# Impacts of land use change and climate variations on annual inflow into Miyun Reservoir, Beijing, China

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## Abstract

Miyun reservoir, the only surface water source for Beijing city, has experienced water supply decline in recent decades. Previous studies suggest that both land use change and climate contributes to the changes of water supply in this critical watershed. However, the specific causes of the decline in Miyun reservoir are debatable under a non-stationary climate in the past four decades. The central objective of this study was to quantify the separate and collective contributions of land use change and climate variability to the decreasing inflow into Miyun reservoir during 1961-2008. Different from previous studies on this watershed, we used a comprehensive approach to quantify the timing of changes in hydrology and associated environmental variables using the long-term historical hydrometeorology and remote sensing based land use records. To effectively quantify the different impacts of the climate variation and land use change on streamflow during different sub-periods, annual water balance model (AWB), climate elasticity model (CEM), and rainfall–runoff model (RRM) were employed to conduct attribution analysis synthetically. We found a significant ($p<0.01$) decrease in annual streamflow, a significant positive trend in annual potential evapotranspiration ($p<0.01$), and an insignificant ($p>0.1$) negative trend in annual precipitation during 1961-2008. We identified two streamflow breakpoints, 1983 and 1999, by the sequential Mann-Kendall Test and Double Mass Curve. Climate variability alone did not explain the decrease in inflow to Miyun reservoir. Reduction of water yield was closely related to increase in actual evapotranspiration due to the expansion of forestland and reduction in cropland and grassland, and was likely exacerbated by increased water consumption for domestic and industrial uses in the basin. The contribution to the observed streamflow decline from land use change fell from 64%-92% during 1984-1999 to 36%-58% during 2000-2008, whereas the contribution from climate variation climbed from 8%-36% during the 1984-1999 to 42%-64% during 2000-2008. Model uncertainty analysis further demonstrated that climate warming played a dominant role in streamflow reduction in the most recent decade (i.e., 2000s). We conclude that future climate change and variability will further challenge the water supply capacity of the Miyun reservoir to meet water demand. A comprehensive watershed management strategy needs to consider the climate variations besides vegetation management in the study basin.

## 1 Introduction

Land use change and climate variations are two main factors directly affecting the watershed hydrological cycle. Land use change influences watershed water yield by changing canopy interception, soil properties, biophysical factors affecting evapotranspiration, and groundwater use whilst climate variations alters precipitation, air temperature, humidity, plant growth, and consequently the hydrologic balances (Baker and Miller, 2013; Wang et al., 2013). Meanwhile, interactions of land use change and climate variations are complex and understanding the individual effects on watershed water yield is of great importance for land-use planning and water resource management (Zheng et al., 2013). To optimize watershed management, it is important to assess hydrological impacts of climate variations and land use change separately and collectively (Mango et al., 2011). Artificial Neural Networks and Soil Conservation Service Curve Number was employed to evaluate the effect of land use change on daily streamflows in western Georgia, USA (Isik et al., 2013). Soil and Water Assessment Tool was also applied to assess impacts of land use and climate change on hydrologic processes in a coastal Alabama watershed in USA (Wang et al., 2014; ) and the Hoeya River Basin, South Korea (Kim et al., 2013). A clear understanding of the driving factors benefits both hydrological model development and hydrologic assessment of global change (Wang et al., 2013). Due to the nonlinearity of streamflow response in the synchronous evolution of driving forces, it is challenging to disentangle the integrative effects of climate forcing and basin characteristics (Risbey and Entekhabi, 1996; Beguería et al., 2003; Arabi et al., 2007; Morán-Tejeda et al., 2010). Many methods have been developed for isolating the effect of land use change from climate variations on regional hydrology. These methods include paired catchment approach (Brown et al., 2005; Zégre et al., 2010), statistical methods (Costa et al., 2003; Sun et al., 2006; Petchprayoon et al., 2010), and hydrological model (Haverkamp et al., 2005; Mao and Cherkauer, 2009; Baker and Miller, 2013). Raymond et al. (2008) suggested that land use change and management were more important than climate variation to increase riverine water export from Mississippi River over the past 50 years. However, other studies considered climate change as a dominant cause of annual water yield change (Aguado et al., 1992; Christensen et al., 2004; Barnett et al., 2005; Sun et al., 2013). Thus, both land use change and climatic variation should be considered to detect causes of hydrologic change at the same time.

The Miyun reservoir provides 70% of the total water supply for Beijing and is the only source of surface water supply for the severely water-stressed megacity with a population of 20 Million (Tang *et al.*, 2011). Over the past half-century, streamflow into the Miyun reservoir has shrunk drastically. Mean annual inflow into the Miyun Reservoir declined from 88.2 $m^3$ $s^{-1}$ in the 1950s to 15.8 $m^3$ $s^{-1}$ in the 1980s (Gao *et al.*, 2002). Meanwhile, population in Beijing increased from 2.8 million in 1953 to 20 million in 2000's (Liu *et al.*, 2003). The local water consumption in the catchment is believed to be the main driving factor in addition to climate.(Ma et al., 2010). Now, 18 reservoirs were built in the catchment with a total storing capacity of 0.214 billion $m^3$ (Li and Li, 2008). The contradiction between increasing water demand and water shortage constrains economic and social development of the region. Therefore, water resource assessment is extremely important to develop effective management strategies.

A few studies have tried to isolate hydrological impacts of land use change from climate change on streamflow in the Miyun reservoir catchment (MYRC) (Wang *et al.*, 2009; Xu *et al.*, 2009; Ma *et al.*, 2010; Zhan *et al.*, 2011; Bao *et al.*, 2012a; Wang *et al.*, 2013). However, conclusions varied significantly. For example, Wang *et al.* (2009) and Ma *et al.* (2010) suggested that climate impact separately accounted for about 33% and 55% of the decrease in reservoir inflow using the distributed time-variant gain model and geomorphology-based hydrological model. The discrepancies are mainly caused by assessment methodology due to parameter uncertainty (Shen et al., 2012), diversities of structural complexity (Velázquez et al., 2013), inconsistent of evaluation period (López-Moreno et al., 2011). It remains a grand challenge in watershed hydrology (especially for large basin) to seperate the hydrological effect of land use and from climate change and variability. Hence, Wei *et al.* (2013) indicate that a combination of two or three methods would be a robust research strategy to assess hydrological effect within a certain range.

This study attempts to: 1) detect the trend and break points of streamflow series for the period from 1961 to 2008, 2) explore an integrated approach to evaluate phased effects of climate and land use change on the inflow into the Miyun reservoir, and 3) provide suggestion to watershed management for the studied watershed.

In this research, the relative contributions of land use change and climate variability to changes of the annual streamflow into Miyun reservoir were quantified using an annual water balance model based on Zhang *et al.* (2001), the climate elasticity model (Sankarasubramanian *et al.*, 2001), and rainfall-runoff models (Jones *et al.*, 2006) for understanding water cycles and balance in the study area. Unlike previous study that use one evaluation period, this study use two evaluation periods to assess hydrological impact of land use change and climate variation over time. Meanwhile, three different hydrological models were combined to assess hydrological effect in each evaluation period.

