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A Distributed Monthly Water Balance Model for Analyzing Impacts of Land Cover Change on Flow Regimes*[1]

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ABSTRACT

The Miyun Reservoir is the most important water source for Beijing Municipality, the capital of China with a population of more than 12 million. In recent decades, the inflow to the reservoir has shown a decreasing trend, which has seriously threatened water use in Beijing. In order to analyze the influents of land use and cover change (LUCC) upon inflow to Miyun Reservoir, terrain and land use information from remote sensing were utilized with a revised evapotranspiration estimation formula; a water loss model under conditions of human impacts was introduced; and a distributed monthly water balance model was established and applied to the Chaobai River Basin controlled by the Miyun Reservoir. The model simulation suggested that not only the impact of land cover change on evapotranspiration, but also the extra water loss caused by human activities, such as the water and soil conservation development projects should be considered. Although these development projects were of great benefit to human and ecological protection, they could reallocate water resources in time and space, and in a sense thereby influence the stream flow.

Key Words: distributed monthly water balance model, land use and cover change (LUCC), remote sensing, scenario analysis

INTRODUCTION

Miyun Reservoir, the largest reservoir in North China, is located in the center of Miyun County, Beijing Municipality that is the capital of China with a population of more than 12 million. The reservoir blocks the water of the Chaohe River and Baihe River; supplies water to Beijing Municipality, Tianjin Municipality and part of Hebei Province; and becomes the most important headwater of the capital. Gao *et al.* (2002) carried out analyses on the time series of inflow water to Miyun Reservoir over recent decades. They concluded that the reservoir's inflow runoff presents an exponentially decreasing trend, and that reduced flooding is greater than that of normal runoff. Their results show that climate changes have little impact on runoff decreases, whereas population increase and cover change are the main driving forces.

Techniques for the analysis of effects due to land use and cover change (LUCC) (Pu *et al.*, 2001) on modeled hydrologic responses are still very much at an early stage. The prediction of effects from future changes (and validation of these predictions) has hardly even started (Beven, 2001). The Soil Conservation Service (SCS) curve number method, developed by the Soil Conservation Service of United States Department of Agriculture (USDA), has been widely used for runoff simulations. The popularity of the method is due to its simplicity, not its accuracy (Thompson, 1999). One of the key issues of the SCS curve is to determine the appropriate CN (Curve Number), which is a function of soil type, land use and cover type, cultivation practice, and antecedent soil moisture.

Other examples include the MIKE SHE Model (Andersen *et al.*, 2002), which establishes the relationship between losses (interception, evapotranspiration) and features such as leaf area index (LAI), vegetation root system and soil moisture content, can describe the effects of LUCC on the hydrologic

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process. In a case study on the Qinhuai River Basin, Wang and Lu (2003) divided land use into four types: surface water body, paddy field, dry land and impervious surface. They then established corresponding runoff generation patterns separately for the four land use types and analyzed the influence of LUCC on the water resource system, especially water balance and flood controls. In another example, after analyzing the hydrometeorological data from 250 basins all over the world, Zhang *et al.* (2001) found that a close relation between long-term evapotranspiration and precipitation for a given forest acreage existed. He proposed a simple two-parameter model (Rational Function Approach) to estimate actual annual evapotranspiration by precipitation, potential evapotranspiration and the water capacity coefficient of plant-available w, where different vegetation types have different w values. Additionally, in the Bagrov formula (Terpstra and van Mazijk, 2001), the actual evapotranspiration was also calculated from the most important influence parameters of precipitation and potential evapotranspiration with a parameter N called the effectivity parameter, reflecting the storage properties of the evaporative zone and being related to land use and soil type.

There have been many related studies, which relied heavily on support of remote sensing information (Wu *et al.*, 2004; Zhao *et al.*, 2004). Most of the studies were conducted in regard to evapotranspiration. However, the SCS method calculated runoff directly with evapotranspiration being considered indirectly. Meanwhile, to describe the characteristics of land use and cover using a parameter set, two kinds of methods can be adopted: one is with dispersed functions, *i.e.* one-to-one correspondence, such as the CN values in the SCS Model and the effectivity parameter N in the Bagrov formula; the other is through continuous functions, like LAI in the MIKE SHE Model.

