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RAINFALL NETWORK OPTIMIZATION IN JOHOR

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Abstract. This paper presents a method for establishing an optimal network design of rain gauge station for the estimation of areal rainfall in Johor. The main problem in this study is minimizing an objective function to determine the optimal number and location for the rain gauge stations. The well-known geostatistics method (variance-reduction method) is used in combination with simulated annealing as an algorithm of optimization. Rainfall data during monsoon season (November – February) for 1975 – 2008 from existing 84 rain gauge stations covering all Johor were used in this study. Result shows that the combination of geostatistics method with simulated annealing successfully managed to determine the optimal number and location of rain gauge station.

Keywords Rainfall network; geostatistics; simulated annealing

1.0 INTRODUCTION

Situated in Southeast Asia, Malaysia is consisted of Peninsular Malaysia, Sabah and Sarawak. The Peninsular Malaysia lies in between of Thailand and Indonesia, while Sabah and Sarawak lies in the Borneo Island. Malaysia is located near the equator where it receives higher concentration of solar energy since the sun rays strikes almost on all year round. It is also surrounded by the sea and the air is moist and is usually covered with clouds.

Every year, Malaysian experiences two types of monsoon, the Northeast Monsoon (wet) and Southwest Monsoon (dry). The Northeast Monsoon started from early November to March, originating from China and the north Pacific, brings heavy rainfall to the east coast states of the Peninsular Malaysia. The Southwest Monsoon (from the deserts of Australia) from late of May and ends in September, and is dried period for the whole country. However, there is also a period that happens in between of both monsoon (April – October) and is known as the inter-monsoon. Due to the combination of these monsoon in equatorial regions with the pressure gradients and the maritime exposure has resulted to the frequent occurrence of floods. This is proven as of the 189 river system in Malaysia (89 in Peninsular Malaysia; 78 in Sabah and 22 in Sarawak) which flows directly to the sea, 85 of it are prone to frequent flooding (DID Manual, Vol.1, 2009).

In December 2006 and January 2007, the Northeast Monsoon had brings heavy rain through series of continuous extreme storms that caused a devastating floods in the northern region of Peninsular Malaysia particularly to Kota Tinggi, Johor without any sign of warning. The disaster had caused more than 100,00 people evacuated from the residents due to rising flood water. This situation has made the researchers become aware on the benefits of having effective and efficient rain gauge system. Such system will help on the prevention of occurring situation as it can predict flood and at the same time help on saving lives and property. The main contribution of this paper is the use of geostatistic integrated with simulated annealing to determine the number and location of rain gauge station in order to design an optimal rain gauge network in flood prediction.

2.0 PROBLEM STATEMENT

A hydrological network is an organized system for the collection of information of specific kinds of data such as precipitation, water quality, rain fall, stream flow and other climate parameters. The accuracy in the decision making in the water project design such as flood prediction depends on how much information is available for the area concerned. Having enough accurate hydrologic data reduces the possibility of overdesign and thus minimizes the economic losses. In order to define the optimum level of hydrologic information, it will require for planning, design and development of an optimal network in a region. The main challenge in planning an optimal network is the difficulties to balance between two major aspects which are economy and accuracy. In economy aspect, every addition of gauges means additional cost and money while in accuracy aspect, it seem that having many gauges is an advantage in getting the accurate information.

There are several ways to define the objectives of the rain gauges network design, but the fundamental one in most studies is the selection of the optimum number of rain gauges stations and their optimum locations. Other considerations that can arise in the network design are achieving an adequate record length prior to utilizing the data, developing a mechanism to transfer information from gauged to ungauged locations when the need arises and estimating the probable magnitude of error or regional hydrologic uncertainty arising from the network density, distribution and record length (Jalvigyan Bhawan, 1999).

The main objective of providing an optimal network of rain gauges is to adequately sample the rainfall and explain its nature of variability within the region concern. The rainfall changeability depends on wind, topography, the movement of storm and the type of storm. The location and spacing of gauges also depend on the mentioned factors. Networks are often designed to monitor rainfall for resource assessment, design, operations and flood warning schemes. Hence, the spatial and temporal behavior of rainfall processes over the catchment need to be monitored and captured to ensure sufficient information for flood warning systems. An adequate network has to be networks that can apply accommodate this variation with an acceptable error.

