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Quantitative assessment of climate change and human impacts on long-term hydrologic response: a case study in a sub-basin of the Yellow River, China

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ABSTRACT: In this study we developed an impact factor formula (IFF) to quantitatively attribute separately the impacts of climate change and local human activities on hydrological response (i.e. run-off) in a sub-basin of Yellow River for the period 1950–2000. Using the daily climatic data, we first calibrated and verified the variable infiltration capacity (VIC) hydrological model to the baseline period 1955–1970. Then we developed the basin's natural run-off for the following three decades (1971–2000) using the VIC model without considering local human impacts, as the VIC model is benchmarked by the 1960's hydrological regime.

On the basis of observed precipitation, run-off and reconstructed natural run-off data from 1971 to 2000, we quantified their long-term trend, decadal and annual variations. Using daily climatic observations, we showed that the precipitation and run-off have decreased from the baseline decade, the 1960s, indicating a drier hydrological regime for recent decades. We further applied the IFF to quantitatively attribute separately the impacts of reduced precipitation and increased temperatures from climate change and then of local human activities on hydrological run-off response. It was found that climate change has a greater impact than human activities on the basin's run-off for the three consecutive decades. The pCC (percentage change of run-off due to climate change impact) is found to be 89% followed by 66% and 56% in 1970s, 1980s and 1990s, respectively. Over the decades, pHA (percentage change of run-off due to human activities) has continuously increased from 11% to 44%. If the trend continues, in future, the pHA is going to outweigh pCC in this basin. This study provides a quantitative assessment methodology for water resources managers to understand the changing process of the hydrological cycle and attribute its causative factors in a sub-basin of the Yellow River. Copyright © 2009 Royal Meteorological Society

KEY WORDS climate change; hydrology; human impact; impact factor formula; run-off

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1. Introduction

The global and regional hydrological cycles have been greatly influenced by climate change and human activities in the past century (Brutsaert and Parlange, 1998; Scanlon *et al.*, 2007; IPCC, 2008). Over the last half of the 20th century, regional climate studies in the Yellow River basin (YRB) have indicated warming temperatures at a rate of 1.28 °C/50 years and precipitation has been decreasing by 45.3 mm/50 years (Shi *et al.*, 2003; Wang *et al.*, 2003; Yang *et al.*, 2004). On the other hand, human activities including land use change and artificial water intake in YRB have led to environmental degradation and water shortages. In particular, the main river along the lower reaches has been drying up since the mid-1970s, with a maximum of approximately 20 dry river days/year increasing to 226 days of a completely dry river in 1997 (Yang *et al.*, 2004). The trend is likely to continue in the future. According to Cong *et al.* (2009), run-off in catchments of the YRB has been altered by both large-scale climate change and small-scale, more direct human impacts. Therefore, it is important to analyse the hydrological regimes' responses to these factors separately for the past half century in order to predict future changes.

Hydrological models have been used widely for water resource assessments, especially for studying the impact of climate change (Nijssen *et al.*, 2001; Oki *et al.*, 2001; Yang *et al.*, 2001; Döll *et al.*, 2003). Li *et al.* (2007), Hao *et al.* (2008) and Ma *et al.* (2008) used water balance models with simple empirical relations to attribute the changes in observed streamflow reduction to climate change (i.e. precipitation) or human intervention in the Wuding River, a sub-basin of the YRB. Several other trend analysis studies have also attempted to explain the changes of the water resources in YRB from historical climate data (Burn and Hag Elnur, 2002; Fu *et al.*, 2004). Results of those studies have identified climate change

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and human activities (artificial water intake and land use change) as the two main factors leading to the drying up of the river (Cong *et al.*, 2009). However, development of a quantitative assessment method in order for the local water managers to understand hydrological changes and attribute the causative factors in the YRB remains a challenge.

This study attempts to develop an impact factor formula (IFF) to quantify separately the influences of regional climate change (as manifested in observations of daily precipitation, wind speed and minimum and maximum air temperatures) and local human activities (such as land use change and water intake) on regional run-off response in a sub-basin of the YRB for the period 1950–2000. More than 50 years of daily hydrometeorological data are used to reconstruct the 'natural run-off' by applying the variable infiltration capacity (VIC; Liang *et al.*, 1994; Liang *et al.*, 1996) model for simulating the hydrological cycle in a sub-basin of the YRB without consideration of the local human factors such as land use change and artificial water intake. The IFF is thus implemented on the basis of the long-term observations and the hydrological reconstruction to quantitatively understand separately the influences of climate change and human activities on run-off in this hydrological regime.

2. Study area and method

2.1. Study area and data

The Baimasi basin is located at the mid-region of the Yellow River, which is also the centre of the People's Republic of China (Figure 1) covering parts of the Henan and Shanxi provinces. This basin extends from 33.7 °N to 34.9 °N latitude and 109.7 °E to 112.6 °E longitude, draining a total area of 13 915 km^2. The elevation varies from 122 to 2465 m. For the past century, the basin has witnessed extreme events, massive floods as well as water shortages (Prieler, 1999). According to Wang (2005), since the late 1970s and early 1980s, increasing human activities such as irrigation and industrialization have presented significant impacts on this hydrological regime.

