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Runoff-Rainfall Prediction Formula for West Dar Fur State using Statistical Methods and GIS

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ABSTRACT

The Runoff-Rainfall prediction formula of annual stream flow was developed for Wadis system in West Dar Fur State using discharge gauged stations, GIS program, and rainfall data analysis together with multiple regression equation were evaluated by XLSATA tool in Excel. The relationship produced R^3 (correlation coefficient) value equal to 0.995. Some stations were chosen to verify the accuracy of the relationship. Finally, the total annual flow was calculated for the State based on two major Wadis are Azum and kaja. The collective flow volume calculated in West Dar Fur State was (2348 Million m^{3})for the two wadies. These results were discussed and compared with previous studies in West Dar Fur State. The integrated approach using GIS and statistical methods proved to be successful and accurate procedure.

Keywords : West Dar Fur, multiple regression, prediction, GIS, XLSATA tools

I. INTRODUCTION

West Dar Fur State has a total area of 150,000 km² and a population of 1,693,000 in 2003. Its capital is Al-Ginaina Town. The main water resources in the State are seasonal streams running from Jebel Mara and the groundwater. It has an arable land of about 8 million feddans, 3 million of which are exploited. The major Wadis are Azum and Kaja. The overall surface area of Wadi Azum –including all three sub-streams is 36965 km2[1], 36700 km2 [2],and 40393 km2 [3] .It drains from the higher western slopes of Jebel Marra with altitudes ranging between 2600m and 600m[1].The surface area of Kaja is 42850 km2 [2], and 47337 km2 [3]. The measured discharge rate is 487 million cubic meter per year[3].

Multiple regression model is one of the statistical methods, it is relation between one depending parameter with more independent one, and it is commonly used to estimate mean annual stream flow of any gauge station. The meteorological and geographic characteristics of stations upstream were related to formulate the adopted multiple regressions model the developed empirical equation has the form:

$$Q = b_0 A^{b_1} P^{b_2} S^{b_3} L^{b_4} \qquad (1)$$

Where: -

Q is discharge value at gauged station (million m^3/s),
A is catchment area (km2),
P is mean annual rainfall precipitation (mm),
S is mean catchment slope (%)
L is longest flow path in catchment (km)
And b_o, b_1, b_2, b_3, b_4 are model coefficients.

The above empirical relationship developed a better linear form by taking logarithms as in the equation below:

$$\log Q = \log b_0 + b_1 \log A + b_2 \log P + b_3 \log S + b_4 \log L \qquad (2)$$

The optimum values of model parameters can be estimate in this equation and several combinations of stations can be investigated in order to optimize the regression equation. Combination achieves maximization of the correlation coefficient R and compatibility of estimated discharge and precipitation. This has resulted in a small difference between estimated and observed discharge in different stations.[4]

The optimum model parameters were estimated with selected independent characteristics such as the mean precipitation, catchment area, and catchment mean slope while the length of Wadis was not considered in previous studies [4]. The model used in this paper uses parameters shown in equation (1).

II. METHODS AND MATERIAL

The data used to predict the equation for the West Dar Fur region include; Wadi discharge data (station names and length of time period), rainfall data (number and name of stations and length of time period) [5],and digital elevation model DEM (90m) of the Shuttle Radar Topography Mission (SRTM). The later was used to create layers such as catchment, stream length and slope employing the Arc-Hydro tool of the ArcGis 10 software following the routine analysis shown in figure (1). The annual stream discharge (Table 1) and rainfall data were analyzed by XLSATA tools in Excel program in order to determine the best distribution for the thirty-year rainfall data. Layers of some parameters were created by using Kringing Method. Mapping all data in GIS environment and the application of multiple regression method reveal the general methodology developed in this study (Figure 2).

The best selected discharge station that has given a high and accurate R value in the regression analysis, belongs to Wadi Azum which has more gauging stations compared to Wadi Kaja (table 1)[3]. The Arc-Hydro tools and the Kriging Method were used to compute all independent characteristics such as catchment area, precipitation, stream length and slope as shown in table (1 and 2). Hence using the data set layers for each wadi, the regression was performed (3 to 13). Table (3) was used to verify the equation. Figures (14 to 15), (16 to 17) show Wadi Azum and Wadi Kaja catchment properties obtained by GIS.

III. RESULTS AND DISCUSSION

The result of regression for West Dar Fur State of figure (18) is summarize in table (4)

i. Firstly, the discharge is considered as the most important parameter in the study. It was revealed from the result that the difference between measured and predicted annual discharges was small ranging from 0.25% to 7.71 %. Furthermore, it is associated with a reasonably high correlation coefficient close to ($R^2 = 0.995150$)
ii. For the verification equation, the analysis is depicted in table (6).
From table (6) it is clearly apparent that the verification stations located in Wadi Azum has smaller difference, (approximately 29.2) than those located in Wadi Kaja (approximately 113.5). Wadi Azum Station has close precipitation data values (indicating homogeneity) and would preferably be used to develop the equation.
iii. Tables (7) and (8) described the simple calculation of annual discharges for both Wadi Azum and Wadi Kaja respectively. They were calculated using the layers prepared in GIS as shown the figures (13, 14, 15, and 16).
iv. Table (9) showed the discharge quantities based on small catchment areas using Kringing Method which identified the rainfall range as (367.923187-970.0508) and (258.8495- 615.3716) for Azum and Kaja, respectively The calculated discharge quantities were less than values obtained by previous studies (references No. (1) and (3)) because these studies did not considered the small size of wadies. The result gave high discharge quantities especially for Wadi Azum. The result of this work was also higher than that of study No.(2) which has used the rainfall parameter values (546),(465) for the two wadis. The validated prediction equation provides an accurate method for estimating stream discharge based on topographic and climatic variables a thing which allows better resource assessment and sustainable management and development.

IV. CONCLUSION

The use Arc-Hydro tools reduced time needed to delineate West Dar Fur catchments. The 3D TIN layer for elevation values and Kringing Method for rainfall data interpolation provided successful tools. This methodology would also help scientists to understand morphology and topographic characteristics of study area. It is highly recommended to use XLSATA tools in Excel to get most suitable probability distributions that fits the annual rainfall data and to use multiple regression method.

V. REFERENCES

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TABLE 1

THE INDEPENDENT CHARACTERISTICS FOR WADI AZUM

Wadi, station	**Q Measured annual discharge ($M.m^3$)**	**A (Km^2)**	**Max.Elev (m)**	**Min.Elev (m)**	**L long flow path (Km)**	**S Slope% $\frac{(Max - Min)}{L \times 10}$**	**P (mm)**
Wadi Saleh, Saleh	180	317.0476	921.527	807.6355	9.133234	1.247	1010.5
Wadi Toro , Toro	45	541.4434	1116.538	1054.94295	34.34349	0.17935	537.5
Wadi Aribo, Aribo	58	1282.083	1196.834	870.829	69.112694	0.4717	566.3232
Wadi Dodari, Dodari	40	1074.1	1835.618	1095.672	68.647	1.0779	494.5
Wadi Bari, Murnei	150	11904	1370.636	736.9433	315.27	0.201	645
Wadi Bari, kabkabiya	70.93	789.8476	1361.172	1160.48433	45.40445	0.442	368.96051

Source: [3],

TABLE 2

THE INDEPENDENT CHARACTERISTICS AT LOG SCALE FOR WADI AZUM

Wadi , station	**Log Q**	**Log A**	**Log P**	**Log S**	**Log L**
Wadi Saleh, Saleh	2.255273	2.501124	3.004536	0.095866	0.960625
Wadi Toro , Toro	1.653213	2.733553	2.730378	-0.7463	1.535844
Wadi Aribo, Aribo	1.763428	3.107916	2.753064	-0.32633	1.839558
Wadi Dodari, Dodari	1.60206	3.031045	2.694166	0.032578	1.836622
Wadi Bari, Murnei	2.176091	4.075693	2.80956	-0.6968	2.498679
Wadi Bari, kabkabiya	1.85083	2.897543	2.56698	-0.35458	1.657098

TABLE 3

VERIFICATION FOR WEST DARFUR EQUATION

Years of measured	Big Wadi-small wadi station	Q Measured annual discharge ($M.m^3$)	A (Km^2)	Max.Elev (m)	Min.Elev (m)	L long flow path (Km)	S Slope% $\frac{(Max - Min)}{L \times 10}$	P (mm)
1977-1997	Azum -wadi elserief kabkabiya	23.27	146.2845	1259.412	1159.3065	14.26003	0.702	372.661407
1965-1973	Kaja - wadi abu sunut Ereigi	9.928482	655.6033	1111.282	945.393	68.21074	0.2432	335.9222
1965-1972	Kaja- wadi abu sunut Tilfou	2.707991	37.57289	868.346	867.981	9.172147	0.00398	262.5257
1964-1973	Kaja -wadi abu sunut Abu Gidad	45.20211	744.33341	892.198	875.323	39.21754	0.04303	408.0355
1978-2002	Azum -wadi bargu Umm Sineina	40.7902068	425.2775	988.376	924.398	39.01083	0.164	403.3955

TABLE 4

COEFFICIENTS OF REGRESSION FUNCTIONS FOR WEST DIFFERENT STATE

Coefficients		Predicted Discharge Function (million m^3) Four Decimal Places.
$log\ b_0$	1.57996091739009	$30.0155 \times A^{2.0113} \times P^{-0.7437} \times S^{-0.008} \times L^{-2.2056}$
b_1	2.01127688478	
b_2	-0.74371290456	
b_3	-0.00795204617	
b_4	-2.20560977060	
R^2	**0.995150**	

TABLE 5

WEST DARFUR STATE PREDICTED AND MEASURED DISCHARGES

Wadi, station	Q Measured annual discharge (M.m^3)	Q Predicted annual discharge (M.m^3)	Difference %
Wadi Saleh, Saleh	180	180.458	0.254646159
Wadi Toro , Toro	45	46.317	2.925721942
Wadi Aribo, Aribo	58	53.530	7.706383996
Wadi Dodari, Dodari	40	41.823	4.557533861
Wadi Bari, Murnei	150	152.136	1.423983613
Wadi Bari, kabkabiya	70.93	70.232	0.984334135