In the recent decade, Malaysia has been hit with numerous accounts of severe floods especially in the period of 19-31 December, 2006 and 12 – 17 January, 2007. During these period, series of storm events generated by the Northeast Monsoon has caused millions of lost and damages in states located in the lower half of the Peninsular namely Negeri Sembilan, Melaka, Pahang and Johor. Thus, a study to determine the optimum number of rain gauge and the location that can best estimate the rain fall area is really needed in which will be fulfilled by this study.

3.0 LITERATURE REVIEW

Earlier studies on meteorological network design and optimization shows that the variance reduction method of geostatistical method arises as one of the most popular method adopted by researchers. Those studies are as followed:

Bras and Iturbe (1976) recognized rainfall as multidimensional stochastic process. By using the knowledge of such process and multivariate estimation theory, they developed a procedure for designing an optimal network to obtain the areal mean precipitation of an event over a fixed area. The methodology used in this research consider three different aspects of network design; spatial uncertainty and correlation of process, errors in measurement techniques and their correlation and nonhomogeneous sampling costs. The optimization technique used in this research is a search moving in the direction of highest partial gradient. They found out that the optimal networks (number and locations of rain gauges) together with the resulting cost and mean square error of rainfall estimation.

Bastin et al. (1984) meanwhile, modeled the rainfall as two-dimensional random field. They proposed a simple procedure for the real-time estimation of the average rainfall over a catchment area which is linear unbiased variance estimation method (kriging). They implement the method in two river basins in Belgium and showed that the method can be used for the optimal selection of the rain gauge location in a basin.

Shamsi et al. (1988) on the other hand, applied Universal kriging techniques based on the generalized covariances corresponding to IRF-k theory to analyze the design of rain gauge networks in regions where the spatial mean is not constant. Symmetric and asymmetric hypothetical rainfall fields are considered to obtain an optimal estimate of watershed precipitation. The result showed that kriging takes into account the spatial variability of the storm within the catchment and not only the location of the rain gauges.

Kassim and Kottegoda (1991) used simple and disjunctive kriging method and compared the estimation of optimum locations of recording rain gauges as part of a network for the determination of storm characteristics to be used in forecasting and design. The method was applied in the area of the Severn-Trent water basin, UK.

Loof et al. (1994) introduced the concept of ‘regionalized variables’ and the theory of kriging. They developed a methodology for selecting the best locations for a given number of rain gauges planned to be added in a network based on the spatial variability of the precipitation obtained by kriging. The methodology has been applied in Karnali river basin, Nepal and they showed that kriging can be of valuable use in identifying the optimal locations for a set of additional rain gauges using kriging standard deviation as an indicator.

Eulogio (1996) presented a method for establishing an optimal network design for the estimation of areal averages of rainfall events. In his study, he use geostatistical variance-reduction method combine with simulated annealing as an algorithm of minimization.

Chen et al. (2008) proposed a method composed of kriging and entropy that can determine the optimum number and spatial distribution of rain gauge stations in catchments. The method has been applied in Shimen Reservoir, Taiwan and they showed that only seven rain gauge stations are needed to provide the necessary information.

Haifa et al. (2010) compared three differents geostatistical algorithms such as kriging with external drift, regression-kriging and cokriging to predict rainfall maps. The estimation variance is used in to locate the regions where new stations must be added to obtain less important error estimation and has been utilized in Tunisia.

Chebbi et al. (2011) proposed a method for assessing the optimal location of new monitoring stations within an existing rain gauge network. It takes account of precipitation as well as the prediction accuracy of rainfall erosivity. They used variance-reduction method with simulated annealing as an algorithm for objective function minimization to define the optimal network in Tunisia.

Ayman (2012) determined the spatial distribution of potential rainfall gauging stations by using the methodology based on the sequential use of kriging and entropy principles. Kriging is used to compute the spatial variations of rainfall in the locations of candidate stations. The methodology is applied on Makkah watershed.

Motivated by the previous studies in determining the optimal rain gauge network, this study is conducted to investigate the capability of both the geostatistics and simulated annealing method in determining an optimal rain gauge network for a study region in Malaysia. The highly variable temporal and spatial rainfall series in a tropical region such as Malaysia will require a detailed examination of the methodology to be adopted. It is also hope that the result will contribute to the field of mathematical modeling and rain gauge network and help Malaysia in solving its annual problem – the occurrence of flood during monsoon season.

