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ARTIFICIAL RECHARGE MODELLING OF GROUNDWATER AQUIFER IN ARID REGIONS

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Abstract

Groundwater is the main source of fresh water in arid regions. The Saq aquifer is a transboundary sandstone groundwater layer that extended into Saudi Arabia and Jordan. The groundwater level of the aquifer is depleted due to extensive pumping with negligible natural recharge. The objective of this study is to predict the artificial recharge supplied from runoff into the Saq aquifer for a selected area in the Qassim region, KSA using mathematical models. The maximum weekly and daily rainfall was quantified at different return periods for urban areas using graphical and probability distribution methods. The predicted surface water from rainfall is suggested to be stored in ponds, consequently the required volume of ponds was estimated according to the results of weekly maximum rainfall and various return periods. The stored surface water is proposed to be recharged into the groundwater aquifer via designed wells. The estimated quantity of the surface runoff was $4 \cdot 10^6$ m^3, $6.2 \cdot 10^6$ m^3, and $10.3 \cdot 10^6$ m^3 for return periods 25, 50 and 75 years respectively. The study is applicable for similar aquifers that suffer from non-renewable resources.

Keywords:

Arid regions;
Saudi Arabia;
Groundwater;
Hydrology;
Saq aquifer.

1 Introduction

The arid regions feature high temperatures, low precipitation, low humidity, and high rainfall losses [1]. Saudi Arabia is considered as one of the driest areas in the world, where rainfall is irregular and unpredictable [2]. The average annual rainfall in Saudi Arabia is less than 100 mm where it is less than 50 mm in most sites [3]. In Qassim regions, average annual rainfall is reported by Alotaibi, et al. [4] as 133 mm based on recorded data from 1978 to 2015, while Hasanean and Almazroui, [5] reported 144 mm based on data analysed from 1979 to 2009.

Fresh water from the underground of Saq aquifer is the main source of water in the Qassim region. The aquifer extends from southern Jordan to a large part of northern Saudi Arabia, with groundwater in this huge aquifer flowing generally from the southern and south-western outcrops to the north and discharging westwards to the Dead Sea [6]. The Saq sandstone thickness is gradually increasing north ward in Qassim. It changes from 400 m in the Southern Part to 700 m in the northern part. The thickness of aquifer reaches to more than 1000 m in Jordan and in the study area it is 500 m [7]. Abstractions of groundwater increased considerably in Saudi Arabia in the early 1980s, at the same time, abstraction was also increased in Jordan for irrigation purposes [8]. The heavy pumping of groundwater decreased the water level up to 32m/year as recorded in the report of the late 1980s [9]. Subsequently, the freshwater reservoirs are depleted with negligible natural recharge due to the scarcity of precipitations.

To estimate the amount of surface water available for recharging, the hydrological phenomena must be studied in detail. Analysis of maximum values of rainfall records gives a good vision of future probabilities of events, such as managing water resources, protection from floods, and extreme rainstorms [10]. The return period is the average elapsed time between occurrences of a rainstorm event of a certain magnitude or greater [11]. Several studies have been recorded in KSA and other countries that modelled maximum values of rainfall for different return periods [12-14]. Ghazaw [7]

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used the Gumbel Distribution for modelling extreme values of precipitation and runoff for return periods of 5, 10, 20, 25, 50 and 100 years. He used the predicted values in optimal design of facilities for controlling, storing, and reusing flood water in Buraydah city, KSA. Al-Amri and Subyani [12] used the Gumbel and Log Pearson III functions to estimate the maximum rainfall for the various return periods in three stations in Al-Madinah region, KSA. El-Sayed [13] constructed the rainfall intensity-duration-frequency (IDF) for different durations ranging from 5 minutes to 24 hours for return periods of 2, 5, 10, 25, 50, 100, and 200 years using probability distribution functions.

The objectives of this study were to compensate the abstraction of groundwater using artificial recharge supplied from runoff into the Saq aquifer, to model the extreme values of runoff based on the recorded rainfall data, and to design the capacity of the ponds that will collect the surface runoff.

2 Materials and methods

2.1 Methodology

In this section the theory behind the used model was presented.