TABLE 6

RESULT OF VERIFICATION WEST DAR FUR EQUATION

Years of measured	Big Wadi-small wadi -station	Q Measured annual discharge (M.m^3)	Q Predict annual discharge (M.m3)	Difference %
1977-1997	Azum -wadi elserief -kabkabiya	23.27	30.070	29.22327729
1965-1973	Kaja - wadi abu sunut- Ereigi	9.928482	21.200	113.5237807
1965-1972	Kaja- wadi abu sunut -Tilfou	2.707991	6.991	158.1689908
1964-1973	Kaja -wadi abu sunut -Abu Gidad	45.20211	81.384	80.04483017
1978-2002	Azum -wadi bargu-Umm Sineina	40.7902068	26.654	34.65571343

TABLE 7

CALCULATED WADI AZUM DISCHARGE

Gird ID of catchment	A (km^2)	Max.Elev	Min.Elev	long flow path (L) km	slope%	P(mm)	Pred Q(M.cm)
162	3231.616	1373.955	923.775	150.97	0.298192	367.9232	84.837
170	1077.417	1111.134	923.775	78.59	0.238401	375.8245	38.760
172	80.09485	923.775	921.221	12.28	0.020798	402.6767	12.087
174	5540.519	921.221	736.43	163.54	0.112994	566.1135	153.832
175	1974.184	1463.652	921.221	135.94	0.399022	425.1625	35.551
182	1526.142	1145.335	1105.925	91.85	0.042907	446.6855	49.351
186	1638.639	1821.245	1060.513	102.81	0.73994	485.4009	40.810
191	30.60531	1060.513	1105.925	11.33	0.400812	541.8088	1.633
192	1203.044	1275.332	1060.513	58.41	0.367778	561.1142	68.870
193	12.60822	1105.925	1005.851	6.07	1.648666	545.1047	1.070
194	1589.628	897.69	735.933	97.22	0.166382	672.0461	34.503
197	1422.191	1302.953	1005.851	73.5	0.40422	644.2181	52.378
198	298.986	1005.851	897.69	29.29	0.369276	513.9307	20.487
199	3119.261	870.46	643.763	114.31	0.198318	767.2358	84.755
200	1282.083	1225.616	897.69	69.06	0.474842	724.5131	44.642
202	1206.129	857.661	643.763	76.69	0.278913	777.2839	29.864
206	3726.948	1091.976	609.183	129.15	0.373823	970.0508	77.405
208	1461.726	887.675	609.183	85.17	0.326984	797.9763	34.161
213	153.4563	609.183	581.34	22.52	0.123637	805.462	6.907
214	191.551	584.703	581.34	18.3	0.018377	807.6827	17.276
215	9.103717	581.34	571.609	6.98	0.139413	816.0332	0.309
223	3186.626	799.402	584.703	115.32	0.186177	911.2453	76.394
225	1456.116	730.879	584.703	66.22	0.220743	818.6612	58.121
Sum	**35418.6744**						**1024.004**

TABLE 8

CALCULATED WADI KAJA DISCHARGE

Gird ID of catchment	A (km2)	Max.Elev	Min.Elev	long flow path (L) km	slope%	P(mm)	Pred Q(M.cm)
138	4363.07	966.998	884.653	183.02	0.044992	275.6788	127.689
139	3167.741	1236.244	900.349	131.15	0.256115	258.8495	144.563
140	2027.09	1108.259	900.349	127.25	0.163387	300.6055	56.530
143	972.4702	928.832	884.653	48.2	0.091658	370.4073	94.440
145	2767.195	991.137	853.652	103.94	0.132273	372.3718	141.103
147	1538.251	912.53	887.591	67.23	0.037095	264.2979	147.604
148	1769.888	1111.594	882.14	134.8	0.170218	335.0053	34.947
150	47.35878	882.14	887.591	12.08	0.045124	354.0999	4.763
151	1418.051	892.362	853.652	66.37	0.058325	402.5789	93.946
152	1373.896	1010.032	882.14	92.33	0.138516	350.459	46.862

156	3793.35	974.261	873.06	116.96	0.086526	494.665	166.625
163	2174.417	908.099	873.06	109.26	0.032069	504.1596	62.831
173	1029.509	995.057	850.921	65.61	0.219686	529.7501	40.830
176	931.0133	873.06	850.921	56.6	0.039115	575.9814	44.012
177	1373.583	892.798	763.928	50.25	0.256458	615.3716	117.326
Sum	**28746.88328**						**1324.073**

TABLE 9

COMPARISON BETWEEN PRESENT AND PREVIOUS STUDIES FOR WEST DAR FUR

NO.	Name of wadi	Catchment area (Km)	Estimated/predicted Annual Discharge (M.CM)	Estimated/predicted Total Annual Discharge (M.CM)	Reference
1	Azum	36965	-	4016	[1]
	Kaja	-	-		
2	Azum	36700	601	900	[2]
	Kaja	42850	299		
3	Azum	40393	2597	4016	[3]
	Kaja	47337	1419		
4	Azum	**35418.6744**	**1024.004**	**2348**	Work study
	Kaja	**28746.88328**	**1324.073**		

