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Rain Gauge Station Network Design for Hormozgan Province in Iran

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Abstract

A rain gauge network should serve general as well as specific purposes such as water supply, hydropower generation, flood forecasting, irrigation, and flood control. The level of accuracy a network can achieve depends on the number and locations of gauges in the network. In this study, a rain gauge network was designed for Hormozgan province in the south of Iran. Monthly rainfall totals from 124 rain gauge stations in the period from 2000 to 2009 were used. This province can be logically divided to four regions using the De Martonne aridity index. Kagan's approach was used to relocate the rain gauge network to obtain the optimal design. In this statistical method, the correlations were classified based on distance. Exponential models were fitted to the average correlations against mean distances in all regions. The number of gauges and the distance between gauges were computed to satisfy user requirements. The results showed that Hajiabad had the minimum value for distance (125 km) and Bandar Lengeh had the maximum value for distance (588 km). Spatial variation of rainfall in Hajiabad was greater than for other stations. The results indicate that 40, 50, 20, and 55 stations were adequate to represent rainfall with 15% average error in the regions of Bandar Lengeh, Bandar Abbas, Hajiabad and Minab, respectively.

Keywords: Rainfall; Rain gauge; Hormozgan; Statistical method

1. Introduction

Rainfall data is essential to many hydrological analyses and engineering design projects, including water budget analysis, frequency analysis and storm water drainage design. Direct measurement of rainfall can only be achieved using rain gauges, and rain gauge networks are often installed to provide measurements that characterize the temporal and spatial variation in rainfall. Rain gauge network design has received considerable attention. The relationship between precipitation and elevation has been investigated by Danard (1971), Sevruk (1974), Osborn (1984) and Puvaneswaran and Smithson (1991), among others. Several studies also have been done on the relationship between rainfall distribution, and orographic and climatic factors (Merva et al., 1971; Peck, 1972; Corradini, 1985).

It is known that the areal variability of rainfall is affected by nature and the orientation of the terrain and that it is necessary to establish greater network density in mountainous areas than in flat areas (Hutchinson, 1970). Four major factors determining rainfall distribution in mountainous areas are the speed of ascending air, water vapor supply, wind speed, and direction. Wind speed is more related to rainfall intensity and less to its distribution. Water vapor supply can be regarded as a sufficient measurement for storm events. In a qualitative discussion, rainfall distribution can be estimated using only the wind direction and the area of ascending air (Oki et al., 1991).

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Newly-developed rainfall network design techniques have been discussed and compared by St. Hilaire et al. (date) and Cheng, et al. (2007). Approaches for optimal design of rainfall gauges take into account the number and location of rainfall gauges to increase the accuracy of areal rainfall estimation at minimum cost. These approaches are generally categorized as variance reduction methods (Bras and Rodriguez-Iturbe, 1976; Hughes and Lettenmaier, 1981; Bastin et al., 1984; Bogardi and Bardossy, 1985; Rouhani, 1985) and involve searching for the appropriate number of rainfall gauges and their locations. Rodriguez-Iturbe and Mejia (1974) applied a hypothetical analytical model of rainfall to present estimates of variance as a function of gauge density, area of interest, and correlation length scale. Their work considered long-term and event rainfall and stratified and random sampling designs. Fontaine (1991) concluded that "gauge density appears to be the most influential factor in areal mean precipitation error", but also indicated that gauge arrangement was significant.

Peters-Lidard (1998) used statistical methods to determine the number of rain gauges in an area. The use of such methods first requires criteria against which the network density can be tested. For some applications, investigation is recommended to determine whether precipitation amounts can be interpolated with sufficient accuracy. Buishand (1986) calculated the average and interpolation errors using statistical methods. Wei et al. (2010) used the ordinary kriging to generate rainfall data in an alpine area located in central Taiwan. Their results showed that 2 and 5 candidate rain gauges could represent 62.93% and 85.21%, respectively, of the variance of rainfall distribution.