2.1.1 Recurrence interval

The recurrence interval *T* which is known also as the return period of a storm magnitude is given by several models such as California method, Hazen's method, or Kimball's method, as presented in equations (1), (2) and (3) respectively [14]. Where *n* is the number of recorded data, and *m* is the rank of the storm event after arranging the recorded data in ascending order. The percent of time *F* (frequency) of a storm magnitude having recurrence interval *T* is given by equation (4) [15-17].

$$California\ method,\ T = \frac{n}{m}, \tag{1}$$

$$Hazen's\ method,\ T = \frac{n}{m-0.5}, \tag{2}$$

$$Kimball's\ method,\ T = \frac{n+1}{m}, \tag{3}$$

$$Fequency,\ F = \frac{1}{T} \times 100\% . \tag{4}$$

2.1.2 Generalized extreme value (GEV)

The GEV distribution is a family of continuous probability distributions that combines the Gumbel EV1, Frechet and Weibull distributions. GEV uses three parameters: location, scale, and shape factors. The EV1 Gumbel distribution only uses 2 parameters; location parameter *u* and scale parameter *α*, which is used in precipitation frequency analysis in several countries. The parameters of the distribution are also used to find the Cumulative Density Function (CDF) and Probability Density Function (PDF) for a series of historical precipitation. The CDF and PDF can be determined using the equations (5) and (6) respectively [18, 19].

$$F(x) = \exp\left[-\exp\left(-\alpha(x-u)\right)\right], \tag{5}$$

$$f(x) = \alpha \times \exp\left[-\alpha(x-u) - \exp\left(-\alpha(x-u)\right)\right], \tag{6}$$

where $\alpha = \frac{\pi}{SD \times \sqrt{6}}$, and $u = E(x) - \frac{0.5772156649}{\alpha}$.

The GEV distributions are also used to predict the probability of maximum occurrences, which is needed for designing and planning water construction projects. The values of the expected precipitation depth *p* for various return periods *T*, could be estimated using equation (7) [18].

$$P_T = \bar{P} + \left(\frac{y-y_n}{\sigma_n}\right)\sigma , \tag{7}$$

$$y = -0.834 - 2.303\log\log\left(\frac{T}{T-1}\right), \quad (8)$$

where $\bar{P}$ is the average precipitation of the recorded data, σ is the standard deviation, y_n and σ_n are the reduced mean and reduced standard deviation depending on the sample size n [14]. The variable y is estimated using equation (8) which is a function of the return period T.

The Log Pearson Type-III distribution is used to estimate the extreme occurrence of precipitation at various recurrence intervals. The procedure is to convert the data series to logarithms as given by formula (9). Where log$P$ is the logarithmic values of the recorded precipitation and $\sigma_{\log P}$ is the standard deviation of the logarithmic values. The frequency factor K for the sample size n and the desired recurrence interval T can be directly read from the tables [14].

$$\log P = \overline{\log P} + K\sigma_{\log P}. \quad (9)$$

A frequency factor K in equation (9) can also be determined as given in equation (10). The expected extreme values of the precipitation according to the various return periods are estimated from formula (11) based on the Powell method [14].

$$K = -1.1 - 1.795\log\log\left(\frac{T}{T-1}\right), \quad (10)$$

$$\mathrm{P} = \bar{P} + K\sigma_P. \quad (11)$$

2.2 Study area

This study was conducted in a very arid region where the average annual rainfall is less than 100 mm. The study was carried out in Unaizah city, Qassim Region; KSA where the geographic coordinates are 26.08^o*N* and 44.02^o*E*. The average temperature is 26 °C while the maximum temperature during the summer was registered as more than 47 °C. The mean annual humidity is 27 % with a minimum recorded value as less than 8 % in the summer, which is indicating as a very dry atmosphere.

2.3 Rainfall data

Daily rainfall data was collected from the station near the study area for a time series from 1964 to 2016. The rain falls, usually in the winter and spring seasons. Statistical analysis is carried out on the collected data to explore some information such as average annual rainfall, maximum of daily rainfall, weekly rainfall, and monthly rainfall for each year as presented in Fig. 1, 2 and Table 1.