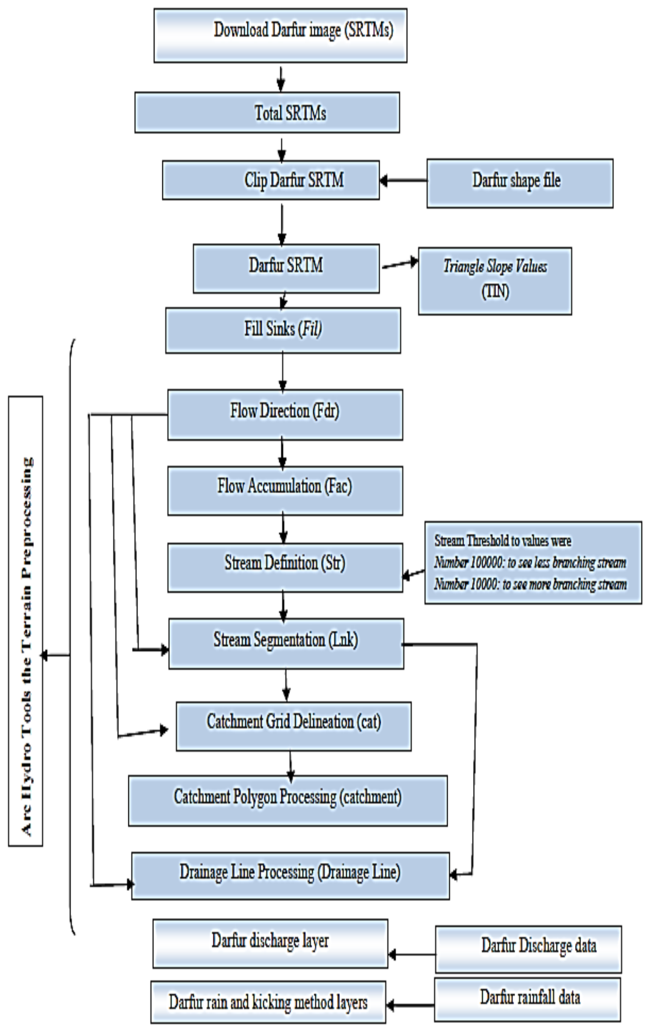


Figure 1. Researcher Developed ArcGIS Analysis and Layers

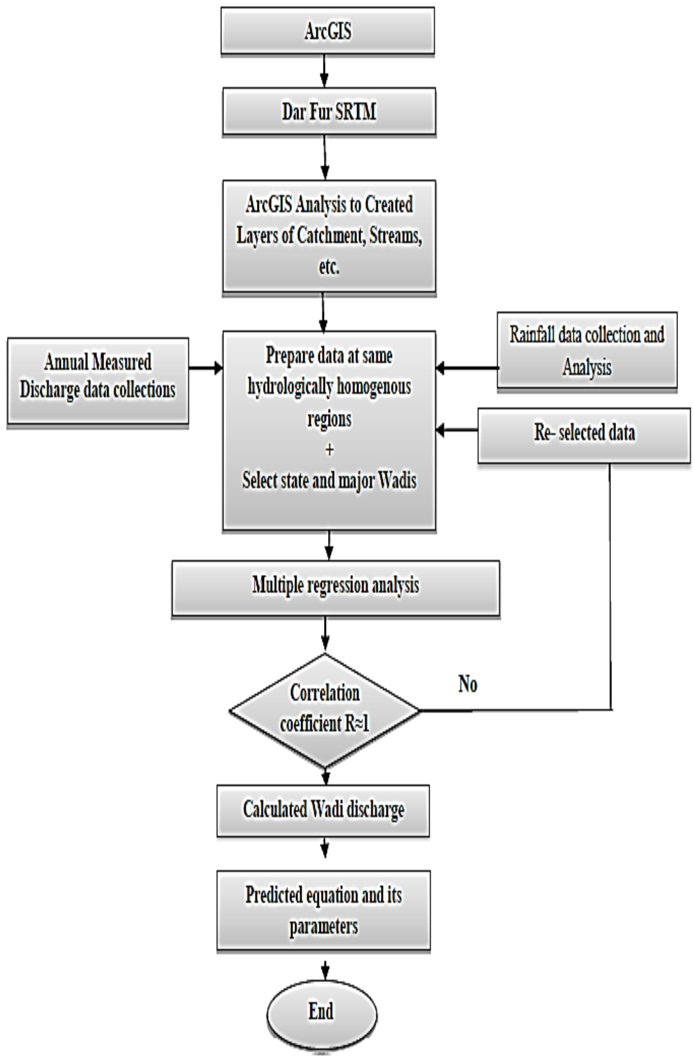


Figure 2. Researcher Developed General Methodology

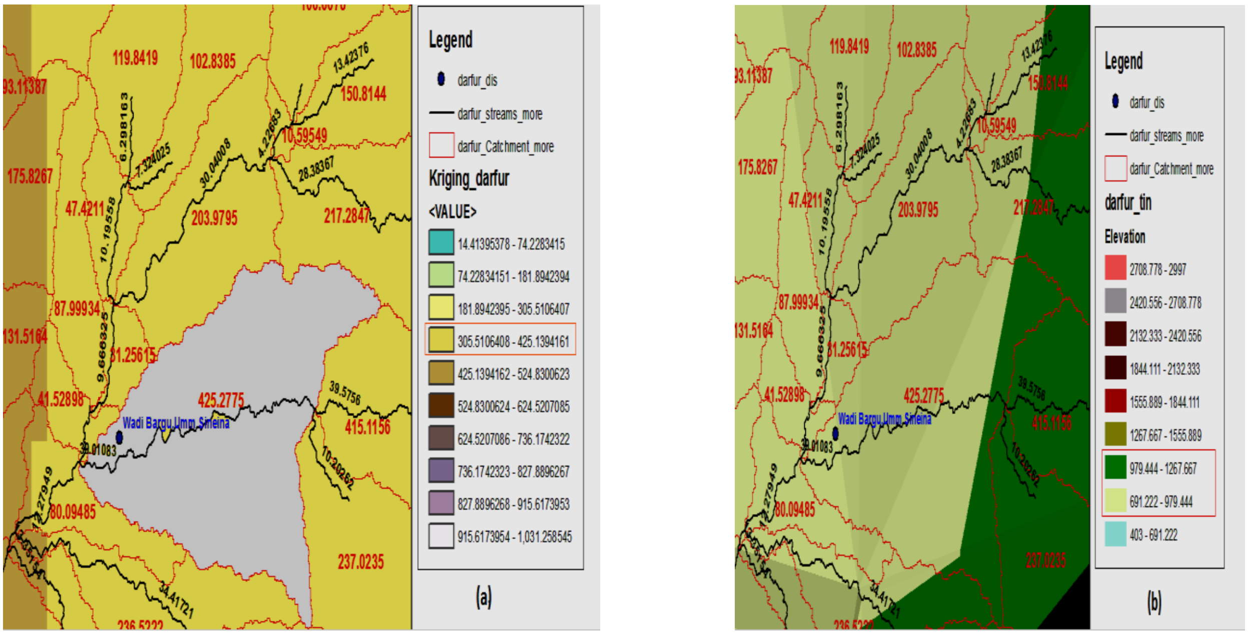


Figure 3. wadi Bari, Umm Sineina station, (a) rain, catchment and stream length, (b) elevation