## 2 Materials and methods

### 2.1 Catchment characteristic

Miyun reservoir, located about 100 km to the north of downtown Beijing, was built in 1960. The reservoir that receives water from the Chao River and the Bai River, has a total storage capacity of approximately 4.4 billion m$^3$, enough to supply more than half of water supply for Beijing City (Dong and Li, 2006). The drainage area is about 15,380 km$^2$ (115°25′～117°33′E, 40°19′～41°31′N) , occupying nearly 90% of the Chaobai River basin area (Figure 1). The local climate is characterized as temperate monsoon and semi-arid (Xu *et al.*, 2009). MYRC drains nine counties of Hebei Province and three counties of Beijing City. The total landmass of Chicheng, Guyuan, Luanping, and Fengning counties in Hebei Province accounts for 77% of the whole catchment area (Wang, 2010). The population of the four counties increased from 0.95 million during 1961-1983 to 1.18 million during 1984-1999, and further to 1.23 million during 2000-2008 (Figure 2). Land use maps were converted from the 1:100,000 land-use map of China, which was obtained from the Resources and Environment Data Center of CAS (http://www.resdc.cn/dataResource/dataResource.asp). Based on data availability and model building, land use maps of sub catchments were used including Yuzhoushuiku (YZSK), Xiabao (XB), Sandaoying (SDY), Zhangjiafen (ZJF), Dage (DG), Daiying (DY), Xiahui (XH) in 1978, 1988, 1998, and 2008; Huaihe (HH), Hongmenchuan (HMC), Banchengzi (BCZ) in 1990, 1995, 2000, and 2005; Tumen (TM) in 2000, and 2005 (Fig. 1). The land use was regrouped into six categories: water, bare land, forestland, cropland, grassland, and residential area.

## 2.2 Hydro-meteorological data

Daily precipitation data recorded at 37 rainfall gauges and daily discharge data of 11 hydrological stations were obtained from “Hydrological Year Book” by the China Hydrological Bureau. Daily meteorological data for the period of 1961-2008, including precipitation, air temperature (maximum, minimum, and mean), wind speed, relative humidity, and sunshine hours of 7 meteorological stations (Zhangbei, Fengning, Weichang, Zhangjiakou, Huailai, Chengde, and Beijing) were obtained from the China Administration of Meteorology. Daily $E_\mathrm{p}$ was calculated using Hamon method (Hamon, 1963; Lu et al., 2005) as described in section 2.4.1. All the hydrometeorological data were processed in accordance with international standards. Abnormal data were replaced by the values obtained from Kriging interpolation using nearby weather stations. Mean hydrometeorological data for the entire catchment were all obtained by the Kriging interpolation method in ArcGIS 9.3.

Average monthly temperatures from November to February were below 0 $^{o}$C. Minimum monthly temperature in January was lowest at -15℃ and maximum monthly temperature in July was highest at 29℃. Precipitation ($P$) in summer (June, July, and August) accounted for 68% of annual total precipitation. In comparison, summer potential evapotranspiration ($E_p$) accounted for 48% of annual totals (Figure 3).

## 2.3 Detecting the break points of streamflow time series

Both the Double Mass Curve (Searcy and Hardison, 1960) and the sequential version of

Mann-Kendall test (Mann, 1945; Sneyers, 1975) were applied to detect the break points. The Double Mass Curve represents two cumulative records. A break in the curve indicates a change in the relationship between the two records that may be caused by the processing of the data (Wigbout, 1973). A non-parametric test method, the sequential version of Mann-Kendall test is used to detect the change point of hydrological data series:

$$S_k = \sum_{i=1}^{k} r_i \left(k = 2,3,\cdots,n\right) \tag{1}$$

Where $r_i$ is as following:

$$r_i = \begin{cases} +1 & (x_i > x_j) \\ 0 & (x_i \le x_j) \end{cases} \left(j = 1,2,\cdots,i\right) \tag{2}$$

For each comparison, the number of cases $x_i > x_j$ is counted, and denoted by $r_i$. It is assumed that the statistic sequential values are random and independent. Then statistic variance ($UF_k$) is defined as follows:

$$UF_k = \frac{\left[s_k - E(s_k)\right]}{\sqrt{Var(s_k)}} \left(k = 1,2,\cdots,n\right) \tag{3}$$

$$E(s_k) = \frac{n(n+1)}{4} \tag{4}$$

$$Var(s_k) = \frac{n(n+1)(2n+5)}{72} \tag{5}$$

where $E(s_k)$ and $Var(s_k)$ are mean and variance of $s_k$, respectively. Statistic variance $UF_k$ is calculated as the forward data series ($UF_1 = 0$). The backward sequence $UB_k$ is calculated using the same equation but in the reverse data series. A null hypothesis is accepted if the critical value ($u_{0.05}$) lies within ±1.96 at a significance level ($\alpha = 0.05$). The positive $UF_k$ denotes an upward trend while the reverse series as a downward trend. When the value of $UF_k$ exceeds the critical value ($u_{0.05}$), it demonstrates an upward or downward trend significantly. If there are intersections of $UF_k$ and $UB_k$ lines in the range of critical value ($u_{0.05}$), the first cross point is the break point.

## 2.4 Hydrological models for attribution analysis

In this study, climate variations primarily refer to the changes of $P$ and $E_p$. Due to difficulty in quantitatively describing anthropogenic effects including water withdrawal and water consumption, land use change is used as the residuals affecting streamflow ($Q$) in addition to climate variations following Stohlgren *et al.* (1998) and Ma *et al.* (2010). Three models were built to provide a comprehensive evaluation on streamflow decreases in MYRC.

### 2.4.1 Annual water balance model (AWB）

To detect the influence of land use change on $Q$, a model was developed based on the sensitivity of land use change to actual evapotranspiration ($E_a$) (Zhang *et al.*, 2001). Formulates were described as follows.

$$Q = P - E_a \pm \Delta\delta \qquad （6）$$

$$E_a = \frac{1+\omega\frac{E_p}{P}}{1+\omega\frac{E_p}{P}+\frac{P}{E_p}} \times P \qquad （7）$$

$$E_{a(tot)} = \sum_{i=1}^{n}\left(E_{a(i)} \times f_i\right) \qquad （8）$$

$$E_p = 0.1651\, D\, V_d\, K\ (E_p = 0 \text{ when } T < 0) \qquad （9）$$

$$V_d = 216.7\, V_s / (T + 273.3) \qquad （10）$$

$$V_s = 6.108 \times \exp\ (17.26939\, T/(T + 273.3)) \qquad （11）$$

where $\Delta\delta$ (mm yr$^{-1}$) is the water storage change of the watershed which can be neglected at long-time averages (Donohue *et al.*, 2010). At a meso-scale, the watershed annual $Q$ (mm yr$^{-1}$) can be estimated as the difference between the $P$ (mm yr$^{-1}$) input and the $E_a$ (mm yr$^{-1}$) output (Sun *et al.*, 2005). $\omega$ is the plant-available water coefficient that varies in soil water use for transpiration. For MYRC, $\omega$ values of different land use, as a key indicator, were estimated by trial and error approach with increments in 0.1 using a computer program. $f_i$ is the percentage of land use area, in which $i$ represents diverse landscapes: forestland, grassland, cropland, water area, residential area, and bare area. $E_{a(tot)}$ is the sum of $E_{a(i)}$. $D$ is the day length (h). $V_d$ is saturated vapor density at the daily average temperature (g m$^{-3}$), $K$ is the correction factor. $T$ is the daily average temperature (℃). $V_s$ is the saturated vapor under a certain temperature (mbar).

