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Modeling of Groundwater Recharge by Rainwater Harvesting-Wadi Bayer (Case Study)

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ABSTRACT

Wadi Bayer is one of Jordan's desertic areas with very low precipitation and limited water resources. It is a typical example of the Jordanian water scarcity chronic condition. Groundwater recharging strategy is one of the long-term solutions of such water scarcity problem due to harsh climatic conditions and high evaporation rate.

The groundwater resources in the area are utilized by the Bedoins for their domestic and cattles' uses. The groundwater is abstracted through three shallow wells drilled in the course of Wadi Bayer. The limited amount of the groundwater in the area is attributed to the limited natural recharge through the wadi bed during the occurrence of floods.

In this study, a location of recharging dike was proposed at a distance of 150-200 m to the south-west of the existing wells, its reservoir area was estimated by 0.0285% of the catchment area of Wadi Bayer, which reflects the rare runoff occurrence.

A home-made spread sheet model and an HEC-HMS model were used in order to estimate the surface runoff.

The alluvium deposits and Rijam formation are the only rock unit groupings in the study area.

The permeability of the topmost 2 meters, which form the floor of the reservoir, is $11.82*10^{-2}$ cm/sec. The top soil column was tested for permeability in the lab through test pit excavation. Seven boreholes were drilled in the site with different depths ranging from 5 to15m, the permeability test was conducted for different depths, ranging between $7.331*10^{-6}$ and $1.805*10^{-3}$.

A groundwater model was run using Processing Mode Flow software to indicate the natural recharge in the area due to the filling of the reservoir from flood water, for 30 day- and 15 day- retention periods. It was found that the groundwater table will rise in the range of 0.33 to 1.5 m and 0.11 to 0.90 m for both retention periods, respectively.

KEYWORDS: Groundwater recharge, Rainwater harvesting, Wadi Bayer, Modeling.

INTRODUCTION

In this study, the available surface water was quantified using a proper surface water model. The storm-by-storm model and the HEC-HMS software were used, compared with a home-made spread sheet model. The generated flow hydrograph was managed through a small reservoir, where the inflow and outflow were developed. The infiltrated water through the reservoir bottom or through a recharge well was defined

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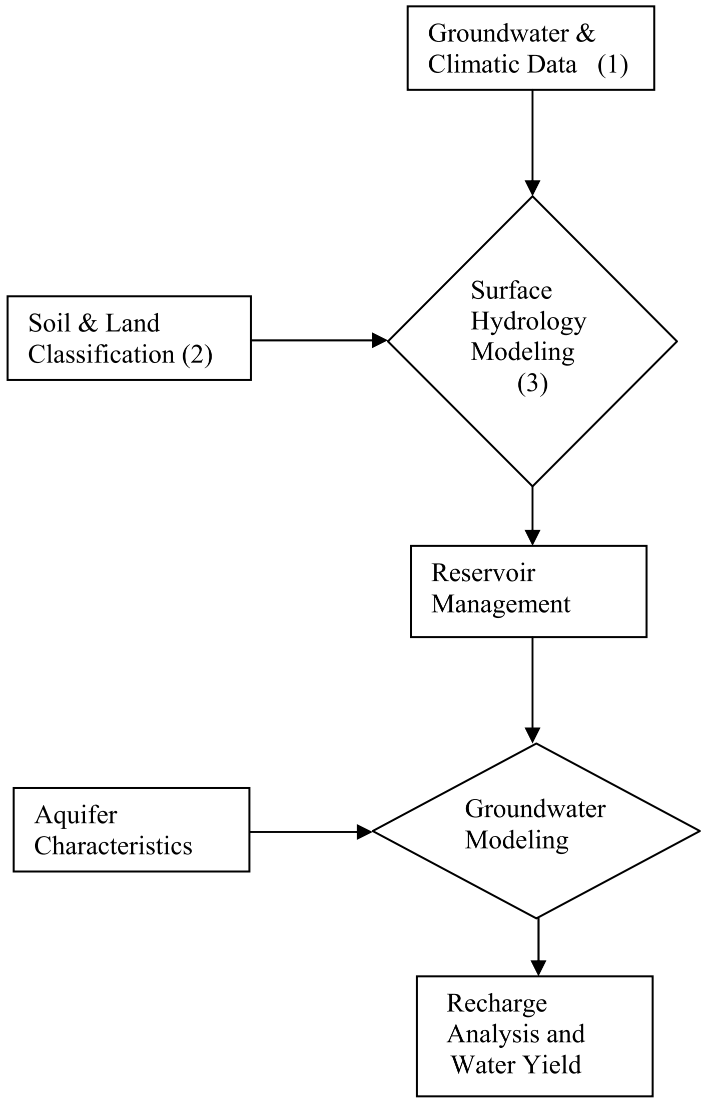
and quantified, where a groundwater recharge model was developed. Wadi Bayer data could be a calibration case study for the general surface-recharge groundwater model. The sequence of the present research is presented in the flow chart of Figure 1. The research comprises the following parts:



(1)	Temperature	(2)	Topography	(3)	Evaluation of Data
	Wind		Surface Geology		Modeling
	Evaporation				Calibration
	Rainfall				
	Groundwater Level				
	Quality				