Rain gauges often are installed for a specific purpose and subsequently may fall into disuse. The density of these networks may be sparse in some regions and high in others. Optimization of a network involves specifying the density of observation sites that is sufficient to obtain reliable data while not requiring establishment of an excessive number of sites (Karasseff, 1986; Shaw and O'Connell, 1976). In Hormozgan province, the locations of the rain gauges in the networks were chosen using unscientific methods and, thus, the configuration of stations is irregular. This study proposed a rain gauge network evaluation and design approach focusing on accuracy assessment of point rainfalls across the study area using a statistical method.

2. Materials and Methods

2.1. Study area and data

Hormozgan province is located in southern Iran between 25° 23', 28 57' N and 52° 41', 59° 15' E. This region has arid and semiarid climates and precipitation is always in form of rain showers. Although the average of annual rainfall is less than 250 mm, severe flooding frequently occurs in the province and causes heavy damage. Hormozgan province is one of 30 Iranian provinces and has an area of over 68,400 km^2. It borders the Persian Gulf and the Sea of Oman Sea to the south (Fig. 1) and lies directly across the gulf from the kingdom of Oman. It is bounded by the provinces of Bushehr and Fars on the west and northwest, Kerman on the east and northeast, and Sistan and Baluchistan on the northeast. Its capital is Bandar Abbas.

The province comprises three zones of differing geography; the coastal zone in the south, a mountainous zone in the north, and a zone comprising a rural plateau and plains in the center. Hormozgan province is situated in a dominantly warm and dry zone of Iran and temperatures sometimes exceed 49°C in the summer. The weather along the coast is very hot and humid in the summer and mild in the winter. Rainfall there occurs mostly from November to February in the form of showers. The relative humidity is usually very high in the coastal zones along the Persian Gulf.

In this study, time series of monthly rainfall data for 10 years, from 2000 through 2009, were analyzed. A total of 124 rain gauges were used over this period. The three zones can be logically divided to four regions based on the provincial climate. Table 1 shows specifications of each region. The regions and rain gauge positions are denoted in Figure 1. For arrangement of the stations, all regions were analyzed using Kagan’s approach (Kagan, 1972). This process was accomplished independently for each region. In some months, the amount of precipitation was zero, thus, the recorded null values led to a strong correlation between two stations. To control for this, the null values were eliminated so that the correlation between the stations was not artificially elevated. About 60% of rain gauges recorded up to 200 mm of rainfall a year, 25% recorded precipitation of between 200-250 mm and 15% recorded precipitation of more than 250 mm a year. The peak precipitation occurred in Bastak, which recorded 342 mm a year; the least occurred in Bandar Lengeh, which recorded 20 mm a year. It was notable that there were 48 stations in Bandar Lengeh and only 4 in Bastak; this clearly illustrates an appropriate distribution of rain gauges. As shown in Fig. 4, the distribution of rain gauges were usually irregular and the length of the province made the expense of measuring and accumulating of rainfall observation data exorbitant.