### 2.4.2 The climate elasticity model (CEM)

To quantitatively evaluate the influence of climate variation on streamflow, the climate elasticity model (CEM) was built. The CEM defines the proportional change of streamflow divided by the proportional change in a climate variable such as precipitation (Ma *et al.*, 2010). The model was first developed by Schaake and Waggoner (1990) to evaluate the sensitivity of streamflow to climate changes, and then employed widely to assess the climate variability impact (Sankarasubramanian *et al.*, 2001; Jones *et al.*, 2006; Fu *et al.*, 2007; Bao *et al.*, 2012b).

$$\frac{\Delta Q_i}{\overline{Q_0}} = \varepsilon_1 \frac{\Delta P_i}{\overline{P}} + \varepsilon_2 \frac{\Delta E_{p(i)}}{\overline{E_p}} \tag{12}$$

$$d\overline{Q}_{c\lim} = \overline{Q_e} - \overline{Q_0} \tag{13}$$

$$d\overline{Q}_{land} = \overline{O_e} - \overline{Q_e} \tag{14}$$

$$d\overline{Q}_{tot} = d\overline{Q}_{c\lim} + d\overline{Q}_{land} \tag{15}$$

Where $\varepsilon_1$ and $\varepsilon_2$ are elasticity coefficients for $P$ (mm yr$^{-1}$) and $E_p$ (mm yr$^{-1}$) , respectively, which are estimated by least square estimation with the Matlab7.0. $\overline{Q_0}$ (mm yr$^{-1}$), $\overline{P}$ (mm yr$^{-1}$) and $\overline{E_p}$ (mm yr$^{-1}$) refer to the mean annual $Q$, $P$ and $E_p$ in the reference period. $\Delta P_i$ and $\Delta E_{p(i)}$ are the change of annual $P$ and $E_p$ compared to $\overline{P}$ and $\overline{E_p}$ , respectively. Annual $Q$ (mm yr$^{-1}$) for the period of 1984–1999 and 2000-2008 can be derived from Eq. 12 and calculated into mean value ($\overline{Q_e}$ ). $d\overline{Q}_{\text{clim}}$ is the average change in $Q$ caused by climate impact. $d\overline{Q}_{land}$ is the average change in $Q$ cause by land use change, and $d\overline{Q}_{tot}$ is the average change in $Q$ between the reference period and evaluation period. $\overline{O_e}$ and $\overline{Q_e}$ are the average annual $Q$ observed and simulated during the evaluation periods, respectively.

### 2.4.3 Rainfall–runoff model (RRM)

In addition to the CEM method discussed in section 2.4.2, the impact of climate variability on streamflow was also estimated using the following empirical rainfall–runoff models (Jones *et al.*, 2006; Li *et al.*, 2007).

$$Q_i = a + bP_i(\sigma_i^2)^c \tag{16}$$

$$d\overline{Q}_{c\lim} = \overline{Q_e} - \overline{Q_r} \tag{17}$$

Here, $Q_i$ (mm yr$^{-1}$) and $P_i$ (mm yr$^{-1}$) are the annual observed streamflow and precipitation, respectively. $\sigma_i^2$ is the variance of the monthly precipitation; a, b, and c are constants determined by hydrometeorological data in the reference period. $\overline{Q_e}$ (mm yr$^{-1}$) and $\overline{Q_r}$ (mm yr$^{-1}$) are the simulated mean annual streamflow during the evaluation period and reference period, respectively.

## 3 Results

### 3.1 Evolution and break points of annual streamflow series

As described in Figure 4, a significant decreasing trend at the rate of 0.96 mm yr$^{-1}$ was observed for annual streamflow during 1961–2008 ($p < 0.01$). Simultaneously, $E_\mathrm{p}$ increased by 1.25 mm yr$^{-1}$ significantly ($p < 0.01$) and precipitation decreased by 0.45mm yr$^{-1}$ insignificantly ($p > 0.1$) (Figure 4). In Chao River basin and Bai River basin, break points occurred in different years according to different methods. Using the Ordered Clustering analysis method (Xie et al., 2005), one break point at 1979 was detected in the runoff record in the river basins (Wang *et al.*, 2009). Yang and Tian (2009) found that abrupt changes in runoff occurred in 1983 and 1980 for Chao River basin and Bai River basin, respectively, based on the sequential Mann-Kendall test. Owing to significantly increasing direct water abstraction from the upstream of the reservoir since 1984, two sub-periods, one from 1956 to 1983 and the other from 1984 to 2005, were detected for Chao and Bai River basins (Ma *et al.*, 2010). Tang *et al.* (2011) noted that soil conservation practice positively affected the intensified reduction of streamflow after 1999. In this study, The year of 1984, as intersection point of the $UF_k$ and $UB_k$ curves inside the dotted lines, was the break point.. In addition, changes in streamflow from 2000 to 2008 were more significant because points of the curves fall outside the dotted lines (Figure 5). Furthermore, the Double Mass Curve was also used to divide annual streamflow series into three phases (Figure 7). Combined sequential Mann–Kendall test analysis with the Double Mass Curve test, we determined the referenced period (1961-1983), the evaluation period I (1984-1999), and the evaluation period II (2000-2008) in MYRC.

## 3.2 AWB model

A total of 41 sub-catchments with different land use composition were used to build the model. According to plant-available water coefficient $w$ of different land use in AWB model, the catchments were composed of forestland, grassland/cropland, water area and residential/bare area. Forestland accounts for more than 50% of the whole area in DG, DY, XH, YZSK, SDY, XB, and ZJF catchment; more than 80% of the total landmass in BCZ, HMC, and HH watershed; 100% of total area in TM catchment (Figure 7). The model was calibrated with the data prior to 2001 and was validated with the data after 2001(Figure 8). The range of $w$ values was determined to be [0, 3] for forestland, [0, 2] for grassland/cropland, and [0, 1] for residential area/bare area. The $E_a$ of water area was assumed to be the smaller between $P$ and $E_p$. Based on the method of trial and error, $w$ values of grassland/farmland, forestland, residential area/bare area were ratified as 1.5, 2.8, and 0 during the calibrated period, respectively. Compared the average annual water balance residual $E_a = P\text{-}Q$ with that estimated using Equation 7 & 8, the determination coefficients were 0.803 and 0.783 during calibration period and validation period, respectively (Figure 8).

Compared to the reference period (1961-1983), annual observed streamflow for 1984-1999 and 2000-2008 reduced by 18.1 mm and 39.7 mm, respectively. Using the land use data in 1988, the model was applied to evaluation periods. The difference of observed value and simulated value represented the impacts of land use change on inflow declines. As showed in Table 1, $d\overline{Q}_{land}$ were -11.5 mm and -19.6 mm which contributed 64% and 49% of $d\overline{Q}_{tot}$ for evaluation period I and II, respectively.

## 3.3 CEM model

Based on Eq. (12) and data in the period of 1961-1983, $\varepsilon_1$ and $\varepsilon_2$ were separately set as 2.12 and -2.25 by the least square estimation. Then the model was applied to simulate the annual $Q$ during the period of 1961-2008. The difference of $Q$ between the simulation period of

1984-2008 and the reference period of 1961-1983 was attributed to the impact of climate variation. Simulated annual $Q$ values were 57.7 mm and 42.6 mm during the periods of 1984-1999 and 2000-2008, respectively. The contribution of climate variation to the decrease of inflow during these two periods is about 1.5 mm (8%) and 16.5 mm (42%), respectively. Correspondingly, land use change contributed 16.6 mm (92%) and 23.2 mm (58%) to the decrease of inflow (Table 1).

### 3.4 RRM model

Using annual $P$ and the variance of the monthly $P$ from 1961 to 1983, the values of a, b, and c were obtained as 0.85, 0.0004, and 0.74 from Eq. 16, respectively. Then annual inflow into the reservoir was simulated as 56.4 mm and 33.8 mm for evaluation period I and II, respectively. Derived from Eq. 17, climate variation constituted for 2.7 mm (15%) and 25.3 mm (64%) of total $Q$ decrease for these two periods (Table 1). Compared to estimations from the CEM model, the contribution of climate variations to the decrease of inflow was about 7% higher during the period of 1984-1999, but 22% lower during the period of 2000-2008.