Figure 1: Flow chart sequence adopted in this study

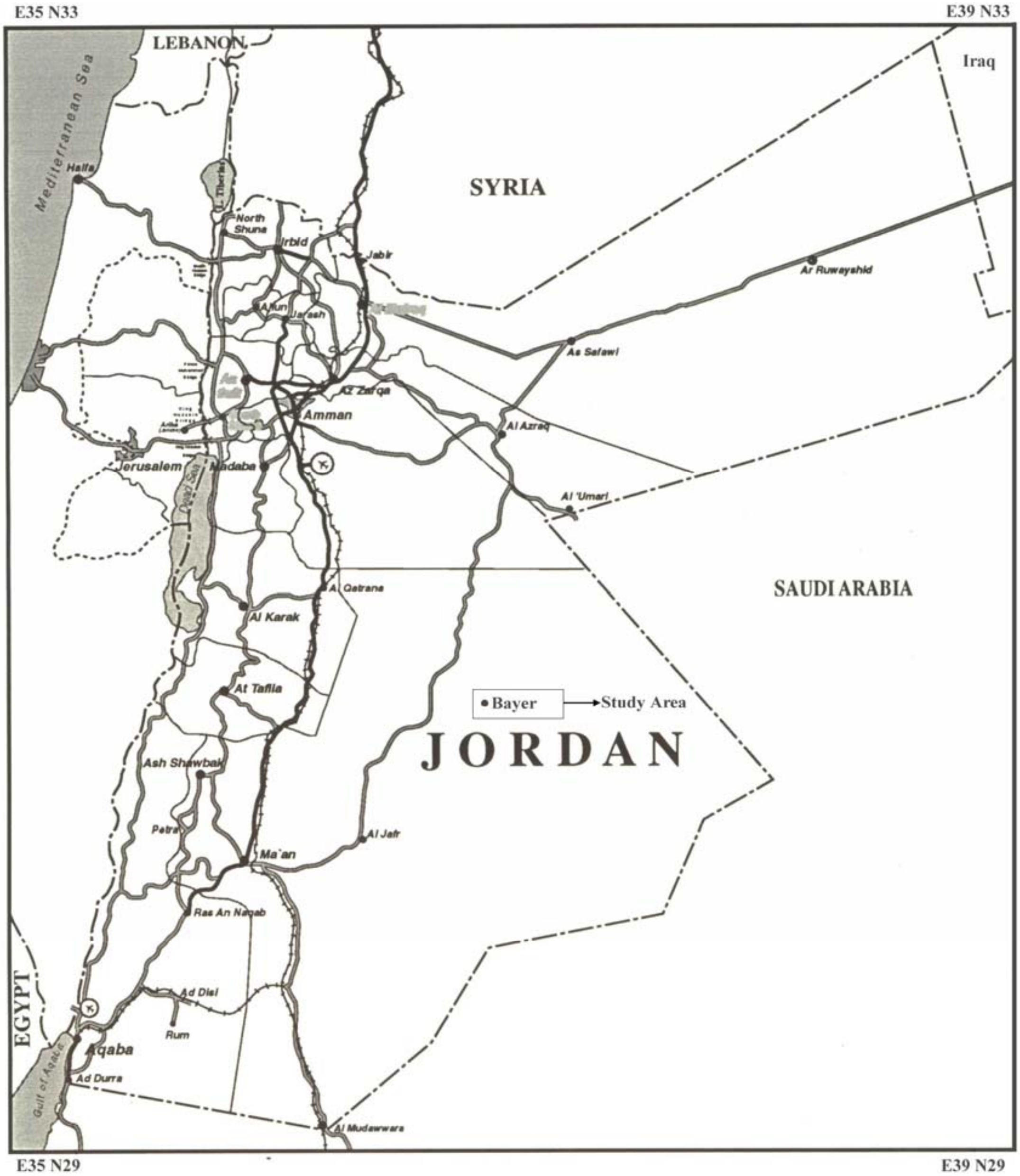


Figure 2: Study area location map

- Hydrological analysis, which includes:
- Collection of climatic data, which includes daily, monthly and annual rainfall, temperature and evaporation (Class "A" Pan) measurements in the surrounding area of Wadi Bayer.
- Evaluation of the collected data in order to estimate the surface runoff using different techniques and models such as: the HEC-HMS model and the SCS-Curve Number method.
- In order to define the appropriate hydrological characteristics of the catchments of Wadi Bayer, the distribution of the different types of soils was defined as well as the exposure of the defined rock formations through using maps of proper scale.

Other catchment characteristics such as: slope and largest length of major wadi were calculated from the topographic and geologic maps with the available scales.

- The implementation of natural or artificial recharge, which requires the availability of sufficient surface water and appropriate quality at a reasonable economic cost.

- Hydrogeological conditions:

The most appropriate geological formations suitable for groundwater artificial recharge are those predominantly granular, fissured or karstic, because of their high vertical permeability. Granular formations usually allow the recharge and storage of large quantities of surface water. In order to determine the suitability of such aquifer for natural recharge, several factors should be investigated;

- The depth to water table in shallow aquifers with the recharge effects.
- The thickness of the non-saturated zone.
- The structure and thickness of the saturated zone with regard to the location of the existing local springs and streams.
- Transmissivity for sufficient thickness of the aquifer.
- Storage capacity of the aquifer in order to secure adequate regularization of groundwater.
- The quality of surface water to be used in groundwater natural or artificial recharge which might have detrimental environmental effects on groundwater if not properly handled.

The quantification of the infiltration water was conducted using the Processing Mode Flow Model. Figure 1 presents the main issues which were tackled by the present study. The flow of the study reflects the sequence of the course of the research starting with climatic parameters and going on to groundwater modeling.

The Study Area

Wadi Bayer location is at the eastern part of Jordan and could be reached at a distance of 120 km from Azraq city through the Azraq-Jafer highway to Bayer New Police station and then 19 km east of the new police station. Figure 2 represents the general location of Wadi Bayer.

Geology and Hydrology

Geology

In order to know the soil and rock formations which exist in the study area, a geological study was carried out. The study was divided into two parts: field work and laboratory testing. Seven bore holes were drilled and seven test pits were excavated. A field permeability test was conducted on the stand pipe piezometer of two boreholes, and falling head permeability tests were done on the rest. The Alluvium Deposits and Rijam Formation (B4) were encountered through the study area.

Hydrogeology

The Rijam Formation forms the slopes of Wadi Bayer as confirmed by the boreholes drilled in the project area, and its thickness is greater than 15 m from the ground surface. This formation is considered a shallow aquifer in the Azraq Basin and Jafer Basin.

However, wadi deposits are of greater importance to this study than the Rijam Formation. These deposits are gravelly in nature with varying proportions of sandy silty matrix in the uppermost 1-2 meters. At further depth, the matrix becomes more and more clayey with the gravels still present. The thickness of the wadi deposits is not exactly known, but may be about 15m. There is no doubt that this gravelly material will even be a better aquifer than the Rijam Formation, particularly the topmost 1-2 meters. From pervious experience in the geology of Jordan in similar situations, both rock units are hydraulically connected. The Rijam Formation and the wadi gravels form one aquifer. The water percolating down through the gravels would eventually be transmitted into the Rijam Formation depending on the quantity of the collected reservoir water and the infiltration capacity.

The permeability of the topmost meter in test pit 1 in the wadi within the site is 0.1182 cm/sec. This is good for the topmost gravelly material which makes the floor of the reservoir. However, much lower permeability values are measured in the 7 boreholes drilled in the site. Their permeability ranges from 1.805 * 10^{-3} m/sec (155 m/day) in borehole BH1 to 7.331*10^{-6} m/sec(0.63 m/day). The upper permeability values are still indicating good permeability, and the reservoir water would reach the existing wells in a matter of 2 days or so. The lower permeability values would indicate a slow passage for groundwater. Reservoir water would seep quickly into the top meter of the gravels then percolate slowly. However, in general, the existing wells situated at a distance of 150-200m away from the proposed dike, will be easily recharged naturally in a relatively short period of time.

The presence of a relatively thick, impermeable marl horizon, 8 m deep, between the dike and the existing wells, would indicate that the groundwater flow is going to be within the upper permeable material overlying the marl and then to the wells.

The permeability of the gravels, their thickness and the presence of a marl horizon in the groundwater flow path are believed to ensure the flow from the reservoir via the gravels to the Bayer wells. Most probably, the Rijam Formation is going to be involved in this process. Natural recharge may be a good way to fulfil the objective of this study.

Rainfall-Runoff Modeling

Runoff was developed through this research. Using Rainfall-Runoff Modeling, the rainfall records over the catchment of Wadi Bayer were analyzed and a rainfall-runoff model was developed according to the following procedures:

1. Data Collection

Data were collected for the project area (recharge site, catchment area) and for the surrounding area according to available information. Hydrological data were used for rainfall-runoff modeling, and the topographic maps and aerial photographs were used for catchment boundaries' determination. The data can be summarized as follows:

- Hydrological data including daily rainfall intensity.
- Climatological data including wind speed and direction as well as minimum and maximum temperature.
- Topographical data including topographic maps; JTM grid of a scale of 1:50,000.
- Aerial photographs of a scale of 1: 30,000.

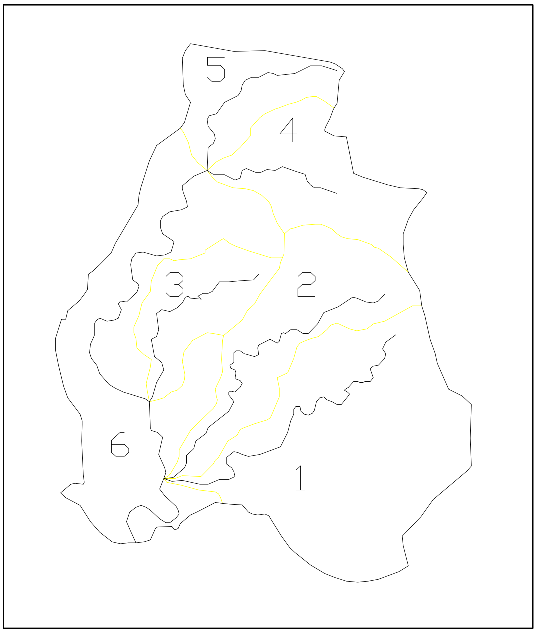


Figure 3: Wadi Bayer catchment areas

2. Data Analysis

Point of interest (the dike) is determined using the topographic maps. All streams with flow direction to the point of interest can easily be known by using the topographic maps, which were scanned as an image. The work was carried out on the AutoCAD for efficiency and accuracy.

