Precipitation Analysis and Water Resource of Wadi Siham Basin, Yemen

Analisis Kerpasan dan Sumber Air Lembangan Wadi Siham, Yaman

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ABSTRACT *Wadi Siham Basin (WSB) is one of the significant agricultural areas in Yemen. This paper aims to analyse the quantity and spatial and temporal variation of rainfalls in WSB. The rainfalls (1979-2008) were collected and statistically analyses to evaluate the rainfall trends. The areal catchment rainfall was estimated using the Theissen polygon method, while the recurrence interval and probability analysis were carried out using the Hazen method. The Mann-Kendall and Sen's slope analyses results showed that the rainfall at Wallan and Al-Amir stations had significant negative values (-4.72 mm/year and -6.11 mm/year respectively), while, the rainfall trend at Dhamar was positive at 50.20 mm/year. The total amount of rainfall was 1711.26 Mm^3. The average annual rainfall in WSB was 346.39 mm/year. The mean annual water runoff was 82.92 Mm^3 or 23.94% of the average annual rainfall in WSB. A total of 570 flood events occurred with a total volume of 53.10 Mm^3 in a span of 20 years. The total water runoff was 4.85% of total volume of rain precipitated in WSB, indicating that the total water loss was 95.15%. In conclusion, the study has demonstrated the urgent need for a sustainable water resource management in WSB.*

Keywords: Rainfall, trend, Mann-Kendall and Sen test, Wadi Siham Basin (WSB), Yemen

ABSTRAK *Lembangan Wadi Siham (WSB) ialah salah satu kawasan pertanian yang penting di Yaman. Tujuan kajian ini adalah untuk menganalisis kuantiti dan perubahan ruangan dan temporal hujan di WSB. Curahan hujan dalam jangka masa 1979-2008 digunakan untuk analisis statistik trend hujan. Hujan di kawasan tersebut dianggarkan dengan menggunakan kaedah poligon Theissen, manakala analisis jangka ulangan dan kebarangkalian dijalankan melalui kaedah Hazen. Hasil analisis nilai kecerunan Mann-Kendall dan Sen menunjukkan bahawa trend hujan di stesen hujan Wallan dan Al-Amir adalah negatif dengan sangat ketara (masing-masing -4.72 mm/tahun dan -6.11 mm/tahun), sebaliknya trend hujan di stesen Dhamar pula mengalami nilai positif yang ketara sebanyak 50.20 mm/tahun. Jumlah purata keseluruhan hujan di WSB adalah sebanyak 1711.26 Mm^3 manakala purata hujan* *tahunan di WSB adalah 346.39 mm/tahun. Purata air larian tahunan adalah 82.92 Mm^3. Sebanyak 570 kejadian banjir telah berlaku dengan sejumlah 53.10 Mm^3 air dalam tempoh 20 tahun. Jumlah larian air adalah sebanyak 4.85% daripada jumlah isipadu kerpasan di WSB, menunjukkan jumlah kehilangan air adalah sebanyak 95.15%. Sebagai kesimpulan, kajian ini menunjukkan peri pentingnya pengurusan sumber air secara lestari di WSB.*

Kata kunci: Hujan, trend, Ujian Mann-Kendall dan Sen, Lembangan Wadi Siham (WSB), Yaman

1. Introduction

Wadi is an ephemeral watercourse in arid regions and a vital source of water in the arid and semi-arid countries such as Yemen). It is seldom that wadi flows at a certain section, which is described as perennial (Nouh, 2006). Catastrophic flash floods occurring in wadis are threat to many communities and the groundwater recharge source after storms. Population growth, land use, and human settlements around the wadi*s* increase the social and environmental issues due to unplanned usage and hydrological calculation which are not based on the optimised methods, and the water resource management programmes in these areas can cause inconvenience. This is because the scientific knowledge of the hydrological processes of wadi*s* is limited in most countries (Sen, 2008).

Rainfall in the arid and semi-arid regions is meager, irregular and highly varied (Bahat, Grodek, Lekach, & Morin, 2009). The amount of rainfall over an area is important to assess the amount of water available to meet the demands of agriculture, industry, and other human activities. Therefore, the study of the rainfall distribution in time and space is crucial for the welfare of the nation’s economy (Abdullah & Mazroui, 1998).

Water resource in Wadi Siham comes from the rainfall throughout the year, which is scarce and varied. Second, the groundwater source within the Wadi Siham is held back to feed the springs and streams in the wadi centre besides the main water drainage, which is characterised by groundwater levels (Katreeb, 1998). These groundwater levels determine the quantity of water drainage. As the surface water running through the Wadi from the eastern and middle rugged mountains, the traces of water runoff have created fractures through which water runs to different sub-wadi*s* towards the Red Sea. The distribution of surface water in the coastal plain runoffs flow all the way through rugged mountains and hills until it reaches the Red Sea. The further it travels, the less (or nothing at all) its runoffs go into the Red Sea due to water leakage through the wadi's cleavage and cracks. A considerable amount of water is also used for irrigating purposes nearby fields stretching alongside the wadi (Katreeb, 1998). The variability of rainfall is useful for time-related data. Similarly, the variability of rainfall with reference to space also a point of interest for hydrologists. However, the spatial variability is influenced by climatic factors as well as the distance from water bodies (ocean and seas), the elevation of the place, and slopes (Bahat et al., 2009). Hydrologists or river engineers dealing with water resource management postulate the rainfall occurrences of specific magnitude. The technique used for this purpose is to define recurrence intervals of various magnitudes of rainfall (Guzzetti, Reichenbach, Cardinali, Galli, & Ardizzone, 2005; Argüello, Dasso, & Sanabria, 2006; Fiorillo, Esposito, & Guadagno, 2007; Purvis, Bates, & Hayes, 2008; Villarini, Smith, Serinaldi, Bales, Bates, & Krajewski, 2009; Villarini, Smith, Baeck, Sturdevant-Rees, & Krajewski, 2010; Pike & Scatena, 2010).

Although Wadi Siham is one of the important wadi*s* in Yemen, it lacks the policies for sustainable management, development, and efficient utilisation of water resources. Therefore, this study is aimed to investigate the surface water resources in the Wadi Siham Basin in terms of source, quantity, spatial and temporal discrepancy based on the historical rainfall data.

2. Material and Methods

2.1 Study area

Wadi Siham is one of the seven largest wadi*s* in the western region of the Republic of Yemen. The Wadi Siham Basin (WSB) is located between longitudes 42º 55′ and 44º 16′ East and latitudes 14º 39′ and 15º 17′ North. The wadi is originated from the rocky-rugged mountains and hills with an altitude of 3400 m stretch as far as the eastern area. The topography is dominated by the mountain that is parallel to the Red Sea coast through Sana'a towards Aden, with three ridges interspersed by upland plains. The geology consists of basement complex, sandstones and volcanics. These mountains merge with ranges running parallel to the coast of the Gulf of Aden, which reach the altitude of about 2000 m. The drainage in the northwestern of the country divides along the north-south watershed between steep rivers, which runs west from the mountains towards the Tihama plain, with a width of 50 km along the Red Sea coast, and drain towards the desert to the east (Farquharson, Plinston, & Sutcliffe, 1996).

The rugged mountains are suitable to gather water that the rainwater runs through the water supply networks and remain within the wadi's basin during the rainy seasons (Van der Gun & Ahmad, 1995). WSB begins at the western highlights across the Tihama Plain. It is distinguished from other basins such as the Surdud Basin in the north, the Rima'a Basin in the south, and the Saba Basin in the east. It covers an area of 4911 km^2. Wadi Siham plain, rocky-rugged mountains and hills with an altitude of 3400 m stretch as far as the eastern area (Figure 1 and Figure 2). The Wadi Siham Basin estuary is connected to the Red Sea, south of Al Hudaydah City.

In fact, the Wadi Siham Basin receives water flowing from the upper, middle, and eastern mountain areas (Fig. 3). The wadi consists of naturally shaped tributaries that contain and absorb the high though rare floods. The strong surface runoff in Wadi Siham enables it to receive huge rainwater during the rainy seasons but most of the times the place is dry throughout the year (Van der Gun & Wesseling, 1991). The water supply to the wadi occurs is irregular after rainstorms fall on some areas around the basin (Elderhorst, 1991). When rainstorms occur, floods cause torrent erosions, where sediments and debris such as wood and stones are transported to the wadi. This in turn changes the level of wadi after each torrent rainfall (Mohammed, 1988).

