Dear Dr. Stefan Uhlenbrook,

Thanks for your comments and suggestions to improve our paper. According to your comments and two reviewers’ comments, we have revised the manuscript substantially.

In this final version, we have highlighted the contributions from this study that offers improved understanding of the study watershed over previous studies.

Enclosed we provide Author’s responses to your minor comments, point by point response to referee #1’s and referee #2’s comments. It was followed by a marked-up manuscript version showing the changes made in our manuscript.

Please let us know if you have further questions.

Kind regards,

Jiangkun Zheng

Minor Comments by Associate Editor

Minor comment:
The unit of delta d of the water balance equation is mm/yr and not just mm.
Response: *"mm" have been replaced by "mm* yr^{-1}*".*

Caption of figure 4 is unclear
Response: *The caption of figure 4 and label in figure 4 are modified.*

Unit of y-axis in fig 5 is not given
Response: UF_k *and* UB_k *are just statistic values. Therefore no unit for y-axis in fig 5.*

POINT by POINT RESPONSE to Reviewer #1

Anonymous Referee #1
General Comments
The authors attempted to quantitatively distinguish the impacts of the changes of land use or climate variables on the water yield as inflow into Miyun reservoir in the past decades. Two statistical approaches for detecting the abrupt change in streamflow data and three types of model were employed for analyzing the contributions to the decline of annual mean discharges. The manuscript is well structured and designed. The purpose of the research is of interest to the hydrologists. However, there are some issues should be clarified before it can be published in HESS.

Specific Comments

The local water consumption in the catchment could be one of the main driving forces for the decline of the streamflow, the authors should present more information about the water abstraction at upstream. At least the construction of the hydraulic works for water abstraction or diversion should be briefly introduced.
Response: *We agree with the reviewer and add a sentence in the revised manuscript. Specifically, we mentioned in the revised manuscript that the local water consumption in the catchment is the main driver, now, 18 reservoirs were built in the catchment , whose total storing capacity is 0.214 billion* m^3 *(Li and Li, 2008). Average annual "direct abstraction" increased from 2.2 mm during 1956-1983 to 13.4 mm during 1984-2005, an increase of 11.2 mm (Ma et al., 2010).*

Did all annual mean flows in the tributaries decreased in the past decades with the same break change at 1984? Did all the precipitation observed at 39 rainfall gauges show no significant trend? I can see the decrease of forestland with the increase of cropland in 2000's at YZSK/DG/XH/XB/ZJF counties while the land uses in DY/SDY counties are opposite in Figure 8. The authors should detect the changes in hydro-meteorological variables in the sub catchments to better address the spatial characteristics and discuss the effects. The total decrease of inflow can be attributed to land use changes in several sub catchment.

Response: *Land use change in several sub-catch ments could also contribute to the total decrease of inflow. However, there are different trends of land use change for different sub-catchments, and it is hard to attribute the streamflow pattern between sub catchments and Miyu reservoir catchment. Our research focuses on the overall Miyun reservoir catchment where land use change and hydrometeorological trend are the main concerns for the purpose.*

All the climate variables used in this research were collected from the measurements at the local hydro/meteorological stations except for potential evapotranspiration, which is crucial for your analysis and simulation. But I only see one meteorological station lies in the catchment in Figure 1, how could you estimate the mean annual Ep for the whole catchment? The Ep in Equation (9) indicates that the zero potential evapotranspiration were input into the model when the temperature below zero in winter. That is inconsistent with the Ep in Figure 3. The average temperatures in Jan/Feb/Nov/Dec are below zero (Figure 3), which implies zero Ep in winter for AWB model. Did you use the same mean annual Ep for the other two models?

Response: *Daily meteorological data were obtained from the China Administration of Meteorology. Just one meteorological station lies in the catchment. Another six stations lie around the catchment in line 10-11, page 7790. The situation of 7 meteorological stations as following.*

Table Meteorological stations in the study

*Station ID**	*Station name*	*Latitude*	*Longitude*	*Altitude(m)*
53399	*Zhangbei*	*41°09'N*	*114°42'E*	*1393.3*
54308	*Fengning*	*41°13'N*	*116°38'E*	*661.2*
54311	*Weichang*	*41°56'N*	*117°45'E*	*842.8*
54401	*Zhangjiakou*	*40°47'N*	*114°53'E*	*724.2*
54405	*Huailai*	*40°24'N*	*115°30'E*	*536.8*
54423	*Chengde*	*40°59'N*	*117°57'E*	*385.9*
54511	*Beijing*	*39°48'N*	*116°28'E*	*31.3*

**Station ID is a unique code assigned to each station by China Meteorological Administration*

The Kriging interpolation was employed to estimate the mean value of Ep and P for whole catchment. Interpolated temperature of 7 Meteorological stations is the mean daily value of winter. In winter, mean daily temperature could be below and above zero, but the climatological mean daily temperature of month is below zero, and we use Hamon method to estimate the accumulated daily value of EP, what we obtained is EP greater than zero in winter.