According to given data, a picture of primary catchment area boundaries become definite. Several points were selected in order to establish the catchment boundaries. These points are located at the highest elevations on the dividing lines between the areas that contribute to surface runoff into the streams toward the point of interest. These points were connected together by lines to form the catchment area boundaries, which should not cross any stream.

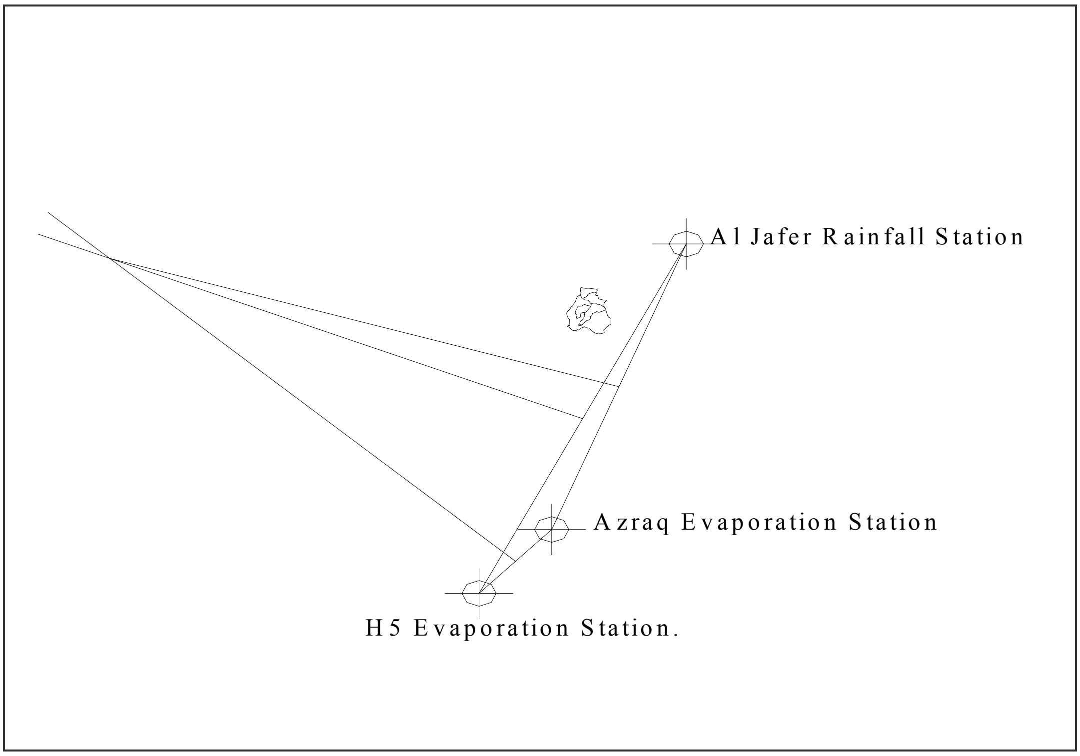


Figure 4: Thiessen polygon diagram

The longest stream (path of water) was considered to be the main stream of the whole catchment, and the other streams became tributaries. Each tributary has a sub-catchment area. All sub-catchment boundaries were developed in the same manner. Certain points were selected in order to establish local coordinates. These coordinates were fitted into AutoCAD Software to form the horizontal projection of all catchment segments. Figure 3 presents all catchment areas and the main streams' tree.

2.1 Stream Profiles

In order to obtain the stream profiles, the coordinates and elevations of start and end points, contour lines intersect points and all changing points were determined.

2.2 Stream Slopes

The slopes of a drainage basin and its channels have a very strong effect on the surface runoff process and on the hydrological calculations. The slopes were developed using different methods, such as Average Slope Method, Area Slope Method, Weighted Slope Method and Slope Index Method.

2.3 Land Slope

One of the commonly used methods of determining the land slope has been presented by Horton (1971). The land slope can be determined using the following formula:

$$S = \frac{x \sec \theta}{L} h$$

where, x = the total number of contour intersections.

L= the total length of grid line segments.
h= contour interval

θ= the angle measured between a normal to the contours and the grid line.

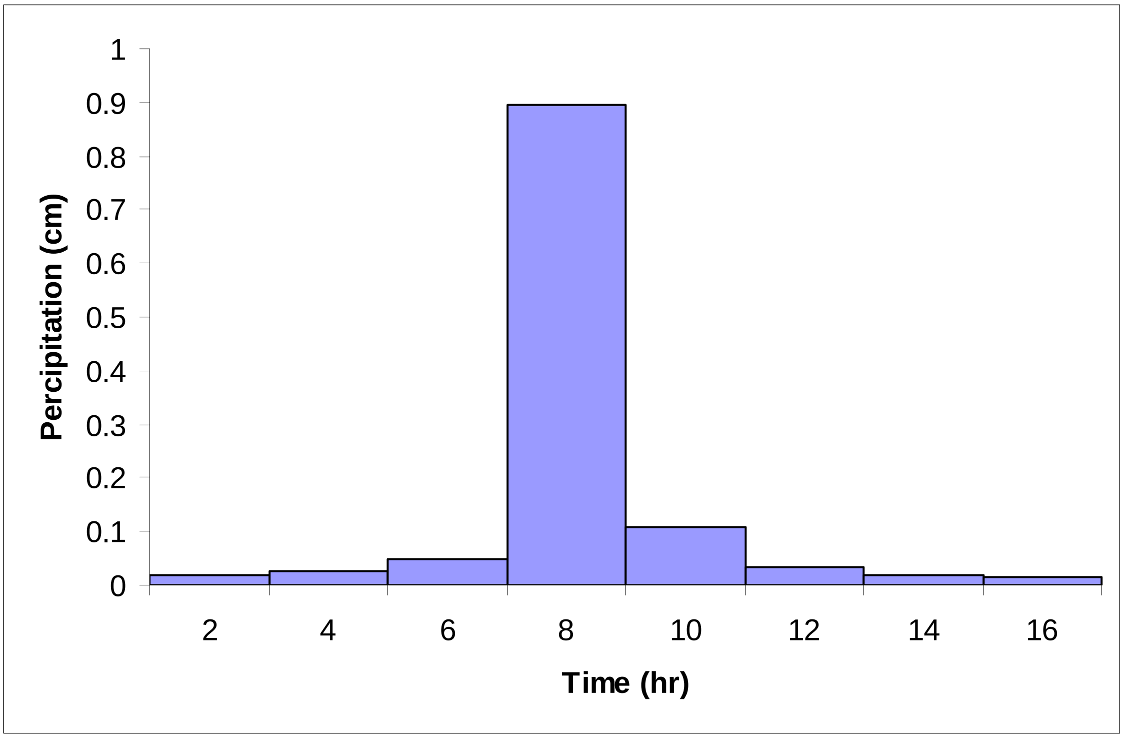


Figure 5: 50-year 16-hour effective design hyetograph

3. Thiessen Polygons

Hydrologic data were collected from several rainfall stations, and the coordinates of each station were imposed on the topographic map using AutoCAD. The locations of the effective stations were analyzed and incorporated within the b catchment, and Thiessen polygons were constructed. The effective rainfall stations were selected and the weighted ratio for each was calculated from Thiessen polygons.

4. Direct Runoff

The Soil Conservation Service (SCS) (1972) Curve Number (CN) procedure was adopted to find the potential runoff of Wadi Bayer. The basic assumption of the SCS curve number method is that, for a single storm event, the ratio of the actual soil retention after runoff begins to potential maximum soil retention is equal to the ratio of direct runoff to available rainfall. The area was classified to have a uniform land use, which is pasture with no treatment or practice and poor hydrologic condition with group C as hydrologic soil group. Through these classifications, the curve number was extracted from the Runoff Curve Number for hydrologic Soil-Cover complexes' table and found to be 86. The direct runoff was estimated using storm by storm analysis according to the effective rainfall station data.

5. Time of Concentration

Catchment time of concentration was estimated using the SCS time of concentration equation:

$$t_c = \frac{1.67L^{0.8}[(1000/CN)-9]^{0.7}}{1900s^{0.5}}$$

where t_c = Time of concentration, in min.

