

Spatial Rainfall Distribution and Network Analysis by Geostatistical Method

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ABSTRACT Rainfall is an important variable used in estimating irrigation water demand. In this paper, geostatistical method based on the minimum unbiased estimation is used to estimate the monthly spatial rainfall distribution in a large scale irrigation system of the Phitsanulok Irrigation Project and shown to be more accurate and reliable than the estimates by the traditional deterministic method viz, the arithmetic mean, Thiessen polygon and isohyetal methods. The mean and standard deviation of the monthly rainfall estimation errors for the geostatistical method are found to be 5.3 mm and 3.4 mm respectively, which are much less than the corresponding figures of 18.4 mm and 13.1 mm for the arithmetic average method, which in turn is found to perform slightly better than the Thiessen polygon and isohyetal methods.

Geostatistic is of particular interested in network design because the accuracy of prediction can be plotted as contour maps of variance, the error reduction of estimation gained by addition of fictitious station in region of high variance. Finally this paper show how the geostatistical estimation method can be used to solve the measurement network problem.

1. Introduction

Planning, design and management of irrigation systems, especially the large ones, require reliable measurements or estimation of rainfall and its distribution with respect to time and space.

Rainfall is an important variable used in estimating irrigation water demand. In practice, rainfall data at a limited number of nearby rainfall station are analyzed to compute the irrigation water demand in the entire irrigation project area. The spatial averaging of rainfall is usually based on simple deterministic methods such as the arithmetic average, Thiessen polygon and isohyetal methods. These methods various uncertainties involved, which may adversely affect irrigation management decisions. Geostatistic and its estimation technique (i.e. kriging) offers a pragmatic stochastic approach for considering these uncertainties, particularly the inherent uncertainty in spatial variables due to randomness and spatial variability (ASCE, 1990a; ASCE, 1990b).

Basic concepts of geostatistic are well-documented (Journel and Huijbregts, 1978; ASCE, 1990a; ASCE, 1990b). Geostatistic provides statistical tools for (a) calculating accurate predictions, based on measurements and other relevant information; (b) qualifying the accuracy of these predictions, and (c) selecting the parameters to be measured, and where and when to measure them. Geostatistic has been applied to a number of problems in water resources such as analyze the observation network (Villeneuve et al, 1979; Bastin et al, 1984;

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Gallichard et al, 1992) and estimate the mean aerial precipitation (Chua and Bras, 1982; Tabios and Salas, 1985; ASCE, 1990b).

The purpose of this paper is to highlight the importance of accurate spatial analysis of rainfall on the planning level and investigate the present situation of observation network of large-scale irrigation systems.

2. Overview of Geostatistical Interpolation

The basic goal of geostatistical methods such as kriging is to interpolate the values for points or areas which have not been sampled, using data from surrounding sampled points to be used in order to compute an interpolated value of the variable of interest (e.g. precipitation). Simple interpolation schemes may assign equal weights to each supporting data point, or they may assign weights inversely proportional to the distance to the estimation point. The first of these methods does not take into account the spatial proximity of the neighboring points in interpolating a value for the estimation point. The second does, but assumes a particular relationship (inverse) between the weight and the distance. Thus, the weights are not necessarily optimal. Kriging is interpolation method which attempt to optimize the weights assigned to the neighboring data points in computing the interpolated value.

Kriging consists of three steps: (1) an examination of the covariation of data values depending on their distances apart; (2) fitting theoretical models to these relationship; and (3) using these models to calculate the weights for a particular set of neighboring points and computing the interpolated value. The first step is referred to as constructing a sample (experimental) semivariogram. All possible pairs of data points are examined, the pairs are grouped by distance classes, and one half the variance of the difference in values (the semivariogram) is graphed vs. the distance class. Second, a theoretical curve (model semivariogram) is fit to these points either by eye, by least-squares regression, or preferably by optimizing the model through cross-validation procedures. Lastly, this model determines the weights to be used for each neighboring point to compute the interpolated values.