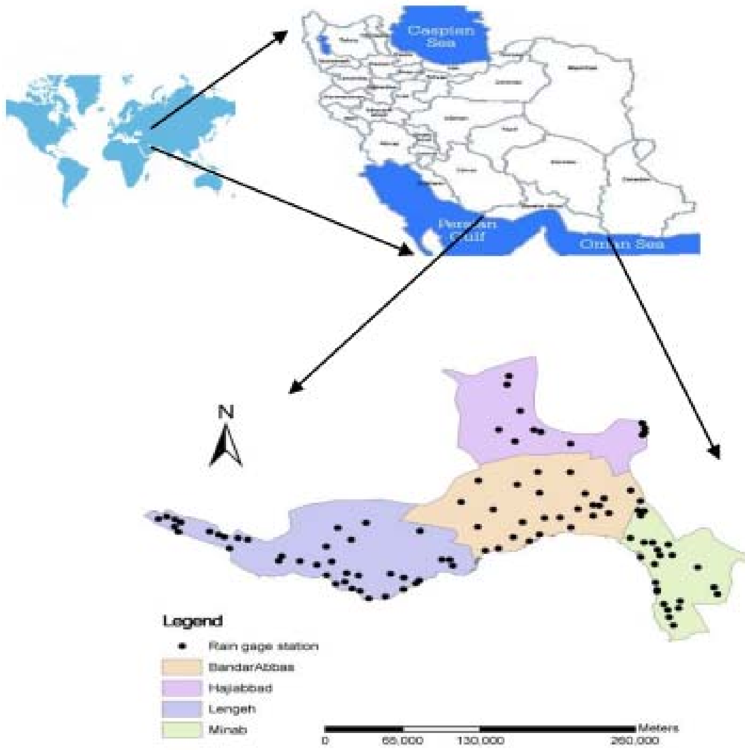

Fig. 1. The study area and rain gauge locations

Table 1. Site-specific gauge networks

Region	Bandarlengeh	Bandarabbas	Hajiabad	Minab
Region area (km^2)	15246	15429	9379	7496
Number of gauge	39	27	16	42
Mean monthly precipitation (mm)	142.5	183.5	219.9	213.6
Average station density (km^2)	391	571	586	178

2.2. Spatial Correlation Technique

Kagan (1972) demonstrated that a network of rain gauges can be designed to meet a specified error criterion, given that the spatial variability of rainfall can be quantified using a spatial correlation function. Applying such an approach, however, requires conditions such as horizontal homogeneity and isotropy to ensure the existence of a spatial correlation function (Shaw and O'Connell, 1976). The basis of the method is that the correlation function is a function of the distance between stations and depends on the characteristics of the area and the type of precipitation. The correlation between the amount of precipitation of two stations at distance d is often described by the following two parameter exponential relation (Kagan, 1972; Stol, 1972):

$$\rho(d) = \rho_0 e^{-d/d_0} \qquad (1)$$

where $\rho(d)$ is the correlation between the precipitation at two stations with distance $d(km)$ and ρ_0 is the correlation corresponding to zero distance. Correlation function $\rho(d)$ at distance d_o equals 0.36 ρ_0.

This relation usually provides a good fit to plots of sample correlations estimated from historic data. It is often found that ρ_0 is less than 1, and thus $\rho(d)$ differs from unity at very short distances. This property is known as the nugget effect (Journel and Huijbregts, 1978) and can either be ascribed to random errors in precipitation measurement or microclimatic irregularities over an area (James and Sreedharan, 1986; Sreedharan and James, 1983; Nandagiri, 2006). The variance of these random errors at a fixed point σ_1^2, is given by:

$$\sigma_1^2 = [1-\rho_0] \times \sigma_h^2 \tag{2}$$

where σ_2^h is the variance of the rainfall time series at this point. The quantities ρ_0 and d_0 provide the basis for assessing the accuracy of a rain gauge network. The error of weight of average rainfall at a given area (E_a), and error of interpolation of rainfall at a given point (E_i), are the main factors for designing a rain gauge network (James, 1983; James and Sreedharan, 1986). The required network density often relates to E_a. The variance of error (v) for the average precipitation over an area is given by Kagan's relation (Kagan, 1972):

$$v = \sigma_h^2[1-\rho_0] + 0.23\sigma_h^2 \frac{\sqrt{S}}{d_0} \tag{3}$$

where S is the area of the region. In Eq. (5), the first term is the random error defined by Eq. (2). The second term is the spatial variation of precipitation in the region (James, 1983; James and Sreedharan, 1986). E_a is defined as:

$$E_a = C_v \sqrt{\frac{1-\rho_0 + \frac{0.23\sqrt{S}}{d_0\sqrt{n}}}{n}} \tag{4}$$

where C_v is the coefficient of variation and n is the number of stations required to obtain E_a. Conversely, E_a can be evaluated if n is given. This equation denotes that ρ_0 and d_0 are primary parameters for rain gauge network design. A triangular grid is usually more convenient if the project region has a complex configuration. In this grid, the spacing between the adjacent stations is defined as:

