).



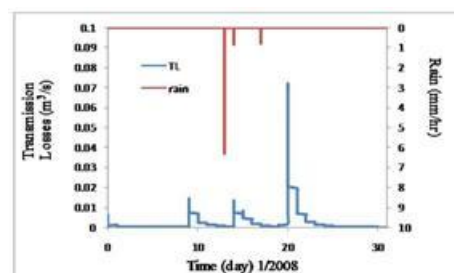
Hourly transmission losses (February, 2006).



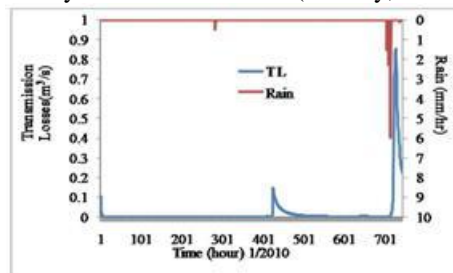
Daily transmission losses (February, 2006).



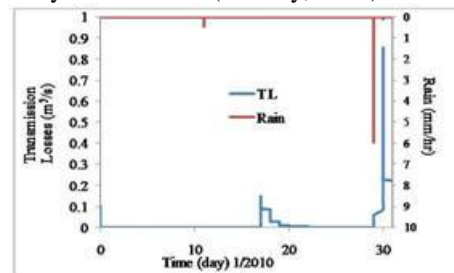
Hourly transmission losses (January, 2008).



Daily transmission losses (January, 2008).



Hourly transmission losses (January, 2010).



Daily transmission losses (January, 2010).

Figure 11. Hourly and Daily transmission losses simulation hydrograph and rainfall hyetograph in Wadi El-Assiuti

The geographic distribution maps of rainfall input and the simulated transmission losses values of the target events are shown in Figure 12 and Figure 13. Despite being affected by significant rainfall, the Wadi El-Assiuti sub-catchments do not record any surface runoff due to their high losses. The transmission losses distribution maps and simulated hydrographs record different patterns for each event, especially in their upstream regions, due to the spatiotemporal variability of rainfall. In the 2010 event, the upstream area recorded higher transmission losses than the downstream area due to the greater rainfall intensity in the upstream region, in contrast to the 2004, 2006 and 2008 events.