## 4 Discussion

### 4.1 Data limitation and likely impact of other human factors on streamflow

This study spans multiple years and uses multiple data sources for land use, meteorology, and hydrology. The bias of data often exist in field measurements, inventory, aggregation and spatial analysis of long series spatiotemporal data (Kavetski et al., 2006; Verburg et al., 2011). In the process of building the annual water balance model, 30 land use scenarios were utilized to calibrate the model and 11 land use scenarios were employed to verify it. To some extent, land use images were not comparable because the data were interpreted from different day of a year. Meanwhile, interpretation of remote sensing imageries also increases possibility of the errors. Only 37 rainfall gauges and 7 meteorological stations were available to clarify spatial change of precipitation and air temperature for a mountainous catchment with a drainage area of 15,380 km$^2$, thus interpolation errors may exist

Since the 1980s, water uses in MYRC have been intensified due to the increased water demand by people (Bao *et al.*, 2012a). On one hand, due to the growth of population (Figure 2) and development of industry and agriculture, the annual direct water withdrawal from the

MYRC increased from 2.2 mm yr$^{-1}$ in 1956-1983 to 13.4 mm yr$^{-1}$ in 1984-2005 (Ma *et al.*, 2010). At the same time, daily water consumption per capita accrued from 0.03m$^3$ in 1959 to more than 0.20 m$^3$ in 2000 (Gao *et al.*, 2002). Population growth aggravates water scarcity because it reduces per-capita availability even with unchanged water resources (Schewe et al., 2014). Meanwhile, soil and water conservation projects have been implemented considerably with slopes transformed into terraces, the construction of silt retention dams and reservoirs in 1970s and 1980s (Chaobai River Management Bureau of Beijing, 2004; Chang *et al.*, 2015). For example, The Yunzhou Reservoir (113.7 million m$^3$) and Baihebao Reservoir (90.6 million m$^3$) were built in 1970 and 1983, respectively (China water yearbook, 1991). In addition to water consumption, these water control projects enhanced evaporation and leakage losses from the catchment (Gao et al., 2013). Consequently, total water loss from the catchment had increased since the 1980s. In recent years, Paddy to Dry Land Project and programs of closing water-based industries were carried out to reduce water consumption that might have compensated the streamflow decline trend and have improved water quality (Wang, 2010).

## 4.2 Model uncertainties

Three different approaches were used to isolate hydrological impacts of land use change from those of climate change. AWB offered direct approach to evaluate hydrological impacts of land use change (Zhang and Wang, 2007). $E_a$, as the predominant part of water cycle, is the key to build this model. It is attributed primarily to land use, and also affected by several other factors such as soil types and topographic slope (Moiwo *et al.*, 2010). The daily $E_a$ (mm day$^{-1}$) might be improved by the Surface Energy Balance Algorithm for Land (SEBAL), remote sensing-based models validated by the Penman–Monteith approach, as well as the Soil and Water Assessment Tools (SWAT) model (Gao and Long, 2008; Gao *et al.*, 2008). The Penman–Monteith method is commonly considered as the best way to estimate the value of $E_p$. However, the application was difficult due to insufficient climate data, especially variable about solar radiation. Therefore, the Hamon method (Hamon, 1963) recommended by the Food and Agriculture Organization of United Nations (FAO) was used to calculate $E_p$. model parameter ($\omega$) had been derived from numerous catchments (Zhang et al., 2001). Then a simple two-parameter model based on these coefficients was applied to many other catchments (Sun et al., 2005; Ma et al., 2008; Zhang et al., 2008). Our research specified an analytical expression to determine the value of 2.8 and 1.5, respectively, for forestland and grassland/cropland with a correlation coefficient of 0.78 and 0.80 during calibration and validation phases, respectively. The data errors combined with uncertainty of model structure, increased uncertain to attribution of land use change. Meanwhile, to detect the potential streamflow response of land use change in MYRC, the model adopted the land use data in 1988 to estimate streamflow since 1984, which may cause errors due to variation of land use from 1984 to 1988. Besides, spatial and temporal variations of land use also affected streamflow change (Donohue *et al.*, 2011; Roderick and Farquhar, 2011). In the model, recharge to groundwater and change of soil water storage might be ignored for water balance at a meso-scale catchment (Sun *et al.*, 2005). Moreover, uncertainty of the model would be exaggerated when applied to small catchments, such as the BCZ catchment (65.2 km$^2$) and the TM catchment (3.4 km$^2$).

In the climate elasticity model (CEM), $P$ and $E_p$ were employed to assess hydrological impacts of climate variation. Annual $P$ in the evaluation period I was 9 mm yr$^{-1}$ more than that in the reference period. Simultaneously, $E_p$ in the evaluation period I was 25 mm yr$^{-1}$ more than that in the reference period. Whereas $d\overline{Q}_{clim}$ was only -1.5 mm yr$^{-1}$ which indicated that $Q$ increment as the result of $P$ increment was slightly less than $Q$ reduction as the result of $E_p$ increment..

As a quantitative assessment on hydrological impacts of climate change, without spatial input, especially for the catchment area of 15380 km$^2$ with altitude range from 50 m to 2292 m (fig.1), the climate elasticity model lacks physical mechanisms and ignores the spatial details of the impact of climate variation (Yang *et al.*, 2014a). The relative error increases with a median of 3.0% and a maximum of 20% when 10% precipitations alteration in moutain in China (Yang *et al.*, 2014b).

The Rainfall–Runoff model (RRM) accounts rainfall as the only climatic indicator to estimate the impact of climate change. This simplification might be the main reason resulting in the differences from other two approaches. $P$ for 1984-1999 was 9 mm yr$^{-1}$ greater than that for 1961-1983 while $d\overline{Q}_{clim}$ was 2.7 mm yr$^{-1}$ smaller correspondingly (Table 1), which illustrated that the variance of the monthly precipitation played an important role on modeling streamflow besides annual $P$. Moreover, the watershed in Miyun reservior was characterized with thin soils (<30 cm) in a rocky mountain environment (He *et al.*, 2010). Therefore, the watershed is rather responsive to rainfall events.

### 4.3 Implications to water resources management

In the Miyun Reservoir catchment, forestlands accounted for more than half of the total area. Compared to 1978, forestland area increased by 5.0% in 1988, 16.3% in 1998 and 18.2 % in 2008, respectively, whereas cropland decreased by 6.6%, 8.7%, and 10.8% correspondingly. Meanwhile, grassland area increased from 16.5 % in 1978 to 18.5 % in 1988, and then reduced to 10.4 % in 1998, and 9.8 % in 2008 (Fig. 9). Compared to the reference period, land use change resulted in streamflow decline for the 1984-1999 and 2000-2008 periods. It appears that land use change effect was most pronounced during 1984-1999. Since January 1982, implementation of the household contract responsibility system has brought a huge impact on cropland and forestland. Reforestation has been widely implemented to develop forest industry and tourism especially along with implementation of "Grain for Green" and "Beijing-Tianjin sandstorm source control project" since later 1990s (Zheng et al., 2010).

