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OPTIMIZATION OF RAIN GAUGE NETWORK IN JOHOR USING HYBRID PARTICLE SWARM OPTIMIZATION AND SIMULATED ANNEALING

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OPTIMIZATION OF RAIN GAUGE NETWORK IN JOHOR USING HYBRID PARTICLE SWARM OPTIMIZATION AND SIMULATED ANNEALING

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A Special Dedication

To my beloved family

Parents, Mohd Aziz Mohd Din & Nik Noraini Raja Abdullah

In – Laws, Ibrahim Abd Ghani & Siti Hajar Wan Mohamad

Wife, Ismi Safia Adila Ibrahim

Children, Muhammad ‘Umar Miqdam**,** Dhiya’ Aisyah Bazilah & Dhiya’ Amna Malika

Siblings, Alif, Mira, Afiq, Asyraf, Yasmin, Izzaaz, Luqman & Amalina

To all the respected UTM lecturers

Thank you for the knowledge and experience

May Allah bless you all.

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ABSTRACT

An optimal design of rain gauge network is important as it produces fast, accurate and important rainfall data used in designing an effective and economic hydraulic structure for flood control. The use of inaccurate rainfall data may result in significant design errors in other water resources project. The objective of this study is to determine the optimal number and location of the rain gauge network in Johor by using geostatistical method integrated with hybrid method consisting of simulated annealing and particle swarm optimization. This study also explored and compared the results of all existing methods namely the coefficient of variations, the maximum covering location problems and geostatistical method with the proposed model. The use of methods such as maximal covering location problem and coefficient of variation can only provide the figure for number of rain gauge stations but not the optimal location for the stations. The geostatistics method however, can provide the optimal number of rain gauge station and its location through the minimum variant value. The integration of geostatistics with hybrid methods comprised of simulated annealing method and particle swarm optimization is successful in providing the optimum number and location of the stations. In order to identify the effect of rain gauge station locations toward rainfall data, this study considered the repositioning of the existing rain gauge into new locations to improve their effectiveness and reduce the error. The analysis analysed the density of the rain gauge, daily rainfall data from 1977 to 2008, latitude and longitude of the rain gauge location, elevation, humidity, wind speed, temperature and solar radiation to determine the new optimal network design for the rain gauge network. The minimum value of estimated variance produced by the proposed method indicates that the method is successful in determining the optimal rain gauge network from the existing 84 rain gauges in Johor. Relocation of all 84 rain gauge stations to new locations give better results in terms of the estimated variance value but, it is not necessary to relocate all of the stations due to the expensive costs. Therefore, the location of the station also influences the result. In this study, hybrid simulated annealing and particle swarm optimization as an optimization method successfully determined the optimal rain gauges network in Johor. In conclusion, this study has shown that a well-design rain gauge network will help to provide essential input for effective planning, designing and managing of water resources project such as flood frequency analysis and forecasting.

