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Changsen Zhao[ab], Changming Liu[cd], Xiangqian Dai[e], Tao Liu[f], Zhen Duan[g], Lifang Liu[c] & Simon M. Mitrovic[h]

[a] State Key Laboratory of Remote Sensing Science, Jointly Sponsored by Beijing Normal University and the Institute of Remote Sensing Applications of Chinese Academy of Sciences, Beijing, China

[b] Beijing Key Laboratory for Remote Sensing of Environment and Digital Cities, School of Geography, Beijing Normal University, Beijing, China

[c] College of Water Sciences, Beijing Normal University, Beijing, China

[d] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China

[e] Development Research Center, Ministry of Water Resources, Beijing, China

[f] Binzhou Survey Bureau of Hydrology and Water Resources, Binzhou, China

[g] Tai'an Survey Bureau of Hydrology and Water Resources, Tai'an, China

[h] Centre for Environmental Sustainability, School of Environment, University of Technology, Sydney, Australia

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Separation of the impacts of climate change and human activity on runoff variations

Changsen Zhao[1,2], Changming Liu[3,4], Xiangqian Dai[5], Tao Liu[6], Zhen Duan[7], Lifang Liu[3] and Simon M. Mitrovic[8]

[1]*State Key Laboratory of Remote Sensing Science, Jointly Sponsored by Beijing Normal University and the Institute of Remote Sensing Applications of Chinese Academy of Sciences, Beijing, China*

[2]*Beijing Key Laboratory for Remote Sensing of Environment and Digital Cities, School of Geography, Beijing Normal University, Beijing, China*
hzjohnson@gmail.com

[3]*College of Water Sciences, Beijing Normal University, Beijing, China*

[4]*Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China*

[5]*Development Research Center, Ministry of Water Resources, Beijing, China*

[6]*Binzhou Survey Bureau of Hydrology and Water Resources, Binzhou, China*

[7]*Tai'an Survey Bureau of Hydrology and Water Resources, Tai'an, China*

[8]*Centre for Environmental Sustainability, School of Environment, University of Technology, Sydney, Australia*

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Abstract A practical approach to separate the impact of the processes of climate change (CC) and human activities (HA) on streamflow is presented. A non-parametric Mann-Kendall-Sneyers test, combined with moving *t* test and Yamamoto methods, was used to recognize abrupt change points in the runoff time series to determine a baseline period. A new algorithm to separate CC and HA influence on streamflow was deduced based on the climate elasticity concept. Application to the Chao River, China, shows that CC imposed a positive impact on streamflow in this region (25%, on average), while HA exerted a continuous negative impact of –75% in the period after the 1950s. These results are of great use in understanding the variation of CC and HA impacts under different human development patterns.

Key words separation; climate change (CC); human activities (HA); runoff variation; Chao River

Séparation des impacts du changement climatique et de l'activité humaine sur les variations de l'écoulement

Résumé Nous présentons une approche pratique de séparation des impact du changement climatique (CC) et des activités humaines (AH) sur l'écoulement. Nous avons utilisé le test non-paramétrique de Mann-Kendall-Sneyers, combiné avec la méthode de Yamamoto et le t-test mobile, pour déterminer les points de changement brusque dans les séries chronologiques de débits, afin de déterminer une période de référence. Sur la base du concept d'élasticité climatique, nous avons élaboré un nouvel algorithme permettant de séparer l'influence du CC et de l'AH sur les débits,. Son application sur le fleuve Chao en Chine, a montré que le CC a provoqué une augmentation de l'écoulement dans cette région (25% en moyenne), tandis que l'AH a provoqué sa diminution continue de -75% depuis les années cinquante. Ces résultats sont d'une grande utilité pour comprendre les processus de variation des impacts du CC et de l'AH en liaison avec différents modes de développement.

Mots clefs séparation ; changement climatique (CC) ; activités humaines (AH) ; variation de débit ; rivière Chao

1 INTRODUCTION

Rapid socio-economic development in developing countries can lead to many quality and quantity related problems in rivers (Szilagyi 2001, Ren *et al*. 2002, Wilk and Hughes 2002, Ye *et al*. 2003, Levashova *et al*. 2004, Liu *et al*. 2010), which can put pressure on available water resources. For example, Beijing, the capital of China, encountered 11 dry years continuously from 1999. Higher air temperatures and less rainfall meant water demand at Beijing City reached its peak (Nie and Fan 2010). Long-term impacts of climate change (CC) and human activities (HA) contributed to this. Water conservation in the catchment area of the Miyun Reservoir, the main water-supply source of Beijing, is critical to ensure adequate supply. Local public administrators have been aware of this and many helpful measures, such as ecological restoration, forestation, and adjustment of agricultural planting structure, have been adopted in this region (Liao and Li 2003, Hao 2004, Wang *et al*. 2009, Nie and Fan 2010). It is not clear how far these actions can alleviate the water supply issues or how to balance expenditure and revenue by water conservation measures.

A clear understanding of the impact processes of CC and HA on regional streamflow should help in determining appropriate strategies and limits. For sustainable water resources management it is important to understand hydrological changes and to differentiate between the impact of CC and HA (Liu *et al*. 2010). However, it is a great challenge to distinguish the impact processes of CC and HA on runoff (Liu *et al*. 2010).

The impacts of climate change on hydrology vary spatially and need to be investigated on a local scale (Liu *et al*. 2010). Many studies on climate and runoff change for individual basins have been conducted (Chen *et al*. 2006, Kezer and Matsuyama 2006, Li *et al*. 2006, Wang 2007, Chang *et al*. 2007, Jiang *et al*. 2007, Pohl *et al*. 2007, Savitskiy *et al*. 2008, Zhang *et al*. 2008, Fu *et al*. 2010) and show that over the past 50 years, climate change has influenced river discharge (Huo *et al*. 2008). Traditional research has mainly focused on the effect of CC on streamflow by studying relationships between runoff and climate variables using hydrological or circulation models. This research emphasised the sensitivity of runoff to climate change across the world. The concept of climate elasticity of streamflow attracted much attention with three categories of research: (a) Multivariate historical record regressions (Revelle and Waggoner 1983, Vogel *et al*. 1999); (b) Single parameter climate elasticity of runoff (Nash and Gleick 1991, Sankarasubramanian *et al*. 2001); (c) Two-parameter climate elasticity of streamflow index (Fu *et al*. 2007, Gardner 2009). In terms of HA effects, most studies were based on statistical methods to analyse land use change, or a combination of hydrological and global climatic models (Li *et al*. 2007, Barnett *et al*. 2008). Most results are qualitative or semi-quantitative, giving an approximate influencing proportion value of either CC or HA.