The data required for this study were mostly collected from local administrative agencies. The observations came from seven meteorological stations for the period of record 1955–2000 and included daily precipitation, wind speed and maximum and minimum temperatures. Daily river discharge was obtained for the site located at the basin outlet in Baimasi (Figure 1).

2.2. Method

2.2.1. Impact factor formula

Previous studies have identified climate change, generally yielding lower precipitation and increased temperatures, and local human activities, such as river water withdrawals and land use changes, as the two main factors leading to the altered run-off observations in the YRB (Cong *et al.*, 2009). In the past half century, Yang *et al.* (2005) found warming temperatures at a rate of 1.28 °C/50 years and precipitation decreasing at a rate of 45.3 mm/50 years. As a relatively small sub-basin of the YRB, the Baimasi hydrological regime has also responded to these impacts for the past half century. To separate and quantify the influences of climate change and local human activities on the run-off variation, we have taken the 1960s as the baseline (benchmark) decade for this study. According to Cong *et al.* (2009), for the successive decades thereafter, i.e. 1970s, 1980s and

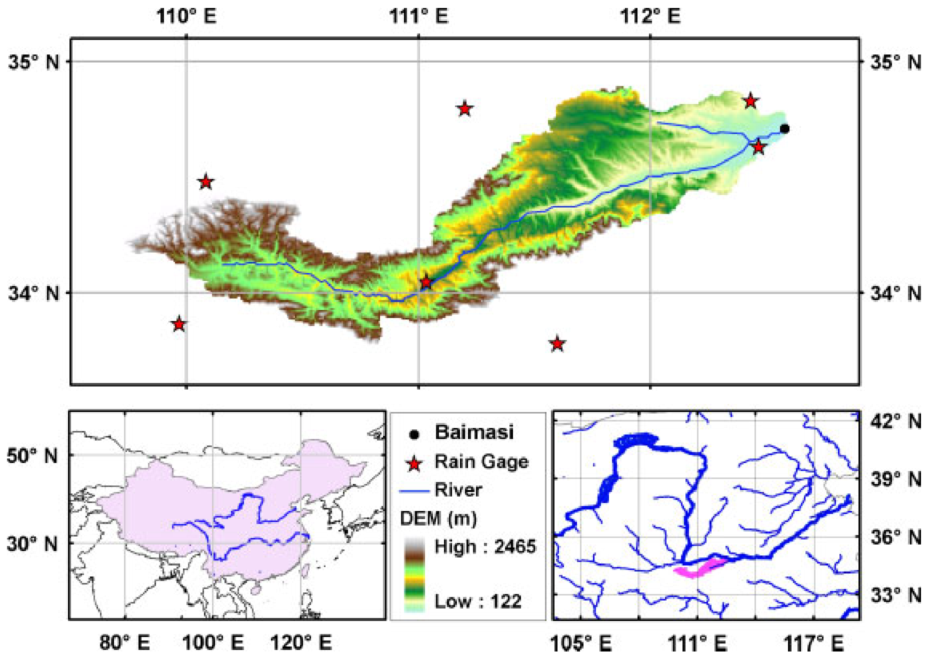

Figure 1. Study area and locations of hydrometeorological stations. Location of streamgauge is in Baimasi. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

1990s, the run-off variation in response to climate change can be quantified by reconstructing the natural run-off from a hydrological model.

An analysis of observed run-off shows the combined impacts of lower precipitation and increased temperatures due to climate change and increased human activities such as direct river withdrawals. A hydrological model represents the non-linear transformation from precipitation to river run-off, and moreover, includes the influences of reduced precipitation and warmer temperatures due to a changing climate system. In this regard, the hydrological model is used to reconstruct the natural run-off, which is responsive to climate change. For this study, using the daily climatic data, we first calibrated the VIC hydrological model (Liang *et al.*, 1994; Liang *et al.*, 1996) to the baseline period of the 1960s as a benchmark. We then simulated the basin natural run-off for the subsequent three decades (1971–2000) with no consideration of local human activities on the sub-basin (i.e. land use change and artificial water intake). Therefore, the reconstructed run-off, hypothetically, is the result of hydrological response impacted by climate change (precipitation and temperature in this case) only, hereinafter I_{cc}. Likewise, we define the run-off changes impacted by human activities as I_{ha}. Thus, the difference between reconstructed natural run-off and observed run-off represents the hydrological response to I_{ha}, which is the residual. The relative change in observed run-off (RO) since the 1960s can be attributed to the combined impacts of human activities and climate change ($I_{\mathrm{ha}} + I_{\mathrm{cc}}$):

$$\mathrm{RO} = I_{\mathrm{cc}} + I_{\mathrm{ha}} = \left(\frac{O_i}{\overline{O}_{\mathrm{base}}} - 1\right) \times 100 \tag{1}$$

where RO is the relative change in observed run-off over the 1960s baseline period (%), I_{ha} indicates impact from human activities (%), I_{cc} indicates impact from climate change (%), $\overline{O}_{\mathrm{base}}$ is the observed mean decadal run-off for the 1960s baseline period (cubic metre per year) and O_i is the observed annual run-off (cubic metre per year) for the assessment period.