ABSTRAK

Satu rangkaian tolok hujan yang optimal penting dalam membekalkan data taburan hujan yang cepat, tepat dan penting untuk merekabentuk struktur hidraulik yang efektif dan ekonomi bagi pengawalan banjir. Penggunaan data taburan hujan yang tidak tepat akan menghasilkan ralat yang signifikan dalam merekabentuk projek sumber air yang lain. Objektif kajian ini adalah untuk menentukan bilangan dan lokasi yang optimal bagi rangkaian tolok hujan di Johor menggunakan kaedah bersepadu geostatistik dengan kaedah hibrid antara simulasi penyepuhlindapan dan pengoptimuman partikel secara berkumpulan. Kajian ini juga meneroka dan membandingkan keputusan dari semua kaedah sediaada iaitu pekali variasi, masalah liputan lokasi maksimum dan kaedah geostatistik dengan model yang dicadangkan. Penggunaan kaedah seperti masalah liputan lokasi maksimum dan pekali variasi cuma boleh mengambarkan bilangan stesen tolok hujan sahaja tetapi bukan lokasi bagi stesen optimal. Walaubagaimanapun, kaedah geostatistik mampu menentukan bilangan dan lokasi stesen tolok hujan yang optimal dengan memberikan nilai varian minimum. Gabungan kaedah geostatistik dengan kaedah hibrid yang terdiri daripada kaedah simulasi penyepuhlindapan dan pengoptimuman partikel secara berkumpulan, berjaya memberikan bilangan dan lokasi stesen tolok hujan yang optimal. Untuk mengenal pasti kesan lokasi stesen tolok hujan terhadap data taburan hujan, kajian ini mempertimbangkan untuk menempatkan semula tolok hujan yang sedia ada ke lokasi yang baharu untuk meningkatkan keberkesanan dan mengurangkan ralat. Analisis ini menganalisa ketumpatan tolok hujan, data taburan hujan harian dari 1975 hingga 2008, latitud dan longitud lokasi stesen tolok hujan, aras tinggi, kelembapan, halaju angin, suhu dan radiasi solar untuk merekabentuk rangkaian tolok hujan baharu dan optimal. Nilai anggaran varian minimum yang terhasil oleh kaedah yang dicadangkan menggambarkan bahawa kaedah ini berjaya menentukan rangkaian tolok hujan yang optimal dari 84 tolok hujan yang sedia ada di Johor. Penempatan semula kesemua 84 tolok hujan ke lokasi yang baharu memberikan hasil yang lebih baik berdasarkan nilai anggaran varian, tetapi tidak semestinya untuk menempatkan semula semua stesen kerana kos yang tinggi. Oleh itu, lokasi stesen juga memainkan peranan yang penting dalam mempengaruhi keputusan kajian. Dalam kajian ini, hibrid antara simulasi penyepuhlindapan dan pengoptimuman partikel secara berkumpulan sebagai teknik pengoptimuman berjaya menentukan rangkaian tolok hujan yang optimal di Johor. Kesimpulannya, kajian ini menunjukkan bahawa rekabentuk rangkaian tolok hujan yang baik akan membantu menyediakan input berguna bagi perancangan, rekabentuk dan pengurusan projek sumber air yang efektif seperti analisis kekerapan dan ramalan banjir.

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LIST OF ABBREVIATIONS

DID	-	Department of Irrigation and Drainage
WMO	-	World Meteorological Organization
SA	-	Simulated annealing
PSO	-	Particle swarm optimization
ME	-	Mean error
RMSE	-	Root mean square error
ASE	-	Average standardized error
MSE	-	Mean standardized error
RMSS	-	Root mean square standardized error
MCLP	-	Maximal Covering Location Problem

LIST OF SYMBOLS

N	-	number of rain gauge stations
ε	-	allowable degree of error
C_v	-	coefficient of variation
P_i	-	precipitation magnitude at the i^{th} station
$\overline{P}$	-	mean precipitation
r_i	-	average daily rainfall at point i
$r_i^{\max}$	-	maximum daily rainfall at point i
S	-	radius of rain gauge
d_{ij}	-	shortest distance between point i and j
h	-	lag or distance
$\gamma(h)$	-	Semivariogram function
C	-	Sill
a	-	range
σ^2	-	Estimated variance
λ_i	-	weights
μ	-	Lagrance multiplier
T_0	-	initial temperature
$P(\delta)$	-	Probability of acceptance
θ	-	Random number between 0 and 1
T_k	-	current temperature

α	-	cooling ratio
δ	-	Change in objective function
Z	-	Objective function
c_1	-	positive constants
c_2	-	positive constants
r_1	-	random numbers with range $(0,1)$
r_2	-	random numbers with range $(0,1)$
v_i	-	Velocity
$v_{\max}$	-	Maximum velocity

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Success in the planning, designing, operating and management of water resources projects depends heavily on its rainfall data. This is because water resources management tasks such as water budget analysis and assessment, flood frequency analysis and estimation, streamflow forecasting, and design of hydraulic structures need rainfall data. It is so important that an optimal and valid rain gauge network will be the foundation in the supplement of current and accurate rainfall data that are essential for successful cost-effective hydraulic structures design for flood control. These data are helpful to minimize and reduce the hydrological and economic risk involved in different water resources projects. Rain gauge networks systems are installed to monitor rainfall reading that mark the spatial and temporal variations of local rainfall patterns in a catchment area.

