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Optimal Design of a Rain Gauge Network Models: Review Paper

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Abstract. Improved streamflow forecasting is considered an important task for researchers and water resources managers. However, streamflow forecasting is often challenging owing to the complexity of hydrologic systems. The accuracy of streamflow forecasting mainly depends on the input data from rainfall. Hence, this is important to make the estimation of rainfall as accurate as possible result in achieve an economical design of watershed management, water budget studies, reservoir operation, and flood forecasting and control. Most of the previous research was highlighted, an optimal rain gauge network is necessary to provide high quality rainfall estimates. The goal of this paper is to provide a concise review of several studies on the optimal design of a rain gauge network models to enhance the accuracy of streamflow forecasting. This study had two components. First, the design of an optimal rain gauge network using the kriging-based geostatistical approach based on the variance reduction framework. Second, the uses of optimization technique for minimizing the kriging variance in order to optimize rain gauge networks. Additionally, a discussion of both techniques to design an optimal rain gauge network is presented. A well designed rain gauge network is capable of providing accurate rainfall estimates with an optimal number of rain gauge network density. This paper closes with a set of recommendations for what observations and capabilities are needed in the future to advance our understanding of an optimal rain gauge network design and their location for improving the estimate of aerial rainfall.

1. Introduction

Monitoring of rainfall in time and space is considered to be a fundamental requirement in managing water resources. In many hydrological analysis and watershed management problems such as water budget studies, flood frequency analysis and sewer drainage design, availability of accurate rainfall data with an appropriate coverage in both time and space is considered a classic issue in surface water hydrology. Rainfall data can be obtained from both ground-based (rain gauge stations) and air-based (radar or satellite) instruments. Even if one uses an air-based measurement, discrete ground-based data are still required for validation and calibration purposes. Among examples in which streamflow forecasts provide significant information is through the analysis and design of hydraulic structures such as dams and bridges, management of extreme events including flood and drought, optimum operation of reservoirs for activities including irrigation water requirements, hydropower generation, domestic water supply objectives and industrial [1, 2]. Hence, this is vital to make the estimation of rainfall as accurate as possible result in achieve an economical design of watershed management, water budget studies, reservoir operation, and flood forecasting and control. Forecasting of streamflow is considered significant result in minimize the risk in a decision taken, at any given point of interest, in various water engineering applications. Hence, there is a growing need for both short-term and long-term forecasting of future streamflow in order to optimize the water resources systems in an efficient way [3]. According to [4], a reliable and improved forecasting of streamflow ensures rational regulation of river runoff, which ultimately results in the enhanced flood control and protection.



Generally, due to the complexity of hydrologic systems, the key challenge of achieving enhanced accuracy of streamflow forecasting is remains. This is by no means an easy task because there is no single streamflow forecasting method that provides optimum forecast results for all types of catchments and under all circumstances [5]. Furthermore, there is always uncertainty when it comes to forecasting because it is unlikely to forecast the exact future conditions. As a result, it is necessary to develop a sustainable streamflow forecasting approach for improved estimation of future streamflow with better accuracy. The accuracy of streamflow forecasting primarily depends on the input data, especially rainfall data as it constitutes the key input in transforming rainfall into runoff [6]. Hence, rainfall is one of the most important inputs to develop streamflow forecasting models. Since streamflow is a consequence of rainfall, uncertainty associated with rainfall causes uncertainty in estimated streamflow and adversely affects the accuracy of streamflow forecasting [7 – 9]. The importance of using accurate rainfall data in streamflow forecasting models is to meet the challenge of enhanced streamflow forecasting. Therefore, it can be expected that the enhanced accuracy in streamflow forecasting can be achieved if catchment rainfall is estimated accurately and fed into streamflow forecasting models.

In the relation to this matter, rain gauge networks are usually installed to get direct measurements of rainfall. However, many of the water resources systems are large in spatial extent and often consist of a rain gauge network that is very sparse due to financial, logistics and geological factors. This results in considerable uncertainty in the rainfall data that are available [10]. Rainfall often shows significant spatial variations within a catchment or region [7, 11]. Therefore, the design and establishment of an optimal rain gauge network is an important task to obtain high quality rainfall estimates. An essential advantage of having such an optimal network is to achieve improved streamflow forecasting. The optimal network improves the accuracy in streamflow forecasting by providing accurate estimates of rainfall data with little or no uncertainty [8] that are used as the input to streamflow forecasting models. Rainfall is often considered independent of streamflow simulation and forecasting such as estimation of areal average rainfall over a catchment [12] or the design of rain gauge networks [8, 13 – 18].