The literature reveals conflicting impacts of LUCC on runoff. For example, in some studies, deforestation produced more stream flow and higher flow peaks, while in others the opposite occurred (Beven, 2001). This means uncertainties exist in predicting hydrologic responses with LUCC. In fact, many simulations have been conducted only paying close attention to changes in vegetation or land surface and neglecting any accompanying changes (Chen *et al.*, 2004; Gong *et al.*, 2003). Some examples for instance, include forest land being converted to meadow that could change the soil structure, *etc.*, and construction of water conservation projects that could not only change the state of land use, but also reallocate water resources in time and space, thus altering the natural process of water cycle. We found influents of two kinds: i) LUCC led to a change in the evapotranspiration rate; and ii) the irrigation systems and construction of water and soil conservation projects, *etc.* resulted in ineffective evapotranspiration or seepage losses.

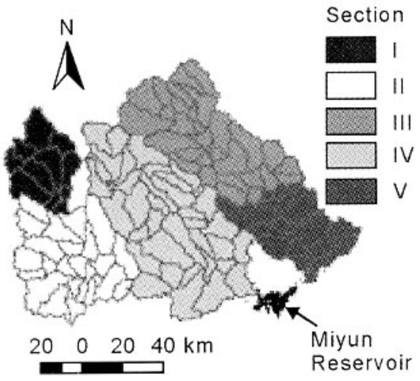
Selecting the Chaobai River Basin above Miyun Reservoir as the research area and using the land map interpreted from remote sensing (RS) images, a distributed monthly water balance model was established to analyze the influents of LUCC upon inflow to Miyun Reservoir.

MATERIALS AND METHODS

Data sources and procedures

This study was conducted in the Chaobai River Basin controlled by the Miyun Reservoir in Beijing Municipality. The whole basin consists of two branches: the east one is the Chaohe River Basin with an outlet at the Xiahui Hydrologic Station; the west one is the Baihe River Basin with an outlet at the Zhangjiafen Hydrologic Station. The total controlled area of the two hydrologic stations is 13 846 km^2 based on a digital elevation model (DEM) (100 m × 100 m) and the river network. This is designated as the Chaobai River Basin and is divided into 136 subbasins. Furthermore, considering the practical situation of the hydraulic works, the 136 subbasins have been placed in five sections (Fig. 1): (I) above the Yunzhou Reservoir, (II) between the Yunzhou Reservoir and the Baihebao Reservoir, (III) above the Dage Hydrologic Station, (IV) between the Baihebao Reservoir and Zhangjiafen Hydrologic Station, and (V) between the Dage Hydrologic Station and the Xiahui Hydrologic Station.

The land use map (scale: 1:10^5, interpreted from the remote sensing images) from the 1980s showed



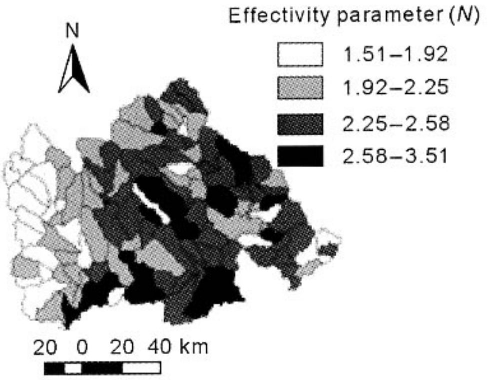


Fig. 1 Sections and subbasin divisions of the Chaobai River Basin.

Fig. 2 Spatial distribution of effectivity parameter (N) in the Chaobai River Basin.

that the main land use types were forest (28.01% in area), spinney (a small wood with undergrowth) (19.72%), grassland (meadows) (28.53%) and barren land (21.86%). The effectivity parameter, N, for each land use type was respectively assigned according to Jankiewicz *et al.* (2001).