$$r = \sqrt{\frac{2S}{\sqrt{3}n}} = 1.07\sqrt{\frac{S}{n}} \tag{5}$$

In hydrological projects, precipitation amounts for given points are often needed. For this purpose, rainfall data is estimated by interpolation of measurements from surrounding rain gauges. E_i often figures in rain gauge network design. For instance, in most projects, to decrease the interpolation error to less than the given errors, a sufficient number of rain gauges should be installed. In a triangular grid, maximum interpolated error occurs at the center of triangles. This error is evaluated by:

$$E_i = C_v \sqrt{\frac{1}{3}[1-\rho_0] + 0.52\frac{\rho_0}{d_0}\sqrt{\frac{S}{n}}} \tag{6}$$

The calculation of E_a and E_i requires estimation of $\rho(d)$ from which ρ_0 and d_0 are derived. The function $\rho(d)$ requires the following steps:

1. the correlation between monthly rainfall for a selected duration at the i^{th} and j^{th} stations (ρ_{ij}) is calculated;
2. ρ_{ij} is classified based on distance between stations;
3. the average distance and average correlation are calculated for each class;
4. this correlation average is plotted against the average distance and an exponential function is fitted to this curve as follows:

$$\rho = \alpha \times e^{-\beta d} \tag{7}$$

where α is ρ_0 and β corresponds to the opposite of d_0 (James, 1983; James and Sreedharan, 1986).

3. Results and Discussion

Kagan's point-to-area method computes errors in the estimates of the areal mean of climatological variables like precipitation. Using this approach, the correlations were classified based on distance. In Table 2 shows the results of this classification for each region. This table gives the average distance, the number of stations within each interval, and mean correlation for different class intervals. Average correlations were plotted against mean distances in Fig. 2 for all regions. These processes were evaluated using Microsoft Excel 2003 software. The exponential functions were fitted to each curve using the least square error method. The value of ρ_0 can be obtained from the intercept of the ordinate. The value of the correlation radius was calculated using Eq. (1) and d_0 and ρ_0 and the relevant errors were determined in Table 3.

R^2 varied between 0.84 and 0.94; Hajiabad had the minimum value at d_0 = 125 km and Bandar Lengeh had the maximum at d_0 = 588 km. Spatial variation for rainfall in Hajiabad was greater than for other regions. This implied that the minimum d_0 was in this region. Bandar Lengeh has the most arid climate in the province and the variation of precipitation in this region was the least, as is indicated by the calculated d_0. The number of stations necessary to attain usable E_a and E_i errors were calculated for all regions (Table 4). The rain gage density required to achieve a specific error was at a minimum in Minab and maximum in Bandar

Lengeh. Variations of E_a were plotted against the number of stations for each region. Fig. 3 gives the relative error of mean areal rainfall and the relative RMSE calculated using Eq. (4). The relative error of spatial interpolation for regular triangular grids is given in Fig. 4.

The relative error of spatial interpolation is a more stringent error criterion and forms the basis of the design (Sreedharan and James, 1983). The error of mean areal rainfall over the region is used mainly in the design of networks where daily rainfall data are considered. Fig. 4 shows that interpolation errors (E_i) were extensive for all regions, and calculating usage errors was not possible, even when the number of stations increased. The climate of Hormozgan justified this consequence, because its precipitation is usually in the form of showers and interpolation was actually impossible. The reasons for this are:

● Monsoons dominate the eastern regions of this province in the spring and summer, but are absent in other portions of the province.
● The mountains in the province are in the east (Bashagard) and north (Hajiabad) and influence the amount and distribution of rainfall.
● Meteorological research on Hormozgan showed that the dominant system in autumn and winter is often a weak Sudan system.
● The position of the rain gage networks to obtain average usage errors were calculated and located with Excel and Arc GIS ver. 9.2 software.
● The primary position for the arrangement was the meteorological synoptic station in each region. The arrangement of these networks are shown in Fig. 5.

To save installation and maintenance costs, precision criteria were determined by the meteorological organization; in the arid and semiarid climate of this province, networks with 20% average error were selected.

