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M. Masoud, S. Schumann & S. Abdel Mogheeth

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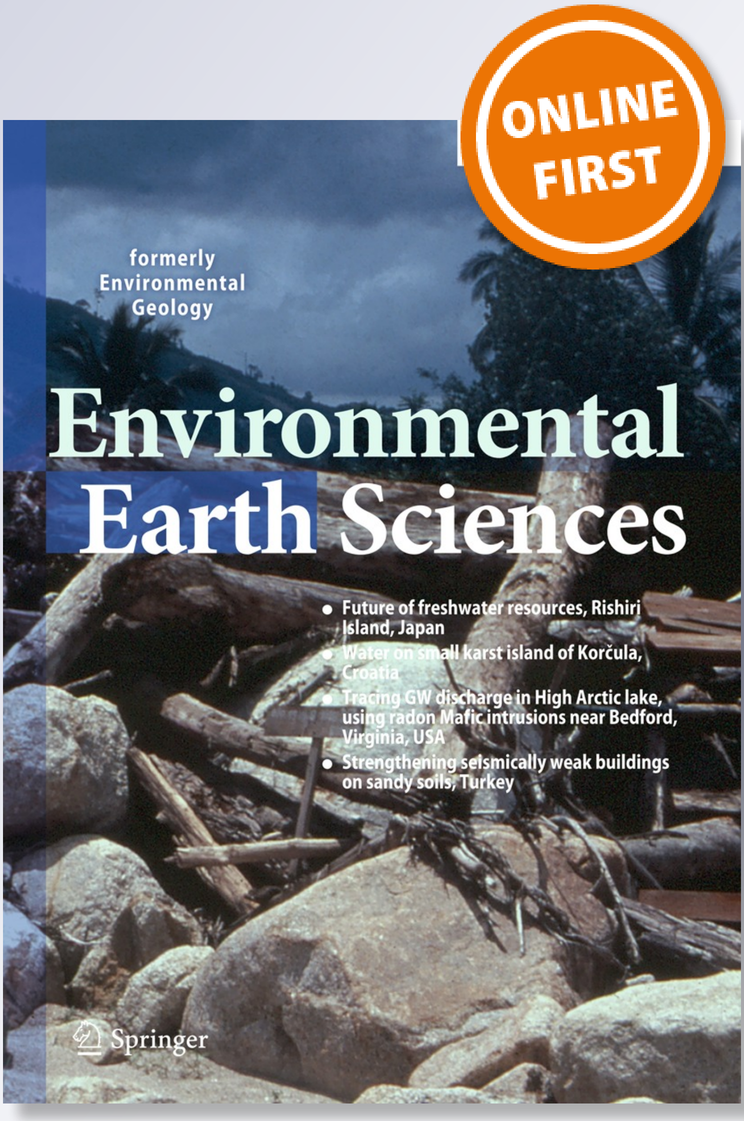

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ORIGINAL ARTICLE

Estimation of groundwater recharge in arid, data scarce regions; an approach as applied in the El Hawashyia basin and Ghazala sub-basin (Gulf of Suez, Egypt)

M. Masoud · S. Schumann · S. Abdel Mogheeth

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Abstract In this study, an approach for runoff and recharge estimations that can be applied in arid regions which suffer from lack of data is presented. Estimating groundwater recharge in arid regions is an extremely important but difficult task, the main reason is the scarcity of data in arid regions. This is true for the Eastern Egyptian Desert where groundwater is used for irrigation purposes in agricultural reclamation along the Red Sea coast line. As a result of the scarcity of hydrologic information, the relation between rainfall and runoff was calculated depending on the paleo-flood hydrology information. Two models were used to calculate the rainfall–runoff relationships for El Hawashyia basin and Ghazala sub-basin. Two computer programs known as Gerinne (meaning channel in German) and SMADA6 (Stormwater Management and Design Aid, version 6) were conjunctively used for this purpose. As a result of the model applied to El Hawashyia basin, a rainfall event of a total of 18.3 mm with duration 3 h at the station of Hurghada, which has an exceedance probability of 5–10 %, produces a discharge volume of 10.2×10^6 m^3 at the delta, outlet of the basin, as 4.7 mm of the rainfall infiltrates (recharge). For the Ghazala sub-basin, the model yields a runoff volume of 3.16×10^6 m^3 transferred from a total rainfall of 25 mm over a period of 3 h, as 3.2 mm of it was lost as infiltration.

Keywords Runoff · Groundwater · Wadi · Infiltration · Model

Introduction

Estimating groundwater recharge in arid regions is an extremely important but difficult task, the main reason is the scarcity of data in arid regions. This is true for the Eastern Egyptian Desert where groundwater is used for irrigation purposes in agricultural reclamation along the Red Sea coast line.

Rainfall–runoff relationships are very important for the catchment managements (i.e. for the sustainable development of the water resources and for the protection from the flood hazard and drought). Rainfall is one of the essential hydrological elements in the modelling of basin systems. Predicting extreme events such as: droughts, floods; estimating both quantity and quality of surface water and groundwater require basic information regarding rainfall. Basin systems in arid regions are commonly subjected to sporadic storm events that usually vary in scarcity and extremely high spatial and temporal variations. Of biggest interest herein is the surface runoff, (i.e. part of the rainfall which flows into the basin channel systems after infiltration, initial abstraction and other abstractions). Usually, the application of hydrologic models in arid regions, are faced by scarcity in the required data that may not allow for the application of rainfall–runoff models.

The aim of this study is to provide an approach for runoff and recharge estimations that can be applied in arid regions suffering from the scarcity of data.

M. Masoud (✉)
Water Research Centre, King Abdulaziz University,
Jeddah, Saudi Arabia
e-mail: zakimilad@hotmail.com

M. Masoud · S. A. Mogheeth
Hydrology Department, Desert Research Centre, Cairo, Egypt

S. Schumann
Geoecology Institute of Technical Braunschweig University,
Brunswick, Germany
e-mail: sybille.schumann@googlemail.com

A number of studies have applied the transmission losses in similar conditions from the point of view of arid to hyper-arid environment, hydrologic characteristics and geologic setting. Walters (1990) proposed three regression equations, two of which were related to transmission losses to upstream volume and channel length. The third equation includes the effect of channel width. Savard (1997) evaluated the relationship between stream flow records and measured water levels in nearby wells in Fortymile Wash in Yucca Mountain, Nevada. Abdulrazzak and Sorman (1994) provided equations to derive transmission losses knowing inflow volume, active flow width, and antecedent soil moisture measurements. Their equations were based on an extensive database for an arid watershed (the Tabalah basin) in the south-western area of the Kingdom of Saudi Arabia. Initial losses occur in the basins before runoff reaches the stream networks, whereas the transmission losses occur as water is channeled through the valley network. Transmission losses are related largely to infiltration, surface soil type, land use activity, and soil moisture content (Gheith and Sultan 2002).

The magnitude and frequency of recharge from ephemeral streams is dependent on the amount of water lost through infiltration into the wadi bed as the flood wave progresses in the downstream direction. Alluvial channels usually infiltrate large volumes of flood flow. The amount of abstraction, which represents the cumulative infiltrated volume, depends on the soil profile, certain physical conditions, and rainfall and runoff characteristics. The infiltrated volume initially satisfies the soil moisture deficit and evaporation requirements, and may eventually contribute towards recharging the alluvial aquifer (Abdulrazzak and Sorman 1988).

Thus, the final model used in the study depends mainly on scarce available information, the required accuracy and the resolution of the output and the time resources that can be directed at the modelling exercise. In this study an approach for runoff and recharge estimations that can be applied in arid regions despite the scarcity of data was provided. As a result of the scarcity of hydrologic information, the relation between rainfall and runoff was carried out depending on the paleo-flood information. Two models were used to reach the rainfall–runoff relationships for El Hawashyia basin and Ghazala sub-basin. The two model programs named Gerinne and stormwater management and design aid (SMADA6) were conjunctively used for this purpose

The generation of the hydrograph for any study basin depends on three main steps, which are:

- Generation of the theoretical hydrograph by the use of the Gerinne model.
- Using SMADA6 model to create the executable files which will be used in the hydrograph generation.
- Final hydrograph generation using SMADA6 with generated data from step 1 and 2 (SBUH method).