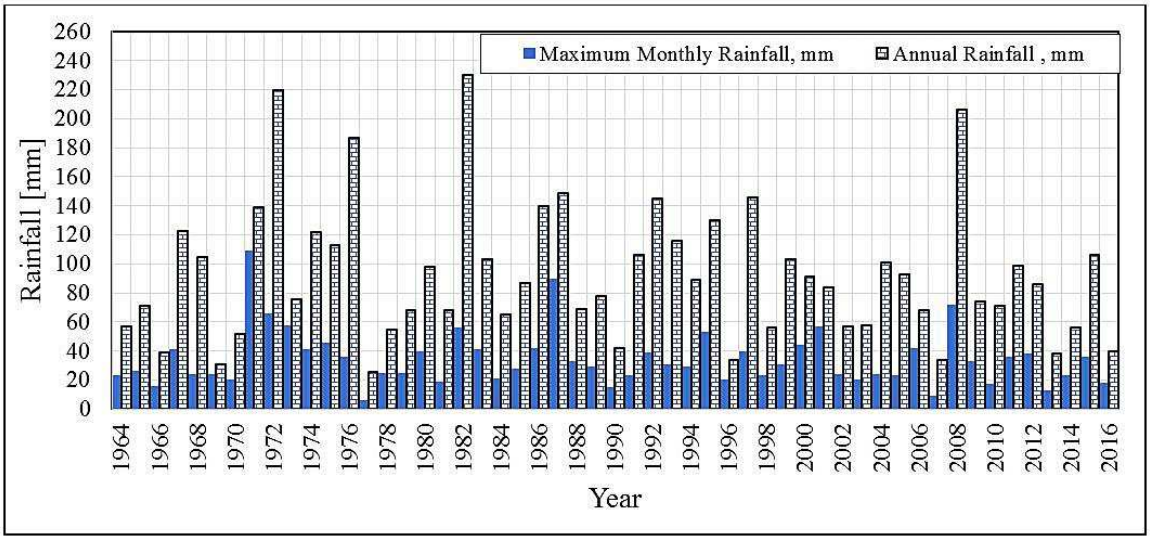


Fig. 1: Total annual rainfall and maximum monthly rainfall in [mm] from 1964 to 2016.

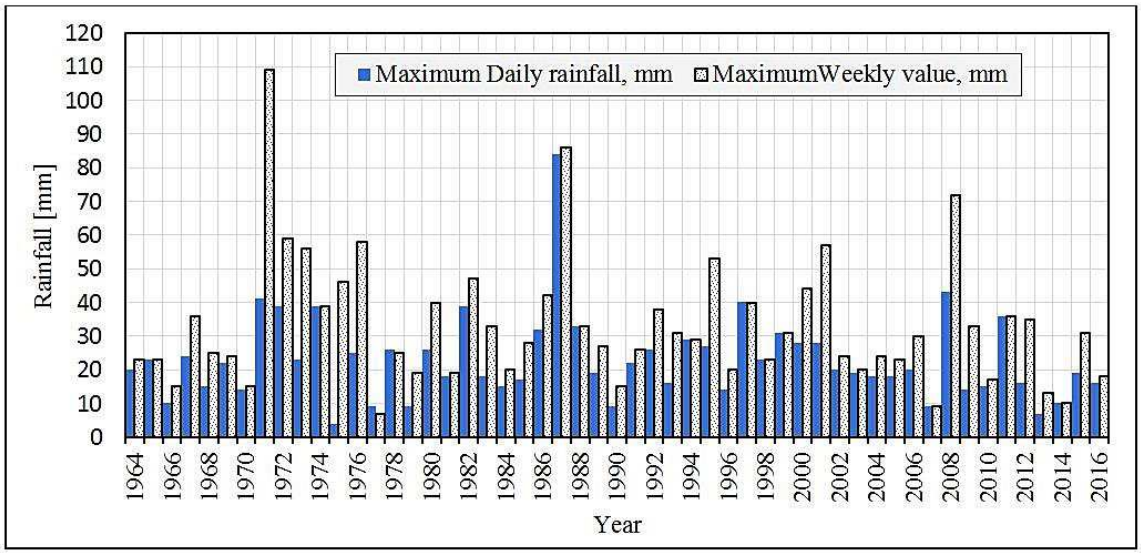


Fig. 2: Maximum weekly rainfall and maximum daily rainfall in [mm] from 1964 to 2016.

Table 1: Statistical parameters of the collected rainfall data.

Parameter	Maximum daily rainfall [mm]	Maximum weekly rainfall [mm]	Maximum monthly rainfall [mm]	Annual rainfall [mm]
Average	23	33	34	92
Median	20	29	29	86
Mode	9	23	23	68
Maximum	84	109	109	230
Minimum	4	7	8	26
SD	13	19	19	47
Skewness	2.19	1.75	1.75	1.11

3 Results and discussion

According to the recorded rainfall data (Table 1), the average annual rainfall is 92 mm, which is much less than 40 cm (the minimum limit for the arid regions) and indicates that the study area is considered a very dry region. The maximum rainfall recorded in the year 1982 (230 mm) is also less than the limited value of the arid region. From Fig. 2, we note that relatively high-intensity rainfall is repeated every 6 years.

3.1 Extreme rainfall using graphical models

The graphical models that were used in this study are California, Hazen, and Kimball methods as described in section 2.1.1. Based on these models, the relationships between frequency events and the expected rainfall for daily, weekly, and monthly durations were depicted in Fig. 3, 4 and 5 respectively. For daily storm duration, the correlation between modelled rainfall and the actual data is 0.91, 0.93, and 0.93 using the California, Hazen, and Kimball methods respectively as given in Fig. 3, while the correlation for weekly and monthly storm duration is 0.97 for the three models as presented in Fig. 4 and 5.

