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ANALYSIS OF DEPTH-AREA-DURATION CURVES OF RAINFALL IN SEMIARID AND ARID REGIONS USING GEOSTATISTICAL METHODS: SIRJAN KAFEH NAMAK WATERSHED, IRAN

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Isohyet maps are were prepared after collection of data and information at 59 rainfall gauging stations in the Sirjan Kafeh Namak Watershed, Iran, and the dominant and maximum rainfall for durations of one to three days were selected. The relationship between rainfall and elevation was investigated, but due to the insignificant difference in the relationship, two methods of geostatistical kriging and inverse distance with powers of 1 to 3 were evaluated to draw the isohyet maps and determine the average rainfall. To evaluate the methods, mean absolute error was used. The results show that the kriging method is better than the inverse distance method for determination of average rainfall. Using the kriging method, the isohyet maps of one to three day duration and depth-area-duration curves were drawn. Conversion of point rainfall to average rainfall for an area of up to 20000 km^2 of the area under study is possible. Also, the curves show that the ratio of the amount of rainfall at the center to the amount of rainfall at an area of 20000 km^2 is 1.98, 1.74 and 1.48 for durations of 1, 2 and 3 days respectively.

INTRODUCTION

One of the important parameters in design of hydraulic structures in a watershed is the average rainfall. The amount and intensity of rainfall are also two basic parameters in design of hydraulic structures and watershed management. The more precise and more scientifically-based are the prediction of the two parameters, the more successful will be the construction of the structures. Rainfall is a variable which changes both in space and time, and the intensity of a specific rainfall will not be the same from the start to the end of a rainfall event. Also, it seldom occurs that a specific rainfall is the same throughout the rainfall area. It is more in some points and less in other points. The location with highest amount of rainfall in a watershed is the center of the rainfall. Away from the center, the rainfall decreases. An investigation of the decreasing trend in the amount of rainfall from its center is one the important problems in the sciences of hydrology and meteorology.

Rain gauge stations show the amount of rainfall at specific points in a watershed and the information about the amount of rainfall is limited to these specific points. Rain gauge stations and their amount of rainfall cannot be used as the basis for design of hydraulic structures. This is especially true in arid and semiarid regions where the number of rain gauge stations is more limited and the areal variability in rainfall is more severe. A knowledge of rainfall variability is critical for the design of hydraulic structures. Analysis of the relationship among rainfall depth-area-duration (DAD) curves is one of the basic factors in investigation of spatial variation of rainfall, and calculations related to floods. Using these curves, point rainfall (recorded in a rain gauge station) is changed to average rainfall over a specific area. These curves also determine the spatial trend of rainfall changes of a specific duration and area.

One the main steps in preparation of DAD curves is drawing isohyet maps. Several methods exist for drawing such maps such as the rainfall gradient method and complicated geostatistical methods like kriging. Although the rainfall gradient method is fast and simple, for short duration rainfall, and the relationship between elevation and rainfall, the method does not give good correlation and does not have enough precision for drawing isohyet maps. All work in Iran has been based on the gradient method by omitting over 50% of data to make the relationship between rainfall and elevation significant. This is not a valid scientific approach. In these cases, geostatistical methods for evaluating both spatial changes of data are more valid.

Geostatistics investigates those variables by examining their spatial structure. A frequently used geostatistical predictor is kriging, which is based on moving averages and can be regarded as a “Best Linear Unbiased Estimator”. Nowadays, geostatistical methods, despite their complexity, have several applications in different branches of science like environmental and natural resources because of powerful computer software such as GS^+ and GIS.

The studies carried out on DAD curves are as follows: The US Weather Service (1958) prepared DAD curves for durations of 0.5 to 24 hours (Rodriguez and Mejia, 1974), using rain gauge station networks and showed that by increasing the area, the amount of rainfall decreases. Leclerc and Schaake (1972) found a relationship to convert point rainfall to the average rainfall in a specific area based on meteorological data. Aghighi (1995) made the analysis of DAD curves in the Jajroud-Tehran-Karaj region and concluded that most rain falls during the first three days. Ahmadi (2002) made the same analysis in Kermanshah Province.

