A new method to estimate the total drainage area of soil-water conservation projects on the upstream of Wangkuai watershed in Daqinghe River basin, China

Zhenquan Li, Qiaoyu Li and Yimin Wang

ABSTRACT

A new approach was presented to calculate the total drainage area (TDA) of many small hydraulic engineering projects on the upstream Wangkuai reservoir watershed considering flood scaling. By establishing the correlation of flood peak between Wangkuai and Fuping hydrological station, the event-based flood scaling in Wangkuai reservoir watershed was analyzed and the scaling exponent θ was 0.5688. Relations between flood peak and maximum 3 h rainfall amount were fitted for the undisturbed and disturbed periods to analyze the effect of small reservoirs on the flood peak. The average change ratio of flood peak was 15.05% and the TDA of small hydraulic structures was 939.88 km^2.

Key words | drainage area, flood scaling, nonstationarity, small reservoirs and check dams

Zhenquan Li (corresponding author)
Yimin Wang
School of Water Resources and Hydropower,
Xi'an University of Technology,
Xi'an 710048,
China
E-mail: lzq1816@163.com

Zhenquan Li
Huangzangsi Project Construction & Management
  Bureau, HRB,
Lanzhou 730030,
China

Qiaoyu Li
Henan Vocational College of Water Conservancy
  and Environment,
Zhengzhou 462000,
China

INTRODUCTION

In recent years, anthropogenic activity, like construction of hydraulic engineering projects and urban expansion, has changed land surface conditions, and therefore caused environmental change which has altered runoff generation mechanisms. It has also resulted in the nonstationarity in hydrological series which invalidate traditional flood frequency analysis based on stationary assumption (Milly *et al.* 2008). The environmental change which results from anthropogenic activity has destroyed the stationary hydrologic regularity, and its effect on the hydrologic cycle is necessary in research. Some research has studied the impact of environmental change on the generation of flood (Archer & Newson 2002; Nirupama & Simonovic 2007; Moel & Aerts 2011).

Land use change is one of most typical forms of environmental change that influence flood. Brath *et al.* (2006) used a distributed hydrological model to simulate flood in Samoggia River, Italy for different kinds of land cover, and the result showed that flood with a small return period was obviously impacted by land use change. Naef *et al.* (2002) found that flood was impacted by land use change in areas with fast runoff generation and the flood flows reduced in these places. Cammerer *et al.* (2013) analyzed flood risk under simulated future land use until 2030 and found settlement expansion inevitably increased risk; and the change rate depended on the land use conversion type. Some researchers have studied the effect of change of land use, such as afforestation and urbanization, on flood peak and duration (Robinson 1980, 1993; Archer & Newson 2002). It was found that urbanization and deforestation could increase flood peak in the present scenario, while afforestation demonstrated the opposite role (Liu *et al.* 2005). Saghafian *et al.* (2008) analyzed land use and flood peak of 1967 and 1996 of Golestan Province in Iran. They found that the agricultural area significantly increased and the peak flow under different return periods increased. Thus, the effect of environmental change is important and should not be neglected in flood risk and management analysis.

However, the effect of hydraulic engineering is an important contributing factor which was not considered in the above researches. Hydraulic engineering can change the mechanism of flood generation and runoff process directly by management measures. Many hydraulic engineering projects have been constructed all over the world for soil-water conservation and water resource management, but they have also influenced regional flood generation significantly and changed the natural runoff process downstream (Zahar *et al.* 2008). The effect of some hydraulic engineering projects was difficult to derive because some small structures, like check dams, lack design data and therefore their effect on the flood process is hard to quantify. In this case, the effect of hydraulic engineering needs to be estimated for further analysis. Li *et al.* (2013) used hourly rainstorm and flood data of Lengkou station in Luanhe River basin, China, and found flood volume and peak decreased by 5.1%–16.6% and 0–57.3%, respectively, due to the construction of soil and water conservation engineering upstream. Yu *et al.* (2014) further estimated water storage capacity as 7.8 mm and drainage area of the small hydraulic structures upstream of Lengkou were estimated as 73% of the whole catchment area.

Around 6,000 check dams have been built in the Wangkuai reservoir catchment. Due to there being no long-term program, observational data was difficult to obtain (Li *et al.* 2016). Also the design information was unknown. Li *et al.* (2016) presented an approach to calculate the total storage capacities (TSC) and drainage areas (TDA) of many check dams in Wangkuai watershed based on rainstorm and flood events. The results showed that the TSC was 14.89 million m^3, and TDA was 1,304 km^2 which accounts for 34.6% of the whole area of Wangkuai watershed.