L = Length of the longest watercourse, in m.

s = average watershed slope, in m/m.

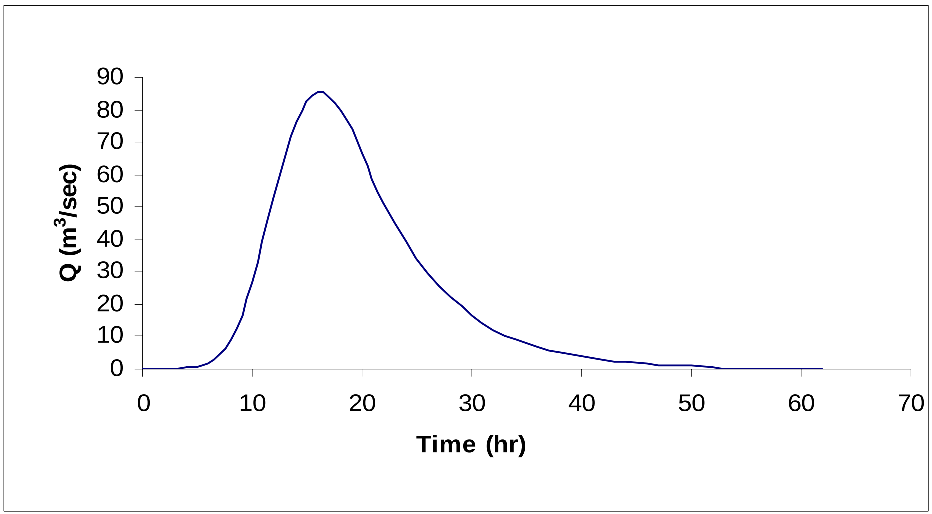


Figure 6: 50-year hydrograph

6. Synthetic Unit Hydrograph (SUH)

A Synthetic Unit Hydrograph (SUH) was used based on watershed characteristics as rainfall-runoff data are not available to develop a unit hydrograph to estimate runoff. The Snyder method and Soil Conservation Service (SCS) method were used to obtain the SUH of the study area.

7. IDF Curve Regression

Intensity -Duration-Frequency (IDF) curve is presented as a graph, with duration plotted on the horizontal axis, rainfall intensity plotted on the vertical axis and a series of curves of different return periods. In the study area, there are no IDF curves available; however there is an IDF curve available for some stations in the surrounding area. El-Umari rainfall station is the closest station to our site, where IDF curves are available. The power formula and intensity formula were used to express El-Umari IDF curves for return periods of 50 and 100 years, through regression process.

Power formula: $I = aX^b$

Intensity Formula: $I = a/(b+X)$

where: I= Intensity (mm/hr).

X = Duration (min).

8. Design of Precipitation Hyetographs from IDF Relationships

The alternating block method is a simple way of developing a design hyetograph from an intensity-duration-frequency curve. It was used to obtain a design hyetograph for Wadi Bayer catchment. Figure 5 presents the hyetograph of a 50-year return period.

9. Hydrograph Construction

For Wadi Bayer, there are no available records or hydrographs, so a hydrograph was estimated by using a unit hydrograph and an effective hyetograph. The discrete convolution equation:

$$Q_n = \sum_{m=1}^{n\le M} P_m U_{n-m+1}$$

was used to yield the direct runoff hydrograph, where the time interval used in defining the effective hyetograph and the unit hydrograph ordinates must be the same. A hydrograph was constructed for Wadi Bayer catchment and all its sub-catchments for return periods of 50 and 100 years. Figure 6 presents Wadi Bayer catchment hydrograph for a 50 year return period.

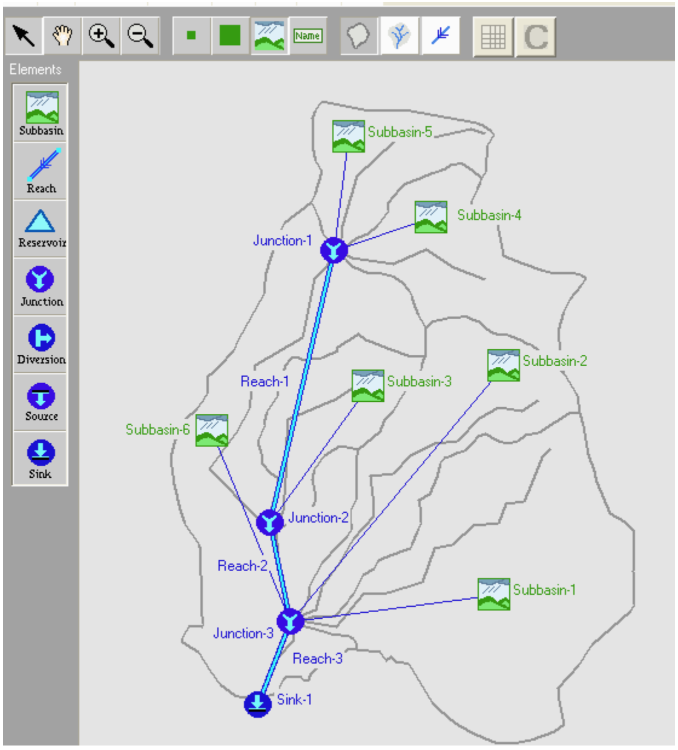


Figure 7: Wadi Bayer basin model schematic

Rainfall-Runoff Modeling Using HEC-HMS Software

The U.S. Army Corps of Engineers Hydrologic Modeling System (HEC-HMS) is a new-generation software for precipitation-runoff simulation that has superseded the HEC-1 Flood Hydrograph Package during the past decade. HEC-HMS is a significant advancement over HEC-1 in terms of both computer science and hydrologic engineering. It is a product of the Corps Civil Works Hydrologic Engineering R&D Program.

Model Construction

The following steps were followed to construct the Rainfall-Runoff model for Wadi Bayer catchment area:

1) Coordinates of basin boundaries were edited to a map file.
2) A schematic representation of Wadi Bayer basin network was created by dragging and dropping icons that represent hydrological elements, and connections between them were established. Figure 7 presents a schematic of Wadi Bayer basin network.
3) Parameters' data for each subbasin were entered using subbasin editor. The required data consisted of subbasin area, loss rate method (SCS Curve Number method was used), transform method (SCS Unit Hydrograph method was used) and baseflow method (No baseflow for Wadi Bayer).
4) Routing method for reaches was determined using routing reach editor. The lag method was used for reaches routing, where the only required parameter for this method was the lag time (travel time).