Some research has been devoted to quantifying the CC and HA impacts on streamflow based on hydrological models, scenarios setting and statistical methods (Su *et al*. 2007, Hao *et al*. 2008, Ye *et al*. 2009, Dong *et al*. 2010, Fan *et al*. 2010, Li *et al*. 2010). Most approaches were based on periodical transfer of climate data or simple periodical data comparison. A potential problem is that errors may be introduced because of CC impact transfer between two different periods, by replacing some climate related variables during a period by those during another period.

Huo *et al*. (2008) and Liu *et al*. (2010) made significant progress in the separation and quantification of CC and HA impacts on streamflow. Huo *et al*. (2008) found that the naturalized flow may be under- or over-estimated because of the replacement of the CC effect during the high human impact period by that during the natural variation period. That also probably results in a failure to accurately estimate the CC effect. It can only explain the rough contributions of CC and HA to the long-term averaged flow decrease. The same issue occurred in Ma *et al*. (2008). The research of Liu *et al*. (2010) could only give an approximate impact ratio of CC to HA on the basis of average runoff decrement (increment) during baseline and variable periods.

Most previous research explains the impact proportions of CC and HA at a large temporal scale (e.g. a decade or even longer) and it is hard to give clear variation in CC and HA impacts. Processes of CC and HA impacts on streamflow are therefore still largely unknown.

The aim of this study was to develop a new method for retrieving the time series of CC impact on streamflows, and thereby estimate the impact of HA on streamflows. In this paper, an algorithm was developed for the computation of CC impact on streamflow in an arbitrary year and then an equation was put forward to estimate the corresponding HA impact. The baseline period was determined by using abrupt-change points in the streamflow sequence. This method was then implemented in the upper and middle reaches of the Chao River to separate and analyse the CC and HA impact from the observed streamflow time series. The study area is extremely important because it lies upstream of the water-supply source of Beijing City.

2 METHOD AND DATA

2.1 Study area

The Chao River, a tributary of the Hai River, is located in the north of China. It has a basin area of 6870 km^2 (Dai 2009). The Miyun Reservoir, one of the most important water-supply sources for the capital of China, Beijing, is downstream on this river, as shown in Fig. 1. The mean annual precipitation is 600–700 mm, more than 70% of which occurs in summer. The mean annual air temperature is in the range 0–14°C, hot in summer and cold in winter (Dai 2009). The mean annual runoff is 0.18 $\times 10^9$ m^3 and this has had a decreasing trend during the period from 1956 to 2000. Runoff is especially sensitive to the variation in the mean annual precipitation (Wu and Jiang 2010). Generally, the maximum monthly runoff occurs in August (Li and Li 2008). Spatially, the upper reaches have approximately the same mean annual runoff depth (51.84 mm) as the middle reaches (52.74 mm). In terms of runoff variation, the coefficient of variation in the upper and middle reaches has the same value of 0.21.

Since the late 1970s, China has experienced rapid socio-economic development, and regional water consumption and land cover have changed dramatically (Wang *et al*. 2009). The result is the intensification of HA and a reduction in streamflow of the Chao River.

In this river, Dage (DG) and Daiying (DY) are two control hydrological stations, located in the upper and middle reaches, respectively (Fig. 1). The DG station, established in 1923, has a catchment area of 1850 km^2. Annual precipitation ranged from 290–750 mm during the period 1951–2002; average annual air temperature ranged from 4.0–8.5°C for 1956–2001, with a maximum in excess of 40°C and a minimum of nearly –30°C. The DY station was established in 1950 and has a catchment area of 4266 km^2. Annual precipitation was in the range 350–1000 mm during the 1951–2002 period.

Our proposed method is used herein to study the variation in CC and HA impacts since the 1950s on streamflows in the 'upper' (upstream of DG) and 'middle' (between DG and DY) reaches of the Chao River.

2.2 Data

Annual data of precipitation, pan evaporation, actual observed runoff and mean air temperature were collected from hydrological and meteorological stations, as shown in Fig. 1. As Table 1 shows, in the upper reach (upstream of DG), precipitation was recorded at Xiaobazi, Fengning and DG; pan evaporation at

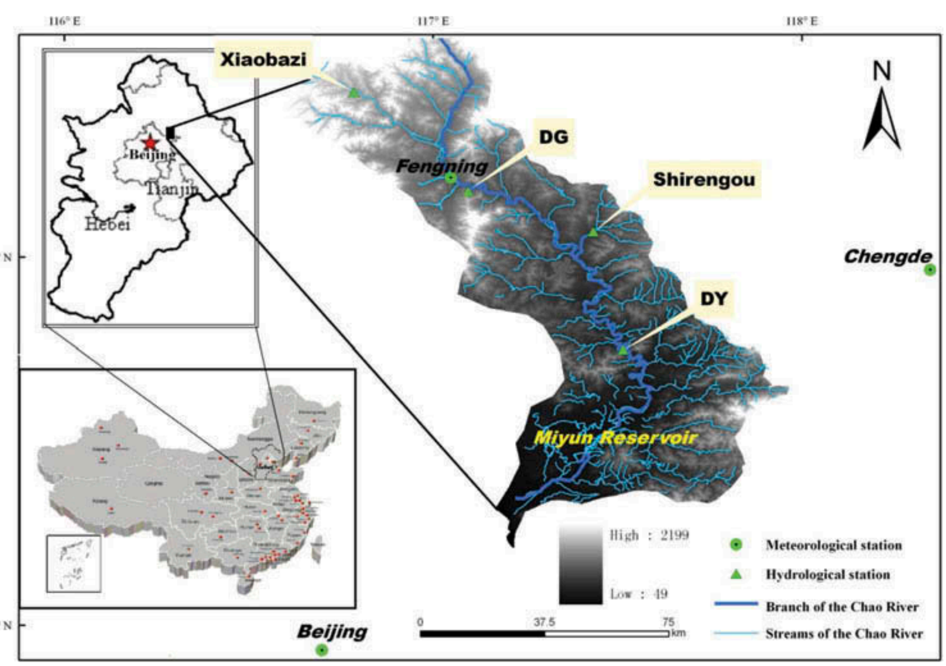

Fig. 1 Location of the Chao River in northern China.