Location and hydrogeology of El Hawashyia basin

The study area is located between longitudes 32°15′ and 33°00′E, and latitudes 28°00′ and 28°35′N. The study area is bounded from the west by the higher mountainous range (water divide) and from the east by western coast of the Gulf of Suez and the Red Sea coast.

Geologically El Hawashyia basin is located in the sedimentary basin called West Bakr that has many productive petroleum wells. These wells tap two aquifers; Post-Miocene and Miocene aquifers. Based on Conoco and the Egyptian general petroleum company (EGPC) 1987 and Conoco 1989, the basement outcrops in El Hawashyia basin cover 51.2 % of the area, Cretaceous outcrop rocks 24.2 % while the Quaternary deposits (Post-Miocene) are represented by 13.5 % of the exposed rocks in the whole area as shown in Fig. 1.

From Figs. 1, 2 and 3, it is noticed that the Post-Miocene deposits which are composed of gravels and sands are represented by large thickness in El Hawashyia basin. This thickness ranges from 100 m in the west to 450 m in the east. From the available scarcity data, it is noticed that the water table level in the Post-Miocene strata in El Hawashyia basin have the same shape of the topography, this reflects that the groundwater aquifer in this area is unconfined aquifer.

The east–west geoelectrical cross section (Fig. 2) shows that the whole succession consists mainly of alluvial deposits with different grain sizes and different porosities. The thickness of the alluvium in the main channel of El Hawashyia basin ranges from 80 to 200 m, and the thickness are thinning at the edge of basin. The clay beds (the second and the lowermost geoelectrical layers) together with the overlying alluvium deposits reflect marked sequential cycles of deposition throughout the history of the basin development. The layers show regular regional dip towards the east. Four major normal faults have been found to affect the whole succession (Figs. 1, 2).

Geomorphology of El Hawashyia basin

El Hawashyia basin and its surrounding area exhibit different geomorphologic units (Fig. 4) as follows:

a. *The mountainous area* The mountainous area is composed essentially of Pre-Cambrian basement rocks which representing the main catchments area of El

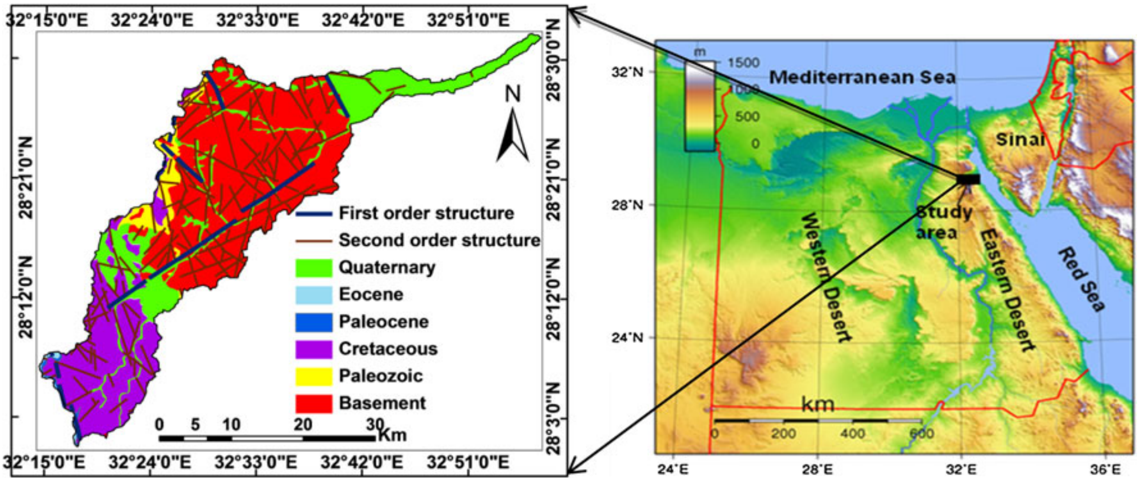


Fig. 1 Location and geology of El Hawashyia basin based on Conoco and the Egyptian general petroleum company (EGPC) (1987) and Conoco (1989)

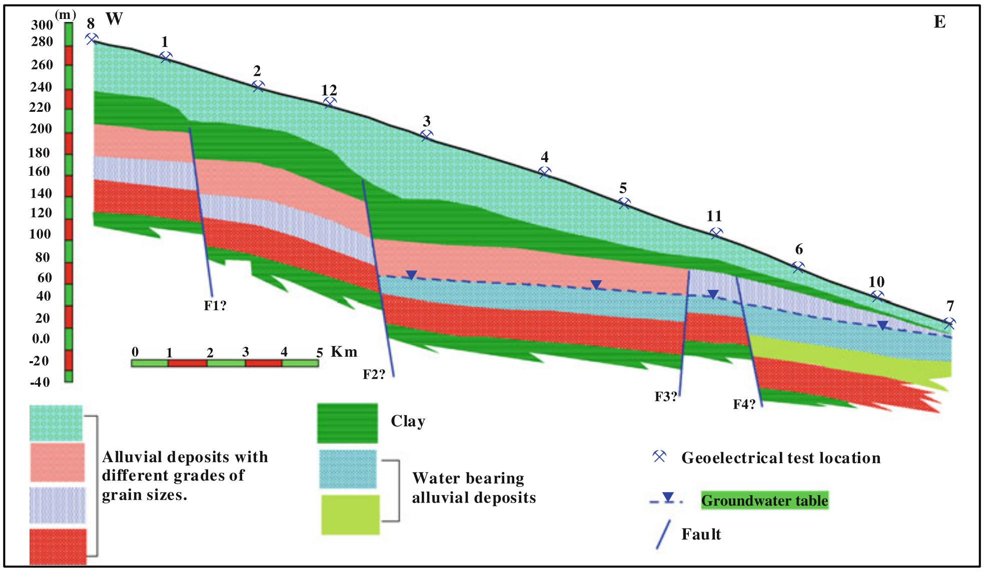


Fig. 2 Hydrogeoelecrical cross section along the main channel of the Delta El Hawashyia basin showing the facies layering of the Post-Miocene sediments (DRC Internal report 2001)

Hawashyia basin. This area rises 1,019 m above mean sea level.

b. *The hilly area* The hilly area occupies the northwestern part of the mountainous area as well as the southern sector where Abu had basin exist. This area is composed of hilly dissected and weathered zone.

c. *The Piedmont plain* The Piedmont plain occupies the low land area between the mountainous area and the Gulf of Suez. It comprises the following geomorphic units

   1. *The morphotectonic depression* The morphotectonic depression occupies the area between the foot cliff of the mountainous area to the west and the gorge of El Hawashyia basin to the east. It is surrounded to the north and south by the dissected alluvial terraces and the dissected peneplain. It represents a good collecting basin for surface water runoff. It has a ground elevation ranging between 260 and 370 m, with general surface slope towards the east.
   2. *The dissected alluvial terrace* The dissected alluvial terraces unit occupies an extended plain covered by thick alluvial terraces. It faces the hilly area and received its outwash of the weathering products as might well the outwash of El Galala El Qibliya plateau.