Several geostatistical approaches have been carried out throughout the world.. Some are as follows: Van Kuilenberg et al. (1982) compared moving average and kriging methods to determine the soil moisture capacity in the Netherlands and concluded the kriging method is better than the moving average method. Pohlman (1993) showed that using kriging variogram analysis for interpolation of data and design of networks in environmental investigations is useful. Mahdian et al. (2002) showed that spline and kriging methods to estimate rainfall and temperature in arid, semiarid and humid climates were better than other methods.

MATERIALS AND METHODS

The study region

The Sirjan Kafeh Namak watershed, which is one of the sub-basins of the Gavekhoni Marsh watershed was investigated. The region lies between 51º 46′ 28″ to 56º 26′ 31″ east longitude and 30º 54′ to 35º 30′ 27″ north latitude, and includes a large section of the cities Sirjan and Shahre Babak and a small portion of the city of Baft in Kerman Province. It is located in the western part of Kerman Province and has an area of 2480 km^2. The highest elevation is 3800 m and the lowest is 1500 m. The climate of the region is variable due to the large difference between the highest and lowest points (2300 m). Mean annual rainfall is 180 mm and varies from 120 mm to 350 mm. Over 65% of rainfall occurs in winter. Mean annual evaporation is 2185 mm and mean annual temperature is 16.1 ºC.

Data collection

The data sources are the Water Resources Research Organization (Tamab in Persian) and the meteorological organization. After determination of the study area on 1:25000 topographical maps, the rainfall data were collected from all stations from the beginning of construction until 1999. The number of stations was 59, out of which 33 belonged to meteorological stations and 26 were related to Ministry of Power (Energy), Tamab Organization. When two stations existed, the data of one station was used. If the two readings were different, the average of the meteorological and Ministry of Power stations were used.

Analysis of rainfall data

After collection of daily rainfall, due to the high volume of data and information, the selection of dominant and maximum daily rainfall from raw data was difficult to carry out manually. The daily rainfall data were incorporated into EXCEL software and an information bank of the region's stations were prepared. The information bank can be used easily. By using EXCEL instructions, the dominant and maximum daily rainfall for durations of one to three-days (for each duration 4 storms for a total of 12 storms) was selected.

Conversion of rain gauge coordinates

As the drawing of isohyet maps requires GS^+ and GIS software, and they work with the metric system, it was necessary to convert meteorological stations coordinates into the metric system (UTM). For this purpose the ILWIS software was used.

Drawing isohyet maps

This method is simple, but may not be practical, because in most cases, especially for short duration rainfall, the relationship between rainfall and elevation may be statistically insignificant. In these cases the drawing of isohyet maps is not recommended. In this study, geostatistical methods were used, because the relationship between elevation and rainfall was statistically insignificant.

Geostatistical methods

In this research two methods of kriging and inverse distance with powers 1 to 3 were evaluated for interpolation. The isohyet maps were drawn using the most suitable method. For this purpose, for each rainfall event, a table was constructed consisting of UTM coordinates and the amount of rainfall on that date. By using this table, a suitable variogram model with respect to spatial structure of each rainfall event was fitted using GS^+ software (for the data which were not normally distributed, square root and logarithm of data were used). Then by using variogram models and its parameters (section effect, threshold, effective radius and the number of points used) interpolation was carried out using kriging and inverse distance with powers 1 to 3.

Fitting the variogram model

To determine the best variogram model with respect to the spatial structure of data, the variogram behavior in the vicinity of the center of coordinates of the residual sum of squares was used (Hassanipak, 1998; Rahimibandarabadi, 2000; Mahdavi, 2002; Goovaevts, 1997; Robertson, 2000).

Method of model evaluation

To investigate the error of each interpolation method and select the best method for the amount of rainfall, the method of cross validation (CV) was used. In this method, for each measured points which are the only tools for comparison, estimation can be carried out. Then the measured and estimated values are compared. In the CV method one point is omitted, then by using other points and interpolating, the point is estimated. The point is returned to its place and the next point is omitted. The same procedure is repeated for all points.

