Strategies to estimate rainfall

Accurate rainfall estimation is an important and challenging task and the spatial distribution of the rain gauge is a most important factor in providing reliable areal rainfall. Modern rainfall network established to monitor hydrological features should provide the necessary and real-time information for purposes such as management of water resources, reservoir operation and flood forecast and control (Chen et al., 2008). Direct measurement of rainfall can only be achieved by rain gauges, and rain gauge networks are often installed to provide measurements that characterize the temporal and spatial variations of rainfall (Cheng et al., 2008). However, even if rain gauges are capable of providing real time rainfall information at very fine temporal resolution under the help of automatic rainfall record equipments, it is still difficult to characterize the spatial variation of rainfall without a well-designed rain gauge network in the catchment.

A well designed rain gauge network with proper densities and distributions is essential to provide the valid precipitation information reflecting the spatial-temporal features in a catchment. However, most river basins of the world are poorly gauged or ungauged, and most rain gauge networks applied for hydrological purposes are largely inadequate according to the most dilute density requirements of World Meteorological Organization (WMO). WMO recommends certain densities of rain gauges to be followed for different types of basins such as 500 km^2 per gauge is recommended in flat regions of temperate zones, while 25 km^2 per gauge is recommended for small mountainous islands with irregular precipitation (WMO, 1994). Moreover, many non-hydrological factors considerably impacted the rain gauge network design, e. g. accessibility, cost and easiness of maintenance, topographical aspects, etc. However, many reviews have noted a marked decline in the amount of hydrometric data being collected in many parts of the world (WMO, 1996; Stokstad, 1999). The decline of hydrometric gauges exists not only in developing countries, but also happens in developed countries, e. g. the U. S. Geological Survey (USGS) network had undergone some significant reductions in the mid-1990s (Mason and York, 1997; Pyrce, 2004). This decline in hydrometric gauges means that at a time when global warming may be exacerbating weather extremes and water shortages, scientists are less able to monitor water supplies, predict droughts, and forecast floods than they were 30 years ago (Stokstad, 1999).

In recent years, satellite remote sensing seems to have the potential to provide full spatial coverage of pixel rainfall estimates, however, many studies have pointed out that the satellite based rainfall data still could not provide accurate rainfall estimates to match rain gauge measurements and could not meet the requirements of hydrological modelling on daily base (e. g. Hughes, 2006; Dinku et al., 2008; Li et al., 2012, 2014). Furthermore, the satellite based precipitation data have to be calibrated with the rainfall provided by the existing rain gauges to correct the bias, and the bias correction results considerably depend on the rain gauge density and distribution. Meanwhile, the widely application of satellite based precipitation data has a consequence of thedeterioration of rain gauge networks in some cases (Ali et al., 2005). Tsintikidis et al. (2002) demonstrated that even when lumped models are used for flood forecasting, a proper gauge network can significantly improve the results. Thus, to build a rain gauge network contains a minimum density of rain gauges from removing redundancy gauges which contain less information is crucial under the background of rain gauge networks deterioration. It can help to understand how the distribution of rain gauges impacts the capability of network and qualify of rainfall information provided by the network.

Rain gauge network design is to analyse the number and location of stations necessary for achieving the required accuracy (Bras, 1990) and meet the objective of information provided by the network as efficiently and economically as possible (Hackett, 1966). Varies approaches using optimal selection of rainfall gauges have been applied in designing rain gauge network to yield greater precise of rainfall estimation with minimum cost. Eulogio (1998) presented an optimal network design for the estimation of areal mean rainfall events by using simulated annealing method which demonstrated that the simulated annealing algorithm of random search for optimal location of rain gauges took into account the double criterion of estimation accuracy and economic cost. Patra (2001) applied a statistical theory for rain gauge network design. The study took use the coefficient of variance and the acceptable percentage of error range to estimate the optimal number of rain gauges. St-Hilaire et al. (2003) evaluated the impact of meteorological network density on the estimation of basin precipitation and runoff in five drainage basins in Mauricie watershed in Quebec, Canada by using Kriging method to estimate the spatial distribution and variance of rainfall. Dong et al. (2005) used variance reduction analysis method to find the appropriate quantity and location of rain gauges in Qingjiang River Basin, China for flow simulation. The study demonstrated that both cross correlation coefficient and modelling performance increase hyperbolically and level off after five rain gauges for the study area. Anctil et al. (2006) applied the method of randomly selection of rain gauges to produce subsets of rain gauge network to optimize the mean daily areal rainfall series in Bas-en-Basset watershed, southern France and using genetic algorithm to orient the rain gauge combinatorial problem toward improved forecasting performance.

Bárdossy and Das (2008) studied the influence of the spatial resolution of rainfall input on the model calibration and application by varying the distribution of the rain gauge network via External Drift Kriging method (EDK) in southwest of Germany and pointed out that the overall performance of the HBV model worsens radically with an excessive reduction of rain gauges, while there is no significant improvement of the model by increasing the number of rain gauges more than a certain threshold number. Chen et al. (2008) applied Kriging and entropy algorithm to design the rain gauge network which contains the minimum number of rain gauges and optimum spatial distribution in Taiwan, China.

The summer flash rainfall exhibits particularly high spatiotemporal variability and produces severe, quick, and sharply peaked flash flooding at the study site (Desilets et al., 2008), and the monitoring of summer flash rainfall represents the most difficult and important challenge for a rain gauge network designed for flood prediction. Volkmann et al. (2010) designed rain gauge networks for flash flood prediction in semiarid catchments with complex terrain to predict flash flood. The results revealed that the multi-criteria strategy provided a robust design by which a sparse but accurate network of rain gauges could be implemented for semiarid basins such as the one studied.

Precipitation gauge network structure is not only dependent on the station density; station location also plays an important role in determining whether information is gained properly. Gupta et al. (2002) and Yatheendradas et al. (2008) pointed out that rapidly changing patterns of precipitation over mountains are poorly monitored, and there are gaps in the information important to the modelling of runoff generation which makes it difficult to obtain sufficient leading time and accuracy on hydrological forecasts. Therefore, the design of hydrological measurement networks has received considerable attention in research settings.

The issue of optimizing rain gauge network can be formulated as that of finding the locations of a limited number of rain gauges which provide sufficient rainfall information of both the spatial distribution and the areal mean precipitation. Thus, the main objectives of this paper are motivated to: (1) understand and quantify the variability of the precipitation in catchment scale using the Shannon’s entropy and mutual information method; (2) design and evaluate a new entropy theory based multi-criteria strategy for identifying the best locations for installation of rain gauges based on the existing dense rain gauge network; and (3) evaluate the impact of the different rain gauge networks on hydrological simulation by using the lumped and distributed hydrological models.