Table 2. Number of stations (NOS), mean distance (MD) and corresponding mean correlation (MC) for each region in Hormozgan province

	Bandarlengeh			Bandarabbas			Hajiabad			Minab		
Distance Class (Km)	NOS	MD (Km)	MC	NOS	MD (Km)	MC	NOS	MD (Km)	MC	NOS	MD (Km)	MC
0-10	12	7	0.90	2	7.1	0.75	1	6	0.83	4	6.6	0.70
10-20	32	15	0.82	20	14.8	0.79	1	19	0.88	9	16.5	0.67
20-30	21	25	0.80	25	25.1	0.71	6	25	0.85	19	24.9	0.69
30-40	30	35	0.78	27	33.8	0.68	5	33	0.73	16	34.5	0.59
40-50	30	44	0.76	29	44.0	0.6	3	45	0.69	17	46.7	0.65
50-60	40	54	0.77	38	54.2	0.60	4	56	0.61	19	55.1	0.60
60-70	28	64	0.70	23	65.2	0.57	6	63	0.62	11	65.4	0.61
70-80	24	75	0.69	34	74.9	0.49	4	86	0.51	22	75.8	0.52
80-90	26	83	0.69	13	84.8	0.51	2	92	0.49	9	84.5	0.44
90-100	18	95	0.75	20	94.6	0.51	3	107	0.58	14	94.7	0.46
100-110	21	105	0.69	13	103.5	0.51	1	110	0.28	13	104.6	0.40
110-120	20	115	0.68	11	114.0	0.48	6	125	0.38	7	114.9	0.40
120<	151	165	0.65	16	148.7	0.31	1	6	0.83	10	125.9	0.41

Table 3. Correlation corresponding to zero distance (ρ_0), zero distance (d_o)and R^2 amounts for each region

Station	Bandarlengeh	Hajiabad	Bandarabbas	Minab
ρ_0	0.838	0.952	0.945	0.766
d_o (km)	588	125	149	189
R^2	0.908	0.842	0.940	0.897

Table 4. Number of station for attainment usage average errors (E_a) and usage interpolation errors (E_i), and distance between the nearest stations in triangular network (R) correspond to these errors

	Bandarlengeh			Bandarabbas			Hajiabad			Minab		
Percent error	E_a	E_i*	R(km)	E_a	E_i*	R(km)	E_a	E_i*	R(km)	E_a	E_i*	R(km)
30	10	inf	42	15	inf	34	6	inf	42	15	inf	24
25	15	inf	34	20	inf	30	9	inf	36	20	inf	21
20	23	inf	28	30	inf	24	12	inf	30	30	inf	17
15	40	inf	21	50	inf	19	20	inf	23	55	inf	12