Evaluation criterion

For evaluation of the amount of error and selection of the best method, different criteria like residual sum of squares, residual mean squares, and the use of statistical comparison methods such as analysis of variance exist. In this study the criterion of mean absolute error (MAE) was used. The method of calculation is as follows:

$$MAE = \frac{1}{n}\sum_{i=1}^{n} \left| z^*(xi) - z(xi) \right| \quad (1)$$

where $Z^*(Xi)$ is the estimated variable of Xi, $Z(Xi)$ is the observed variable of Xi, n is the number of observed variables and MAE is the mean absolute error. The most suitable method has the lowest MAE. When the MAE is zero it shows that the model estimates the variable whatever it is.

Drawing isohyet maps

After determination of the most suitable method by using GS^+ software, it was necessary to use software which could calculate the area and overlap the maps. GS^+ software was not able to carry out these two functions. For this purpose, the isohyet maps were drawn in GIS software in the ILWIS medium for each rainfall, using the suitable spatial structure and effective parameters in the model determined by GS^+ software.

Drawing primary DAD curves

After drawing the isohyet maps, the following steps were carried out to draw the primary DAD curves (it is called primary because in later steps these curves should be combined).

Determination of the area between isohyet lines

In this step the area between each two isohyet lines was specified by using GIS software. The isohyet lines are drawn from higher to lower values.

Determination of cumulative areas

In this step the cumulative area between isohyet lines was calculated.

Determination of rainfall volume

The average of the two isohyets multiplied by the area between them gives the volume of rainfall.

Cumulative volume of rainfall and determination of average rainfall based on the area

After determination of rainfall volume, the cumulative rainfall is obtained. Then by dividing cumulative rainfall volume by cumulative area, the average rainfall of each area is calculated.

Drawing primary DAD curves

By drawing maximum rainfall against cumulative area in one coordinate axis, the primary DAD curves are obtained

Drawing final DAD curves

As the maximum rainfall is under consideration in the final curves, for different areas on the x-axis, the amount of rainfall is obtained from the y-axis of primary DAD curves. For each area the highest amount of rainfall is obtained. If the obtained maximum rainfall is drawn against the related areas in a coordinate axis system for each duration, the final DAD curves are obtained.

RESULTS AND DISCUSSION

Investigation of the relationship between rainfall and elevation

Table 1 shows the correlation equations and correlation coefficients between rainfall and elevation of the stations for each rainfall. In this table the lowest and highest correlation coefficients are 0.014 and 0.58 mm, respectively. The highest value is for the 3-day storm of March 6, 1998, and the lowest value is for the one-day storm of March 1, 1998. Also, the coefficients of determinationR^2 are lowest (0.0002) for the rainfall of March 1, 1998 and highest (0.3016) for the rainfall of March 6, 1998. As it can be concluded from the table, there is no suitable correlation between rainfall and elevation, so that from 12 rainfall events in 12 cases (100%), the correlation coefficient is less than 0.6 and in 10 cases (83%) the coefficient is less than 0.5.

Selection of suitable models

In this stage, by using GS^+ software, fitting the best model to the spatial structure was performed. Table 2 shows the parameters related to the best fit model to spatial structure of data for each rainfall. Based on the Table, from the 12 rainfall events, the spherical, Gaussian and exponential models had the highest frequency occurrence of 5, 4, and 3 respectively.

