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A framework approach for unravelling the impact of multiple factors influencing flooding

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Key words
Conditional inference tree analysis; cross-correlation analysis; dam construction; flooding; framework approach; precipitation–discharge relationship.

Abstract

To have a better understanding of the influence of topographic, climatic, and, especially, anthropogenic factors on hydrological discharge and flooding, this study proposes a new framework approach using a set of methods to answer the questions why, where, when, and how flooding occurs. Including conditional inference tree (CIT), cross-correlation, and double-mass curves analysis, the approach is demonstrated in an application to the Wei River Basin, China. From the CIT analysis, dam construction period was identified as the most important factor (why), and the sub-catchment farthest upstream contributed the most to the flooding of the downstream floodplain (where). We then analysed the effect of the periods of dam construction on the time lag change (when) and the precipitation–discharge relationship (how) using cross-correlation analysis and double-mass curves analysis, respectively. The results suggested that the dam construction delayed the precipitation for 0.4 days on average compared to before the dam construction period, and the discharge at the outlet of the basin was reduced by 44%. This framework approach is promising as it can quantitatively evaluate the importance of multiple factors on multiple years of flooding, while many studies evaluate single flooding events.

Introduction

Flood hazard has become a growing concern due to an increasing number of extreme meteorological events and human intervention in the hydrological cycle (IPCC, 2013). Studies of the causes and characteristics of different kinds of floods, ranging from coastal regions, urban areas, and large river catchments to flash floods have been undertaken worldwide (Islam and Sado, 2000; Thumerer *et al.*, 2000; Cançado *et al.*, 2008). The assessment of flood risk on different scales has also been studied worldwide (Islam and Sado, 2000; Gao *et al.*, 2007; Delgado *et al.*, 2010; Mohamed Elmoustafa, 2012). Studies of palaeofloods have suggested that extreme floods are usually associated with unique atmospheric patterns (Huang *et al.*, 2007; Li *et al.*, 2014). The interaction between precipitation and stream flow has thus been the main focus for flood prediction and studies of risk assessment (Peng *et al.*, 2014; Huang *et al.*, 2015a,b). These and other studies worldwide have concluded that the causes of flooding can be categorised into three groups: (1) topographic factors; (2) climatic factors, and (3) anthropogenic factors (Table 1). A comprehensive and accurate evaluation of flood risk requires knowledge of the factors that have triggered a flood and how these indicators influence the flood risk.

Precipitation has a direct impact on flooding, and the topography of catchments has an influence on the spatial distribution of soil moisture and thus evapotranspiration and surface and subsurface run-off (Wilson *et al.*, 2005; Hardie *et al.*, 2011). The differentiation in the hydrology of upslope and downslope regions caused by steep slopes can be offset by fine-textured soil and an increase in evapotranspiration (Berger and Entekhabi, 2001; Neupane *et al.*, 2015; Peng *et al.*, 2015).

The stationary theory of flood risk on a fluvial system has been challenged due to the effect of sediment deposition and the influence of water infrastructure, channel

Table 1 Synopsis of the factors influencing floods

Topographic factors	Climatic factors	Anthropogenic factors
Slope	Temperature	Change in land use and cover
Elevation	Precipitation	Vegetational coverage
Soil properties	Wind	Water diversion
	Solar activity	Dam and reservoir construction

modifications, and changes in land cover and use (Plate, 2002; Milly *et al.*, 2008). The diversion of water, construction of reservoirs, and even the installation of small dams can dramatically alter the hydrological characteristics of a drainage basin (Braatne *et al.*, 2008; Shaw *et al.*, 2014). Gao *et al.* (2010) have identified water diversions for irrigation and urban and industrial use, measures of soil and water conservation, and the construction of water-control projects as some of the human interventions that led to the trend of decreasing discharge in the Yellow River. The construction of the Sanmenxia Dam on the Yellow River was the most influential project. The dam has changed the processes and morphology of the Wei River (Wang *et al.*, 2007) because the outlet of the Wei River is controlled by the elevation and discharge of the Yellow River. The Sanmenxia Dam has increased sediment deposition in both rivers, and the raised bed of the Wei River has reduced the drainage capacity of the river and has even led to water drawback. The number of floods has thus increased since the construction of this dam.

Urbanisation decreases the cover of vegetation and increases direct runoff, which increases discharge. Urbanisation also decreases the time lag between the effective precipitation and peak discharge (Islam and Sado, 2000; Liu *et al.*, 2014b). The large Grain to Green project implemented in 1999 is an example of land-use change in which farmers are compensated for converting cultivated areas to green land (Jian *et al.*, 2015). Not only the urbanisation developed rapidly, but also the conversion of cropland to woodland and grassland increased substantially between 2000 and 2010 on the central Loess Plateau (Liu *et al.*, 2014a). The impact of these dramatic changes on discharge, however, has been poorly studied.

Many methodologies have been applied to evaluate the impact of distinctive factors on flooding or the associated hydrological processes. Models are often used to explore the effect of unique factors on river discharge or water yield (Braud *et al.*, 2001; Schreider *et al.*, 2002; Brath *et al.*, 2003; Bormann *et al.*, 2005; Bormann *et al.*, 2007; Yihdego and Webb, 2013). Double-mass curve analyses are widely used to understand the precipitation–discharge relationships in hydrological studies and for filling gaps in gauge records (Kliment and Matoušková, 2006; Abedini *et al.*, 2013; Gao *et al.*, 2013; Choi *et al.*, 2016). Double-mass curves are also used to test long-term discharge trends and together with Mann–Kendall tests are thus suitable for examining the impact of human activities over a certain time period (Kliment and Matoušková, 2009; Matoušková *et al.*, 2011; Zhang *et al.*, 2012). Cross-correlation is able to identify the time lag between precipitation and its correlated discharge measured at the hydrological station for a single event (Talei and Chua, 2012; Löwe *et al.*, 2014) but has not been used for exploring the precipitation–discharge relationship over a long period.

The effect of climate change and human activities on hydrological processes has been studied in a variety of Chinese catchments (Ma *et al.*, 2010; Wang *et al.*, 2010; Ye *et al.*, 2013). The Wei River Basin is one of the most important sites for studying the influence of all factors on hydrological processes due to its delicate environment and large-scale human intervention. The causes and characteristics of individual floods in the basin have been extensively analysed (Jiang *et al.*, 2004; Xing *et al.*, 2004; Pang, 2007; Tao and Dang, 2011). Human activities have contributed up to an estimated 80% of the change in discharge of the Wei River (Gao *et al.*, 2013; Zhao *et al.*, 2013). A large range of studies has begun to address the flood hazard of the Wei River Basin (Jiang *et al.*, 2004; Li and Wu, 2011; Yin *et al.*, 2012; Peng *et al.*, 2014). However, a comprehensive study or an integrated approach to identify the most influential factors causing flooding in the Wei River over multiple years (as opposed to individual floods) at both spatial and temporal scales is still lacking. Especially in the multitude of impacts from multiple factors, it is difficult to explore the importance and the contribution of each factor in comparison to others.

The objective of this study was thus to analyse the characteristics of floods in the Wei River Basin over the last 60 years and to understand the impacts of various factors on flooding and discharges using a new framework approach that is capable to analyse this multitude of potentially contributing factors over multiple years. Using this framework, we specifically focused on the following questions. (1) Why: what are the most important factors influencing flooding of the catchment on a monthly and yearly basis? (2) Where: what is the most influential location (sub-catchment) to the downstream flood regarding the discharge? (3) When: what is the effect of the identified factor on the time lag between precipitation and discharge? And (4) How: how does the identified factor affect the precipitation–discharge relationship? The new framework approach includes a set of methods to answer the above four questions in a systematic way.