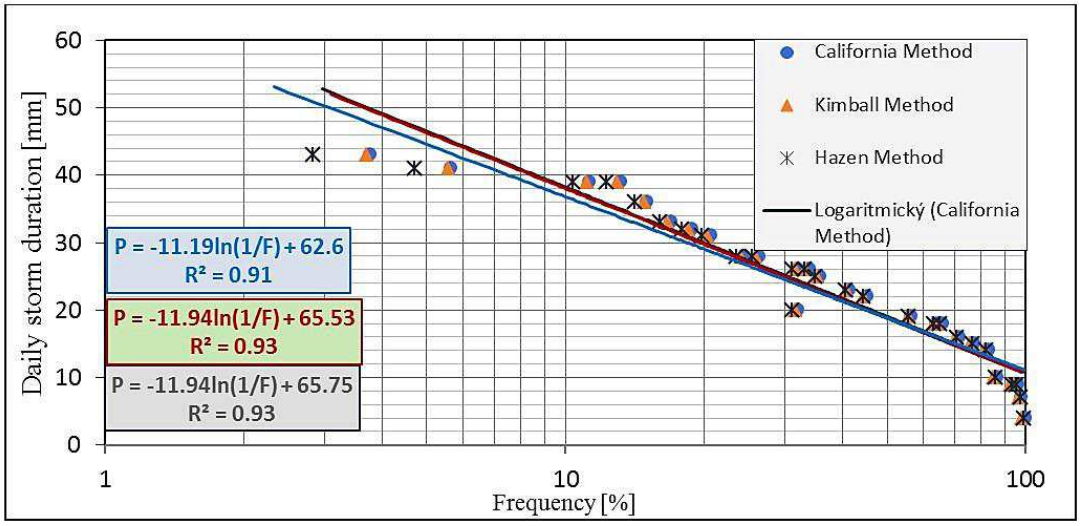


Fig. 3: Expected daily rainfall duration against the frequency of events.

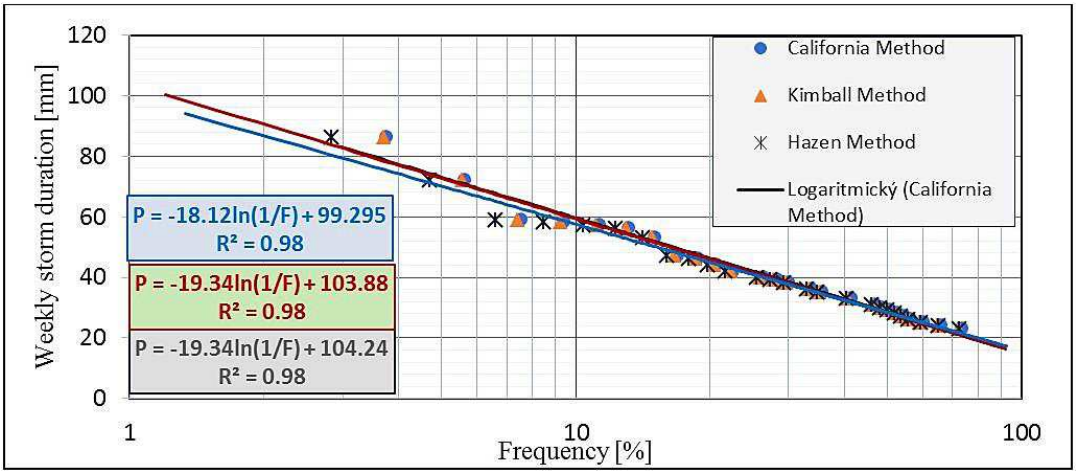


Fig. 4: Expected weekly rainfall duration against the frequency of events.