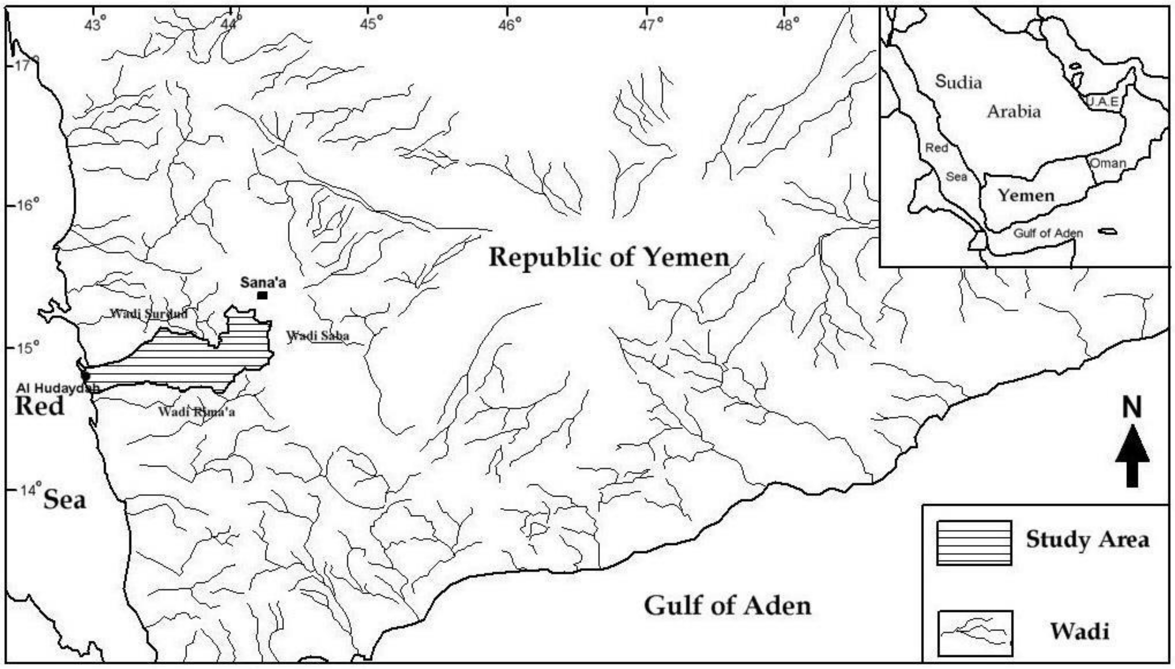


Figure 1. Location of the study area, the Wadi Siham Basin

Figure 2. The terrains in the Middle Zone (left) and the Eastern Zone (right) of Wadi Siham Basin

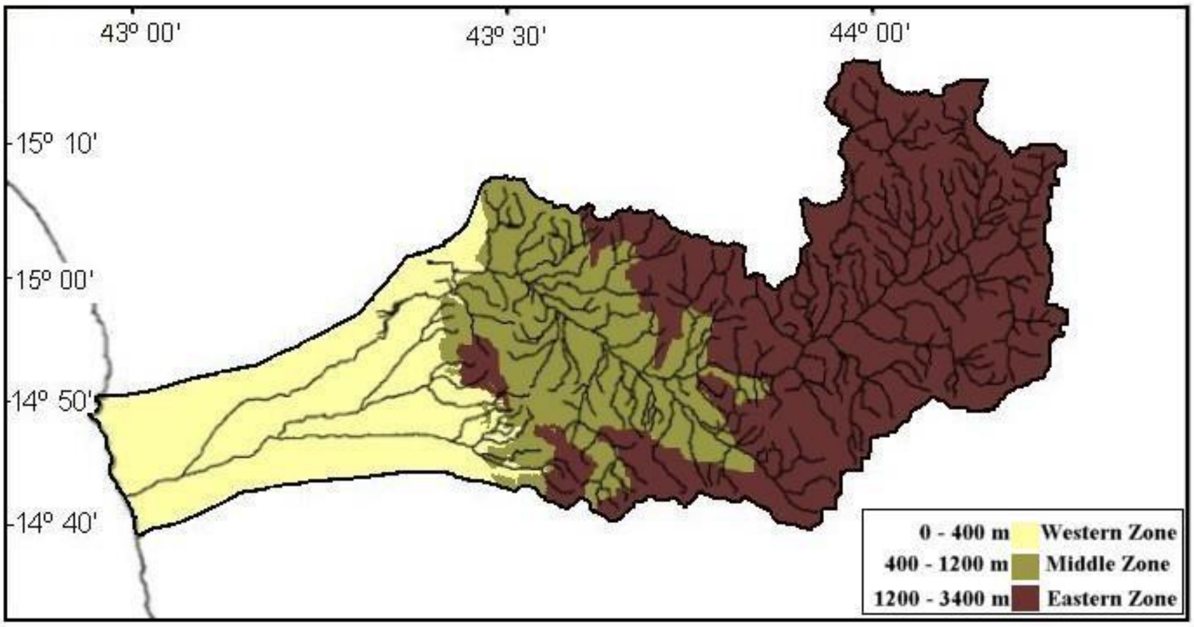


Figure 3. The three relief zones of Wadi Siham Basin

3. Data & Analysis

As water is a vital resource and its availability is dependent on rainfall, the occurrence of rainfall becomes an interest among hydrologists. This study was based on the secondary data collected from various government agencies in Yemen. The data were categorised into two; (A) data bank and (B) data map. The data bank (A) was collected from the General Authority for Water Resources (Sana'a, Yemen), the Tihama Development Authority (Al-Hudaydah, Yemen) and the Research Agriculture & Extension Authority (Dhamar, Yemen). Data map (B) topographical maps (1:100,000) were collected from the Survey Authority (Sana'a, Yemen).

The data bank consisted of two types of data; rainfall data and water runoff data. These were collected from 13 rainfall stations (No. 1-13), two meteorological stations (No. 14-15) and one hydrological station (No. 16), as illustrated in Table 1 and Figure 2. The data collected include the monthly and annual rainfall as well as daily water runoff. These maps provide valuable information about drainage network and contour lines. The rainfall data were collected in 30 years from 1978 to 2008.

The basin has 13 rainfall stations and 2 full-fledged meteorological stations. Data from these stations are used for climate analysis. For example, the 30 years (1979-2008) rainfall data were used for the rainfall analysis. Since the objective of this study was to assess the water availability, more focus was given to the rainfall analysis, in particular the rainfall analysis in space and time to estimate the areal mean rainfall and available water volume. The analysis was conducted in the 15 stations of Wadi Siham Basin.

3.1 Aerial rainfall analysis

The Thiessen polygon method is used in hydrometeorology to determine the average areal rainfall over drainage basin when there are several rain gauge sites (Buytaert et al., 2006; Jia et al., 2006; Ruelland, Ardoin-Bardin, Billen, & Servat, 2008; Symeonakis, Bonifaçio, & Drake, 2009). The concept of this method is to divide the drainage basin into several polygons, each one around a site, and then take the weighted measurement average based on the size of each polygon area. In this way, the measurements of large polygons are given more weight than smaller polygons (Sen, 2008). Topographical maps of the Wadi Siham Basin with 1:100000 scale were used with the Arc-View GIS extension to delineate the stream area networks and sub-basin (Figure 4) and Thiessen polygon (Figure 5).

Table 1. Monthly Data of the Rainfall, Meteorological and Hydrological Stations in Wadi Siham Basin from 1979 to 2008

NO.	Name	Elevation (m)	Coordinates		Agency	Data Available	
			Longitude	Latitude		From	To
1	Sukhna	350	43º 26′ 11"	14º 47′ 36"	TDA	1979	2008
2	Al-Dabrah	1000	43º 47′ 07"	14º 47′ 43"	TDA	1979	2008
3	Al-Hamal	2000	43º 57′ 01"	14º 45′ 03"	TDA	1979	2006
4	Wallan	2500	44º 16′ 23"	15º 04′ 02"	TDA	1980	2008
5	El-Haima	1600	43º 54′ 39"	15º 05′ 47"	TDA	1979	2008
6	Al-Amir	2200	43º 42′ 21"	15º 02′ 57"	TDA	1979	2008
7	Deir Zinkah	450	43º 29′ 33"	15º 00′ 27"	TDA	1979	2007
8	Maghreba	1200	43º 28′ 23"	14º 51′ 30"	TDA	1979	2008
9	Al-Mrawah	70	43º 09′ 29"	14º 49′ 59"	TDA	2004	2008
10	Waqir	120	43º 16′ 52"	14º 53′ 00"	TDA	1979	2008
11	Al-Qutta	105	43º 12′ 08"	14º 54′ 06"	TDA	2004	2008
12	Mahal Shamiri	200	43º 21′ 12"	14º 59′ 30"	TDA	1990	2008
13	Al-Hudaydah	6	42º 57′ 34"	14º 46′14"	TDA	1992	2008
14	Al-Khalifa*	160	43º 19′ 27"	14º 53′ 07"	TDA	1988	2007
15	Dhamar*	2400	44º 12′ 02"	14º 54′ 11"	RAEA	1999	2008
16	Mahal Saleem**	230	43º 23′ 00"	14º 58′ 18"	TDA	1990	2008

Notes: * Meteorological Station and ** Hydrological Station

Source: Tihama Development Authority (TDA) and the Research Agricultural & Expansion Authority (RAEA).