Table 1 Meteorological and hydrological stations and parameters used in this study.

Name	Range (year)	Data categories
Xiaobazi	1953–2002	Precipitation
DG	1951–2001	Precipitation, pan evaporation and runoff
Shirengou	1952–2002	Precipitation
DY	1953–2002	Precipitation, pan evaporation and runoff
Fengning	1956–2001	Precipitation, pan evaporation and air temperature
Chengde	1951–2001	Precipitation, pan evaporation and air temperature
Beijing	1951–2001	Precipitation, pan evaporation and air temperature

Fengning and DG; runoff at DG; air temperature at Fengning and averages calculated. Averaged values of precipitation at DG, Shirengou and DY; pan evaporation at DG and DY; air temperature at Fengning, Chengde and Beijing were used in the middle reach (between DG and DY). Runoff at DY minus that at DG was used to represent the runoff in the middle reach.

All data collected were quality controlled before distribution by hydrological and meteorological departments. Data of annual precipitation, pan evaporation, air temperature and streamflow were smoothed using the T4253H smoothing function in the SPSS 17.0 statistical software package (http://www-01.ibm.com/software/analytics/spss/) to lower the influence of observation errors and make trends clearer.

3 METHODOLOGY

3.1 Main framework

For a catchment with huge impacts from CC and HA, regulation or diversion can be categorized into impact of HA on streamflow. Then streamflow can be modelled as a function of climatic and HA variables:

$$Q = f(P, T, V) \tag{1}$$

where Q is streamflow; P is precipitation and T is temperature, representing dominant CC factors on the hydrological cycle; and V is a factor that represents the integrated effects of HA on streamflow.

On the assumption that the HA factors are independent of the climate factors, equation (1) can be written as:

$$\mathrm{d}Q = \mathrm{d}Q^{\mathrm{C}} + \mathrm{d}Q^{\mathrm{V}} \tag{2}$$

$$\mathrm{d}Q^{\mathrm{C}} = f'_{\mathrm{P}}\mathrm{d}P \tag{3}$$

with $f'_{\mathrm{P}} = \partial Q/\partial P = 1 - 0.9(0.9 + P^2/I^2)^{-1.5}$, $I = 300 + 25T + 0.05T^3$ (Liu and Woo 1996); and

$$\mathrm{d}Q^{\mathrm{V}} = f'_{\mathrm{V}}\mathrm{d}V \tag{4}$$

where $\mathrm{d}Q$, $\mathrm{d}P$ and $\mathrm{d}V$ are changes in annual streamflow, precipitation and HA, respectively; $\mathrm{d}Q^{\mathrm{C}}$ and $\mathrm{d}Q^{\mathrm{V}}$ are changes in streamflow due to CC and HA change, respectively; and $f'_{\mathrm{V}} = \partial Q/\partial V$ (Zheng *et al.* 2009).

With the concept of the climate elasticity of streamflow $\varepsilon_{\mathrm{P}} = (\mathrm{d}Q/Q)/(\mathrm{d}P/P)$, equation (3) can be written as:

$$\mathrm{d}Q^{\mathrm{C}} = \frac{f'_{\mathrm{P}}}{\varepsilon_{\mathrm{P}}} P \frac{\mathrm{d}Q}{Q} \tag{5}$$

with $\varepsilon_{\mathrm{p}} = 1 + \phi F'(\phi)/[1 - F(\phi)]$ (Zheng *et al.* 2009), where ϕ is an aridity index; $F(\phi) = (1 + \omega\phi)/(1 + \omega\phi + 1/\phi)$ with ω a parameter relating to vegetation type, which is set to 2.95 according to the research of Sun (2007).

Considering the lead–lag effect of climate change on the streamflow, the average of the following N values of streamflow was taken as the current value, i.e.

$$Q(t) = \text{-}\frac{1}{N}\sum_{t'=t}^{t+N-1} Q(t') \tag{6}$$

Then one obtains

$$Q(t) = \frac{1}{N}\int_{t}^{t+N-1} Q(t')dt' \tag{7}$$

where t is the year number; $Q(t')$ is fitted by the polynomial $Q(t') = \sum a_i t'^{N\text{-}i}$ ($i = 1, \ldots, N$; $t' = [t, t{+}N{-}1]$); and a_i is the polynomial coefficient.

Taking the period before the first abrupt-change point of the streamflow sequence as the baseline period, and under an assumption that in the baseline period CC and HA have no impact on streamflow (i.e. Q^C and Q^V are equal to zero), letting $N = 3$, and substituting equation (7) for Q in equation (5), the response function of streamflow variation induced by CC (Q^C) can be deduced with an initial condition of $Q^C(0) = 0$ by:

$$Q^{C}(t) = \frac{f'_P}{\varepsilon_P} P\{\ln[3a_1t^2 + 3(2a_1 + a_2)t + 4a_1 + 3a_2 + 3a_3] - \ln[4a_1 + 3a_2 + 3a_3]\} \tag{8}$$

Assuming that

$$Q(t) = Q^0(t) + Q^C(t) + Q^V(t) \tag{9}$$

where Q^0 is the normal rainfall–runoff induced streamflow variation, $Q^0 = f(P, [a])$, determined with the data of P and Q^0 in the baseline period; and Q^C and Q^V are as defined above. Thus, Q^V can be derived using equations (8) and (9) with $Q^0 = f(P, [a])$, and the period after the first change point (when $dV \neq 0$ and $Q^V \neq 0$) is used.