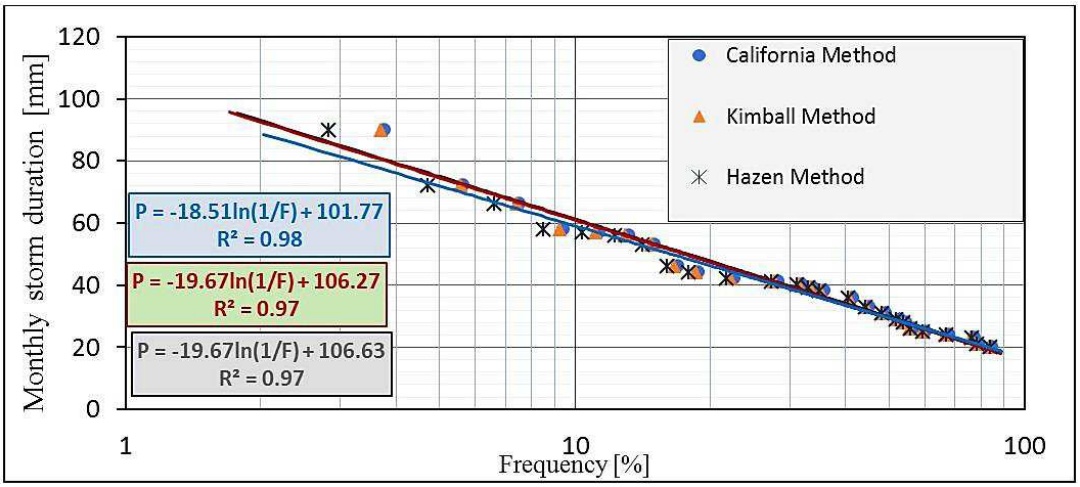


Fig. 5: Expected monthly rainfall duration against the frequency of events.

Equation (4) is used to find the relationship between the frequency of a rainstorm event for the required return period. The extreme rainfall events for each storm duration and return period were estimated from the fitted equations in Fig. 3, 4 and 5, where the ordinate is the expected rainfall *P* in mm and the horizontal axis *F* is the frequency of occurrence of that rainstorm. The predicted rainfall values are given in Table 2 for each storm duration at various return periods. The extreme rainfall

values estimated from the Kimball's method and the California's method are identical and are greater than those values estimated from the Hazen's method. The predicted values of rainfall for weekly and monthly storm durations are equal as presented in the Fig. 3, 4 and 5 because the rainstorm does not fall continuously for more than three days during any month of any year.

Table 2: Extreme values of rainfall for different return periods and storm durations using the graphical methods.

Return period [years]	Rainfall intensity [mm/day]			Rainfall intensity [mm/week]			Rainfall intensity [mm/month]		
	Hazen	Kimball	California	Hazen	Kimball	California	Hazen	Kimball	California
5	29	30	30	45	46	46	46	48	48
10	37	38	38	58	59	60	59	61	61
25	47	49	49	74	77	77	76	79	79
50	55	57	57	87	90	91	89	93	93
75	59	62	62	94	98	99	96	101	101
100	63	66	66	99	104	104	102	107	107
200	70	74	74	112	117	118	115	120	120

3.2 Expected rainfall using probability functions

The extreme values of rainfall are also estimated for daily, weekly, and monthly storm durations using probability function methods. Gumbel distribution (GE1), log Pearson Type III, and R.W. Powell's models predict the rainfall for various return periods. The PDF and CDF are statistical tools which are used to understand the random variables of rainfall values. The PDF and CDF functions for the collected data are illustrated in Fig. 6 and 7 for daily, weekly, and monthly storm durations. The rainfall for the three storm durations (daily, weekly, and monthly) gave a positive skew where the mean >median> mode as given also in Table 1. In addition, the figures showed equal values for the weekly and monthly storm durations. The CDF presented in Fig. 7 shows that 93 % of the recorded data is less than 43 mm for daily storm duration in any year, while 99 % is less than 90 mm for weekly and monthly storm duration.

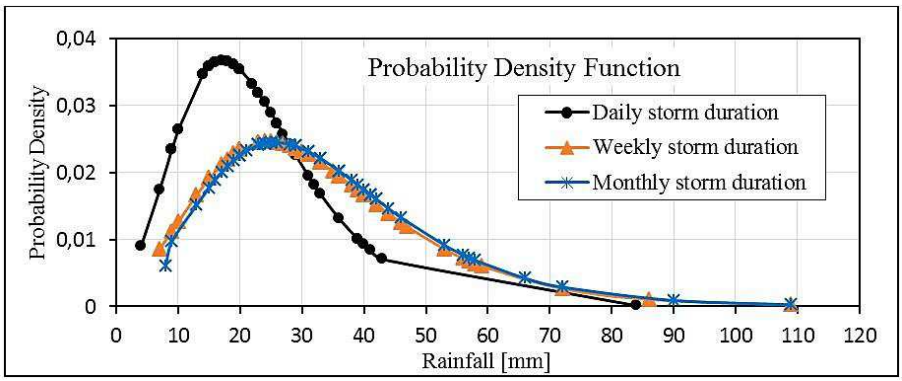


Fig. 6: Probability density function of daily, weekly, and monthly storm duration.