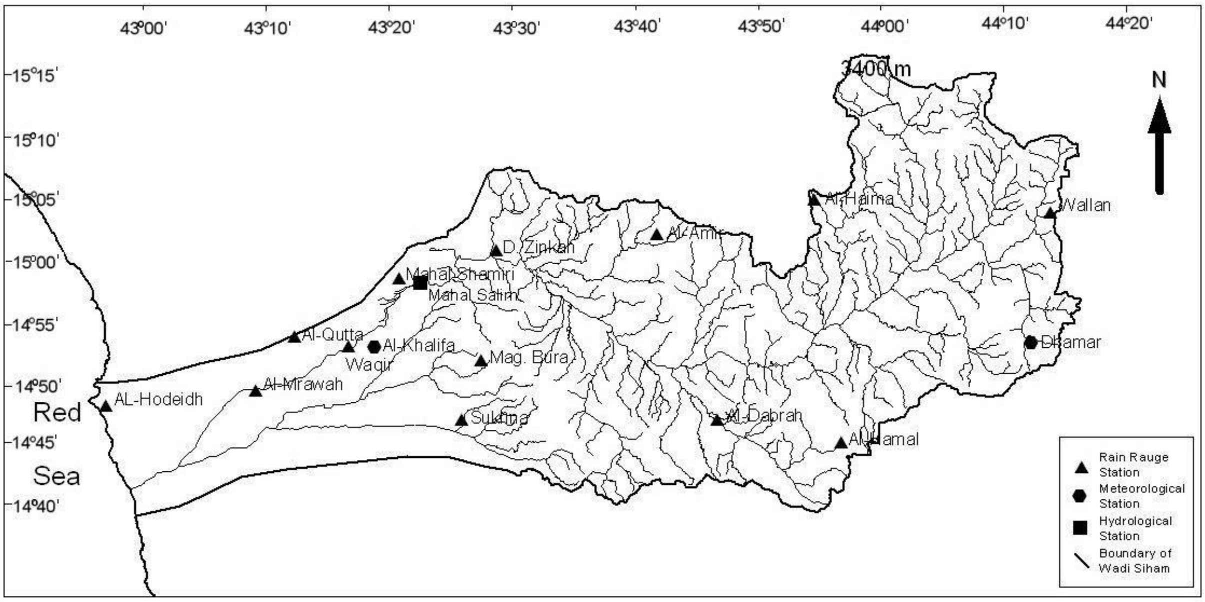


Figure 4. Drainage pattern and location of rain gauges in Wadi Siham Basin

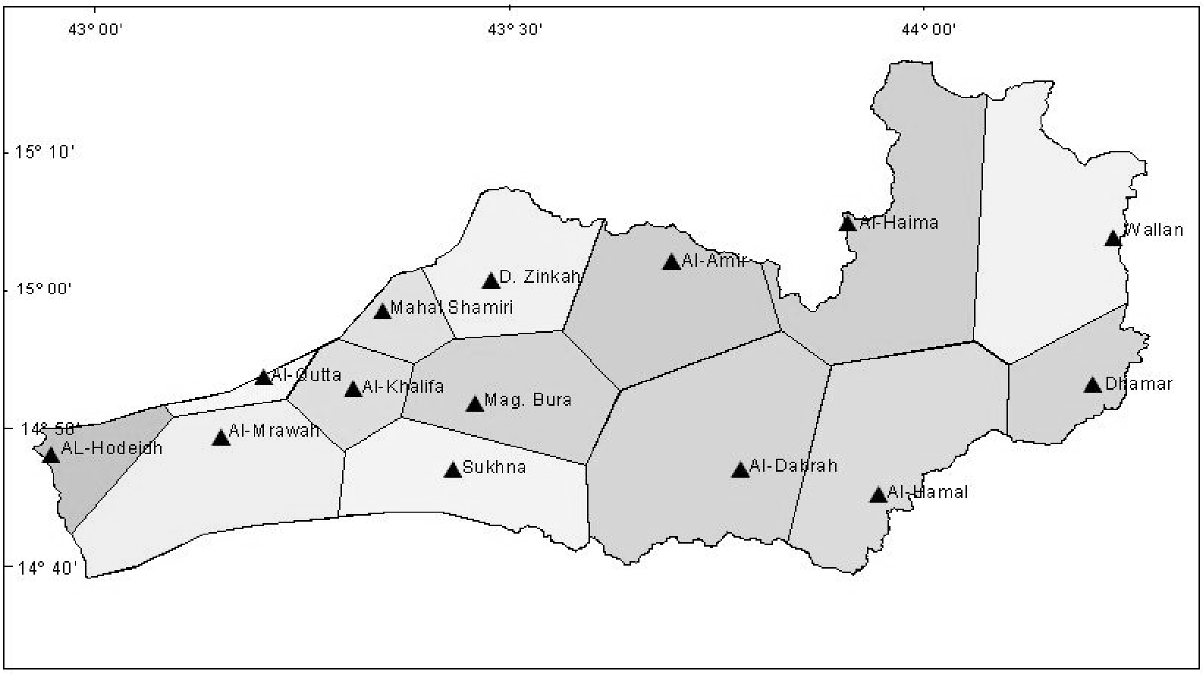


Figure 5. Thiessen polygon to calculate the areal rainfall in Wadi Siham Basin

3.2 Statistical Analysis

The data were analysed using Excel 2003 and statistical analysis was carried out using SPSS software (Version 15, USA). The homogeneity test for variances of data was also investigated. The annual and seasonal series were tested for normality using skewness and kurtosis coefficient. The Mann-Kendall (MK) test was applied to assess the existence of significant trend of rainfall time-series (Önöz & Bayazit, 2003; Cislaghi, De Michele, Ghezzi, & Rosso, 2005; Luo, Liu, Fu, Liu, Wang, & Zhou, 2008; Pal & Al-Tabbaa, 2010). In this study, the MK test used the following equation:

$$S = \sum_{i=2}^{n} \sum_{j=1}^{i-1} \operatorname{sign}(x_i - x_j), \tag{1}$$

where x_j are the sequential data values, n is the length of the time-series and sign $(x_i\text{-}x_j)$ is −1 for $(x_i\text{-}x_j)<0$; 0 for $(x_i\text{-}x_j)=0$ and 1 for $(x_i\text{-}x_j)>0$.

The mean $E[S]$ and variance V[S] of the S value were obtained as follows:

$$E[S] = 0, \tag{2}$$

$$\mathrm{Var}[S] = \frac{n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p-1)(2t_p+5)}{18}, \tag{3}$$

where t_p is the number of ties for p value and q is the number of tied values. The second term represents an adjustment for tied or censored data. The standardized MK test statistic (Z_{MK}) was computed by:

$$Z_{\mathrm{MK}} = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}\,(S)}} & \text{if } S>0, \\ 0 & \text{if } S=0, \\ \frac{S+1}{\sqrt{\mathrm{Var}\,(S)}} & \text{if } S<0. \end{cases} \tag{4}$$

The positive Z_{MK} values indicate increasing trend, while the negative ones indicate decreasing trend. To test the monotonic trends (increasing or decreasing) at p significance level, the hypothesis was rejected for the Z values greater than $Z_{1-p/2}$, obtained from the cumulative normal distribution tables (Modarres & de Silva, 2007).