4.0 METHODOLOGY

Two main methods discuss in this paper are geostatistics and simulated annealing. The first part of the methodology describes the geostatistical framework that has been use for application of variance reduction techniques. The second part of the methodology meanwhile is the presentation of simulated annealing as a method of random search and optimization.

4.1 Geostatistics

Many approaches use to optimize the rain gauges network try to attain the maximum yield of areal rainfall with a minimum density of rain gauges. Kriging is a form of generalized linear regression for the formulation of an optimal estimator in a minimum mean square error sense (Ricardo, 2003).

The estimation variance σ^2 is a basic tool of variance reduction techniques for optimal selection of sampling locations. For the application of the variance reduction method to optimal location of sampling sites, a variogram must be modelled. The estimated variance depends on the variogram model, the number *N* of rain gauges and its spatial location.

Let *h* be the lag, then the experimental variogram used in this study is

$$\gamma(h) = C\left(1 - e^{\frac{-3h}{a}}\right), \tag{1}$$

where *C* is the sill and *a* is the range.

Once the model of the variogram is fixed, the estimation variance only depends on the number *N* and the location of the rain gauges. To calculate the estimation variance using ordinary kriging,

$$\sigma^2(x_0) = 2\sum_{i=1}^{k} \lambda_i \gamma(x_i, x_0) - \sum_{i=1}^{k}\sum_{j=1}^{k} \lambda_i \lambda_j \gamma(x_i, x_j) \tag{2}$$

Where

$$\hat{Z}(x_0) = \sum_{i=1}^{k} \lambda_i Z(x_i) \tag{3}$$

$$\text{Subject to } \sum_{i=1}^{k} \lambda_i = 1.$$

This is an algorithm for the ordinary kriging estimation (Olea, 2003):

1. Calculate each term in matrix *G*.

   Let x_i's be the sampling sites of a sample subset of size k, $i = 1,2,\ldots,k$ and let $\gamma(x_i, x_j)$'s be the experimental variogram. Then the *G* is the matrix

$$G = \begin{bmatrix} \gamma(x_1,x_1) & \gamma(x_2,x_1) & \cdots & \gamma(x_k,x_1) & 1 \\ \gamma(x_1,x_2) & \gamma(x_2,x_2) & \cdots & \gamma(x_k,x_2) & 1 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \gamma(x_1,x_k) & \gamma(x_2,x_k) & \cdots & \gamma(x_k,x_k) & 1 \\ 1 & 1 & \cdots & 1 & 0 \end{bmatrix} \tag{4}$$

2. Calculate each term in matrix g.
   Let x_0 be the estimation location, then the *g* is the matrix

$$g = [\gamma(x_0, x_1) \quad \gamma(x_0, x_2) \quad \cdots \quad \gamma(x_0, x_k) \quad 1]' \tag{5}$$

3. Solve the system of equations

$$GW = g,$$

$$W = gG^{-1}$$

Where $W = [\lambda_1 \quad \lambda_2 \quad \cdots \quad \lambda_k \quad -\mu]'$.

4. Calculate the ordinary kriging estimation variance

$$\sigma^2(x_0) = g'W = g'G^{-1}g. \tag{6}$$

4.2 Simulated Annealing (SA)

The minimisation of the objective function given in this study is done by simulated annealing. SA is a family of techniques for creating metals with desirable mechanical properties. The SA technique originates from the theory of statistical mechanics and is based upon the analogy between the annealing of solids and solving optimization problem. SA was first introduced by Kirkpatrick et al. (1983). It comes from the annealing process of solids where a solid is heated until it melts, and then the temperature of the solid is slowly decreased (according to the annealing schedule) until the solid reaches the lowest energy state or ground state. The initial temperature must be set at a very high value. This is because if the initial temperature is not high enough or if the temperature decreased rapidly, the solid at the ground state will have many defects or imperfections.

In the rain gauge network problem, the energy of the annealing process is given by the value of objective function and the temperature, *T* is a global time-varying parameter that is adjusted empirically for a given data set. For the starting of the simulation, the temperature must be set at a high value to permit the probability of any configuration of rain gauges, and the cooling process is done following a precise annealing schedule.