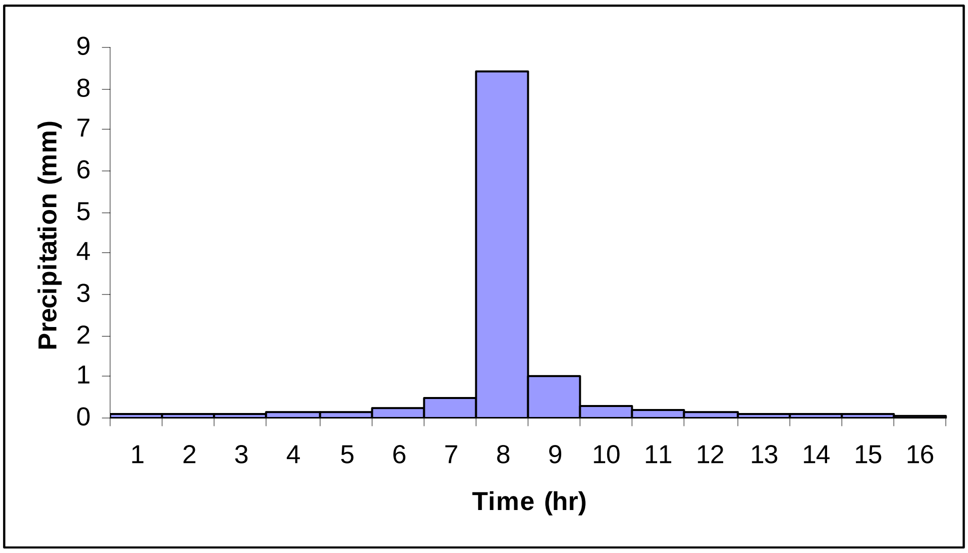


Figure 8: 50-year, 1-hour effective hyetograph

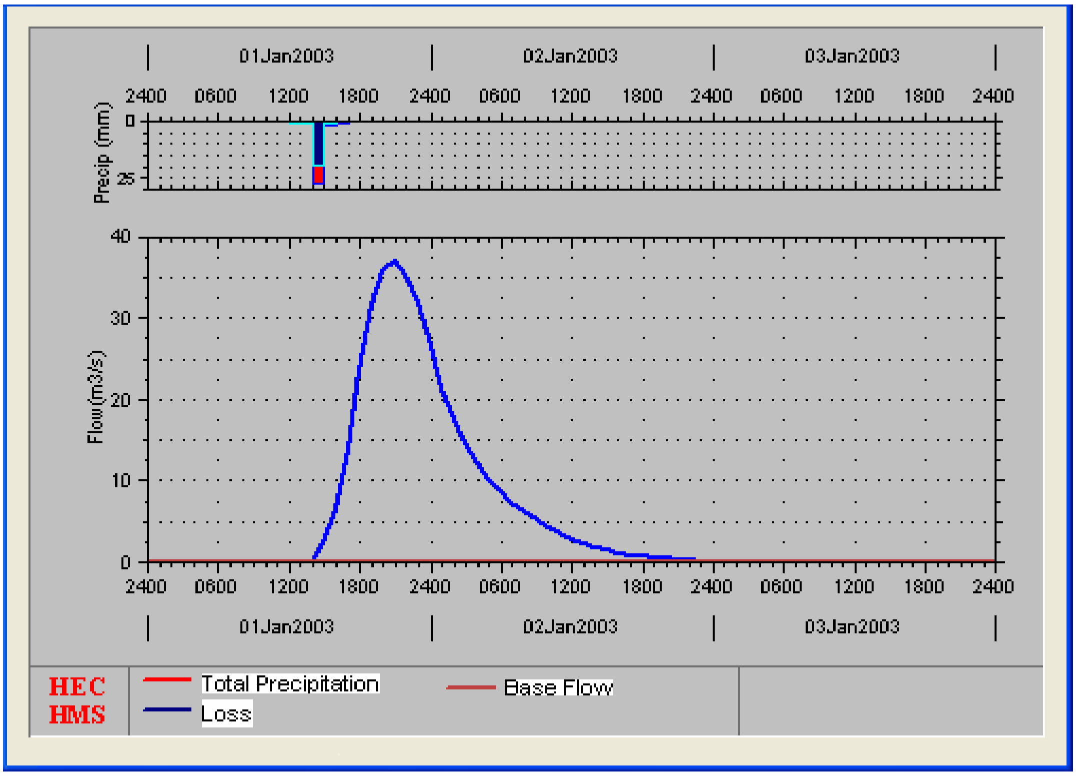


Figure 9: 50-year, 1-hour HEC-HMS hydrograph of sub-catchment #1

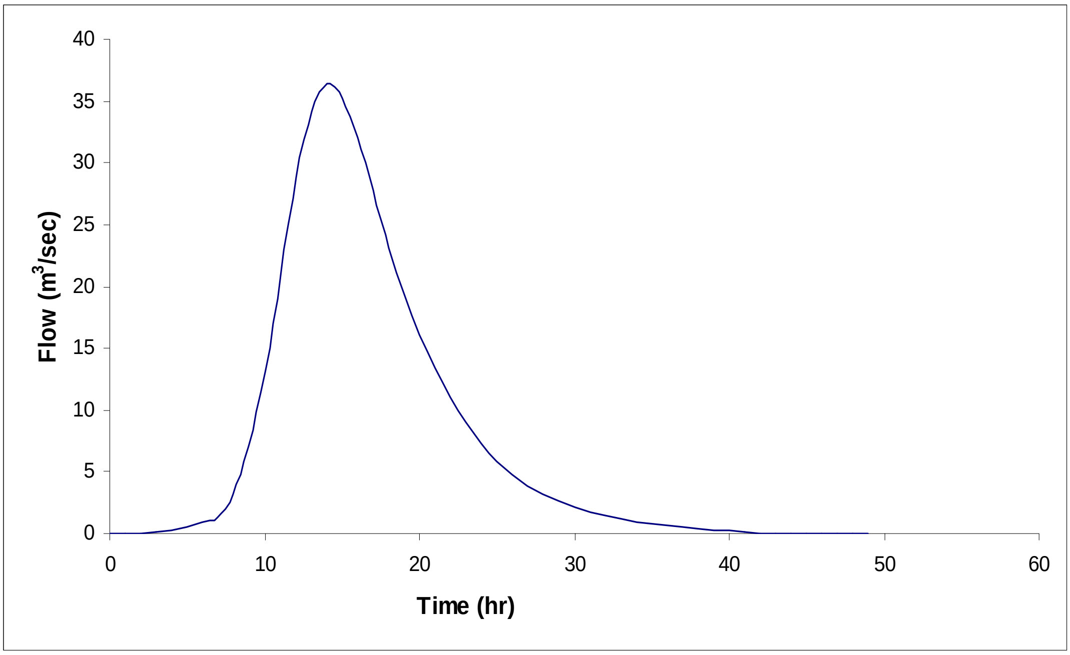


Figure 10: 50-year, 1-hour home-made hydrograph of sub-catchment #1

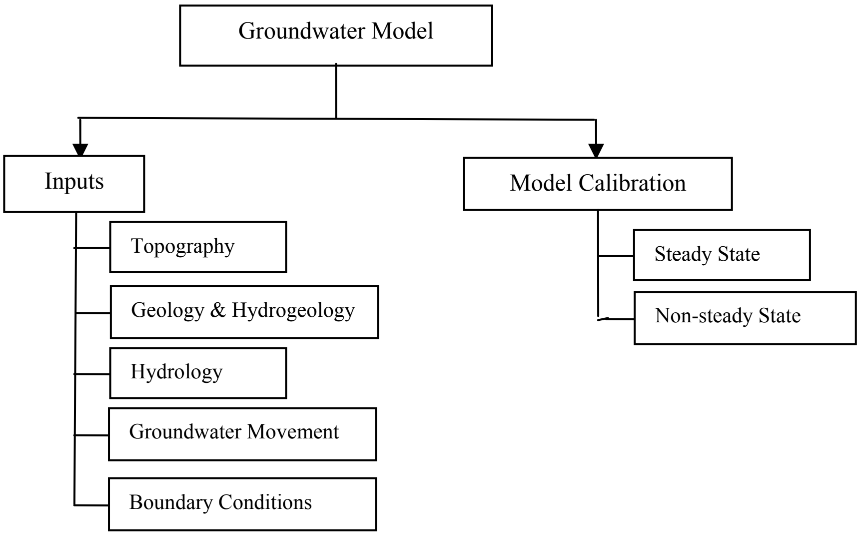


Figure 11: Groundwater modeling data

5) Creating a precipitation model by entering the precipitation data.
6) The control specifications of a four day simulation period was selected with 1 hour time interval.
7) Creating and executing simulation runs: two runs were created; one for the 50-year return period and the other one for the 100-year return period, each with its own precipitation gage.
8) Viewing the simulation results.

Figure 8 presents a 50-year hyetograph.