The relative change in reconstructed run-off over the baseline period (RC) can then be stated as:

$$\mathrm{RC} = I_{\mathrm{cc}} = \left(\frac{R_i}{\overline{R}_{\mathrm{base}}} - 1\right) \times 100 \tag{2}$$

where RC is the relative change in reconstructed run-off over the baseline period (%), I_{cc} indicates the impact from climate change (%), $\overline{R}_{\mathrm{base}}$ is the reconstructed mean decadal run-off for the 1960s baseline period (cubic metre per year) and R_i is the reconstructed annual run-off for the assessment period (cubic metre per year).

RO includes impacts from both local human activities and climate change for the recent three decades as compared with the baseline decade of the 1960s, whereas RC is the relative change of reconstructed natural run-off caused by climate change factors only. From equations (1) and (2) we can separate the percentage of climate change impact I_{cc} from the summation of combined impacts

$$\frac{\mathrm{RC}}{\mathrm{RO}} = \frac{I_{\mathrm{cc}}}{I_{\mathrm{ha}} + I_{\mathrm{cc}}} = \left(\frac{\dfrac{R_i}{\overline{R}_{\mathrm{base}}} - 1}{\dfrac{O_i}{\overline{O}_{\mathrm{base}}} - 1}\right) \tag{3}$$

Equation (3) calculates the proportional run-off change brought about by climate variation over observed run-off changes impacted by both climate and human activities. We therefore define pCC as the percentage of run-off change due to climate change as opposed to the total impact:

$$\mathrm{pCC} = \frac{I_{\mathrm{cc}}}{I_{\mathrm{ha}} + I_{\mathrm{cc}}} = \left(\frac{\mathrm{RC}}{\mathrm{RO}}\right) \tag{4}$$

Likewise, pHA, the percentage of run-off change due to human activities, can be derived as:

$$\mathrm{pHA} = \frac{I_{\mathrm{ha}}}{I_{\mathrm{ha}} + I_{\mathrm{cc}}} = 1 - \mathrm{pCC} \tag{5}$$

Equations (1)–(5) constitute the IFF that quantitatively attributes separately the impacts of climate change and human activities on run-off in the study basin for the period 1950–2000. The next step is to reconstruct natural run-off, which is the run-off subject to climate change factors (i.e. temperature and precipitation) and not local human activities, using the VIC hydrological model given meteorological observations surrounding the basin (Figure 1).

2.2.2. *Run-off reconstruction*

2.2.2.1. VIC model: The VIC hydrological model has been implemented over the study area at a 0.125° spatial resolution (Figure 1), and simulations are run at a daily temporal resolution. The suitability of the spatiotemporal resolution employed by VIC is a subject to be assessed in the model calibration procedure. The VIC model is a land surface model based on the fundamental hydrological processes which includes interaction of the atmosphere with underlying vegetation and soils, where the dynamic water and energy fluxes are considered. One distinguishing characteristic of the VIC model is that it represents the sub-grid spatial heterogeneity of precipitation with sub-grid spatial variability of soil infiltration capacity. The land surface is divided into different land cover types horizontally, whereas soils are partitioned into three vertical layers. Quick bare soil evaporation following short-duration summer rainfall events happens in the top-most soil layer; the upper soil layer is designed to represent the dynamic change of soil moisture and the production of run-off in response to rainfall events. Soil moisture changes and contributions to baseflow mainly occur in the lower soil layer of the model. A variable infiltration curve is used to represent the sub-grid variability of soil infiltration capability under different land cover and soil types (Zhao *et al.*, 1980a, 1980b). Three types of evaporation are considered in the model: evaporation from the canopy layer of each vegetation class, transpiration from each of the vegetation classes, and bare soil evaporation. Evapotranspiration from each vegetation type is calculated using the Penman–Monteith formulation (Liang *et al.*, 1994). Total evapotranspiration over a grid cell is computed as the sum of the above components, weighted by the respective surface cover area fractions. For more information on the VIC model and its application in different catchments, the reader is referred to Su *et al.* (2008), Xie *et al.* (2007), and the VIC website, http://www.hydro.washington.edu/.

2.2.2.2. Model calibration and verification: The model is first calibrated for the decade 1961–1970 using the daily climatic data as mentioned in Section 2.1. Figure 2 shows simulated and observed discharge for the calibration and validation period, with outputs computed on a monthly basis. For the calibration period, a bias (defined as the sum of simulated minus observed run-off, divided by the sum of observed run-off, in percentage) and a Nash–Sutcliffe coefficient of efficiency (NSCE) value of 0.7% and 0.93, respectively, were obtained, with slight overestimation of the lower peaks and underestimation of the higher peaks. The model is then validated for the period 1955–1960 yielding a bias of −4.7% and an NSCE of 0.89, showing some underestimation of streamflow particularly for the high peaks. Overall, the calibration and verification accuracy of the model is acceptable for inter-annual run-off analysis, which also supports our chosen model resolution of 0.125° with daily time step.