However, Li *et al.* (2016) did not take flood scaling into consideration in calculating the drainage area of the check dams. Flood in similar regions was usually considered to exhibit a power law which was also the basis of regional flood frequency analysis (Gupta *et al.* 1996; Medhi & Tripathi 2015). By developing regression relationships between flood peak and basin attributes, flood scaling was often used to estimate flood frequency in ungaged basins where observed data are deficient (Haddad *et al.* 2011; Han *et al.* 2012; Furey *et al.* 2016). Due to good reflection of drainage characteristic, drainage area is widely used to analyze

flood scaling (Jothityangkoon & Sivapalan 2001; Furey & Gupta 2007; Ishak *et al.* 2011). Flood scaling can be expressed by a power law as $Q = \alpha A^{\theta}$, where Q means the flood peak, A is the catchment area, $\log \alpha$ means the intercept parameter, and θ means scaling exponent. Because t θ is generally less than 1, it should not be neglected in estimating the effect of many hydraulic structures.
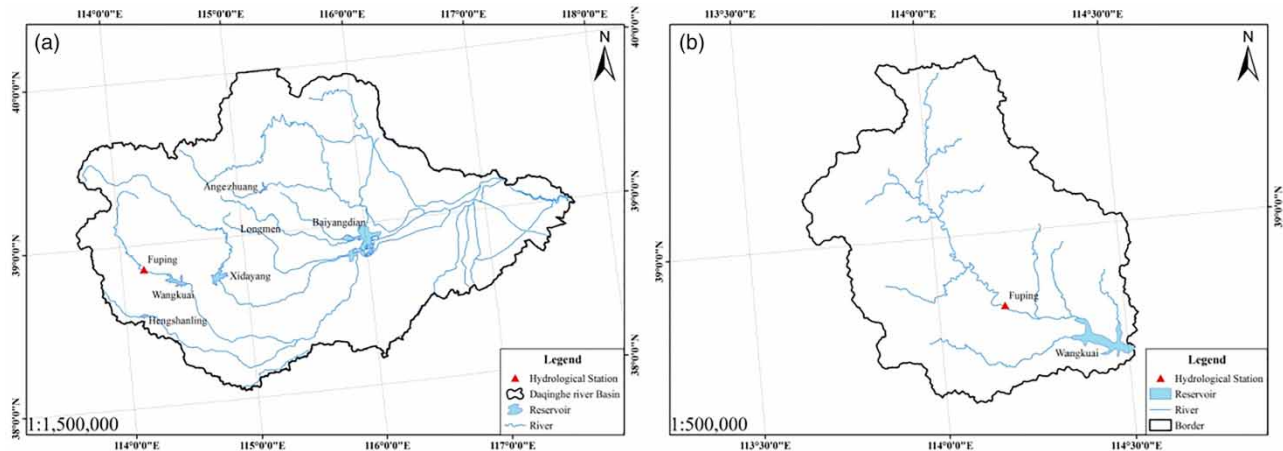
The aim of this study is to (1) analyze event-based flood scaling in Wangkuai watershed and (2) estimate the total drainage area of small hydraulic structures upstream of Wangkuai reservoir considering flood scaling.

STUDY AREA AND DATA

Study area

Wangkuai (WK) reservoir, located in Daqinghe River basin, was chosen as the study region (Figure 1). Wangkuai reservoir watershed is located at 114°29′E longitude and 38°45′N latitude. Building of the reservoir started in the year 1958 and was completed in the year 1960, with a storage capacity and drainage area of 1.39 billion m^3 and 3,770 km^2, respectively. It was built for the multiple functions of flood controlling, irrigation, and electricity generation. The watershed has an average precipitation of 626.4 mm per year, most of which is in July to September (70–80%). The average annual temperature is around 12.5 °C and annual pan evaporation is around 1,265 mm. Grassland and forest land are the main land use in the study region, derived from the remote sensed land use data of the year 2014 (over 90%). Fuping hydrologic station is on the upstream of Wangkuai reservoir (Figure 1). Fuping (FP) station was built in June 1958, with a drainage area of 2,210 km^2 and annual mean precipitation of 600 mm.