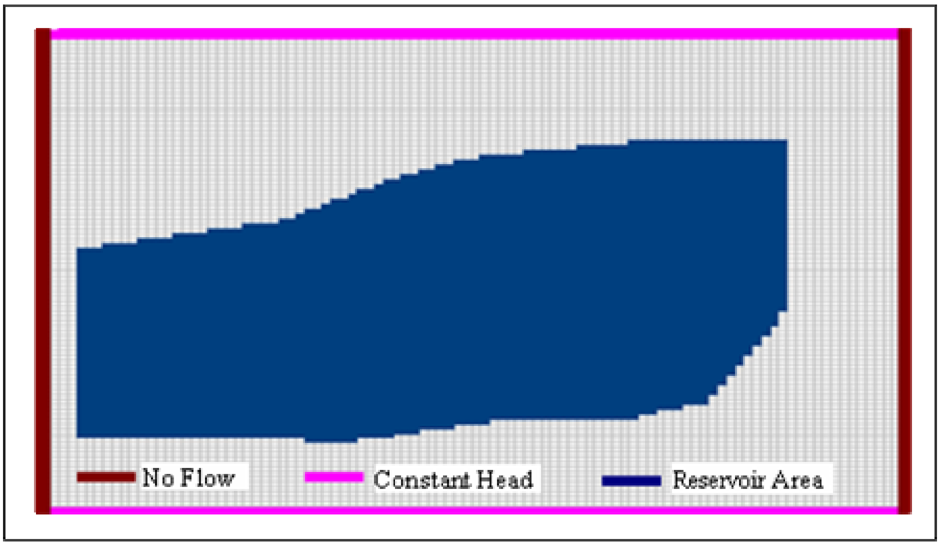


Figure 12: Boundary conditions

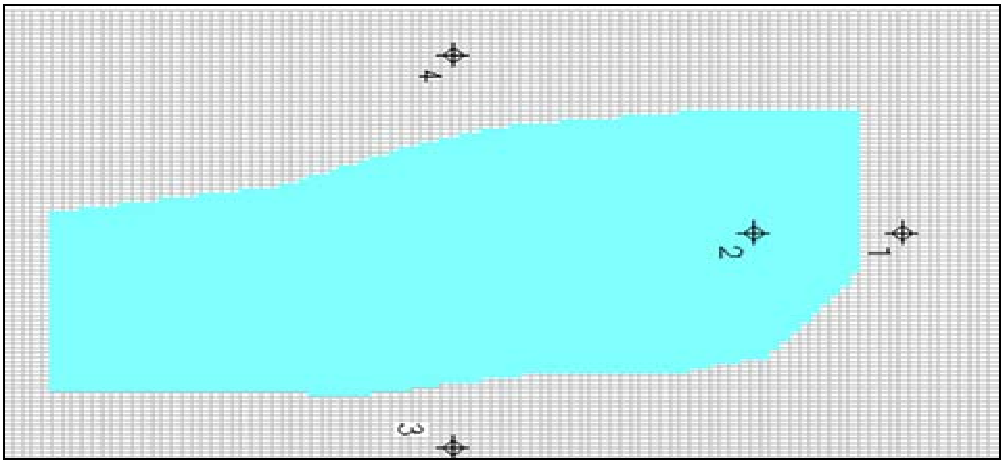


Figure 13: Model area with reservoir and observation wells' location

A comparison of Home-Made Spread Sheet *versus* HEC-HMS Rainfall-Runoff Model was made. The differences were between 0.13% and 16.63% for the 50-year return period and between 0.77% and 16.14% for the 100-year return period.

This shows very little discrepancies, leading to an important conclusion regarding home-made spread sheet capability to produce an accurate hydrograph. Figure 9 and Figure 10 represent the results of the home-made spread sheet and the HEC-HMS results for a 50-year return period, respectively.

Groundwater Modeling

A groundwater model was run using Processing Mode Flow software to indicate the natural recharge in the area due to the filling of the reservoir from flood water, for 30-day and 15-day retention periods.

The modeling process followed two phases, as shown in Figure 11.