* inf stands for infinite

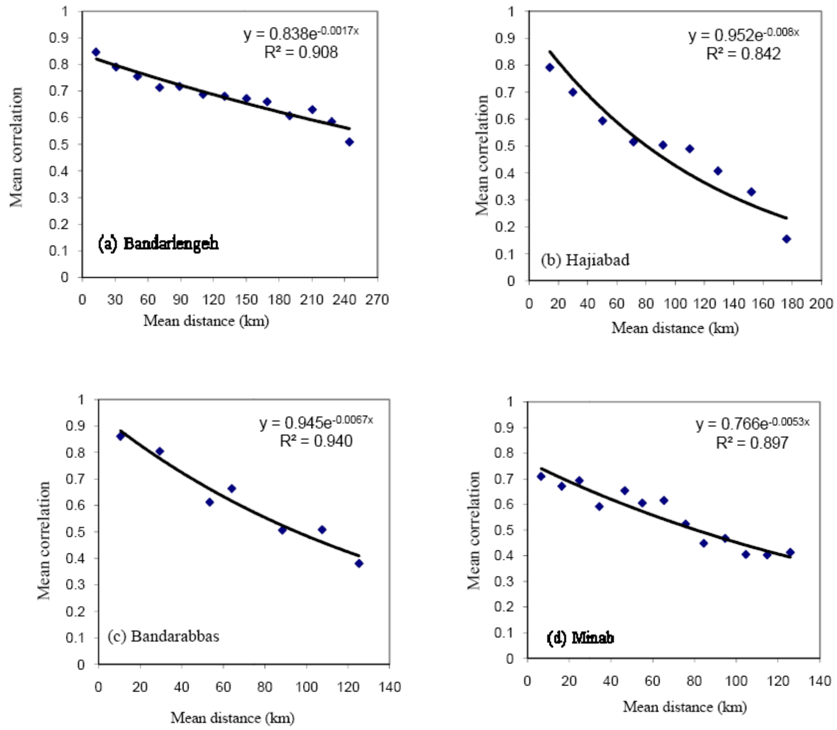

Fig. 2. Relationship between distance and correlation for each region in Hormozgan province

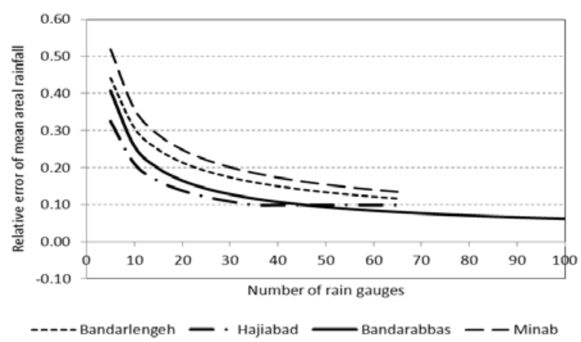

Fig. 3. Number of station against relative error of average areal rainfall (E_a) for each region