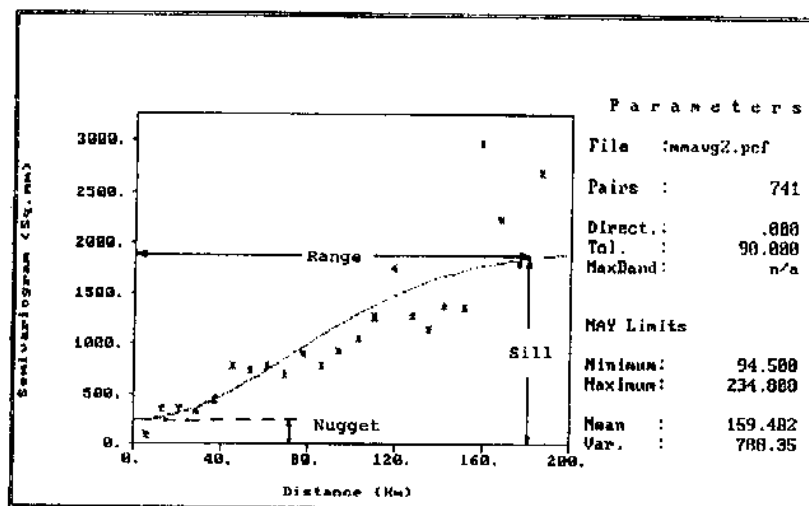


Figure 1 Example semivariogram of rainfall for May.

A common form of the theoretical semivariogram model is defined by the nugget variance (the variance at zero distance), the sill (the variance to which the semivariogram asymptotically rise), and the range (the distance at which the sill or some predetermined fraction of the sill is reached). (See Fig. 1 for an example semivariogram).

In its simplest form, kriging assumed that there is no 'trend' or 'drift' in the data, i.e. no consistent, directional gradient in the variable(s). This assumption can be used if the range distance of the model is smaller than the distance over which the trend is apparent (the neighborhood of points used in interpolation is smaller than the distance over which the trend is apparent). A related concept is isotropy, the condition under which the semivariance is the same for a given distance, regardless of direction (Phillips et al, 1992).

The advantage of geostatistical method over the traditional method is its capability to produce the contour map of estimated standard deviation. The usefulness of this maps of contour standard deviation is to show how much the estimation could be improved when the additional station are added to the network. Hence the optimal number of station can be obtained if the error will not decrease with additional stations.

3. Analysis, Results, and Discussion

This section presents the results obtained in the Phitsanulok Irrigation Project, located in the northern part of Thailand's Central Plain (Fig. 2). The total project are of 107,200 ha on both banks of the Nan river is divided into four sub-projects viz., Naresuan (15,200 ha), Phlai Chumphon (35,000 ha), Dong Setthi (30,000 ha) and Thabua (27,000 ha). The climate of the project area is subtropical with marked difference between the wet (May to October) and the dry (November to April) seasons. At present, a total number of 39 rainfall stations exist in the area (Fig. 2). For all these stations, monthly rainfall data from 20 years (1970-1989) of records were utilized in the geostatistical analysis. All the variogram and kriging analysis were done using GEO-EAS, which is a public domain micro-computer software developed by the U.S. Environmental Protection Agency (Englund and Sparks, 1988). The detail are provided in Phattaporn (1992).

Semivariogram Fitting

Let $Z(x)$ and $Z(x+h)$ are random variables at particular points x and $(x+h)$ of a random field respectively. The intrinsic hypothesis assumes that for a random variable $Z(x)$: (1) the mathematical expectation, $E[Z(x)]$, does not depend on the position x and (2) the variance of each pair, $[Z(x), Z(x+h)]$, does not depend on the position x for any separation vector h . Then the semivariogram gives a measure of the spatial correlation of a random variable or variables as a function of separation distance.

Semivariogram (γ) of an intrinsic random function is defined as:

$$\gamma(h) = \frac{1}{2} \text{Var}[(Z(x+h) - Z(x))] \quad (1)$$

This may also be written as:

$$\gamma(h) = \frac{1}{2} E[(Z(x+h) - Z(x))^2] \quad (2)$$

The isotropic experimental semivariograms of study area are constructed using lag distance = 8.217 kilometers and fitted by three standard models(i.e. spherical, gaussian, and exponential). Among these standard model types, the gaussian type model was found to yield the least errors of estimation as shown in Table 1, and therefore, was selected for kriging.

Cross-validation procedures for the analysis of errors for conditional bias, heteroscedasticity, and spatial trend did not indicate any significant flaw in the selected model (Englund and Sparks, 1988; Phattaporn, 1992)

Table 1 Comparison of monthly aerial rainfall and kriging standard deviation estimated by difference models.