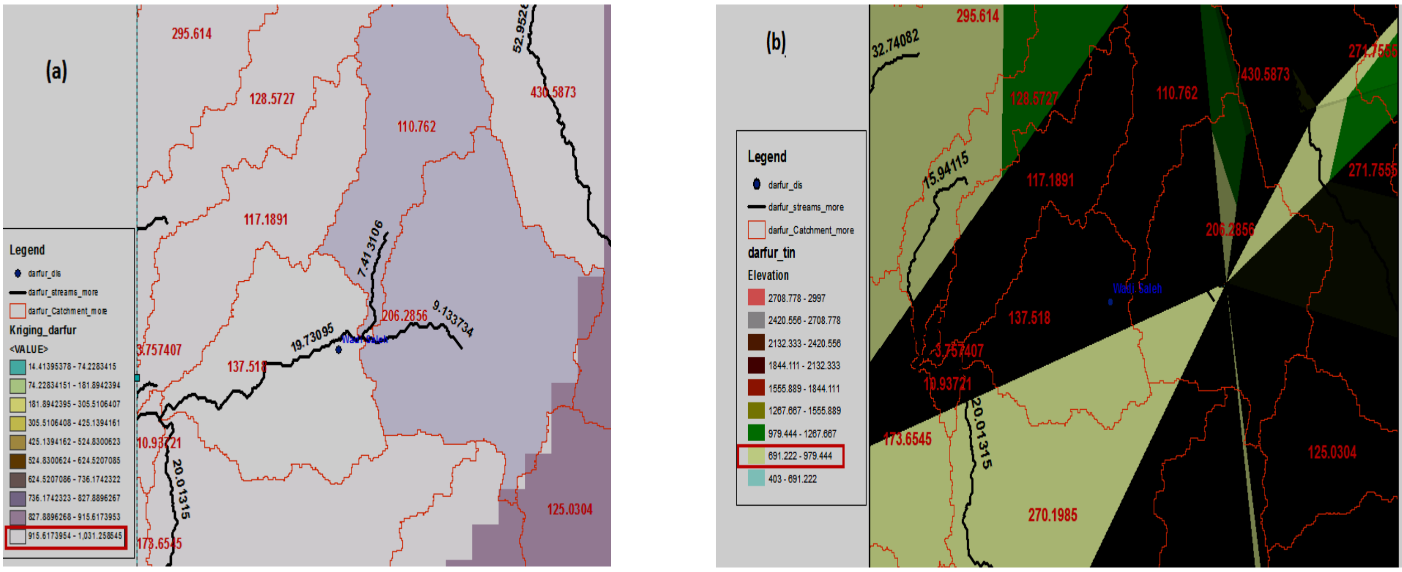


Figure 4. Wadi Saleh,(a) rain, catchment and stream length,(b) elevation

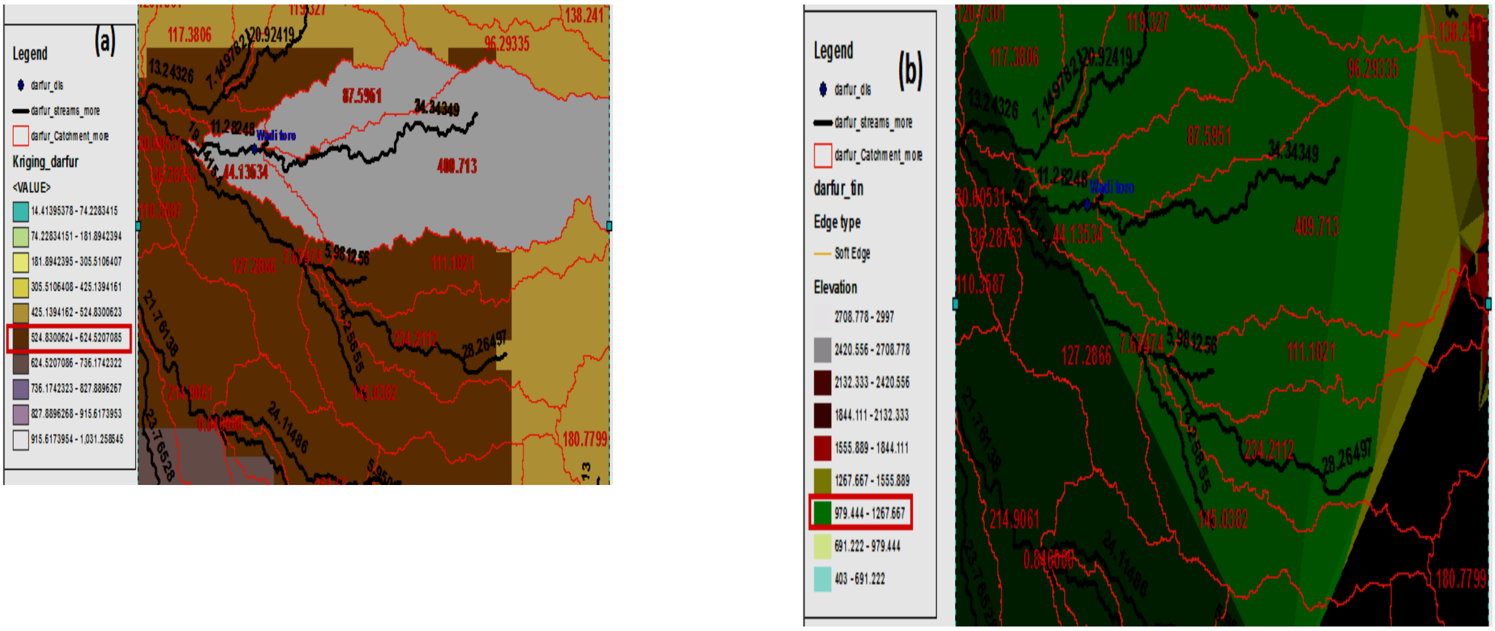


Figure 5. Wadi Toro,(a) rain, catchment and stream length,(b) elevation

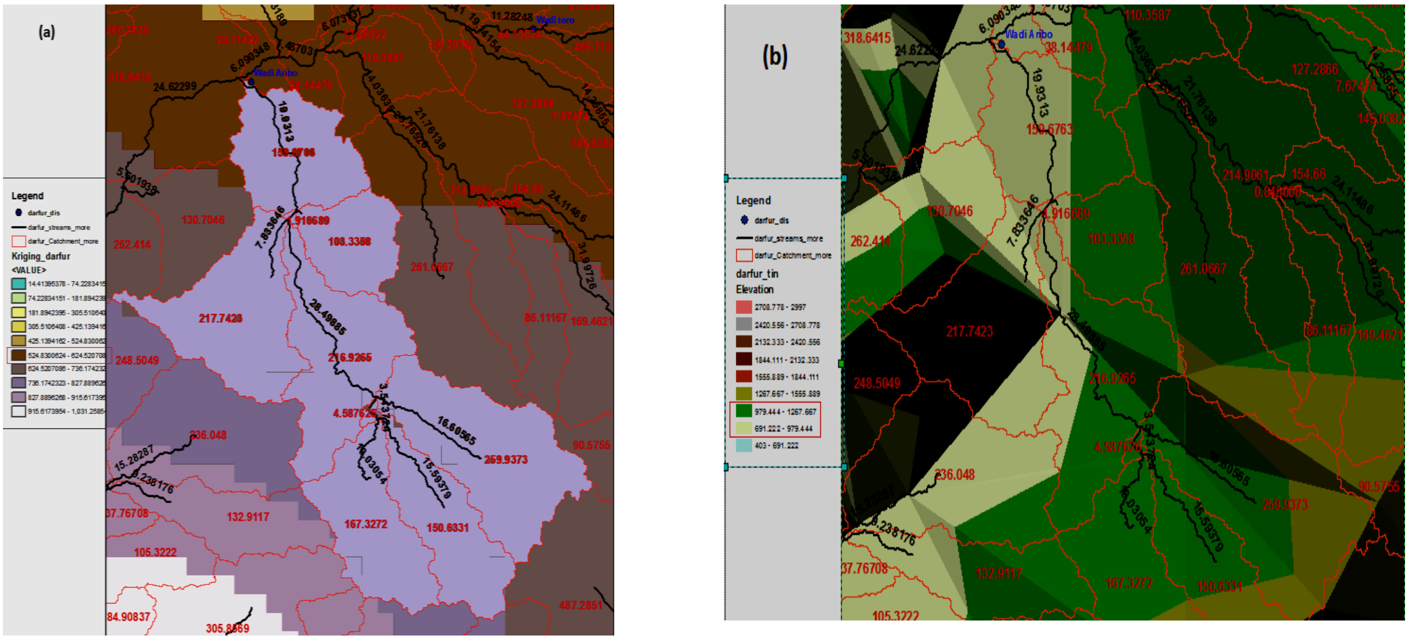


Figure 6. Wadi Aribo,(a) rain, catchment and stream length,(b) elevation

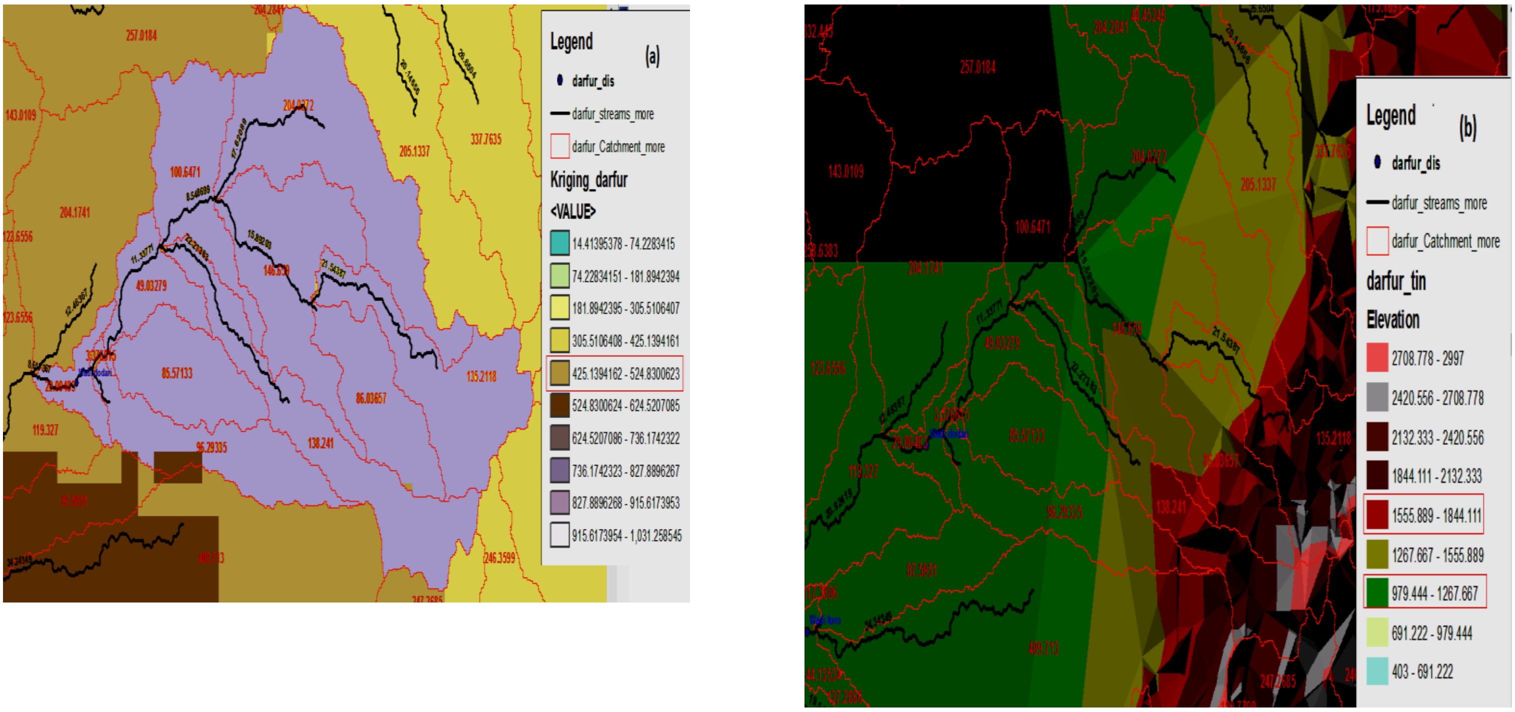


Figure 7. Wadi Dodari,(a) rain, catchment and stream length,(b) elevation

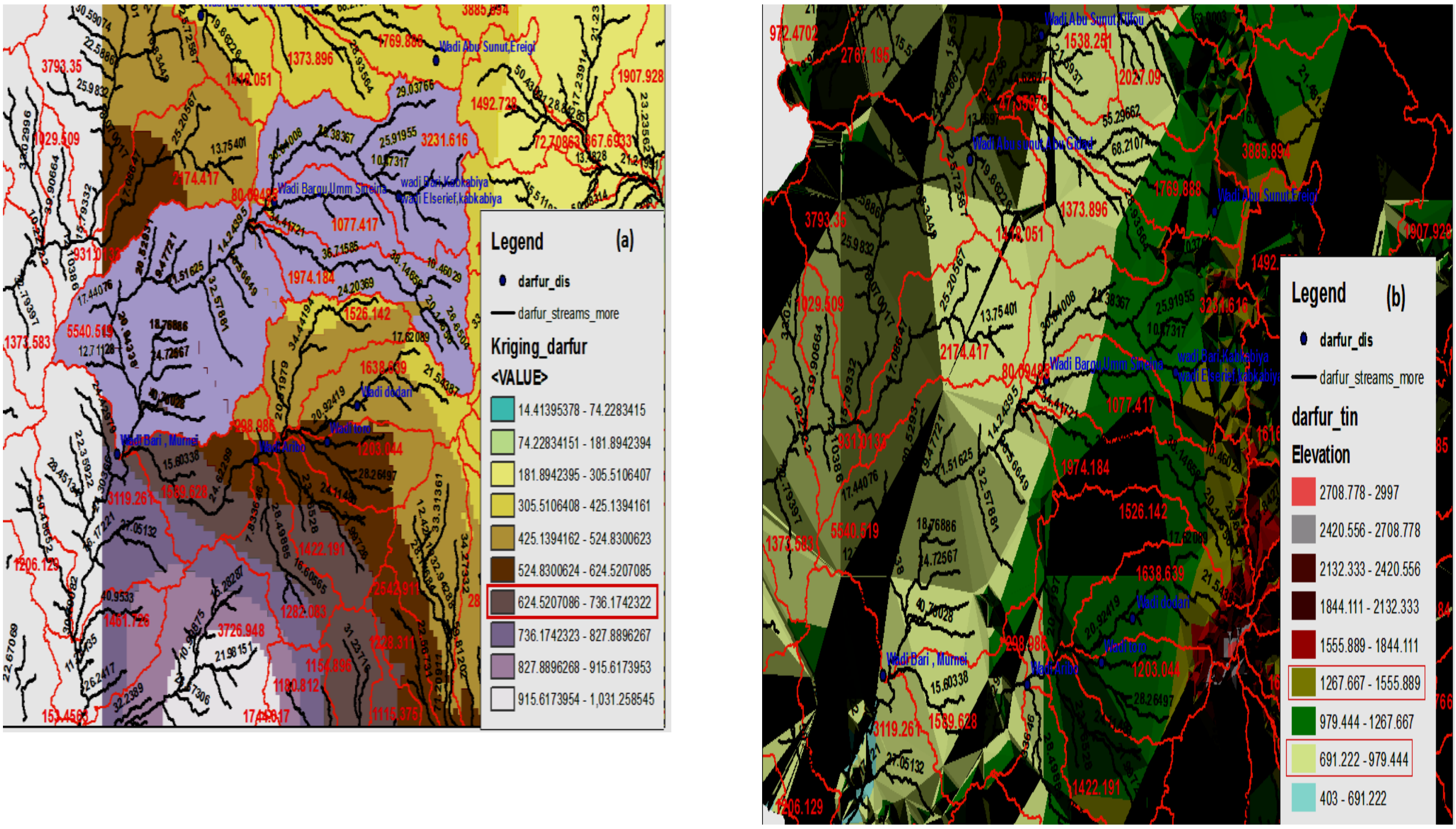


Figure 8. Wadi Bari, murnei station, (a) rain, catchment and stream length,(b) elevation

