Flood duration frequency analysis in a changing climate: the methodology applied to Fengle River (Yangtze basin, China)

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Abstract The Chao Lake, located in the Yangtze basin, is the fifth largest freshwater lake in China. The lake catchment (9130 km^2) includes the city of Hefei (3.5 million inhabitants) and a large extent of paddy fields and rural areas. The Fengle River is a tributary of the Chao Lake. It is currently subject to flood risks and inundation issues. Many changes are expected in land use and agricultural practices in the future, due to the tourist appeal of the Chao Lake shore and the fast expansion of the city of Hefei. Climate changes are also expected in this region, with a high impact on the rainfall regime. The consequences of all these changes on flood occurrence and magnitude are a major issue for the economic development of the area and tools are needed to carry out such an analysis. Here, a methodology is proposed for investigating the potential impact of rainfall regime change on flood duration and frequencies in the future. The methodology consists of three steps: first from a literature review scenarios of changes in precipitation are identified and used to build future series of daily rainfall; secondly, future daily discharges are simulated using a distributed hydrological model (MERCEDES) previously calibrated on current rainfall–discharge data; finally the current *vs* future discharge dynamics are characterized in terms of flood frequencies from discharge–duration–frequency curves. The methodology is implemented on the Fengle River, for which 20 years of daily discharges (Taoxi station), daily rainfall (eight stations), temperature and evapotranspiration (Hefei weather station) are available.

Key words flood duration frequency; rainfall; downscaling, land use and climate changes

INTRODUCTION

Future water management challenges such as flood risk are highly relevant to climate and land-use changes. Climate change is expected to lead to an ongoing intensification of effects on changes in precipitation and evapotranspiration which could exacerbate flooding issues (Huntington, 2006; Wilby *et al.*, 2008). Land-use changes, modifications of agricultural practices and urbanisation alter the apportionment of the different hydrological processes at the basin scale and can significantly affect the seasonality of streamflow (Guo *et al.*, 2008; Poelmans *et al.*, 2010). At the local scale, the consequences of climate and land use changes on flood occurrence and magnitude are a major issue for the economic development and policy protection of the basin area.

Zhao *et al.* (2009) underlined that in the Yangtze basin limited research was conducted at a regional catchment scale and more attention was paid to the frequency and intensity of extreme climatic events and floods. At the basin scale, the usual approach to simulate the hydrological impacts of rainfall and land-use changes is to consider climate scenario outputs from general circulation models (GCM) downscaled at the basin level with a land-use change scenario based on the local policy development plan, and to finally apply these in a hydrological model (Mareuil *et al.*, 2007). The hydrological model generates possible future river discharges from which estimates of changes in the frequency and magnitude of floods can then be derived. Ben Aissia *et al.* (2012) reported that most studies of the impact of climate change on the hydrological regime paid attention to flood peaks and that little effort has been directed to other flood characteristics such as flood volume or flood duration.

Our study aimed to provide tools for estimating consequences of land use and precipitation changes on streamflow dynamics, accounting for uncertainties in scenario data and hydrological model parameters. We present here the first part of the methodology which applies to precipitation changes, and its implementation on the Fengle River, a small tributary of the Chao Lake (Yangtze basin, China). The future discharge time series were simulated from a calibrated and validated distributed hydrological model, using predicted rainfall time series based on scenarios of changes. The observed and predicted discharges of Fengle River were used to derive discharge–duration–frequency curves of the current and future periods. The study area, the available data, the hydrological model and the description and implementation of the methodology on the Fengle River are outlined in this paper.

APPLICATION AREA

Fengle River

The Fengle River basin is located in the northeast part of Yangtze basin (Anhui province, China) (Fig. 1). The river is one of the main tributaries of the Chao Lake, the fifth largest natural lake in China. The lake catchment is 9130 km^2 in area, including the city of Hefei and a large extent of agricultural and rural areas. Many changes are expected in land use and agricultural practices in the future, due to the touristic appeal of the Chao Lake shore and the growth of the city of Hefei. The Fengle catchment area is 1500 km^2 and the main stream length is approx. 50 km. The catchment elevations range from 6 to 463 m. Land use includes agriculture, mainly paddy fields (about 45%), forest (39%), town and roads (10%) and water, ponds and river areas (6%). No large cities or industrial factories are yet located in this catchment. The climate is dominated by the southeast Asian monsoon during summer. The average annual rainfall over the past 20 years is 1115 mm, with a standard deviation of 267 mm. From May to September, 65–80% of the annual rainfall is observed. Heavy storms and floods occur predominantly during summer.