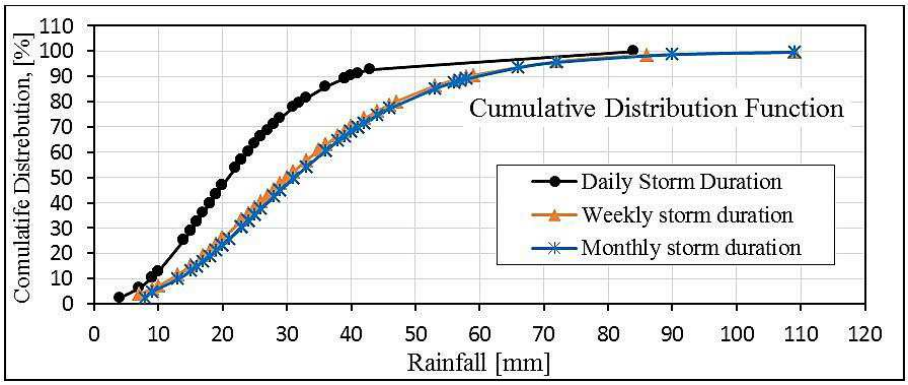


Fig. 7: Cumulative distribution function of daily, weekly, and monthly storm duration.

Table 3 gives the results of the predicted extreme rainfall based on the probability models explained in section 2 for three storm durations (daily, weekly, and monthly). The maximum rainfall values are determined for the same return periods (from 5 years to 200 years) to compare the results with the graphical method. From this table, we note that the Gumbel distribution gives larger values than both Powell's and log-Pearson type III methods. Therefore, the predicted values of rainfall by Gumbel distribution are suitable to use as basic values in designing the capacity of required ponds to store the surface water. The estimated values for weekly and monthly storm duration are even equal due to the behaviour of rainfall in the study area. The maximum estimated rainfall was 112 mm for a return period of 200 years. Although the expected extreme values of rainfall are low, they are important for designing ponds' capacity and other hydraulics projects such as storm drainage networks and culverts.

Table 3: Extreme values of rainfall for different return periods and three storm durations using probability functions methods.

Return period [years]	Rainfall of extreme daily storm duration [mm]			Extreme rainfall for weekly storm duration [mm]			Extreme rainfall for monthly storm duration [mm]		
	Gumbel distribution	Powell method	Log-Pearson type-III	Gumbel distribution	Powell method	Log-Pearson type-III	Gumbel distribution	Powell method	Log-Pearson type-III
5	33	32	32	49	47	46	50	48	47
10	42	40	39	61	58	57	62	59	58
25	52	49	48	77	72	73	78	74	72
50	60	56	54	88	83	85	89	84	83
75	64	60	57	95	89	91	96	90	92
100	68	63	61	100	93	98	101	95	93
200	75	70	67	111	104	111	112	105	104

Comparison between the expected rainfall using the graphical methods, Table 2, and the probability functions methods, Table 3, is presented in Table 4. The estimated rainfall from the two methods is nearly identical for the three storm durations as illustrated in the table. For the return period of 50 years and weekly storm duration, the average determined rainfall is 85 mm by probability functions methods, but it is 89 mm using the graphical methods. The two models proved that any method (graphical and statistical) could be used to design the water constructions in the study area.

Table 4: Estimated average values for three storm durations by the two methods.

Return period [years]	Rainfall intensity [mm/day]		Rainfall intensity [mm/week]		Rainfall intensity [mm/month]	
	Graphical method	Probability function method	Graphical method	Probability function method	Graphical method	Probability function method
5	30	32	46	47	47	48
10	38	40	59	59	60	60
25	48	50	76	74	78	75
50	56	57	89	85	92	85
75	61	60	97	92	99	93
100	65	64	102	97	105	96
200	73	71	116	109	118	107

3.3 Capacity of the storing's ponds

The main objective of this study is to recharge the collected surface water into the underground Saq aquifer to compensate for part of the pumped water. Consequently, the capacity of ponds was estimated based on the expected stream values for the weekly storm duration. The total area of the urban study city is 46 km^2 and is divided into four drainage areas according to the watershed analysis using the Global Mapper as presented in Fig. 8. The areas of the sub drainages are 24 km^2, 9 km^2, 6.8 km^2 and 6.3 km^2 as illustrated in the figure. The stream directions are illustrated by the arrows in each stream which give the direction of the runoff. According to the runoff streams, the storm network should be tolerated to drain the collected surface water to the selected sites of the ponds.

