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Confluent flow impacts of flood extremes in the middle Yellow River

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ABSTRACT

Flood disaster has been one of the most frequent and devastating forms in middle Yellow River, China. Huge flood events transport sediments from upstream to downstream, and lead to changes of river morphology, such as river bed slope, channel roughness, and flood routing process. Flood disasters in the middle Yellow River were constantly caused by backwater effects due to multiple river stream confluence effects. The study aims to investigate confluent flood flow effects on flood routing processes, river morphology, and human activities based on a proposed flood flow model. The proposed model is constructed through coupling hydraulic equations, artificial intelligence neural network and probability theory. Flood frequency analysis is coupled with studies of hydrological routing processes that reduce the flood capacity of the rivers. Flood routing to the confluence were simulated using kinematic wave theory. Case studies have been carried out through field work and model simulation during the past years. Findings are achieved as followings. Firstly, flood frequency at the confluence implies that the confluent extreme flood occurs more frequently in the main streams than that in the tributaries due to influential intensity of East-Asian summer monsoon. Secondly, river morphology was altered partly due to complex flood routing processes in the middle Yellow River under the operation of Sanmenxia Reservoir. The alternated river channels changed the boundary conditions of flood routing, especially for backwater. Bed slopes have greater impacts on flood routing process than roughness does when there is larger flood flow. Finally, the evolution process of the sediment transportation is closely linked with the operations of the Sanmenxia Reservoir.

1. Introduction

Historically, flood extremes caused the most frequent and devastating forms of disasters (Zolina et al., 2004; Herget and Meurs, 2010; Kehew et al., 2010; Diodato and Bellocchi, 2012; Naidu et al., 2012; Tramblay et al., 2012). Flood disasters in the middle Yellow River were constantly caused by backwater effects due to the multiple river stream confluence effects (Qian, 1992; Yu and Lin, 1996; Wang, 2004; He et al., 2006, 2008). Much of the sediment is deposited on the channel bottom when the river flows downstream. Huge flood events transport sediments from upstream to downstream, and lead to changes of river morphology, such as river bed slope, channel roughness (He et al., 2006, 2008). River banks are frequently breached after heavy rains, leading to catastrophic floods which are regularly responsible for heavy loss of life and economic damage in the area (Cunnane, 1988; Burn, 1990, 1997; Bobee et al., 1996; Jain and Lall, 2000; Jun-Haeng et al., 2001; McKillop and Clague, 2007; Greenbaum et al., 2010; Herget and Meurs, 2010; Kehew et al., 2010). The operation of Sanmenxia Reservoir is regarded as a key contributor to severe silting and backwater refluxing (Qian, 1992; Yu and Lin, 1996; Wang, 2004; He et al., 2006, 2008).

The frequency of large-scale flood events shows an increasing trend in the middle Yellow River basin (Qian, 1992; Yu and Lin, 1996; Wang, 2004; McKillop and Clague, 2007). Flood frequency analysis has often been used previously in studying the trend of river floods (Beven, 1997; Macdonald and Werritty, 2001; Glaser and Stangl, 2003). Various indices, including skewness coefficient, Monte Carlo experiments distribution functions of normal, three-

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parameter lognormal, Gumbel, Pearson Type 3, Weibull, Pareto, and uniform, have been introduced to monitor river floods on the basis of the regional flood characteristics (Cunnane, 1988; Burn, 1990, 1997; Bobee et al., 1996; Jain and Lall, 2000; Jun-Haeng et al., 2001; Javelle et al., 2002; Palmer and Raisanen, 2002; Christensen and Christensen, 2003; Mudelsee et al., 2003; Greenbaum et al., 2010; Herget and Meurs, 2010; Naidu et al., 2012). These flood indices are effective in relating flood dynamics to precipitation. Simple correlation coefficients of flood discharges between rivers have been used to describe the frequency distribution of historic flood series (Obled and Creutin, 1986; Rao and Hsieh, 1991; Hisdal and Tveito, 1993; Loboda et al., 2005; He et al., 2006; Alpert et al., 2008). With gauge data, non-parametric multivariate empirical orthogonal function model is efficient to address the relationship between flood events of rivers (He et al., 2006).

Flood routing computational schemes are mostly derived from the Saint–Venant equations (Daluz, 1983; Cunnane, 1988; Ramamurthy, 1990; Camacho and Lees, 1999; Carrivick, 2006; Elleder, 2010) and other simplified wave models such as the kinematic wave, non-inertia wave, quasi-steady dynamic wave, and gravity wave approximations (Walters et al., 1980; Begin, 1986; Bartholy and Pongrácz, 2007; McKillop and Clague, 2007; Alpert et al., 2008; Elleder, 2010; Greenbaum et al., 2010). The common issues reported in previous studies are that simplified kinematic wave and gravity wave models were unable to account for the downstream backwater effect, and were not suitable for modeling the flood wave propagation in mild-sloped rivers. Special attentions have been paid to the investigation of the distinctive drainage characteristics of the middle Yellow River in the study of flood routing to simulate the flood wave propagation with a downstream backwater effect of complex flood routing, such as bidirectional flow (He et al., 2006, 2008). A bidirectional flood flow evolution computation scheme is developed and efficiently used to simulate the complicated flood flow evolution according to the complex flood flow situation in the middle Yellow River (He et al., 2006, 2008). Computational scheme for bidirectional flow is focused on modeling of backwater flood flows travelling in the opposite directions.