The annealing process for optimal location of *M* rain gauges may be simulated through the following steps:

1. The initial configuration of rain gauges is obtained by randomly select $1, 2, 3, \ldots, M, M+1, M+2, \ldots, N$ rain gauges available (in the optimal subset selection problem).

2. An energy is defined as a measure of the difference between different configurations. The energy is given by the objective function (equation 2).
3. The initial temperature is determined as:

   $$T_0 = 1000\sigma^2$$

   where T_0, is the initial temperature, σ^2 is the estimated variance of the experimental data. As mention earlier, the initial T must be set at a very high value. With the selection of 1000, there is a guarantee that the initial temperature is higher than the difference in energy between any two configurations taking at random.
4. The initial configuration is perturbed by randomly selecting one from N of the rain gauges, and the objective function is calculated.
5. For each value of constant T, a number of $100N$ new configurations are tried. The simulation remains at constant temperature until $100N$ configurations have been tried and the minimum value of objective function for the configurations is accepted.
6. For each new configuration, the algorithm must decide whether to reject it or accept it. Let $\Delta OF = OF_{new} - OF_{old}$. If $\Delta OF \leq 0$, the new configuration is accepted because the objective function has been minimized. However, if $\Delta OF \geq 0$, the new configuration is accepted with probability acceptation criterion, $e^{\frac{-\Delta OF}{T}}$ (Eulogio, 1998).
7. The temperature is decreased at a certain amount, in this study by 10% and step 5 is applied again.
8. The running of the simulation process is defined by steps 6 and 7 continues until:
   - i. a number of prefixed numbers of iterations is reached
   - ii. at a given constant T none of the numbers of new configurations have been accepted
   - iii. changes in the objective function for various consecutive T steps are slight.

5.0 STUDY AREA

Johor is the second largest state in the Malaysia Peninsular, with an area of 18,941 km^2. The Johor River and its streams are important sources of water supply for the people of Johor. The river comprises 122.7 km long drains, covering an area of 2,636 km^2. It originates from Mount Gemuruh and flows through the south-eastern part of Johor and finally into the Straits of Johor. The catchment area is irregular in shape. The maximum length and breadth are 80 km and 45 km, respectively. The catchment area also contain a dense rain gauge network, 84 rain gauges covering 19,210 km^2 in Johor (see Figure 1). For this catchment area, daily rainfall at each rain gauge during monsoon season which starts from November until February of 1975 through 2008 was obtained from Department of Irrigation and Drainage (DID) Malaysia.

Figure 1 Johor Topography with 84 Rain Gauge Stations.

From Figure 1, it can be seen that a lot of the rain gauge stations located in the west of Johor. The western and eastern Johor is separated by the Titiwangsa Mountains extending from southern Thailand to Mount Ledang, Johor. It also can be noticed that there is no rain gauge station located along the Titiwangsa Mountains. This is because the rain gauge station cannot be placed in a hilly area because of the wind effect. This is because the increment of the height results to increment of the wind which influences the increment of error associated with the measured rainfall (WMO, 2008).