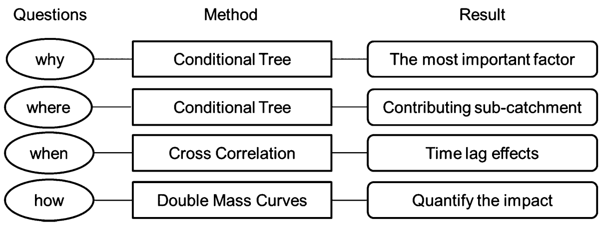

Figure 1 The structure of the framework approach for analysing the impact of multiple factors on flooding.

Methods

Introduction of the framework approach for unravelling the impact of multiple factors on flooding at the catchment scale

In order to answer the questions of why, where, when, and how flooding occurred in a catchment in a systematic way, a framework approach was proposed in this study with a suggested set of method shown in Figure 1. The methods included in the framework approach are conditional inference tree analysis (CIT), cross-correlation analysis and double-mass curves, which are able to qualitatively and quantitatively assess the impact of multiple factors on flooding occurrence using either qualitative or quantitative data. The result on flood occurrence of this framework is able to identify the driving factor(s) or sub-catchment (s) and also give the ranking among all factors or sub-catchments leading to flood occurrence by applying the CIT. Based on the factors that are identifed by the CIT, the data set should then be reorganised for conducting the cross-correlation analysis and the double-mass curves analysis. These two analyses are able to give more detailed insight into the impact of the identifed driving factor on the time-lag effect and the quantitative change of the relation between precipitation and discharge. The detailed explanation of each method and its application regarding the questions and the interpretation of the result are demonstrated in a case study of the Wei River Basin, China.

Case study – application of the framework approach to the Wei River Basin, China

Study area

The Wei River in China is the largest tributary of the Yellow River and is regarded as the 'Mother River' of the Guanzhong Plain with a total catchment area of 134 800 km^2 (Figure 2(a)). The river originates in the Niaoshu Mountains in Gansu province and flows east through Ningxia and Shaanxi provinces to the Yellow River, with a total length of 818 km. Two important tributaries, Jing River and Beiluo River, comprise 34% and 20% of the total catchment area of the Wei River Basin, respectively.

The climate of the basin is controlled by the continental summer monsoon, which brings an average annual precipitation of approximately 570 mm, over 60% of which falls in summer (July–September), the flood season (Gao *et al.*, 2013). Precipitation is concentrated on the South Bank of the Wei River in the Qinling Mountains, with an average annual precipitation of 800 mm. A yearly average of 540 mm falls north of the river. The catchment can be divided into four sub-catchments (Figure 2(a)): Jing River (J), Beiluo River (B), upstream along the Wei River (U), and the South Bank (S). Jing River and Beiluo River are the two largest tributaries of the Wei River, with Zhangjiashan (J1) and Zhuangtou (B1) hydrological stations located at their respective outlets. Linjiacun (U1) is a control station of the upstream Wei River sub-catchment, and Huaxian is the most downstream control station in the Wei River Basin, although the Beiluo River flows into the Wei River below the Huaxian station. The corresponding meteorological and hydrological stations with data for the various sub-catchments are shown in Table 2. Daily discharge data were unfortunately not available for the hydrological stations for the period 1990–1999.

Land use in the catchment consists mainly of farmland (~38%) and grassland (~50%). After the Grain for Green project conducted in 1999, the forest area of the basin was raised from 4.8% to 14.4% in the year 2005, while the grass land area decreased from 58.7% to 44.0% in the same time span. Residential areas contributed only 0.8% to the total catchment area in the 1980s but had increased to 2.2% by 1996. This change in residential area is negligible compared to that of other land-use types, but the increase within a time span of 10 years is significant. Land use, however, generally did not change significantly between 1980 and 2005 (Gao *et al.*, 2013).

Soils in the Wei River Basin vary but have developed from the dominant loess deposits that are widely distributed in the Jing and Beiluo River Basins, with an average thickness of approximately 100 m (Zhang *et al.*, 2014). The South Bank sub-catchment, with a total area of about 15 200 km^2, is sharply defined by the abrupt cliff-like northern face of the Qinling Mountains, with steep slopes that accelerate surface discharge.

The Tongguan elevation, defined as the water table corresponding to a discharge of 1000 m^3/s at the Tongguan hydrological station on the Yellow River, is the base level of erosion of the lower Wei River. The Tongguan elevation is negatively correlated with the bankfull discharge at Huaxian (Li and Wu, 2010) and has been raised by approximately 5 m since the construction of the Sanmenxia Dam in the 1960s (Wang *et al.*, 2007).

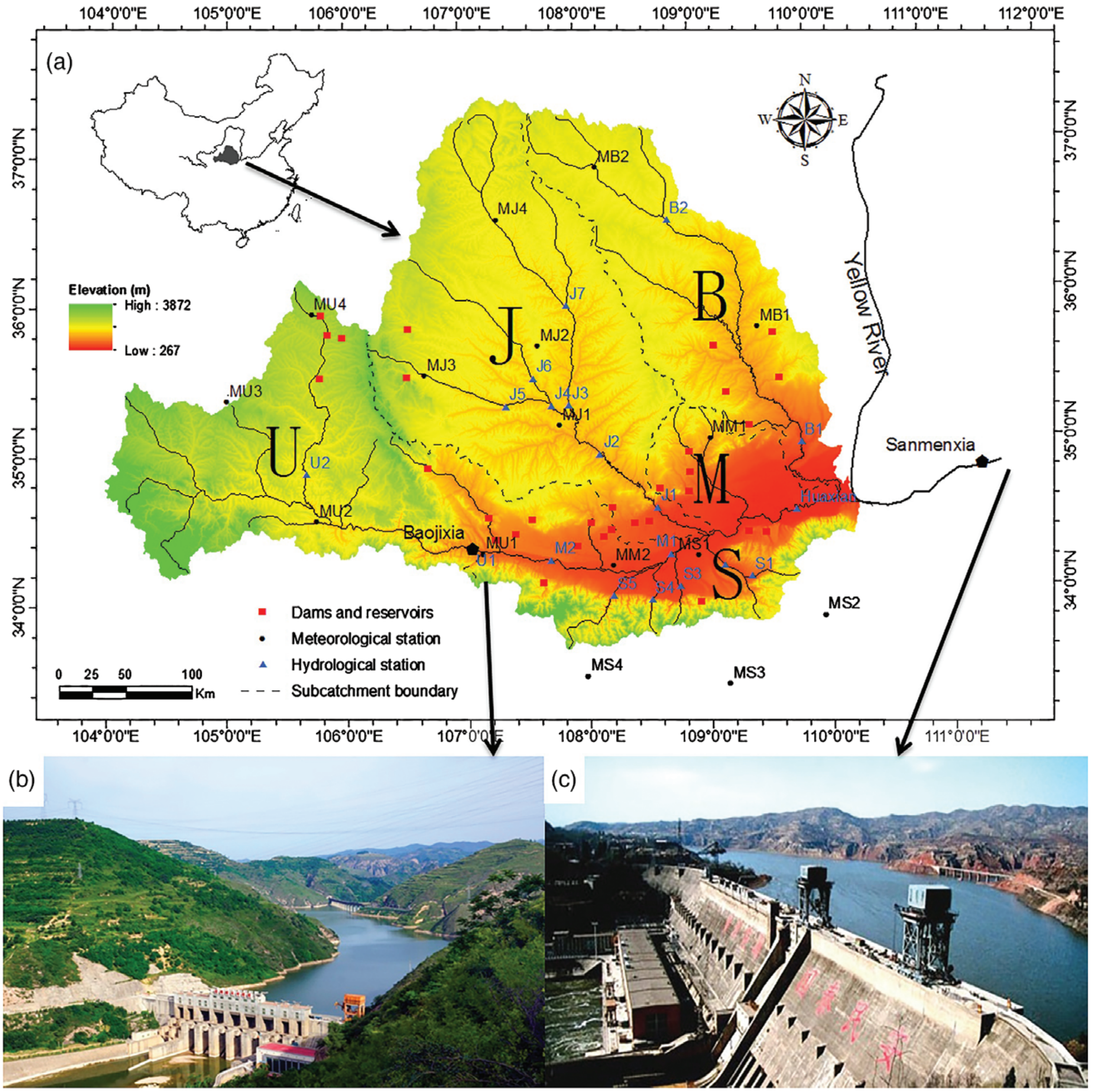

Figure 2 (a) Location of the study area and distribution of the hydrological and meteorological stations (abbreviations as in Table 2), dams and reservoirs, sub-catchments, and example pictures of (b) the Baojixia Dam, and (c) the Sanmenxia Dam.

