Quantitative analysis of human impact on river runoff in west Liaohe basin through the conceptual Xin'anjiang model

LILIANG REN[1], VU VAN NGHI[1], FEI YUAN[1], CHUNHONG LI[2] & JIXIN WANG[1]

1 *State Key Laboratory of Hydrology, Water Resources and Hydraulic Engineering, Hohai University, no. 1 Xikang Road, Nanjing 210098, China*
rll@hhu.edu.cn

2 *Hydrological Telemetering and Environmental Monitoring Division, NARI Group Corporation, Nanjing 210003, China*

Abstract To understand the decreasing trend of river runoff, quantitative analysis of the human impact on decadal surface water resources was carried out using a hydrological model with long term observational hydrological data. The Laohahe River was selected as the study area, which lies in the west upper reach of the Liaohe basin, China. Since the study basin is located in the semihumid region of northeast China where both saturation excess (Dunne) and infiltration excess (Horton) runoffs exist, a parameterization scheme that dynamically represents both Dunne and Horton runoff generation mechanisms was added to the original Xin'anjiang hydrological model. Then this version of the Xin'anjiang model was used to perform hydrological simulations, to separate human impact from the climatic impact on river runoff and to make quantitative analysis of human impact on water resources in the Laohahe watershed. Results show that human activity made river runoff decrease by 1.02, 50.67 and 58.06 mm in the 1960s, 1970s and 1980s, respectively, and by 97.2 mm in the 1990s in terms of mean annual runoff in the Laohahe watershed.

Key words climate change; conceptual model; human activity; river runoff; water resources

INTRODUCTION

Water resources are mainly subjected to climatic circumstances and land surface characteristics. With socioeconomic development, the amount of runoff is to some extent influenced by human activities, such as agricultural production, industrial development, and municipal construction, etc. In particular, the Laohahe River, the west upper tributary of the Liaohe River, China, is concerned. Figures 1 and 2 show that there is an obvious decreasing tendency in the observed annual runoff series, while there is no remarkable trend towards decrease in the series of annual precipitation from 1953 to 1998, i.e. the equivalent quantity of precipitation produced less runoff in the Laohahe watershed in the 1990s than that in the 1950s. There is no doubt that the variation of river runoff depends upon climatic conditions, such as precipitation and temperature. The issue to be proposed is whether or not human activities exert a certain influence on runoff production under the background of climatic variability and what the extent of influence is. In this paper, an attempt is made to analyse the quantitative impact of human activities on decadal river runoff with the aid of a conceptual hydrological model.

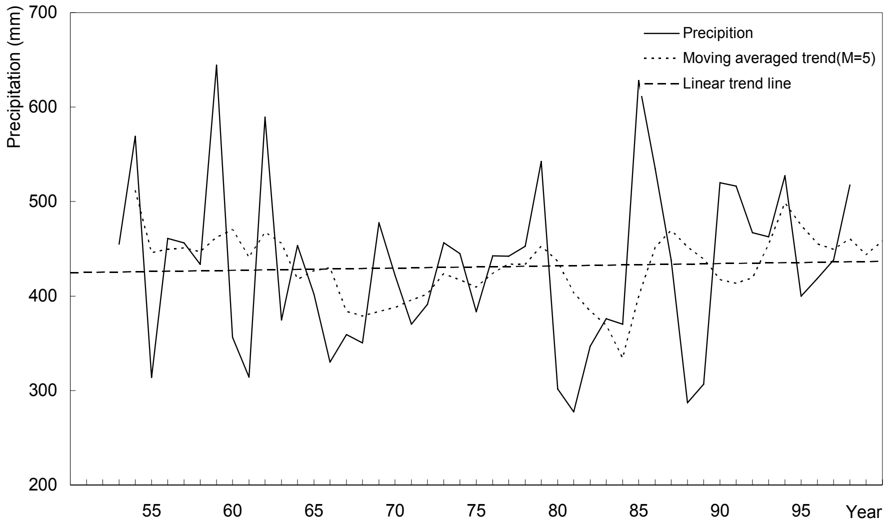

Fig. 1 Annual precipitation in the Laohahe watershed from 1953 to 1998.