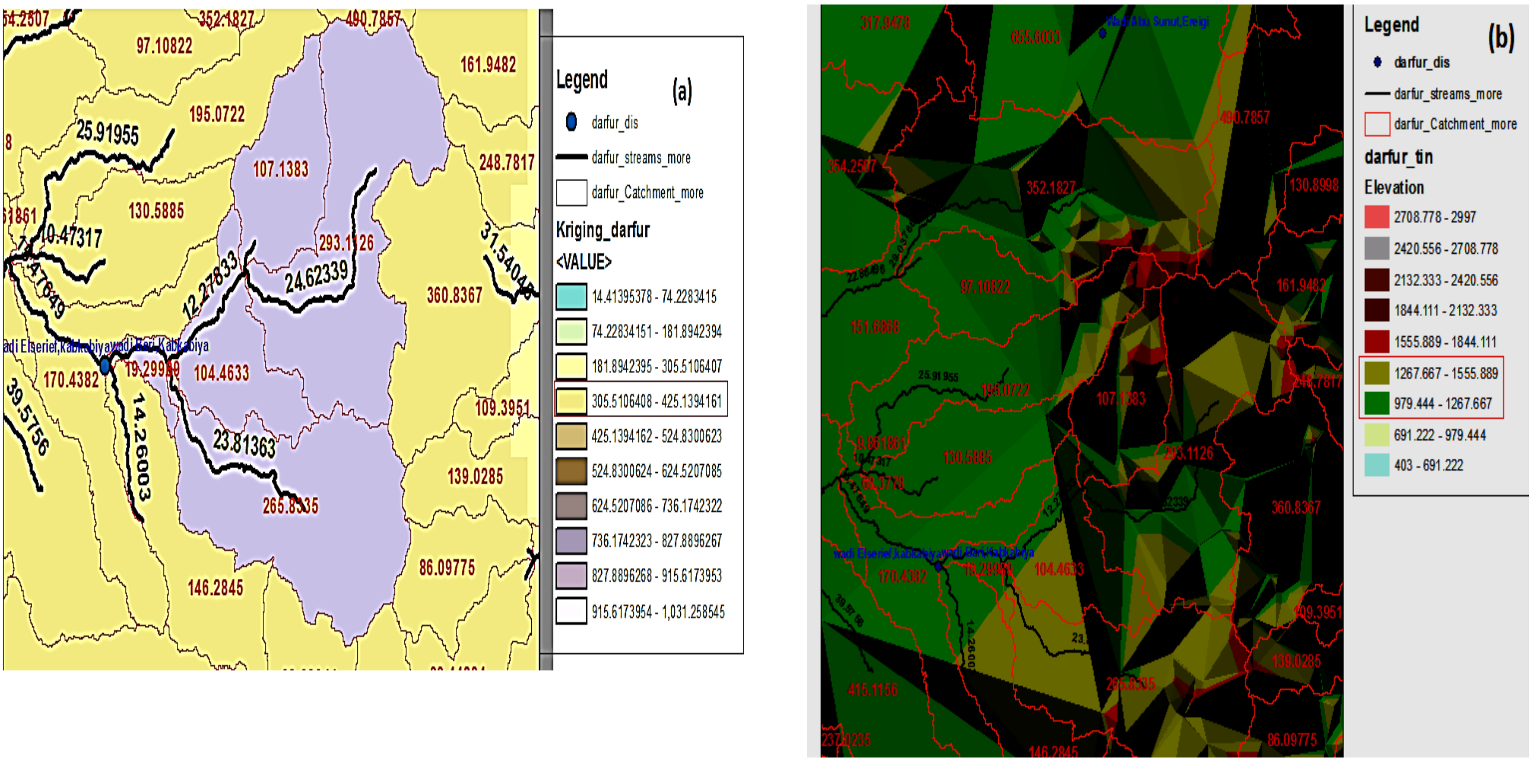


Figure 9. Wadi Bari, kabkabiya station, (a) rain, catchment and stream length,(b) elevation

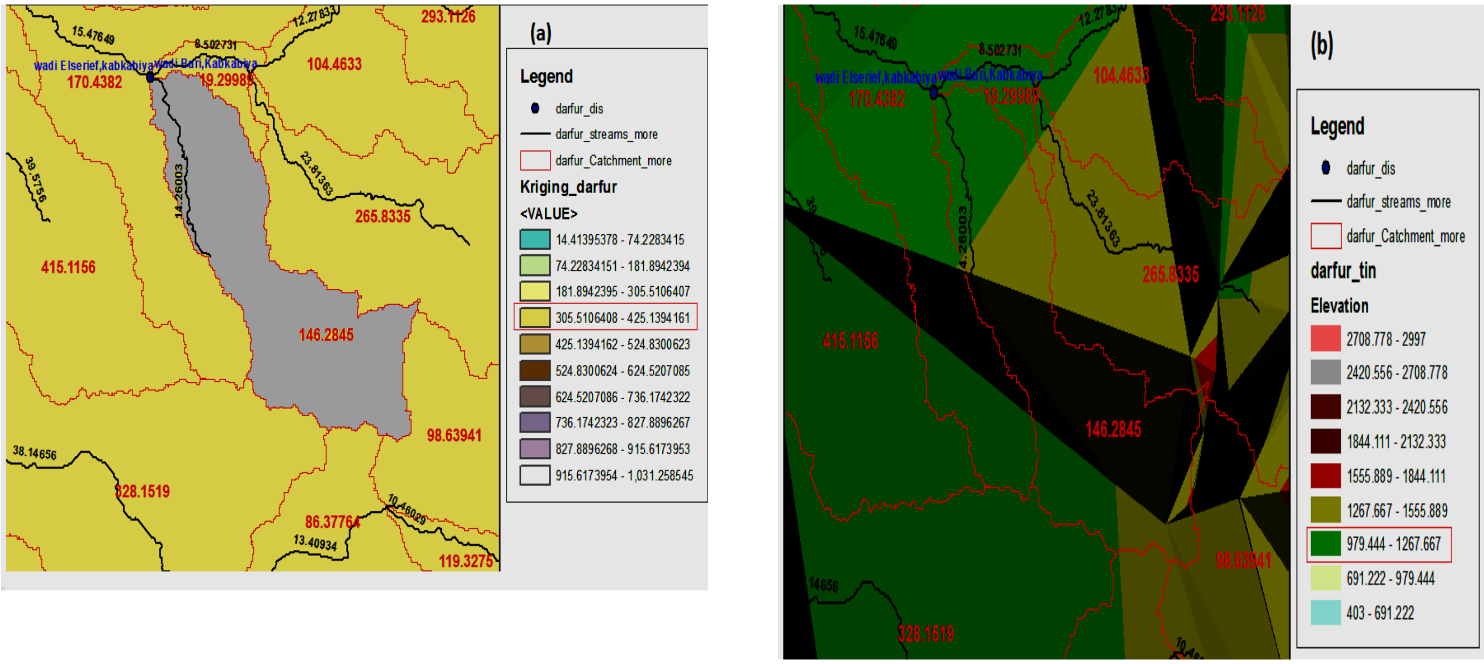


Figure 10. Wadi elserief, kabkabiya station, (a) rain, catchment and stream length, (b) elevation

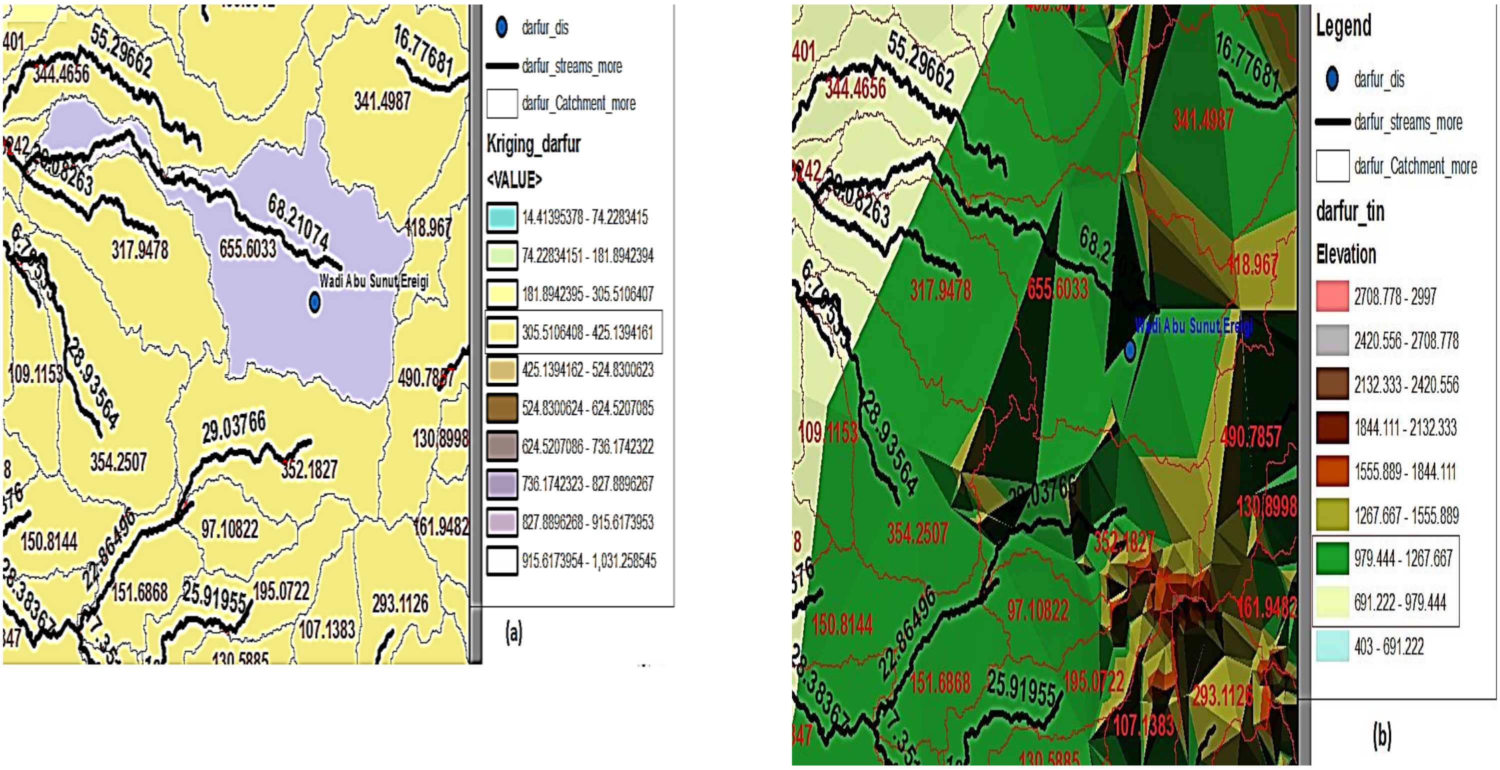


Figure 11. Wadi Abu Sunut, Ereigi station,(a) rain, catchment and stream length,(b) elevation