This study shows that the study region has experienced global warming and climate change may increase the uncertainty of the estimated land use impact (Lauri et al., 2012). Climate change should be considered as a critical factor to optimize future water management (Gosling et al., 2011). Furthermore, anthropogenic effects, including water withdrawal and water restriction policy, could have both negative and positive effects on water supply to Miyun reservoir. Monitoring and objectively evaluating spatial and temporal variation of water resources are the prerequisites for water resource planning. Land use could also offset the negative effects of climate variation. For example, Paddy to Dry land conversion in the study basin is considered as an effective mean to increase inflow into Miyun reservoir. Moreover, artificial forest plantations widely implemented during the last 30 years is considered to aggravate water stress in this semi-arid region (Wang *et al.*, 2012). More local vegetation rather than man-made forests with exotic tree species should be established to achieve the desired hydrological functioning of MYRC. In the same time, proper allocation of water resource such as water demand mangement, can play an important role in solving water crisis. In summary, comprehensive measures including vegetation restoration and water allocation are necessary to deal with water shortages facing MYRC.

## 5 Conclusions

The comprehensive modeling approach developed by this study offers insights to the hydrological changes in the Miyun reserior that experienced a significant decreasing trend of streamflow in the past three decades due to a combination of changes in land use and climate. The dramatic change of land use in the 1980s and 1990s due to expansion of forestland and reduction of cropland had exacerbated streamflow decline by boosting catchment evapotransiration. Climate change during the 1990s-2000s has resulted in an increase in air temperature and thus poential evapotransiration, resulting in an increase in total water loss from the study basin. Land use change dominated the streamflow decline in the 1980s-1990s, but climate change contributed most to the water supply decline in the 2000s.

We conclude that future climate change must be considered in designing watershed management strategies including reforesation efforts to protect water quality and to reduce soil erosion in the Miyun reservoir to meet the increasing water supply demand of the megacity of Beijing. Active land use management such as converting marginal croplands to natural grasslands, planting local species rather than exotic species and water resources management such as irrigation or industry water uses should be optimized to adapt to future climate changes to sustain the water supply functions of the Miyun reservior. Future studies should focus on sceanario analysis to examine the tradeoffs of water management options in terms of hydrologic impacts under future climate change conditions.

## Acknowledgements

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Table 1. Estimations on the contribution of land use change and climate variability to streamflow decreasing. The numbers directly following the ± signs are the standard deviation. The numbers in bracket represent the contribution percentage.

(mm yr$^{-1}$)

| Period | $\overline{P}$ | $\overline{E_p}$ | $\overline{Q}$ | $d\overline{Q}_{tot}$ | Annual water balance model | | The climate elasticity model | | Rainfall–runoff model | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | $d\overline{Q}_{land}$ | $d\overline{Q}_{c\mathrm{lim}}$ | $d\overline{Q}_{land}$ | $d\overline{Q}_{c\mathrm{lim}}$ | $d\overline{Q}_{land}$ | $d\overline{Q}_{c\mathrm{lim}}$ |
| Reference (1961-1983) | 446 ±75 | 847± 23 | 59.1 ±30.3 | — | — | — | — | — | — | — |
| Evaluation I (1984-1999) | 455 ±84 | 872± 24 | 41.0 ±21.0 | -18.1 | -11.5 (64%) | -6.6 (36%) | -16.6 (92%) | -1.5 (8%) | -15.4 (85%) | -2.7 (15%) |
| Evaluation II (2000-2008) | 412 ±41 | 890± 17 | 19.4 ±8.8 | -39.7 | -19.6 (49%) | -20.1 (51%) | -23.2 (58%) | -16.5 (42%) | -14.4 (36%) | -25.3 (64%) |

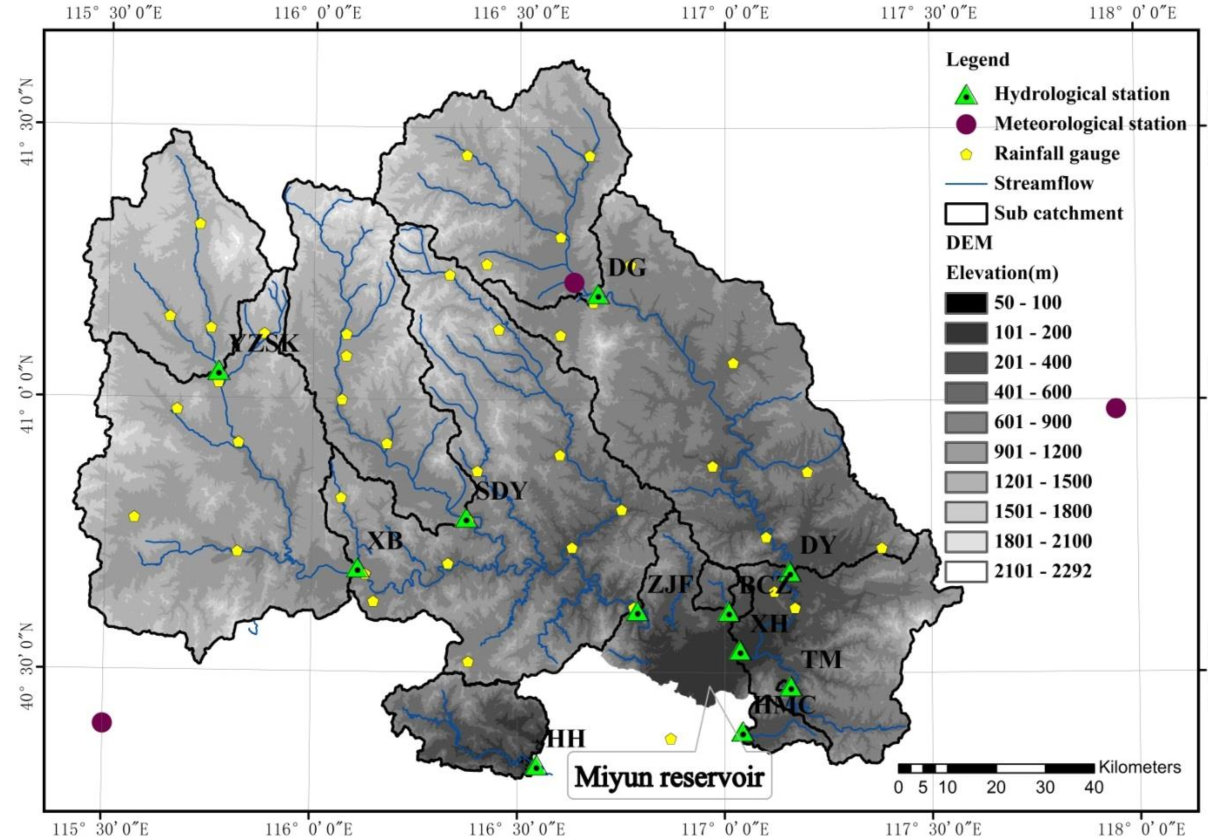

Figure 1. Information of Miyun reservoir catchment and sub catchments including YZSK(Yunzhoushuiku, 1193km$^2$), XB(Xiabao,3960km$^2$), SDY(Sandaoying, 1536 km$^2$), ZJF(Zhangjiafen, 8762 km$^2$), DG(Dage, 1660 km$^2$), DY(Daiying, 4634 km$^2$), XH(Xiahui,5891 km$^2$), HH(Huaihe, 486 km$^2$), HMC(Hongmenchuan, 111 km$^2$), BCZ(Banchengzi, 65 km$^2$), and TM(Tumen, 3 km$^2$).