Using the Sen's slope method (Sen, 1968), the linear trend analysis was conducted to estimate the rainfall trend. This method is method to estimate the trend of climate parameters including rainfall (Yue, Pilon, & Cavadias, 2002; Shahid, 2010). The method requires an equally spaced time series data, in which the slope is calculated as a change in measurement per change in time:

$$Q/ = (xt/ - xt)/(t/ - t) \quad (5)$$

where, $Q/$ = slope between n data points $xt/$ and xt, $xt/$ = data measurement at time $t/$ xt = data measurement at time t. The Sen's estimator of slope is given by the median slope:

$$Q = Q/\,[(N+1)/2] \qquad \text{if } N \text{ is odd} \quad (6)$$

$$= (Q/[N/2] + Q/[(N+2)/2])/2 \qquad \text{if } N \text{ is even} \quad (7)$$

The records of annual rainfall for the periods of 5-30 years were used as input, in which the Hazen equation was applied (Ward & Trimble, 2003).

$$Fa=100(2n-1)/2y=100/\text{Return Period, T} \quad (8)$$

where, Fa is the probability (%) of each event, y is the total number of events, and n is the rank for each event.

4. Results

4.1 Rainfall analysis

Table 2 shows the average monthly rainfall in Wadi Siham Basin (WSB). The highest average monthly rainfall of 76.18 mm (1979-2008) was recorded in August whereas the lowest average monthly rainfall of 6.79 mm was recorded in December. Figure 6 depicts the average monthly rainfall in WSB stations represented by isohyetal maps. Meanwhile, Table 3 shows the average annual rainfall in WSB. The average annual rainfall was 349.86 mm, with the highest value of 597.06 mm in Maghreba station, while the lowest rainfall was 80.91 mm in Al-Hudaydah station.

The averages of seasonal rainfall during winter, spring, summer and autumn were 25.04 mm, 98.46 mm, 145.56 mm and 80.80 mm, respectively. The summer season exhibited the highest rainfall value (145.56 mm), while the lowest (25.04 mm) was during winter. There is a significant difference ($p<0.05$) in terms of annual and seasonal rainfall in WSB between seasons. All annual and seasonal rainfall are significantly different between seasons. The strongest correlation between seasonality and rainfall was found in summer while the lowest correlation was in autumn. However, the correlation between annual and seasonal rainfall was insignificant in winter ($p>0.05$). Table 4 shows that the annual and seasonal rainfall are significantly correlated during spring, summer and autumn.

Table 2. Summary of monthly rainfall in Wadi Siham Basin (1979–2008)

Month	Average (mm)	Variance (mm^2)	SD (mm)	CV%	Min (mm)	Max (mm)
Jan	9.5	55.17	7.43	78.18	0.68	26.12
Feb	8.75	40.49	6.36	72.69	0.06	26.15
Mar	18.28	247.73	15.74	86.09	0	52.14
Apr	42.82	912.51	30.21	70.55	3.06	101.03
May	37.36	644.68	25.39	67.97	0.9	82.25
Jun	22.19	207.82	14.42	64.96	1.41	48.37
Jul	47.19	919.4	30.32	64.26	7.62	110.98
Aug	76.18	1122.92	33.51	43.99	14.61	120.92
Sep	45.64	1331.51	36.49	79.95	5.24	124.89
Oct	25.69	453.51	21.3	82.9	5.75	71.41
Nov	9.47	49.87	7.06	74.55	0	24.98
Dec	6.79	34.32	5.86	86.33	0	21.38

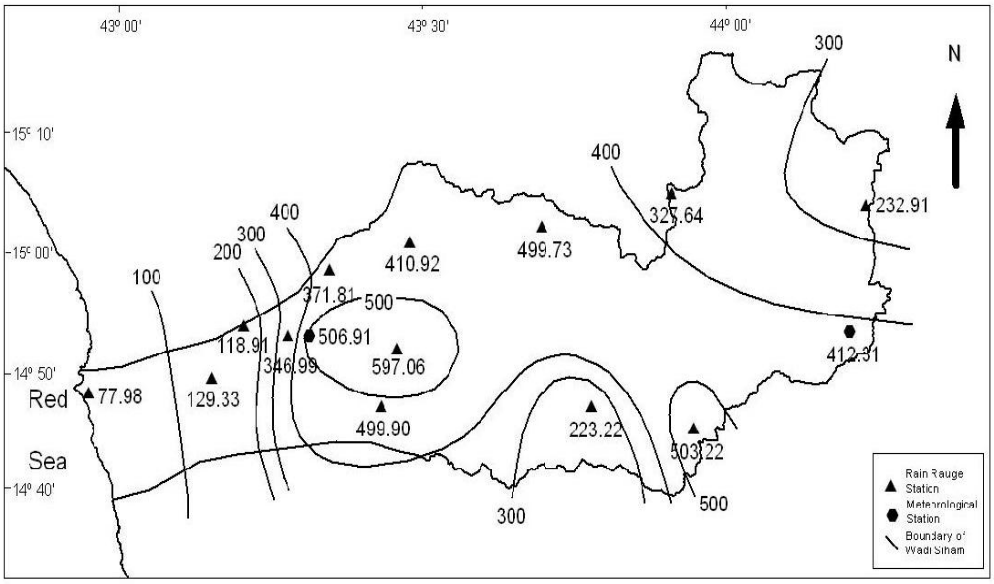


Figure 6. The annual rainfall distribution in the Wadi Siham Basin

Table 3. Summary of seasonal rainfall (1979– 2008) in Wadi Siham Basin

Station	Annual	Winter	Spring	Summer	Autumn
Al- Sukhna	478.49	39.89	122.60	182.42	154.99
Al- Dabrah	217.50	19.03	82.35	86.82	35.03
Al- Hamal	493.80	28.47	178.48	226.55	69.72
Wallan	232.21	23.92	109.54	78.27	21.18
El-Haima	327.64	27.23	128.32	136.69	35.40
Al-Amir	497.20	40.18	217.58	185.61	56.37
Deir Zinkah	407.86	14.68	103.70	212.10	80.45
Maghreba	587.88	73.64	200.47	233.82	89.12
Al-Khalifa	506.91	21.01	70.16	212.04	203.71
Dhamar	401.31	18.18	112.69	239.17	31.27
Al-Mrawah	129.33	7.15	12.18	54.12	55.88
Waqir	346.99	14.68	55.27	131.50	145.54
Al-Qutta	118.91	2.10	6.36	52.31	58.14
Mahal Shamiri	371.81	16.47	69.48	127.33	158.52
Al-Hudaydah	77.98	28.96	7.65	24.69	16.67
Average (mm)	346.39	25.04	98.46	145.56	80.80
Variance (mm^2)	26230.54	291.34	4340.46	5369.60	3360.17
SD (mm)	161.96	17.07	65.88	73.28	57.97
CV%	46.29	68.17	66.92	50.34	71.74
Skewness	-0.33	1.66	0.29	-0.23	0.92
Kurtosis	-1.05	4.12	-0.55	-1.42	-0.29
Minimum (mm)	80.91	2.10	6.36	24.69	16.67
Maximum (mm)	597.06	73.64	217.58	239.17	203.71

Notes: And measures of distribution such as skewness and kurtosis indicate how much a distribution varies from the normal distribution.

Table 4. Correlation coefficients between annual and seasonal series

	Winter	Spring	Summer	Autumn
Pearson	0.63*	0.80*	0.93*	0.52*
Spearman	0.49	0.70*	0.88*	0.64*

Note: *Statistical significance at $p<0.05$

4.2 Coefficient of Variation

The coefficient of variation (CV) indicates low variability in inter- and intra-annual rainfall in Wadi Siham Basin during different seasons, ranging from 50.34% (summer) to 71.74% (autumn), as shown in Table 3. In comparison to the CV of rainfall in the 15 stations between seasons, winter exhibited the highest rainfall variability, ranging from 80.6% to 261.91% (Fig. 7a).