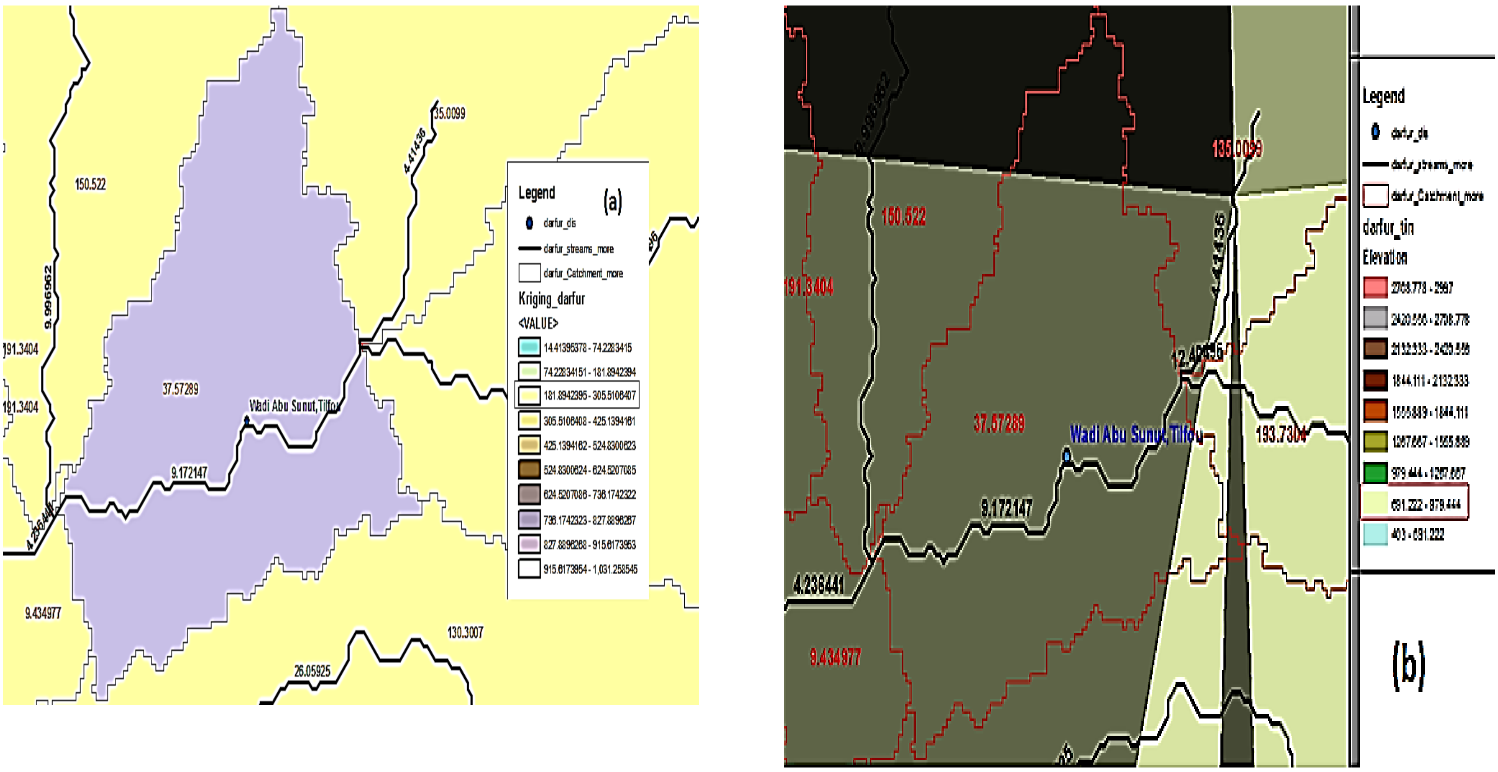


Figure 12. Wadi Abu Sunut, Tilfou station,(a) rain, catchment and stream length,(b) elevation

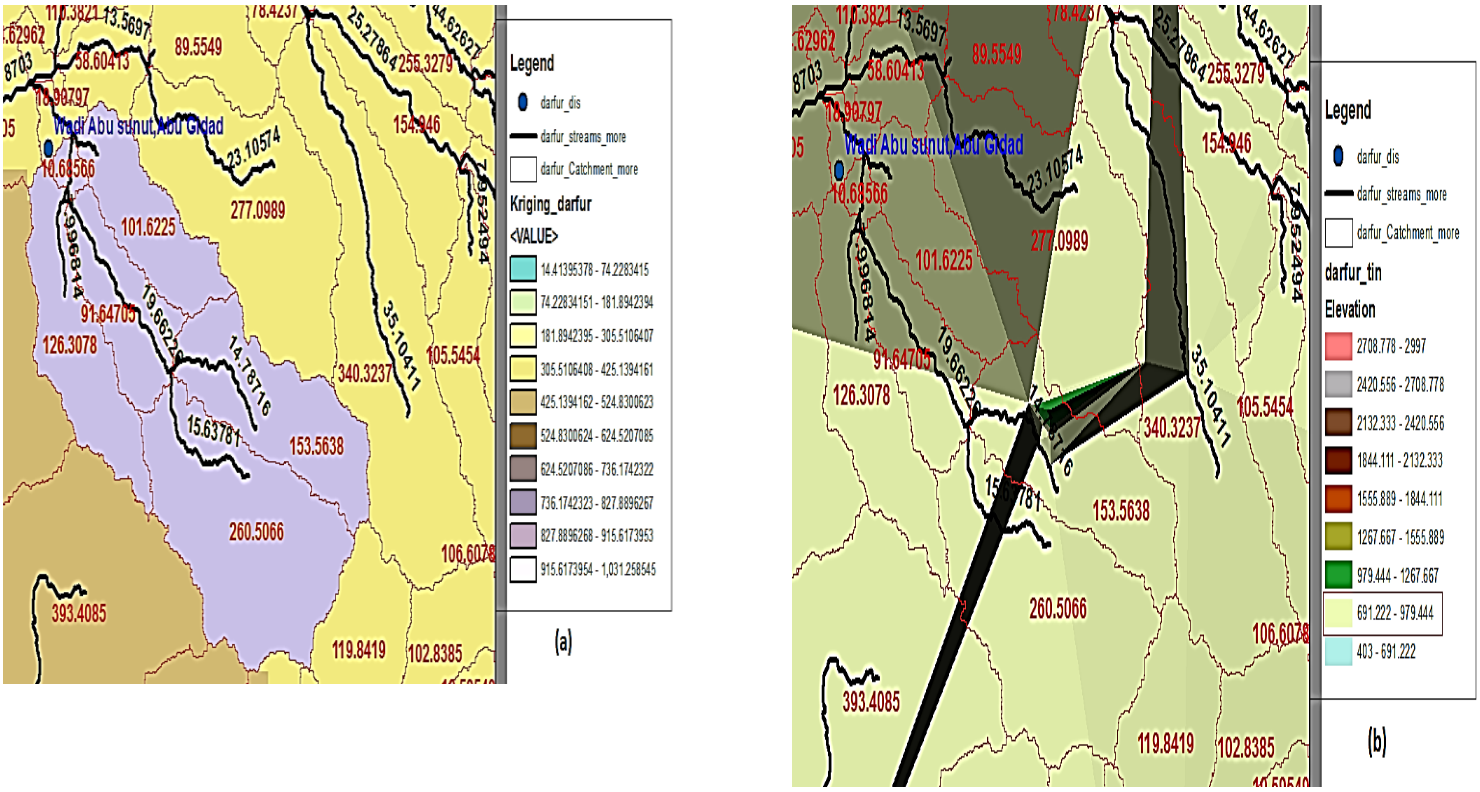


Figure 13. Wadi Abu Sunut, Abu Gidad station,(a) rain, catchment and stream length,(b) elevation

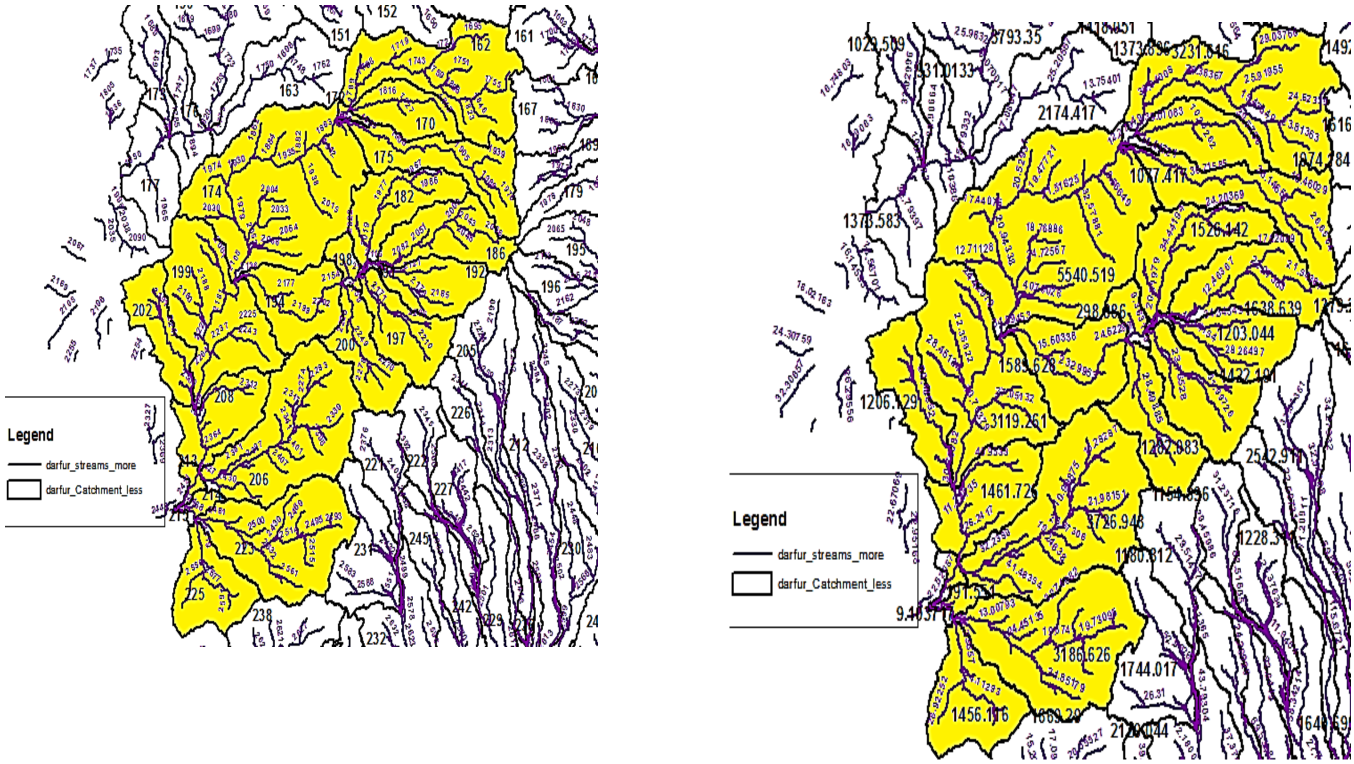


Figure 14. Wadi Azum,(a) Grid ID catchments and streams length, ,(b) values of catchments and streams length