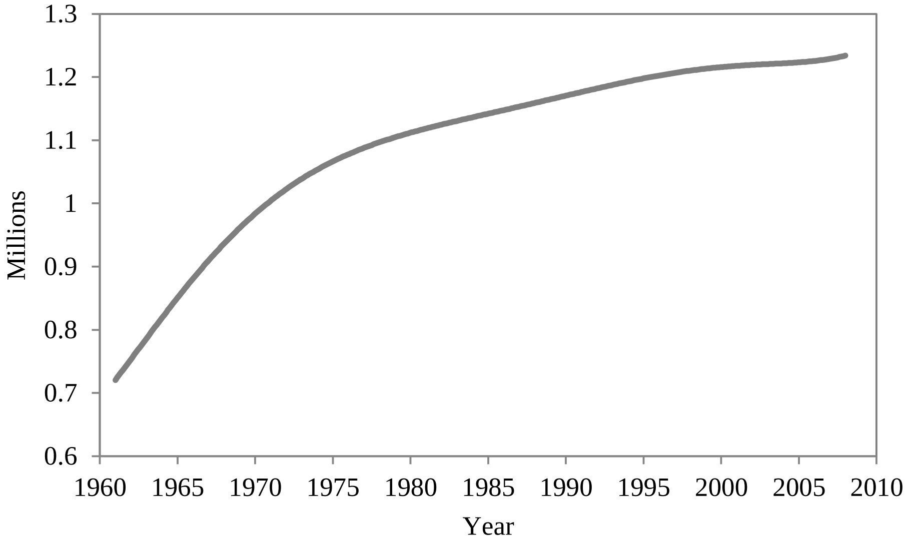

Figure 2. Change in the population of 4 main counties located in Hebei province from 1961 to 2007.

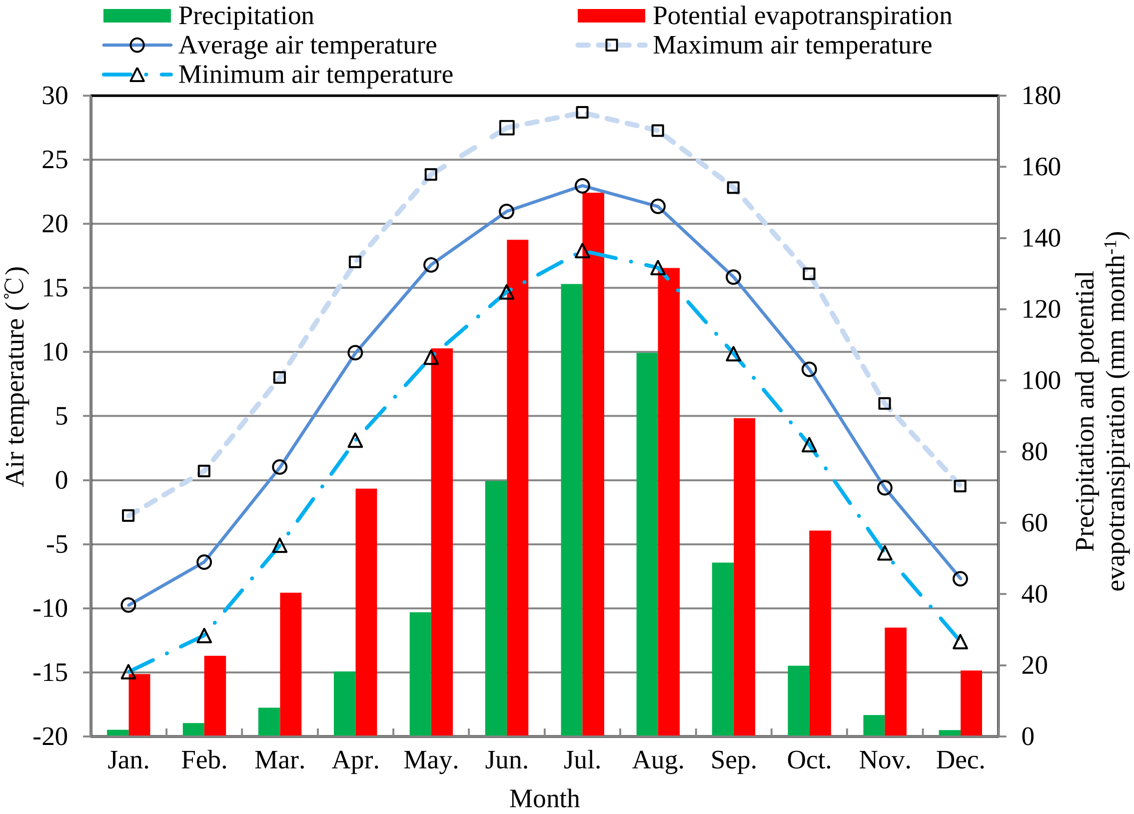

Figure 3. Monthly average precipitation, potential evapotranspiration and air temperature during 1961-2008 in Miyun reservoir catchment.

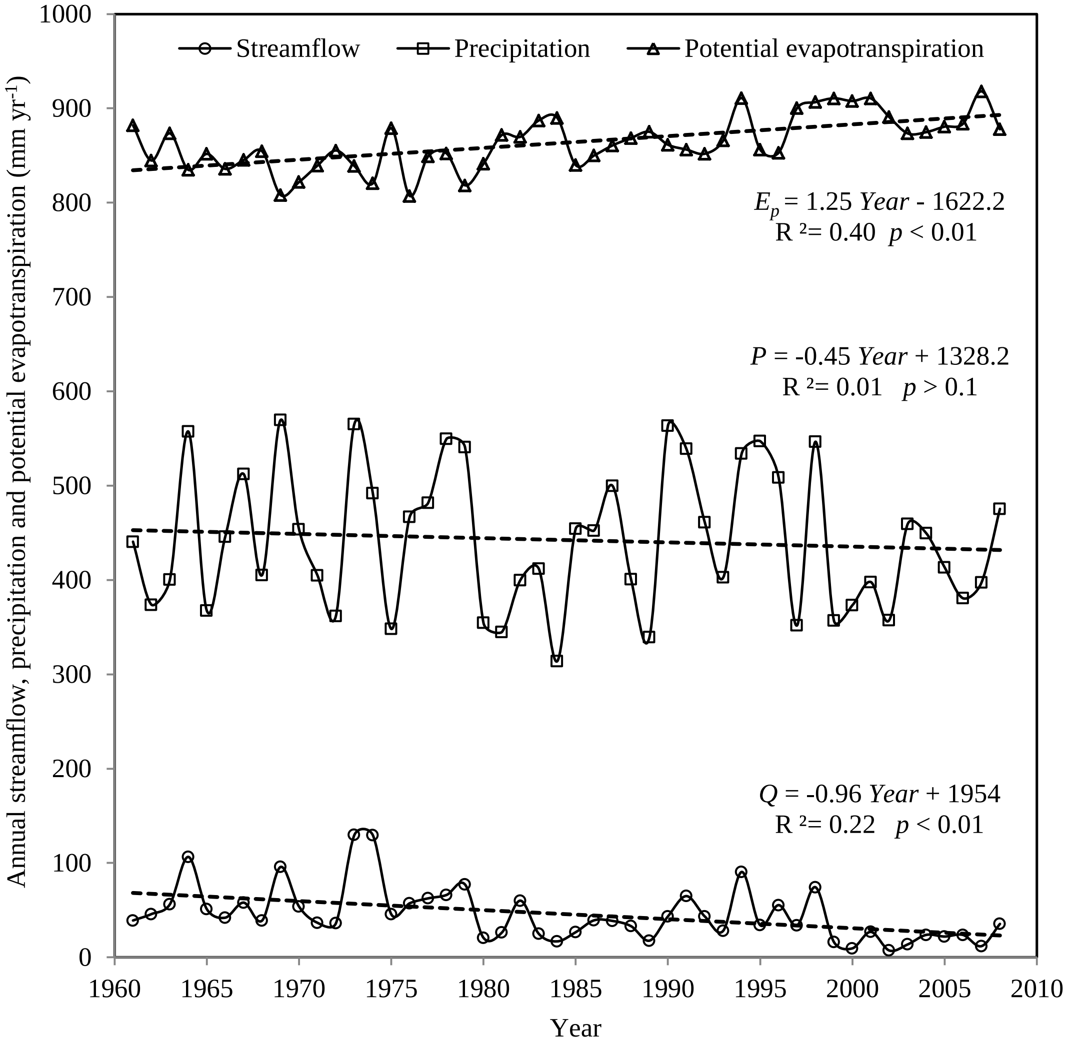

Figure 4. Evolution of streamflow ($Q$), precipitation ($P$), and potential evapotranspiration ($E_p$) of Miyun reservoir catchment over 1961-2008.The dashed lines are the fitted linear trend for variables.