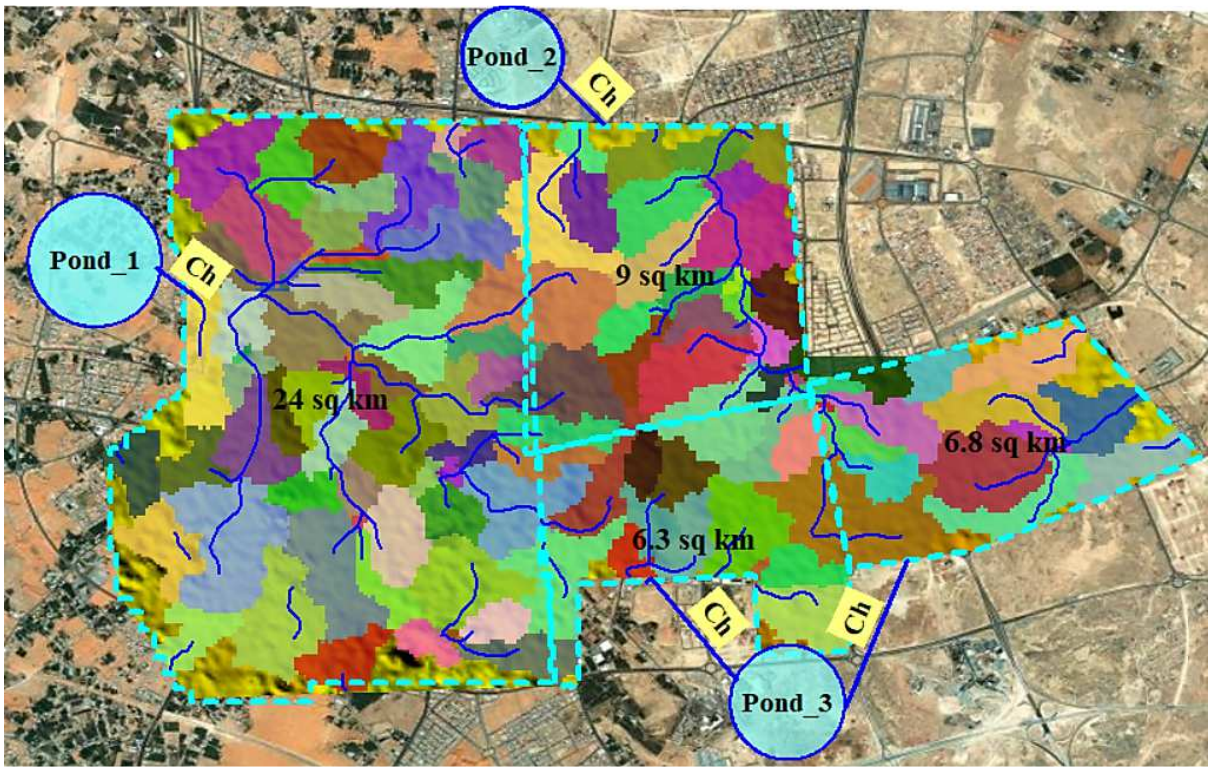


Fig. 8: Drainage streams, and sub drainage areas of the study area.

The capacity of the ponds was estimated using the rational method based on the weekly expected rainfall, return period, area of the sub drainage, and runoff coefficients. The average runoff coefficient is considered as 0.6 according to literature for the urban areas within the study region and other sites [20]. The urban growth of Unaizah city has increased by 28 km^2 in 16 years (from 2002 to 2018) according to Al-Kharafi [21] which is determined to be 1.8 km^2/year. This study assumes the same urban growth for the next 50 years. The capacity of storing ponds was estimated based on the expected rate of this urban growth. The required capacity of ponds is presented in Table 5 after considering the annual growth. The open channels are designed based on the total discharge from the sub drainage areas and the return period of the project. Also, Table 5 gives the discharge and a trapezoidal cross-section area of the water canal according to the maximum water velocity assigned for the channels limited by 1.5 m/s.

Table 5: Capacity of storing ponds for the sub drainage areas capacity of storing ponds based in urban growth 1.8 km^2/year.

Sub drainage area [km^2]	Return period [years]	Expected rainfall [mm]	Annual urban growth [km^2]	Area of sub drainage [km^2]	Capacity of the ponds ×1000 [m^3]	Surface area of ponds based on 3 [m] depth [km^2]	Canal discharge [m^3/s]	Canal cross section area [m^2]
Part_1	25	75	0.9	46.50	2093	0.70	8.07	5.38
Part_2			0.4	19.00	855	0.29	3.30	2.20
Parts_3&4			0.5	25.50	1148	0.38	4.43	2.95
Sum			**1.8**	**91.00**	**4095**			
Part_1	50	87	0.9	69.00	3229	1.08	12.46	8.31
Part_2			0.4	29.00	1305	0.44	5.03	3.36
Parts_3&4			0.5	38.00	1710	0.57	6.60	4.40
Sum			**1.8**	**136.00**	**6244**			
Part_1	75	95	0.9	91.50	5216	1.74	20.12	13.41
Part_2			0.4	39.00	2223	0.74	8.58	5.72
Parts_3&4			0.5	50.50	2879	0.96	11.11	7.40
Sum			**1.8**	**181.00**	**10317**			
Part_1	100	100	0.9	114.00	6498	2.166	25.07	16.71
Part_2			0.4	39.00	2223	0.741	8.58	5.72
Parts_3&4			0.5	50.50	2879	0.960	11.11	7.4
Sum			**1.8**	**203.50**	**11600**	**3.867**		