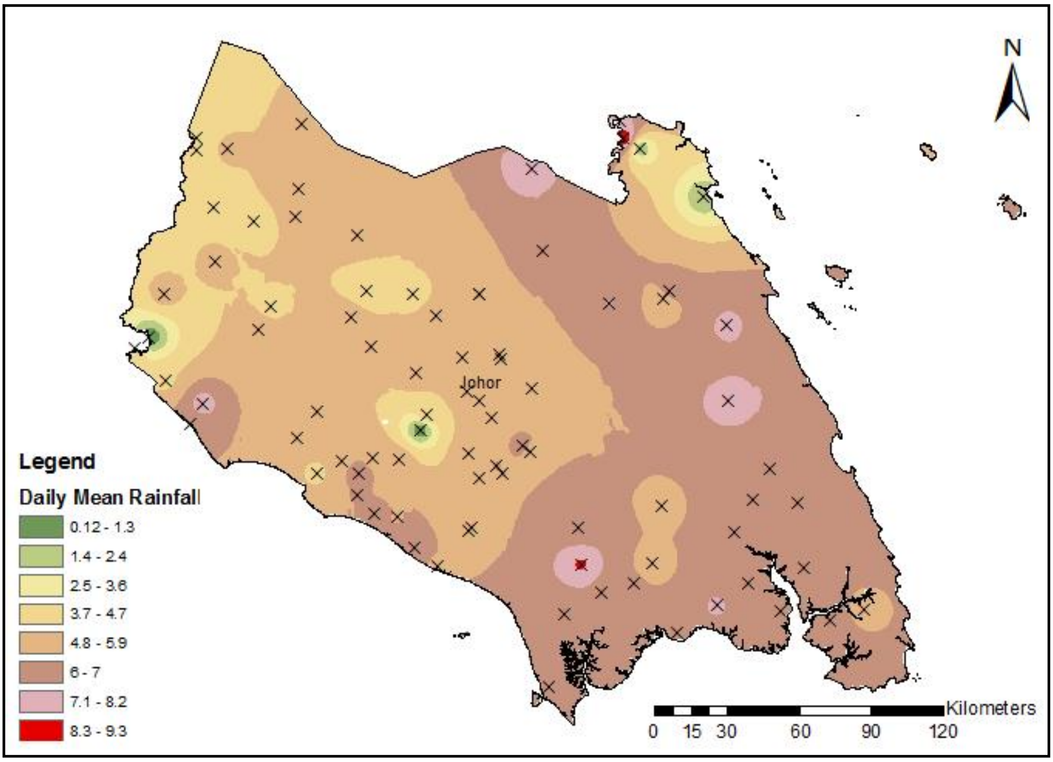

Figure 2 Daily Mean Rainfall with 84 Rain Gauges in Johor

Figure 2 shows the daily rainfall for the whole of Johor. It is noted that the eastern Johor receive more rain than areas in western Johor. This is caused by the northeast monsoon season commences in early November and ends in March. As we can see from Figure 2, almost 81% of the rain gauge stations are located at the eastern region and another 19% located at western region of Johor. The northeast monsoon is the major rainy season in the country. Monsoon weather systems which develop in conjunction with cold air outbreaks from Siberia produce heavy rains which often cause severe floods along the east coast states of Kelantan, Terengganu, Pahang and East Johor in Peninsular Malaysia, and in the state of Sarawak in East Malaysia.

6.0 RESULTS AND ANALYSIS

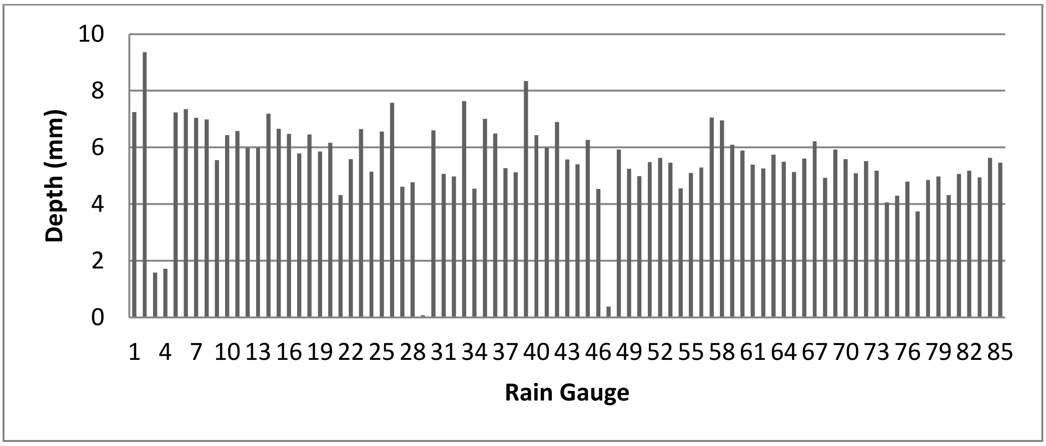

Figure 3 Mean Daily Rainfall at 84 Rain Gauges during Monsoon Season

Figure 3 shows the mean daily rainfall totals at each of the rain gauges for all monsoon season from the year 1975 until 2008. The figure shows the rainfall patterns at every rain gauge in the state of Johor. The rain gauges are arranged based on their location from the nearest to the beach up to the farthest to the beach. The figure shows that rain gauges that are near to the beach have higher total of rainfall in comparison to those that are far from the beach. This shows that the coastal area of the Johor receives heavy rainfall all year round specially during the monsoon season.