However, this does not allow one to focus on the strength and weakness of an established optimal rain gauge network that really matters when rainfall data from the optimal network are fed into streamflow forecasting models. Therefore, it is logical to design an optimal rain gauge network for providing a satisfactory solution to the specific requirement of enhanced streamflow forecasting for which the network is being established. In the past, rainfall data were used in streamflow forecasting models directly from the existing rain gauge network (which may not be an optimal network) rather than using improved rainfall data from an optimally designed rain gauge network [6, 9, 19 – 22]. This ultimately results in the less accurate forecasting of streamflow. Thus, it can be hypothesized that the integration of rainfall input from an optimal rain gauge network with streamflow forecasting models is expected to improve the accuracy of streamflow forecasting.

Therefore, this paper is to provide a concise review of recent studies on the optimal design of a rain gauge network models to enhance the accuracy of streamflow forecasting using a geostatistical approach based on the variance reduction framework and the uses of optimization technique for minimizing the kriging variance in order to optimize rain gauge networks.

2. Optimal design of a rain gauge network models to enhance the accuracy of streamflow forecasting

A review of the existing optimal rain gauge network design approaches is vital to come up with a suitable approach for the optimal design of rain gauge network. Optimal rain gauge network can be defined as a balanced network that neither suffers from lack of rain gauge stations nor is over-saturated with redundant rain gauge stations [23, 24]. Hence, in any hydrological study, an optimal rain gauge network is often considered as crucial component. The design of hydrometric networks is a classical problem in hydrometeorology [23], which has received significant attention from the researchers for many years. Since myriad concerns are associated with hydrometric network design [25], many approaches have been developed for that purpose around the world.