Flooding, defined as water overflowing the riverbanks onto the floodplain, occurred in the Wei River Basin on average 1.3 times per year in the last 60 years. The floodplain of the catchment covers the lower reaches of the Wei River Basin where the elevation is relatively low, especially where most of the South Bank tributaries join the main river. The floodplain of the Wei River begins at the Baojixia Dam midway along the main river (Figure 2(b)), but most floods occur east of the city of Xi'an (meteorological station MS1 in Figure 2(a)). Sedimentation upstream of the Sanmenxia Dam on the Yellow River (Figure 2(a) and (c)) has raised the lower sections of most of the tributaries in the South Bank above the level of the ground surface. These raised rivers are the main cause of flooding in the floodplain. Numerous dams and reservoirs have been constructed in the catchment both for controlling flooding and for water and

Table 2 Hydrological and meteorological stations in the sub-catchments

	J	B	U	S	M
Sub-catchments	Jing River	Beiluo River	Upstream of Wei River	South Bank of Wei River	Wei + Jing Rivers
Corresponding hydrological stations	**J1** (Zhangjiashan)	**B1** (Zhuangtou)	**U1** (Linjiacun)		**Huaxian**
Catchment area (km^2)	43 216	25 154	30 661	106 498	105 350
Hydrological stations*	**J2** (Jingcun) **J3** (Yuluoping) **J4** (Yangjiaping) **J5** (Jingchuan) **J6** (Maojiahe) **J7** (Qingyang)	**B2** (Liujiahe)	**U2** (Qin'an)	**S1** (Luolicun) **S2** (Maduwang) **S3** (Qinduzhen) **S4** (Laoyukou) **S5** (Heiyukou)	**M1** (Weijiabao) **M2** (Xianyang)
Meteorological stations*	**MJ1** (Changwu) **MJ2** (Xifengzhen) **MJ3** (Pingliang) **MJ4** (Huanxian)	**MB1** (Luochuan) **MB2** (Wuqi)	**MU1** (Baoji) **MU2** (Tianshui) **MU3** (Huajialing) **MU4** (Xiji)	**MS1** (Xi'an) **MS2** (Shangzhou) **MS3** (Zhen'an) **MS4** (Fuping)	**MM1** (Tongchuan) **MM2** (Wugong)

*Increasing numbers indicate increasing distances from the hydrological station at the outlet.

soil conservation. Thirty-one large-scale (storage >10^6 m^3) reservoirs (Figure 2(a)) in the catchment with a total storage capacity of approximately 1.4 billion m^3, 21 of which were built between 1970 and 1983 and the rest were built before 1970, have been included in this study.

Collection of flooding records

An extensive literature and internet search was performed to collect information of flooding records onto the floodplains at the Wei River Basin during 1956–2010. The characteristics of each flood were extracted from the Table of Flooding Elements in the Annual Hydrological Report of the P. R. China – Hydrological Data of the Yellow River Basin, including the date and amount of peak discharge, level of the water table at peak discharge, and peak sedimentation at Huaxian.

Data sets

To apply the framework approach, a wide range of data sets regarding the factors possibly affecting flooding were collected and organised based on the CIT model requirements (Table 3). Slope data were derived from the Digital Elevation Model of the basin using ArcMap 10.0. Land use was calculated from land use data sets of the years 1980, 1985, 2000, and 2005, and we assumed the land use for 1956–1984 to be the same as that in 1980 (no earlier records of land use were available), 1985–1990 the same as that in 1985, 2000–2004 the same as that in 2000 and 2005–2010 the same as that in 2005. Both the DEM and land use data were provided by the Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China (http://westdc.westgis.ac.cn) and International Scientific Data Mirror Website of Computer Network Information Center of Chinese Academy of Science (http://datamirror.csdb.cn). Meteorological data were obtained from The National Meteorological Information Centre. Data of the elevation of the outlet were obtained from the Shaanxi Administration Bureau of Sanmenxia Reservoir. Three periods were analysed based on the time of dam construction: (1) before extensive dam construction (1956–1969), (2) during the construction of most of the dams (1970–1983), and (3) after most of the dams had been constructed (1984–2010). The factors were classified into three groups corresponding to the influencing factors identified in the introduction: topographic, climatic, and anthropogenic factors shown in Table 3. All analyses excluded 1991–1999 due to the lack of daily discharge data for all hydrological stations.

Why – CIT analysis for identifying the most influential factor causing flooding

A CIT analysis was constructed to identify the driving factor and the contribution of each factor associated with flooding occurrence on both a monthly and yearly basis by recursive

Table 3 Description of the data sets used in the framework approach

Variable	Variable name	Description
Topographic factors		
Slope	Average slope of the catchment (°)	J sub-catchment: 14.10 B sub-catchment: 13.51 U sub-catchment: 12.50 S sub-catchment: 16.80
Climatic factors		
Temperature	Average monthly temperature (°C)	Continuous value
Precipitation	Average monthly precipitation (mm)	Continuous value
Humidity	Average monthly humidity (%)	Continuous value
Sunshine hours	Total monthly hours of sunshine (h)	Continuous value
Sunshine percentage	Average monthly sunshine percentage (%)	Continuous value
Season	Rainy or dry season	Rainy season: June–October Dry season: November–May
Month		Continuous value
Year		Continuous value
Anthropogenic factors		
Grass	Grassland area (% of total area)	
Water	Water area (% of total area)	
Cultivation	Cultivated area (% of total area)	
Residence	Residential area (% of total area)	
Forest	Forested area (% of total area)	
Elevation of the outlet	The water table at the Tongguan hydrological station* (m)	Water table corresponding to a discharge of 1000 m^3/s at the Tongguan hydrological station, continuous value
Period of dam construction		Before: 1956–1969 During: 1970–1983 After: 1984–2010

*The Tongguan water table is influenced by the accumulated sedimentation because of the downstream Sanmenxia Dam. Tongguan is considered as the outlet and erosion base of the Wei River.

binary partitioning in a conditional inference framework (Hothorn *et al.,* 2006). This non-parametric class of regression trees supports all types of variables, including nominal, ordinal, numeric, and multivariate response variables (Hothorn *et al.,* 2006). The statistics-based approach of CIT uses non-parametric tests as splitting criteria, corrected for multiple testing to avoid overfitting. This approach results in unbiased predictor selection and does not require pruning. Stopping criteria based on multiple test procedures are implemented and it is shown that the predictive performance of the resulting trees is as good as the performance of established exhaustive search procedures (Hothorn *et al.,* 2006). We assumed that the distribution of the responding variables depended on a function of the variables. Flooding was the responding variable, and the influencing factors were the variables. Flooding was defined as 'Yes' or 'No', with 'Yes' indicating an occurrence of flood in a certain month or year. A subset of available factors possibly affecting flooding was included in the model (Table 3). The model generated a tree-shaped graph, with each node of the tree representing the case weights of the observations of the responding variable. The *P* value represents the result of multiple significance tests under a permutation test algorithm. The covariate with the minimum *P* value was selected among all covariates for further splitting. The *P* value shown in the tree indicates the level of significance of the selected covariate (Hothorn *et al.,* 2006).