The land use map was then overlain with the subbasin map, and the percentage of each land use type in one subbasin was obtained. Next, the mean N for each subbasin (Fig. 2), weighted by the area of each land use type, was calculated.

Afterward, the hydrometeorological data (precipitation, runoff and water surface evaporation) from 1961 to 1966 and 1973 to 1990 were processed into monthly data. Among the subbasins, there were 43 rain gauges in the Baihe River Basin and 15 in the Chaohe River Basin with one discharge station for each of the two basins and three water surface evaporation stations. Precipitation was allocated to each subbasin through the gradient plus reverse distance squared (GRDS) interpolation approach (Lin *et al.*, 2002).

Water balance

The distributed monthly water balance model, distributed time-variant gain model (DTVGM), in the Chaobai River Basin was established on the basis of geographic information system (GIS) and RS information with the basin being divided into subbasins according to DEM and the land use and cover information being obtained from the RS images. DTVGM calculated runoff, evapotranspiration, variation in soil moisture storage, and water losses in the subbasins and analyzed the impacts of LUCC on stream flow. The water balance procedure can be expressed as:

$$\Delta AW_t = AW_{t+1} - AW_t = P_t - ETa_t - RS_t - RSS_t - WU_t \tag{1}$$

where ΔAW_t is the change in soil moisture storage; AW_t and AW_{t+1} are the soil moisture content at time t and $(t+1)$, respectively; P_t is the precipitation; ETa_t is the evapotranspiration; RS_t and RSS_t are the surface runoff and subsurface runoff, correspondingly; and WU_t is the water loss, including water use, sink filling, ineffective evapotranspiration and seepage loss.

The runoff generation calculation came from the daily-scale hydrological model of DTVGM (Xia *et al.*, 2003a, b).

Revised Bagrov evapotranspiration model

In order to estimate the change in evapotranspiration rate due to LUCC, a revised Bagrov formula was developed. The Bagrov formula (Terpstra and van Mazijk, 2001) is convenient for calculating the actual evapotranspiration according to the monthly potential evapotranspiration and precipitation.

The Bagrov formula can be applied at the monthly or the annual scale and only consider the contribution of precipitation toward evapotranspiration. However, much research has indicated that actual evapotranspiration is closely related to the antecedent soil moisture content as well as precipitation (Davie, 2002; Thompson, 1999). Therefore, by introducing soil moisture, we put forward a revised Bagrov formula:

$$\frac{ETa}{ETp} = \left[(1 - KAW) \cdot KET_{Bagrov} + KAW \cdot \frac{AW}{AWC}\right] \tag{2}$$

where ETa is the actual evapotranspiration, ETp is the potential evapotranspiration; KAW is a weighting factor; KET_{Bagrov} is calculated by the original Bagrov formula and is the ratio of actual evapotranspiration to potential evapotranspiration, representing the contribution of precipitation to the actual evapotranspiration; and AW and AWC are the soil moisture content and the saturated soil moisture content, respectively. Thus, AW/AWC describes the relative saturation, reflecting the contribution of the antecedent soil moisture to actual evapotranspiration.

Water loss estimation model

Due to data scarcity, water loss was difficult to calculate. Therefore, an influence factor was added to the rainfall-runoff model; for example, the influence factor for subbasin k is A_k. Thus, the runoff flowing into the stream is $(R_k \times A_k)$ and the water loss is $R_k \times (1 - A_k)$, where R_k is the runoff calculated by the runoff generation model.

According to actual conditions, each subbasin should have its own influence factor, which means that the influence factors are spatially distributed. On the other hand, during a hydrologic year, there are water supply and storage periods, which reflect the temporal variation of the influence factors. During water supply, the actual runoff will surpass the natural runoff, *i.e.* A_k is greater than 1.0; for water storage (including inefficient evapotranspiration and water seepage), A_k is less than 1.0. The influence factor for each subbasin can be expressed as:

$$A_{j,k} = \alpha_j + \beta_k \tag{3}$$

where $A_{j,k}$ is the influence factor for subbasin k in month j; α_j is the average influence factor for the whole basin in month j, and β_k is the adjustive factor for subbasin k.