Surface runoff contains plenty of pollutants such as sand, hydrocarbons, and plastics among others. To capture the contamination, a circular sand filter with a 2.5 m inner radius was suggested to be constructed around the recharging well inside the ponds. The filter is supported by ten centimetres of perforated brick from both sides, as illustrated in Fig. 9. The filter is designed for a return period of 50 years. The filter consists of one-meter fine sand, 1.5 m coarse sand and 2.0 fine aggregate layer as presented in Table 6, with equivalent hydraulic conductivity of 0.097 m/s. As shown in Table 7, the expected losses due to the vertical permeability of the proposed pond range from 9 to 14 % of the collected surface runoff.

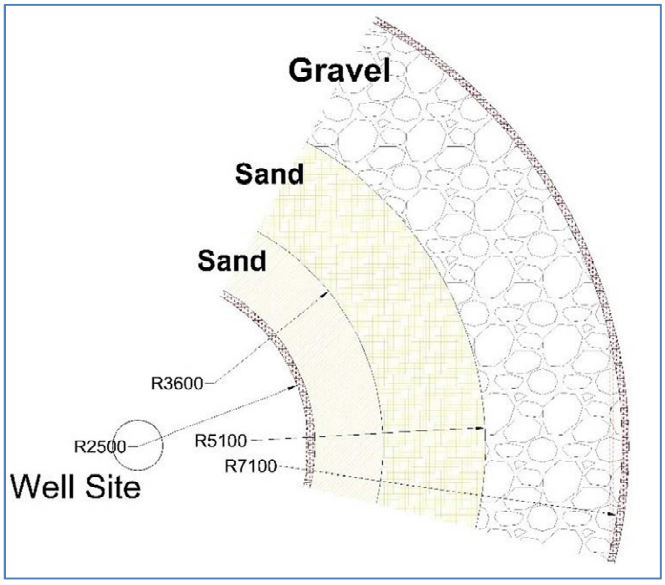


Fig. 9: Cross section of the suggested sand filter.

Table 6: Sand filter properties.

Filter layers	K [m/s]	Thickness [m]	K_{equ} [m/s]
Find sand layer	0.01	1.00	0.097
Coarse sand layer	0.015	1.50	
Coarse aggregate	0.105	2.00	

Table 7: Capacity of filter for 50-year return period.

Sub drainage area	Capacity of the ponds [m^3]	Filtration rate [m^3/day]	Retention time [days]	Pond losses [m^3]	Loss [%]
Part_1	3,229,200.0	1,458,500.9	2.2	206,897.5	14 %
Part_2	1,305,000.0	75,100.5	1.5	83,612.4	10 %
Part_3&4	1,710,000.0	166,800.7	1.5	109,561.1	9 %

4 Conclusion

In arid regions such as Saudi Arabia rainfall is scarcity and most of the time the atmosphere is dry. While in some cases rain falls with high intensity and in short duration may cause flash floods and damage to properties. Also, water resources are very vital in the arid regions therefore exploiting any source of water is highly considered even its quantity is small. The historical data of rainfall for the study area concluded that 93 % of the recorded rainfall is less than 43 mm for the daily storm duration, while 99 % of the rainstorm is less than 90 mm for the weekly and monthly duration. The study proved that the graphical and probability distribution methods give almost equal results of the predicted rainfall for different return periods. Therefore, any method of both can be used in the design of hydraulic projects. The research studied the collection of storm runoff that prevents urban areas from flash floods by storing surplus rain in retention ponds and partly compensates for groundwater level decline caused by pumping water from the aquifer. The predicted quantity of the collected water runoff is $2.4 \cdot 10^6$ m^3 in current situation which it is expected to be $6.2 \cdot 10^6$ m^3 after 50 years due the urban growth. Although the projected amount of water in the research region is small, the study is applicable to any metropolitan area that includes non-renewable aquifers. A feasibility assessment is needed to ascertain the environmental and economic impacts of such projects' adoption.

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