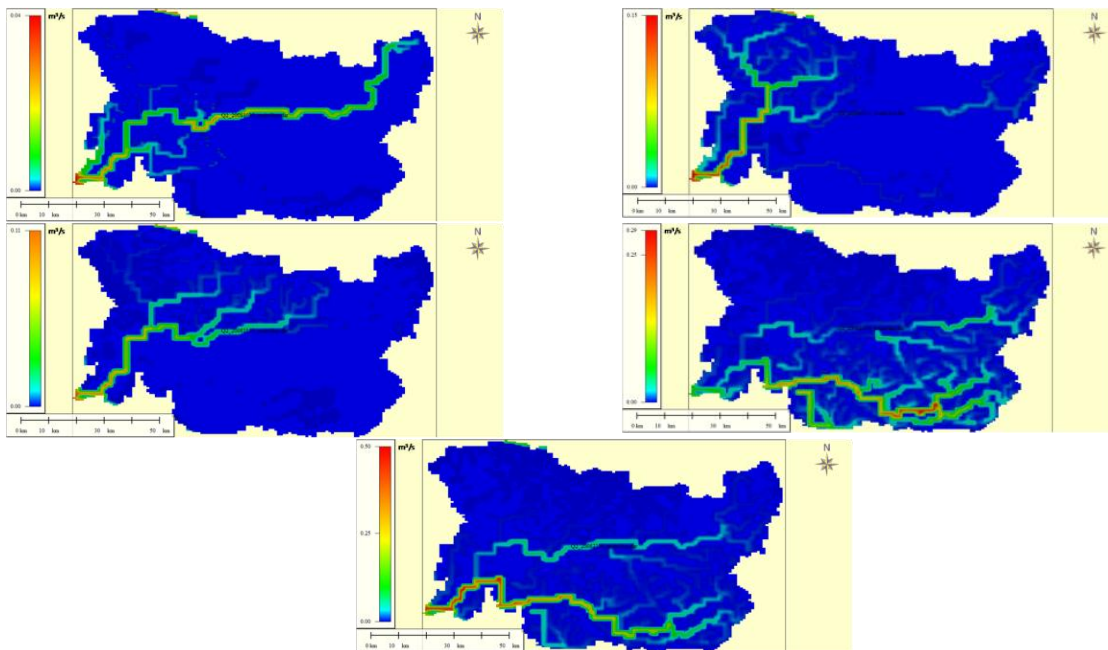


Figure 12. Distribution maps of transmission losses at Wadi El-Assiuti, Egypt (8-24 Jan. 2008).

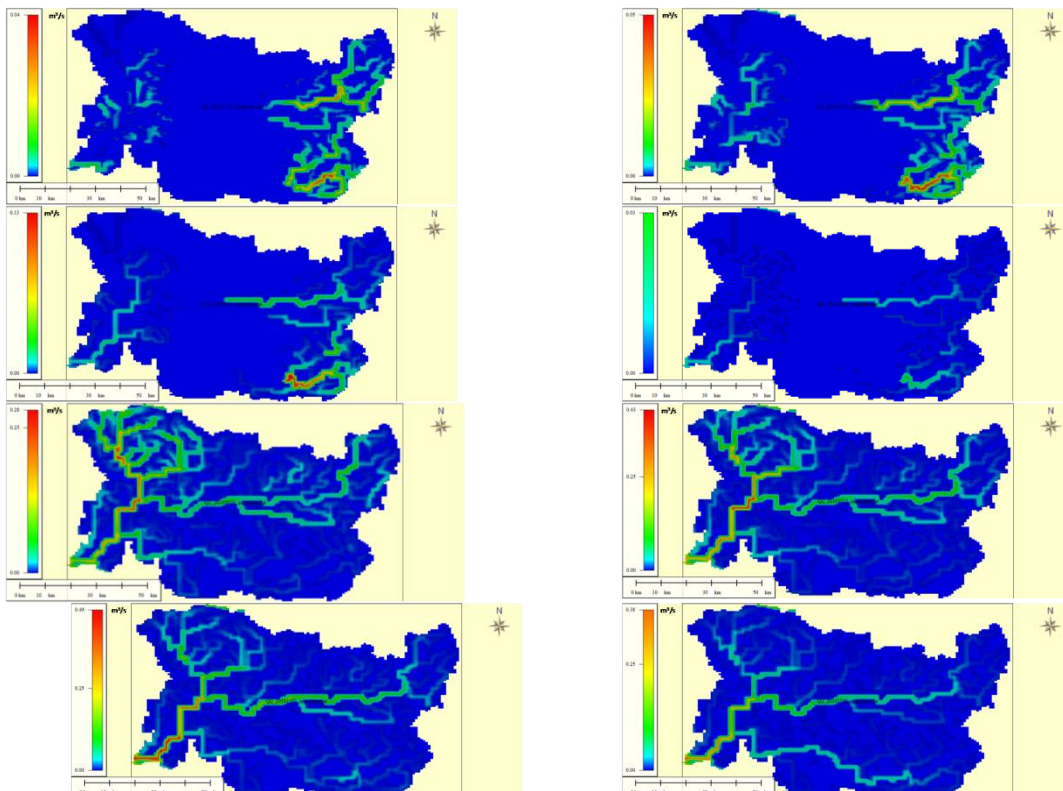


Figure 13. Distribution maps of transmission losses at Wadi El-Assiuti, Egypt (17-18 Jan. 2010).

The estimating of transmission losses is important due to their effect on channel flow reduction as well as their influence on recharging the groundwater of alluvial and quaternary aquifers in wadi El-

Assiuti. The results indicate that estimated transmission losses are affected by the volume of surface runoff as a translation of Walter's equation. In real flood events, the volume and percentages of total transmission losses are usually bigger than the total volume of surface runoff which pass the outlet; which indicates how significant transmission losses are as processes in wadi systems. Synthetic storms which have much higher rainfall than real one, the volume and percentages of transmission losses are smaller than volume and percentages of surface runoff which pass the outlet; transmission losses percentage increasing rate is smaller than the surface runoff which pass outlet increasing rate as the rainfall intensity increases. This is because the channel bed capacity for surface water infiltration is limited and more surface runoff will pass without losses.