Where – CIT analysis to identify the sub-catchments contributing to flooding

CIT was constructed to analyse the most important hydrological stations and sub-catchments contributing to flooding downstream. Monthly averaged discharge data from 18 hydrological stations (Table 2, the Huaxian station was excluded because it was the control station for the entire basin and did not represent a sub-catchment) were the input variables, and monthly and yearly flood occurrence were the responding variables. In this analysis, we assumed the distribution of the flood occurrence on a monthly or yearly basis is based on a function of the discharge of the 18 hydrological stations.

When – cross-correlation analysis for time-lag investigation

Cross-correlation analysis investigated and quantified a possible time lag between precipitation and discharge (or flood) (Bieger *et al.,* 2012; Talei and Chua, 2012; Löwe *et al.,* 2014). We analysed the time lags between the precipitation at the meteorological stations (Table 2) and the measured discharge at the control (Huaxian) hydrological station at the outlet of the Wei River Basin. Precipitation data for 122 days in the rainy season (from 1 June to 30 September) of each year of a recorded flood were extracted from the data set of daily precipitation. Based on the most influential factor identified by the CIT analysis done in Sections *Why – CIT analysis for identifying the most influential factor causing flooding* and *Where – CIT analysis to identify the sub-catchments contributing to flooding*, the data sets can be divided into subsets accordingly to be used as comparison with each other. The precipitation data from each meteorological station are then cross-correlated with the discharge data at Huaxian within each subgroup using the ccf function of R version 2.14.0 (Venables and Ripley, 2002). This result is aiming at explaining the impact of the most influential factor (or any factor of interest) on the time lag effect between precipitation and discharge.

How – double-mass curves to analyse the effect of dam construction on the precipitation–discharge relationship

Double-mass curves are widely used in hydrology to test the consistency and long-term trends of hydro-meteorological data (Abedini *et al.,* 2013; Gao *et al.,* 2013; Choi *et al.,* 2016). A straight line between cumulative precipitation and discharge indicates that the proportionality between the two remains unchanged. This method is able to smooth and show the main trends of time series. However, a change in the regression slope (proportionality) of the plotted curve indicates the change of trends, which is usually caused by external factors. In order to investigate the impact of the most influential factor or sub-catchment identified by the CIT analysis in Sections *Why – CIT analysis for identifying the most influential factor causing flooding* and *Where – CIT analysis to identify the sub-catchments contributing to flooding*, in this study we divided the precipitation and discharge data into contrastive subsets according to the identified factor. Double-mass curves are then plotted regarding each subgroup to quantify the overall influence of the factor on the change between cumulative average precipitation from all meteorological stations in the catchment and discharge at Huaxian hydrological station. The significance in differences among the changes in the regression slopes were compared using analysis of covariance (ANCOVA) using R version 3.1.2.

Results

Floods

Six large-scale (recurrence interval > 100 years) and more than 37 medium- and small-scale floods occurred between 1956 and 2010 on the floodplain of the Wei River Basin (Table 4), with an average frequency of 1.3 per year. All floods occurred between May and October, with more than half in July and August. The peak discharge at Huaxian (control station) averaged 3912 m^3/s, and the depth of the water table averaged 339.8 m. The peak discharges are homogeneous over time while the level of the water table shows an increasing trend (Table 4).

Why – factors influencing flooding

CIT analysis was first constructed to identify the driving factor and the contribution of each factor to the occurrence of flooding on a yearly basis. As 'Yes' (shown as dark area in Figure 3) indicating the occurrence of flood, the node of the tree represents the case weights of the 'Yes' observations of the total responding variable (Figure 3). The period of dam construction was identified as the most important factor for flooding occurrence on a yearly basis. The number of floods was significantly higher before and during the period of dam construction than after the period of dam construction (Nodes 8, 10, and 11 compared to Nodes 3, 5, and 6 in Figure 3). A further division (Node 7) shows that more flooding occurred before than during the period of dam construction (Nodes 10 and 11 compared to Node 8). Elevation of the outlet was subsequently identified as the second most important factor after the dam construction period. Before the dam construction period, there were more floods when the elevation of the outlet is higher than 323.69 m (Node 9 in Figure 3). After the dam construction period, there is a clear division for the occurrence of flood when the elevation of the outlet reached 327.75 m (Node 2 in Figure 3). Floods were much more common before dam construction even though the identified elevation of the outlet was lower (323.69 m compared to 327.75 m) than in the period after dam construction (compare Nodes 3 and 11 in Figure 3).

CIT analysis was also applied to analyse the factors influencing flood occurrence on a monthly basis. Similar to the yearly analysis, the corresponding factor is the 'Yes' case (shown as dark area in Figure 4) indicating the occurrence of a flood in the month. Average monthly precipitation appeared to be the dominant factor for flooding on a monthly basis (Nodes 1, 2, and 3 in Figure 4). There is a significant difference between the number of occurrence of floods from precipitation more and less than 97 mm (Node 8 and 9 compared to Nodes 4, 5 and 6 in Figure 4). In the category of precipitation more than 97 mm, which is the condition leading to more flooding, the dam construction period appeared to be the second most important factor causing flooding. It can be clearly seen that even with the same precipitation condition, less floods occurred after the dam construction period than before and during.

Table 4 Characteristics of the floods at the Huaxian hydrological station with the highest peak discharge for each year with a flood

Year	Month	Day	Peak-discharge water table (m)	Peak discharge (m^3/s)	Peak sedimentation (kg/m^3)
1958	8	21	338.46	6040	213
1959	7	16	336.77	3920	438
1960	8	4	337.23	2900	605
1961	10	20	337.48	2700	25.9
1962	7	28	338.07	3540	65.4
1963	5	25	338.45	4570	59
1964	9	15	338.78	5130	85.7
1965	7	9	337.48	3200	357
1966	7	28	339.47	5160	636
1967	5	19	338.27	2110	80.6
1968	9	12	340.54	5000	76
1970	8	31	340.55	4320	235
1973	9	1	341.57	5010	428
1974	7	14	340.13	3150	47.8
1975	10	2	340.97	4010	96
1976	8	29	340.15	4900	117
1977	7	7	340.43	4470	795
1980	7	4	340.35	3770	33.3
1981	8	23	341.05	5380	68.7
1983	9	28	339.37	4160	38.3
1984	9	10	339.16	3900	50.6
1985	9	16	339.24	2660	31.1
1986	6	28	339.02	2980	485
1990	7	8	339.24	3210	55.4
1992	8	14	340.95	3950	528
1994	7	9	338.54	2000	765
1996	7	29	342.25	3500	565
1998	8	23	340.06	1620	130
2003	9	1	342.76	3570	598
2005	10	4	342.32	4820	31.4
2010	7	26	341.15	2040	459