2.2.2.3. Run-off reconstruction for the impacted period: After the VIC hydrological model is benchmarked with the hydrometeorological conditions of the baseline period, meteorological data (daily precipitation, wind speed and maximum and minimum temperatures) for the later decades, the 1970s, 1980s and 1990s, are used as input to simulate natural river discharge (i.e. run-off reconstruction) with no consideration of land use changes or artificial water intake (i.e. no impacts from local human activities). Therefore, taking the 1960s as the baseline decade, we reconstructed the basin natural run-off for the assessment period 1971–2000. The reconstruction results and analyses are presented in the following section.

3. Results and analysis

3.1. Long-term trend analysis

The monthly variation and long-term inter-annual trend of observed precipitation, observed run-off and reconstructed natural run-off subject to climate change factors in the study basin are presented in Figure 3(a). The annual observed precipitation and run-off show a decreasing trend (Figure 3(b)). The precipitation has decreased at a rate of 0.74% per year, whereas the observed run-off, influenced by both climate change (I_{cc}) and local human activities (I_{ha}), has decreased by 1.88% per year. For the same time period, it is found that the reconstructed natural run-off (impacted by climate change I_{cc} only) has decreased at a rate of 0.86% per year. The larger rate of run-off decrease due to I_{cc} and I_{ha} combined compared with I_{cc} alone indicates that I_{ha} has increased over this time period.

3.2. Decadal and annual rainfall–run-off variation analysis

Table I shows the decadal variation of precipitation, observed run-off and reconstructed natural run-off against the benchmark decade of the 1960s. Figure 4 displays the scattergram of annual precipitation and observed (diamonds) and reconstructed (stars) run-offs. For simplicity, we regressed two lines to represent the rainfall–run-off relationships in this study basin. We found that, according to the annual mean, there is a 3840 m^3 of run-off in

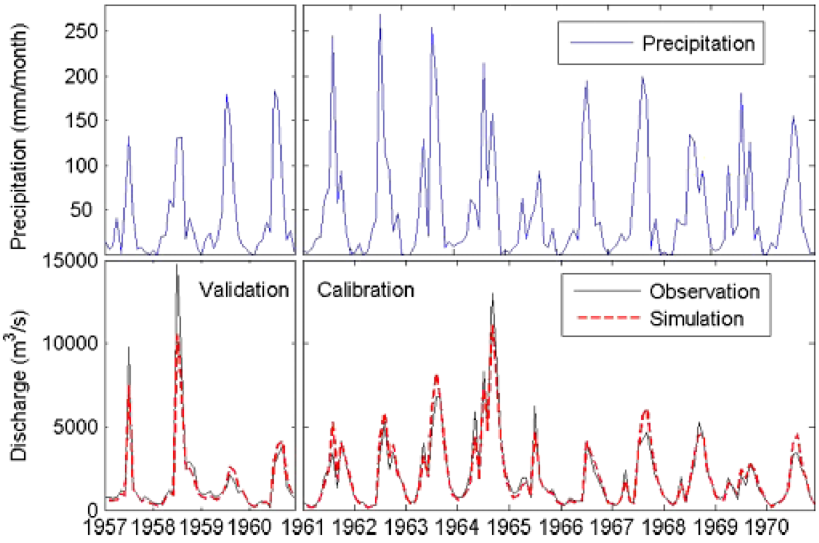

Figure 2. Variable infiltration capacity model calibration and validation for the pre-1970 baseline period. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

