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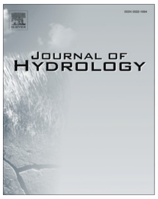

Watershed rainfall forecasting using neuro-fuzzy networks with the assimilation of multi-sensor information

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SUMMARY

The complex temporal heterogeneity of rainfall coupled with mountainous physiographic context makes a great challenge in the development of accurate short-term rainfall forecasts. This study aims to explore the effectiveness of multiple rainfall sources (gauge measurement, and radar and satellite products) for assimilation-based multi-sensor precipitation estimates and make multi-step-ahead rainfall forecasts based on the assimilated precipitation. Bias correction procedures for both radar and satellite precipitation products were first built, and the radar and satellite precipitation products were generated through the Quantitative Precipitation Estimation and Segregation Using Multiple Sensors (QPESUMS) and the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Cloud Classification System (PERSIANN-CCS), respectively. Next, the synthesized assimilated precipitation was obtained by merging three precipitation sources (gauges, radars and satellites) according to their individual weighting factors optimized by nonlinear search methods. Finally, the multi-step-ahead rainfall forecasting was carried out by using the adaptive network-based fuzzy inference system (ANFIS). The Shihmen Reservoir watershed in northern Taiwan was the study area, where 641 hourly data sets of thirteen historical typhoon events were collected. Results revealed that the bias adjustments in QPESUMS and PERSIANN-CCS products did improve the accuracy of these precipitation products (in particular, 30–60% improvement rates for the QPESUMS, in terms of RMSE), and the adjusted PERSIANN-CCS and QPESUMS individually provided about 10% and 24% contribution accordingly to the assimilated precipitation. As far as rainfall forecasting is concerned, the results demonstrated that the ANFIS fed with the assimilated precipitation provided reliable and stable forecasts with the correlation coefficients higher than 0.85 and 0.72 for one- and two-hour-ahead rainfall forecasting, respectively. The obtained forecasting results are very valuable information for the flood warning in the study watershed during typhoon periods.

1. Introduction

Rainfall is a key hydrological variable that links the atmosphere and land surface processes. The complex temporal heterogeneity of typhoon rainfall coupled with mountainous physiographic context makes the development of accurate forecasting reservoir inflow several hours ahead of time a great challenge. Typhoons are commonly coupled with heavy rainfall. For instance, the highest rainfall record of Typhoon Morakot was over 1000 mm/day in southern Taiwan in 2009. Due to abundant rainwater, the inundation disaster occurred in most of this area and caused more than USD 0.5 billion losses. The fatally rainfall-induced landslide buried the entire Shaoling village, which killed about 500 people in the village alone. Consequently short-term typhoon rainfall forecasting is recognized as the most important study for reservoir watershed management and flood mitigation in Taiwan. As far as rainfall forecasting is concerned, the accuracy of precipitation products and their nowcasting is continuously improved and becomes more reliable for practical applications in recent years. For example, Kober et al. (2012) blended a probabilistic nowcasting method with a high-resolution numerical weather prediction assimilated for convective precipitation forecasts. Haiden et al. (2011) presented the integrated nowcasting through a comprehensive analysis system and provided the products of precipitation amount and types. Sokol (2006) applied a multiple linear regression model

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complemented by a correction procedure for nowcasting of 1-h precipitation using radar and numerical weather prediction data. Sokol and Pesice (2012) proposed a model SAM for nowcasting 1 to 3-h precipitation totals and improved forecasts accuracy. Zahraei et al. (2012) introduced a pixel-based algorithm for short-term quantitative precipitation forecasting using radar-based rainfall data and shown promising performance in severe storms forecasting.

Precipitation observations, in general, are available from several sources, such as ground rain gauges, radars and satellites. These sources not only have significant differences in both spatial and temporal resolutions but also have different limitations subject to hardware mechanisms. Ground gauges observe surface precipitation continuously and directly, however, gauges are sparsely located and only provide point-scale measurements, which imply the spatial representation of gauges is weak. Radars use reflected microwave energy to derive precipitation at a height between about 500 m and 5000 m above sea level, however, radar coverage is many times limited by orography. Satellites, whose coverage is not limited by orography, provide rapid precipitation information over large areas. However, satellite measurements not only are indirectly related to surface precipitation but also have lower spatial and temporal resolutions, as compared to those of radar products. On account of the different strengths and weaknesses of each measurement technology, a potential advantage is thereby to integrate precipitation measurements from different measurement apparatuses such as gauges, radars and satellites for improving the accuracy of rainfall forecast (Grecu and Krajewski, 2000; Kidd et al., 2003; Chiang et al., 2007a; Mittermaier, 2008).