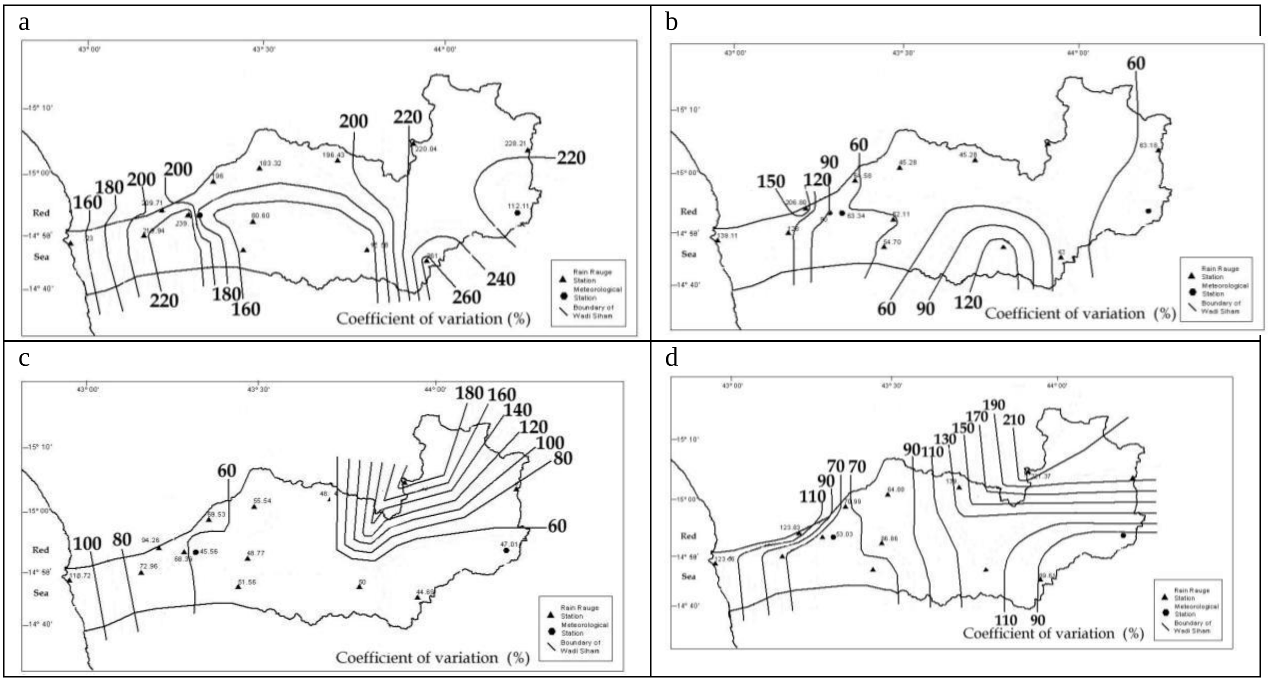


Figure 7. Coefficients of variation (%) of the total seasonal rainfall in (a) winter, (b) spring, (c) summer, and (d) autumn using isohyetal maps

4.3 Mann-Kendall rainfall analysis

The Mann-Kendall analysis was applied to investigate the rainfall trend in the Wadi Siham Basin (Table 5). The results showed that the Z_{MK} values are only significant at three stations and in two seasons ($p<0.05$). Wallan (-2.4 mm/year) and Al-Amir (-2.03 mm/year) stations as well as winter (-2.50 mm/year) and spring (-3.14 mm/year) seasons demonstrated negative Z_{MK} values, which indicate a negative rainfall trend (Figure 7). The Sen's slopes demonstrated negative values in the average annual rainfall with a decreasing rate of -4.72 mm/year (Wallan station), -6.71 mm/year (Al-Amir station), -1.25 mm/year (winter season) and -3.43 mm/year (spring season). However, a positive rainfall trend ($p<0.05$) was shown in Dhamar station with Z_{MK} of 1.97 and Sen' slope of 50.20 mm/year (Table 5).

Table 5. The Mann-Kendall rainfall trend analysis at the 15 stations in Wadi Siham Basin

Stations	p value	Z_{MK}	Sen's slope
Al- Sukhna	0.572	0.57	3.3
Al- Dabrah	0.54	-1.93	-4.344
Al- Hamal	0.469	0.73	2.404
Al- Wallan	0.016	-2.40	-4.72*
El-Haima	0.724	-0.36	-1.082
Al- Amir	0.410	-2.03	-6.11*
Deir Zinkah	0.400	-2.03	-6.112
Maghreba	0.596	-0.54	-2.500
Al-Khalifa	0.351	-0.94	-5.982
Dhamar	0.047	1.97	50.200*
Al-Mrawah	0.233	na	10.633
Waqir	0.189	1.32	4.745
Al-Qutta	0.252	na	-25.705
Mahal Shamiri	0.143	-1.47	-12.700
Al-Hudaydah	0.592	0.49	1.369

* Significant at $p<0.05$.
na: not applicable.

4.4 Recurrence Interval and Probability Analysis

Table 6 shows the probability and recurrence interval based on the Hazen method of rainfall at 15 stations in Wadi Siham Basin. The highest rainfall values within 30 years was recorded at Al-Amir and Maghreba stations at 887.20 and 1158.2 mm. The probability of repetition in both stations was 1.7% with a recurrence interval of 60 years. However, the lowest rainfall values were 74.2 and 15.70 mmat Al-Dabrah and Waqir stations. The probability of repetition in both stations was 98.3% with a recurrence interval of 1.02 year. The annual rainfall in Wallan station (29 years) showed a maximum of 242 mm (1979) and minimum of 66.20 mm (2007) and the probabilities of repetition were 1.7% and 98.3% with recurrence intervals of 58 years and 1 year respectively. However, the annual rainfall in Mahal Shameri station (18 years) showed a maximum of 711.90 mm (1990) and minimum of 136.30 mm (2008) and the probabilities were 2.8 and 97.2% with recurrence intervals of 36 years and 1 year respectively. The highest rainfall values of 391.20 mm and 165.40 mm for 5 years were recorded in Al-Mrawah and Al-Qutta stations, with probability of repetition of 10.0% and recurrence interval of 10 years. However, the lowest rainfall values of 95.30 mm and 117.50 mm were recorded in Al-Mrawah and Al-Qutta stations, with probability of repetition of 90% and recurrence interval of 1.1 year.

Table 6. Probability of rainfall (P%) and Recurrence Interval (RI) in 30 years (Al-Sukhna, Al-Dabrah, El-Haima, Al- Amir, Maghreba and Waqir stations)**,** 29 years (Wallan and Deir Zinkah stations), 28 years (Al-Hamal station)**,** 20 years (Al-Khalifa)**,** 18 years (Mahal Shamiri station), 17 years (Al-Hudaydah station), 10 years (Dhamar station) and 5 years (Al-Qutta and Al-Marwah stations)

Rank	30 year		29 year		28 year		20 year		18 year		17 year			10 year		5 year
	P%	RI (Year)	P%	RI (Year)	P%	RI (Year)	P%	RI (Year)	P%	RI (Year)	P%	RI (Year)	P%	RI (Year)	P%	RI (Year)
1	1.7	60.0	1.7	58.0	1.8	56.0	2.5	40.0	2.8	36.0	2.9	34.0	5.0	20.0	10.0	10.0
2	5.0	20.0	5.2	19.3	5.4	18.7	7.5	13.3	8.3	12.0	8.8	11.3	15.0	6.7	30.0	3.3
3	8.3	12.0	8.6	11.6	8.9	11.2	12.5	8.0	13.9	7.2	14.7	6.8	25.0	4.0	50.0	2.0
4	11.7	8.6	12.1	8.3	12.5	8.0	17.5	5.7	19.4	5.1	20.6	4.9	35.0	2.9	70.0	1.4
5	15.0	6.7	15.5	6.4	16.1	6.2	22.5	4.4	25.0	4.0	26.5	3.8	45.0	2.2	90.0	1.1
6	18.3	5.5	19.0	5.3	19.6	5.1	27.5	3.6	30.6	3.3	32.4	3.1	55.0	1.8	-	-
7	21.7	4.6	22.4	4.5	23.2	4.3	32.5	3.1	36.1	2.8	38.2	2.6	65.0	1.5	-	-
8	25.0	4.0	25.9	3.9	26.8	3.7	37.5	2.7	41.7	2.4	44.1	2.3	75.0	1.3	-	-
9	28.3	3.5	29.3	3.4	30.4	3.3	42.5	2.4	47.2	2.1	50.0	2.0	85.0	1.2	-	-
10	31.7	3.2	32.8	3.1	33.9	2.9	47.5	2.1	52.8	1.9	55.9	1.8	95.0	1.1	-	-
11	35.0	2.9	36.2	2.8	37.5	2.7	52.5	1.9	58.3	1.7	61.8	1.6	-	-	-	-
12	38.3	2.6	39.7	2.5	41.1	2.4	57.5	1.7	63.9	1.6	67.6	1.5	-	-	-	-
13	41.7	2.4	43.1	2.3	44.6	2.2	62.5	1.6	69.4	1.4	73.5	1.4	-	-	-	-
14	45.0	2.2	46.6	2.1	48.2	2.1	67.5	1.5	75.0	1.3	79.4	1.3	-	-	-	-
15	48.3	2.1	50.0	2.0	51.8	1.9	72.5	1.4	80.6	1.2	85.3	1.2	-	-	-	-
16	51.7	1.9	53.4	1.9	55.4	1.8	77.5	1.3	86.1	1.2	91.2	1.1	-	-	-	-
17	55.0	1.8	56.9	1.8	58.9	1.7	82.5	1.2	91.7	1.1	97.1	1.0	-	-	-	-
18	58.3	1.7	60.3	1.7	62.5	1.6	87.5	1.1	97.2	1.0	-	-	-	-	-	-
19	61.7	1.6	63.8	1.6	66.1	1.5	92.5	1.1	-	-	-	-	-	-	-	-
20	65.0	1.5	67.2	1.5	69.6	1.4	97.5	1.0	-	-	-	-	-	-	-	-
21	68.3	1.5	70.7	1.4	73.2	1.4	-	-	-	-	-	-	-	-	-	-
22	71.7	1.4	74.1	1.3	76.8	1.3	-	-	-	-	-	-	-	-	-	-
23	75.0	1.3	77.6	1.3	80.4	1.2	-	-	-	-	-	-	-	-	-	-
24	78.3	1.3	81.0	1.2	83.9	1.2	-	-	-	-	-	-	-	-	-	-
25	81.7	1.2	84.5	1.2	87.5	1.1	-	-	-	-	-	-	-	-	-	-
26	85.0	1.2	87.9	1.1	91.1	1.1	-	-	-	-	-	-	-	-	-	-
27	88.3	1.1	91.4	1.1	94.6	1.1	-	-	-	-	-	-	-	-	-	-
28	91.7	1.1	94.8	1.1	98.2	1.0	-	-	-	-	-	-	-	-	-	-
29	95.0	1.1	98.3	1.0	-	-	-	-	-	-	-	-	-	-	-	-
30	98.3	1.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 7 and Figure 9 show the rainfall distribution polygons in the Wadi Siham Basin. Based on the Thiessen polygon method, the total rainfall volume was 1711.26 Mm^3 per total polygons of 4911.04 km^2. The highest rainfall volume was 255.67 Mm^3 in Al-Hamal polygon, followed by Al-Amir polygon with a rainfall volume of 204.19 Mm^3. The lowest rainfall volume was 5.94 Mm^3 in Al-Qutta polygon, followed by Al-Hudaydah polygon with rainfall volume of 10.67 Mm^3. Table 7 also shows the distribution of 10 rainfall polygons in Wadi Siham Basin. The hydrological stations at the Tihama region is at the place where Wadi Siham leaves the transition zone and gets into the Tihama Plain. Hence, the hydrological station receives water runoff from 10 rainfall polygons. The total area of the 10 polygons was 3545.84 km^2 with annual areal rainfall of 337.76 mm. However, the rainfall volume was 1041.43 Mm^3.