Networks used to measure other meteorological elements such as temperature should be less complex than rain gauge network systems. This is because rainfall pattern is highly variable and its spatial distribution cannot be represented successfully without having enough spatial density networks (Pardo-Igúzquiza, 1998). Hence, an efficient rain gauge network design should contain a sufficient number of rain gauges that potray the spatial and temporal variability of rainfall in a catchment area (Yeh *et al.*, 2011).

Survey on sample measurements at neighbouring locations often required the researchers to calculate the mean areal rainfall reading over the catchment area and/or point rainfall at unsampled locations and explain its nature of variability within the region concern. This objective can only be achieved with the existence of rain gauge network with optimum design that is deemed necessary for any hydrological study. The rainfall changeability depends on wind, topography, the movement of storm and the type of storm. Hence, the spatial and temporal behaviour of rainfall processes over the catchment need to be monitored and captured to ensure sufficient information for flood warning systems. However, most rain gauge network in various catchment area which were used mainly in most of the hydrological studies are often sparsed, resulting the network system to be incapable of providing accurate rainfall data needed for efficient hydrological analysis and design of water resources projects. Usage of imprecise and inaccurate rainfall data can lead to serious design errors in the water resources projects, which can result to fatal effects such as damage of properties and loss of life.

Hence, determination of the best rain gauge network with ideal number and locations of rain gauge stations is the solitary objective of any network design. Such network should be able to supply optimum rainfall information with minimum uncertainty and cost (Kassim and Kottegoda, 1991; Basalirwa *et al*., 1993; Pardo-Igúzquiza, 1998). This can be done either by eliminating the unnecessary stations from the network to minimize the cost or by widening the network with installation of additional stations to reduce the estimation uncertainty (Mishra and Coulibaly, 2009).

The design of hydrometric networks is a famous known problem in hydrometeorology (Mishra and Coulibaly, 2009) and has been a popular area of investigation for many years. Various approaches have been established for an ideal network design as hydrometric network design is associated with scores of variables. The most popular approach is the kriging-based geostatistical approach that has expansive implementation in the rain gauge network design. The provision of kriging error that shapes the foundation for the rain gauge network design is the vital feature of this approach (Adhikary *et al*., 2015). Reducing the kriging error can help determine the optimal network configuration. It can be done through methodical search where optimal composition of the appropriate number and locations of stations that produce the errors are found. Further detailed research about kriging-based geostatistics can be discovered in the literature by Isaacs and Srivastava (1989) and Webster and Oliver (2007).

In various studies, the kriging technique was used individually for the rain gauge network design (Shamsi *et al*., 1988; Kassim and Kottegoda, 1991; Loof *et al*., 1994; Papamichail and Metaxa, 1996; Tsintikidis *et al*., 2002; Cheng *et al*., 2008). Nevertheless, various studies have employed the kriging technique with other techniques such as entropy (Yeh *et al*., 2011) and multivariate factor analysis (Shaghaghian and Abedini, 2013) for the network design. Other studies integrated optimization method based on simulation tools such as simulated annealing with the kriging technique (Pardo-Igúzquiza, 1998; Barca *et al*., 2008; Chebbi *et al*., 2011) to achieve the optimal rain gauge network.