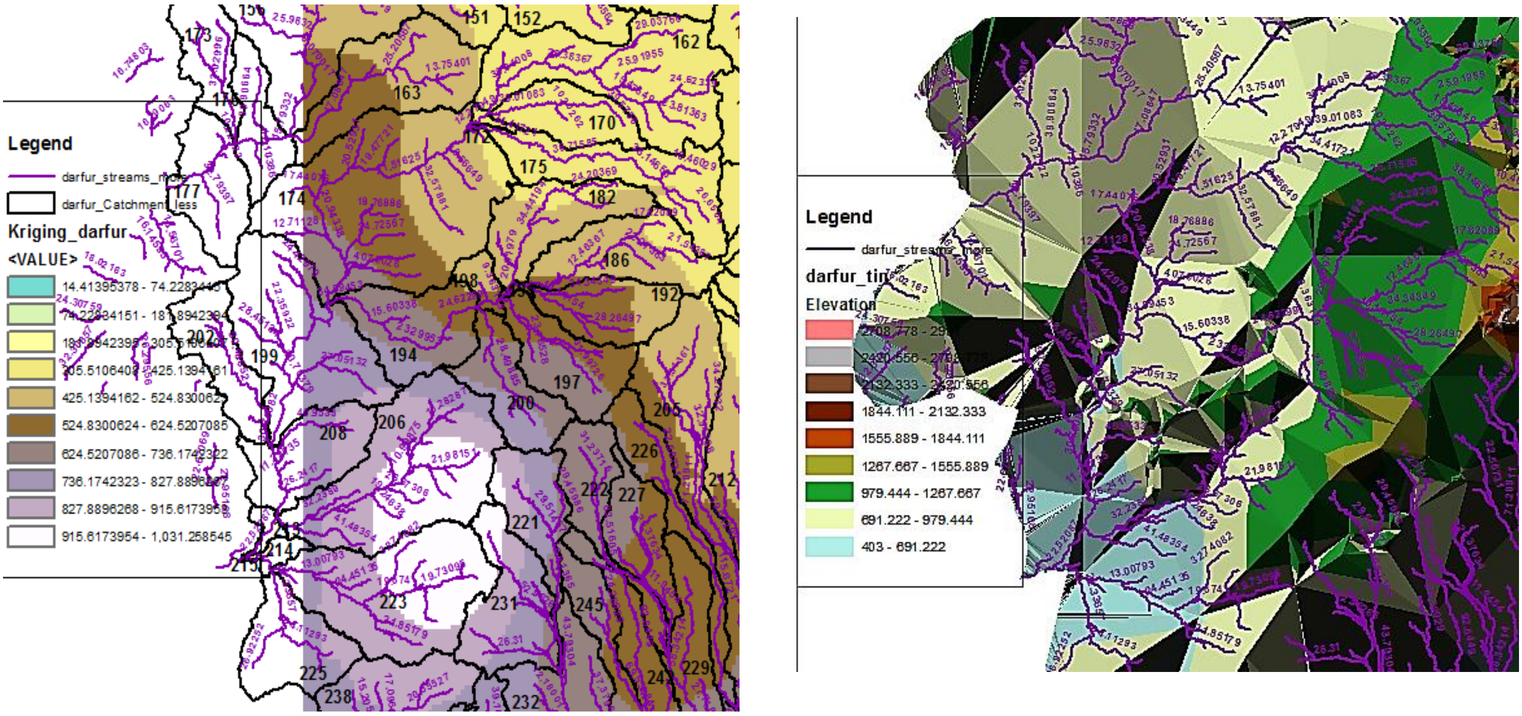


Figure 15. Wadi Azum ,(a) rain, catchment and stream length,(b) elevation

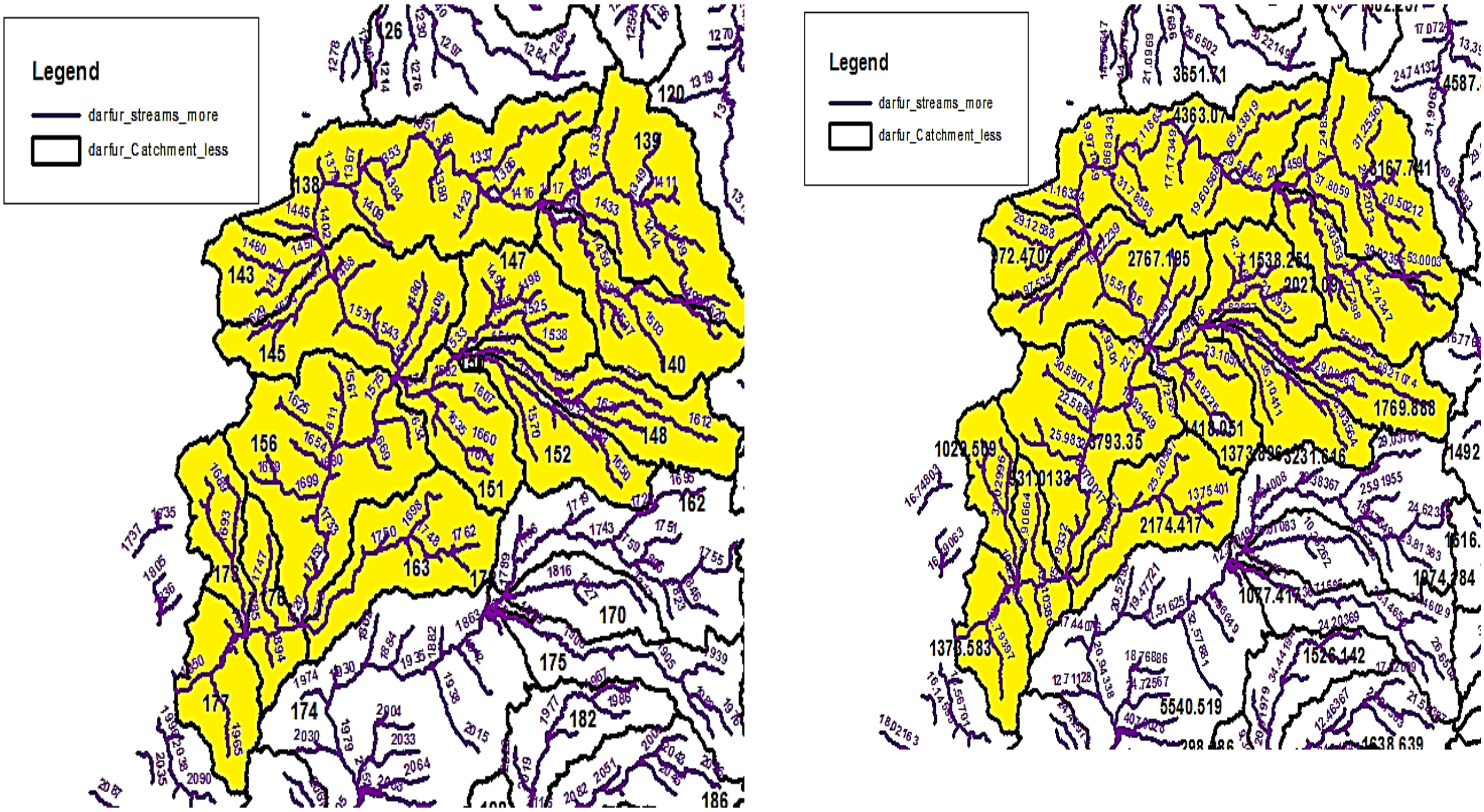


Figure 16. Wadi Kaja,(a) Grid ID catchments and streams length, ,(b) values of catchments and streams length

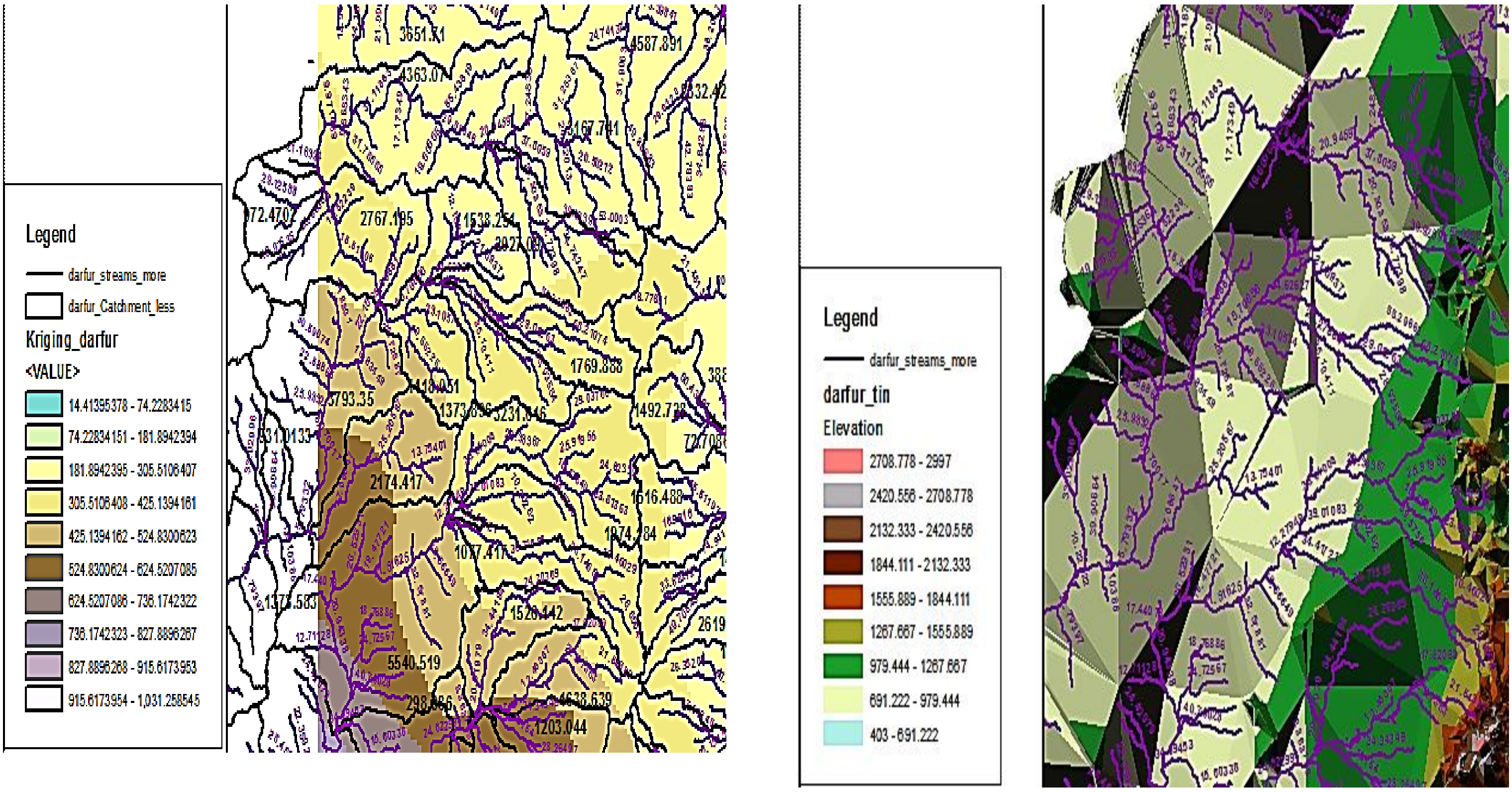


Figure 17. Wadi Kaja ,(a) rain, catchment and stream length,(b) elevation

XLSTAT 2016.02.27444 - Linear regression - Start time: 10/2/2016 at 2:44:13 PM

Y / Dependent variables: Workbook = regression.xlsx / Sheet = stations / Range = stations!$Q$1:$Q$7 / 6 rows and 1 column