In brief, this framework can be applied as follows: first, parameters $[a]$ in the model $Q^0 = f(P, [a])$ need to be calibrated with the data in the baseline period. Then, the model is used to calculate $Q^0(t)$ in the non-baseline period. In the non-baseline period, a_1, a_2, a_3 in equation (8) of year t can be easily calibrated with flow series for the period t to $t+N-1$ by using $N = 3$ in the above polynomial of $Q(t')$. With the three calibrated parameters, $Q^C(t)$ can be calculated using equation (8), and then, $Q^V(t)$ is easy to calculate with equation (9).

3.2 Determination of abrupt-change points of a streamflow sequence

Abrupt-change points are recognized herein to help determine the baseline period for a streamflow sequence. Here a non-parametric Mann-Kendall-Sneyers test, combined with the moving t test method and Yamamoto method, was adopted to recognize the abrupt-change points in the runoff time series.

The non-parametric Mann-Kendall-Sneyers test (Mann 1945, Kendall 1975, Sneyers 1975) is a sequential version of the Mann-Kendall rank statistic (Li *et al*. 2007). Here, it was used to analyse the runoff trend and help determine the change points. This method (Li *et al*. 2007) is widely used.

Recognition of abrupt-change points has attracted considerable attention globally and a number of methods can be applied to determine the abrupt-change points of a time series (Yamamoto and Sanga 1986, Wei 1999, Hubert 2000, Shao and Campbell 2002, Kehagias and Fortin 2006, Zheng *et al*. 2007, Aksoy *et al*. 2008, Gedikli *et al*. 2008, Gedikli *et al*. 2010a, 2010b, Abrate *et al*. 2013).

The moving t test is globally used to detect the changes in a time series (Zheng *et al*. 2007). The t value in this method will be positive if the first mean is larger than the second, and negative if it is smaller (Shao and Campbell 2002). Yamamoto used signal-to-noise ratio (SNR) to study the abrupt change in time series of air temperature, precipitation etc. (Yamamoto and Sanga 1986, Wei 1999). In the research of Yamamoto and Sanga (1986), SNR was defined as:

$$\mathrm{SNR} = \frac{|\overline{x_1} - \overline{x_2}|}{s_1 + s_2} \tag{10}$$

where, s_1, s_2 are the standard deviation of sub-series x_1 and x_2. For details, the reader is referred to the research of Wei (1999) and Yamamoto and Sanga (1986). In this paper, the moving t test and the SNR methods were employed to detect abrupt-change points in the streamflow sequences.

4 RESULTS AND DISCUSSION

4.1 Abrupt-change points in DG and DY

The Mann-Kendall-Sneyers test was primarily used to distinguish the trend in the streamflow sequence with $\alpha = 0.01$. The results indicate that, from the start, runoff was decreasing. It is also shown that there may have been large changes during the period 1960–1965 and around 1975.

The moving t test method and the Yamamoto method were used to further identify the abrupt-change points. Figure 2 shows that change points occurred at about 1961 and 1976 with both methods. The results suggest 1961 as the first change point of runoff in the upstream reach (upper DG) and, similarly, 1960 as the first change point of runoff in the middle reach (DG–DY). Therefore, 1951–1961 and 1951–1960 were selected as baseline periods in the upper and middle reaches, respectively. The analysis above was completed with the help of DPS (data processing system) (Tang and Zhang 2012).

