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Rain gauge network design for flood forecasting using multi-criteria decision analysis and clustering techniques in lower Mahanadi river basin, India

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ABSTRACT

Study region: Mahanadi Basin, India.
Study focus: Flood is one of the most common hydrologic extremes which are frequently experienced in Mahanadi basin, India. During flood times it becomes difficult to collect information from all rain gauges. Therefore, it is important to find out key rain gauge (RG) networks capable of forecasting the flood with desired accuracy. In this paper a procedure for the design of key rain gauge network particularly important for the flood forecasting is discussed and demonstrated through a case study.
New hydrological insights for the region: This study establishes different possible key RG networks using Hall's method, analytical hierarchical process (AHP), self organization map (SOM) and hierarchical clustering (HC) using the characteristics of each rain gauge occupied Thiessen polygon area. Efficiency of the key networks is tested by artificial neural network (ANN), Fuzzy and NAM rainfall-runoff models. Furthermore, flood forecasting has been carried out using the three most effective RG networks which uses only 7 RGs instead of 14 gauges established in the Kantamal sub-catchment, Mahanadi basin. The Fuzzy logic applied on the key RG network derived using AHP has shown the best result for flood forecasting with efficiency of 82.74% for 1-day lead period. This study demonstrates the design procedure of key RG network for effective flood forecasting particularly when there is difficulty in gathering the information from all RGs.

1. Introduction

Information of rainfall is the primary requirement of all flood forecasting models. It is not always possible to gather information from all rain gauges (RGs). The reason could be many. In particular, during flood time there may be chances of failure, breaking, non-recording of RGs, difficulty in transmission of information etc. In large catchments these uncertainties are more prominent. Furthermore it is also mentioned that the climatic changes affect rainfall amounts, rainfall patterns, runoff amounts, and runoff coefficients (Ponce et al., 1997). Research for establishing key RG network is imperative. Kagan (1966) suggested a procedure to compute the error in estimation of aerial rainfall which could be used in estimation of

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key network density of RGs. Hall (1972) suggested a rational method for determination of key station network. Lohani and Arora (1992) suggested key network stations for flood forecasting purpose. Morin et al. (1979) advocated the use of principal component analysis in conjunction with optimal interpolation for RG network design. Sreedharan and James (1983) used the spatial correlation technique proposed by Kagan for design of RG network. Cheng et al. (2008) have applied a geo-statistical approach for evaluation and augmentation of an existing rain-gauge network in northern Taiwan. Lohani and Arora (1995) compared various precipitation network design methods.

Saaty (1980) has introduced analytical hierarchical process (AHP) for solving the complex decision oriented problems. It can make decisions involving many kind of concerns including planning, setting priorities, selecting the best among a number of alternatives and allocating resources. From its inception, and arising from its concise mathematics and easily obtained input data, the AHP has been of great interest to researchers of many different fields (Triantaphyllou and Mann, 1995; Lin (2006)). Anane et al. (2008) have located and ranked suitable sites for soil aquifer treatment in Jerba Island by integrating a single-objective AHP method into a GIS model. Sinha et al. (2008) have done a multi-parametric approach using AHP and integrates geo-morphological, land cover, topographic and social (population density) parameters to propose a Flood Risk Index for Kosi River. Kevin et al. (2009) has initiated AHP for finding of best management practices in selection and design of storm water schemes. An AHP can effectively deal with both qualitative and quantitative factors in multiple criteria decision environments. AHP is an important decision tool because of its ability to synthesize multi-attributed scenarios and provide diagnostic information, which enables decision makers to better understand the behavioral processes underlying choices.

Acreman and Sinclair (1986) used hierarchical clustering (HC) algorithm for clustering basins for flood frequency in Scotland according to their physical characteristics. Fovell and Fovell (1993) used HC along with principal component analysis (PCA) for identifying climatic regions of the United States based on monthly rainfall and temperature data. Lim and Lye (2003) used hierarchical clustering (average linkage method) in order to delineate homogeneous sub-regions in Sarawak, Malaysia. Jingyi and Hall (2004) used K-mean, Fuzzy C-mean, hierarchical clustering (Ward's method) and Kohonen self organising feature map for clustering the Gan-Ming River basin of China. Kar et al. (2011) used clustering technique for regional flood frequency analysis.

Earlier artificial neural network (ANN) has been applied successfully in several fields of water resources. However the applications in the field of rainfall–runoff modeling and flood forecasting are most popular. The works of Tokar and Markus (2000), Zhang and Govindaraju (2000), Harun et al. (2001), Rajurkar et al. (2002), Sudheer et al. (2002), Riad et al. (2004), Kalteh (2008), Modarres (2009) have shown significance of ANN in rainfall–runoff modeling. In flood forecasting, there is need for models capable of efficiently forecasting water levels and discharge rates. In this regard application of ANN is more effective and the works of Minns and Hall (1996), Campolo et al. (1999, 2003), Imrie et al. (2000), Lekkas et al. (2004), Coulibaly et al. (2000), Dawson and Wilby (2001), Muhamad and Hassan (2005), Mukerjee et al. (2009), Kar and Lohani (2010), Kar et al. (2011), Agarwal et al. (2013) and Lohani and Krishan (2015) emphasized the capability of artificial neural networks over other methods.

Simultaneously, fuzzy logic based approaches (Zadeh, 1965) are also found suitable for hydrological modeling like rainfall–runoff, flood forecasting and risk assessment (Rai et al., 2014). Hundecha et al. (2001) developed fuzzy rule based routines to simulate different processes involved in the generation of runoff from precipitation. These routines were implemented in Neckar river catchment of Germany within a conceptual, modular and semi-distributed HBV model. Casper et al. (2007) framed the runoff model taking soil moisture and rainfall as input through a fuzzy rule based model. Nayak et al. (2005) developed the fuzzy model for forecasting the river flow of Narmada River basin in India. Lohani et al. (2005a, 2014) have applied fuzzy logic in real time flood forecasting of Narmada River basin. Capability of fuzzy logic in hydrologic modeling and forecasting is also demonstrated by Yu and Chen (2005), Valenca and Ludermir (2009) and Lohani et al. (2005b, 2006, 2011, 2012).

The conceptual NAM model is also very popular in rainfall–runoff modeling and thereby very useful for setting the flood forecasting models. Dharmasena (1997) successfully applied Mike-11 package to simulate one-dimensional unsteady flow. He also found conceptual models giving better results especially for rivers subjected to prolonged droughts. Tingsanchali and Gautam (2000) compared two lumped conceptual hydrologic models like tank and NAM with a neural network model applied in two river basins in Thailand. The works of Rabuffetti and Barbero (2005) also showed the application of NAM model.

In this study different possible key RG networks have been designed from the available RG network in the Tel sub-catchment, Mahanadi, India using Hall method, AHP, HC and SOM. Efficiency of the key networks is tested by ANN, Fuzzy and NAM and the best network has been used for flood forecasting. Further, flood forecasting has been carried out with the key RG networks. Although, the best RG network has shown highest efficiency, simultaneously other networks were also tested with certain designated efficiency in order to use them at the time of failure of the best RG network.

2. Study Area

The Mahanadi basin is one of the major basins of eastern part of India. It lies between 80°-30′ to 86°-50′ of East Longitude and 19°-20′ to 23°-35′ of North Latitude. The total catchment area of the basin is 141,569 km^2 comprises major part of two states Chhatisgarh and Orissa. The major reservoir Hirakud with 83400 km^2 catchment lies at central part of the Mahanadi basin.