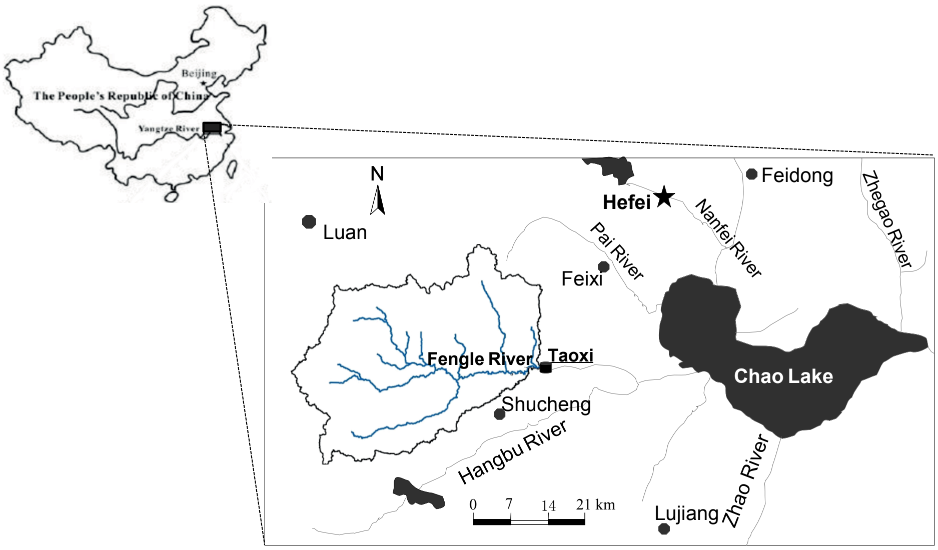

Fig. 1 Location of the Fengle River basin.

The area is subject to heavy and devastating floods and the hydrological system has been under great pressure from human activities since 1950 (Dai *et al.*, 2009). Moreover, predicted changes in the area of the Chao Lake basin suggest that the region may experience a higher risk of floods in the future. Piao *et al.* (2010) concluded that heavy rainfall events became more and more frequent over the mid to lower reaches of the Yangtze River. Gu *et al.* (2012) suggested an increased risk of floods due to extreme precipitation changes, with the strongest increases of daily rain intensity and maximum five-day rain amounts occurring for most of the Yangtze River basin. Zhang *et al.* (2011) emphasized that the streamflow changes were mainly the result of precipitation changes.

Available data

Since the late 1980s, a monitoring network has been constructed in the Fengle catchment. Water level is recorded at Taoxi streamgauge station located 10 km upstream from the outlet in the Chao Lake. River water levels are converted to daily discharges with an accuracy of ±10%. Daily rainfall data are available from a network of eight tipping bucket raingauges. Potential evapotranspiration is derived using the Thornthwaite equation (Thornthwaite, 1954) from the daily temperature recorded at the Hefei weather station.

METHODOLOGY

The methodology consists of three steps:

(1) Generation of daily rainfall time series: the estimates of inter-annual rainfall variations are created from GCM outputs and downscaled to basin scale as well as to the season scale. The downscaling at daily scale assumes that the future daily rain sequences are identical to the observed sequences and that the variations are the same for all the raingauges. For a given year i, the rainfall variation rate (X_i) is drawn from a normal distribution. The year is divided into three periods: summer (June to August), winter (December to February) and inter-season (March to May and September to November). The rainfall variation rates of the summer and winter periods (X_{is} and X_{iw}) are drawn from uniform distributions; the variation rates of the inter-season period are calculated with respect to X_i for the eight raingauges independently. In the case of positive rates, the rainfall amount of the rainy days of the corresponding period is increased following four different modes. Mode1 scales each rainy day by the variation rate; Mode2 uniformly reports on the rainy days the seasonal rainfall amount increase; Mode3 uniformly reports on rainy days of the wettest month the seasonal rainfall amount increase; and Mode4 reports the seasonal rainfall amount increase on the wettest day of the period. In the case of negative variation rates the rain amount of the rainy days are scaled by the variation rate of the period.