Table 7. Distribution and catchment areas of Thiessen Polygon for areal rainfall in the Wadi Siham Basin stations

	14 Polygons			10 Polygons		
Stations	Average Rainfall (mm)	Area (km^2)	Rainfall Volume (Mm^3)	Average Areal Rainfall (mm)	Area (km^2)	Rainfall Volume (Mm^3)
Al-Sukhna	478.49	352.97	168.89	451.29	15.44	6.968
Al-Dabrah	217.50	680.55	148.02	154.77	678.45	105.005
Al-Hamal	493.8	517.77	255.67	415.60	517.77	215.185
Wallan	232.21	546.92	127.00	159.83	546.92	87.413
El-Haima	327.64	607.85	199.16	253.90	607.85	154.333
Al-Amir	497.20	410.68	204.19	366.56	410.68	150.538
Deir Zinkah	407.86	305.24	124.50	347.78	305.24	106.157
Maghreba	587.88	346.7	203.81	508.64	226.75	115.323
Dhamar	401.31	201.26	80.77	452.34	201.26	91.039
Mahal Shamiri	371.81	109.81	40.83	266.86	35.50	9.473
Al-Khalifa	506.91	154.81	78.47	-	-	-
Al-Mrawah	129.33	489.76	63.34	-	-	-
Al-Qutta	118.91	49.92	5.94	-	-	-
Al-Hudaydah	77.98	136.8	10.67	-	-	-
Mean	346.35	-	-	337.76	-	-
Total	-	4911.04	1711.26	-	3545.84	1041.434

5. Discussion

5.1 Rainfall

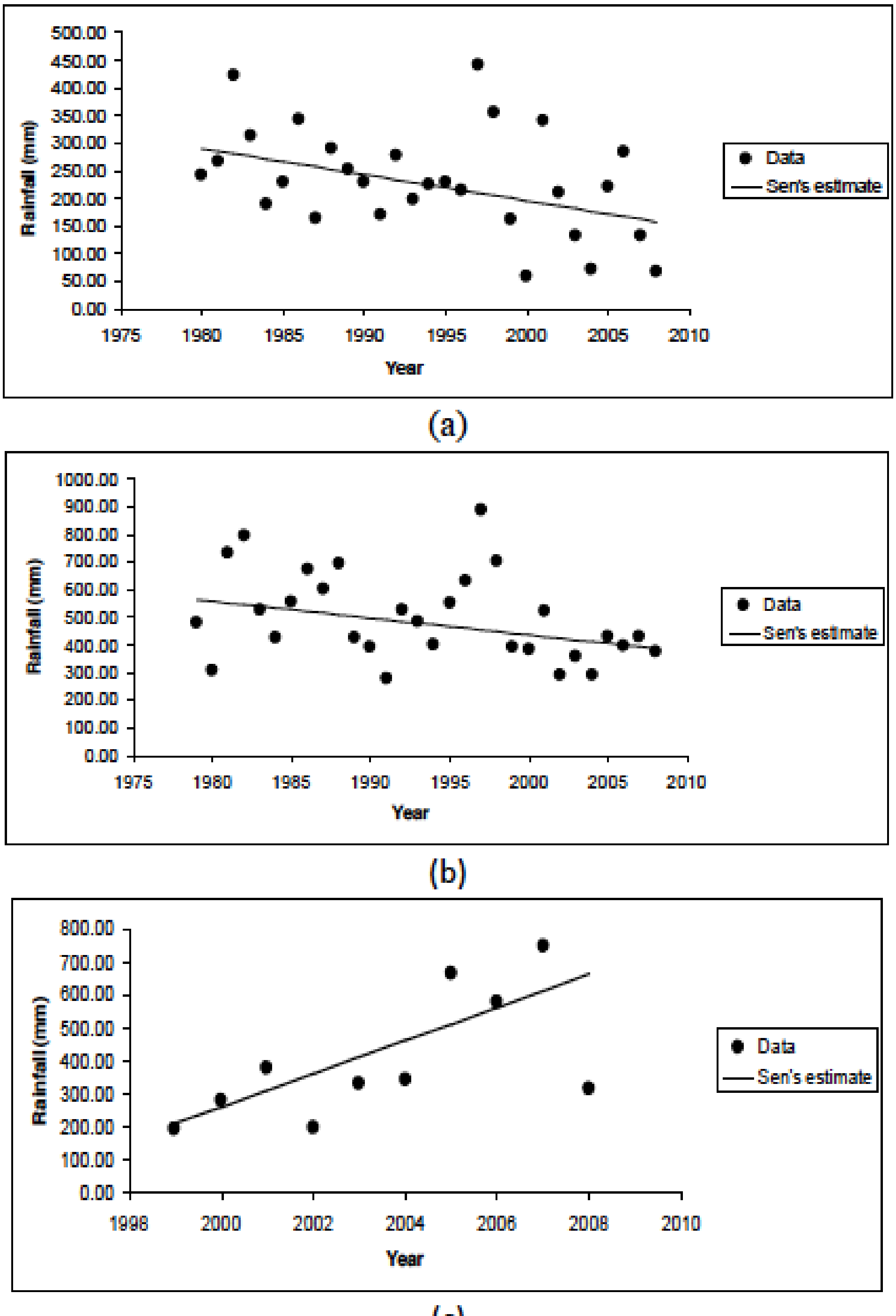
In this study, the average annual rainfall was 346.39 mm. The results are in line with other studies from arid and semi-arid regions in Iran. Modarres et al. (2007) reported that the CV% was 44.4%. In addition, Dinpashoh, Fakheri-Fard, Moghaddam, Jahanbakhsh, and Mirnia (2004) found that CV% from arid and semi-arid regions in Iran were from 15% to 60%. On the other hand, the coefficients of variation were low in the plain stations and high in the highland stations, which is consistent with a study from similar geographical area (Abdullah & Al-Mazroui, 1998). The CV% values reported in this study were lower than those of Lazaro et al. (2001), who reported high rainfall variability of 135% during summer in semi-arid areas of Spain. This may because WSB comprises both arid and semi-arid areas.