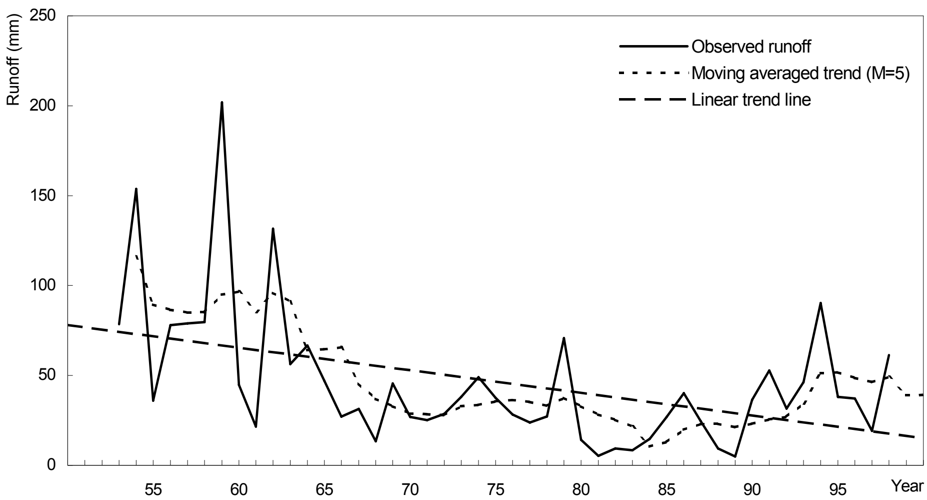

Fig. 2 Observed annual runoff depth in the Laohahe watershed from 1953 to 1998.

In the past, the human effect on surface water resources was estimated by investigating the impact of human activities on each item in the water balance equation, so as to calculate hydrological components in the original natural status. This method seems to be conceptually clear and could differentiate one impact from another. It is just appropriate in the case of direct impact, such as water transfer from one basin to another and water storage by various scales of hydraulic projects. However, this traditional method is difficult to compute water consumption directly due to such human activities as implementation of soil conservation measures, improvement of farming techniques, population growth, and socio-economic structure change. In such a situation, the hydrological modelling approach could be used to separate the human impact from the climatic one on water resources based on the measured runoff series. Conceptual hydrological models are useful mathematical tools in which hydrological processes from rainfall to runoff over a watershed are conceptualized and formularized. Model parameters, i.e. coefficients in the mathematical equations or relations amongst variables, are used to represent the hydrological characteristics of a watershed. When the model structure is determined, the parameters, which are calibrated by the observed data in the specific basin, may reflect the hydrological properties of that basin within the calibration period. If model parameters are kept unaltered, runoff series computed by a long series of precipitation could be regarded as the series under the condition of unvarying properties of the basin.

The methodology adopted in this study is described as follows. Firstly, gauged hydrological data in some specific periods are used for model calibration. The parameter values calibrated in a specific period could reflect land surface characteristics and the situation of human activities in the watershed within that duration. Then, the calibrated parameters are applied to runoff computation, and the calculated runoff series represent the impact of climatic variation on runoff under the same situation of land surface characteristics and human activities' level as in the first calibration period. Consequently, the human impact on river runoff will be analysed and discussed.

STUDY AREA

The Laohahe watershed is located within 41.0–42.5ºN latitude and 107.0–119.5ºE longitude. The watershed is in the west upper reach of the Liaohe River, one of the main large rivers in northeast China. Elevation within the watershed ranges from 405 m at the outlet to 1935 m above mean sea level at the top of the watershed divide. It has a semiarid climate, with the mean annual precipitation being 430.9 mm and the mean annual runoff depth being 46.1 mm.

Before 1976, the Xiaoheyan hydrological station was the watershed outlet with a contributing area of 18 599 km^2; due to the construction of the Hongshan reservoir in the upper reach of Xiaoheyan, the control station was moved to the location of the Xinglongpo hydrological station, which has a drainage area of 18 112 km^2. There are 20 rainfall gauges and six evaporation pans within the watershed.

HYDROLOGICAL MODEL AND APPLICATION

In order to analyse and quantify the influence of human activities on watershed hydrology, the following are done stepwise, namely: (i) selection of a hydrological model; (ii) model calibration based on observed data in various periods; (iii) runoff simulation for the whole period using the parameter set calibrated from the observed data in a specific period; and (iv) analysis of simulation results.

