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Research paper

Fuzzy logic based flood forecasting model for the Kelantan River basin, Malaysia

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Abstract

Among other flood forecasting tools, fuzzy logic is one of a simple and flexible approach which can be implemented in river basins where adequate hydrologic data is available and not good enough to use in a more sophisticated model. This paper assesses the potential of fuzzy logic approach for real time flood forecasting using the minimum implication function type Mamdani fuzzy inference system by applying the model to the Kelantan River basin in Malaysia. The developed models were tested for forecasting the downstream water levels of Guilemard and Kuala Krai stations using upstream hourly telemetric water levels of Dabong and Tualang stations. The membership functions (MFs) of triangular shapes with several fuzzy rule sets were utilized to check the efficiency of the fuzzy logic approach for the Kelantan River flood forecasting. For the Guilemard station, models of 8, 10 and 15 rules' sets were tested. In the calibration and validation events, the Guilemard station models' achieved MAE, ranges 0.35–0.45 m, N–S coefficient, ranges 0.87 – 0.89 and Coefficient of Determination ranges, R^2 ranges 0.91–0.95. The water level prediction model developed for the Kuala Krai station consisted of 19 rules with triangular shape MFs. It shows the ranges for MAE: 0.26–0.76 m, N–S coefficient: 0.78–0.93 and R^2: 0.91–0.96 in calibration and validation periods. The efficiencies of the developed models show acceptable levels according to the tested performance indicators implying the potential of establishing a flood forecasting system by using the fuzzy logic approach in the Kelantan River basin, Malaysia.

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1. Introduction

Physically based, conceptual and data driven models are common in hydrology as a tool to convert measurable input data set that trigger floods into a measurable output data set which can estimate the flood. Physically based models are descriptive in physical processes of the target catchment. A large number of parameters are involved in physically based modeling and the estimation of those parameters is a tedious task. Conceptual models assume a simplified structure for the rainfall–runoff process such as the tank model, which is less realistic and their flexibility is low. Data driven models are based on empirical, stochastic or systems theory concepts. The data driven approaches such as artificial neural networks, support vector machines and fuzzy logic based models which are based on system theory, are widely used in modern day applications. Simple and flexible models with minimum data requirement are sought to solve problems where the data required for physical models is limited and the incidence where the inherited processes of the system is complex enough to solve by physically based or conceptual models. As an option to such inconveniences, mathematical models based on linguistic variables rather than conventional numerical variables have emerged in hydrological modeling. Fuzzy logic is an approach based on linguistic variables to model the processes which take place within the hydrologic cycle.

Zadeh (1965) developed fuzzy set theory allowing the mathematical modeling in zones of imprecisions and uncertainties. Fuzzy set theory is a generalization of the Boolean logic to situations where data are modeled by entities whose attributes have zones of gradual transition, rather than sharp boundaries. In the fuzzy logic approach input and output relationships are

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described verbally rather than considering the known physical relationships. Establishment of these relationships depends on the observations of trends between the inputs and outputs. Unlike mathematical models that require precise knowledge of all the contributing variables, fuzzy logic, on the other hand, offers a more flexible, less assumption-dependent and self-adaptive approach to model hydrological processes, which by their nature, are inherently complex, non-linear and dynamic. Moreover, this technique can be used for modeling systems on a real-time basis. Other advantages include: the potential for improved performance, faster model development and execution time and, therefore, reduced costs, the capability to plug fuzzy logic directly into conventional models and the ability to provide a measure of prediction certainty.