The Mann-Kendall (MK) test indicated significant trends in only three stations (Table 5). Meanwhile, Figure 8 showed decreasing annual rainfall trend of -4.72 mm/year and -6.11 mm/year ($p<0.05$) at Wallan and Al- Amir stations, respectively. Yet, there was an increasing trend of 50.20 mm/year ($p<0.05$) at Dhamar station. The annual rainfall trend in WSB follows the rainfall trends in arid and semi-arid regions in Iran and Spain (Moddares & de Silva, 2007).

MK test was applied to detect seasonal rainfall trends in WSB. The seasonal data (Table 8) showed that winter and spring had negative ($p<0.05$) rainfall trends in WSB. Since the general tendency was insignificant, there was decrease in the rainfall amount because the surface water volume was receding (Figure 9).

Table 8. Mann-Kendall analysis for seasonal trend in Wadi Siham Basin

Season	P value	Z_{MK}	Sen’s slope
Winter	0.012	-2.50	-1.257
Spring	0.001	-3.14	-3.436
Summer	0.321	1.00	1.672
Autumn	0.596	0.54	0.277



(a)

(b)

(c)

Figure 8. The rainfall trend in (a) Al-Wallan station, (b) Al-Amir station, and
(c) Dhamar station of Wadi Siham Basin

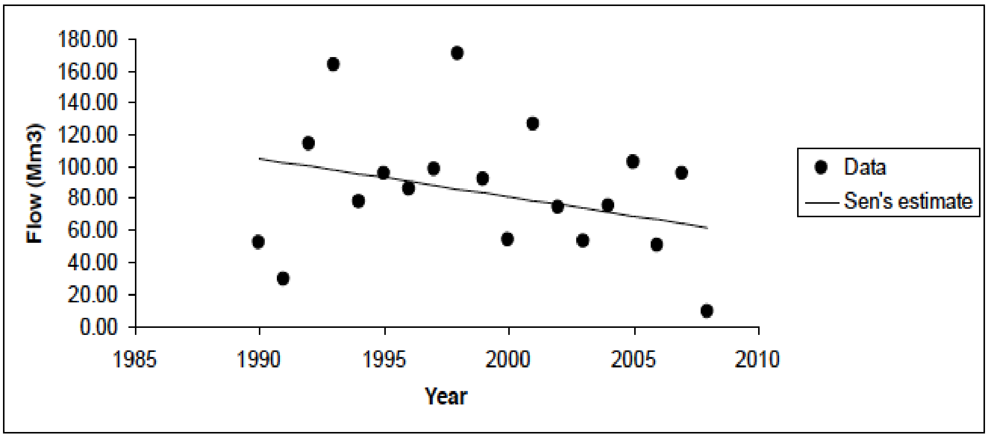


Figure 9. Trend of average annual runoff of Wadi Siham Basin

5.2 Seasonal Rainfall in Wadi Siham Basin

In the winter (December to February), the pattern is influenced by the air masses moving from the north (Alyamani & Sen, 1993). During winter, there were cyclones over the Mediterranean Sea, occurs easterly and brings rainfall over Yemen. Hence during winter the rainfall is of cyclonic type. According to Table 3, the average monthly rainfall during winter in December was heading north-south, with high rainfall in the southwest-northeast direction in January. In fact, the highest monthly rainfall occurred in January. Similar findings are found in Saudi Arabia (Alyamani & Sen, 1993).

During the spring season (March-May), intertropical front moves northwards and south of Yemen due to monsoonal air stream from the Indian Ocean, resulting in rain throughout the southern area and along the escarpment. The highest average rainfall occurred in April, as shown in Table 5. The least areal effectiveness took place in March during spring with the least rainfall amount.

The southwest monsoon that flows from the Indian Ocean and the Arabian Sea during summer (June-August) produces thunderstorms, thus increasing the rainfall amount over the Red Sea escarpment (Fleitmann et al., 2007; Lezine et al., 1998). The rainfall towards the eastern of Wadi Siham decreases even this area is high. This is due to distal proximity of the area from the monsoon (Subyani, 2004).

In the autumn (September-November), south-easterly air has diminished and once again the westerlies from the Mediterranean bring air moisture, resulting in tropical winter. Interestingly, November is the driest month in autumn (Table 3). During the end of autumn, the westerlies are more frequent due to retreat of monsoon front, medium to high rainfall throughout the escarpment and the northwestern region. Therefore, it is proven that the rainfall distribution in Wadi Siham is different between seasons. According to the average monthly rainfall, the highest rainfall occurred in August (summer) while the minimum was in December (winter) (Taher & Al Shaikh, 1998).

5.3 Spatial and temporal variation of rainfall

Variation in falling precipitation at certain sites is controlled by two gradients; spatial and temporal. The factors influencing the precipitation is expressed as static and dynamic factors. Static factors include altitude, aspect and slope. Meanwhile, the dynamic factors include those with the potential to change the precipitation in relation to weather. The factors influencing the distribution of precipitation are dynamic (variation in weather) and static such as topography, that cause huge variation via rain shadow effect (Davie, 2008). However, Abdullah and Al-Mazroui (1998) stated that the spatial factor affecting the rainfall distribution is due to mountains.

The 30 years rainfall data showed that the spatial distribution in Wadi Siham Basin follows a definite trend. As such, the rainfall continuously increases from west to east at an average annual value of 80.92 mm at Al-Hudaydah station to 587.88 mm at Maghreba station. The increase in the rainfall amount from west to east of Wadi Siham Basin is explained due to appearance of Western Highlands and the direction of wind and influence of the southwest runoff of Mediterranean depressions (Taher & Alshaikh, 1998). This is in line with previous findings in Saudi Arabia (Abdullah & Al-Mazroui, 1998). However, Wallan station received 232.21 mm average annual rainfall, which experience a major variation. The variation in annual rainfall in terms of elevation was also investigated in this study. In fact, the average annual rainfall at high elevation area is higher than the rainfall in low elevation areas, as shown in Table 1 and Table 3. However, there are some low elevation areas that receive higher amount of rainfall and vice versa. In the study area around the regions of western coastal plain and eastern highland mountains, the highest annual rainfall does not occur at the highest elevation. It implies that elevation is not the main factor that controls rainfall distribution. Other geographic factors such as distance from the moisture source, temperature, pressure and topography are also affecting the rainfall distribution (Subyani, Al-Modayan, & Al-Ahmadi, 2010).

5.4 Recurrence interval and probability of rainfall in Wadi Siham Basin

As shown in Table 7, the recurrence interval of the highest rainfall is uncommon but the recurrence interval of the lowest rainfall is more frequent. There is a relationship between rainfall amount and recurrence interval, in which higher rainfall amount takes longer to reoccur. In contrast, lower rainfall amount needs shorter time to reoccur. The findings are in line with the studies conducted in Saudi Arabia (Abdullah & Al-Mazroui, 1998). Recurrence interval analysis is important to understand the duration of reoccurrence of rainfall with specific amount.

For prediction and planning purposes, the potential rainfall value determined from those with 90% probability (Shirazi, Ismail, Akib, Sholichin, & Islam, 2011). Furthermore, the rainfall value can be predicted at a specific locality. Therefore, this predicted rainfall value is useful to estimate and predict the water resources (Srikanthan & Mc Mahon, 2001; Perry, 2008). It was observed that the total areal rainfall volume in the Wadi Siham Basin was 1711.26 Mm^3. The highest was from Al-Hamal polygon, which is 14.9% even though Maghreba had the highest rainfall. Its polygonal area was 346.7 km^2, amounting over 2% of the area of the basin. This is followed by Wallan polygon, with an area of 546.92 km^2 and contributed about 127.00 Mm^3 to the total rainfall volume in the basin. The variation in rainfall volume is influenced by polygonal areas and the average rainfall. The runoff volume in the basin was very low at 82.92Mm^3, which is 3.8% of the total rainfall volume inWSB. The highest was from Al-Hamal, amounting to 14.9%. However, the lowest was from Al-Qutta, which was 0.3%. It was recorded that the total runoff volume was 4.85% of the rainfall volume in WSB. However, this is related to Mahal Saleem station.

5.5 Surface water runoff

In Table 9, the average annual runoff in Wadi Siham Basin within 20 years (1990-2009) was 82.92 Mm^3. The runoff trend was investigated using the Mann-Kendall trend analysis and Sen’s slope (Figure 9). In a study carried out in Morocco (semi-arid region), the runoff trend in six stations within 20 years was negative in all stations, with Z_{MK} ranging from -1.962 to -3.095 (Oueslati, de Girolamo, Lo Porto, & Abouabdillah, 2009). On the other hand, another study in the wet region of the western Europe showed an annual runoff positive trend within 35 years (1968-2003) (Hannaford, Laize, & Marsh, 2007). In fact, the runoffs in Scotland and Ireland were increasing and the trend in the Great Britain was increasing as well (Hannaford et al., 2007). Like the Great Britain and western Europe, the Mann-Kendall results were found to be positive at three rivers in Czech for 40 years, ranging from 0.349 to 0.717 (Kliment & Matouskova, 2008).