Runoff generation model

With DTVGM, the relationship between rainfall and runoff is nonlinear, and in the course of runoff generation, differing antecedent soil moisture contents will lead to a variation of runoff generation (Xia, 2002). The surface runoff (RS_t) generated in a subbasin can be described as:

$$RS_t = g_1 \cdot \left(AW_t/AWC\right)^{g_2} \cdot P_t \tag{4}$$

where g_1 and g_2 are undetermined coefficients.

For the subsurface layer, the water balance equation is:

$$AW_{t+1} - AW_t = P_t - RS_t - ETa_t - RSS_t \tag{5}$$

In addition:

$$RSS_t = Kr \cdot \overline{AW_t} = Kr \cdot (AW_t + AW_{t+1})/2 \tag{6}$$

where Kr is the subsurface runoff generation coefficient; and $\overline{AW_t}$ is the mean soil moisture content during time interval t.

According to the above-mentioned water loss estimation method, the actual runoff generated in the month t is:

$$R_t = A_t \cdot (RS_t + RSS_t) \tag{7}$$

where R_t is the actual runoff and A_t is the influence factor in the water loss model.

Analysis

Due to the inability of obtaining a land use map from the 1960s, a map from the 1980s was used to conduct the entire study. In 1960s, the influence of human activities was not serious, which means the water loss could be ignored. Without considering the water loss process, the rainfall-runoff processes from 1961 to 1966 were used for model calibration and verification. After parameterization using the data from 1961 to 1966, the rainfall-runoff simulations from 1973 to 1990 were directly carried out without the water loss model and compared to the simulation with the water loss model to show water loss due to human activities.

The impacts of LUCC on evapotranspiration were conducted without considering the water loss model. With 1966 as the benchmark, since precipitation was invariant, a certain single land use type was assumed to cover the basin, from which three scenarios were designed: the basin would be covered by i) forest with the percentage of forest area going from 28.01% to 100%; ii) meadow where the percentage of meadow went from 28.53% to 100%; or iii) barren land in which the percentage of barren land area rose from 21.86% to 100%. This would assess the extent of influence on the changes in land use and cover.

Then, monthly average influence factors (Eq. 7) depending on the relative number of diversion projects was estimated for the whole basin. From this a mean adjusted annual influence factor was estimated to show runoff generation in the Chaohe River Basin and Baihe River Basin.

RESULTS

Rainfall-runoff simulations from 1973 to 1990 without the water loss model revealed that the simulated runoff volumes were always greater than observed (12% for the Chaohe River Basin and 33% for the Baihe River Basin) (Table I). Two performance criteria were used to assess the simulation results: one is RSO, ratio of simulated runoff volume to observed runoff volume; the other is NSEC (Nash-Sutcliffe efficiency criterion), reflecting the fitness between simulated hydrograph and observed hydrograph.

TABLE I

Performance criteria of simulations

Basin	Year	RSO[a]	NSEC[b]	Comments
Chaohe River	1961–1966	0.98	0.90	Without water loss model; model calibration and verification
	1973–1990	1.12	0.36	Without water loss model
	1973–1990	1.03	0.91	With water loss model
Baihe River	1961–1966	1.00	0.90	Without water loss model; model calibration and verification
	1973–1990	1.33	0.13	Without water loss model
	1973–1990	0.97	0.90	With water loss model

[a] RSO: Ratio of simulated runoff volume to observed runoff volume.
[b] NSEC: Nash-Sutcliffe efficiency criterion (Mishra *et al.*, 2003).

For scenario (a) with 100% forest coverage the runoff volume decreased by 7.3%; for scenario (b) with 100% meadow coverage the runoff volume increased by 14.1%; and for scenario (c) with 100% barren land coverage the runoff volume increased by 7.2%.

The mean annual adjustive factors, which took into account the amount of construction for diversion projects in the Chaohe River Basin and Baihe River Basin, are shown in Fig. 3.