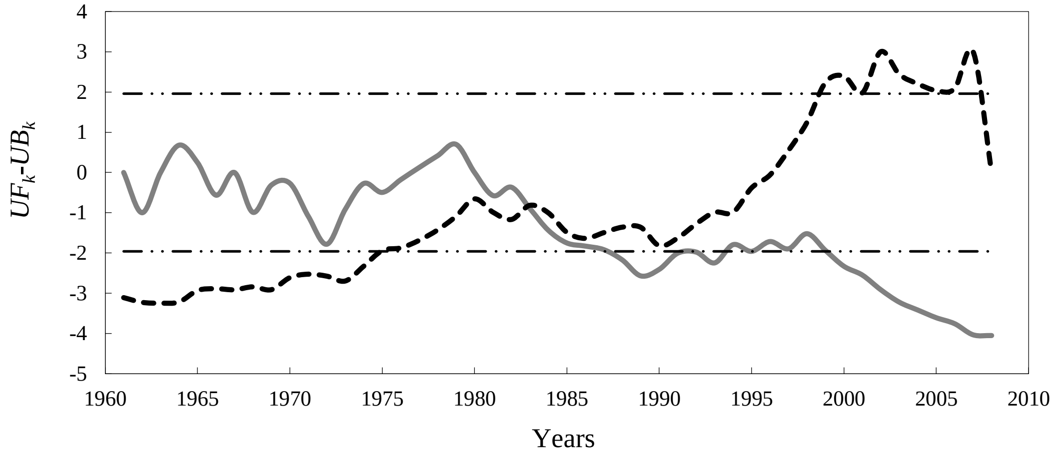

Fig. 5 The Sequential Mann-Kendall test for annual streamflow in Miyun reservoir catchment with forward-trend $UF_k$ (solid line), and backward-trend $UB_k$ (dotted line). Dashed bold horizontal lines represent critical values at the 95% confidence.

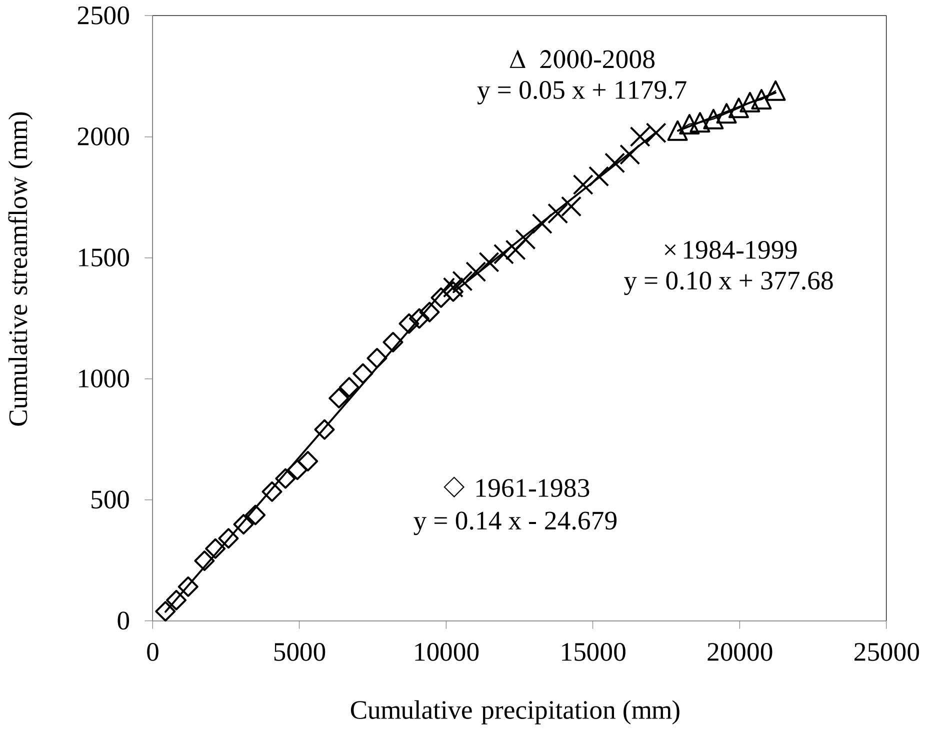

Figure 6. The Double Mass Curve showing the relations between cumulative streamflow and cumulative precipitation for Miyun reservoir catchment (1961-2008).