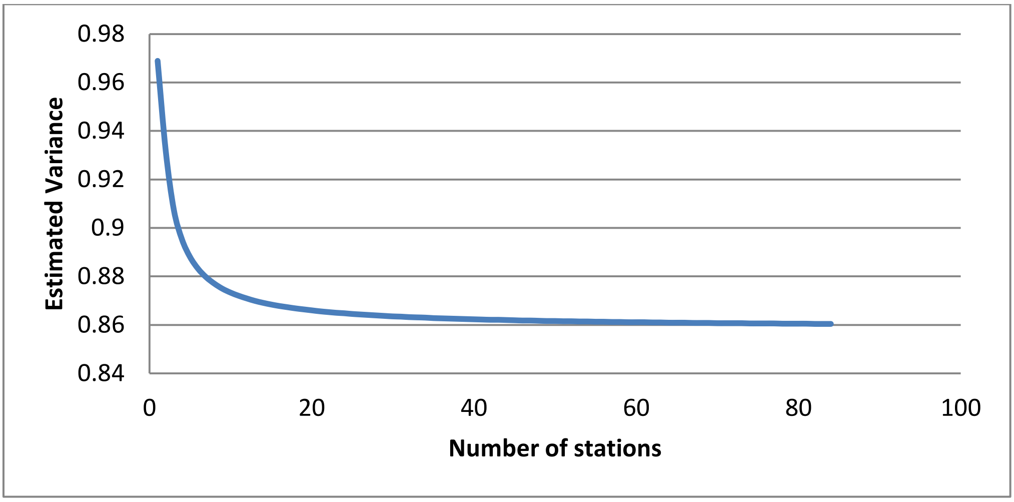

Figure 4 Estimation variance versus number of rain gauges station

In Figure 4, the variance of estimation is plotted against number of stations. It can be seen that the gain of accuracy as the number of rain gauges increases. It also can be noted as the number of rain gauges increase, the decrease in estimated variance is less significant at each step. The number of rain gauges station, if any economic limitation exists, can be chosen in according with the accuracy desired. From Figure 4, the lowest estimated variance is when the number of rain gauges is 64. That means it is need to be decided from 85 stations, which is the 64 optimum locations of the rain gauges.

It is well known that if a set has N elements, then the number of its subsets consisting of n elements each equal:

$$\binom{N}{n} = \frac{N!}{n!(N-n)!}\,. \tag{7}$$

In this study, $N = 84$ and $n = 64$, and the number of combinations will be approximately 1.0736×10^{10}. To find the optimal combinations of 64 rain gauge stations from 1.0736×10^{10} is not an easy job. Simulated annealing provides an algorithm of better efficiency which can find the solution to the problem more rapidly and the results of the 64 optimum rain gauge stations are shown in Figure 5 below.