Model	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Spherical												
Nugget (Sq.mm)	50	140	350	550	400	1,000	180	40	0	6	13	70
Sill (Sq.mm)	340	780	1,580	1,250	2,400	2,100	370	102	40	10	38	270
Range (Km)	80	80	90	75	110	100	50	50	200	80	50	50
Rainfall (mm)	43.1	159.6	141.5	150.6	194.4	208.6	130.9	25.5	1.8	3.2	7.4	35.0
Ksd. (mm)	6.4	9.8	13.7	13.2	15.3	15.6	8.2	4.3	1.2	1.2	2.6	7.0
Gaussian												
Nugget (Sq.mm)	50	240	700	700	800	1,300	150	55	2	7	15	100
Sill (Sq.mm)	390	1,940	3,100	1,500	2,900	2,500	420	105	42	12	40	250
Range (Km)	85	180	200	120	130	150	50	50	180	80	50	50
Rainfall (mm)	44.2	157.6	145.5	152.9	199.0	212.3	130.5	25.9	2.3	3.3	7.5	34.2
Ksd. (mm)	3.3	5.3	7.9	8.5	9.8	10.4	6.4	3.4	0.5	0.9	2.0	5.1
Exponential												
Nugget (Sq.mm)	0	30	500	600	600	1,000	100	40	0	7	10	70
Sill (Sq.mm)	340	2,030	2,300	1,400	3,000	2,000	420	100	45	10	37	250
Range (Km)	85	300	200	120	200	100	50	50	300	80	50	50
Rainfall (mm)	41.1	160.8	141.8	150.8	195.2	207.7	129.5	25.7	1.8	3.3	7.3	35.0
Ksd. (mm)	7.3	10.2	15.7	14.5	17.8	18.0	10.5	5.0	1.4	1.2	3.1	8.1

Kriging Procedure

Kriging is a best linear unbiased estimator (BLUE) of the estimation problem solution. Briefly this means that.

1) Kriging is a linear estimator. Thus, the optimal estimate $Z^*(x_0)$ of the value $Z(x_0)$ can be written as a linear combination of the n measured values:

$$Z^*(x_0) = \sum_{i=1}^n w_i Z(x_i) \quad (3)$$

where w_i = weight of the measured value Z at location x_i .

2) By "best" estimator means that the weight in eqn. (3) are determined by minimizing the estimation variance.

$$\min. \text{Var}[Z^*(x_0) - Z(x_0)] \quad (4)$$

3) Kriging is unbiased estimator. This means that:

$$E[Z^*(x_0) - Z(x_0)] = 0 \quad (5)$$

This yields the kriging system of equations (Kettunen and Varis; 1990, Phattaporn; 1992, ASCE B, 1991)

$$\sum_{i=1}^n w_i \gamma(x_i - x_j) + \mu = \gamma(x_i - x_0) \quad (6)$$

where $\gamma(x_i - x_j)$ = average semivariogram of point i and j ,

μ = lagrange multiplier,

and the variance of this estimation is given by

$$\sigma^2 = - \sum_{i=1}^n \sum_{j=1}^n w_i w_j \gamma(x_i + x_j) + 2 \sum_{i=1}^n w_i \gamma(x_i - x_0) \quad (7)$$

The program 'krige' in Geo-Eas package produces the interpolated value and error (kriging standard deviation) over the regular grid using the weights obtained from eqn. 6 and measured value from selected neighborhood stations. In this study, the regular grid 5x5 km. and eight nearest stations in the range distance are selected.

Since each kriged and standard deviation represent average values over a block. The mean aerial rainfall and the mean standard deviation obtained from kriging for the total area are simply the arithmetic averages of corresponding kriged values for all the blocks.

3.1 Suitable method for spatial estimation of rainfall

In order to identify the suitable method for spatial interpolation, the mean monthly estimation error and standard deviation are used as the indicators. For the arithmetic mean, Thiessen polygon and isohyetal methods, estimation error is given by the standard error as defined in eqn. (8) below.

$$\sigma = \left[\frac{1}{n} \sum_{i=1}^n (P_i - \bar{P})^2 \right]^{1/2} \quad (8)$$

where P_i = monthly rainfall at station i ;
 \bar{P} = monthly average rainfall; and
 n = number of stations.

Table 2 Estimation of monthly rainfall and associated errors (mm) by different methods