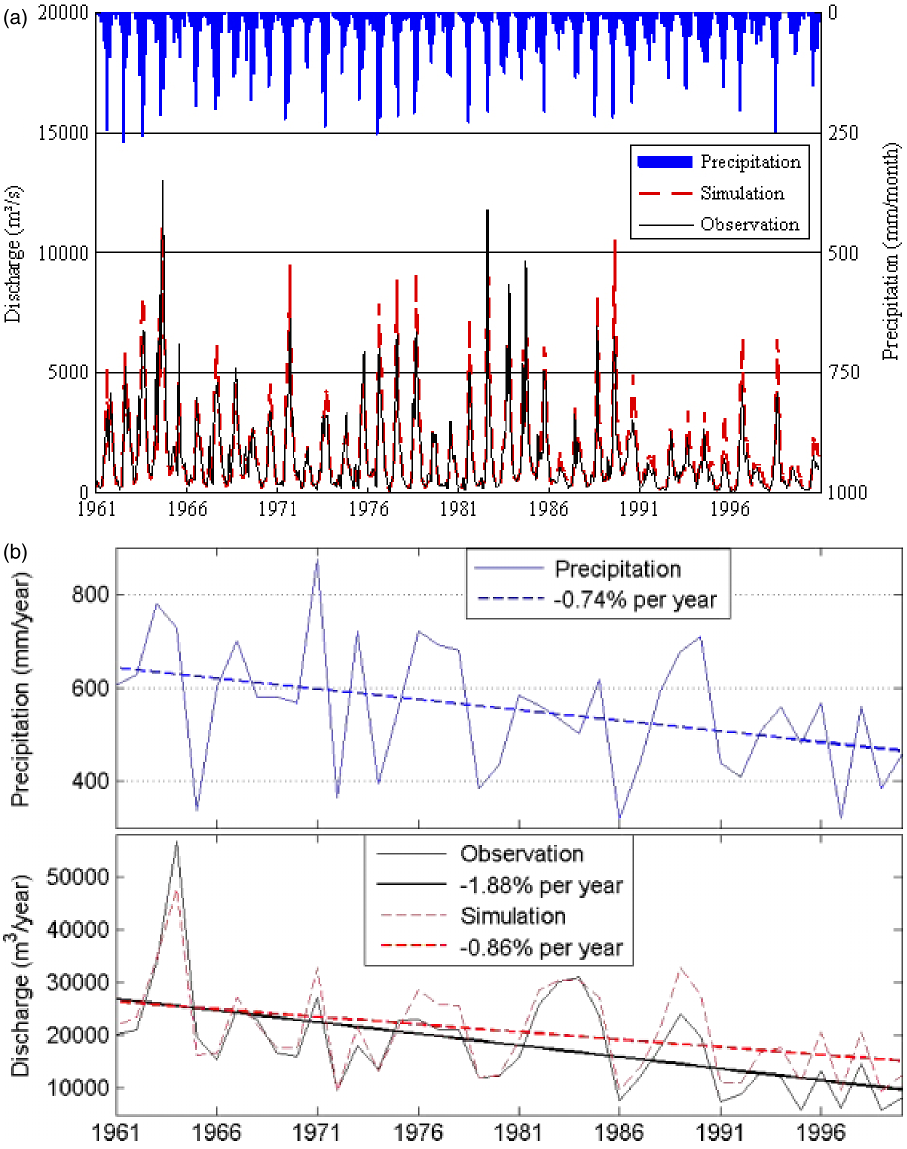

Figure 3. (a) Monthly time series of precipitation, observed discharge and simulated discharge for the period 1960–2000. (b) Same as (a) but with a 5-year moving average of inter-annual variations and long-term linear trends. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Table I. Decadal variation of observed precipitation, run-off and reconstructed run-off.

Duration	Precipitation		Run-off observation		Run-off reconstruction	
	(mm/year)	Decadal relative change (%)	(m^3/year)	Decadal relative change (RO) (%)	(m^3/year)	Decadal relative change (RC) (%)
1961–1970	609.5	N/A	24 718.5	N/A	24 518.7	N/A
1971–1980	554.1	−9.1	18 098.8	−26.8	20 363.5	−16.9
1981–1990	583.2	−4.3	20 870.9	−15.6	24 176.7	−1.4
1991–2000	468.3	−23.2	9 578.9	−61.2	14 077.2	−42.6

response to a 100 mm precipitation input, whereas reconstructed run-off yields 5000 m^3 for the same precipitation input. Corresponding to observed reductions in precipitation and increased temperatures, the reconstructed natural run-off has a larger slope than the observed run-off; there is less observed run-off per unit rainfall input to the basin as compared with the reconstructed natural run-off. This statement assumes that model error doesn't introduce bias into the reconstructed run-off. In addition, it is possible that climate change has altered the time of the year at which a majority of rainfall has occurred, which would also influence the annual run-off response. A detailed

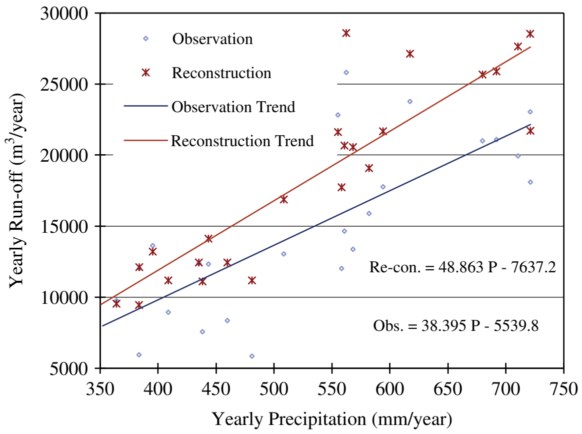

Figure 4. Scatterplots of annual precipitation *versus* observed run-off and reconstructed natural run-off. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

analysis of model error and sub-annual (seasonal) impacts of run-off response to climate change and human factors is an area inviting future research.

3.3. Quantification of the impacts

According to the IFF shown in Equations (1)–(5), the difference between the annual observed run-off and the reconstructed natural run-off implies that the additional run-off reduction is a result of local human activities (I_{ha}). Given the observed run-off and reconstructed natural run-off data (Figure 3), the impact indices can be derived from IFF and the decadal average results are shown in Table II and Figure 5. It is found that the impact due to climate change on run-off (I_{cc}) is greater than the impact due to human activities (I_{ha}) for the three consecutive decades studied. In the 1970s the percentage change of run-off due to climate change (pCC) is found to be 89% followed by 66% and 56% in the 1980s and the 1990s, respectively. Correspondingly, for the same three decades, the percentage change caused by human activities (pHA) is found to be 11%, 34% and 44%, respectively. The developed IFF indicates that over the decades studied herein, the percentage run-off changes due to human activities has continuously increased whereas the percentage changes due to climate change has decreased from 89% to 56% (Table II). With a likely similar trend in future, the impact due to human activities (pHA) is going to outweigh the impact due to climate change (pCC) in the study basin (Figure 5).