Due to the serious soil erosion in Wangkuai watershed before the 1980s, a great deal of construction and soil-water conservation have been conducted from the 1980s, which have significantly changed the land surface of the watershed. Taking the Fuping hydrologic station as an example, there are 11 small reservoirs located in the control area with a total storage capacity of 5.9 million m^3. They have a total control area of about 124.95 km^2. Moreover, more than 6,000 check dams have been built since 1980,

Figure 1 | The study region: (a) Daqinghe river basin and (b) Wangkuai reservoir watershed.

and these small-scale hydraulic structures are used for irrigation and soil-water conservation. These measures have influenced the flood mechanism in Wangkuai watershed, but the accurate area of these soil-water conservation projects cannot be derived.

Data

In this study, Wangkuai reservoir watershed and Fuping hydrological station (located on the upstream of Wangkuai watershed) are selected to estimate the area of many small hydraulic structures in the Wangkuai reservoir watershed. Data of the Wangkuai reservoir watershed are from 1955 to 2008 and Fuping from 1958 to 2002.

METHODOLOGIES

Flood scaling analysis

Flood is known to exhibit scaling law in similar areas which is necessary for regional flood frequency analysis. Event-based scaling has a clear relation with physical processes (Furey *et al.* 2016), and a flood generation mechanism was considered as not affected by anthropogenic activity before the 1980s, therefore the flood events in the undisturbed period were selected to analyze flood scaling in Wangkuai reservoir watershed. By establishing the correlation of flood peak with drainage area in the same flood event in

Wangkuai reservoir and Fuping watersheds, we can calculate the scaling exponent according to Equation (1):

$$\frac{Q_W}{Q_F} = \left(\frac{A_W}{A_F}\right)^{\theta} \tag{1}$$

where Q_W and Q_F are the flood peak of Wangkuai and Fuping in the same flood event, A_W and A_F are the drainage area of Wangkuai and Fuping, respectively. Hence, scaling exponent θ can be calculated and is considered as the scaling exponent in Wangkuai watershed.

Calculating the catchment area of many check dams

A large amount of hydraulic structures like check dams were built in Wangkuai reservoir watershed. However, their drainage area could not be derived due to lack of design data. Thus, we propose a new approach to calculate the total catchment area of many check dams by using observed rainfall and flood data of Wangkuai reservoir, combined with flood scaling theory. Due to the impound function of soil-water conservation projects, the flood peak in the disturbed period is smaller than that in the undisturbed with the same rainfall. Thus, the observed flood in the disturbed period is not contributed to by the rainfall in the whole of Wangkuai watershed. In this case, we consider that when a rainfall-flood event occurred, the check dams in Wangkuai reservoir watershed impounded and stored part of the flood. Hence, the actual area that contributes to flood peak is considered as $A-A_r$,

in which A is the drainage area of Wangkuai reservoir and A_r is the drainage area of many check dams upstream of Wangkuai reservoir. Li *et al.* (2016) estimated flood peak relations with drainage area linearly in Wangkuai watershed by using the flood data after 1980, which is expressed by Equation (2) to estimate total drainage area (TDA):

$$\frac{A - A_r}{A} = \frac{Q}{Q_0} \qquad (2)$$

where A is the drainage area of Wangkuai watershed, A_r is the total drainage area of many check dams upstream of Wangkuai reservoir, Q and Q_0 are theoretical and observed flood peaks of the same event in the undisturbed and disturbed period, respectively.

However, flood was considered to follow scaling law and flood peak showed a power law with drainage (Gupta *et al.* 1996, 2007, 2010; Medhi & Tripathi 2015). Therefore, the flood scaling in Wangkuai watershed should not be neglected and Equation (3) can be improved as:

$$\left(\frac{A - A_r}{A}\right)^\theta = \frac{Q}{Q_0} \qquad (3)$$

where θ is scaling exponent in Wangkuai watershed. As Q and Q_0 cannot be obtained simultaneously for the same rainfall-flood event based on observed flood data, the relation between flood peak and rainfall was established to estimate Q and Q_0. Due to flood peak showing significant correlation with 3-hr maximum rainfall intensity in the study region, the

relation between peak discharge and 3-hr maximum rainfall intensity in the undisturbed and disturbed period was established. Based on the observed rainfall and flood data, the fitted relations of the two periods were obtained and the flood peak corresponding to the same rainfall can be calculated. Therefore, the decreased flood peak is considered as a result of the many check dams in Wangkuai watershed.