X / Quantitative: Workbook = regression.xlsx / Sheet = stations / Range = stations!$R$1:$U$7 / 6 rows and 4 columns

Confidence interval (%): 95

Tolerance: 0.0001

Summary statistics (Quantitative data):

Variable	bservatior	/ith missin	thout miss	Minimum	Maximum	Mean	:d. deviation
log(Q)	6	0	6	1.602	2.255	1.883	0.273
log(A)	6	0	6	2.501	4.076	3.058	0.544
log(P)	6	0	6	2.567	3.005	2.760	0.145
log(S)	6	0	6	-0.746	0.096	-0.333	0.352
log(L)	6	0	6	0.961	2.499	1.721	0.500

Figure 18. regression analysis results

Correlation matrix:

	log(A)	log(P)	log(S)	log(L)	log(Q)
log(A)	1	-0.111	-0.502	0.947	0.232
log(P)	-0.111	1	0.310	-0.382	0.699
log(S)	-0.502	0.310	1	-0.554	0.094
log(L)	0.947	-0.382	-0.554	1	-0.084
log(Q)	0.232	0.699	0.094	-0.084	1

Regression of variable log(Q):

Goodness of fit statistics (log(Q)):

Observati	6.000
Sum of we	6.000
DF	1.000
R²	0.995
Adjusted I	0.976
MSE	0.002
RMSE	0.042
MAPE	0.751
DW	3.103
Cp	5.000
AIC	-38.664
SBC	-39.705
PC	0.053

Analysis of variance (log(Q)):

Source	DF	m of squa	ean squar	F	Pr > F
Model	4	0.370	0.092	51.300	0.104
Error	1	0.002	0.002		
Corrected	5	0.372			

Computed against model Y=Mean(Y)

Type I Sum of Squares analysis (log(Q)):

Source	DF	m of squa	ean squar	F	Pr > F
log(A)	1	0.020	0.020	11.130	0.185
log(P)	1	0.198	0.198	109.660	0.061
log(S)	1	0.000	0.000	0.172	0.750
log(L)	1	0.152	0.152	84.240	0.069

Type III Sum of Squares analysis (log(Q)):

Source	DF	m of squa	ean squar	F	Pr > F
log(A)	1	0.173	0.173	96.147	0.065
log(P)	1	0.014	0.014	7.696	0.220
log(S)	1	0.000	0.000	0.015	0.923
log(L)	1	0.152	0.152	84.240	0.069

Figure 18. Cont

Model parameters (log(Q)):

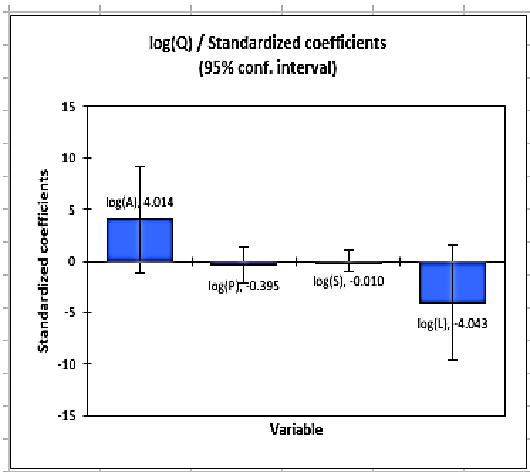
Source	Value	andard err	t	Pr > |t|	er bound (9	er bound (95%)
Intercept	1.580	0.587	2.691	0.227	-5.880	9.040
log(A)	2.011	0.205	9.805	0.065	-0.595	4.618
log(P)	-0.744	0.268	-2.774	0.220	-4.150	2.663
log(S)	-0.008	0.065	-0.122	0.923	-0.838	0.822
log(L)	-2.206	0.240	-9.178	0.069	-5.259	0.848

Equation of the model (log(Q)):

log(Q) = 1.57996091739009+2.01127688478229*log(A)-0.743712904562729*log(P)-7.95204616685415E-03*log(S)-2.20560977060285*log(L)

Standardized coefficients (log(Q)):

Source	Value	andard err	t	Pr > |t|	er bound (9	er bound (95%)
log(A)	4.014	0.409	9.805	0.065	-1.188	9.216
log(P)	-0.395	0.142	-2.774	0.220	-2.204	1.414
log(S)	-0.010	0.084	-0.122	0.923	-1.083	1.062
log(L)	-4.043	0.441	-9.178	0.069	-9.641	1.554



Predictions and residuals (log(Q)):

Observatio	Weight	log(Q)	red(log(Q	Residual	td. residu	ntized res	. on pred.	ound 95%	ound 95%	n pred. (O	nd 95% (O	nd 95% (Observation)
Obs1	1	2.255	2.256	-0.001	-0.026	-1.000	0.042	1.717	2.796	0.060	1.494	3.019
Obs2	1	1.653	1.666	-0.013	-0.295	-1.000	0.041	1.150	2.181	0.059	0.920	2.412
Obs3	1	1.763	1.729	0.035	0.820	1.000	0.024	1.420	2.037	0.049	1.107	2.350
Obs4	1	1.602	1.621	-0.019	-0.456	-1.000	0.038	1.141	2.101	0.057	0.899	2.343
Obs5	1	2.176	2.182	-0.006	-0.145	-1.000	0.042	1.649	2.716	0.060	1.423	2.941
Obs6	1	1.851	1.847	0.004	0.101	1.000	0.042	1.310	2.383	0.060	1.086	2.607

Figure 18. Cont

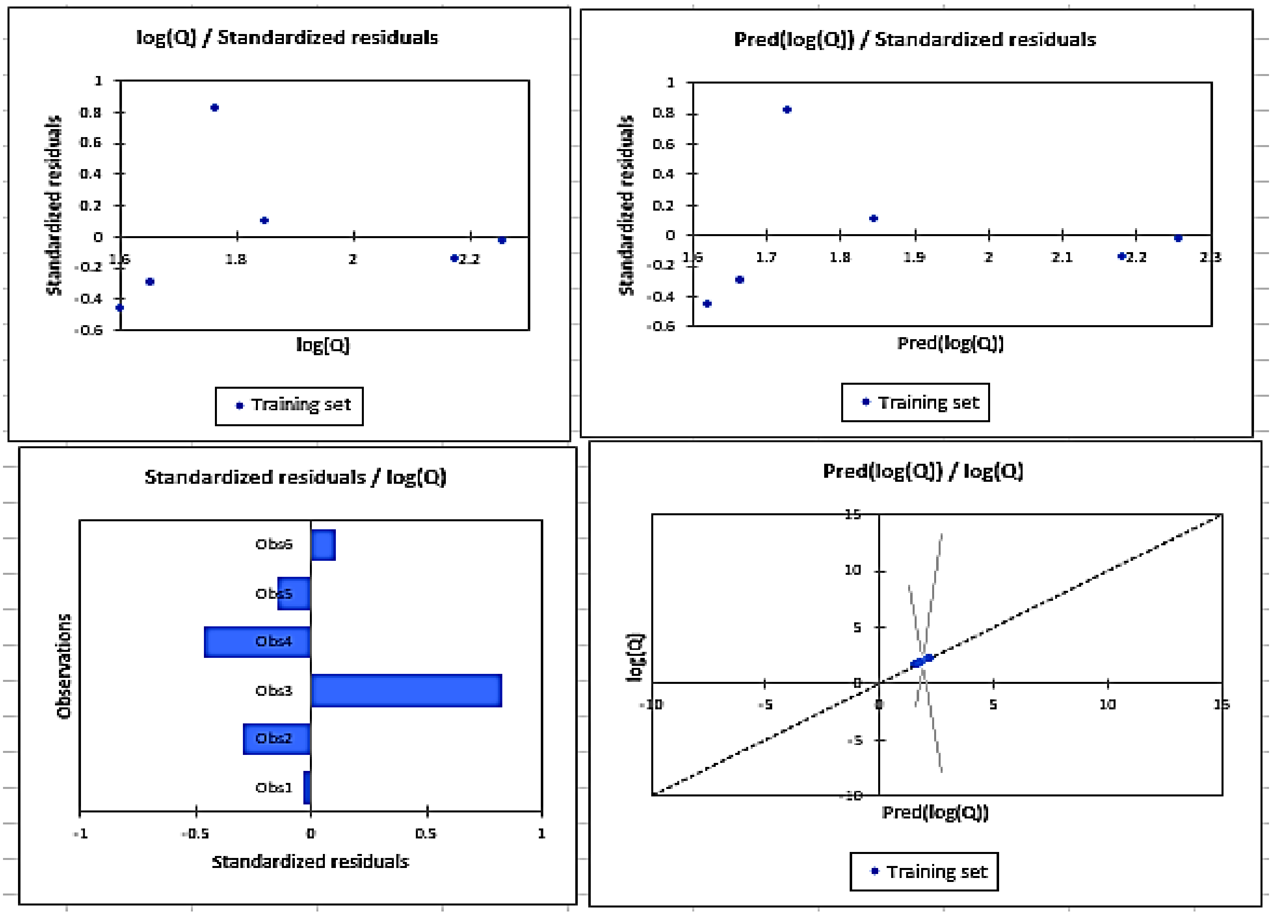


Figure 18. Cont