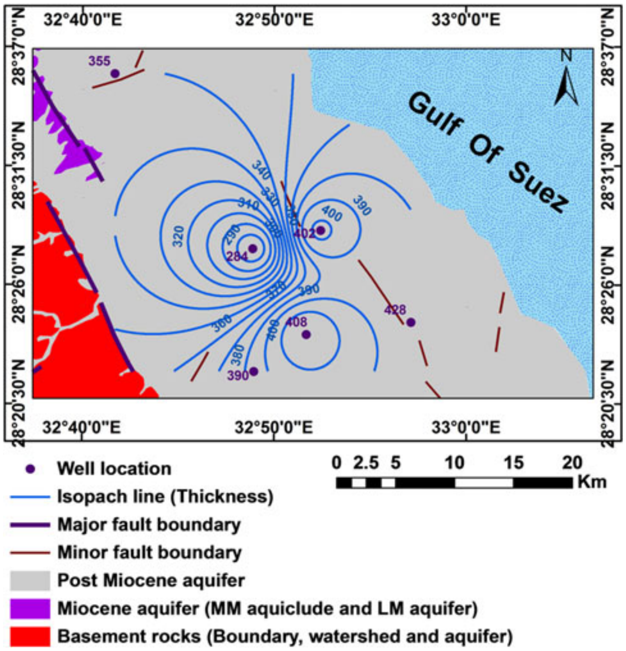


Fig. 3 Isopach map of the Post-Miocene deposits in El Hawashyia basin

Fig. 4 Photo showing the highlands area (watershed) at the El Hawashyia basin of the study area (photo taken by S. Schumann, December 2004)

3. *The coastal plain* The coastal plain occupies a limited zone towards the east between the dissected alluvial plain and the Gulf of Suez shoreline. This coastal plain is narrow to the north and becomes wider towards the south. It receives the finer sediments carried through streams, which cut the dissected alluvial plain and the peneplain.
4. *The internal salinas and paleo-lake* The Salinas and lakes occupy a low land area north of Ras Abu Bakr and appear below sea level. Sabkhas, salt marshes and ponds of saline water surround it. They receive their water through inundation and seepage from the surrounding flow.
5. *The southern dissected peneplain* The southern dissected peneplain occupies the elevated land south El Hawashyia basin and slopes towards the south and northeast. The alluvial terraces of this plain are coalesced to the east, while it is well defined at the foot slope of the mountainous area.
6. *The wadi channel* The main channel of El Hawashyia basin and its tributaries, drain the high mountainous area, the hilly areas and alluvial terraces. In the peneplain area and its outlet from the high mountainous area, the length of wadi channel extends about 76 km. The course of the wadi channel is highly controlled by structure and topography.

Morphometric characteristics of El Hawashyia basin

The study of the morphometric analysis of El Hawashyia basin is mainly based on the tracing of the drainage network using digital elevation model (DEM) with 85 m resolution and topographic maps (scale 1:50,000). Depending on Strahler method (Strahler 1957), the streams are ordered and the different parameters are measured and calculated according to Horton (1932, 1945) as shown in Table 1. Morphometrically, five effective sub-basins (Fig. 5b) are evaluated to determine the hazards of the main basin.

To evaluate the flood hazard of the studied basins, nine morphometric parameters having a direct effect on flooding were chosen, and their relationship with the flash flood was analysed. These parameters are: watershed area (*A*), drainage density (*D*), stream frequency (*F*), shape index (Ish), slope index (SI), relief ratio (Rr), ruggedness ratio (Rn), texture ratio (Rt) and weighted mean bifurcation ratio (WMRb). All these parameters have a directly proportional relationship with the hazard morphometric parameters except for the weighted mean bifurcation ratio which shows an inverse proportion. A hazard scale number starting with one (lowest) to five (highest) was assigned to all parameters. The distribution of the hazard degrees for the studied drainage basins has been carried out as follows:

- Determination of the minimum and maximum values of each morphometric parameter for all drainage basins and their sub-basis.
- Assessments of the actual hazard degree for all parameters which are located between the minimum and maximum values were depending on a trial to derive the empirical relation between the relative hazard degree of a basin with respect to flash floods and the morphometric parameters, the equal spacing or simple linear interpolation between data points procedure was chosen.

Table 1 Morphometric parameters and hazard degree of El Hawashyia basin and their sub-basins

Morphometric Parameters	El Hawashyia basin	Upstream-1 sub-basin	Upstream-2 sub-basin	Abu Boaithrane sub-basin	Thamila sub-basin	Ghazala sub-basin
No.	1	1	2	3	4	5
Kc	6	5	5	5	5	5
SNu	3,837	842	283	264	328	589
Slu (km.)	2,682.2	600.1	208.6	202.0	198.6	436.2
A (km^2)	976	199.3	70.7	64.5	77.9	154.9
Pr (km)	252.3	89.1	62.9	36.7	47.0	65.3
LB (km)	90	26.6	22.3	9.3	17.1	20.9
VL (km)	76.6	26.3	0.6	4.0	11.4	9.5
Rf (m)	1,019	415	162	300	465	620
E (m)	456	68	2	11	107	87
Rb	5.0	4.87	4.03	3.97	4.11	4.91
WMRb	4.05	4.01	5.07	3.94	3.81	4.14
F (km^{-2})	3.93	4.22	4.00	4.09	4.21	3.80
D (km^{-1})	2.8	3.01	2.95	3.13	2.55	2.82
Lo (km)	0.18	0.17	0.17	0.16	0.20	0.18
Ish	0.15	0.36	0.18	0.95	0.34	0.45
Rc	0.19	0.32	0.22	0.60	0.44	0.46
Re	0.39	0.60	0.42	0.97	0.58	0.67
Sv	8.3	3.55	7.03	1.34	3.75	2.82
Si	0.850	0.989	0.0270	0.430	0.667	0.455
Sl (%)	0.79	0.34	0.44	0.37	1.25	1.22
Rr (%)	1.00	2.00	1.00	3.00	3.00	3.00
Rn	2.80	1.25	0.48	0.94	1.19	1.75
Rt (km^{-1})	15.21	9.45	4.5	7.19	6.98	9.02
SH	2.3	1.8	2.1	1.3	1.5	1.5
W (km)	10.8	7.49	3.17	6.94	4.56	7.41
Hazard degree	1	5	1	5	4	5

No number of basin and sub-basin

Measured parameters: *kc* order of trunk channel, *Snu* sum of stream numbers, *Slu* sum of stream lengths (km), *A* area of the basin (km^2), *Pr* perimeter of the basin (km), *LB* basin length (km), *VL* valley length (km), *Rf* relief (m), *E* internal relief (m)

Calculated parameters: *Rb* bifurcation ratio, *WMRb* weighted mean bifurcation ratio, *F* stream frequency (km^{-2}), *D* drainage density by Horton method (km^{-1}), *Lo* length of overland flow (km), *Ish* shape index, *Rc* circularity ratio, *Re* elongation ratio, *Sv* inverse shape form, *Si* sinuosity, *SI %* slope index, *Rr* relief ratio, *Rn* ruggedness number, *Rt* texture ratio (Km^{-1}), *SH* compactness ratio, *W* basin width (km)

Assuming a straight linear relation exists between the sample points, the intermediate values can be calculated from the geometric relationship (Davis 1975) and (Sewidan 2000, unpublished).

$$\text{Hazard degree} = \frac{4(X - \mathrm{X}_{\min})}{(X_{\max} - X_{\min})} + 1 \qquad (1)$$

For the weighted mean bifurcation ratio (WMRb) which shows an inverse proportion, the hazard degree was calculated using the following equation (Sewidan 2000):

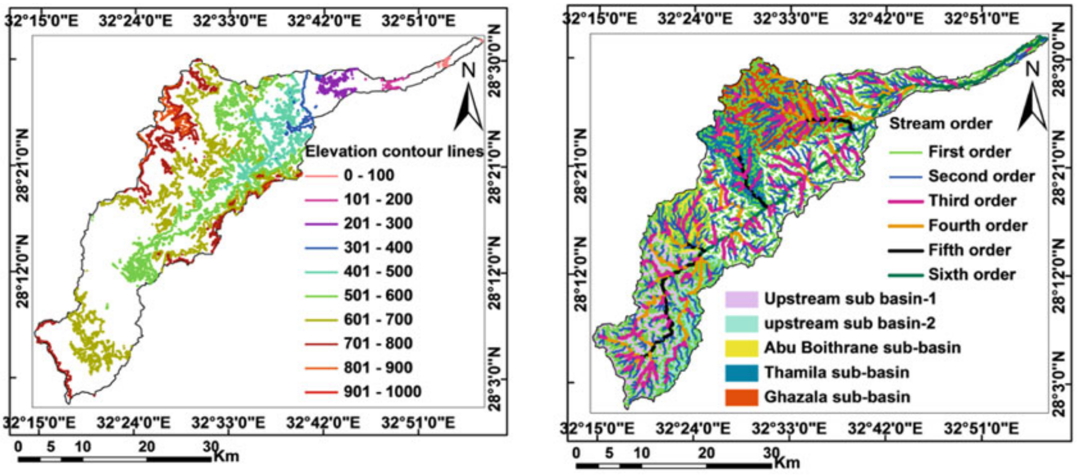
$$\text{Hazard degree} = \frac{4(X - X_{\max})}{(X_{\min} - X_{\max})} + 1 \qquad (2)$$

where X is the value of the morphometric parameters to be assessed for the hazard degree for each basin and $X_{\min}$ and $X_{\max}$ are the minimum and maximum values of the morphometric parameters of all basins, respectively. The calculated hazard degrees as shown in Table 2 shows that all sub-basins of El Hawashyia basin are of high hazard degree except the upstream-2 sub-basin which is of a low hazard degree.