RESULTS

Detection of nonstationarity in peak discharge series

In order to analyze the impact of many small check dams on the flood in Wangkuai watershed, the nonstationarity of the annual maximum flood peak discharge (AMFP) series (Figure 2) of Wangkuai and Fuping was identified. Non-parametric Mann–Kendall test (Mann 1945; Kendall 1975) and Pettitt test (Pettitt 1979) were applied for detecting the nonstationarity of the AMFP series. The statistical values of Mann–Kendall test were −3.31 and −2.82 for WK and FP, respectively, exceeding the critical value (−1.96) at significance level of 0.05. This illustrated that AMFP series in the WK watershed showed a significant downward trend. The results of the Pettitt test are shown in Figure 3. Both WK and FP exhibited significant change point in 1979. There were a mass of small reservoirs and check dams built around the 1980s in WK watershed, so the most probable change point was deemed to be 1979. Some other studies also agree with the result (Gong *et al.* 2012; Li & Tan 2015; Deng *et al.*
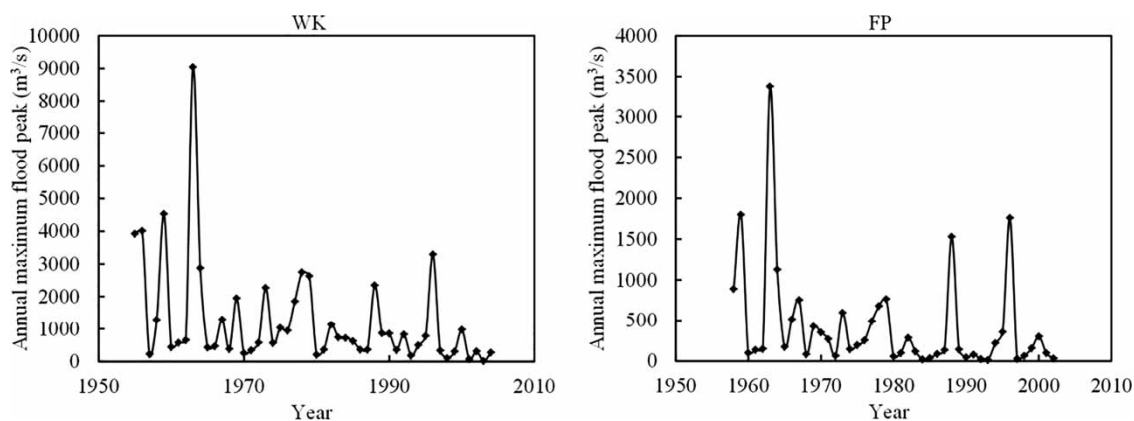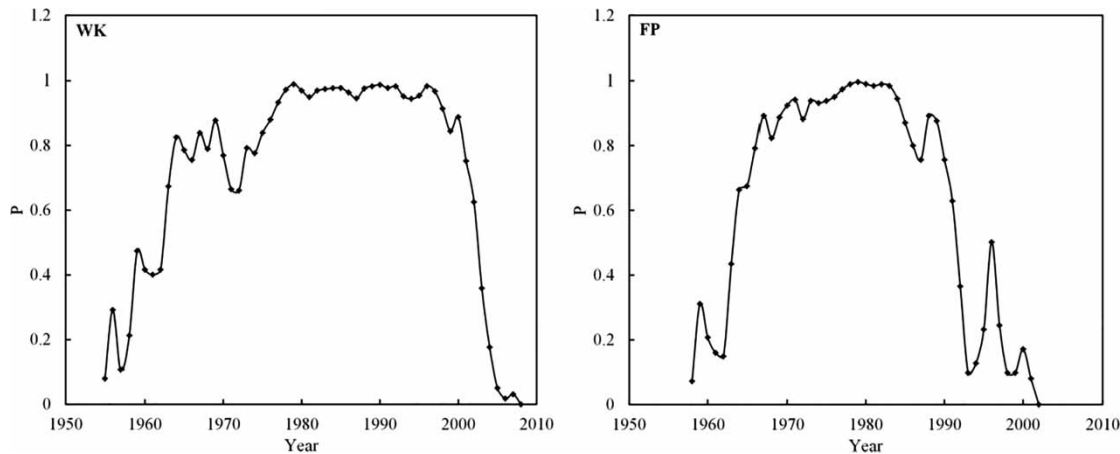

Figure 2 │ The annual maximum peak discharge series of Wangkuai and Fuping.