4. Summary and conclusions

The soil infiltration rate is an important factor in analysis of the hydrological system that determines the fraction of rain water entering the soil or irrigation and the amount of runoff generated that is responsible for subsequent soil erosion. Two methods to measure the soil infiltration rate are introduced together with corresponding models. These can be considered as good methods in soil infiltration rate measurement. The initially high soil infiltration rate can be measured using double ring infiltrometer. The rainfall simulator method can be used to analyze the effects of raindrops, slope, surface seal formation, etc., on soil infiltration rate. This method is capable of measuring the soil infiltration rate that can be used to quantify the effects of many factors on soil, as well as measuring transmission losses.

The transmission losses and runoff were measured using a rainfall simulator at three observation sites at Wadi El-Assiuti. All experiments were performed with a portable rainfall simulator. Portable rainfall simulators have been widely used for variety purposes. The rainfall simulator method was thus able to provide a new way to obtain a good estimate of the initial losses and transmission losses under artificial rainfall. It provides a useful tool to investigate losses and associated infiltration rate under rainfall conditions

A variety of field tests exists for determining the infiltration rate of a soil. Infiltration rate was calculated according to the installation and operating instruction for the double ring in ASTM 2003. Final infiltration rates were 18 cm h^{-1} , for the first observation site, 24.2 cm h^{-1} for the second site and 59 cm h^{-1} for the third site. The analysis indicated that the soil for the three selected areas is sandy soil. Infiltration rates were taken at 0 to 70 minutes of 10 minutes intervals. The infiltration rate at the third site is high compared to the other two selected sites.

The Hydro- BEAM model estimates transmission losses and groundwater recharge from runoff events in arid Environment wherever hydrological and meteorological records are scanty for direct estimation of transmission losses and groundwater recharge from runoff events. The transmission loss can be evaluated using Walter's equation and the result is reasonable due to its agreement. It is concluded that transmission losses participate as the main if not the only source of recharge to the subsurface. It is noticed that the volume of transmission losses is affected by the volume of surface runoff as evidence that the rate of transmission losses is linearly related to the volume of surface discharge.

Application of the model to another arid reach whose transmission losses and groundwater recharge were directly estimated, results in good agreement between the transmission losses for this reach and that for a reach of Wadi El- Assiuti of similar size and flow volumes. This agreement indicates that the transmission losses along the Wadi El- Assiuti reaches are reasonable.

The transmission losses were subdivided into channel moistening, which subsequently evaporates, and groundwater recharge. Estimation of actual evaporation from channel alluvial fill indicated that large event evaporation is substantially smaller than the transmission losses. It can be concluded, therefore, that most of the lost volume percolates towards aquifers. The mean annual groundwater recharge from runoff events in the Wadi El-Assiuti watershed is estimate as 0.12 MCM. Considering the litho-stratigraphy of the Wadi El- Assiuti watershed, the groundwater recharge could be distributed between the underlying lithologic groups.

The incorporation of geological and lithological information into a quantitative hydrological model helps surmount a shortage in hydrological and meteorological records. This new approach was

successfully applied for additional watercourses in Wadi El-Assiuti and appears suitable for application in other similar arid areas throughout the world.

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 equation are used to estimate the surface runoff and roughness coefficient in each mesh of the watershed basin. B-D-Layers are subsurface layers, which are evaluated using linear storage model, with the assumption of that the flow in each of B and C layers toward the river, but D-layer is considered as groundwater storage. It makes the ground-water zone which does not exert influence in river flow. When storage water content reaches to thickness and becomes saturated state, water content flows into the upper layer of model as returns style.

Hydro-BEAM consists mainly of three main modeling parts; climatic modeling, watershed modeling and the main program modeling. Numerous numerical codes for transmission losses and surface runoff analysis have been developed. Specific 50 source codes were created and saved using Parallel programming, next all source file must be compile. Implement of all codes can be done by using Intel Parallel Studio

As an extension of this study, we plan to use the assessed transmission losses and surface runoff in some Arabian valleys

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