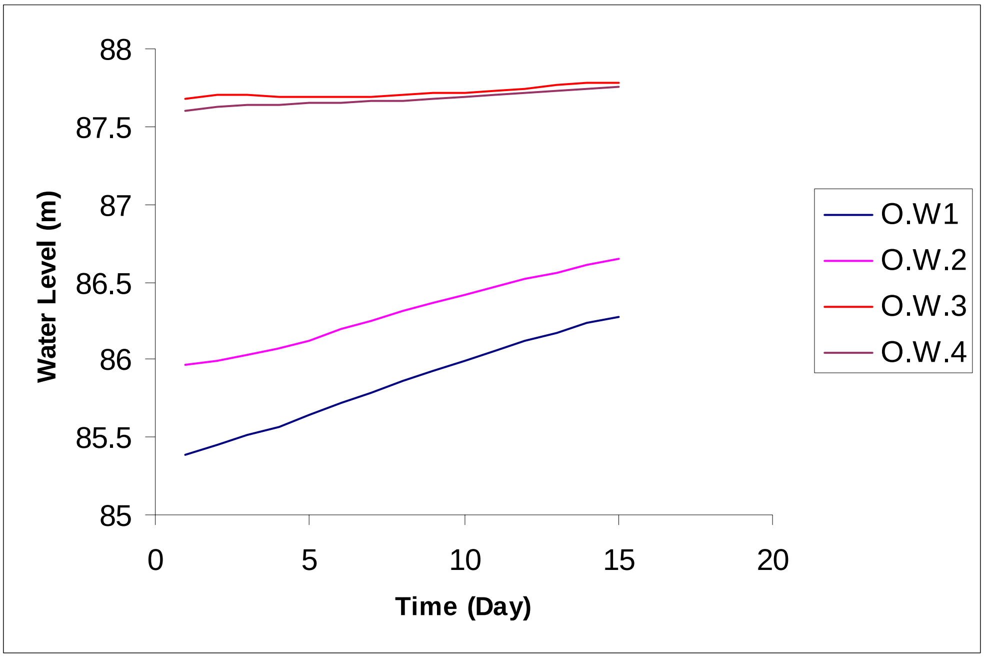


Figure 14: Groundwater level fluctuation in observation wells, scenario 1

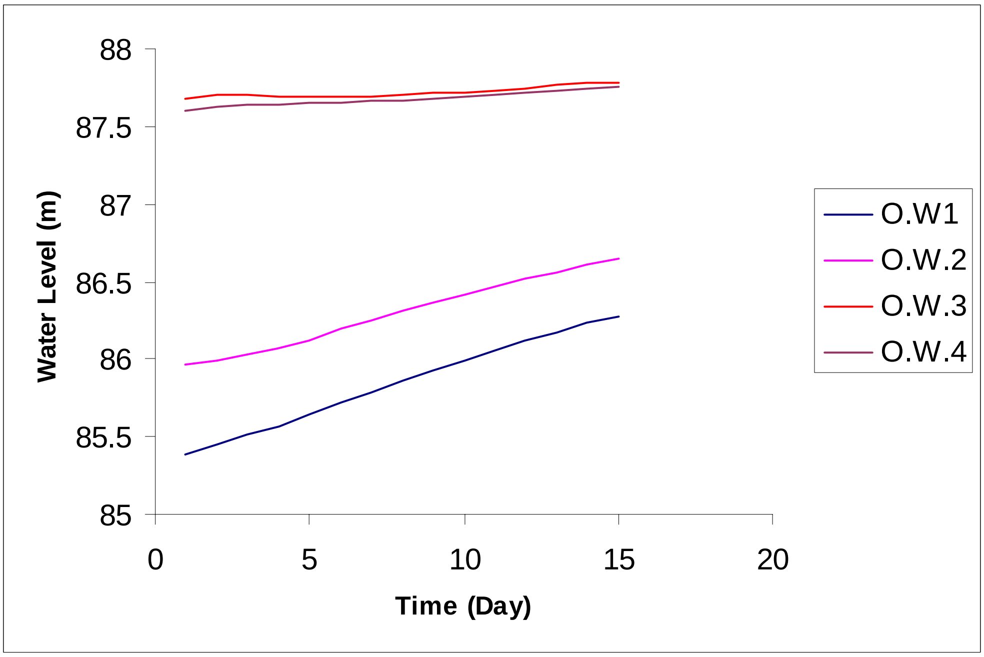


Figure 15: Groundwater level fluctuation in observation wells, scenario 2

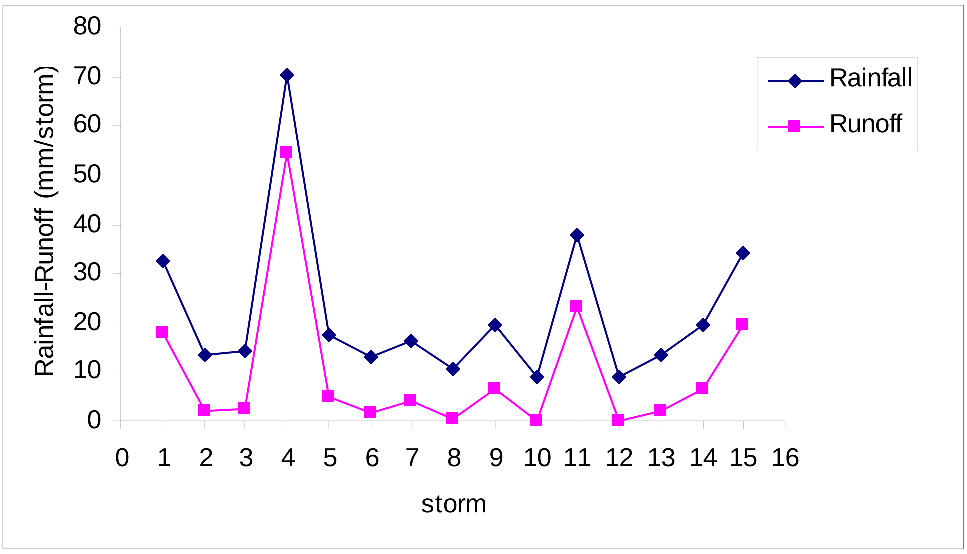


Figure 16: Rainfall-runoff storm by storm analysis

Inputs

Topography

Professional land topographic survey was carried out on the area of interest covering up and down stream areas of the proposed dike.

Geology and Aquifer

Rijam Formation (B4) and the Alluvial wadi deposits, both of which are considered an unconfined aquifer, are directly (vertically and horizontally) interconnected.

There are limited numbers of wells penetrating alluvial sediments. Also, there are three hand dug wells drilled downstream the dike.

Hydrogeology

The total thickness of the whole aquifer system which is constituted from the alluvial wadi deposits and partly the Rijam Formation (B4) is about 50 m. About 30 m of them represent the alluvial deposits and 20 m correspond to the non-exposed B4. The hydraulic characteristics of this composite aquifer system are taken from other basins in Jordan; e.g. Azraq and Jafr basins. The vertical hydraulic conductivity for modeling purposes was taken to range between 10 and 30 m/day.

Hydrological Information

It was assumed that the reservoir bed will be of a constant level, with a maximum depth of 1.5 m and side slopes of 1:3. Using AutoCAD software, the area of the reservoir was estimated at different depths ranging between 0 m and 1.5 m with 0.5 m step size.

At each depth, the volume of the reservoir was calculated in order to obtain the capacity curve for the reservoir. From the available 23-year rainfall record, the number of storms creating runoff was estimated by storm-by-storm analysis, and these were categorized according to wet and dry years. The runoff volume was calculated and compared with the maximum reservoir volume. The runoff volume is greater than the maximum reservoir volume except for two storms. The reservoir was estimated to be full at least once every two years, which forms the recharge source for the interest area.

Groundwater Movement

From the available water level in the wells as well as the geomorphic characteristics of the area, the water table contour map was delineated.

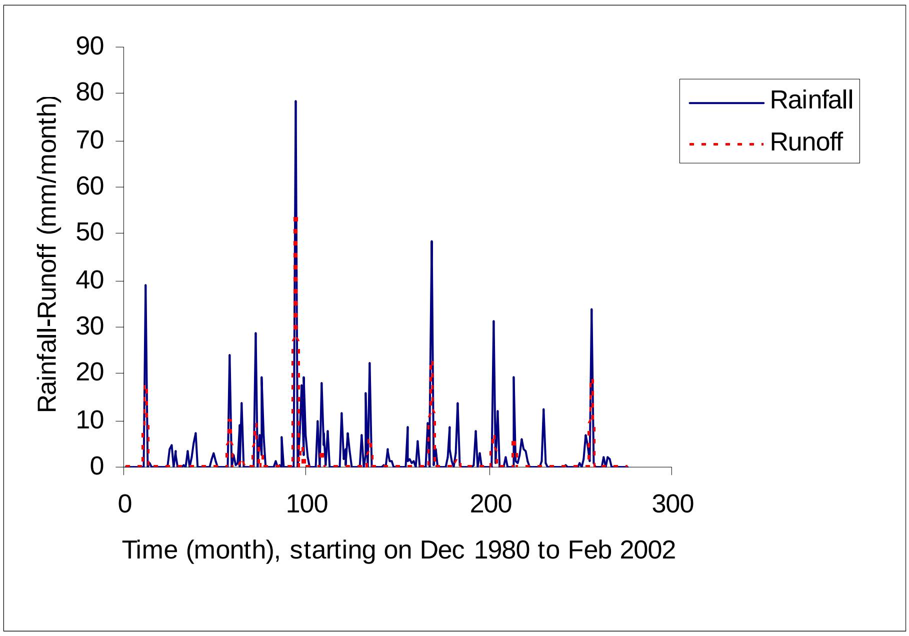


Figure 17: Monthly rainfall-runoff analysis

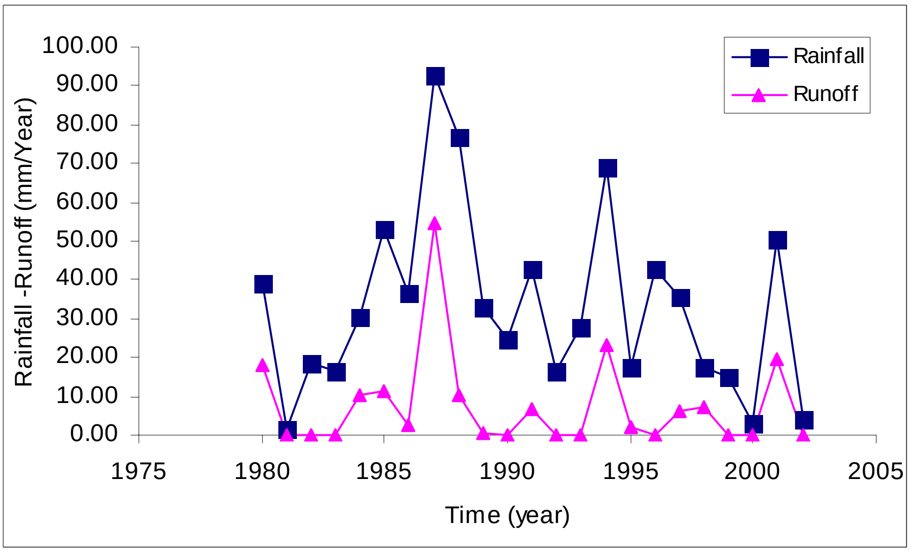


Figure 18: Annual rainfall-runoff analysis

Boundary Conditions

In Mode Flow, 3 types of boundary conditions are used:

Type 1- specified head boundaries are identified by assigning the values (-1) to represent a constant head cell and (1) for a variable head cell.

Type 2- no flow boundaries, and the value (0) represents an inactive cell.

Type 3- boundaries are identified as General-Head boundaries due to the presence of a river and a drainage system. The third type of boundary conditions is not presented in the study area.