Figure 3 | Change point analysis of AMFP series of Wangkuai and Fuping by Pettitt test.

2016). The nonstationarity showed that the many check dams in WK have influenced the flood obviously and, indeed, caused nonstationarity in AMFP series.

Flood scaling in Wangkuai watershed

Due to 1979 being deemed to be the change point, the pre-1979 period was seen as the undisturbed period. In this period, influence of anthropogenic activity *on* the physical mechanism of flood was minor and ignored. Therefore, four rainfall-flood events before 1979 in Daqinghe River basin were selected to analyze the correlation of flood peak between WK and FP, then to investigate the event-based flood scaling in the WK watershed. The event-based flood scaling in Daqinghe River basin is shown in Figure 4. Event-based flood peak in Daqinghe River basin showed significant power law and the mean value of scaling exponent θ is 0.5688. The flood scaling in Wangkuai watershed is considered as Equation (4) according to Equation (1):

$$\frac{Q_W}{Q_F} = \left(\frac{A_W}{A_F}\right)^{0.5688} \tag{4}$$

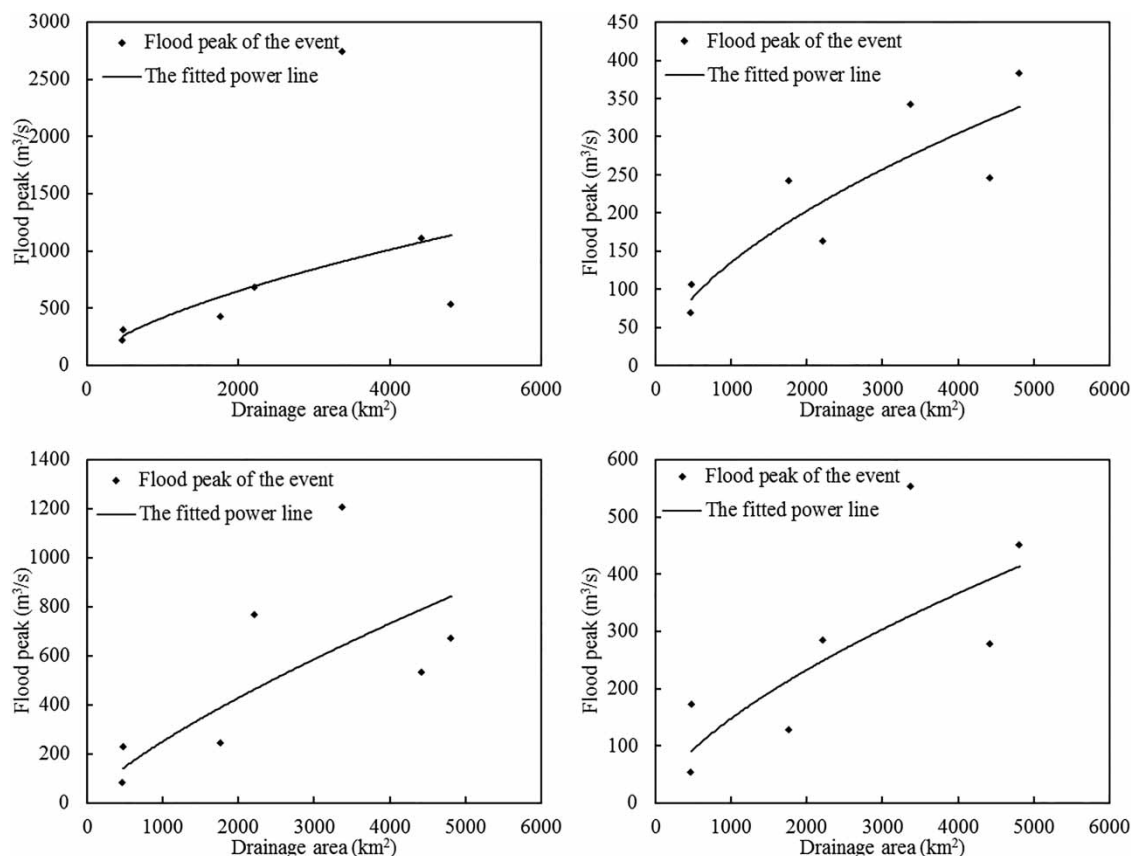## Estimation of catchment area of many check dams in the study region