In this study, the conceptual Xin'anjiang model is selected, which was developed in 1973 and published in 1980 (Zhao, 1992). It has been used widely and successfully in China. Its main feature is the concept of runoff formation on repletion of storage, which means that runoff is not produced until the soil moisture content of the aeration zone reaches field capacity, and thereafter runoff equals the rainfall excess without further loss. Since the study area belongs to the semiarid region where both Horton and Dunne runoffs coexist, a new runoff parameterization scheme developed by Hu (1993) was added to the original Xin'anjiang model, which dynamically represents both Dunne and Horton runoff generation mechanisms.

The study watershed is divided into 48 sub-basins with regard to area and terrain by the digital elevation drainage network model (DEDNM, Martz & Garbrecht, 1992), then the Xin'anjiang model is applied to runoff calculation over each sub-basin, and subsequently flow routing from the sub-basin outlet to the whole basin outlet is achieved by using the Muskingum method to get the total basin runoff.

Supposing the Laohahe watershed experienced little human disturbance in the 1960s, the observed hydrological data from 1962 to 1967 are selected for model calibration and thus the calibrated model parameters could represent the hydrological characteristics of a natural basin. Meanwhile the hydrological data from 1993 to 1998 were used for model calibration, and the calibrated model parameter values were compared with those based on the data from 1962 to 1967. Model calibration is performed manually. Two criteria are selected for model calibration. They are:

(1) Relative error ($E_r\%$) between simulated and observed runoff volume:

$$E_r = (\overline{Q}_c - \overline{Q}_o)/\overline{Q}_o,$$

where $\overline{Q}_c$ and $\overline{Q}_o$ are the simulated and observed runoff volume, respectively;

(2) Nash-Sutcliffe coefficient (C_e) (Nash & Sutcliffe, 1970):

$$C_e = \frac{\sum (Q_{i,o} - \overline{Q}_o)^2 - \sum (Q_{i,c} - Q_{i,o})^2}{\sum (Q_{i,o} - \overline{Q}_o)^2}$$

where $Q_{i,o}$ is the observed streamflow (m^3 s^{-1}), $Q_{i,c}$ is the model simulated streamflow (m^3 s^{-1}), and $\overline{Q}_o$ is the mean observed streamflow (m^3 s^{-1}).

C_e and E_r in the first calibration period (from 1962 to 1967) are 0.871 and 0.14% respectively, and those in the second calibration period (from 1993 to 1998) are 0.554 and 0.08%. It shows that the Xin'anjiang model is able to reproduce the hydrological processes reasonably in the 1960s, but the model performs poorly in the 1990s. This is because the local hydrological system is possibly disturbed by human activities.

RESULT ANALYSIS

In the Xin'anjiang model, WUM and WLM are the parameters that are closely related to the vegetation in the basin. Higher values of WUM and WLM tend to represent denser vegetation coverage in a river basin. As shown in Table 1, the values of WUM and WLM in the 1990s are much higher than those in the 1960s, indicating that the land cover in the river basin has changed a lot since the 1960s, probably due to human activities. Moreover, the increase of KC also reveals that the land surface status has been altered intensively, which results in a remarkable increase in potential evapotranspiration. It also proves that human activity might have a tremendous influence on basin characteristics in the Laohahe watershed.

Table 1 Calibrated parameters in the Laohahe watershed.

Parameters	Descriptions	Calibration period 1962–1967	1993–1998
WM	Areal mean tension water capacity	175	300
WUM	Areal mean tension water capacity of upper soil layer	10	40
WLM	Areal mean tension water capacity of lower soil layer	95	160
KC	Ratio of potential evapotranspiration to pan evaporation	0.7	0.92
C	Coefficient of evepotranspiration from deeper soil layer	0.08	0.08
B	Exponent of the tension water capacity distribution curve	0.3	0.3
EX	Exponent of the free water capacity distribution curve	1.5	1.5
KG	Outflow coefficient of free water to groundwater	0.3	0.3
KSS	Outflow coefficient of free water to interflow	0.4	0.4
KKG	Daily recession constant of groundwater storage	0.99	0.99
KKSS	Daily recession constant of interflow storage	0.96	0.96
IMP	Factor of impervious area	0.02	0.02

Table 2 Decadal hydrological components in the Laohahe watershed.