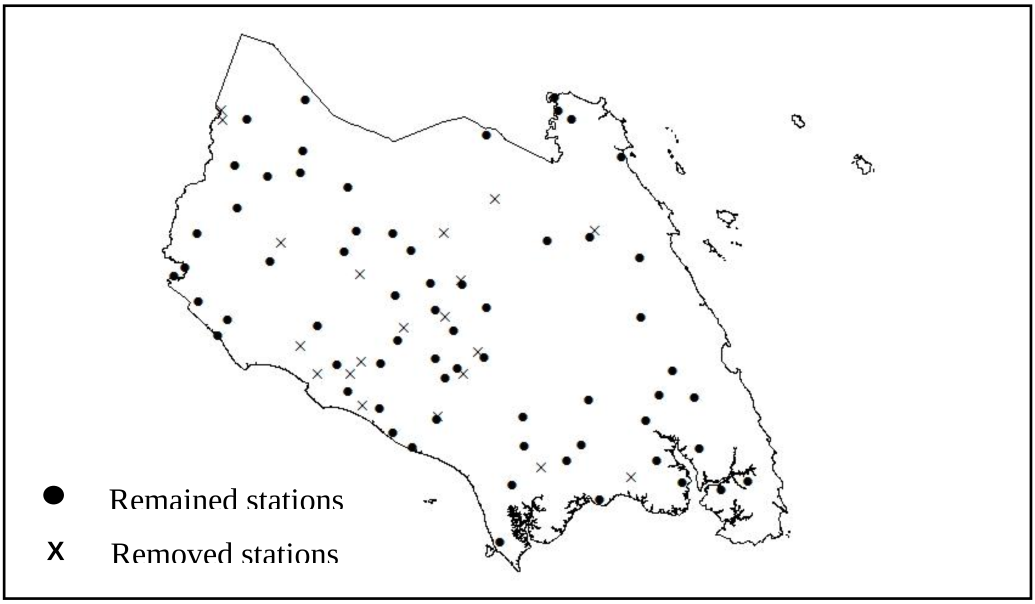

Figure 5 Optimum locations of 64 rain gauges station

In order to examine the quality of the semi variogram model, the errors of the exponential semi variogram need to be calculated. Five different errors are calculated which are mean error (ME), root mean square error (RMSE), average standardized error (ASE), mean standardized error (MSE) and root mean square standardized error (RMSS).

$$\text{ME} = \frac{1}{N}\sum_{i=N}^{N}\left[z(x_i) - \hat{z}(x_i)\right] \tag{8}$$

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[z(x_i) - \hat{z}(x_i)\right]^2} \tag{9}$$

$$\text{ASE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\sigma^2(x_i)} \tag{10}$$

$$\text{MSE} = \frac{1}{N}\sum_{i=1}^{N}\frac{ME}{\sigma^2(x_i)} \tag{11}$$

$$\text{RMSS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{ME}{\sigma^2(x_i)}\right)^2} \tag{12}$$

where $z(x_i)$ is the observed value, $\hat{z}(x_i)$ is the predicted value, N is the number of values in the dataset and σ^2 is the kriging variance for location x_i (Robinson and Metternicht, 2006).

The first step to determine the accuracy of the model is to find the mean error value and it should be closer to 0. Mean error is the average difference between the measured and the predicted values. Meanwhile, the root mean square (RMS) error is based on the square error and its value should also be closer to 1. The average standard error value should be near to the RMS error and the mean standardized error value should be near to 0. The RMS standardized error is the average standard error divided by the RMS and the value should be closer to 1 (ESRI, 2001). If it is greater than 1, then the prediction model underestimates the variability of the dataset but if it is less than 1, then the prediction model overestimates the variability of the dataset.

Table 1 ME, RMSE, ASE, MSE and RMSS for exponential semi variogram

	Mean	**Root mean square (RMS)**	**Average standard**	**Mean standardized**	**RMS standardized**
Errors	0.007185	1.392	1.185	0.005195	1.168

Table 1 shows the five different types of calculated errors in cross validation technique. As with cross validation, the goals are to have an average error value that is close to 0, a small RMSE value, an ASE similar or closer to the RMSE, a MSE closer to 0 and the RMSS near to 1. For ME, the value is 0.007185 and very close to 0. The RMS is 1.392 and the value is close to 1. The ASE value is 1.185 and the value should be close to RMS value. The difference between RMS and ASE is 0.207. Meanwhile, MSE is 0.005195 and the value is very near to 0. Lastly, RMSS value is 1.168 and very close to 1. This analysis shows that the errors calculated fulfill the criteria that were mention earlier in order to determine the accuracy of the semi variogram model. This result has clearly indicated that exponential semi variogram model is fitted model to the observation data.

7.0 CONCLUSION

Combination of geostatistics methods and simulated annealing as an algorithm of optimization can be used as a framework for rain gauge network design models and improves the existing rainfall network by minimizing the variance of estimation value. Simulated annealing as an algorithm of numerical optimisation, improves the optimal network of rain gauge stations in Johor by variance reduction method. From the data analysis, it is found that the optimal network design of rain gauges can be achieved with the selection of 64 stations.

This study also shows that exponential semi variogram model is best fitted model based on the calculated ME, RMSE, ASE, MSE and RMSS. The results shows that the errors fulfill the characteristics needed to be considered as an excellent semi variogram model.

Overall, this study has illustrated that the geostatistics method with simulated annealing technique can be used as the optimization method to provide the solution for optimal number and the location of the rain gauges in order to get better rainfall data.

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