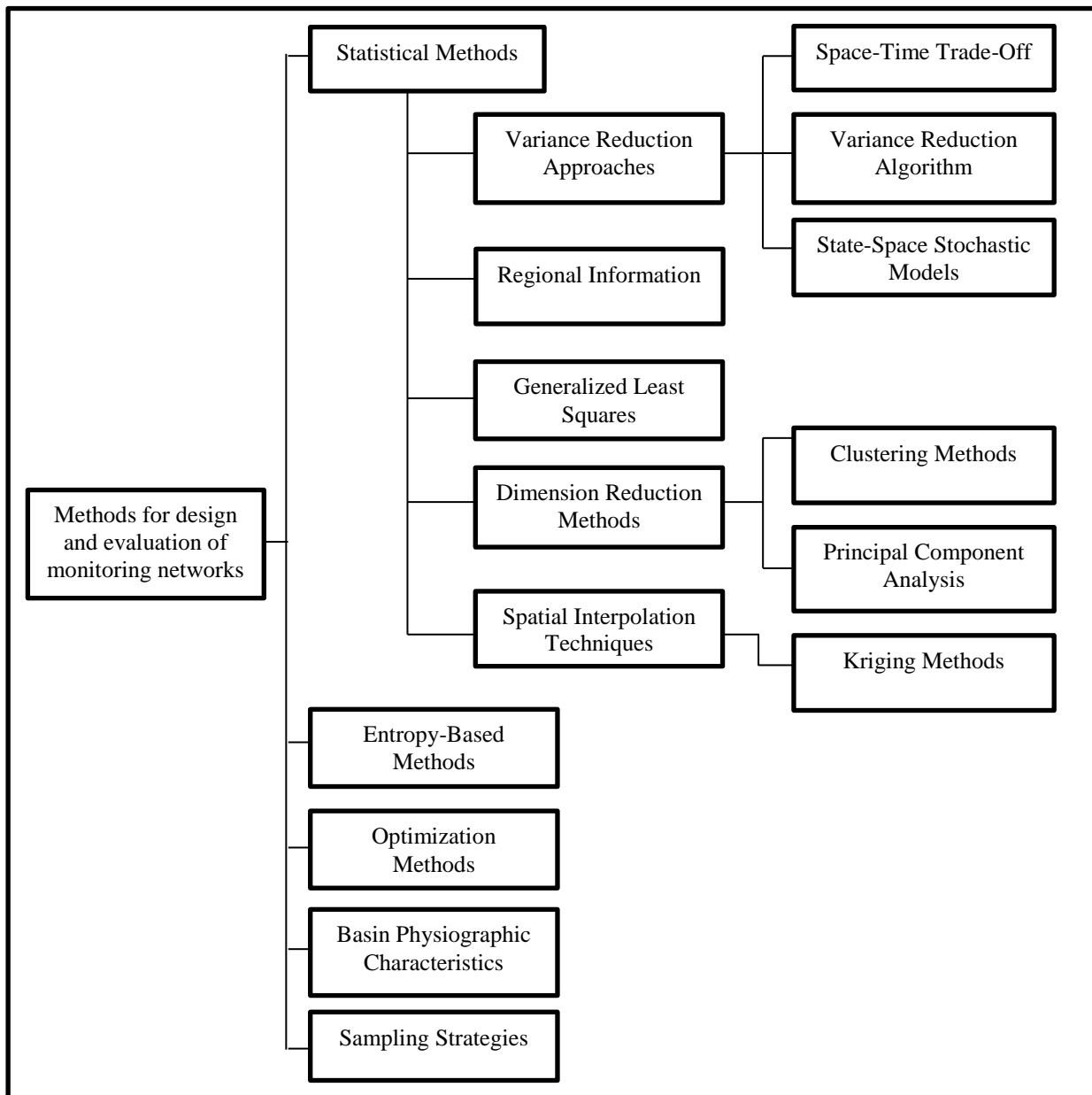


Figure1. Classification of methods for hydrometric networks design and evaluation

A number of available network design and evaluation methods can be found in [23]. These approaches can be broadly classified as statistical methods, entropy methods, optimization methods, basin physiographic characteristics and sampling strategies (as showed in Figure 1), a comprehensive review of which is presented in the work by [23]. [23] mentioned that statistical methods are the most developed. Furthermore, it is found based on the available literature that among all the statistical methods, the kriging-based geostatistical method is the most commonly used method for the design and evaluation of rain gauge networks. An important advantage of this method is that it can be implemented with the combination of other methods such as entropy method, multivariate statistical techniques, and different multi-objective optimization techniques using genetic algorithms, simulated annealing, particle swarm optimization, and artificial bee colony (ABC) in order to achieve a balanced or optimal rain gauge network. Therefore, a detailed review of kriging-based geostatistical and optimization techniques for the design of a rain gauge network is presented in this chapter.

2.1. Kriging-Based Geostatistical and Approach

Geostatistics defines the statistical study of natural phenomena, which can be generally characterized by a distribution of one or more variables in space. These variables are referred to as regionalized variables [26]. The unique feature of a regionalized variable is that it can take values according to its spatial location [27]. Geostatistics is thus based on the theory of regionalized variables, which allows modelling of the spatial variability of the variable based on the spatial dependence between neighbouring observations. The degree of spatial dependence is generally expressed by variogram (also called semivariogram) in geostatistics, which has the structural (spatial variability) information required on a regionalized variable. A variogram is a mathematical function of the distance and direction separating two locations used to quantify the spatial autocorrelation in regionalized variables [26]. The variogram has a key role in geostatistics, which was first applied and developed through kriging.

Kriging refers to a family of generalized least square regression methods in geostatistics [28, 29] that estimate values at unsampled locations using the sampled observations in a specified search neighbourhood. As it will be seen, kriging-based geostatistical method for the design of rain gauge networks depends on the correct estimation of variogram models in which the design criteria are often related to the accuracy of the spatial estimation (i.e., the kriging standard error or the kriging variance) [28]. Therefore, prior to any kriging-based geostatistical assessment, the variogram must be computed from the regionalized variable data. In most of the studies for rain gauge network design, kriging was implemented alone where only rainfall was considered as a single regionalized variable in kriging analysis. However, it is also found from the literature that the kriging-based geostatistical approach offers an advantage over other network design methods because kriging is able to complement the sparsely sampled primary variable, such as rainfall by the correlated densely sampled secondary variable, such as elevation, radar-based rainfall data etc [30, 31].

In this section, a series of studies have presented similar findings. Among those, the methods namely kriging-based geostatistical approach was used for the optimal design of a rain gauge network by researchers. They found that with an increasing of the network with additional rain gauge stations will result in achieve the desired network density and identifying the optimal location of the additional stations in the network to improve the rainfall estimation accuracy [8, 13, 14, 22, 27, 32 – 35]. With respect to this context, another study by [15, 24, 36, 37] revealed that by choosing an optimal representative subset of rain gauge from an existing dense network will result in achieve as much information as possible maintaining the desired level of accuracy. On the other hand, [16 – 18, 38 – 41] found that by prioritizing the rain gauge in the network with respect to their contribution in estimation error reduction and accuracy improvement will result in enhance the accuracy of streamflow forecasting.