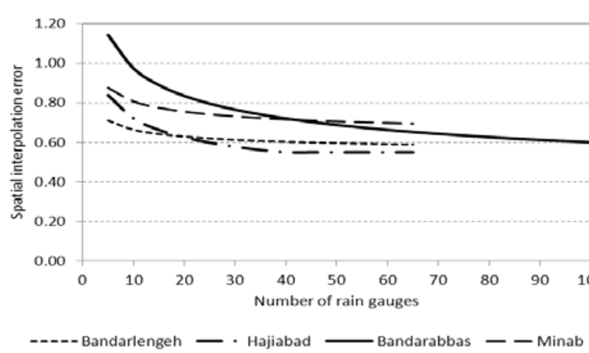

Fig. 4. Number of station against interpolation errors (E_i) for each region

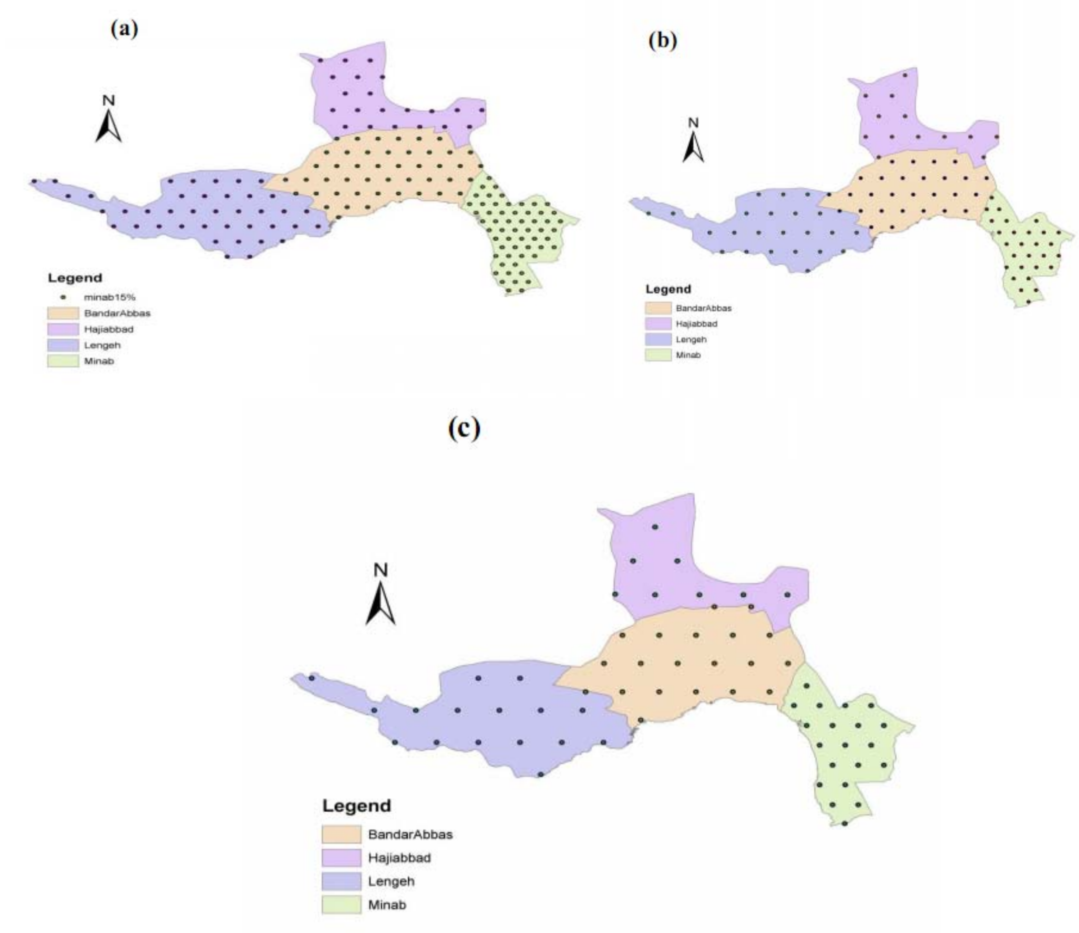

Fig. 5. Schematic map of rain gage location in triangular network in each region by Kagan's method. (a): correspond to 15 percent average error, (b): correspond to 20 percent average error, (c): correspond to 25 percent average error

4. Conclusion

Rainfall is the most basic data required for any water resource study. The estimation of the number and location of rain gauge stations needed to provide adequate information regarding rainfall over a catchment is referred to as network design. This study designed an optimum rain gauge network for Hormozgan province in Iran. The results show that selecting 20% measurement average error decreased the number of rain gauges required in all regions except Bandar Abbas. On average, the percentage of decrease was about 31%. This indicates that a more regular arrangement of rain gauge would allow the whole area to be covered, which would result in no area being without reliable data.

Because of the existence of several rainfall regimes in the province, the scale distance for the arrangement between these stations differed markedly. It was shown here that the interpolation of rainfall data at a given point is not possible with acceptable estimation. Since the arrangements are only based on observed data, it is suggested that additional research that includes environmental, economic, urban and rural development factors should be undertaken for provide the most effective result. Because of the unrealistic locations for the suggested stations, it is strongly recommended, based on the precedence of the regions, that the networks be arranged in several stages and that their efficiency over long periods should be analyzed. An optimal network design provides climatological data samples that are the best representatives of all unique rainfall characteristics over a region. A network of rain gauges can be established in the province based on the results of the present study after defining the level of accuracy required by the users.

References

Bastin, G., B. Lorent, C. Duque and M. Gevers, 1984. Optimal estimation of the average areal rainfall and optimal selection of raingauge locations. Water Resour. Res., 20: 463-470.

Bogardi, I. and A. Bardossy, 1985. Multicriterion network design using geostatistics. Water Resour. Res., 21: 199-208.

Bras, R.F. and I. Rodriguez-Iturbe, 1976. Network design for the estimation of areal mean rainfall events. Water Resour. Res., 12: 1185-1195.

Buishand, T.A., 1986. Sensitivity of measures of precipitation network performance to certain assumptions about inter station correlation and to network density. Integrated Design of Hydrological Networks, IAHS Publ., 158: 23-33.

Corradini, C., 1985. Analysis of the effects of orography on surface rainfall by a parameterized numerical model. Journal of Hydrology, 77: 19-30.

Danard, M., 1971. A simple method of computing the variation of annual precipitation over mountainous terrain. Boundary-Layer Meteorol., 2: 188-206.