We selected 23 and 25 flood events in the undisturbed (pre-1979) and disturbed period (post-1979), respectively, to

analyze the influence of many check dams on peak discharges. In Wangkuai watershed, flood peak usually lags behind 3-hr maximum rainfall by around 3 or 4 hours (Li *et al.* 2016); the correlation relationship between flood peak and maximum 3-hr rainfall amount in undisturbed and disturbed period was established (Figure 5). It can be seen that flood peak showed exponential relationship with maximum 3-hr rainfall amount, and for the same rainfall, flood peak decreases in the disturbed period rather than in the undisturbed period. The fitted exponential function between flood peak and rainfall is shown as Equations (5) and (6):
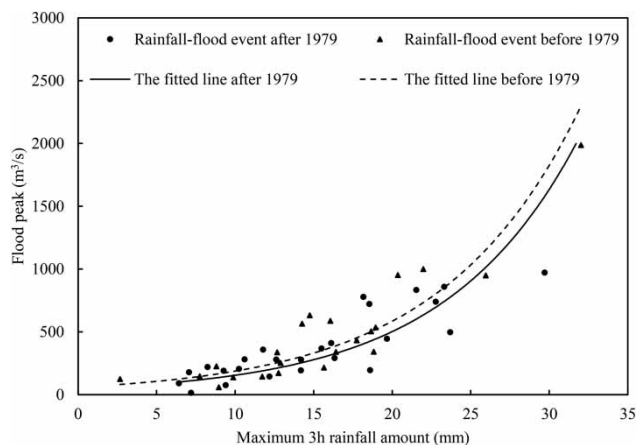
$$Q_{pre} = 59.979\exp(0.114I_3) \tag{5}$$

$$Q_{post} = 47.360\exp(0.118I_3) \tag{6}$$

where I_3 is maximum 3-hr rainfall amount, Q_{pre} and Q_{post} are flood peak pre- and post-1979, respectively. It can be found that the change ratio of flood peak varies as the maximum 3-hr rainfall amount changes because the small reservoirs and check dams are known to have more influence on small floods but show weaker impound effect on large floods. However, most maximum 3-hr rainfall for rainfall events falls within the range of 5–30 mm in Wangkuai drainage area. The change ratio of flood peak with 5 mm and 30 mm maximum 3-hr rainfall amount is 10.70% and 19.40%, respectively (Table 1). Thus, the average change ratio of flood peak with 5 and 30 mm maximum 3-hr rainfall amount, which is calculated as 15.05%, is seen as the

Figure 4 │ Event-based flood scaling in Daqinghe River basin.

Figure 5 │ Correlation between flood peak and maximum 3-hr rainfall amount before and after 1979.

influence of the many check dams on peak discharges in Wangkuai watershed. Then, the total catchment area of the many check dams upstream of Wangkuai reservoir is 939.88 km^2 based on Equation (3).

Table 1 │ Change of flood peak pre- and post-1979

Maximum 3-hr rainfall amount (mm)	Q_{pre} (m^3/s)	Q_{post} (m^3/s)	Change ratio of flood peak (%)	Average change ratio (%)
5	106.01	85.44	19.40	15.05
30	1,828.03	1,632.35	10.70	

DISCUSSION

Previous research considered that flood peak and drainage area showed a simple linear relation (Yu *et al.* 2014; Li *et al.* 2016). However, flood in watersheds exhibits a scaling effect in many studies (Goodrich *et al.* 1997; Ogden & Dawdy 2003; Ayalew *et al.* 2014). Hence, the former methods are unreasonable and need to be improved upon. In this paper, we analyzed the event-based flood peak scaling in Wangkuai reservoir watershed based on

the correlation of event flood peak between Wangkuai reservoir and Fuping station according to the actual flood data. The flood peak of two watersheds showed significant linear correlation and the scaling exponent θ of WK watershed was calculated as 0.5688. While event-based flood scaling should be analyzed based on actual data of more sub-watersheds in Wangkuai reservoir watershed, due to a lack of data we only used flood data of two watersheds and the result may be inaccurate. Flood scaling is affected by factors like rainfall spatio-temporal distribution and land surface condition. In this paper, the coefficient of determination for fitted scaling curve is around 0.6 and rainfall spatial distribution should be considered in future research.