(2) Generation of future daily discharge time series: after calibration and validation of the hydrological model on the past observed rainfall–discharge series assuming that the hydrological processes are not affected by changes, scenarios of discharges are generated, using ATHYS hydrological tool box (Bouvier & Delclaux, 1996). A distributed modelling approach was selected to account for land use and land occupation spatial distribution and changes in a further study.

(3) Flood frequency–duration analysis: past and future flood-duration frequencies are compared, through the application of QDF, i.e. the discharge duration–frequency method (Galéa & Prudhomme, 1997; Javelle *et al.*, 2002). The frequency analysis considers the usual peak flow, the flood volume, but also the flood duration. Apart from the peak flow return period the QDF approach takes into account the multi-duration aspect of flood hydrographs (Cunderlik & Ouarda, 2006).

IMPLEMENTATION ON THE FENGLE BASIN

Generation of future daily rainfall

The 2080–2100 daily rainfalls are predicted following the above described methodology and taking into account the estimations of changes reported by Cao *et al.* (2011). For the end of the century the inter-annual variation would be in the range +5% to +10% in the area of the Fengle basin. These changes are supposed to affect differently the precipitation according to the period of the year. During the winter period, average precipitation has a decreasing trend, with rates within a range of –10% to 0%. For the summer period, rainfall variation rates would cover a range from negative variation (–10% to 0%) to positive variation (0 to 20%). Therefore the four downscaling modes are run on a two-fold approach: Modes 1P, 2P, 3P and 4P assuming positive variation rates in summer and Modes 1N, 2N, 3N and 4N assuming negative rates. For the 21-year period (2080–2100) annual variation rates are drawn from a normal distribution $N(5,1)$. Seasonal variations for winter are drawn from a uniform distribution *U*(–10,0) and summer variations from *U*(–10,0) for negative trend and *U*(0,20) for positive trend. For the eight modes, the yearly drawn variations are uniformly applied to the eight raingauges rainfall series. For each raingauge, an individual adaptive variation is applied to the inter-season periods in order to agree to the annual variation. The implementation of the methodology is exemplified here on a single run. Figure 2(a) and (b) illustrate the current and predicted mean monthly rainfall over the Fengle basin for two downscaling modes. As expected, monthly rain amounts from Mode 4P show an increase during the summer period and light increase during the inter-season period. Mode 4N acts differently, rainfall amount during the inter-season period increases, while it decreases during the summer period. Overall the seasonal contrast is more marked with Mode 4P while it is lightened by Mode 4N. At the day scale the observed maximum rainfall amount over the basin, i.e. 135 mm, increases to 225 mm and 239 mm for 4P and 4N downscaling modes, respectively.

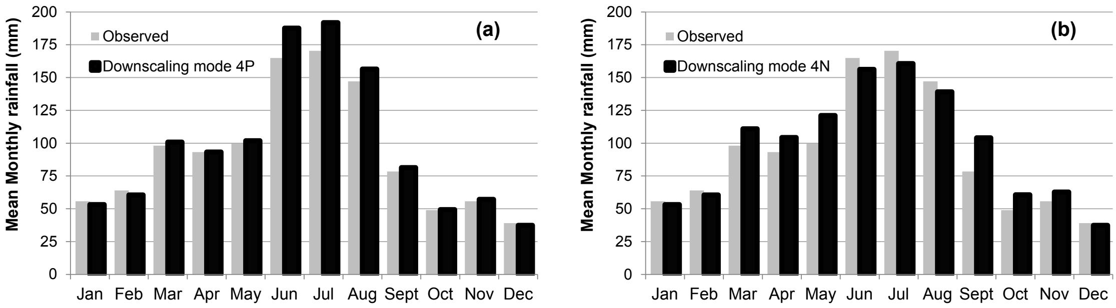

Fig. 2 Mean monthly rainfall from a single random simulation for downscaling: (a) mode 4P (summer rainfall amount is increasing) and (b) mode 4N (summer rainfall amount is decreasing).