Flood flow and sediment transport in reservoir are important in addressing engineering hydrodynamics research. Conventional methods and models available for estimation of reservoir sedimentation process differ greatly in terms of complexity, inputs, and other requirements (Jain and Lall, 2000; Jun-Haeng et al., 2001; Javelle et al., 2002; Palmer and Raisanen, 2002). Quantitative analysis is required for understanding of the character of the sediment in motion (Ramamurthy, 1990; Camacho and Lees, 1999; Carrivick, 2006). A number of empirical and semi-empirical sediment transport formulae have been developed for use in riverine applications (Obled and Creutin, 1986; Rao and Hsieh, 1991; Hisdal and Tveito, 1993; Carrivick, 2006; McKillop and Clague, 2007; Alpert et al., 2008). However, estimation of reservoir sedimentation has been the subject for quite a long time, and it is not an easy task due to complicated simultaneous processes involved such as sediment transport, erosion, and deposition. In recent years, the artificial neural network ANN technique has shown excellent performance in regression, especially when used for pattern recognition and function estimation (ASCE Task Committee on Application of the Artificial Neural Networks in Hydrology, 2000a, 2000b). It is a highly nonlinear tool that can capture complex interactions among the input and output variables without any prior knowledge about the nature of these interactions. In comparison to conventional, ANNs can tolerate imprecise or incomplete data, approximate information, and presence of outliers and are well suited to this problem (Sudheer et al., 2002; McKillop and Clague, 2007).

The study aims to investigate flood extremes impacts in the middle Yellow River in perspectives of occurrence frequency, refluxing flood routing process, and river morphology changes along with sediment transportation. The characteristics of flood wave propagation under different flood routing boundary conditions is investigated by backwater refluxing computation scheme, followed by analysis of impacts of flood propagation and sediment transportation on river morphology. The simulation analysis is able to improve our understanding of flood routing of backwater refluxing and sediment transportation in the middle Yellow River.

2. Study area

Our study area is in the middle of Yellow River (between Hekou to Huanyuankou–Taohuayu) spanning from (35° N, 105° E) to (41° N, 115° E) as displayed in Fig. 1. The site has a drainage area of 32,354 km^2, which accounts for 43% of the whole Yellow River watershed. We focus on the main stream and its two tributaries, the Weihe River and the Luohe River. The Luohe River is the tributary of the Weihe River which flows into the middle Yellow River at Tongguan. The elevation of Tongguan controls the base level of the Weihe River, and influences the operation behaviours of Sanmenxia Reservoir (construction in1957–1960 and reconstruction in 1969–1978). The confluence area of the middle Yellow River network consists of the main river stream and its four tributaries, including Weihe River, Jinghe River, Luohe River and Fenhe River in the middle Yellow River.

Annual precipitation in the study area ranges from 300 mm to 1000 mm. About 48% of the annual totals (145 mm–480 mm) fall in the summer season (from July to August) in the form of rainstorms (rainfall amounts are over 50 mm in 24 h). Floods occur frequently after rainstorms. They transport large amount of sediments along the Weihe River and the middle Yellow River and finally deposits them in the lower Weihe River. The fluvial sediments gradually change river channel conditions, such as river bed elevation and roughness. Improper human activity, such as the construction of Sanmenxia Dam, also contributed to the shrinkage of river channels in the study area. Consequently, backwater happened in the middle Yellow River basin due to hydraulic condition changes.

3. Material and methods

3.1. Data collection

A catalogue of historic flood events for the study area is compiled primarily from the archives of Systematic Research and Countermeasures for Huge Natural Disasters (China Disaster Prevention Committee, 1993), and using documents on China History Floods before 1990 (Huang, 1989). Gauge data (1950–2010) collected from the State Flood Control and Drought Relief Headquarters is used to improve the accuracy of the flood evaluation in the study area. Gauge data of 17 flood events were collected in different time periods from 1954 to 2010, of which four flood events were used to calibrate the model, and four others were selected to examine the model efficiency through simulation results. Input data to simulation model include topographic, hydraulic and hydrometric datasets. Topographic data, such as river channel roughness, river bed slope, distance between particular cross-sections, were extracted from 30-m Digital Elevation Model (DEM, from IRSA, CAS). Hydraulic and hydrometric data such as flood flow radius, width, and cross-section area, flood flow velocity, discharge and water level in each cross-section were obtained from gauge data compiled in the State Flood Control and Drought Relief Headquarters (State Flood Control and Drought Relief Headquarters, 1992).

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