Hundecha et al. (2001) developed a fuzzy rule-based routines to simulate the different processes involved in the generation of runoff from precipitation. Luchetta and Manetti (2003) applied fuzzy clustering approach to forecast a real time hydrological model in the Padule di Fucecchio basin in Italy. Takagi-Sugeno fuzzy inference system based rainfall–runoff model was developed by Jacquin and Shamseldin (2006) and tested for six catchments located in Australia, China, Ireland, Nepal, and USA. Chen et al. (2013) used an event-based fuzzy inference model to forecast the typhoon flood stages of Wu River in Taiwan. Jayawardena et al. (2014) tested the performances of Mamdani, Larson and TSK fuzzy logic approaches by applying those models to several basins in Asia and highlighted the importance of high resolution data such as hourly data to achieve high performances from fuzzy models. In the present paper, authors applied Mamdani fuzzy inference system with hourly data and simple triangular shaped MFs to forecast water levels at two gauging stations located at the Kelantan River basin. Apart from the aforementioned applications, fuzzy logic based hydrological modeling applications can be found in various studies, include water level forecasting (e.g. See and Openshaw, 1999, 2000; Alvisi et al., 2006), water consumption prediction (e.g. Altunkaynak et al., 2005), river flow or flood forecasting (e.g. Yu and Chen, 2005; Tareghian and Kashefipour, 2007; Barreto-Neto and Filho, 2008; Lohani et al., 2012), infiltration modeling (e.g. Bárdossy and Disse, 1993), rainfall–runoff modeling (e.g. Xiong et al., 2001; Samanta and Mackay, 2003; Casper et al., 2007), reservoir operation (Fontane et al., 1997; Panigrahi and Mujumdar, 2000; Tilmant et al., 2002; Rusell and Compbell, 1996), water quality management (Sasikumar and Mujumdar, 2000) amongst others.

A flood forecasting model that can be easily understood and implemented is beneficial for the conditions prevailing in the Kelantan River basin, Malaysia. Several studies have been conducted to predict the Kelantan River runoff in recent past. Hong (2001) has studied the flood forecasting for the Kelantan River by employing a modified Tank model. Further Hoong (2007) has developed a Tank model based flood forecasting model for the basin. Basarudin et al. (2014) have analyzed extreme flood events occurred in the basin in 2004 and 2008 via semi-distributed HEC–HMS hydrological model. Ibrahim and Wibowo (2014) applied support vector regression to predict the water level of Galas River, an upstream sub-catchment of the Kelantan River. Comparing the studies that have been done in Kelantan basin for flood forecasting, and to the best of authors knowledge no studies have been conducted based on fuzzy logic to predict water levels in the Kelantan River. Therefore the purpose of this study is to demonstrate the applicability of fuzzy logic approach as a flood forecasting tool for the Kelantan basin.

2. Description of study area

The state of Kelantan belongs to the eastern region of peninsular Malaysia and is one of eleven states in peninsular Malaysia facing the South China Sea (Fig. 1). Kota Bharu is the capital of Kelantan as well as the development center of North Kelantan. Kelantan State has a total area of 15,099 km^2 which is equivalent to 4.4% of Malaysia's land area. The population is 1.539 million (DID, 2013). The basin has an annual rainfall of about 2500 mm, much of which occurs during the northeast monsoon between mid-October and mid-January. The mean annual temperature at Kota Bharu is 27.5 °C and the mean relative humidity is 81%. The Kelantan is the major river in the state of Kelantan. It has 4 main tributaries, namely Galas, Nenggiri, Lebir and Pergau. It is subjected to the northeast monsoon and flooding has been occurring every year typically during the months from November to January. Fig. 1 shows the river network of the Kelantan basin, major cities and hydrological stations. The total length of the river from the head of its longest tributary is 388 km and drains an area about 13,000 km^2 occupying more than 85% of the Kelantan state. The main river, Kelantan, with the length of about 105 km, is named for the stretch after the confluence of Lebir and Galas rivers at Kuala Krai. Kelantan River flows through several populated cities such as Kuala Krai, Tanah Merah and the state capital of Kota Bharu before discharging to the South China Sea. The population is also concentrated in the downstream where the capital city, Kota Bharu of the Kelantan state is located. The total population of the city is about 0.5 million and population density in the urbanized most downstream area is exceeding 20,000 ppl/km^2. Table 1 shows the historical floods and their impacts from 1990 to 2004 in Kelantan state. According to the Table 1, highest number of deaths was recorded as 12 in 2004 with the number of evacuees of 10,400 causing monetary loss of US$ 370,000. The highest monetary damage occurred in 1993 with value of US$ 2.22 million. The recorded historical floods, that the number of evacuees was always 100 or above which implies that those floods were severe. According to the past records intensive precipitations have become more frequent and more severe which cause frequent floods. Thus, a flood early warning system is essential to provide sufficient time for the authorities to evacuate the downstream communities to safer places and take necessary measures to protect physical properties in vulnerable areas.

At each of the water level stations in the Kelantan basin, the designated critical levels have been identified by the Drainage and Irrigation Department (DID) of Malaysia based on the local topography, previous flood disasters and local community information etc. where those levels are used to issue flood warnings to the downstream communities. The levels indicated

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