Fontaine, T.A., 1991. Predicting measurement error of areal mean precipitation during extreme events, Water Resour. Bul., 27(3): 509-520.

Hughes, J.P. and D.P. Lettenmaier, 1981. Data requirements for kriging: estimation and network design. Water Resour. Res., 17: 1641-1650.

Hutchinson, P., 1970. A contribution to the problem of spacing rain gauges in rugged terrain. Journal of Hydrology, 12: 1-14.

James, E.J., 1983. Towards the Establishment of a hydro meteorological data bank for surface water studies at CWRDM, Scientific Methods of Collection and Documentation of Hydro meteorological Data. CWRDM Publ, Kozhikode, India, pp. 29-35.

James, E.J. and K.E. Sreedharan, 1986. Design of rain gauge network using spatial correlation for the Bharathapuzha basin on the Malabar Coast of India. Integrated Design of Hydrological Networks, IAHS Publ. 158: 49-55.

Journel, A.G. and Ch.J. Huijbregts, 1978. Mining geostatistics. Academic Press, New York.

Kagan, R.L., 1972. Planning the spatial distribution of hydrometeorological stations to meet an error criterion. In: Casebook on Hydrological Network Design Practice, III-1.2. WMO Publ. No. 324.

Karasseff, I.F., 1986. Principles of specifications of optimum networks of hydrologie observation sites, Integrated Design of Hydrological Networks, IAHS Publ. No.158, pp. 3-10.

Merva, G.E., N.D. Strommen and E.H. Kidder, 1971. Rainfall variation as influenced by wind speed and topography. In American Society of Agricultural Engineers, Winter Meeting, pp. 71-727.

Nandagiri, L. and G. Kovoor, 2006. Performance Evaluation of reference evapotranspiration equations across a range of Indian climates. J. Irrig. and Drain. Eng., 132 (3): 238-249.

Oki, T., K. Musiake and T. Koike, 1991. Spatial rainfall distribution at a storm event in mountainous regions, estimated by orography and wind direction. War. Resour. Res., 27: 359-369.

Osborn, H.B., 1984. Estimating precipitation in mountainous regions. J. Hydrol. Eng. ASCE, 110: 1859-63.

Peck, E.L., 1972. Distribution of precipitation in mountainous areas. In WHO Geilo Symposium, Norway. Vol. 2: 234-242.

Peters-Lidard, C.D., 1998. Raingauge network design for the Catskill Mountains. Georgia Institute of Technology, 114 p.

Puvaneswaran, K.M. and P.A. Smithson, 1991. Precipitation-elevation relationship over Sri Lanka. Theor. Appl. Climatol., 43: 113-122.

Rodriguez-Iturbe, I. and J.K. Mejia, 1974. The design of rainfall networks in time and space. Water Resour. Res., 10(4): 713-728.

Rouhani, S., 1985. Variance reduction analysis. Water Resour. Res., 21: 837-846.

Sevruk, B., 1974. The use of stereo, horizontal, and ground level orifice gauges to determine a rainfall-elevation relationship. Wat. Resour. Res., 10: 1138-1141.

Shaw, E.M. and P.E. O'Connell, 1976. Design of network and data transfer for precipitation. Hydrological Networks and Methods, WMO Publ., 433: 129-135.

Sreedharan, K.E. and E.J. James, 1983. Design of rain gauge network for the Chaliyar River basin. J. Instn. Eng., 64: 170-174.

Stol, P.T., 1972. The relative efficiency of the density of rain gauge networks. Journal of Hydrology. 15: 193-208.

St-Hilaire, A., T.B.M.J. Ouarda, M. Lachance, B. Bob´ee, J. Gaudet and C. Gignac, 2003. Assessment of the impact of meteorological network density on the estimation of basin precipitation and runoff: a case study. Hydrol. Process. 17: 3561-3580.

Wei, C., J.L. Chiang, T.H. Wey, H.C. Yeh and Y.C. Cheng, 2010. Rain gauges network design using discrete entropy and kriging approach. Geophys. Res. Abstr, Vol. 12.