Method	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Total Annual Rainfall	Est. Error	
														Mean	SD
Geostatistics															
Aerial Precipitation	44.2	157.6	145.5	152.9	199.0	212.3	130.5	25.9	2.3	3.3	7.5	34.2	1,115.2		
Standard Deviation	3.3	5.3	7.9	8.5	9.8	10.4	6.4	3.4	0.5	0.9	2.0	5.1		5.3	3.4
Arithmetic Mean															
Aerial Precipitation	41.4	160.1	135.9	147.4	197.3	194.9	134.2	24.0	1.8	2.3	5.3	36.2	1,080.8		
Standard Deviation	10.4	19.5	31.2	26.2	39.4	38.1	17.8	9.9	2.1	3.1	4.8	18.4		18.4	13.1
Difference	2.8	-2.5	9.6	5.5	1.7	17.4	-3.7	1.9	0.5	1.0	2.2	-2.0			
% Difference	6.3	1.6	6.6	3.6	0.9	8.2	2.8	7.3	21.7	30.3	29.3	5.8			
Thiessen Polygon															
Aerial Precipitation	40.3	161.5	131.3	141.0	186.3	188.0	127.7	23.5	1.5	2.2	6.2	38.7	1,048.2		
Standard Deviation	10.6	21.9	34.4	29.6	43.6	37.7	19.3	9.4	2.1	3.4	5.5	18.4		19.6	14.1
Difference	3.9	-3.9	14.2	11.9	12.7	24.3	2.8	2.4	0.8	1.1	1.3	-4.5			
% Difference	8.8	2.5	9.8	7.8	6.4	11.4	2.1	9.3	34.8	33.3	17.3	13.2			
Isohyetal															
Aerial Precipitation	41.1	161.5	135.3	144.7	189.3	194.7	129.0	24.3	1.7	2.4	6.9	36.1	1,067.0		
Standard Deviation	10.4	19.6	31.2	26.4	40.2	38.1	18.5	9.9	2.1	3.1	5.0	18.4		18.6	13.2
Difference	3.1	-3.9	10.2	8.2	9.7	17.6	1.5	1.6	0.6	0.9	0.6	-1.9			
% Difference	7.0	2.5	7.0	5.4	4.9	8.3	1.1	6.2	26.1	27.3	8.0	5.6			

Table 3 Monthly rainfall and standard deviation (mm) of sub-projects estimated by Geostatistical Method.

Month	Phlai Chumphon		Dong Setthi		Thabua		Average	
	mean	SD	mean	SD	mean	SD	mean	SD
April	45.3	3.3	41.9	3.3	43.6	3.2	43.6	3.3
May	168.3	5.2	151.6	5.3	147.0	5.3	155.6	5.3
June	161.5	7.9	133.7	7.9	128.1	7.9	141.1	7.9
July	164.9	8.3	144.7	8.5	140.4	8.6	150.0	8.5
August	225.9	9.6	184.3	9.8	173.8	9.8	194.7	9.8
September	214.7	10.4	208.1	10.4	207.6	10.4	210.1	10.4
October	144.4	6.4	122.4	6.4	122.5	6.3	129.8	6.4
November	30.5	3.4	22.7	3.4	22.6	3.4	25.3	3.4
December	2.6	0.5	2.0	0.5	1.9	0.5	2.1	0.5
January	3.5	0.9	2.8	0.9	3.6	0.9	3.3	0.9
February	7.9	2.0	6.2	2.0	7.4	2.0	7.2	2.0
March	26.9	5.1	41.4	5.1	39.3	5.0	35.9	5.1
Total/Average	1,196.4	5.3	1,061.8	5.3	1,037.8	5.3	1,098.7	5.3

Table 2 compares the mean estimation error and its standard deviation along with the annual aerial precipitation for the total project area (including Naresuan) estimated by various methods. It is clear that the geostatistical method gives the most accurate and reliable results because both the mean and the standard deviation of the monthly rainfall estimation errors are minimum. It is observed that although the aggregated annual rainfall values estimated by the deterministic methods are within 6% of that estimated by kriging, many monthly values are underestimated by more than 10%. It is interesting to note that the arithmetic mean method performs slightly better than the Thiessen polygon and isohyetal methods. Table 3 provides the kriged values of monthly rainfall and standard deviation for each sub-project area (excluding Naresuan).

3.2 Monthly Irrigation Water Requirements

In order to study the impact of accurate spatial estimation of rainfall on the irrigation water demand, monthly irrigation requirements of the Phitsanulok Irrigation Project (excluding Naresuan sub-project) estimated using the mean aerial rainfall values obtained from the geostatistical method and the arithmetic mean method as described previously, and using the values under various project studies carried out in the past were compared. The monthly irrigation requirements per hectare was calculated using eqn. (9) as follows:

$$IR = \frac{f}{PE} [ET - RE + WM] \quad (9)$$

where IR = project irrigation requirements (m^3 /period);
 PE = overall project efficiency (-);
 ET = total crop evapotranspiration (mm);
 RE = effective rainfall (mm);
 WM = miscellaneous water requirements, if any (mm); and
 f = conversion factor (= 10) from mm/ha to m^3 .