The Artificial Neural Network (ANN) was inspired by neurobiology to perform brain-like computations and has been recognized as an effective tool for modeling complex nonlinear systems in the last two decades. The applications of ANNs to various aspects of hydrological modeling have provided many promising results, such as rainfall estimation/prediction (Hong et al., 2005, 2006; Chiang et al., 2007a; Chen et al., 2011), flood forecasting (Chiang and Chang, 2009; Siou et al., 2011; Yilmaz et al., 2011), and water level prediction (Chiang et al., 2010; Adamowski and Chan, 2011). Neuro-fuzzy systems that combine ANNs and fuzzy theories have proven to be another powerful intelligent system and have received much attention in recent years (Chang et al., 2005; Coulibaly and Evora, 2007; Firat, 2008; Lohani et al., 2011). Both ANNs and fuzzy theories have been developed to simulate the thinking process of human brain for learning similar strategies or experiences to make optimal decisions. Nevertheless, the fundamental mechanisms of these two theories are different, in which ANNs offer a superior capability to extract significant features from complex databases and are capable of learning the relationship between any data pairs, whereas the fuzzy logic is based on the way how brains deal with inexact information. Due to the lack of learning capability for fuzzy theories, it is difficult to tune the fuzzy rules and membership functions based on training data. Therefore, the neuro-fuzzy system was developed for capturing the advantages and strengths of both ANNs and fuzzy logic in a single framework. The adaptive network-based fuzzy inference system (ANFIS), proposed by Jang (1993), is one of the famous neuro-fuzzy systems and has been applied to modeling daily discharge responses (Kurtulus and Razack, 2010), water level prediction (Chiang et al., 2011), and rainfall-runoff simulations (Shu and Ouarda, 2008).

This study aims at providing reliable and accurate short-term typhoon rainfall forecasts using artificial intelligent (AI) techniques based on the assimilation of satellite- and radar-derived rainfall estimations and ground gauge measurements. The organization of this paper is addressed as follows. The description of the study area, ground measurements, radar-derived and satellite-derived precipitation estimation as well as the model construction is provided in Section 2. Section 3 presents the methodologies, including the back-propagation neural network (BPNN) for bias adjustment, the genetic algorithm (GA) for data merge, and the ANFIS for rainfall forecasting. Section 4 shows the results and comparison of two bias correction strategies, the effectiveness of merging precipitation products, and the performance of rainfall forecasting. Finally, the conclusions are given in Section 5.

2. Materials

2.1. Study area and gauging station datasets

The study area of this study belongs to the Shihmen Reservoir watershed and is located on the upstream of the Tahan River in northern Taiwan. Fig. 1 shows the locations of the Shihmen Reservoir watershed where the reservoir inflow gauging station is denoted with a blue[1] star, each radar station is denoted with a purple square, and each of thirteen rain gauging stations is denoted with a red dot. All the thirteen rain gauging stations are spatially well distributed below 2000 m in elevation. Under this condition, no rain gauge is set up above 2000 m. Alternatively, remote sensing, such as radar and satellite, is considered to provide rainfall information for areas above 2000 m. This watershed receives an annual rainfall of about 2500 mm, which mainly comes from typhoons. Because rainwater usually occurs in a short duration with great intensity, heavy rainfall coupled with huge runoff would flows into the Reservoir in just a couple of hours. Consequently, reliable typhoon rainfall forecasting plays an important role in reservoir operation and management because typhoons usually affect Taiwan for about 3–5 days. Four types of data, including reservoir inflow (m^3/s), rain gauge measurements (mm), and radar- and satellite-derived precipitation estimations (mm) were collected from 2006 to 2009 in this study. A total of 641 hourly data associated with thirteen historical typhoon events were obtained.

2.2. Radar-derived precipitation datasets

The radar-derived precipitation estimation applied in this study can be referred to the QPESUMS (Quantitative Precipitation Estimation and Segregation Using Multiple Sensors) system (http://qpesums.cwb.gov.tw/taiwan-html2/), which was developed by the Central Weather Bureau (CWB) of Taiwan and the National Severe Storms Laboratory (NSSL) of National Oceanic and Atmospheric Agency (NOAA) of the USA. The QPESUMS system mainly composes of four weather Doppler radars that cover the whole of Taiwan and the adjacent ocean, and it records base reflectivity with a spatial resolution of 0.0125° in both longitude and latitude and a temporal resolution of 10 min. The R_1 radar station has the shortest distance to the study area (less than 80 km) and is located at longitude 121.46°E and latitude 25.04°N with an elevation of 760 m. This radar belongs to the Weather Surveillance Radar 1988 Doppler (WSR-88D) with a wavelength of 10 cm (S-band) and performs approximately 10 different elevation scans (between 0.5° and 15° above the horizon) that consist of a complete volume scan. The beam width is 0.857°. The system generates the constant altitude plan position indicators (CAPPI) at the elevation of 1000 m and estimates rainfall using the Z–R relation with the function type $Z = 32.5R^{1.65}$. Therefore, the records of 434 grid pixels are collected to cover the whole of the watershed for every 10 min. Even though the QPESUMS system is used to monitor rainfall in Taiwan, the Z–R relationship for converting radar reflectivity to rainfall rates can be affected by various problems, such as ground clutter and beam

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[1] For interpretation of color in Figs. 1 and 5, the reader is referred to the web version of this article.