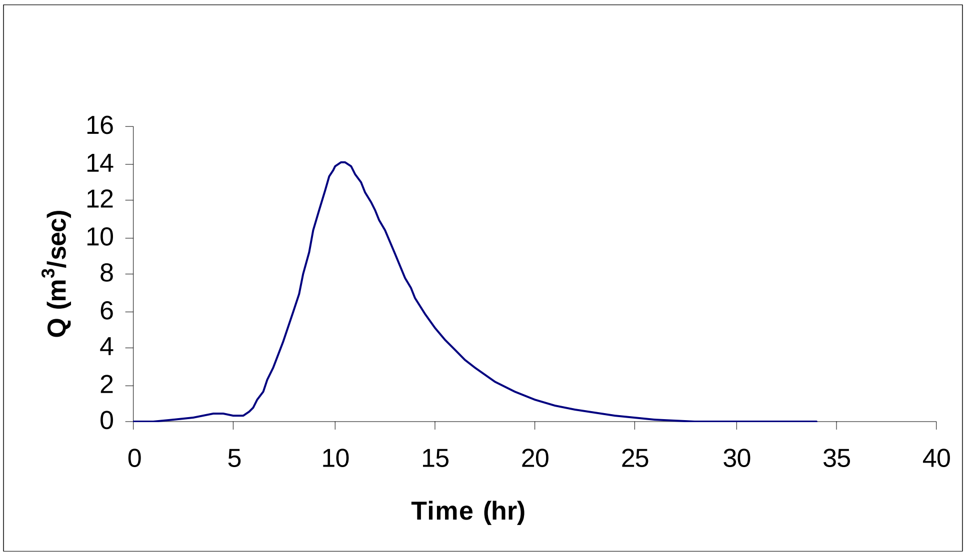


Figure 19: 50-year, 2-hour hydrograph of sub-catchment #5

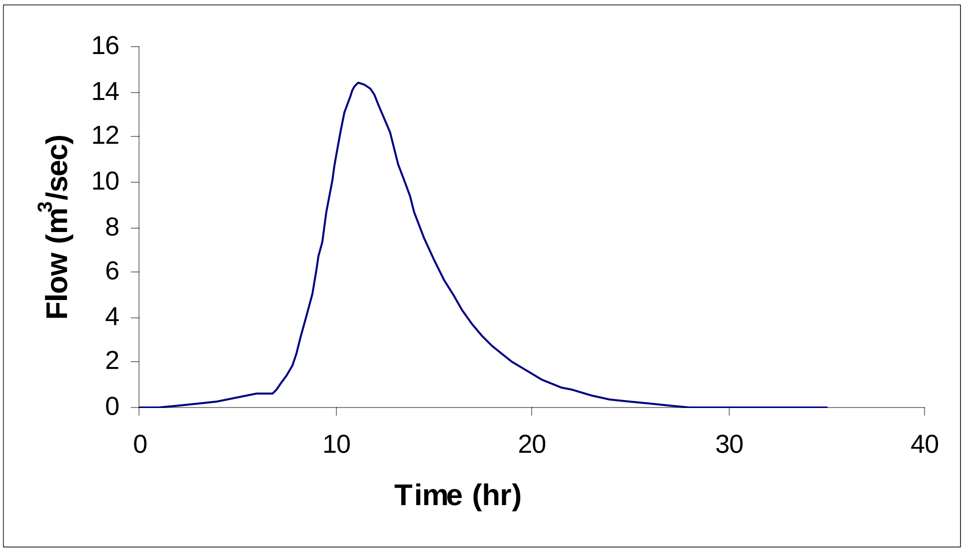


Figure 20: 50-year, 1-hour hydrograph of sub-catchment #5

The boundary conditions were identified for Wadi Bayer as follows:

At the southern part of the model area near the entrance of the reservoir, the boundaries were defined as constant head cells. Also, constant head cells were defined in the northern part of the model. Head is considered constant at these boundaries, because water flows steadily either as input or output from these boundaries. At the east and west sides of the model area, the boundaries were defined as no-flow boundaries.

Model Calibration

Steady State Calibration

Matching the initial heads of the groundwater with the hydraulic heads of the groundwater simulated by PM5 which is governed by changing the hydraulic parameters by trial and error, at each trial the simulated groundwater level was compared with that of the initial head of groundwater until the simulated groundwater level matched the initial head of groundwater.

Non-Steady State

It cannot be tested at this stage of research, hence there is no actual data on the groundwater level monitoring, and actually there is no dike constructed yet in the area.

Two scenarios were assumed for how long it will take the water depth in the reservoir to decrease from the maximum depth of 1.5m to 0.0 m depth.

- Scenario 1: at this scenario, it was assumed that it will take 30 days for water depth in the reservoir to decrease from 1.5 m to 0.0m. These 30 days were divided into three stress periods; each stress period is equal to 10 time steps, each time step is equal to 1 day.
- Scenario 2: at this scenario, it was assumed that it will take 15 days for water depth in the reservoir to decrease from 1.5 m to 0.0m. These 15 days were divided into three stress periods; each stress period is equal to 5 time steps, each time step is equal to 1 day.

Results

Figure 13 presents the locations of the observation wells, which are used to simulate the fluctuation in groundwater elevation. These wells are distributed in different locations on the model area.

Figure 14 and Figure 15 represent the change in simulated water level with time.

From Figures 14 and 15, we notice that the increasing rate of groundwater level in O.W.1 which is in the downstream direction is the maximum of all wells. Also, it's recognized that the increasing rates in O.W.3 and O.W.4 are less than the rates of the other ones, which means that the recharge in the side direction of the reservoir is less than in the downstream direction.

CONCLUSIONS AND RECOMMENDATIONS

The nature of the present study leads to crucial issues such as water availability to local community. The important points raised by this research were discussed and important conclusions were listed. Recommendations for further studies were developed and listed according to priority.

Conclusions

a) According to the SCS CN storm-by-storm analysis, it’s found that the runoff is perfectly matching the rainfall. Figure 16 represents rainfall-runoff modeling and shows the perfect matching between the two series.

b) Monthly time series of rainfall-runoff analysis is represented in Figure 17, which shows the maximum rainfall for the period of the last 22 years in Oct. 1987 with a depth of 78.4 mm. This rainfall generates a runoff of 54.5 mm/month. The spikes, or as named by Sritharan and Gee (1996) “pulse and decaying”, present a moderatly frequent occurrence of high rainfall intensity storms as shown in the Figure. This condition is matching the research conducted by Taylor and Howard (1996).

c) Annual rainfall-runoff analysis is represented in Figure 18, which shows the wet year 1987 for the mentioned record. Also, it shows that the pattern of runoff is perfectly matching the rainfall pattern.

d) The flow hydrographs generated by both HEC-HMS software and home-made spread sheet were compared; the results are comparable except the total catchment hydrograph, due to the difference in the routing method between the two models.

e) Different slope evaluation methods were conducted and the following was concluded:
   - Step size is important in slope index estimation.
   - Estimated elevation according to weighted slope is perfectly matching the ground elevation shape.

f) Hydrograph shape is highly affected by the time interval (step size) of the synthetic unit hydrograph and the design hyetograph. Decreasing the step size leads to a high smoothness of the hydrograph shape, as shown in Figure 19 and Figure 20. The 50-year hydrograph of sub-catchment #5 with two hour step sizes was smoothened by decreasing the step size into one hour.

g) From the PM5 groundwater model results, it was found that the rise in water table in the downstream direction is more than the rise in the groundwater table at the side of the stream.

Recommendations

a) This research is a part of an ongoing project of a 3 year period. Therefore:
   1. After the construction of the dike, its highly recommended to install a monitoring system for the water level in the reservoir to obtain real data to be used with the groundwater recharge model for calibration.
   2. For further study, the use of a digital elevation model will highly enhance the determination of the catchment boundaries, streams slopes and catchment area calculations through using higher modeling software that can deal with the topographic changes.
   3. Recharge process is sensitive to fine material accumulation on the reservoir bed. Therefore, removing silt clay from the reservoir bed every year to enhance the infiltration rate is a must.
   4. Producing a well in the downstream direction is required, where the recharge rate is the best.

b) Installing both a meteorological station and a flood gage is required to check and enhance records.

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