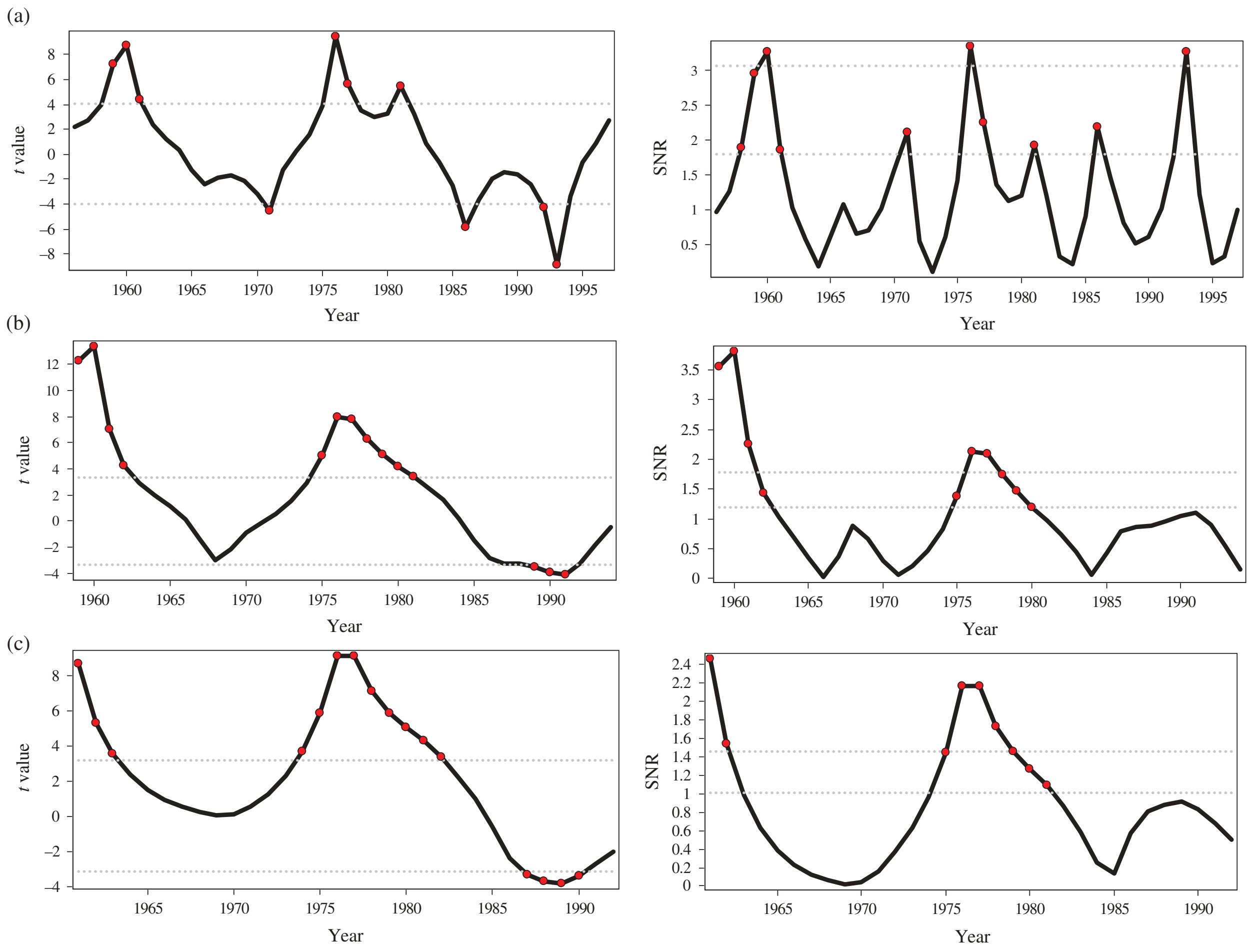

Fig. 2 Change points of DG streamflow obtained by using the moving *t* test (left) and the Yamamoto index (right), with $\alpha = 0.01$ and different sub-series length (a–c): IH = 5, 8, 10. Sub-series length is the length of a sub-sequence (IH), i.e., number of data in the sub-sequence. In the moving *t* test, a sequence is divided into two sub-sequences whereby to test the changing points in the sequence.

4.2 Runoff yield before and after abrupt-change points

The two abrupt-change points (1961 and 1976) in the upstream reach divide the 1951–2001 period into three parts: 1951–1961 (S1), 1962–1976 (S2) and 1977–2001 (S3). There are great differences in the runoff yield in the three periods, as Fig. 3 demonstrates. The middle reach showed a similar situation, with the runoff–yield coefficient reduced to a large degree.

Undoubtedly, socio-economic development has had an enormous influence on the runoff yield situation. From S1 to S3, the same rainfall yields less river runoff. Moreover, the slope of the *P–R* curve also decreases. This implies that an equivalent increase in rainfall produces much more streamflow, which makes the flood peak higher and therefore threatens the safety of local and downstream residents. This may be attributed to the great change in the land use (e.g. deforestation, ground surface hardening) by human activities in the study area (Sun *et al.* 2007, Li and Li 2008).

4.3 Normal rainfall–runoff induced streamflow, Q^0

Since we assumed that in the baseline period $Q^C(t) = 0$ and $Q^V(t) = 0$, $Q^0(t) = Q(t)$ in this period, according to equation (9). A relationship can then be fitted between annual rainfall data ($P(t)$) and $Q^0(t)$, as follows: $Q^0(t) = 0.31P(t)^{0.91}$ with $R^2 = 0.87$, root mean square e-rror, RMSE = 10.73, $F = 52.36 >> F_{0.01}(1,10) = 10.04$ in the upper reach and $Q^0(t) = 5.20 \times 10^{-5}P(t)^{2.31}$ with $R^2 = 0.97$, RMSE = 8.99, $F = 268.23 >> F_{0.01}(1,9) = 10.56$ in the middle reach. The *F* test shows the relationship is significant and it can be used to retrieve the normal rainfall–runoff induced streamflow (Q^0), as Fig. 4 illustrates.

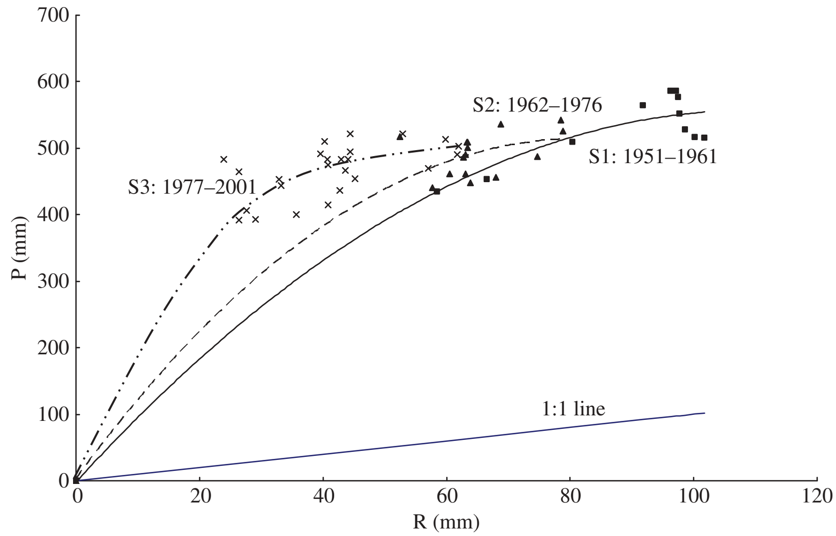

Fig. 3 Runoff yield change in the three periods (S1, S2, S3) at DG station.

Overall, Q^0 fluctuated and showed no evident rise or decline after the 1950s; Q^0 in the middle reach fluctuates more than Q^0 in the upper reach.

4.4 CC-induced streamflow, Q^C

By using equation (8), Q^C sequences in the two regions after the 1950s were obtained (Fig. 4). On the whole, they show a rising trend and an increase of about 30 mm in the upper reach and 35 mm in the middle reach over four previous decades, accounting for 6.10% and 5.76% of mean rainfall in the baseline period, respectively.