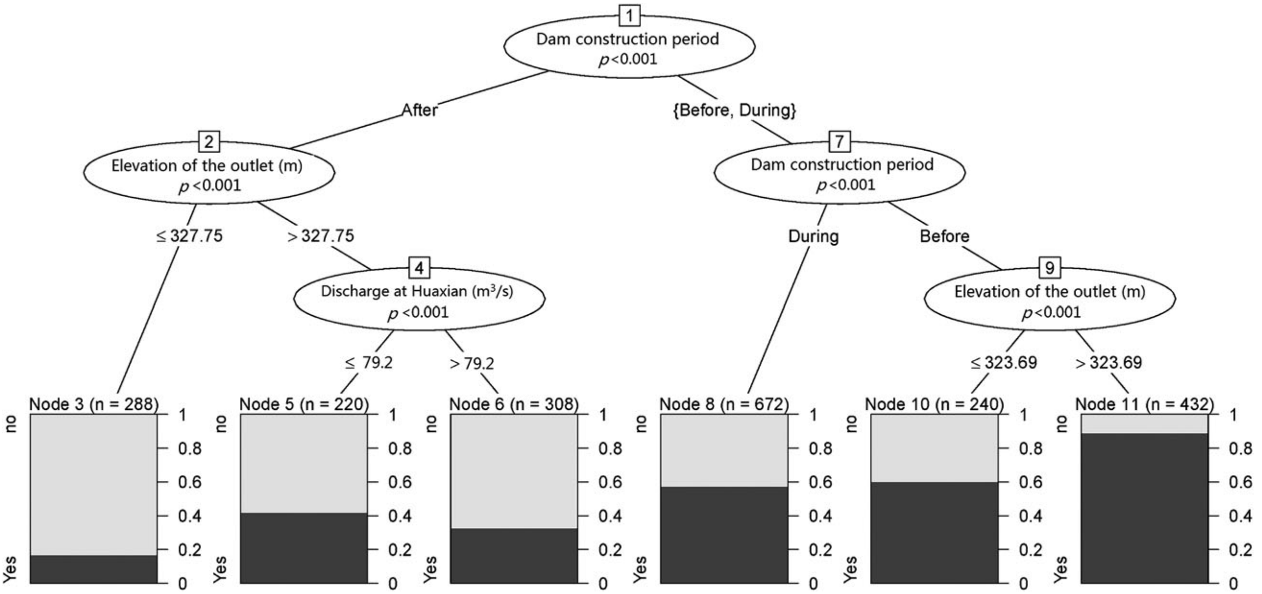

Figure 3 Results of CIT analysis of yearly flooding with all factors shown in Table 3. The dark areas indicate the ratio of the number of flooding cases to the total number of the cases (*n*) in the node. (Total number of cases in all categories is 2160).

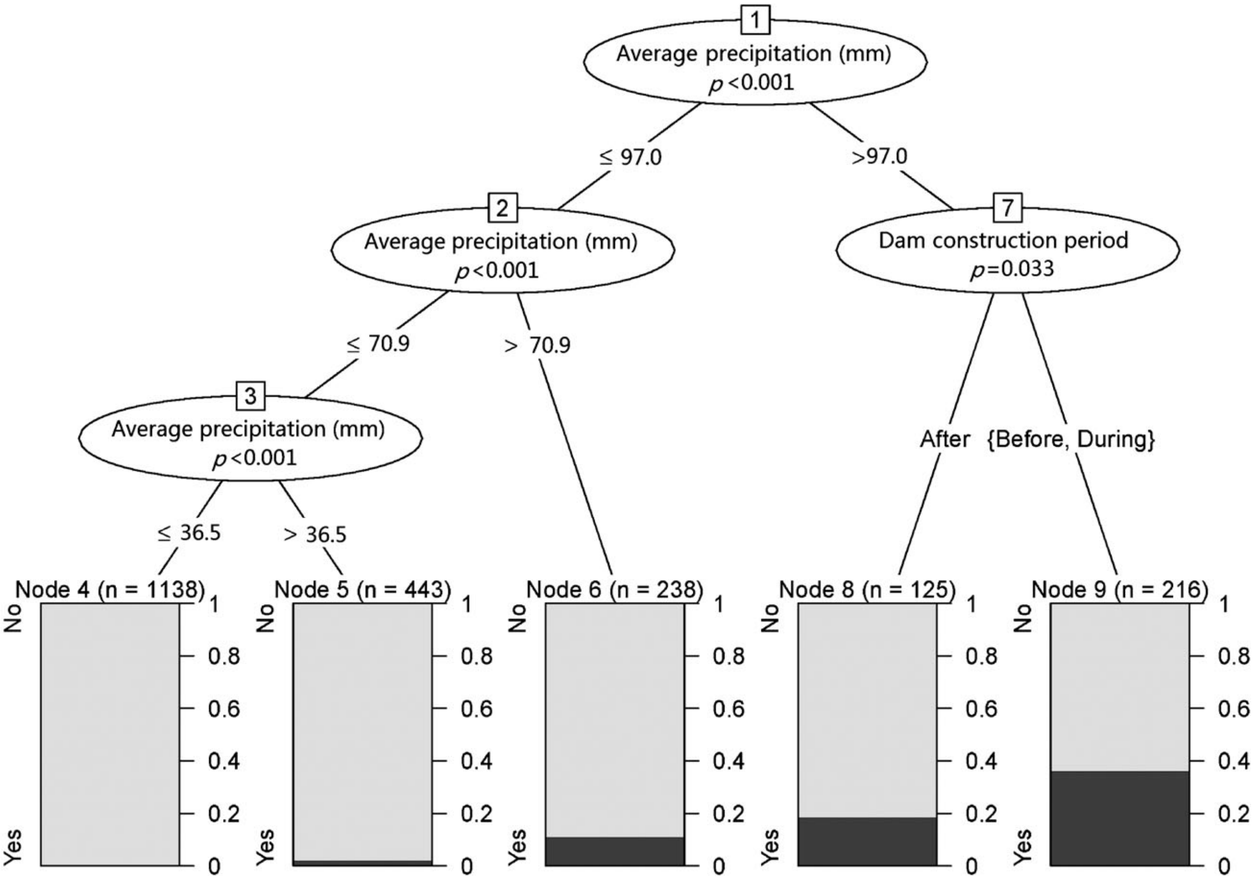

Figure 4 Results of CIT analysis of monthly flooding with all factors shown in Table 3. The dark areas indicate the ratio of the number of flooding cases to the total number of the cases (*n*) in the node. (Total number of cases in all categories is 2160).

Where – effect of discharge of sub-catchments on flooding

Figure 5 shows the results of the CIT analysis conducted based on the variables being the discharge of the control hydrological stations of each sub-catchment and the responding variable being the occurrence of flooding on a monthly basis. Only the control hydrological stations in sub-catchments U, J, and B (U1, J1, and B1 in Table 2) and the hydrological stations in sub-catchment S (S1, S2, S3, S4, and S5 in Table 2) were included in the model to identify the most influential sub-catchment, i.e. the most important control station of the tributaries. The most upstream sub-catchment (U) was identified as the dominant contributor (Node 1 in Figure 5). Additionally, the South Bank discharge was the second most important factor contributing to the flooding downstream. Especially when the discharge of U1 station is above 131 m^3/s and the discharge of S5 station is higher than 19.4 m^3/s (Node 7 in Figure 5), the flooding occurrence is significantly higher than for all the other cases (Node 9 compared to Nodes 4, 5, 6, and 8 in Figure 5). When the discharge of the S2 station is higher than 53 m^3/s, more floods occurred (Nodes 6 compared to Nodes 4 and 5 in Figure 5). The results highlight the importance of the South Bank and upstream discharge on the flooding of the floodplain.

When – effect of dam construction on time lag with respect to precipitation to discharge

The period of the dam construction was identified as the most important factor causing the flood occurrence downstream in section *Why – factors influencing flooding*. Therefore, as a next step, we analysed the time lags between the precipitation at the meteorological stations (Table 2) and the measured discharge at the control hydrological station (Huaxian) at the outlet of the basin for the three periods subsequently. Meteorological and hydrological data sets were subdivided into the three groups regarding the periods described in Section Data set based on the dam construction periods.