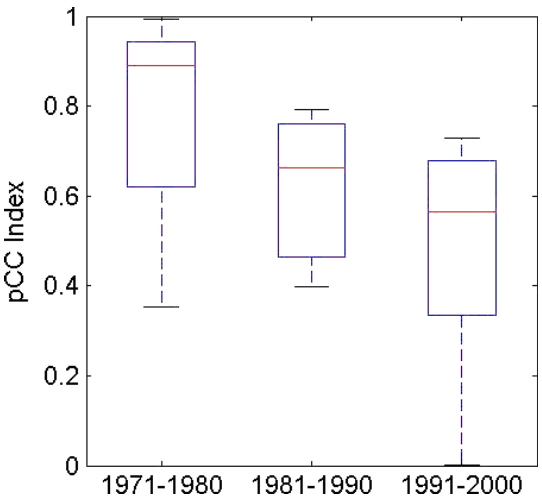

Figure 5. Boxplots of percentage change of annual run-off due to climate change (pCC) analysed for three decades. Note that the 1960s is the baseline decade. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

3.4. Human impact on wet and dry years

Figure 6(a) shows the frequency distribution of the observed run-off and reconstructed annual run-off. Figure 6(b) displays the ratio of observed run-off to the reconstructed run-off. It shows that the ratio decreases consistently and gradually from years with high flows (0.9) to the lowest flow years (0.6). Particularly, during the top 20 percentile wettest years (discharges $>25\,000$ m^3/year), the ratios are on the order of 0.8 or above whereas for the drier years (discharges at bottom 20%: $<15\,000$ m^3/year) the ratios are on the order of 0.7 or below. Recall that the difference between the observed run-off and the reconstructed natural run-off implies that the additional run-off reduction is a result of local human activities (I_{ha}). This shows that human activities on the land surface and river water withdrawals have larger impacts on streamflow in the drier years than in the wetter years, with an average reduction of 10% in run-off (Figure 6(b)). This result indicates the complexity of human factors, withdrawing more water per annum in this case, when water becomes scarce.

Table II. Quantification of the impacts.

Duration[a]	Combined impact on run-off	Impact due to climate change (I_{cc})		Impact due to human activities (I_{ha})	
	Relative change (RO) (%)	Impact to discharge (%)	Percentage change (pCC) (%)	Impact to discharge (%)	Percentage change pHA) (%)
1971–1980	−26.8	−23.9	89.1	−2.9	10.9
1981–1990	−15.6	−10.3	66.3	−5.3	33.7
1991–2000	−61.2	−34.5	56.4	−26.7	43.6

[a] The period 1960–1970 is the baseline period.

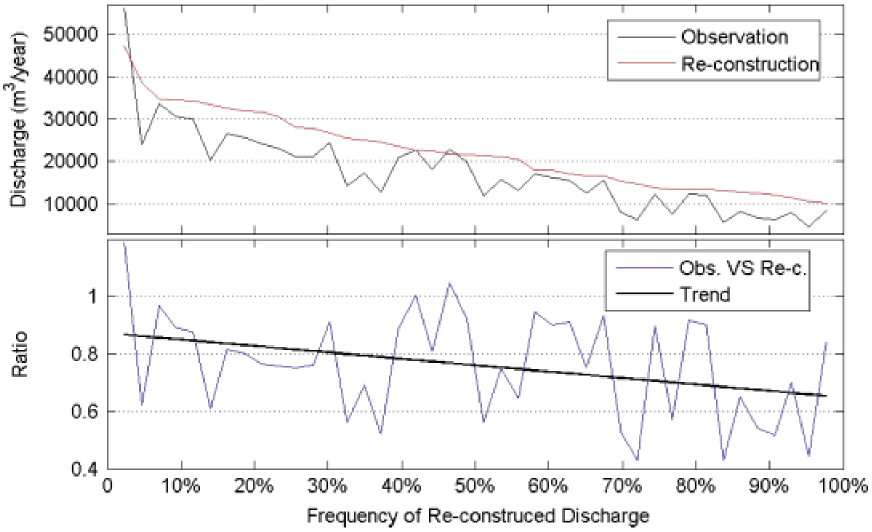

Figure 6. (a) Annual run-off frequency distribution and (b) ratio of the observed run-off and reconstructed annual run-off. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