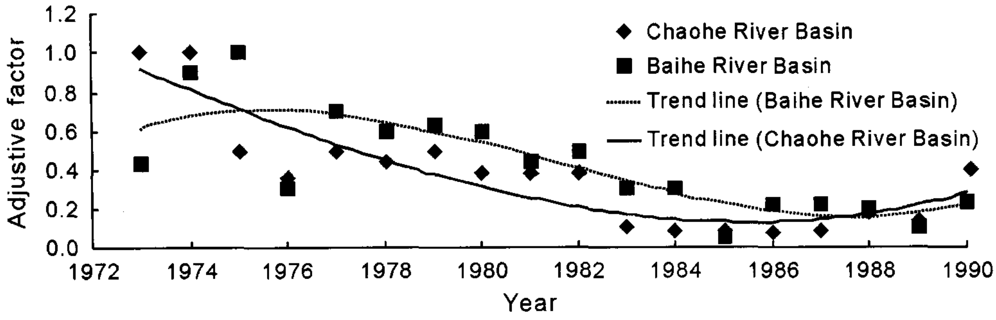


Fig. 3 Mean annual adjustive factors in the Chaobai River Basin.

DISCUSSION

Impacts of LUCC on evapotranspiration

In this study, emphasis was placed on evapotranspiration and water loss models related to LUCC. The three scenarios without considering the water loss model showed that regardless of the spatial distribution, land use changes in cover meant runoff would change. For instance, using proportions from the results of the scenarios, if the forest land area doubled, runoff volume would decrease by 2.8% (with evapotranspiration increasing); when the meadow area doubled, runoff would increase by 5.6% (with evapotranspiration decreasing); and if barren land doubled, runoff would increase by 2.0% (with evapotranspiration decreasing). Thus, with the area of land cover type doubled, the changes in runoff did not exceed 6%. In addition, compared to meadow and barren land an increase in forest area will decrease runoff volume (Liu *et al.*, 2004).

Using the land use map from the 1980s instead of the 1960s for calibration and verification and then to conduct the study would introduce some errors. With earlier data for calibration, where the impacts of human activities on water loss were almost nonexistent, results would have been better. Nevertheless, before the 1960s there was limited data to satisfy the data request. As it turned out, however, this error was not very important, as from the 1960s to the 1990s the area of the three kinds of land cover did not change greatly.

The results without the water loss model (Table I) indicated that the simulated runoff volume for the Chaohe River Basin and Baihe River Basin was 12% and 33% more than the observed, respectively. This proved that only considering the change in evapotranspiration rate was not enough; human activities resulting in water loss (consumptive water use, storage and inefficient evapotranspiration) should also be considered. Thus, due to the construction of irrigation systems and water and soil conservation projects, the natural runoff generation process was altered. This also meant that the impacts of human activities led to water loss in the Chaobai River Basin, and only small amounts of water were returned to the river. Therefore, the water loss model must be involved in the simulations from 1973 to 1990.

The influence factor with the water loss model

In this study, two important reservoirs in the Baihe River Basin, the Yunzhou Reservoir and Baihebao Reservoir, were involved; and there were more diversion projects in the Chaohe River Basin. The average monthly influence factor for the whole basin was estimated after considering these development projects. Since there was a water supply period in spring, the influence factor was much greater; while there was a water storage period in summer, so the influence factor was very small.

The annual adjustive factors for the Chaohe River Basin and Baihe River Basin, showed a decreasing trend from 1973 to the mid 1980s (Fig. 3) because the water and soil conservation projects had continuously been built. This meant that water loss had an increasing trend. Changes in precipitation also caused fluctuations among the influence factors. Therefore, as shown in Fig. 3, in the mid 1980s variations with the Chaohe River Basin had maintained a relatively steady state, *i.e.* the construction projects in the basin had already reached a saturated condition, and even increased going into the 1990s; whereas, the development projects in the Baihe River Basin still continued, leading to a continuous decrease in runoff generation ability through the latter half of the 1980s.

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