Irrigation water demand was computed for several cases based on different criteria of estimating effective rainfall and overall project efficiencies as adopted by the previous studies. These studies were: (1) Appraisal of the Phitsanulok Irrigation Project by IBRD (1975); (2)

Chao Phraya-Meklong Basin Study Preliminary Phase Report by ACRES (1977); (3) Chao Phraya-Meklong Basin Study Phase I Report by ACRES (1979); and (4) Phitsanulok Water Management Study by ACRES (1982). The consumptive use for various crops based on the experimental data from the Samchook Water Use Experiment Station and the cropping pattern adopted by IBRD (1975) was used for all the cases. Water for land preparation (185 mm for wet season and 210 mm for dry season) was considered as miscellaneous requirement for paddy but neglected for other crops.

The detailed calculations for different cases are presented by Phattaporn (1992). This paper presents only few selected results. Two cases are considered: (1) Case 1: Effective rainfall as 75% of the total monthly rainfall and overall project efficiency from April to October and from November to March as 0.28 and 0.525 respectively, as adopted by ACRES (1977); and (2) Case 2: Effective rainfall as a function of the total monthly rainfall and the season as given in Table 4, and efficiency of 0.3 from July to October, 0.45 from November to January, and 0.40 from February to June, as adopted by ACRES (1982).

Table 4 Monthly effective rainfall (mm) as per ACRES (1979)

Total monthly rainfall		0	25	50	100	150	200	300	400	500
Effective rainfall	Nov-Sep	0	25	50	80	93	100	120	120	120
	Oct	0	25	43	58	71	82	84	84	84

The basis for calculating mean monthly rainfalls under previous studies was slightly different. Rainfall A under the present study by the geostatistical method, as mentioned previously, utilizes 20 years of data (1970-1989) for 39 stations. Rainfall B utilizes arithmetic average values from the same data base as above. Rainfall C under IBRD (1975) represents arithmetic average for a number of stations in the project area during the period 1952-1968. Rainfall under ACRES (1977) represents arithmetic average of two stations, namely 38012 in Phichit Province and 39013 in Phitsanulok Province, during the period 1952-1975. Rainfall D under ACRES (1979) is similar to ACRES (1977) but with extended records for 1952-1977.

Table 5 presents the irrigated areas for various crops including their consumptive use and the monthly irrigation water requirements (in million cubic meters, MCM) for the previously mentioned two cases utilizing four different values of estimated rainfalls for the whole project area (excluding Naresuan sub-project). Irrigation demands are compared with reference to the values obtained using kriged rainfall under the present study. It is seen that although the arithmetic mean method estimates monthly rainfall within 10% of the kriged values during the wet season, monthly irrigation water demands are overestimated by significant margins. For case 1, the margins are much as 24% and 52% in August and September respectively while for case 2, the demand is overestimated by 30% in July. For the dry season, of course, the difference between the two methods is of less importance because the contribution of rainfall in estimating irrigation water demand is almost negligible.

Table 5 also shows how the effect of considerable overestimation of rainfalls under the previous studies by IBRD (1975) and ACRES (1979) is translated into the corresponding irrigation water demands terms. It is observed that the demands in some months, especially July, August and September, are grossly underestimated. The effect is more sensitive for case 1 compared to case 2 due to the combined effect that irrigation efficiency and effective rainfall have on irrigation water demand.

Table 5 Comparison of total project area monthly irrigation water requirements.