Figures 6–9 show the results of the cross-correlation between precipitation, as measured at the meteorological stations in Table 2, and discharge, as measured at the main

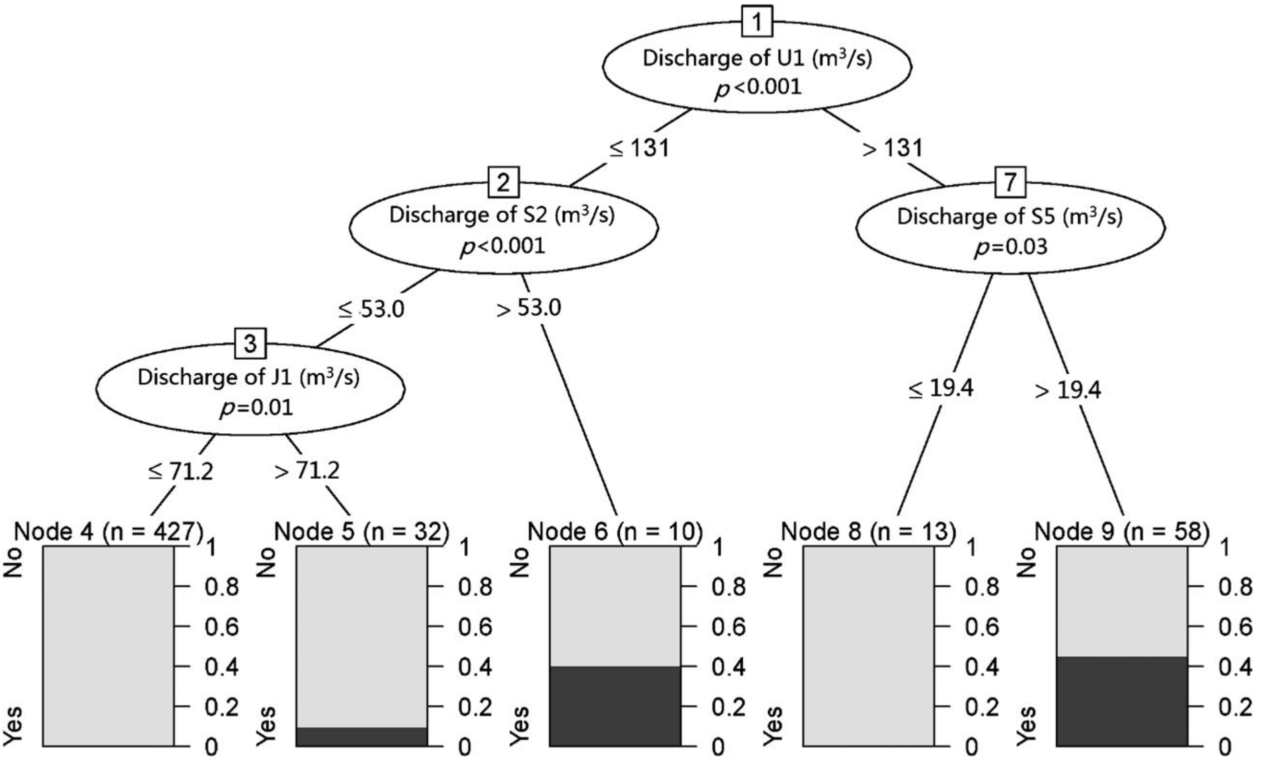

Figure 5 Results of CIT analysis of monthly flooding with discharge of the hydrological stations of sub-catchment S and the control stations of sub-catchments J, U, and B. The dark areas indicate the ratio of the number of flooding cases to the total number of the cases (*n*) in the node. (Total number of cases in all categories is 540).

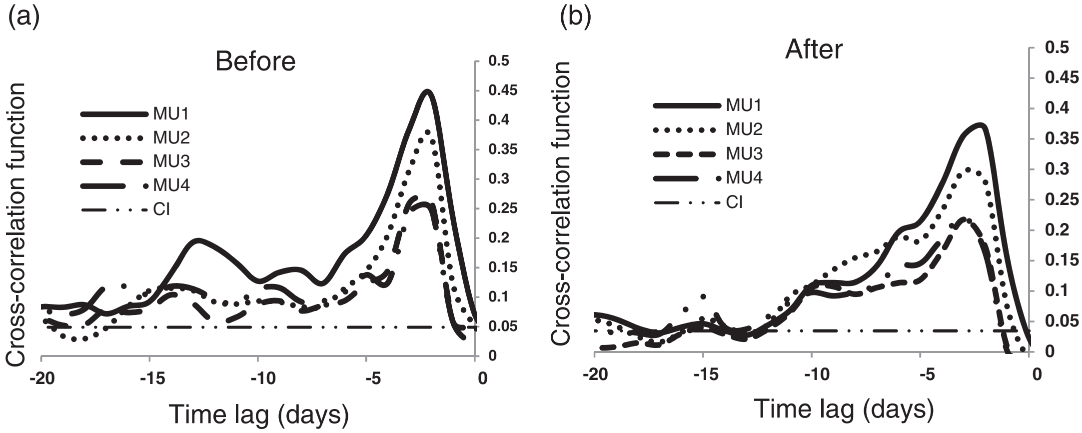

Figure 6 Cross-correlations between precipitation measured at meteorological stations and discharge at the Huaxian station for the U sub-catchment before (a) and after (b) dam construction (abbreviations as in Table 2; CI, 95% confidence interval).

river outlet (Huaxian) for the four sub-catchments and two periods (before and after dam construction). In general, for all sub-catchments, the highest cross-correlation indicates the highest correlated time lags, i.e. the highest correlated discharge of all meteorological stations occurred within 5 days after precipitation. In addition, the strength of the correlation decreased with increasing distance to the outlet for all meteorological stations located in the catchment (the ascending number of the meteorological stations indicates the increasing distance to the outlet, for instance, MU1 is located closer to the outlet compared to MU2), except for sub-catchment M. The detailed time lag effects of meteorological stations of different sub-catchments regarding the periods are shown in Table 5.

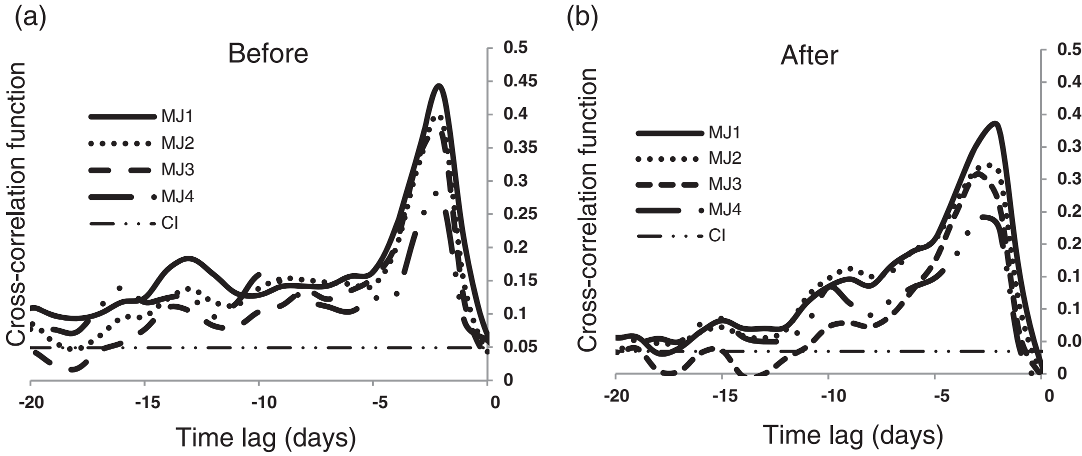

Figure 7 Cross-correlations between precipitation measured at meteorological stations and discharge at the Huaxian station for the J sub-catchment before (a) and after (b) dam construction (abbreviations as in Table 2; CI, 95% confidence interval).