The increasing rate in the upper reach slows down gradually since $d^2Q^C(t)/dt^2 = -7.95 \times 10^{-4}t + 1.56$ was negative in the upper reach during 1960–1999. The trend in the middle reach during the same period is divided into two stages: an accelerating period from 1961 to 1979, as $d^2Q^C(t)/dt^2 = -0.16t + 31.72$ was positive before 1979; and a decelerating period from 1980 to 1999 as $d^2Q^C(t)/dt^2$ was negative after 1979. This suggests that the increasing rate in the middle reach accelerated before 1979 and then slowed down after 1979.

To verify the Q^C results, the corresponding process of rainfall minus evaporation ($P - E$) was drawn, which can be considered as the potential water for runoff yield. In the two regions, $P - E$ shows a similar upward trend (Fig. 5). It is clear that in the study area, solely considering climatic factors that are induced by climate change, there exists a great potential for streamflow increase. According to Wang *et al.* (2005), a large decrease in E may be due to reductions in regional water area. The increasing pattern of $P - E$ is different in the two regions: in the middle reach, the decadal average of $P - E$ continually increases, while in the upper reach it is more complicated with a reduction in $P - E$ in the 1980s. The growth rate in the middle reach is greater than in the upper reach, which indicates that CC impact in the middle reach is larger than that in the upper reach. On the whole, the process of $P - E$ after the 1950s in the two regions justified that of Q^C.

At a decadal scale (Table 2), upper reach Q^C values have on average an increasing rate of 8.62 mm per decade in the 1970s and 12.25 mm in the 1980s, but the rate slows down to only 6.32 mm in the 1990s. This implies that Q^C has increased since the 1960s, but it will reach its maximum value sometime in the future. Middle reach Q^C values show a similar decadal trend as that in the upper region.

This suggests that the trend of Q^C in the Chao River is upward after the 1950s, but the pattern of increase is different between the upper and middle reaches and it is more complex in the middle reach. At a decade scale, the highest values occur in the 1990s, but the acceleration in the 1980s is the greatest.

4.5 HA-induced streamflow, Q^V

The HA-induced streamflow (Q^V) takes on a decreasing trend after the 1950s in the two regions (Fig. 4). In the four decades considered, it reduced by more than 65 mm (13.21% rainfall but 74.57% streamflow on average in the baseline period) in the upper

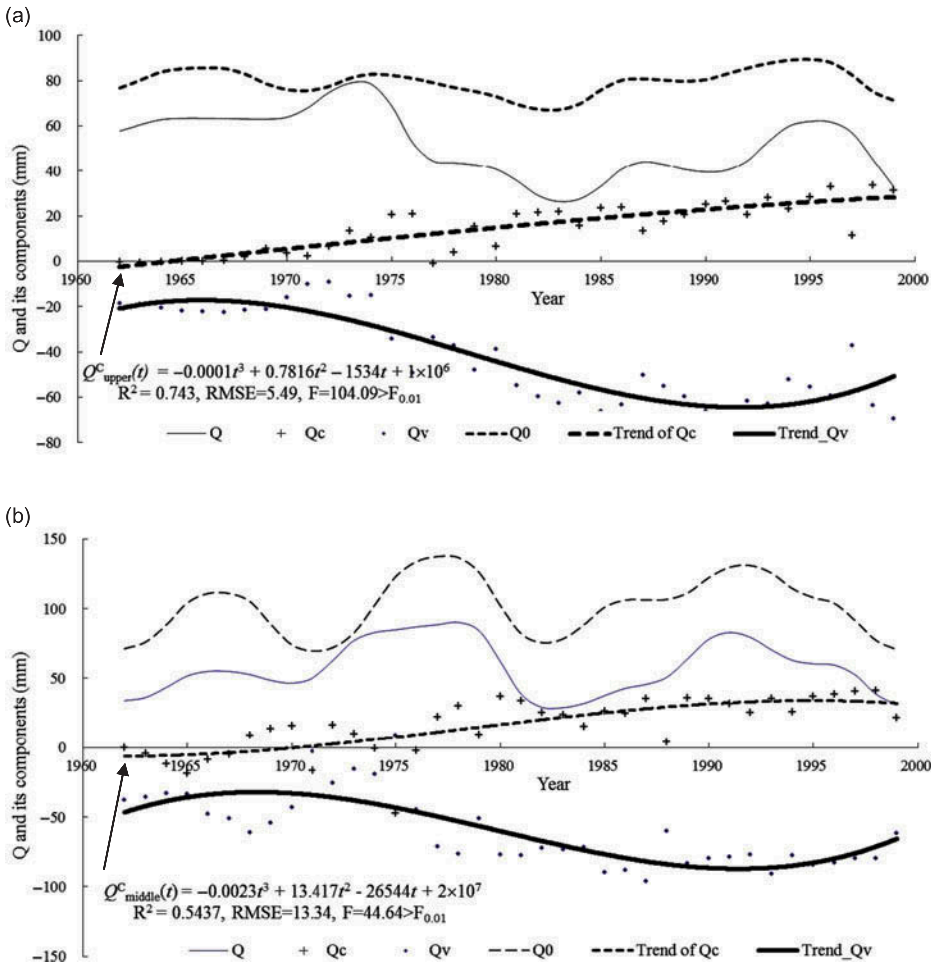

Fig. 4 Processes of observed streamflow (Q); CC-induced (Q^{C}), HA-induced (Q^{V}) and normal rainfall–runoff induced (Q^{0}) streamflow variations in (a) the upper reach and (b) the middle reach.