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Monthly Irrigated Area ('000ha.)													
Broadcast Rice					10	15	15	15	15	15	15		
Transplanted Rice	28.0	27.0				65.5							
	-	28.0	55.0	55.0	27.0		65.5	65.5	65.5	35.5			
All other Crops	24.5	13.0	13.0	13.0	14.5	14.5	14.5	14.5	14.5	5.5	5.5	24.	
Consumptive Use (mm)													
Broadcast Rice					160	160	160	160	180	190	180		
Transplanted Rice	210	210				185							
	-	200	200	200	200		190	190	180	180	190		
Other Crops	120	120	120	120	120	120	120	120	120	120	120	120	
Rainfall Data (mm)													
Rainfall A*	3.3	7.2	35.9	43.6	155.6	141.1	150.0	194.7	210.1	129.8	25.3	2.1	1,099
Rainfall B	2.0	5.2	41.4	39.8	157.6	128.4	142.0	183.5	194.9	130.8	22.4	1.6	1,050
Rainfall C	9	17	26	59	166	158	175	213	268	124	21	4	1,240
Rainfall D	7.6	18.6	30.5	56.3	185.1	175.2	198.6	275.7	297.8	143.9	22.4	3.4	1,415
Irrigation Water Requirements (MCM)													
Case 1 Effective Rainfall	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	
Overall Efficiency	0.525	0.525	0.525	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.525	0.525	
Irrigation Demand A	166	237	204	369	97	221	210	109	64	159	57	55	1,948
Irrigation Demand B	167	239	199	376	95	254	231	135	97	157	57	55	2,062
% Difference	-0.6	-0.8	2.5	-1.9	2.1	-14.9	-10.0	-23.9	-51.6	1.3	0.0	0.0	-5.9
Irrigation Demand C	161	228	214	341	85	179	153	71	0	168	58	55	1,713
% Difference	3.0	3.8	-4.9	7.6	12.4	19.0	27.1	34.9	100.0	-5.7	-1.8	0.0	12.1
Irrigation Demand D	162	226	210	346	67	141	102	0	0	138	57	55	1,504
% Difference	2.4	4.6	-2.9	6.2	30.9	36.2	51.4	100.0	100.0	13.2	0.0	0.0	22.8
Case 2 Effective Rainfall	Effective rainfall estimated from Table 3												
Overall Efficiency	0.45	0.40	0.40	0.40	0.40	0.40	0.30	0.30	0.30	0.30	0.45	0.45	
Irrigation Demand A	192	309	253	240	98	191	258	239	218	207	63	64	2,332
Irrigation Demand B	194	312	244	246	97	199	335	247	227	207	64	64	2,436
% Difference	-1.0	-1.0	3.6	-2.5	1.0	-4.2	-29.8	-3.3	-4.1	0.0	-1.6	0.0	-4.5
Irrigation Demand C	186	292	270	220	96	183	247	228	181	210	65	63	2,241
% Difference	3.1	5.5	-6.7	8.3	2.0	4.2	4.3	4.6	17.0	-1.4	-3.2	1.6	3.9
Irrigation Demand D	187	289	262	223	92	177	237	188	162	200	64	63	2,144
% Difference	-2.6	6.5	-3.6	7.1	6.1	7.3	8.1	21.3	25.7	3.4	-1.6	1.6	8.1

*Note: Rainfall A : Present Study(Reference); Rainfall B : Arithmetic Average(excluding Naresuan); Rainfall C : IBRD(1975); Rainfall D : ACRES(1979)

3.3 Network Analysis

The relative advantage of geostatistic to the traditional method is that the kriging standard deviation can be computed along with the kriging estimates of rainfall in each block. The kriging standard deviation can be plotted as contour maps for each month as example presented in Fig. 3. The shapes of the kriging standard deviation contour covers were conserved from one month to the next while the rainfall data changed. This consistency in the shape of the kriging standard deviation contour curves is an indication that the relative changed in kriging standard deviation do not depend on the absolute value of the rainfall, but rather on the station density.

To improve the aerial rainfall estimation, we should install the new additional station in the area of high standard deviation level. In order to illustrate this point we add the first additional station in poorly estimated region of month September and evaluated the reduction in kriging standard deviation, next we add the second station combined with the first one and observed the reduction in kriging standard deviation. This procedure can be continued, adding more stations and monitoring the decrease of kriging standard deviation of the estimation. After adding 5 stations as show in Fig. 4 we found that the kriging standard deviation almost no longer decrease, the result presented in table below.