4. Summary

Previous studies have identified global and regional climate changes (i.e. increased temperatures and reduced precipitation) and local human activities (e.g. river water withdrawals for irrigation, land use changes from urbanization) as the two main causative factors yielding significantly reduced run-off in sub-basins of the Yellow River (Cong *et al.*, 2009). In this study we developed an IFF (Equations (1)–(5)) to quantitatively attribute separately the impacts of climate change (i.e. increased temperatures and reduced precipitation) and local human activities (e.g. land use change and water intakes) on run-off. Using daily climatic observations in the Baimasi sub-basin in the Yellow River (Figure 1), we first calibrated and verified the VIC hydrological model to the baseline period 1955–1970 as a benchmark (Figure 2). Then, we simulated the basin natural run-off for the subsequent three decades (1971–2000) using the VIC model with no consideration of local human activities (Figure 3). As a result, the reconstructed run-off, hypothetically, is the result of run-off impacted by climate change only (I_{cc}). This assumes that VIC model error does not impart a bias to the reconstructed run-off. Thus, the difference between reconstructed natural run-off and observed run-off represents the hydrological response resulting from impacts of human activities (I_{ha}). It should be noted that it is possible that some impacts from human activities and climate are inter-related, and as such are not readily separable; an example might be increased temperatures from extensive urbanization.

On the basis of observed precipitation, run-off, and reconstructed natural run-off, we quantified the long-term trend and decadal and annual variations of climate change (i.e. precipitation and temperature) and run-off in the Baimasi basin. The annual observed precipitation and run-off both show a decreasing trend for the second half of last century (Figure 3). The precipitation has decreased at a rate of 0.74% per year, whereas the observed run-off, influenced by both climate change (I_{cc}) and local human activities (I_{ha}), decreased by 1.88% per year. However, the reconstructed natural run-off (impacted by I_{cc} climate change only) has decreased at a rate of 0.86% per year, following a similar trend as the precipitation; this implies changes in the natural run-off are controlled by the climate change factors of decreasing precipitation and increasing temperatures. The observations also showed that the mean decadal precipitation and run-off has decreased from the baseline decade, the 1960s, indicating a drier hydrological regime for the last three decades of the 20th century (Table I). In particular, a 23% decrease in precipitation yielded a 61% reduction in the run-off in the 1990s. This is in agreement with that observed in previous studies, particularly in arid and semi-arid climates (Sankarasubramanian and Vogel, 2001). Similar findings were also made in some earlier studies in different parts of China (Mo *et al.*, 2006; Hao *et al.*, 2008) and in the USA (Christensen *et al.*, 2004). For simplicity, we regressed two lines to represent the rainfall–run-off relationships in the study basin. We found that, according to the annual mean of observations and reconstructed run-off, there is a 3840 m^3 of run-off in response to a 100 mm precipitation input to the basin, whereas reconstructed run-off yields 5000 m^3 to the same unit input of precipitation; the difference is attributed to local human activities such as withdrawing water from the river channel for irrigation purposes.

We further applied the IFF to quantitatively attribute the influences of climate change and human activities on run-off. It is found that climate change factors have greater impacts on basin run-off than human activities for the three recent decades (Figure 5). In the 1970s the pCC (percentage change of run-off due to climate change) is found to be 89% followed by 66% and 56% in the 1980s and 1990s, respectively. Correspondingly, the percentage change of run-off caused by human activities (pHA) is 11%, 34% and 44%, respectively. Over the study period, the pHA has continuously increased whereas the pCC, for the same decades, has decreased from 89% to 56%. With a likely similar trend in future, there is a credible possibility that the impact of local human activities (I_{ha}) in the basin is going to outweigh the impacts due to climate change (I_{cc}) (Figure 5). This study also observed the impacts of human activities on run-off during wetter *versus* drier years. It showed that human activities have larger impacts on run-off in the drier years (discharges at the bottom 20%: $<15\,000$ m^3/year) than in the wetter years (discharges $>25\,000$ m^3/year), with an average reduction in run-off of 10% (Figure 6(b)). This result indicates the complexity of human factors, withdrawing more water per annum in this case, when water becomes scarce.

The results of this study portend, in conjunction with others' findings, an upcoming crisis in water supply in the YRB (Cong *et al.*, 2009). This study also provides a quantitative assessment methodology for water resources planners and managers to understand the changing process of the hydrological cycle and attribute its causative factors in catchments of the Yellow River. This research calls for a future study that will reconstruct multiple natural run-off scenarios, with each scenario accounting for a specific human activity or a climate-forcing factor. As there is very little control that local actions could possibly bring in terms of reducing immediate impacts from reduced precipitation and increased temperatures due to climate change, quantitative assessment of hydrological impacts from specifically identified human activities is a practically possible proposition for local administrative managers.

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References

Brutsaert W, Parlange MB. 1998. Hydrologic cycle explains the evaporation paradox. *Nature* **396**: 30.

Burn DH, Hag Elnur MA. 2002. Detection of hydrologic trends and variability. *Journal of Hydrology* **255**: 107–122.

Christensen NS, Dennis PL, Palmer RN. 2004. The effects of climate change on the hydrology and water resources of the Colorado river basin. *Climatic Change* **62**: 337–363.

Cong Z, Yang D, Gao B, Yang H, Hu H. 2009. Hydrological trend analysis in the Yellow River basin using a distributed hydrological model. *Water Resource Research* **45**: W00A13, DOI:10.1029/2008WR006852.

Döll P, Frank K, Bernhard L. 2003. A global hydrological model for deriving water availability indicators: model tuning and validation. *Journal of Hydrology* **270**: 105–134.