Early studies were mostly based on random searches and enumeration (Shaghaghian and Abedini, 2013). However, for the past three decades or so, researchers have considered some other more systematic approaches, including the geostatistics method, simulated annealing as optimization techniques in numerous fields of rain gauge network design. Existing method such as coefficient of variation successfully determined the optimal number of stations but not the optimal locations of stations. The utilization of geostatistics method successfully obtained the optimal number and locations by calculating the minimum estimated variance. The integration of optimization method in geostatistics improves the ability of geostatistics method to achieve the optimal number and locations of rain gauge. The attempt of using the hybrid particle swarm optimization and simulated annealing to determine the optimal number and locations of rain gauge is expected to further enhance the ability of geostatistics method compare to individual optimization method in term of rain gauge network design. The next section of the study is devoted to relocate and redesign the existing rain gauge network into a new optimal rain gauge design by considering multiple criteria such as elevation, wind speed, solar radiation, humidity and temperature as these considerations have not been done yet in Malaysia.

In this study, the state of Johor was selected as the study area. The state is with a total land area of 18,941 km^2 and has 84 rain gauge stations in which are scattered across the state. An optimal rain gauge network system in Johor will be an advantage in term of water research in Malaysia and Johor specifically.

1.2 Problem Statement

Interest in rainfall network optimization has increased substantially over the past decade due to the need to improve the existing rainfall network. Many methods are used by various researchers to determine the best rainfall network including the number and the locations of rain gauges. In the case of Johor, Malaysia, a state which flood has become an expected end-of-the-year event, the optimum rainfall network for the state has never been determined for by any researchers or government associations. The existing rainfall network in Johor is determined based on *Jabatan Pengairan dan Saliran Johor* (JPS) calculation and is acknowledged by JPS as not an optimum rainfall network. The motivation to carry out this study arises from the need to formulate the optimal rain gauge network systems as a stepping stone in acquiring more accurate rainfall data that can be used in various water researches specifically for modelling flood prediction. The study is concerned with the following problem statements:

1. Various methods have been applied by researchers all over the world in their effort for optimal number and location for rain gauge station. Do the methods used by past researchers can be applied for rain fall data in Johor?

2. Single optimization method has been employed by several researchers integrated with geostatistics method. Simulated annealing has been known to be successful in identifying optimal number and location for rain gauge system. Fortunately, the optimal number and location can be acquired accurately through the use of hybrid optimization method integrated with geostatistics method.

3. For an already optimal rain gauge network system, there will be redundant rain gauge in the system. The rain gauge can either be disposed or be moved to new location to enhance the chance of better rain gauge network system.

4. Many researchers have made the effort for an optimal rain gauge network from existing network. However, with increasing number of rain fall catchment area, researchers may need to come up with new rain gauge system for the area. Therefore, this study also considers the issue of redesignation of existing rain gauge network systems.

1.3 Objectives of the Study

The objective of this research is to justify the used of mathematical modeling and optimization technique in the analysis and investigation of main problems:

1. To determine the optimal number and locations of rain gauges stations using existing method such as Coefficient of Variation, Maximal Covering Location Problem and Geostatistics.
2. To propose hybrid simulated annealing with particle swarm optimization model of optimization in determining the optimal number and locations of rain gauges stations.
3. To restructure the rain gauge network in Johor using the proposed model.

1.4 Scope of the Study

This study involved 84 existing rain gauges stations in Johor as the case study. The collation of long term daily rainfall data is collected from the Department of Irrigation and Drainage, Malaysia. Hydrological record over 32 years (1980-2012) consists of monsoon, non-monsoon and annual data was compiled. There are no missing data as the studied rain gauges stations is an automatic stations. The collation of elevation, humidity, wind speed, solar radiation and temperature data starting 1980-2012 was compiled from Malaysia Meteorological Organization.