From Fig. 5 it is observed that the El Hawashyia basin is an elongated basin which allows by recharging the surface water to feed the shallow Post-Miocene aquifer.

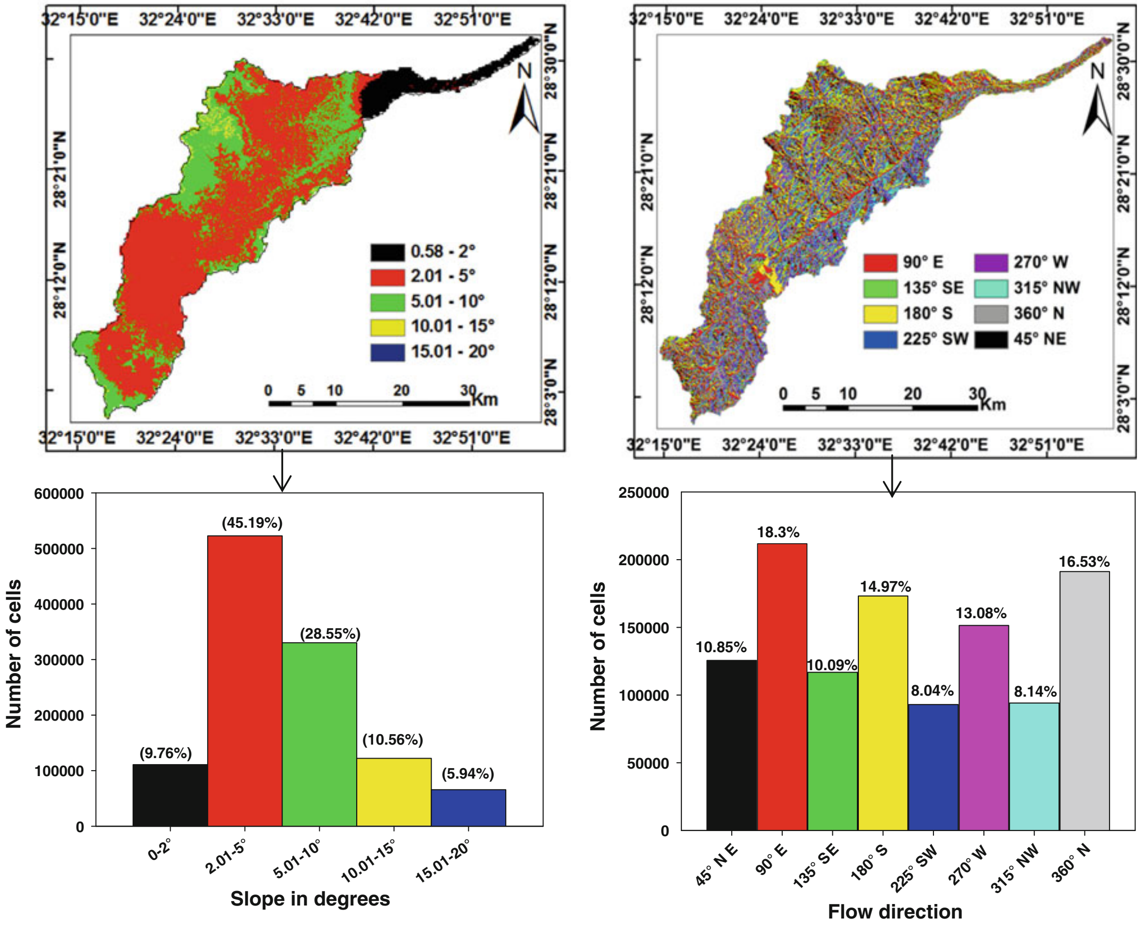
Catchment model

The aim of this part in this study is to provide an approach for runoff and recharge estimations that can be applied in arid regions suffering from scarcity of data.



(a) Elevation contour lines map (meters a. m.s. l)

(b) Stream order and the main sub-basins



(c) Mean slope map (Values in degree)

(d) Flow direction map

Fig. 5 Basic characteristics of El Hawashyia basin

Thus, the model to be used will depend upon the scarce available information, the required accuracy, resolution of the output and the time resources can be directed at the modelling exercise.

The final result of the modelling is to forecast hydrographs and possible recharge rates for El Hawashyia basin and Ghazala sub-basin as an example of the Red Sea coastal basins. El Hawashyia basin is divided into five sub-

Table 2 Input data, as selected for the respective studied basins

Parameters	El Hawashyia basin	Ghazala sub-basin
Paleo-flood height (m)	0.70	0.55
Valley width at the point of measured paleo-flood (m)	304	216
Strickler coefficient K_{st} ($m^{1/3}/s$)	30	30
Area (km^2)	976	155
Overland flow (m)	180	180
Mean slope (m/m)	0.0160	0.0149
Retardance coefficient	0.042	0.031
Pervious area (km^2)	225	25
Impervious area (km^2)	751	130
Percentage of impervious directly connected (%)	80	90
Weighted curve number	84	90
Initial abstraction factor	0.2	0.2
Additional abstraction on pervious (mm)	5.0	2.5
Additional abstraction on impervious	2.5	1.3
Maximum infiltration capacity	–	–
Total rainfall depth (mm)	18.3	25.0
Total rainfall duration (h)	3.0	3.0
Rainfall intensity (mm/h)	6.1	8.33
Type of rainfall distribution (hyetograph)	SCS	SCS
Calculated time of concentration (min)	150	90

basins, namely upstream-1, upstream-2, Abu Boithrane, Thamila and Ghazala sub-basins (Fig. 5b). This basin and its sub-basins were chosen, as an example of the great thickness of alluvial Post-Miocene deposits in the delta of El Hawashyia basin which may allow for the infiltration of the rainwater to recharge the shallow aquifer aiming to sustainable development. On the other hand, it is noticed that observations of paleo-flood marks on the wadi channels and sides (depth and width of flood marks) were used as input data to generate the basin hydrograph.

To generate the regional hydrograph of the study area, two programs named: Gerinne and stormwater management and design aid (SMADA6) were used for this purpose. SMADA6 program is a complete hydrology package which includes a number of separate executable files that allow for hydrograph generation, pond routing, storm sewer design, statistical distribution and regression analysis, pollutant loading modelling, matrix calculation, etc. The executable files of SMADA6 were the watershed characteristics, the rainfall event characteristics and the hydrograph generation. In this study, a paleo-flood height mark on the wadi sides was used as a reference to generate a synthetic hydrograph. The connection between Gerinne and SMADA6 models is schematically shown in Fig. 6 which summarises the generation of the hydrograph for any studied basin based on three main steps, they were:

1. Generation of the theoretical hydrograph by the use of the Gerinne model.
2. Using SMADA6 model to create the executable files which will be used in the hydrograph generation.
3. Final hydrograph generation using SMADA6 with generated data from step 1 and 2 (SBUH method).

Modelling data base

Geomorphologic and lithologic information were generated from DEM (85 m resolution), topographic maps (1:50,000) and geologic maps (1:500,000) used to enable recharge and runoff calculations. Rainfall data was taken from meteorological station of Hurghada and the paleo-flood marks were measured from the field. A summary of the available data is shown in Table 2.

For the first step, the rating curve generation by Gerinne, the following geomorphological data are necessary:

1. Mean slope until discharge outlet defined by the given flood marks, which was analysed by ArcView/ArcGIS.
2. Paleo-flood measurements (valley width, paleo-flood height, measured in the field).
3. The theoretical Strickler coefficient related to the surface geological information (Martin and Pohl 2000).