It was found in most of the past studies that expansion of the existing network by adding supplementary stations has been the main underlying criterion to achieve the optimal rain gauge network. However, the location and modification of stations significantly influence the quality of the obtained hydrological variable in a network [39]. Furthermore, [23] mentioned that an existing network

may consist of redundant stations that may make small or no contribution to the network performance in providing quality data. [23] suggested that one can approach the problem either by eliminating redundant stations from the network to minimize the cost or by expanding the network with the installation of additional stations to reduce the rainfall estimation uncertainty. Therefore, optimal placement of redundant stations, as well as additional stations, must be ensured in order to achieve the optimal rain gauge network.

2.2. Optimization Technique Approach

Generally, optimization refers to the study of problems in which one seeks to minimize or maximize a real function by systematically choosing the values of real or integer variables from within an allowed set. The application of optimization in network design is to maximize information with respect to minimizing cost [23]. According to [42], the design of rain gauge networks need not essentially be based on formal schemes of optimization, such as the minimum cost of attaining data accuracy. A design can be based upon judgmental analyses to accommodate a mix of design criteria. Available literature indicates that most of the past studies used a sequential trial and error procedure to minimize the kriging variance of rain gauge networks to optimize the network [13, 32, 35].

However, a few studies used optimization techniques such as simulated annealing, genetic algorithm, particle swarm optimization and artificial bee colony (ABC) for minimizing the kriging variance in order to optimize rain gauge networks [14, 15, 27, 33, 37, 41, 43]. Several optimization techniques have been proposed in the literature since the early work of [44, 45], who demonstrated a methodology of rain gauge network design based on the minimization of the mean areal kriging variance. The adoption of optimization techniques in combination with the kriging-based geostatistical method for rainfall network sizing and augmentation was also performed by [14, 15, 27, 33, 37, 41, 43].

Optimization technique, namely simulated annealing [45] was adopted in [14] research which found that simulated annealing improves the optimal network design by minimising an objective function which includes both the accuracy of the areal mean estimation (as expressed by the kriging variance of estimation) and the economic cost of the data collection by variance reduction. [33] provided a methodology for assessing the optimal location of new rain gauge stations within an existing rain gauge network. The methodology used kriging and probabilistic techniques (simulated annealing) combined with a geographic information system (GIS). [27] have considered mono-objective criteria in simulated annealing technique assuming 1-hour rainfall intensity interpolation and erosivity factor interpolation and using one single extreme rainfall event to perform the analysis. Rainfall quantities retained in previous studies were mainly taken in a deterministic way. Effectively, a single rainfall pattern was selected for which the average kriging variance was minimized to achieve the best new rain gauge locations [14, 27, 45].

In the recent past, genetic algorithm and particle swarm optimization techniques in combination with geostatistics were also used for rain gauge network design to minimize the kriging variance for network optimization [15, 37]. They have found that the optimal number of stations of rain gauge with the estimated variance was improving the optimal network of rain gauge stations. Particle swarm optimization as an algorithm numerical optimization also improves the optimal network of rain gauge stations by variance reduction method with help of rainfall, elevation, humidity, solar radiation, temperature and wind speed data [15].

Furthermore, a study was conducted by [41] found that artificial bee colony (ABC) as an algorithm of minimization make the estimation of long term average annual rainfall more accurate and efficient in order to prioritization the rain gauge stations in the network with respect to their contribution in estimation error reduction and accuracy improvement. The result presented that as the number of rain gauges increases, the variance of residual over the study area decreases. The couple of atifical bee colony and kriging seems to be an appropriate, robust and efficient approach to identify the exponentially decaying function of the variance versus the number of rain gauge stations.

3. Conclusion and Recommendation

In conclusion, as mentioned earlier, the goal of this paper was to provide a brief review of past recent studies on the optimal design of a rain gauge network models to enhance the accuracy of streamflow forecasting. In a rain gauge network design exercise, network expansion (using additional stations) as well as network rationalization (eliminating or re-locating redundant stations) and identification of optimal locations of both additional and redundant stations are seen as a potential way to achieve the optimal rain gauge network. In other words, the additional stations that contribute to reduce kriging variance of the network can be selected. Also, the redundant stations that have little or no contribution to the network variance reduction can be either eliminated or optimally located in the high variance areas of the network. However, this study focused on kriging and optimization approach in optimal rain gauge network for enhancing streamflow forecasting which was found highly effective in improving the streamflow forecasting accuracy.

To sum up, future studies can be focused on reviewing the combination of other statistical methods such as entropy method, multivariate statistical techniques, GIS and others.

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