Existing method studied in this research is maximal covering location problem, coefficient of variation and geostatistics with simulated annealing used to determine the optimum number and locations for the rain gauges stations. The determination of the best fitted semivariogram model for geostatistics used based on the cross validation method is also discussed. Proposed method to determine the optimal number and locations of rain gauges stations is geostatistics integrated with simulated annealing hybrid with particle swarm optimization as the optimization tools. The possibility of restructuring of existing 84 stations into a new optimal design is also explored.

1.5 Significance of the Study

In Malaysia, floods are the most important natural hazard when the population affected, frequency, areal extent, and socio-economic damages are taken into account (Pradhan and Youssef, 2011). Malaysians are historically a riverine people since early settlements mostly grew on major river banks in the peninsula. Coupled with natural factors such as heavy monsoon rainfall, intense convection rain storms, expansion of developed or impervious areas, and poor drainage maintenance, floods have become a common yet devastating feature for many Malaysians (Weng Chan, 1995). Kia *et al*. (2012) stated that floods are affected by several factors such as rainfall, initial soil moisture, geology, land use, evaporation, watershed infiltration, and geomorphology. This is particularly so for floods brought about by monsoon rains (Razi *et al*., 2010).

Heavy rainfall and large concentration of runoffs are often the cause of flooding in Malaysia. For that, various flood forecasting and warning systems built upon advanced hydraulic and hydrological models have been employed to estimate floods (Razi *et al*., 2010). According to the Department of Irrigation and Drainage (DID), the massive flood in December 2006 and January 2007 that had severely affected the Johor state was due to the abnormal heavy rainfall events. At the peak of the incident, about 110,000 people were evacuated and moved to relief centers, and the death toll was said to be 18 lives (Sulaiman, 2007). The damage can be controlled with the existence of an optimal rain gauge network system that can provide accurate rainfall data in which is essential for flood estimation.

This research will contribute significant findings especially on the methodology in determining the optimized number and locations of rainfall monitoring networks for an improved flood forecasting for Malaysia. The methodology on rainfall network optimization conducted on tropical region such as Malaysia is completely new especially in Johor. The lack of information and research on the mentioned issue have making it to be interesting for the researcher to be one of the earliest to indulge in the investigation of the optimum rainfall network research in Johor. In the search of optimum rainfall network, researchers worldwide used single model of optimization. However so far, the use of hybrid model of optimization to determine the optimal number and locations of rain gauges stations has never been used. The proposition of hybrid simulated annealing model to determine Johor optimum rainfall network is needed due to its yearly end-of-the-year flood crisis. The use of hybrid model is considered as better than the single model of optimization due to the use of multiple models of optimization and thorough procedures which resulted to a more accurate result. This study will establish hybrid particle swarm optimization and simulated annealing as a model to determine the number and locations of rain gauges stations in Johor.

1.6 Organization of the Thesis

This thesis consists of six chapters as described below:

1. **Chapter 1** presents the background, problem statement, and outlines the objectives and scope of this research.

2. **Chapter 2** provides an overview and literature on existing method and development of rain gauge network systems. It also describes the hybridization of simulated annealing with particle swarm optimization and opportunities to explore

the hybrid optimization technique in solving rain gauge network problems. The advantages of hybrid optimization technique are also highlighted.

3. **Chapter 3** presents the research methodology which describes the study area, data cleaning, maximal covering location problem, coefficient of variation approach, geostatics method, semivariogram model, simulated annealing and particle swarm optimization. Steps to perform the optimization technique and hybridization of simulated annealing and particle swarm optimization are also discussed in detail.

4. **Chapter 4** presents the results on the existing method. The best fitted semivariogram model for the use of geostatistics method is also presented.

5. **Chapter 5** put forth the results of the proposed method. The optimal number and locations of the rain gauge are obtained from the integration of geostatistics with hybrid particle swarm optimization and simulated annealing as the optimization technique. The comparisons of the results are also discussed.

6. **Chapter 6** concludes the thesis by highlighting important findings in relation to the study objectives. This chapter also suggests recommendations for future works.

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