Selection of the best method and drawing isohyet maps

In this stage, interpolation was carried out by two methods of common kriging and inverse distance with powers of 1 to 3 for each rainfall. To compare these two methods and select the suitable method the mean absolute error (MAE) criterion was used. Table 3 shows the MAE of each method for each rainfall event. Based on this Table, in 7 out of 12 cases (58.3%) the kriging method had lower MAE

Table 1. The Relationship Between Elevation and Rainfall

Duration	Date of rain	Correlation coefficient(r)	Coefficient of determination (R^2)	Number of stations	Gradient equations, x is elevation in m, y is rainfall in mm
One-day	2.6.1998	0.0335	0.1127	33	63.23-x0264.0=y
	2.4.1992	0.064	0.0042	23	979.61+x0069.0=y
	3.8.1998	0.014	0.0002	32	564.30-x0002.0=y
	2.6.1994	0.42	0.183	28	13.27-x0258.0=y
Two-day	3.1.1998	0.3	0.0931	33	2612.2+x0183.0=y
	3.10.1993	0.33	0.1053	29	0538.1+x0159.0=y
	2.5. 1998	0.58	0.3106	33	271.69-x0557.0=y
	2.3.1992	0.07	0.0049	23	565.50+x012.0=y
Three-day	2.28.1998	0.49	0.2429	33	8.30- x0398.0=y
	2.6.1994	0.46	0.212	29	984.48- x0523.0=y
	3.10.1993	0.47	0.2209	29	835.29- x0382.0=y
	2.3.1992	0.289	0.084	23	7544.6+ 0.0477x=y

Table 2. Effective Parameters in the Spatial Structure Model of Each Rainfall

Coeff. of skewness	Range of data, m	Base of the distance, m	Type of model	Co , mm^2 Effect of section	Co+C mm^2	Ao, Km, threshold	C/(Co+C)	R.S.S, mm^2	No. of neiboring points	Radius of search,K m
0.12	175810	17581	Exponential	0.0514	0.3678	46	0.86	0.434	10	150
0.07	136885	13688.5	Spherical	0.95	6.91	250	0.826	4.09	6	170
0.02	179612	17961.26	Gussian	0.3340	2.678	273	0.875	0.046	16	200
0.02	179612	17961.26	Spherical	0.136	0.3074	411	0.558	0.0132	10	80
0.05	164710	16471	Exponential	69.7	273	86	0.749	11531	6	90
0.22	175810	17581	Spherical	2.81	12.62	365	0.77	15.8	8	170
0.07	179612	15500	Gussian	0.38	0.803	102	0.527	0.148	16	200
0.12	179612	17961.26	Exponential	6.5	288	143	0.977	14708	16	224
0.14	175810	17581.04	Spherical	2.05	10.2	366	0.798	3.99	16	219
0.25	175810	17581.04	Spherical	250	660.1	411	0.621	81591	5	100
0.05	164715	8000	Exponential	0.014	0.321	134	0.956	0.0976	8	205
0.08	179612	17961	Spherical	196	1065.7	411	0.816	56101	5	224

Table 3. Mean Absolute Error in the Methods

Date of raining	**Kriging**	**IDW^{-1}**	**IDW^{-2}**	**IDW^{-3}**	**Mean of observed values**	**Mean by Kriging**
2.4.1992	21.44	20.95	21	21.17	45.86	47
2.6.1994	10.49	12.253	10.88	11.021	22.917	20.004
2.6.1998	10.995	11.846	11.8692	11.491	33.785	30.75
3.8.1998	7.090	10.997	11.213	11.359	27.395	27.701
3.10.1993	8.116	8.177	8.208	8.177	40.007	37.825
2.3.1992	32.43	9.8	30.77	32	70	65.2
2.5.1998	16.55	15.811	21.682	23.445	38.218	44.9
3.1.1998	17.076	14.869	14.512	14.455	41.064	39.806
2.3.1992	30.2	33.473	35.878	38.321	97.366	100.080
2.3.1992	12.058	22.542	23.837	24.776	48.57	49.19
2.6.1994	16.812	20.07	20.218	18.95	59.457	56
2.28.1998	22.064	20.645	20.239	20.826	50.604	51.659

with respect to other methods. Three rainfall events out of 12 (25%) with inverse distance of power -1, one rainfall (8.3%) with inverse distance of power -3, and one case (8.3%) with inverse distance of power -2 had the lowest MAE. Table 3 also shows the observed and estimated amounts of samples by the kriging method. The results of this part show that in general the kriging method is better than the inverse distance method for estimation of average rainfall. So, to draw the isohyet maps