Fu GB, Chen SL, Liu CM, Shepard D. 2004. Hydro-climatic trends of the Yellow river basin for the last 50 years. *Climatic Change* **65**: 149–178.

Hao X, Chen Y, Xu C, Li W. 2008. Impacts of climate change and human activities on the surface runoff in the Tarim river basin over the last fifty years. *Water Resources Management* **22**: 1159–1171, DOI 10.1007/s11269-007-9218-4.

IPCC. 2008. In *Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change*, Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (eds). IPCC Secretariat: Geneva; 210pp.

Li JL, Zhang L, Wang H, Wang J, Yang JW, Jiang DJ, Li JY, Qin DY. 2007. Assessing the impact of climate variability and human activities on stream flow from the Wuding River basin in China. *Hydrological Processes* **21**: 3485–3491.

Liang X, Lettenmaier DP, Wood EF, Burges SJ. 1994. A simple hydrologically based model of land surface water and energy fluxes for GSMs. *Journal of Geophysical Research* **99**(D7): 14.415–14.428.

Liang X, Lettenmaier DP, Wood EF, Burges SJ, Wood EF, Lettenmaier DP. 1996. Surface soil moisture parameterization of the VIC-2L model: evaluation and modification. *Global and Planetary Change* **13**: 195–206.

Nijssen B, Greg M, O'Donnell AF, Dennis P. 2001. Hydrological sensitivity of global rivers to climate change. *Climatic Change* **50**: 143–175.

Ma Z, Kang S, Zhang L, Tong L, Su X. 2008. Analysis of impacts of climate variability and human activity on streamflow for a river basin in arid region of northwest China. *Journal of Hydrology* **352**: 239–249.

Mo X, Pappenberger F, Beven K, Liu S, de Roo A, Lin Z. 2006. Parameter conditioning and prediction uncertainties of the LISFLOOD-WB distributed hydrological model. *Hydrological Sciences Journal* **51**(1): 45–65.

Oki T, Agata Y, Kanae S, Saruhashi T, Yang D, Musiake K. 2001. Global assessment of current water resources using total runoff integrating pathways. *Hydrological Sciences Journal* **46**: 983–996.

Prieler S. 1999. Climatic variability and extreme events in China, http://www.iiasa.ac.at/Admin/INF/OPT/Summer99/climatic_variability_and_extreme_events_in_china.htm (assessed on July 29, 2009).

Sankarasubramanian A, Vogel RM. 2001. Climate elasticity of stream flow in the United States. *Water Resources Research* **37**: 1771–1781.

Scanlon BR, Jolly I, Sophocleous M, Zhang L. 2007. Global impacts of conversion from natural to agricultural ecosystem on water resources: quantity versus quality. *Water Resources Research* **43**: W03437.

Shi YF, Sheng YP, Li DL, Zhang GW, Ding YJ, Hu LJ, Kang ES. 2003. Discussion on the present climate change from warm-dry to warm-wet in northwest China. *Quaternary Sciences* **23**(2): 152–164.

Su F, Hong Y, Lettenmaier DP. 2008. Evaluation of TRMM multisatellite precipitation analysis (TMPA) and its utility in hydrologic prediction in the La Plata basin. *Journal of Hydrometeorology* **9**: 622–640.

Wang X. 2005. Grain production in the Yellow River basin: report for the water for food project, http://www.iwmi.cgiar.org/assessment/files_new/research_projects/River_Basin_Development_and_Management/YRB_Wang_2005.pdf (assessed on March 25, 2009).

Wang SR, Zheng SH, Cheng L. 2003. Studies on impacts of climate change on water cycle and water resources in northwest China. *Climatic and Environmental Research* **8**(1): 44–51.

Xie Z, Yuan F, Duan Q, Zheng J, Liang M, Chen F. 2007. Regional parameter estimation of the VIC land surface model: methodology and application to river basins in China. *Journal of Hydrometeorology* **8**: 447–468, DOI: 10.1175/JHM568.1.

Yang D, Li C, Hu H, Lei Z, Yang S, Kusuda T, Koike T. 2004. Analysis of water resources variability in the Yellow River of China during the last half century using historical data. *Water Resources Research* **40**: W06502, DOI: 10.1029/2003 WR002763.

Yang X, Yan J, Liu B. 2005. The analysis on the change characteristics and driving forces of Wuding River runoff (in Chinese). *Advances in Earth Science* **20**(6): 637–642.

Yang H, Zehnder A. 2001. China's regional water scarcity and implications for grain supply and trade. *Environment and Planning* **A 33**: 79–95.

Zhao R, Zhang Y, Fang L, Liu X, Zhang Q. 1980a. The Xinanjiang Model, Hydrological Forecasting (*Proceeding of the Oxford Symposium, April 1980*): IAHS-Publ. no. **129**, 351–356.

Zhao ZC, Ding YH, Xu Y, Zhang J. 1980b. Detection and prediction of climate change for the 20th and 21st century due to human activity in northwest China. *Climatic and Environmental Research* **8**(1): 27–34.