Based on historical hydrological data, Yu *et al.* (2014) and Li *et al.* (2016) estimated the water storage capacity of soil-water conservation projects upstream of Lengkou watershed and Wangkuai watershed, respectively. Due to scaling exponent θ generally less than 1, the result should be larger in the same study area if considering flood scaling according to Equation (3). However, Li *et al.* (2016), who did not consider flood scaling in Wangkuai reservoir watershed, found that the drainage area of the small hydraulic structures upstream of Wangkuai reservoir was 1,304 km^2, that result being larger than the result in this paper (939.88 km^2). The main reason is that more rainfall-flood events were selected in the undisturbed and disturbed period in this paper and, indeed, the influence of environmental change on flood peak was 15.05% which is larger than the research of Li *et al.* (2016) whose result was 34.6%. The larger sample size reduced the sampling error and the result was more credible in this paper.

CONCLUSIONS

Hydraulic engineering has a significant function of regulation to floods. The effect of large hydraulic engineering projects is usually easy to determine because the design data and scheduling rule are generally available. However, it is difficult to quantify the effect of small structures without sufficient data, such as small reservoirs and check dams. By using rainfall and flood data of Wangkuai reservoir and Fuping station upstream, we presented a new method to

calculate the control area of many check dams considering flood scaling in Wangkuai watershed.

The nonstationarity was detected based on the AMFP series of WK and FP and a significant downward trend was diagnosed in both series. Moreover, 1979 was detected as the change point of AMFP series. Thus, in this paper, pre-1979 and post-1979 periods were considered as the undisturbed and disturbed period, respectively.

By establishing the correlation between WK and FP, the event-based flood scaling in Wangkuai watershed was analyzed. The flood peak showed significant linear correlation between WK and FP ($R^2 = 0.7436$), and event-based flood scaling exponent θ was calculated as 0.5688. Then, rainfall-flood events in disturbed and undisturbed periods were selected to analyze the effect of the many check dams on flood. The exponential function between peak discharge and maximum 3-hr rainfall amount pre- and post-1979 were fitted and the average change ratio of flood peak was 15.05%. Therefore, the total drainage area of all the check dams upstream of Wangkuai reservoir was estimated as 939.88 km^2.

REFERENCES

Archer, D. & Newson, M. 2002 The use of indices of flow variability in assessing the hydrological and instream habitat impacts of upland afforestation and drainage. *Journal of Hydrology* **268** (1–4), 244–258.

Ayalew, T. B., Krajewski, W. F. & Mantilla, R. 2014 Connecting the power-law scaling structure of peak-discharges to spatially variable rainfall and catchment physical properties. *Advances in Water Resources* **71**, 32–43.

Brath, A., Montanari, A. & Moretti, G. 2006 Assessing the effect on flood frequency of land use change via hydrological simulation (with uncertainty). *Journal of Hydrology* **324** (1–4), 141–153.

Cammerer, H., Thieken, A. H. & Verburg, P. H. 2013 Spatio-temporal dynamics in the flood exposure due to land use changes in the alpine Lech Valley in Tyrol (Austria). *Natural Hazards* **68** (3), 1243–1270.

Deng, X., Ren, W. & Feng, P. 2016 Design flood recalculation under land surface change. *Natural Hazards* **80** (2), 1153–1169.

Furey, P. R. & Gupta, V. K. 2007 Diagnosing peak-discharge power laws observed in rainfall–runoff events in Goodwin Creek experimental watershed. *Advances in Water Resources* **30** (11), 2387–2399.

Furey, P. R., Troutman, B. M., Gupta, V. K. & Krajewski, W. F. 2016 Connecting event-based scaling of flood peaks to regional flood frequency relationships. *Journal of Hydrologic Engineering* **21** (10), 04016037.

Gong, A., Zhang, D. & Feng, P. 2012 Variation trend of annual runoff coefficient of Daqinghe river basin and study on its impact. *Water Resources & Hydropower Engineering* **6** (6), 25–29.

Goodrich, D. C., Lane, L. J., Shillito, R. M., Miller, S. N., Syed, K. H. & Woolhiser, D. A. 1997 Linearity of basin response as a function of scale in a semiarid watershed. *Water Resources Research* **33**, 2951–2965.

Gupta, V. K., Castro, S. L. & Over, T. M. 1996 On scaling exponents of spatial peak flows from rainfall and river network geometry. *Journal of Hydrology* **187** (1), 81–104.

Gupta, V. K., Troutman, B. M. & Dawdy, D. R. 2007 Towards a nonlinear geophysical theory of floods in river networks: an overview of 20 years of progress. In: *Nonlinear Dynamics in Geosciences*. Springer, New York, pp. 121–151.