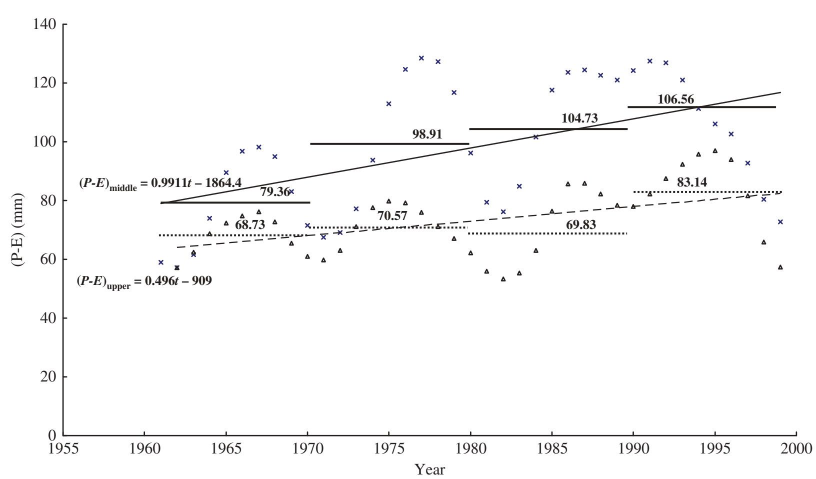

Fig. 5 Process of difference between precipitation and evaporation in the upper and middle reaches to verify results of Q^{C}: E is estimated according to equation (14) by Liu and Woo (1996). Lines and values above them denote the decade average value.

Table 2 Change of streamflow related variables in the upper and middle reaches during four previous decades and the four-decade average.

Decade	α = R/P	Q (mm)	Q^0 (mm)	Q^C (mm)	Q^V (mm)	$Q - Q^0$ (mm)	$Q^C/(\|Q^C\| + \|Q^V\|)$ (%)	$Q^V/(\|Q^C\| + \|Q^V\|)$ (%)
Upper reaches								
1960s	0.13	63.07	83.36	−0.05	−21.42	−20.29	−0.23	−99.77
1970s	0.14	65.96	78.27	8.58	−24.70	−12.31	25.78	−74.22
1980s	0.09	38.14	74.43	20.83	−58.83	−36.29	26.15	−73.85
1990s	0.11	49.00	84.16	27.15	−62.15	−35.16	30.40	−69.60
Average	0.12	51.84	79.52	14.42	−42.10	−27.68	25.51	−74.49
Middle reaches								
1960s	0.09	48.60	88.70	−4.43	−37.48	−40.10	−10.58	−89.42
1970s	0.14	83.49	112.85	9.80	−34.28	−29.36	22.24	−77.76
1980s	0.08	40.85	101.72	25.89	−77.11	−60.87	25.14	−74.86
1990s	0.11	61.75	111.24	35.44	−79.54	−49.49	30.82	−69.18
Average	0.11	52.74	103.86	21.80	−70.98	−51.12	23.49	−76.51

region, and more than 90 mm (14.81% rainfall but 62.84% streamflow) in the middle reach. This signifies that HA had a great impact on streamflow. However, the decreasing trend slows down gradually, especially after 1990, as shown in Fig. 4. This may be attributed to some ecological rehabilitation, afforestation and agricultural restructuring in the study area that ultimately led to a substantial increase in forest coverage, but a reduction in farmland and grassland (Wang *et al*. 2005).

Considering the decadal average, Q^V decreased continuously (Table 2), yet the rate of decrease slowed. In the upper and middle reaches, respectively, Q^V decreased by less than 25 and 40 mm in the 1960s to 1970s, but more than 55 and 75 mm in the 1980s and 1990s, which signifies that HA intensified greatly from the 1980s. Compared with the previous decade, Q^V decreased by 3.28 mm (upper reach) and increased by 3.20 mm (middle reach) in the 1970s, and decreased by 34.13 mm (upper) and 42.83 mm (middle) in the 1980s, and by only 3.32 mm (upper) and 2.43 mm (middle) in the 1990s. This implies that local countermeasures using ecological rehabilitation and environmental protection by transferring agricultural land and grasslands to forestry (Wang *et al*. 2005) had a positive effect on the HA reduction.

In brief, streamflow variation induced by HA (Q^V) takes on a decreasing trend after the 1950s in the Chao River, and rainfall reduced by around 13–15%, with average streamflow in the baseline period reduced by 62–75%. A greater Q^V usually resulted from a larger runoff yield area: Q^V is about 30 mm more in the middle reach than in the upper reach. Human activity has greatly influenced streamflow in the four decades considered, but the impact weakened from the 1990s due to effective environmental protection and increase in forestry.

4.6 Comparison of CC and HA effect in the four decades

Table 2 shows the variation of runoff-yield coefficient (α), observed streamflow (Q), normal rainfall–runoff induced streamflow (Q^0), CC-induced streamflow (Q^C), HA-induced streamflow (Q^V) and the integrated effect of CC and HA ($Q - Q^0$). The values of α and Q decreased with the intensification of HA, especially in the 1980s when the two variables reached their minimum values. Unexpectedly, Q^0 fluctuates over time and displays no evident trend.

Conversely, Q^C and Q^V show opposing trends: the former rises and the latter drops. Their integrated impact on streamflow was different in different decades. The value of $Q - Q^0$ during the 1980–1990s was about twice that during the 1960–1970s, which suggests the integrated impact in the former period was much more drastic. The value of $Q - Q^0$ in the upper and middle reaches increased by 7.97 and 10.73 mm, respectively, in the 1970s compared with the previous decade; it decreased by 23.98 and 31.50 mm, respectively, in the 1980s and increased again in the 1990s by 1.13 and 11.38 mm, respectively, which indicates that the integrated effect of CC and HA on streamflow has declined since the 1990s. Evidently, the 1980s was the most affected period in terms of HA.

The proportion of the impact of the two factors on streamflow also varied greatly in different decades. In the 1960s, Q^V dominated in a less negative integrated impact. In the 1970s, CC had a positive effect of 25.78% and 22.24% in the upper and middle reaches, respectively, while HA had a negative influence of 74.22% and 77.76%, and CC impact was 29–35% that of HA. In the 1980s, there was more CC impact and less HA intensity. In the 1990s, the trend continued. In the Chao River, upstream of the Miyun Reservoir, on average, Q^{C} had a positive 25% impact on streamflow, while Q^{V} exerted a negative effect of –75% in the four decades since the 1950s, and HA exerted a more negative effect in the middle reach than in the upper.