For the second step with SMADA6, the following data are necessary:

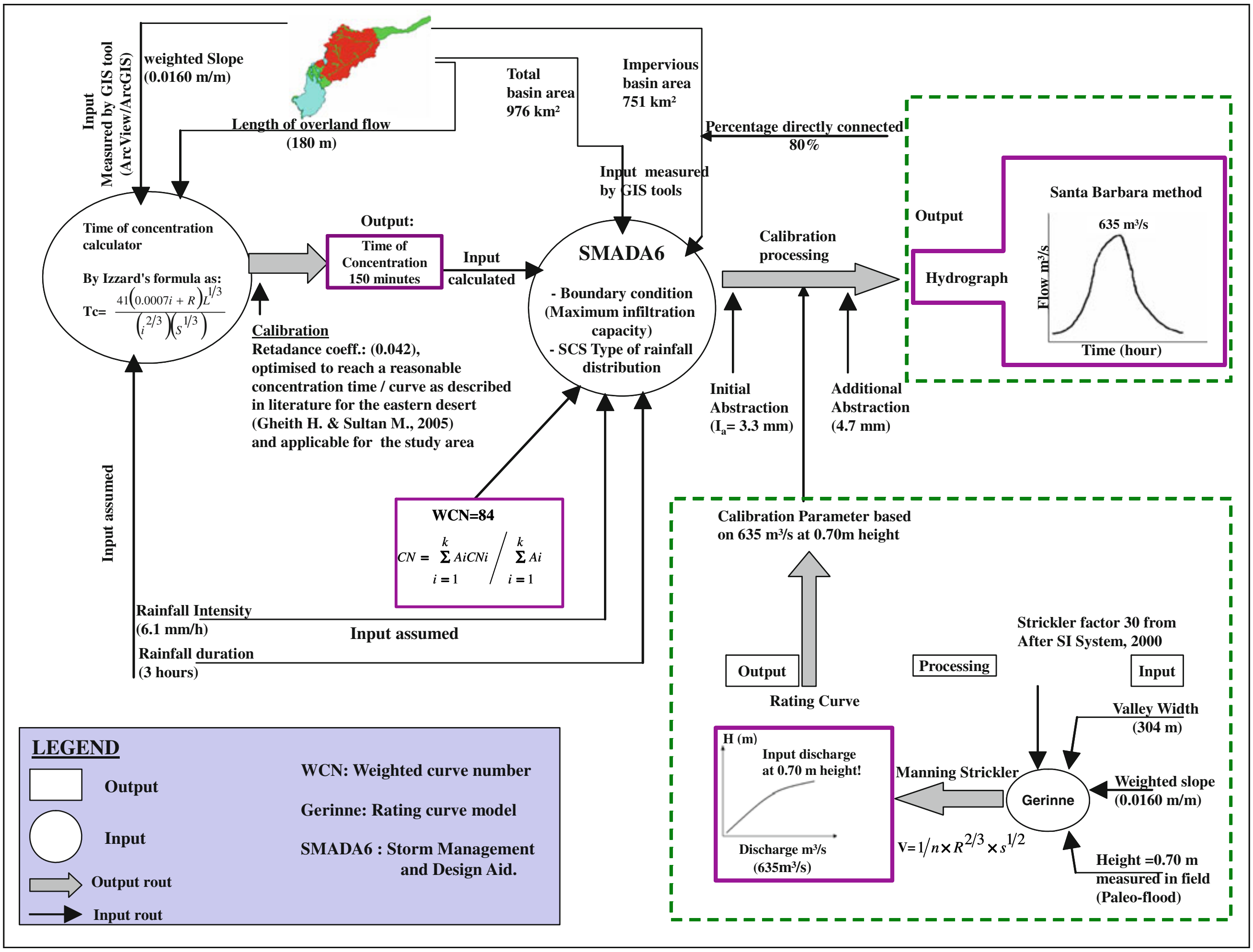
1. Geomorphological information (basin area, mean slope and length of overland flow, given by DEM analysis in Table 1).
2. Geological information (area of pervious surface, impervious drainage areas and percentage of channel flow directly connected to the impervious drainage area), analysed by ArcView/ArcGIS of DEM.
3. Hydrological information (calculated time of concentration, infiltration capacity, calculated weighted curve number, rainfall intensity and type of hyetograph).

For the third step, the hydrograph generation by the SBUH method, the input data are as shown in Table 2 for Hawashyia major basin and also for Ghazala sub-basin.

Models applied

Gerinne model (channel model)

The Gerinne model is a German model, which means “channel model”. This model is also called rating table or rating curve. Gerinne model is a simple hydraulic program



$$T_c = \frac{41\left(0.0007i + R\right)L^{1/3}}{\left(i^{2/3}\right)\left(S^{1/3}\right)}$$

$$CN = \sum_{i=1}^{k} AiCNi \Big/ \sum_{i=1}^{k} Ai$$

$$V = 1/n \times R^{2/3} \times s^{1/2}$$

Fig. 6 Schematic representation shows the model of El Hawashyia basin using Gerinne and SMADA6 models

to calculate the open-channel flow via rating curve without any spatial discretization along the river or wadi channels Ronald (Aigner 2000). A rating table or rating curve is the relationship between the stage in metres and discharge (in m^3/s) at a cross section of a river. Because of the scarcity of hydrological data (flood measurements, detailed precipitation data, measured actual hydrograph, etc.), the channel model was applied to generate a rating curve. This model is based on the Manning–Strickler formula (Eq. 3); (Manning 1891; Strickler 1923) which is considered as one of the best known and commonly used equations to calculate the channel flow velocities.

$$V = 1/n \times R_{\mathrm{h}}^{2/3} \times s^{1/2} (\mathrm{m/s}) \tag{3}$$

where V is the flow velocity (m/s), n is the channel bed roughness (Manning–Strickler coefficient), R_{h} is the hydraulic radius (m) and s is the channel slope (m/m). The hydraulic radius (R_{h}) is the ratio between cross-sectional area of flow at a point in an open channel or closed conduit and wetted perimeter. The hydraulic radius of a specific channel cross section is temporally variable due to the channel geometry and the actual water level. The hydraulic radius is the cross-sectional area of channel (A) divided by the wetted perimeter (P_{w}) as follows:

$$R_{\mathrm{h}} = A/P_{\mathrm{w}}. \tag{4}$$

It is assumed that the channel bed of Hawashyia basin and Ghazala sub-basin are rectangular. Then, the cross-sectional area of the channel is determined by multiplying the channel depth (d, in metre) by channel width (w in metre) along a transverse section of the stream, whereas the wetted perimeter (P_{w}) is the portion of the channel that is wet and it refers to the extent to which water is in contact with its channel which equals the width plus twice the depth that the water touches as follows:

$$P_{\mathrm{w}} = w + 2d. \tag{5}$$

Therefore R_{h} value can be calculated as a function of the channel depth (d) and width (w) as follows:

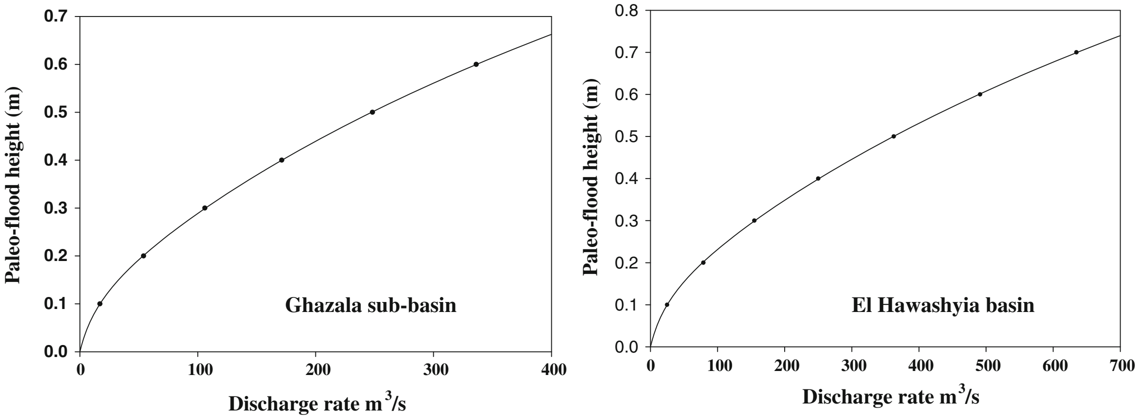


Fig. 7 Rating curves for Ghazala sub-basin and El Hawashyia basin, by applying the Gerinne model

$$R_h = \frac{A}{w + 2d}(m). \tag{6}$$

The value of $1/n$ also known as the Strickler coefficient (K_{st}) was selected in this model as equal 30, with the SI system dimension m$^{1/3}$/s. This value of (K_{st}) was chosen, based on literature survey and recommendation from Professor Wittenberg, University of Lueneburg in Germany based on Martin and Pohl (2000).