Generation of future daily discharge

The distributed hydrological model is run on a 90-m squared regular mesh grid at a 1-day calculation time step. Each individual mesh is characterized by soil type and land use and it provides a runoff contribution to the outlet derived from a 4-parameter rainfall–runoff function (Ambroise *et al.*, 1995). The inputs are daily rainfall and daily potential evapotranspiration data. The four parameters of the rainfall–runoff function are adjusted according to land use categories. Three categories are considered: agricultural areas with rice paddies equivalent of a pond, other agricultural and natural areas, and urban areas. The mesh elementary runoff contribution is transferred to the catchment outlet by a specific translation-storage routine (Bouvier *et al.*, 1994). The complete flood hydrograph is obtained by summation of the elementary mesh contributions, calculated for each time step.

The calibration and validation of the model are done using the 21-year rainfall–discharge–evapotranspiration data (1990–2011). A trial-and-error procedure is used to calibrate the parameters on the first 10 years of the dataset (1990–1999) while the last 11 years (2000–2010) are used for validation purposes. The model performance is assessed qualitatively with graphical displays of the hydrograph and quantitatively using a statistical objective function: the Nash & Sutcliffe (1970) coefficient (NS). For both calibration and validation periods the simulation outputs match well with the discharges observed at Taoxi station. Some discrepancies are observed during baseflow conditions and when the paddy fields are drying. For the 10-year calibration period, the average NS value equals 0.85 (annual NS ranges from 0.45 to 0.91). The validation gives similar scores: the 11 years average NS value is 0.86 varying from –0.11 to 0.93. For the purpose of this study, attention was paid to high flow periods. In Fig. 3, the maximum simulated annual discharges are plotted *versus* observed maximum annual discharge. The results are plotted for 1-day and 5-day duration in Fig. 3. The uncertainty of the simulated discharge is not yet assessed, but in a first approach we consider that the uncertainty is at least of the same order of magnitude as the observed discharge (i.e. 10%). With regard to the 10% uncertainty there is agreement between the observed and the simulated annual peak discharges except when 1-day duration discharges are larger than 750 m^3/s.

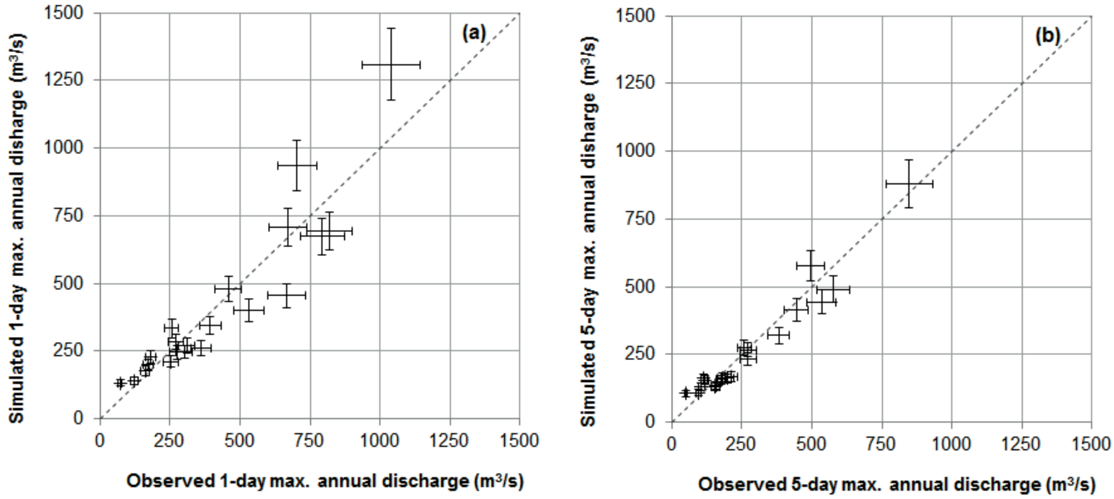

Fig. 3 Maximum annual discharges: observed *vs* simulated by the MERCEDES hydrological model considering (a) 1-day duration and (b) 5-day duration. The dotted line is the 1:1 slope line.