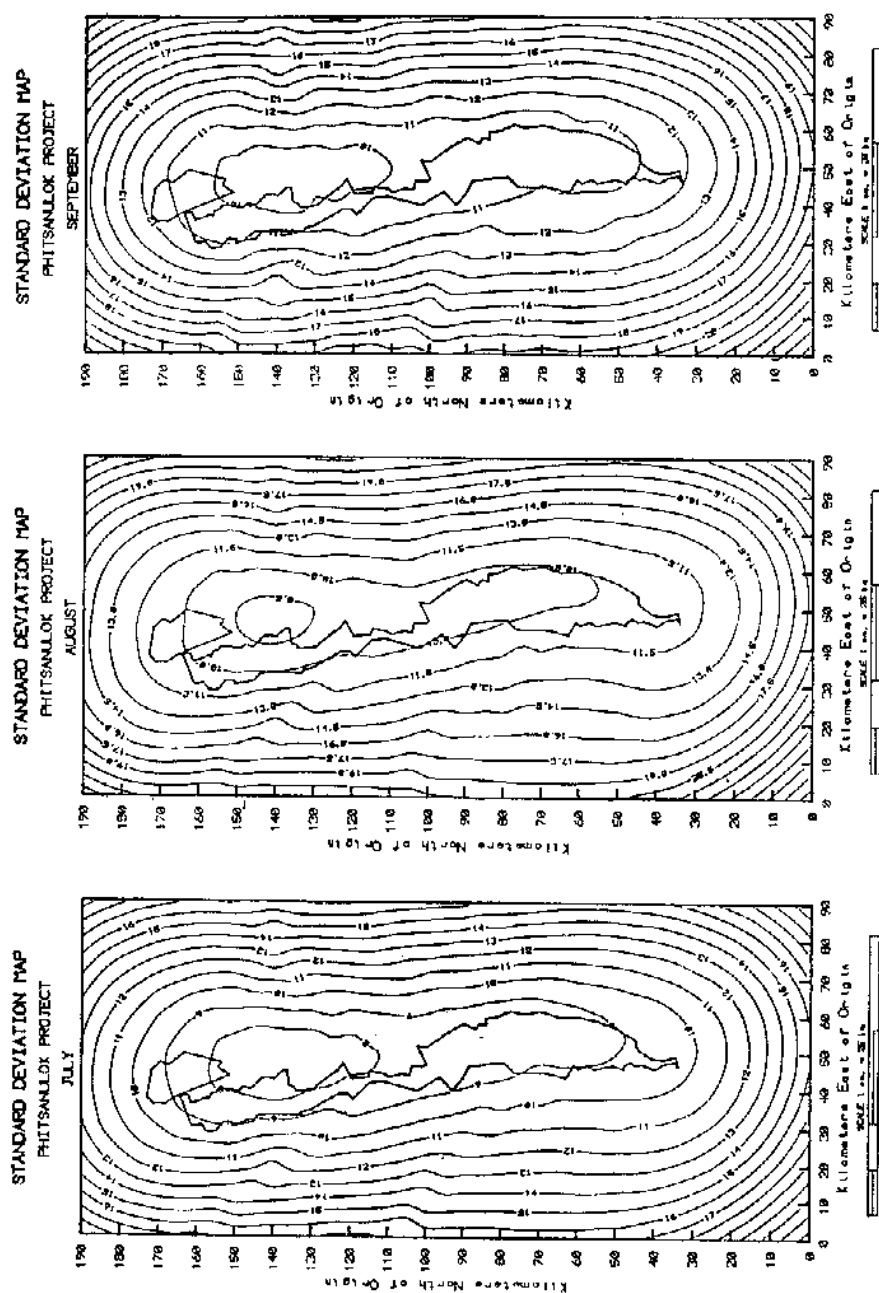


Figure 3 Example contour map of Kriging standard deviation for July-September.