Table 9. The runoff (Mm^3) in Wadi Siham Basin

Year	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov	Dec.	Total
1990	1.00	7.20	2.10	9.70	0.90	0.60	11.80	15.60	2.30	0.50	0.20	0.30	52.20
1991	0.17	0.62	3.94	1.23	8.78	0.44	1.23	7.63	2.97	1.37	0.39	0.45	29.22
1992	0.40	0.40	1.60	3.70	22.00	0.7	6.71	53.80	6.99	12.10	3.60	1.70	113.70
1993	1.00	0.97	5.23	49.69	22.40	13.75	17.58	33.20	7.39	4.39	1.68	5.91	163.19
1994	1.14	0.70	4.01	10.86	2.30	5.05	11.80	28.93	8.22	0.71	3.80	0.36	77.89
1995	0.38	0.43	7.94	16.30	2.23	1.56	16.36	37.11	11.15	0.88	0.48	0.81	95.61
1996	0.62	0.59	4.26	5.86	10.05	28.95	10.78	15.46	5.40	1.52	1.22	0.82	85.51
1997	0.30	0.30	1.80	8.50	11.68	11.76	3.80	7.99	1.40	41.50	7.20	1.30	97.53
1998		0.70	0.93	6.52	7.43	0.00	39.17	72.89	25.50	7.03	5.56	4.48	170.21
1999	3.61	2.76	3.83	1.74	6.17	1.68	36.60	22.54	8.80	1.82	1.09	1.31	91.95
2000	1.30	0.91	0.62	1.68	1.89	0.84	4.05	9.96	23.91	6.02	1.69	1.02	53.89
2001	0.71	2.46	4.73	6.90	7.62	4.77	17.42	40.74	15.63	11.18	7.51	6.54	126.20
2002	1.00	1.00	1.12	3.99	1.15	0.64	40.60	20.06	2.20	0.83	0.35	0.85	73.80
2003	0.60	0.48	7.98	13.52	4.36	6.79	1.65	11.52	3.64	0.82	0.70	0.62	52.67
2004	0.52	0.28	0.29	12.91	5.31	2.99	12.28	29.18	3.07	5.81	1.72	0.94	75.29
2005	0.52	0.46	11.12	26.21	11.37	1.02	9.06	37.31	1.63	3.61	0.34	0.12	102.76
2006	0.53	3.57	21.35	4.36	1.40	1.00	2.59	12.62	1.37	0.48	0.37	0.72	50.37
2007	0.54	0.19	0.57	6.15	7.19	0.77	12.42	59.64	6.66	0.66	0.45	0.29	95.54
2008	0.12	0.10	0.17	0.22	0.32	3.01	1.31	0.87	0.81	1.09	0.28	0.13	8.44
2009	0.22	0.14	0.19	2.14	0.39	2.66	5.85	27.46	0.78	1.90	0.36	0.42	42.51
Mean	0.77	1.21	4.19	9.61	6.75	4.45	13.15	27.23	6.99	5.21	1.95	1.45	82.92
Median	0.54	0.61	2.96	6.33	5.74	1.62	11.29	25.00	4.52	1.67	0.90	0.81	81.70
SD	0.76	1.69	5.04	11.31	6.44	6.88	12.24	18.95	7.20	9.23	2.33	1.88	40.97
CV%	98.92	139.31	120.31	117.74	95.41	154.61	93.06	69.59	102.98	177.12	119.79	129.53	49.38

The area beyond Mahal Saleem station forms a part of Wadi Siham catchment around 1411.7 km^2, with an average annual runoff of 82.92Mm^3. The range of annual runoffs is between 8.44 Mm^3 and 126.20 Mm^3. The median annual runoff was 81.70 Mm^3. The runoff measured at any location is a sum of the base runoff and flood runoff while the occurrence of floods is the result of storm events. The amount of discharged water collected at a point and exceeds the carrying capacity of a channel becomes runoff. The variation in surface runoff is because of variation in rainfall amount and intensity, soil water content, filtration, watershed size and slope. Consequently, the variation in the annual runoffs in Wadi Siham Basin over the years is due to the variation in rainfall amount and intensity (Abu-Awwad & Shatanawi, 1997).

5.6 Floods in Wadi Siham

Floods in Wadi Siham Basin were investigated within 20 years period from 1990 to 2009 (Figure 10), showing a sporadic pattern with increased variability in duration of floods and total amount of water. The number of floods occurred in Wadi Siham was 570. Interestingly, some are considered as mega due to high discharges to the basin. The highest peak discharges of floods occurred in 2005 (about 2000 m^3/s) and 2007 (about 1800 m^3/s and runoff nearly 6000 m^3). The results were comparable to those in hyper-arid areas of Dead Sea (Greenbaum, Uri Schwartz, & Bergman, 2010). The drainage area in Wadi Siham Basin was 4911 km^2 but in other studies, the drainage area was lower, ranging from 32 to 1400 km^2. In the study by Greenbaum et al. (2010) in Dead Sea, the peak discharge in the highest drainage site (Zin) was 1280 m^3/s and the volume of floods were from 11 Mm^3 to 13 Mm^3. Since the Wadi Siham Basin has higher drainage area, the mean volume of floods was higher for 19 years at 53.10 Mm^3. Meanwhile, the peak discharge was 2135 m^3/s.

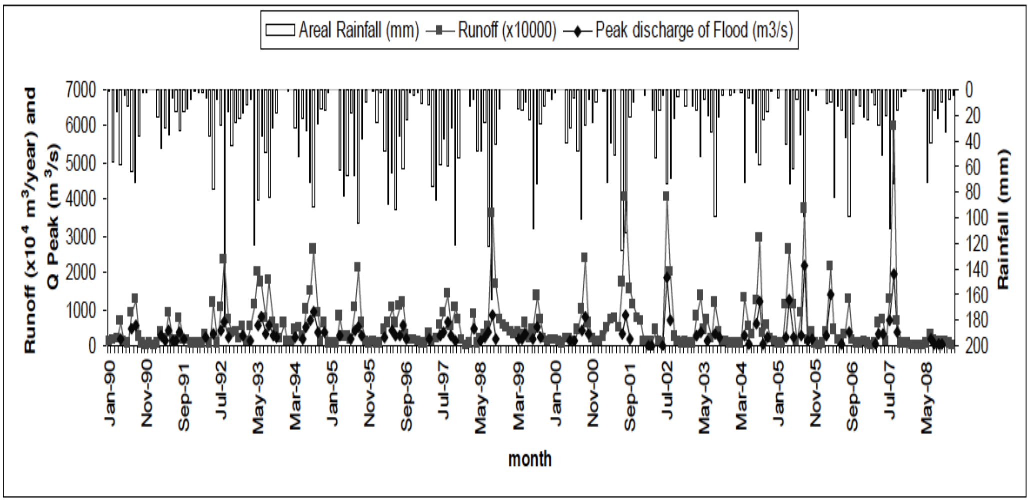


Figure 10. Areal rainfall (mm), Flood volume (Mm^3) and peak discharge (m^3/s)

6. Conclusion

Rainfall in Wadi Siham Basin (WSB) were evaluated, estimated and analysed. The average annual rainfall was 346.39 mm. There are spatial and temporal variations in the amount of rainfall. The spatial distribution of rainfall in WSB has an increasing trend from the west to the east with averages of 80.92 mm at Al-Hudaydah station to 587.88 mm at Maghreba station. The rainfall data in WSB indicates high variability. There was an inverse correlation between amount of rainfall and probability of repetition, where the high amount of rainfall has lower probability of repetition and the recurrence interval is lesser.

The highest peak discharge of floods occurred in 2005 (about 2000 m^3/s) and 2007 (about 1800 m^3/s with runoff volume almost 6000 m^3). The variation in rainfall volume is influenced by polygonal areas and the average rainfall. Overall, the annual runoff volume in the basin is very low at 82.92Mm^3, which is 4.85% of the total rainfall volume, indicating that the total water loss was 95.15%. The highest runoff came from Al-Hamal, amounting to 14.9%. There were 570 flood events within 20 years, with a total volume of 53.10 Mm^3, about 3.10% of the rainfall. The results demonstrate the urgent need for sustainable water resource management in WSB.

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