Hydrological component	1950s	1960s	1970s	1980s	1990s	Mean
Precipitation (mm)	476.12	400.65	434.79	386.66	474.14	430.89
Observed annual runoff depth (mm)	100.94	48.5	35.54	15.81	45.92	46.05
Simulated annual runoff depth (mm)		49.52	86.21	73.87	143.12	88.93
Effect of human activity (mm)		1.02	50.67	58.06	97.2	42.88

Since the model parameters obtained from the 1962–1967 hydrological data might be regarded as the representation of hydrological features in a less human-disturbed river system, those parameters are used to perform hydrological simulations from the 1960s to the 1990s. The simulated runoff time series can be assumed to be the hydrological responses under a natural river system with less human disturbance. Thus comparison of the simulated runoff time series with the observed runoff from the 1960s to the 1990s is made. Table 2 and Fig. 3 show the mean decadal statistics of hydrological components from the 1950s to the 1990s in the Laohahe watershed. As indicated in Table 2, compared with the 1950s the decadal runoff depths in the 1960s, 1970s and 1980s decrease by 1.02, 50.67 and 58.06 mm, respectively, and that in the 1990s has a runoff reduction of 97.2 mm in the Laohahe watershed.

As indicated in Fig. 3, the observed runoff process from the 1950s to the 1980s tends to decrease continuously, although the amount of mean annual precipitation in the 1970s is higher than that in the 1960s. Among the five decades, only the observed runoff in the 1990s increased remarkably, owing to plenty of rainfall in that period, but

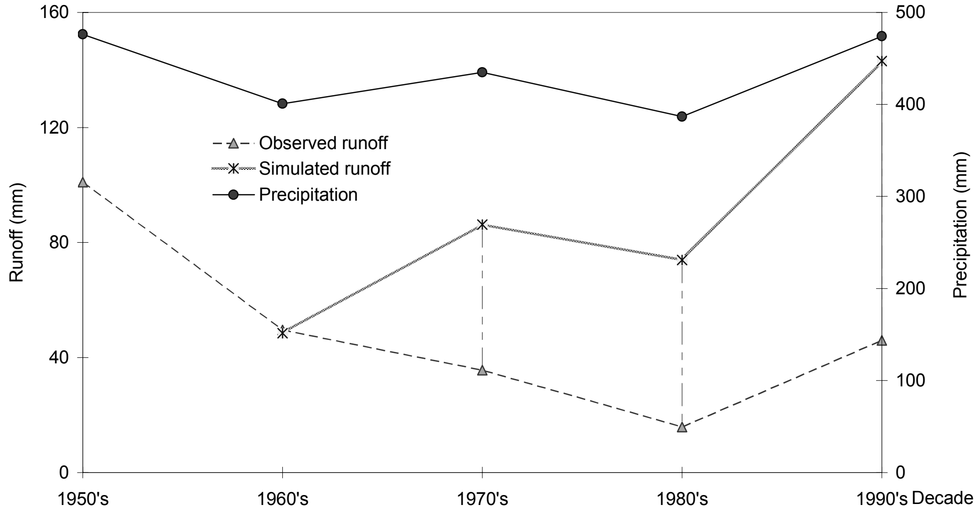

Fig. 3 Comparison of decadal precipitation, observed runoff depth and simulated runoff depth in the Laohahe watershed.

the effect of human activities might still become intensive. Multiplied by 18 112 km^2, the value of catchment area, the "losses" of river runoff can be estimated to be about 9.18×10^8 m^3, 10.52×10^8 m^3 and 17.6×10^8 m^3 in 1970s, 1980s and 1990s, respectively, as shown in Fig. 3.

As mentioned in the previous section, watershed runoff, an important component in the hydrological cycle is mainly affected by climate, land surface and human activities. In modelling the basin runoff, generally, if only the climate element is taken into account, the calculated runoff process using the antecedent parameters should basically agree with the observed runoff. But it can be seen in Fig. 3 that the annual average runoff deviates from the simulated one more and more, and particularly, in the 1990s the difference between them is 97.2 mm. This phenomenon might imply that human activities are very likely to lead to the decrease in runoff in the Laohahe basin in recent decades.