The input parameters for the paleo-flood height and channel slope were measured in the field. The mean slope was taken from DEM data processed in ArcView/ArcGIS. The Gerinne model was run based on the existing data given in Table 4. The outputs of rating curves are shown in Fig. 7 for both Ghazala sub-basin and El Hawashyia basin.

From the rating curves (Fig. 7), the maximum flow rates at a flood height of 0.55 m for Ghazala basin and at 0.70 m for El Hawashyia basin were calculated to be 290 and 635 m^3/s, respectively. The results from Gerinne model were used as calibrated input data for hydrograph construction by SMADA6 model.

Stormwater management and design aid (SMADA6)

The SMADA6 program is composed of several separated executable files. They were the first file for the watershed characteristics, the second file for the rainfall event characteristics and the third file for the hydrograph generation.

Watershed file data base The watershed file is one of the separated executable files of the SMADA6 program which includes the characteristic parameters of the watershed, namely;

- *Total drainage area* it is the area of the studied basin in km^2
- *Impervious drainage area* this is land which allows for abstraction but upon which no infiltration takes place. Rain which fall onto this type of the land will either be abstracted, flow directly to the outlet of the watershed or flow onto the pervious watershed regions.
- *Percentage of impervious area directly connected* these are regions of the basin from which the water flows directly to the watershed outlet.
- *Additional abstraction on pervious area* where the water from precipitation is retained in the watershed by infiltration.
- *Additional abstraction on impervious areas* where water from precipitation is retained on the watershed on the surface or water which intentionally routed to a collection device. Additional abstraction on such type of lands cannot result in infiltration or runoff.
- *Maximum infiltration capacity* it is the maximum infiltration capacity of the soil in mm.
- *Infiltration characteristics* the infiltration characteristics in this program depends on the type of curve number used in the Soil Conservation Service (SCS 1972, 1985) formula.

The curve number was developed by the Soil Conservation Service (SCS) (1972, 1985) to assist in the estimation of infiltration during rainfall events. The curve number is always less than 100. High curve numbers (>90) represent little or no infiltration while low curve numbers (<50) represent pervious surfaces.

The Soil Conservation Service (SCS) (1972, 1985) combines infiltration losses with initial abstraction and estimates rainfall excess or equivalent runoff volume by the following relationship:

$$R = \frac{(P - I_a)^2}{P - I_a + Sn} \qquad P > 0.2Sn \tag{7}$$

where R is the accumulated runoff depth or rainfall excess, P is the accumulated rainfall, (I_a) is the initial abstraction and Sn is a parameter in mm, called the potential maximum retention capacity of a soil at the beginning of a storm or the maximum amount of water that will be absorbed after runoff begins. The initial abstraction (I_a) equals to *0.2Sn*, hence Eq. 7 can be equalised to Eq. 8 and *Sn* is given by Eq. 8.

$$R = \frac{(P - 0.2Sn)^2}{P + 0.8Sn} \qquad P > 0.2Sn \tag{8}$$

$$\mathrm{Sn} = \frac{25{,}400}{\mathrm{CN}} - 254 \tag{9}$$

CN represents the curve number. Tables of curve number are available from a number of sources.

Equation (8) indicates that P must exceed 0.2S before any runoff is generated Haan et al. (1994) noted that eq. (8) is a runoff equation and not an infiltration equation, hence using it as an infiltration equation can lead to errors.

Originally, the CN values were assigned by plotting observed runoff versus measured rainfall for a number of experimental plots scattered throughout the US. The CNs were then correlated with land use. The term "good conditions" or "poor conditions" in CN tables refers to the relative runoff potential. An area in good hydrologic condition would have higher infiltration rates and lower runoff rates than an area in poor condition.

The curve number is a function of the antecedent moisture condition, the land use, the hydrologic condition and the soil type. The antecedent moisture content is a function of the total rainfall in the 5-day period preceding a storm (Gheith and Sultan 2002). Since the rain events in the study area are very rare, the moisture content can be neglected. The land use type and hydrologic conditions were classified as natural desert landscape and desert shrub (poor coverage, <30 % ground cover). Three substrates crop out in the study area: Quaternary channel deposits fractured limestone and fractured basements. According to the SCS (1986) classification of hydrologic soils, the Quaternary deposits in the study area were classified as type A soils with a curve number of 63, the fractured limestone as type B with a curve number 77 while the fractured basement was classified as type C with curve number equal to 97 (Table 4).

The weighted CN for mixed land uses can be computed using Tables 3 and 5 as follows:

$$\mathrm{CN} = \sum_{i=1}^{k} A_i \mathrm{CN}_i \Big/ \sum_{i=1}^{k} A_i \tag{10}$$

where CN_i corresponds to the appropriate CN for the part of the watershed that has an area A_i. Once the proper CN is obtained, Eqs. (9) and (10) can be used to estimate the accumulated runoff as a function of total accumulated rainfall.

The respective assignments of the curve numbers for the Ghazala sub-basin and El Hawashyia basin based on Eq. (10) are summarised in Table 4.

- *Initial abstraction factor* (I_a) The initial abstraction factor I_a is empirically derived from the maximum soil water retention (Sn), which is related to the soil drainage characteristics (e.g. CN values). I_a accounts normally for losses due to evaporation, plant uptake, and water retained in surface depressions during the rainfall event. Sn accounts for the total amount of water retained in the drainage basin during the rainfall event, essentially I_a + infiltration.

Time of concentration (T_c) The time of concentration (T_c) is a fundamental basin parameter. It is used to compute the peak discharge for a basin. The peak discharge itself is a function of the rainfall intensity, which is based on the time of concentration. Time of concentration is the longest time required for a particle to travel from the basin water divide to the basin outlet. Izzard's formula (Eq. 11) from SMADA6 program is one of many equations which are used to calculate the time of concentration of basin. In the present study, the Izzard's formula was used, where the obtained results were found reasonable and matching with the literature:

$$T_c = \frac{41(0.0007i + R)L^{1/3}}{(i^{2/3})(s^{1/3})} \tag{11}$$

where T_c is the time of concentration, i is the rainfall intensity, R is the retardance coefficient, L is the flow length for sheet flow over surface (overland flow) and s is the average land slope for the sheet flow over the surface.

The calculated results for the time of concentration of Ghazala sub-basin and El Hawashyia basin by Izzard's formula are 90 and 150 min, respectively. These results were used as input parameters to the SMADA6 modelling and do not correspond to the final time of concentration of the modelled hydrographs.

Rainfall file database The rainfall input file requires a rainfall volume in millimetres for a series of time increments. The following input parameters were used:

- For the total rainfall duration and time increments 3 h duration with 10 min increments were used.
- For the total rainfall depth, 25 mm in Ghazala sub-basin and 18.3 mm in El Hawashyia basin were chosen

Table 3 Input parameters to the Gerinne model

Input parameters	El Hawashyia basin	Ghazala sub-basin
Paleo-flood height (m)	0.70	0.55
Mean slope (m/m)	0.016	0.0149
Channel width (m)	304	216
Strickler coefficient K_{st} ($m^{1/3}$/s)	30	30

Table 4 Assignments of curve numbers for different land types in El Hawashyia basin and Ghazala sub-basin

Name of basin	Total area (km^2)	Substrate		Type of soil group	Value of CN	Weighted CN
		Type	Area (km^2)			
Ghazala sub-basin	155	Basement	130	C	97	91
		Quaternary	25	A	63	
El Hawashyia basin	976	Basement	500	C	97	84
		Cretaceous	242	B	77	
		Quaternary	234	A	63	

as input data in the central SMADA6 model to generate a synthetic hydrograph with a maximum flow rate which is nearly the same as obtained from Gerinne model (635 m^3/s for El Hawashyia basin and 290 m^3/s for Ghazala sub-basin).