Li and Li (2008) studied the influences of CC and HA on streamflow based on precipitation, air temperature and runoff data between 1961 and 2005. Their results showed that precipitation and air temperature changes were not the main factors leading to the drastic decrease in annual runoff, and the runoff reduction was affected more by HA, such as water resources utilization, land-use change, construction of reservoirs and inter-basin water transfer. Our results suggest similar conclusions in that HA is the main factor causing the reduction in annual runoff.

Yao *et al*. (2003) analysed HA and precipitation impacts on runoff during the period 1967–2000 at DY station using an annual runoff accumulation curve. Their results indicated that HA was the main factor leading to a reduction in annual runoff. During the four decades considered, the reduction induced by HA accounts for 53.92% of the total reduction in annual runoff, while that due to changed precipitation accounts for 46.08% (both impacts from HA and precipitation are negative). Our results indicate that HA leads to 76.51% reduction in runoff (i.e. negative), while the effect of CC of 23.49% increase is positive. This has several reasons. Firstly, we considered air temperature in addition to precipitation. The former is one of the dominant influencing factors for evaporation. Because Yao *et al*. (2003) only accounted for precipitation, reduction in precipitation undoubtedly resulted in reduction in runoff. If they considered the difference between precipitation and evaporation ($P - E$), the impact of CC deduced from their results may have been positive. A slower decrease in precipitation plus a faster decrease in evaporation may lead to an increase in $P - E$. Secondly, they only used point-observed data (at DY station) of precipitation and runoff to establish the precipitation–runoff model, while we employed the areal rainfall and regional runoff (observed at DY station) to study the impacts of HA and CC. Obviously, the latter is more accurate. Thirdly, our result is for the middle reach between DG and DY, while they examined the whole area upstream of DY station including the region upstream of DG where HA is less intense. So it is reasonable that their HA impact value is smaller than ours.

According to Wang *et al*. (2009), the coverage of forest increased from 48% in 1980 to 65% in 1995, while grassland and cultivated land decreased from 28% and 22% to 16% and 17%, respectively. Supporting our results, this may lead to a decrease in agricultural water consumption and therefore lower HA impact intensity.

4.7 Advantages and uncertainties in the method

The method used in this study was compared with other studies such as Kezer and Matsuyama (2006), Zheng *et al*. (2006), Chang *et al*. (2007), Jiang *et al*. (2007), Pohl *et al*. (2007), Savitskiy *et al*. (2008), Huo *et al*. (2008), Fan *et al*. (2010), Fu *et al*. (2010) and Liu *et al*. (2010). The advantages of this method include: (a) it is able to retrieve the annual quantitative time series of CC and HA impact based on the observed streamflow sequences; (b) its base is climate elasticity, not periodical data transfer; therefore, it can compute CC impact more precisely; and (c) it is not based on period data comparison, so, unlike previous studies, it can describe CC- and HA-induced streamflow at a much smaller temporal scale (annual).

Theoretically, this method can be applied to any region where the CC and HA have an influence on streamflow. It can be employed by local water resources administrators to better understand the impact of CC and HA processes under different development patterns. It should also be considered that there are uncertainties in the results because of the assumption that streamflow variations induced by rainfall–runoff changes due to CC and to HA are independent of each other. Selection of the baseline period, when the CC and HA impacts can be disregarded, may also produce some uncertainties because of data limitations. The uncertainties need to be investigated in the future and further verification of the method by applying it to other regions is suggested.

5 CONCLUSIONS

A novel method is presented in this research to retrieve two time series from the observed streamflow: one is climate-change (CC) induced streamflow and the other is the human activities (HA) induced partition. This method is able to give the annual streamflow processes induced by both CC and HA. Its temporal resolution (one year) is much higher than that of traditional methods (a decade or even longer). Taking the 1950s as the baseline period, the method was used to separate and analyse the streamflow variation during the four decades since the baseline period, based on hydrological and meteorological data from the upper and middle reaches of the Chao River. This is upstream of the important water-supply source, the Miyun Reservoir, and enabled us to study the processes of CC and HA impacts on local streamflow. The results show that:

1. CC imposed a positive impact on streamflow. CC-induced streamflow (Q^C) has had a rising trend in the four decades since the 1960s. Its increment accounts for 5.76–6.10% of the mean rainfall in the baseline period. This is in accordance with the increasing trend in the runoff potential (rainfall minus evaporation), as shown in Fig. 5. At the decadal scale, the maximum occurred in the 1990s, while the acceleration was greatest in the 1980s.
2. HA exerted a continuous negative impact on streamflow. In the past four decades, it made streamflow reduce by 62–75% of the mean value in the baseline period. HA intensified greatly from the 1980s, which made the decadal mean decrement of HA-induced streamflow (Q^V) in the 1980–1990s more than twice that in the 1960–1970s. However, the rate of decrease slowed in the 1990s owing to large-scale ecological restoration in the Chao River basin. HA impact on streamflow is about 30 mm more in the middle than in the upper reach. On the whole, the runoff-yield coefficient and observed streamflow decrease with the intensification of HA, especially in the 1980s.
3. Normal rainfall–runoff induced streamflow variation shows no apparent trend whereas Q^C and Q^V reveal opposite trends: positive and negative, respectively. Their integrated impact on streamflow in the 1980–1990s was nearly twice that in the 1960–1970s, signifying that the integrated impact in the 1980–1990s was more drastic. The greatest integrated impact appeared in the 1980s.
4. The individual impact proportion of the two factors varies greatly in different decades. In the 1960s, Q^V dominated within the integrated impact; in the 1970s, CC *vs* HA exceeded 1/3; the CC proportion kept increasing after that until in the 1990s when CC *vs* HA was almost 1/2, which suggests a great reduction in HA in this decade with a lesser integrated impact, compared with the prior decade. On average, CC imposed a positive 25% impact on streamflow, while HA exerted a negative effect of –75% in the Chao River Basin, upstream of the Miyun Reservoir during the four decades after the 1950s.

These results are useful for local water resources management sectors to quantitatively evaluate the expenditure and revenue of water conservation measures, and make accurate decisions on allocation of valuable water resources to ensure the sustainable development of the regional society and economy.

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