The reduced runoff might be composed of the following two parts:

(1) Restorable flow refers to the transferred water and drainage between watersheds, and water storage and discharge from large water projects, etc., which can be measured and estimated accurately on the basis of onsite observation or statistical data. It can be easily obtained or estimated directly; and

(2) Un-restorable flow refers to the water consumed due to the improvement of farming technology, agricultural structure adjustment, rapid industrial development and population growth in the watershed, etc., which is not able to be computed exactly. It can not be easily obtained or estimated directly.

Hydrological models are useful tools to estimate the un-restorable flow. Usually, the model parameters that are calibrated on the basis of the hydrological data in the earlier period (from 1962 to 1967 in this study) can to some extent represent the hydrological features in the natural river system. Similarly, those model parameters obtained from the hydrological data in the later period (from 1993 to 1998 in this study) indicate the hydrological characteristics in the human-disturbed watershed. Therefore, the difference between the runoff processes that are calculated by those two types of model parameters could reflect the total influence of human activities on hydrology. Since the restorable flow can be measured, the un-restorable flow can be derived by subtracting the restorable flow from the above difference between those two runoff time series.

Based on the data in the case study from 1986 to 1990, the total observed runoff is 20.93×10^8 m^3, and the calculated runoff using the parameters based on the hydrological data from 1962 to 1967 is 89.51×10^8 m^3; since then, the total reduced runoff is 68.58×10^8m^3. With the investigated data of restorable flow as 4.58×10^8 m^3, the quantity of un-restorable flow is consequently equal to 64.00×10^8 m^3, occupying 93.32% of the total reduced runoff.

CONCLUSION AND DISCUSSION

It can be seen from the above analysis that river runoff in the Laohahe watershed has a remarkable downward trend, and this decrease trend becomes more and more obvious.

The factors that influence the water resources are very complicated. In other words, it is not easy to evaluate the quantitative effect of human activities on the hydrological regime because natural factors vary simultaneously. Some of the human effect on river runoff can be calculated easily, such as water transfer and drainage between watersheds, and water storage and discharge from large water projects. Other human effects on river runoff are difficult to estimate, such as the consumed water due to the improvement of farming technology in agriculture, rapid development of enterprises in towns and villages, and land use/cover change.

Therefore the feasible solution is to differentiate between the effect of climate change and the impact of human activities on river runoff. The impact of human activities on river runoff can be divided into restorable and un-restorable flows. The un-restorable flow may be estimated by the Xin'anjiang model with the parameters obtained from the 1960s data under the background of climate change. It implies the assumption that the model parameters can to some extent reflect the influence of land surface characteristics on hydrological regime over the studied basin.

However, this hydrological approach to estimate the impact of human activities on watershed hydrology involves quite a few uncertainties. They may come from the structure of hydrological models, model parameters and even observed data. Those uncertainties will definitely have a certain impact on the computational results, which are not included in this paper. Therefore, more work should be done on this aspect in the future.

Acknowledgements Financial support for this research was provided by the National Key Basic Research Program of China under Project no. 2006CB400502, Fund of State Key Laboratory of Hydrology, Water Resources and Hydraulic Engineering, Hohai University under Grant no. 2005406211, and National Natural Science Foundation of China under Grant no. 40171016. We would like to give thanks to the anonymous reviewer and editors for their pertinent comments, leading to improvements in the paper.

REFERENCES

Hu, C. Q. (1993) Computational method of runoff generation in semi-humid and semi-arid regions. In: *Proc. Symp. on Hydrological Information and Forecasting*, 57–62. China Water Power Press, Beijing, China (in Chinese).

Martz, W. & Garbrecht, J. (1992) Numerical definition of drainage network and subcatchment areas from digital elevation models, *Computers & Geosciences* **18**(6), 747–761.

Nash, J. E. & Sutcliffe, J. V. (1970) River flow forecasting through conceptual models, Part I: A discussion of principles. *J. Hydrol*. **10**, 282–290.

Zhao, R. J. (1992) The Xin'anjiang model applied in China. *J. Hydrol.* **135**, 371–381.