These values of rainfall depth have a return period of 20 years when compared to Hurghada climate station and a probability of 5 %. Table 5 and Fig. 8 summarize the return periods and their probabilities for the maximum daily rainfall in 1 year for a 30-years period (Hurghada meteorological station). Figure 8 indicates that the power relationship is more significant where the determination coefficient (R^2) of the power model is 0.95 for Hurghada station and 0.91 for Quseir station. The type of rainfall distribution in the study area is based on the SCS IA (SMADA6) method as shown in Fig. 9.

Hydrograph generation The final step carried out in the modelling process was the generation of hydrograph using SMADA6. It contains a number of hydrograph generation routines, as follows:

- Santa Barbara urban hydrograph method (SBUH)
- SCS method
- Unit hydrograph method
- Clark method

Table 5 Summary of the return periods and probability distribution of the maximum daily rainfall in 1 year for a 30-years period (after Hurghada meteorological station 1960–1990)

Maximum daily rainfall (mm)		Return period (year)	Probability (%)
Hurghada	Quseir		
32.2	20.25	100	1
28.0	17.75	50	2
20.0	12.75	20	5
13.0	9.0	10	10
8.0	4.0	5	20
7.0	3.0	4	25
5.0	1.0	3	33
3.0	0.1	2	50
0.0	0.0	1	99

However, Santa Barbara urban hydrograph method (SBUH) was selected for the present study among the other methods for hydrograph generation. SBUH was presented first by Stubchaer (1975). Previous literatures proved that SBUH method was found to be the most suitable method for the study area as the hydrograph results that agree with those of the paleoflood. The calibration parameters for SMADA6 were based on the discharges and flood heights as calculated in step one by Gerinne (Fig. 7), i.e. on 635 m^3/s at 0.7 m height for El Hawashyia basin and 290 m^3/s for Ghazala sub-basin. The other input parameters are summarized in Table 7.

SBUH was actually developed by Santa Barbara Country Food Control and Water Conservation District to determine a runoff hydrograph for an urbanized area. SBUH computes a hydrograph directly without going through intermediate steps to determine the runoff hydrograph. The SBUH method was similar to the Soil Conservation Service Unit Hydrograph (SCSUH) method, which is based on the curve number (CN) approach, and also uses SCS equations for computing soil absorption and rainfall excess.

The SCSUH method works by converting the incremental runoff depths (rainfall excess) for a given basin and design rainfall event into a runoff hydrograph via application of a dimensionless unit hydrograph. The shape of SCS unit hydrograph (time to peak, time base and peak) is determined by a single parameter of the basin time of concentration. The SBUH method on the other hand converts the incremental runoff depths into instantaneous hydrographs that were later routed through an imaginary reservoir with a time delay equal to the basin time of concentration. The SBUH method depends on some variables as follows:

- pervious and impervious land areas,
- time of concentration calculations,
- runoff curve numbers (CN) applicable to the site,
- hyetograph distribution.

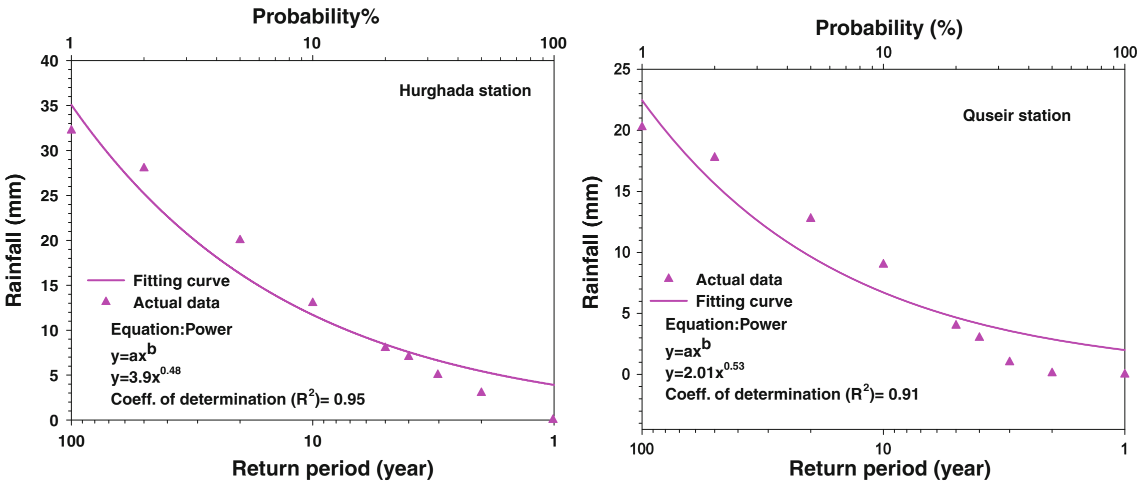


Fig. 8 Return period and probability distribution of the maximum daily rainfall in 1 year for a 30-year period in Hurghada and Quseir meteorological stations

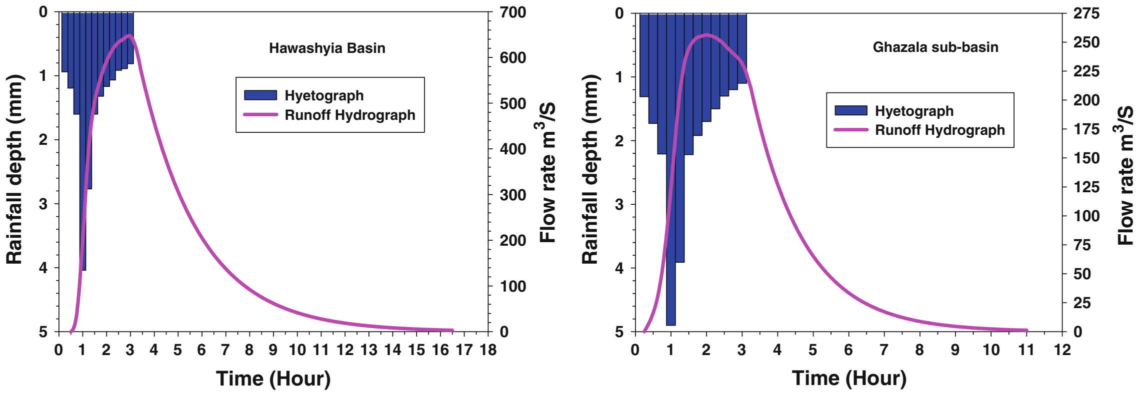


Fig. 9 Hyetograph based on the SCS distribution and final synthetic hydrographs of El Hawashyia basin and Ghazala sub-basin

The SBUH method uses two steps to synthesis the runoff hydrograph:

1. computing the instantaneous hydrograph and
2. computing the runoff hydrograph.

The instantaneous hydrograph, (I_t) in m^3/s, at each time step d_t, is computed in metric units as follows:

$$I_t = (R_t A)/d_t \tag{12}$$

where R_t is the total runoff depth (over both pervious and impervious lands) in millimetres with a time increment d_t in minutes and the basin area A in km^2. The runoff hydrograph, Q_t, is then obtained by routing the instantaneous hydrograph I_t, through an imaginary reservoir with a time delay equal to the time of concentration T_c of the drainage basin. The following equation estimates the routed flow Q_t

$$Q_{t+1} = Q_t + w\,(I_t + I_{t+1} - 2Q_t) \tag{13}$$

where w is the routing coefficient and is determined by

$$w = d_t/(2T_c + d_t) \tag{14}$$

The resulting synthetic hydrographs of El Hawashyia basin and Ghazala sub-basin show maximum flow rates (maximum peak) matchable to those modelled with Gerinne model given as 635 m^3/s (El Hawashyia basin) and 290 m^3/s (Ghazala sub-basin) with concentration times of 15 and 10 h, respectively.