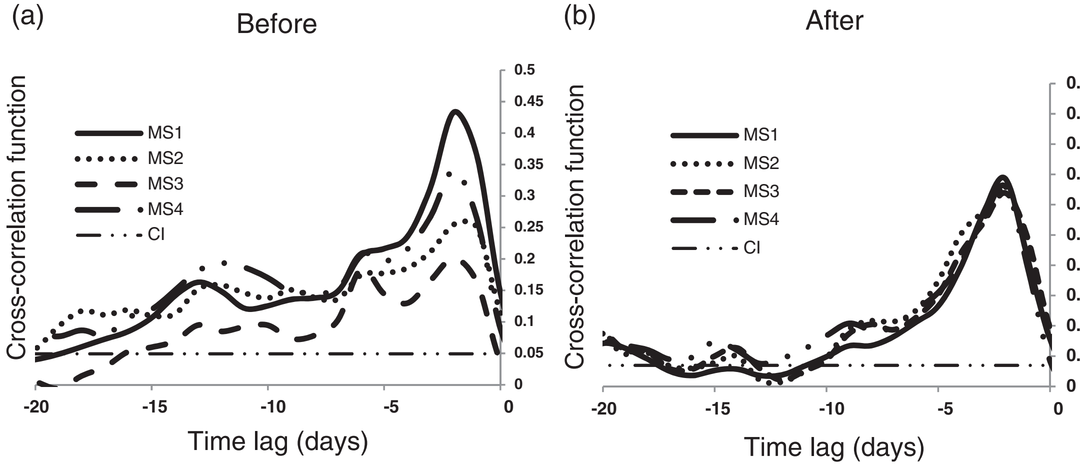

Figure 8 Cross-correlations between precipitation measured at meteorological stations and discharge at the Huaxian station for the S sub-catchment before (a) and after (b) dam construction (abbreviations as in Table 2; CI, 95% confidence interval).

The time lags between precipitation in the Wei River Basin and discharge at Huaxian increased after the period of dam construction by an average of 0.4 days (Table 5). The delay was most pronounced in sub-catchment J (0.75 days), while sub-catchment M had no time lag change. The fact that the construction of the dams has the most impact in sub-catchment J is consistent with the result obtained from the CIT analysis in Section *Where – effect of discharge of sub-catchments on flooding*. As the dam construction successfully delayed the precipitation, the discharge in sub-catchment J appeared to be not important for the flood occurrence. Moreover, the time lag increased with distance from Huaxian. The construction of the dams and reservoirs thus had a large effect on the time lags for sub-catchments U and J.

How – effect of dam construction on the precipitation–discharge relationship

In order to investigate how much the dam construction period affects the precipitation–discharge relationship, we plotted double-mass curves for the three periods mentioned in section Data sets, i.e. before, during and after construction of most of the large dams. Figure 10 shows the results of the double-mass curve analysis of the precipitation–discharge relationship at Huaxian for the three periods. The slope of the regression lines decreased over time (analysis of covariance, $P < 0.0001$); it was highest for the period before dam construction and was lowest after construction. This decline indicates that the discharge decreased with the same amount of precipitation, which may have been due to

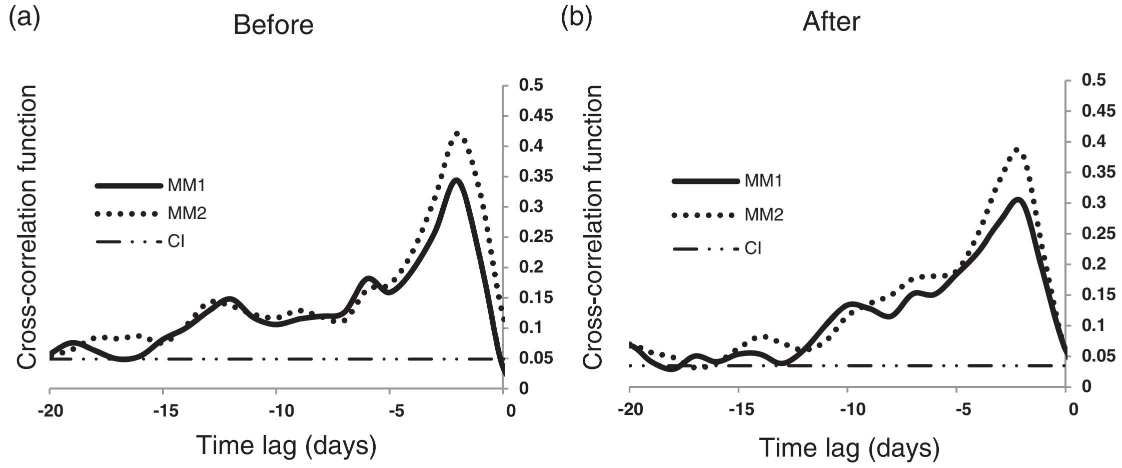

Figure 9 Cross-correlations between precipitation measured at meteorological stations and discharge at the Huaxian station for the M sub-catchment before (a) and after (b) dam construction (abbreviations as in Table 2; CI, 95% confidence interval).

Table 5 Time lags (days) between precipitation measured at meteorological stations and the discharge at the Huaxian station before and after dam construction based on the cross-correlations in Figures 6–9

	U sub-catchment				J sub-catchment				S sub-catchment				M sub-catchment		
	MU1	**MU2**	**MU3**	**MU4**	**MJ1**	**MJ2**	**MJ3**	**MJ4**	**MS1**	**MS2**	**MS3**	**MS4**	**MM1**	**MM2**	**Average**
Before	2	2	2.5	2.5	2	2	2	2	2	1.5	2	2	2	2	2.0
After	2	3	3	3	2	3	3	3	2	2	2	2	2	2	2.4
Change	0	1	0.5	0.5	0	1	1	1	0	0.5	0	0	0	0	0.4

the construction of the dams and reservoirs. Compared with the accumulative discharge for the period before dam construction, the accumulative discharge for the period after dam constructions was reduced by 44%.

Discussion

This study presented and evaluated a framework approach consisting of a set of methods to answer the questions why, where, when, and how flooding occurs in a catchment with complex conditions, multiple potential contributing factors, and including multiple years. CIT analysis is a relatively new method used mainly in biological and medical studies to identify the factors and primary components of phenomena (Blank and Blaustein, 2014; Johnstone *et al.*, 2014; Zeng *et al.,* 2015). It has not often been applied in hydrological studies. Many studies of flooding in the Wei River Basin have focused on one or two factors, mainly those involved in the precipitation–discharge or sediment load relationships. We introduced CIT analysis in this study to determine the most important factors, among all climatic and anthropogenic factors, and their impacts on flooding. The result from this study was able to present statistical evidence to the fact that the dam construction period has the most important impact on flooding occurrence in a catchment. Together with the cross-correlation analysis and double-mass curves analysis, we were able to identify the quantitative influence of the identified factors. The results of the three methods were consistent among themselves, highlighting the importance of dams effects on flooding control in the catchment. However, the framework method can be applied in any catchment flooding analysis where many factors need to be considered.