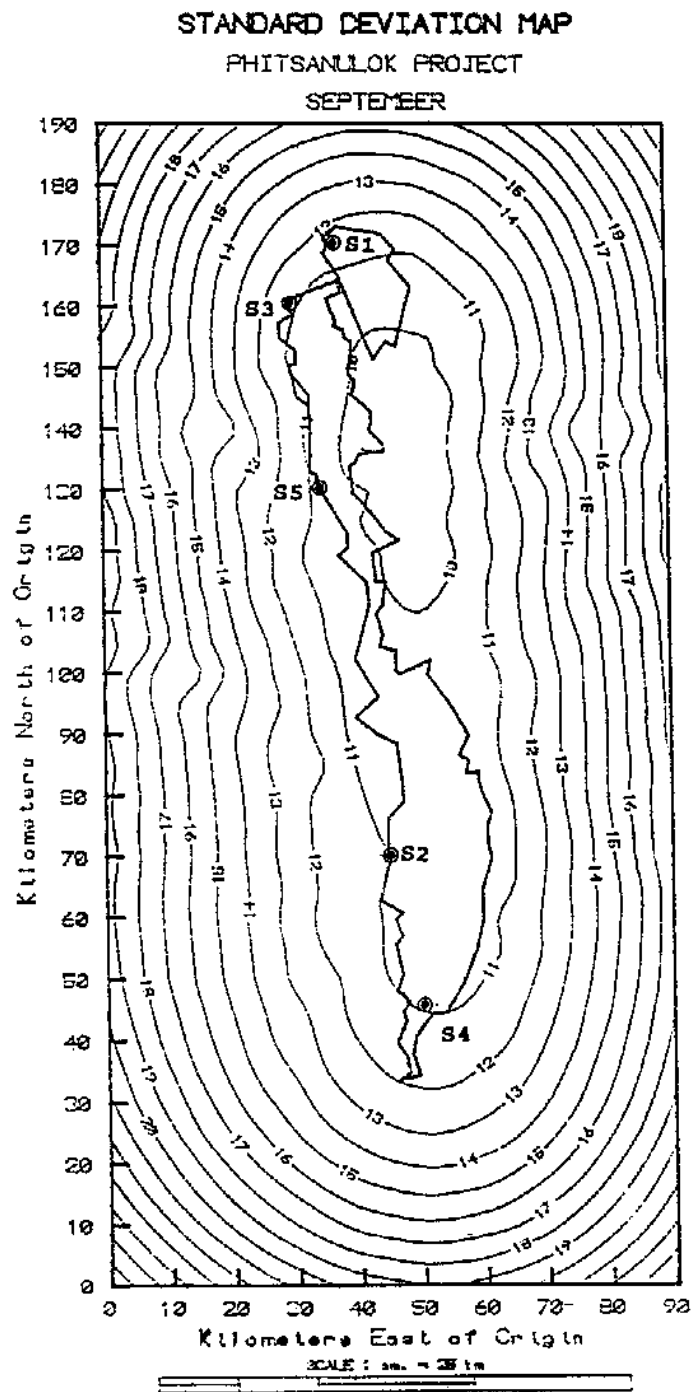
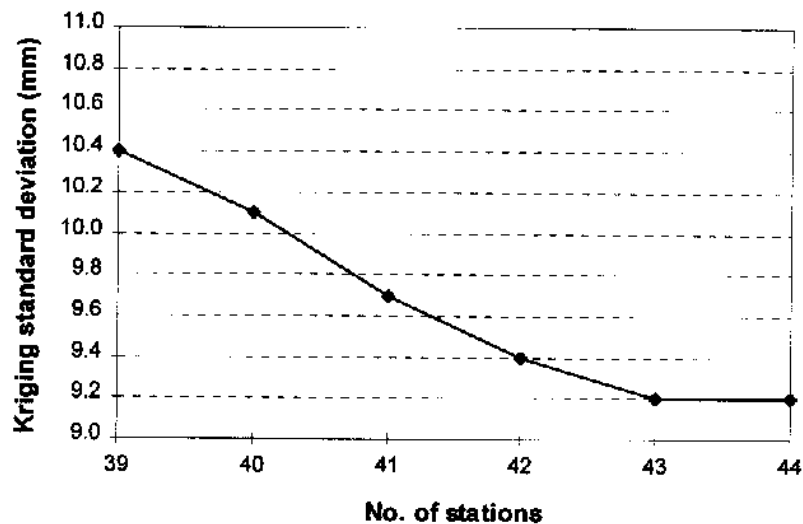


Figure 4 Location of additional stations.

Table 6 Kriging Standard Deviation (Ksd.) of estimation after adding the additional stations

No. of stations	39	40, s1	41, s2	42, s3	43, s4	44, s5
Ksd. of estimation	10.4	10.1	9.7	9.4	9.2	9.2

From the table above and Fig. 5, we notice that the first 3 additional stations (s1, s2, s3) give the significant decrease of kriging standard deviation for aerial rainfall estimation while the last 2 stations can not reduce this value. Therefore, if the new stations were to be established for improve the rainfall estimation, these three sites should be considered first.

**Figure 5** Relationship between number of stations and Kriging standard deviation.

4. CONCLUSIONS

The estimation of rainfall and its distribution with respect to time and space, is of considerable importance in the planning, design and management of irrigation systems, especially the large ones. Using geostatistic is a practical approach to compute accurate aerial estimates of rainfall based on point measurements and other information characterizing the rainfall variable. Unlike the deterministic approaches, the geostatistical approach also provides the accuracy of estimates. In this study, kriged estimates of monthly rainfalls in a large irrigation project area have been shown to be more accurate and reliable than the estimated by traditional methods viz. the arithmetic mean, Thiessen polygon and isohyetal methods. The Phitsanulok Irrigation Project in northern Thailand is considered as the case study. In the study, the mean and standard deviation of the monthly rainfall estimation errors for the geostatistical method are found to be the minimum at 5.3 mm and 3.4 mm respectively. The corresponding figures for the arithmetic method, which performs slightly better than the Thiessen polygon and isohyetal methods, are 18.4 mm and 13.1 mm respectively.

During the wet season, aerial monthly rainfalls using the arithmetic mean method are underestimated within 10% of the kriged values; however, the irrigation water demands are overestimated significantly higher. The overestimation is as much as 52% in some months

depending upon the irrigated cropped area, consumptive use of various crops, overall irrigation efficiency and effective rainfall.

The case study example also illustrates how the geostatistic can be used for selecting the optimum number of stations in study area for improving the accuracy of rainfall estimation.

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