Flood frequency–duration analysis

Discharge duration curves for 6-year and 14-year return periods are plotted on Fig. 4. QDF plots are derived from the current observed and the eight simulated "future" discharge 21-year series. The results highlight some aspects of the modes of generation of daily rainfall series. For the 6-year return period, the Mode 2P QDF has specific features due to its definition: increase of precipitation during summer and uniform report of the increase on the rainy days. For the duration less than 8 days the discharge associated to a given duration is larger for Mode 2P than for current discharge data. The other modes predict future QDF in the same range or below the current QDF. For a larger period return, i.e. 14-year, Mode 2N and Mode 4N (increase of rain amount during the inter-season) stand out from the others for durations less than 8-day. For the 2-day duration the 14-year period return discharge is 1170 m^3/s, 50% larger than the current estimated discharge (800 m^3/s). The Mode 4N differs for the entire explored duration range, surely because the hypothesis of this mode "report of increase of the rainfall amount on a single rainy day" is strong.

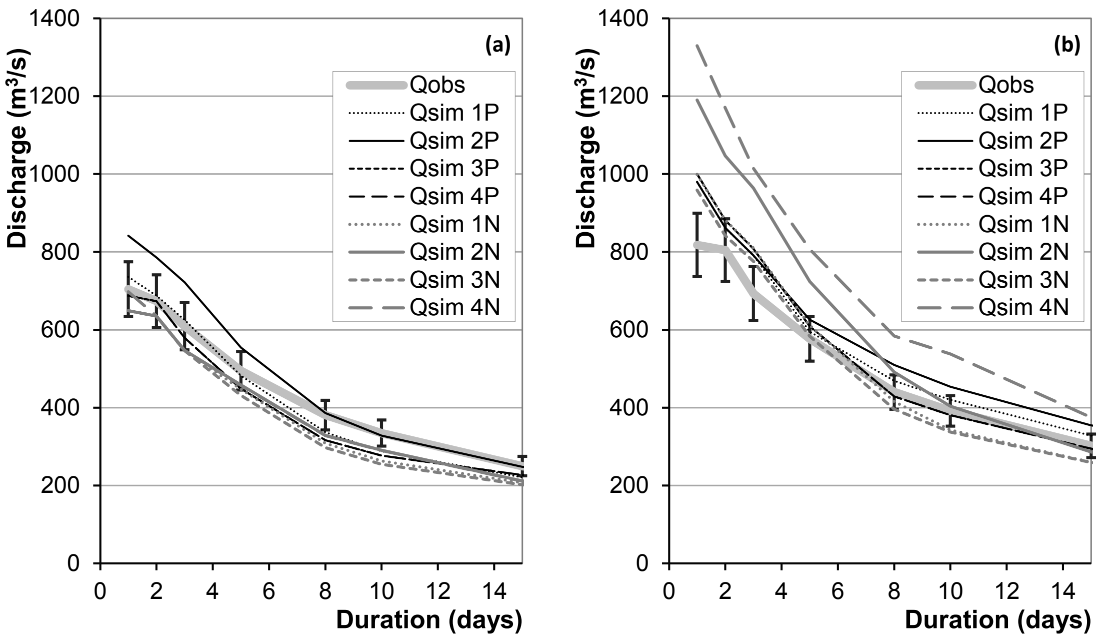

Fig. 4 Discharge duration curves from measured discharges and MERCEDES simulated discharges with predicted rain: (a) 6-year return period and (b) 14-year return period.

CONCLUSION

The proposed methodology was successfully implemented on the Fengle River. It helps to analyse the potential consequences of climatic changes on flood occurrence, duration and magnitude. However, care should be taken that the presented results are based on a single run of the methodology.

Several improvements are still in progress: (1) a complete Monte Carlo simulation must be performed for a complete analysis of potential changes in flood frequency due to rainfall changes; (2) changes in evapotranspiration rates, due to temperature changes must also be considered; and (3) scenarios of land-use changes must also be implemented and considered in the rainfall–runoff model.

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