Gupta, V. K., Ricardo, M., Troutman, B. M., David, D. & Krajewski, W. F. 2010 Generalizing a nonlinear geophysical flood theory to medium-sized river networks. *Geophysical Research Letters* **37** (11), 402.

Haddad, K., Rahman, A. & Stedinger, J. R. 2011 Regional flood frequency analysis using Bayesian generalized least squares: a comparison between quantile and parameter regression techniques. *Hydrological Processes* **26** (7), 1008–1021.

Han, S. J., Wang, S. L., Xu, D. & Zhang, Q. B. 2012 Scale effects of storm-runoff processes in agricultural areas in Huaibei Plain. *Transactions of the Chinese Society of Agricultural Engineering* **28** (8), 32–37.

Ishak, E., Haddad, K., Zaman, M. & Rahman, A. 2011 Scaling property of regional floods in new south Wales Australia. *Natural Hazards* **58** (3), 1155–1167.

Jothityangkoon, C. & Sivapalan, M. 2001 Temporal scales of rainfall–runoff processes and spatial scaling of flood peaks: space–time connection through catchment water balance. *Advances in Water Resources* **24** (9–10), 1015–1036.

Kendall, M. G. 1975 *Rank Correlation Measures*. Charles Griffin, London.

Li, J. & Tan, S. 2015 Nonstationary flood frequency analysis for annual flood peak series, adopting climate indices and check dam index as covariates. *Water Resources Management* **29** (15), 5533–5550.

Li, J. Z., Wei, Z. Z. & Liu, Y. 2013 Analysis on the response of flood processes to soil and water conservation engineering. *Journal of Irrigation & Drainage* **32** (5), 137–140.

Li, J., Sun, H. & Feng, P. 2016 How to update design floods after the construction of small reservoirs and check dams: a case study from the Daqinghe river basin, China. *Journal of Earth System Science* **125** (4), 795–808.

Liu, Y. B., Smedt, F. D., Hoffmann, L. & Pfister, L. 2005 Assessing land use impacts on flood processes in complex terrain by using GIS and modeling approach. *Environmental Modeling & Assessment* **9** (4), 227–235.

Mann, H. B. 1945 Nonparametric test against trend. *Econometrica* **13** (3), 245–259.

Medhi, H. & Tripathi, S. 2015 On identifying relationships between the flood scaling exponent and basin attributes. *Chaos* **25** (7), 075405.

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P. & Stouffer, R. J. 2008 Stationarity is dead: whither water management? *Science* **319** (5863), 573–574.

Moel, H. D. & Aerts, J. C. J. H. 2011 Effect of uncertainty in land use, damage models and inundation depth on flood damage estimates. *Natural Hazards* **58** (1), 407–425.

Naef, F., Scherrer, S. & Weiler, M. 2002 A process based assessment of the potential to reduce flood runoff by land use change. *Journal of Hydrology* **267** (1–2), 74–79.

Nirupama, N. & Simonovic, S. P. 2007 Increase of flood risk due to urbanisation: a Canadian example. *Natural Hazards* **40** (1), 25.

Ogden, F. L. & Dawdy, D. R. 2003 Peak discharge scaling in small Hortonian watershed. *Journal of Hydrologic Engineering* **8** (2), 64–73.

Pettitt, A. N. 1979 A non-parametric approach to the change-point problem. *Journal of the Royal Statistical Society* **28** (2), 126–135.

Robinson, M. 1980 *The Effect of pre-Afforestation Drainage on the Streamflow and Water Quality of A Small Upland Catchment*. Institute of Hydrology Report 73, Wallingford, UK.

Robinson, M. 1993 Impacts of plantation forestry on streamflow regimes – a case study. British Hydrological Society, Fourth National Symposium, pp. 2.41–2.45.

Saghafian, B., Farazjoo, H., Bozorgy, B. & Yazdandoost, F. 2008 Flood intensification due to changes in land use. *Water Resources Management* **22** (8), 1051–1067.

Yu, P., Li, J. Z. & Liu, Y. 2014 Assessment of the effects of soil and water conservation engineering on flood characteristics. *Journal of Arid Land Resources and Environment* **28** (7), 90–95.

Zahar, Y., Ghorbel, A. & Albergel, J. 2008 Impacts of large dams on downstream flow conditions of rivers: Aggradation and reduction of the Medjerda channel capacity downstream of the Sidi Salem dam (Tunisia). *Journal of Hydrology* **351** (3), 318–330.