The cross-correlations indicated that dam construction had a more pronounced effect on the discharge than on the time lag after precipitation. The operation of the reservoirs can account for this result. We assume that reservoirs store the runoff from upstream precipitation. The reservoirs in our study, however, only stored the amount of runoff sufficient to prevent flooding downstream and passed along most of the runoff generated from the upstream precipitation (RDRSMPRC, 1991; LFPPRC, 1998). The effect of the time lag was thus not very pronounced. With the amount of the runoff stored in the reservoir, infiltration and water diversions led to the decrease in the total discharge at the outlet gauging station, accounting for the results of the double-mass curve analysis.

Changes in land use are assumed to be extensive in the study area due to the Grain to Green project (Liu *et al.,*

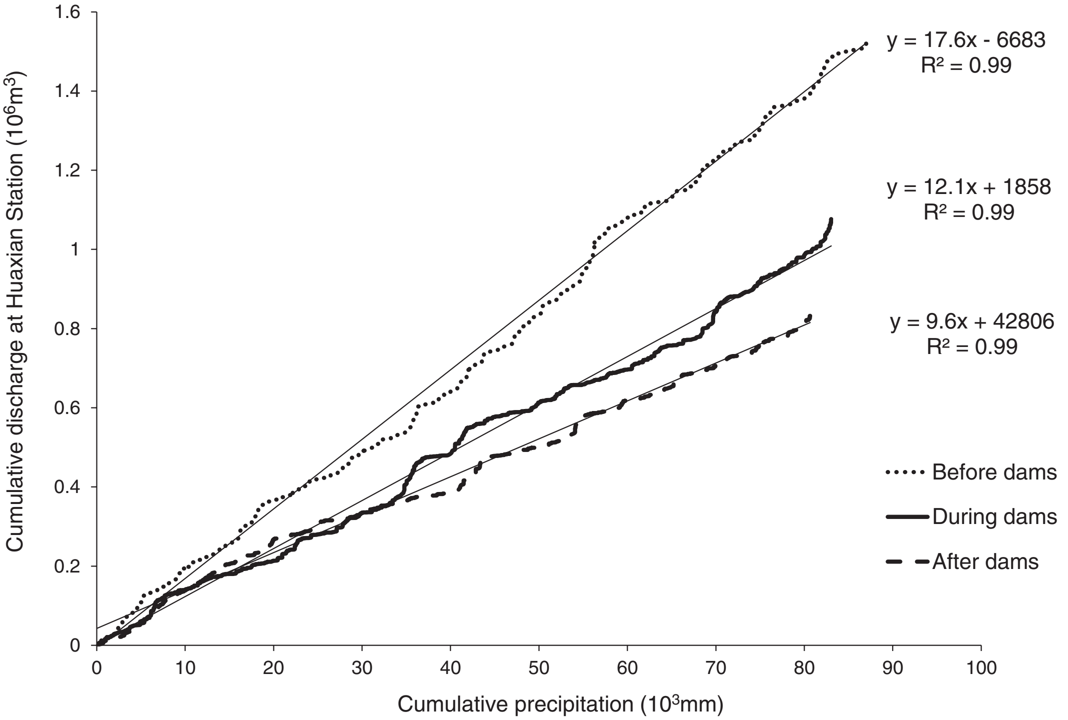

Figure 10 Double-mass curves of precipitation-discharge at the Huaxian station. The straight lines are the regression lines for the cumulative data before, during, and after the construction of dams.

2014a; Jian *et al.,* 2015). Land-use changes are also an important factor influencing the infiltration and interception of rainwater (Fohrer *et al.,* 2001; Costa *et al.,* 2003), which were responsible for the change in discharge downstream. Our study did include land use change as factors in the analysis; however, they were not identified as an important factor for flooding occurrence. This is consistent with Gao *et al.* (2014), who also suggested a low impact of land-use change on streamflow and sediment load in the Wei River Basin. We further investigated the effect of land use on flooding by changing the criteria of the CIT analysis to generate another level of separation based on the current result of Figure 3. Residential area was a branch of Node 5 below the discharge at Huaxian, indicating the influence of built-up areas on river discharge. Pfister *et al.* (2004) and Yang *et al.* (2015) suggested that land-use changes may have a more significant impact on local and small catchments than on regional or mesoscale catchments, consistent with the results of our study.

Xia *et al.* (2014) found that discharge and sediment load were the two dominant factors determining the bankfull channel dimensions in an alluvial river, but sediment load was not identified as an important factor in our study. Sediment load was not correlated with either flood-peak discharge or flood-peak water table (Table 4). Sediment loads may affect the morphology of riverbeds, which affects flooding, especially associated with downstream dams (Batalla and Vericat, 2009; Magilligan *et al.,* 2013; Opere, 2013). The effect of sediment load on channel morphology and flooding should thus be studied further.

The slope of sub-catchment S (South Bank) was higher than those in the other three sub-catchments (Table 3), but slope was not identified as an important factor affecting flooding (Figure 3), which was unexpected and perhaps due to the averaged slope. The slopes of the Qinling Mountains in sub-catchment S are very steep, but nearly half of the area of this sub-catchment is floodplain, which decreases the average slope. The steeper slopes, combined with the different geology of sub-catchment S compared to the other three sub-catchments, produced a larger discharge from this sub-catchment. The effect of discharge from sub-catchment S was successfully identified in the spatial analysis using CIT (Figure 5). The discharge from sub-catchment S was responsible for most of the flooding in the Wei River Basin on a monthly basis (Nodes 6 and 9 in Figure 5).

Factors that lead to flooding can be identified by analysing the characteristics of individual floods but are difficult to include in our type of analysis. For example, cultivation on the floodplain affects the retreat of flood water. The small dikes and roads for protecting cultivated areas also increase the vulnerability of the floodplain to flooding. These factors were difficult to include in our analysis because they were unregulated, temporal, and small in scale (Jiang *et al.,* 2004). Dike failure or exceeding the designed threshold of the dikes, as occurred with the flooding on the Yangtze River in 1998 (Plate, 2002), were difficult to be included for the same reasons.

As the dams in the study area were constructed mainly for flood control and irrigation purposes, the discharge generated from precipitation of the upper stream of the river are collected and stored in the reservoirs. The propagation time from precipitation to the discharge at the outlet of the catchment is thus extended. This process is consistent with the observation of the CIT analysis that dam construction period is the most important factor explaining the occurrence of flood. The time lag between precipitation and discharge on average increased from the cross-correlation analysis. It can be concluded that the dam constructions successfully delayed the precipitation.

Factors other than dam construction not included in the double-mass curve analysis may also have played a role in lowering the slope of the regression line of the precipitation–discharge relationship, so determining the exact contribution of each factor was not possible. The CIT analysis (Figures 2 and 3 in Section *Why – factors influencing flooding*), however, suggested that the period of dam construction was the most influential factor for flooding. The analysis was thus constructed based on the division of the dam construction period.

Further studies are required to quantify the effects on flooding of the factors we have identified. A model including all the above factors as input that is able to simulate the hydrology of a large-scale catchment will be applied by changing the input data according to their changes in the past and to scenarios of the future. The main focus will be the influence on flooding of the construction of dams and reservoirs, water-diversion projects, precipitation, and land-use changes.

Conclusions

A new framework approach for flood analysis capable of including multiple potential factors and multiple years of data was proposed by this research with a demonstration of a case study of the Wei River Basin, China. The approach identified the dam construction and the most upstream sub-catchment of Wei River Basin were the most important factors influencing flooding, highlighting the importance of the effects of dams on flooding control in the basin and the effect of precipitation of the most upstream sub-catchment on the discharge downstream. This upstream sub-catchment contained the fewest dams and land-use changes and was important for managing soil and water to avoid flooding in the Wei River Basin. The approach can be used in any large spatial and temporal scale analysis of multiple factors affecting flooding.

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