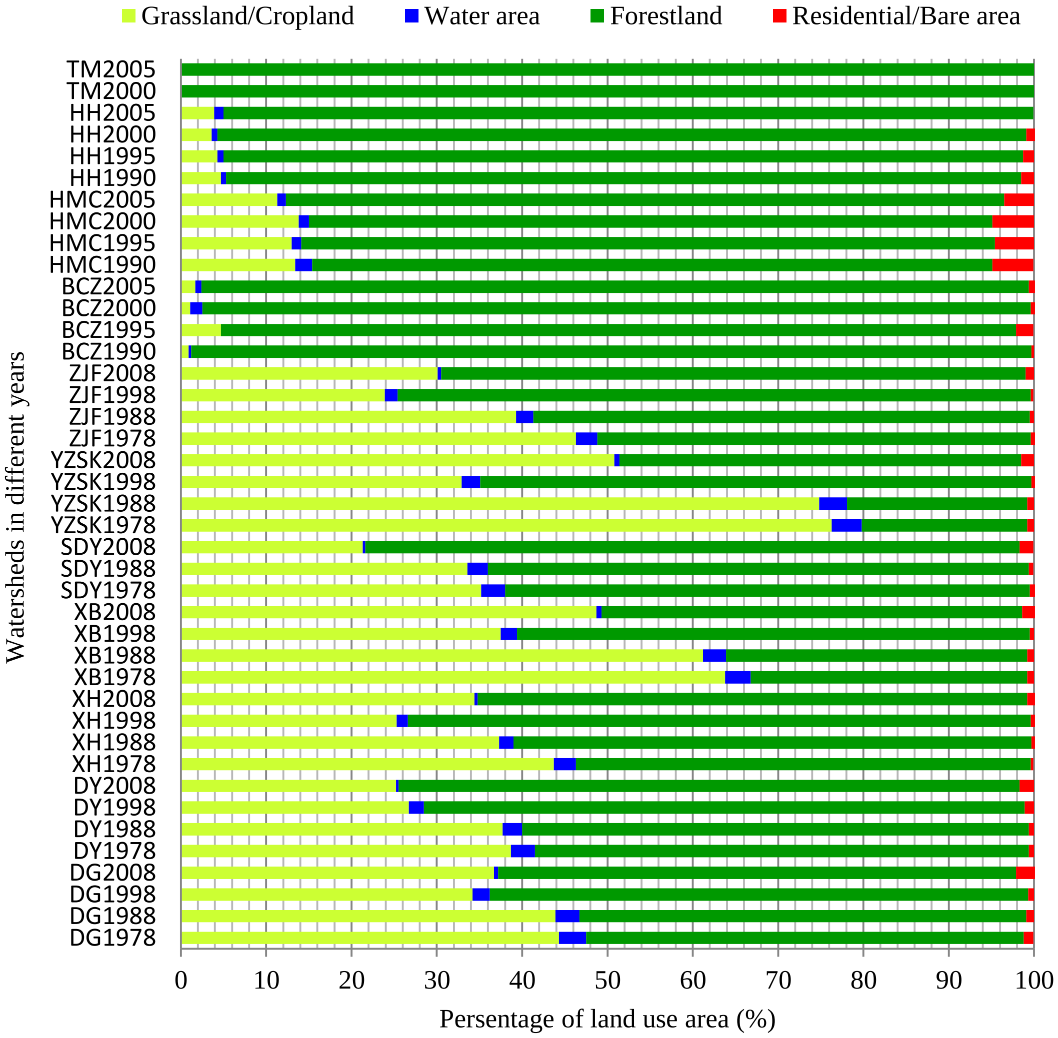

Figure 7. Land use composition of watersheds in different year used for annual water balance model building. For example, DG1978 refer to Dage Watershed in 1978. Data prior to 2001 was used for the model calibration. Data after 2001 was used for the model validation.

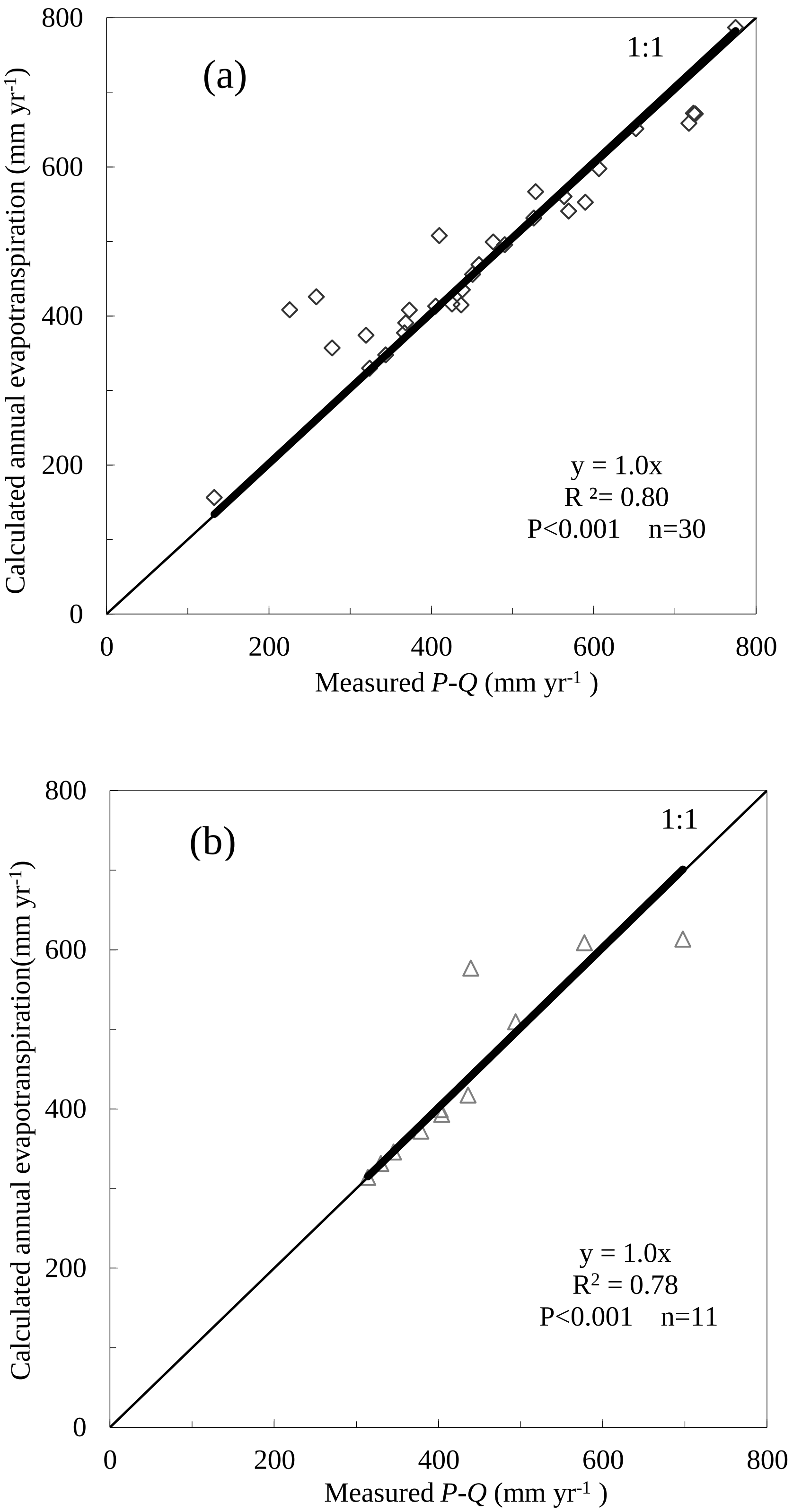

Figure 8. Scatter plots of calculated evapotranspiration using equation (7 & 8) against $E_a = P-Q$ during calibration phase (a) and validation period (b). The thin line is the 1:1 line and the bold line is the line of best-fit provided by the equation.

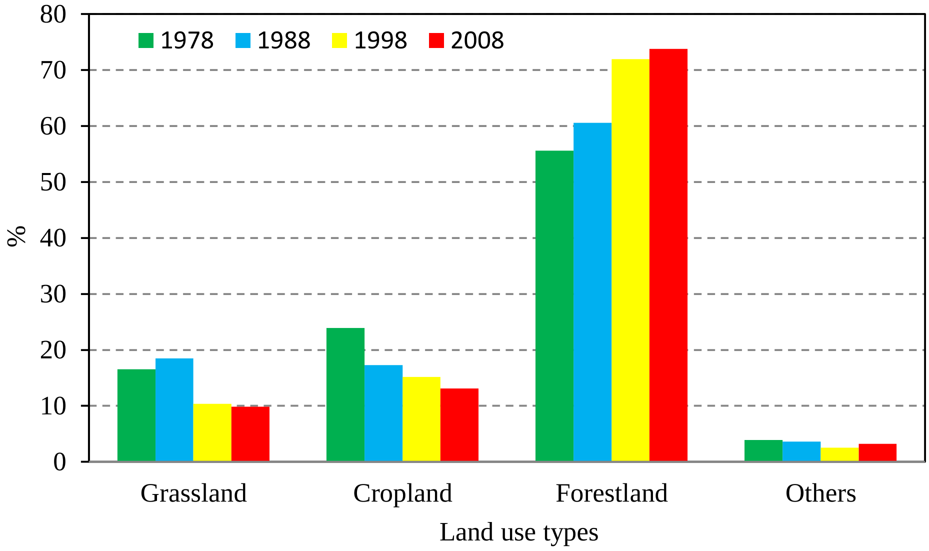

Figure 9. Land use composition of Miyun reservoir catchment (14,653 km$^2$) in 1978, 1988, 1998, and 2008.