Results and discussion

The final results of the modelling are summarised in Table 6, show exemplary, that when a rainfall event occurs in El Hawashyia basin with a total of 18.3 mm within 3 h,

Table 6 Input and output parameters of the studied basins for hydrograph generation using SBUH

Parameters	Type of parameters	El Hawashyia basin	Ghazala sub-basin
Area (km^2)	Input parameters	976	155
Overland flow (m)		180	180
Slope (m/m)		0.0160	0.0149
Retardance coefficient		0.042	0.031
Pervious area (km^2)		225	25
Impervious area (km^2)		751	130
Percentage of impervious directly connected (%)		80	90
Weighted curve number		84	90
Initial abstraction factor		0.2	0.2
Additional abstraction on pervious (mm)		5.0	2.5
Additional abstraction on impervious		2.5	1.3
Maximum infiltration capacity		–	–
Total rainfall (mm)		18.3	25.0
Total rainfall duration (h)		3.0	3.0
Rainfall intensity (mm/h)		6.1	8.33
Type of rainfall distribution (hyetograph)		SCS	SCS
Calculated time of concentration (min)		150	90
Infiltration (mm)	Output parameters	4.70	3.20
Initial losses (mm)		3.30	2.10
Rainfall excess (mm)		10.30	19.70
Maximum flow rate (peak discharge) (m^3/s)		650	259
Runoff volume (m^3)		10.2 × 10^6	3.2 × 10^6

which itself has a probability of 5–10 % if compared to the Hurghada station. A discharge volume of 10.2 × 10^6 m^3 is transferred to the delta while approximately 4.7 mm infiltrate. In Ghazala sub-basin, this leads to an infiltration of 3.2 mm during a rainfall event (25 mm) at duration of 3 h and a total runoff volume of 3.16 × 10^6 m^3.

The study area is characterised by hyper-arid conditions with high mean daily evaporation, scarce vegetation and shows a high hydraulic conductivity of the Quaternary deposits in the delta of basins and along the basin channels. Hence it is assumed that recharge of the Quaternary aquifer could be approximated by the additional transmission water losses that arise from the infiltration through the channel. The transmission losses were controlled by the basin and channel physical characteristics (geometry, shape, slope, etc.), type of soil, depth to bed rock, temperature and duration of flow. However, it must be taken into account that while the physical characteristics of the basins are relatively well known from the DEM analysis, the other control parameters have to be assumed in this study due to the lack of reliable data. The calculated infiltration quantities of 4.7 and 3.2 mm result in recharge percentages during flood events of 26 and 13 % in El Hawashyia basin and Ghazala sub-basin, respectively. The difference in the infiltration percentage between El Hawashyia (26 %) and Ghazal sub-basin (13 %) can be matched to the fact that most of the surface area of the Ghazala sub-basin is covered by basement rocks (84 %) of high curve number while in El Hawashyia basin the basement rocks accounted to 51 % with the remaining area covered by fractured limestone, sand, shale and alluvial deposits (Table 4). Hence, in El Hawashyia basin the percentage of infiltration losses must be higher than in Ghazala sub-basin.

Whereas the transmission losses occur as water is channeled through the valley network, and the area of channels network (Quaternary deposits) is about 225 km^2 and the infiltration is about 4.7 mm at El Hawashyia basin, the amount of groundwater recharge reaches to 1.1 × 106 m^3 per event of rainfall 18.3 mm and duration 3 h. For Ghazala sub-basin the Quaternary area (channel networks) is about 25 km^2 and the infiltration is about 3.2 mm, so the amount of the groundwater recharge is about 80,000 m^3 per event of rainfall 25 mm and time duration 3 h.

Evaporation losses (initial losses) cannot be neglected, since the daily mean evaporation accounts to approximately 10.4 mm/day. From the archival data and from oral information from the inhabitants, the time of concentration in El Hawashyia basin ranges from 12 to 20 h. This matches with the results of 15 h for El Hawashyia basin and 10 h for Ghazala sub-basin. For these discharge events, the modelling resulted in calculated values for evaporation of about 3.3 and 2.1 mm with percentages of 18 and 8 % for El Hawashyia basin and Ghazala sub-basin, respectively.

Using the formula (Eq. 8), where the I_a equal to 0.2 of Sn, the initial abstraction I_a was 9.7 and 5.6 for El Hawashyia basin and Ghazala sub-basin, respectively. The difference in the values of evaporation (I_a) between the resulted values from SMADA6, the calculated values using SCS formula (Eq. 9) and the daily mean evaporation due to that the rainfall and the flash floods in the study area take place normally in the winter and the sun in most cases are not shined.

The calculated values of rainfall excess are 10.3 and 19.7 mm with percentages of 56 and 78 % in El Hawashyia basin and Ghazala sub-basin, respectively.

The maximum flow rates (flow peaks) at the assumed values of rainfall 18.3 and 25 mm were 650 and 259 m^3/s for El Hawashyia basin and Ghazala sub-basin, respectively. These values of rainfall were assumed to reach the

Table 7 Results of maximum flow rate and height of flash floods modelled based on assumed rainfall events for El Hawashyia basin and Ghazala sub-basin

Basin name	Rainfall (mm)	Return period (year)	Probability (%)	Flow peak (m^3/s) (SBUH)	Height of flood (m) (Gerinne model)
El Hawashyia	5	3	33	110	0.24
	8	5	20	225	0.37
	13	10	10	408	0.53
	18	15	7.5	650	0.70
	28	50	2	1,130	1.00
	32	100	1	1,343	1.10
Ghazala sub-basin	5	3	33	36	0.17
	8	5	20	65	0.22
	13	10	10	118	0.31
	18	15	7.5	175	0.42
	28	50	2	301	0.56
	32	100	1	340	0.60

values of the modelled flow rate of paleo-flood for the same basins. The resulted accumulated volume of runoff are 10.2×10^6 and 3.2×10^6 m^3 for El Hawashyia and Ghazala sub-basin, respectively. These values of rainfall have return period of about 20 and 50 years for El Hawashyia basin and Ghazala sub-basin, respectively (Table 5; Fig. 8).

The flow peaks for El Hawashyia basin and Ghazala sub-basin were estimated for each corresponding maximum daily rainfall recorded in Hurghada station as shown in Table 5. From the obtained results (Table 7), it is noticed that the Ghazala sub-basin with an area 155 km^2 (i.e. 15 % of the total area of El Hawashyia basin) has a maximum flow rate and accumulated runoff ranges from 25 to 33 % compared with the El Hawashyia basin.

From the previous discussion, it can be conclude that:

1. The climatic and morphometric data of the study area as one of the Red Sea Coastal areas were used to estimate the rainfall–runoff relationship for El Hawashyia basin as a whole and Ghazala sub-basin in particular. Such data were used by the application of some recent hydrological models e.g. Gerinne and SMADA6 models. The results obtained by the proposed models were calibrated and verified.
2. Gerinne model which is based on real paleo-flood measurements was applied giving the maximum flow rate of 635 m^3/s for El Hawashyia basin (975 km^2) and 290 m^3/s for Ghazala sub-basin (155 km^2).
3. The application of SMADA6 model resulted in a synthetic hydrograph with a maximum flow peak of 650 and 259 m^3/s for El Hawashyia basin as a whole and Ghazala sub-basin in particular, respectively based on measured parameters (e.g. weighted slope, length of overland flow, total basin area and percentage directly connected of impervious area) and assumed data (e.g. weighted curve number, rainfall amount and rainfall duration).
4. The volumes of surface runoff for both El Hawashyia basin and Ghazala sub-basin were estimated for one storm which has return periods of 15 and 50 years to be 10.2×10^6 and 3.2×10^6 m^3, respectively. Such amounts of runoff correspond to rainfall depth of 18.3 mm for El Hawashyia basin and 25 mm for Ghazala sub-basin. This means that surface runoff in Ghazala sub-basin with an area 155 km^2 (15 % of the total area of El Hawashyia basin) represents nearly one-third of the total surface runoff on the whole El Hawashyia basin.
4. The results obtained from the applied mathematical models (Gerinne and SMADA6) based on the paleo-floods are considerably matching with those obtained from field measurements done by Gheith and Sultan (2002) for Wadi Qena in the western preference of the Eastern Desert. The groundwater recharge through the transmission losses ranged from 13 to 26 % for the Ghazala sub-basin and the El Hawashyia basin, respectively, and these results are consistent with results of Gheith and Sultan (2002) where the groundwater recharge through the transmission losses ranged from 2 to 31 % for the basins which nearly have the same hydrogeological conditions of the study area.
5. On the other hand, the installation of telemetric meteorological stations on the top of the mountains along the Red Sea Series will help a lot for water resource studies, since there is a great lack of meteorological data in the area especially on the water divide line.

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