Table 4. The Maximum Rainfall (mm) for Different Areas and Durations

Area (km^2)	Duration of 24 hr	Duration of 48 hr	Duration of 72 hr
0	105	135	160
20000	84	113.5	142.7
4000	80	107	132.8
6000	74	102.5	129.48
8000	70	98.5	122.84
10000	68	94.6	121.18
12000	66	92	117.86
14000	63	89	112.88
16000	61.5	85	109.56
18000	57	82	106.24
20000	53.5	78	102.92

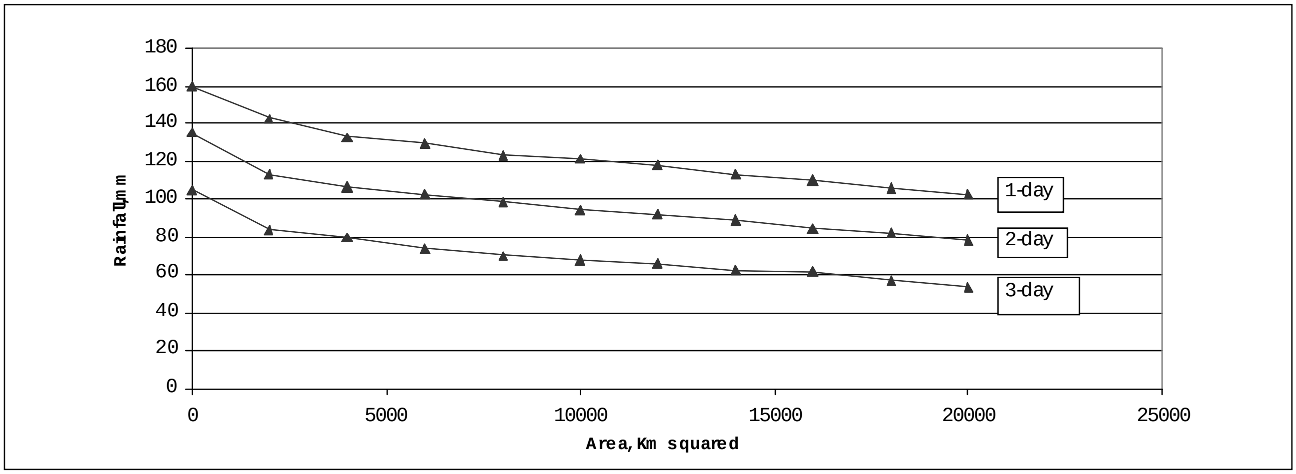

Figure 1. Final DAD curves for the sequences of 1, 2, and 3 days.

in later steps the kriging method is preferred to the inverse distance method. Kriging was used for drawing isohyet maps and then by using the maps the primary DAD curves were prepared.

Drawing Final DAD curves

In this stage the primary DAD curves were combined, i.e., for each duration the maximum amount of rainfall for each area was obtained and by drawing maximum rainfall against area in each duration, the final DAD curves were obtained. Table 4 shows the maximum rainfall for different areas and Figure 1 shows the final DAD curves.

CONCLUSIONS

1. Figure 1 shows the DAD relationship for 1-3 day durations of the rainfall of the area under study is shown. Based on these curves, the point rainfall can be converted to average rainfall for an area of up to 20,000 km^2. The curves can be used to determine average rainfall of the watershed for study and design purposes.

2. The ratio of point rainfall to average rainfall in an area of 20,000 km^2 in durations of 1-3 days is 1.8, 1.73 and 1.47. So, by increasing duration from 1 day to 3 days, the ratio decreases.

3. In the watershed the dominant and maximum rainfall with duration of 4 days does not exist. This means that all rains occur during the first 3 days.

4. All dominant and maximum rainfall occurs in winter (February and March). These two months are considered critical for flood occurrence.

5. The study shows that the relationship between rainfall and elevation is not statistically significant, so it cannot be used for calculation of the average rainfall.

6. Comparisons of other methods show that kriging is better than the inverse distance method.

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