It is debatable while interpreting the model results in table 1. The AWB model can detect the influence of land use on the streamflow through quantitative analysis, while the CEM focus on the effect of climate change in this study. I would use the term dQland and dQother(include climate) for results from AWB, dQother(include land use)

and dQ-climate for the results from CEM. The results of AWB imply that the land use change accounts for 49% of decline of the water yield, while less than 51% can be attributed to climate in 2000’s. It is clear that water consumption has been increased in the past decades; hence the climate variables may have less effect on the streamflow compared with that of land use. The coefficients used in the rainfall-runoff model were estimated with the rainfall and discharge data in reference period. The P and standard deviation in the rainfall-runoff model (Equation 16) represent the climate variation, while the coefficients in the model describe catchment properties including the land use status in the reference period. Since the coefficients remains the same during the simulation, the term in table1 for results from rainfall runoff model should be dQother(no land use) and dQclimate. But the dQclimate could be overestimated with the variation of monthly rainfall in different periods. The contrary conclusion may be draw that the land use contributes more than that of climate on the decline of the streamflow according to the results of AWB and CEM model.
***Response:** As line 2-5,page 7792, land use was considered as the residuals affecting streamflow in addition to climate variations. In AWB model, Equation 6 was employed to build the model. So, land use was acted as dQ (all except climate). Land use change, Water consumption, water abstraction and other activities make anthropogenic effects complicated. In order to simple the issue, land use change was assumed as DQother.*

Technical Corrections:
Page 7786, line 19-23, the forestlands in some sub catchments decreased in 2000’s from Figure 8.
***Response:** Page 7786, line 19-23, it is for the whole catchment of Miyun reservoir, not for some sub catchments. We rewrote the sentence to make it clear.*

Page 7787, line 12-13, there are more natural resources in such developing arid region that should be concerned. I suggest the authors focus on the scientific purpose, delete the "allocate limited resources".
***Response:** we have deleted the “allocate limited resources” according to the comment.*

Page 7788, line 2-4, should be passive tense.
Page 7788, line 8, should be "mean annual inflow".
Page 7788, line 10, better use "in 2000’s" instead of "today".
***Response:** Page 7788, line 2-4, 8,10, these have been changed according to the comment.*

Page 7789, line 2-4, such exclusive sentence is not encouraged, the "vegetation change" should be "land use change".
***Response:** Page 7789, line2-4, the “vegetation change” have been replaced by “land use change”. We also delete “the first study”.*

Page 7790, section 2.2, as the one of the three main variables used in the research, the estimation of Ep should be introduced, perhaps some of the contents in section 2.4.1 and 4.2 can be moved to here. The spatial interpolation for the areal P and Ep from the 37 rainfall gauges and the 7 meteorological stations should be detailed. How many meteorological stations were selected for data analysis? I can only see one within the catchment in Figure 1.

Response: *According to the comments,* E_p *and spatial interpolation have been detailed. 7 meteorological stations were selected for data analysis (table above). We included the table into the revised manuscript.*

Page 7792, section 2.4, the flow regime could be altered by construction of hydraulic engineering for water supply and water diversion, at least the change of water supply or the water abstraction to the local society should be introduced.

Response: *The sentence have been modified according to the comment.*

Page 7794, line 18, "simulate" should be "simulated" .

Page 7795, line 17, the abbreviation of PET should be explained when first appears in the manuscript.

Response: *Page 7794, line 18, "simulate" have been replaced by "simulated".*

Page 7795, PET have been replaced by Ep.

Page 7795, line 20, needs citation.

Response: *Reference has been added (xie et al.,2005)*

Xie, P., G. C. Chen, D. Li, and Y. Zhu. 2005. Comprehensive diagnosis method of hydrologic time series change-point analysis (in Chinese), Water Resour. Pow., 23(2), 11–14.

Page 7795, line 24, where are the two water abstractions? Are they all at the main river?

Response: *We added a sentence to specifically mention the two water abstraction in the introduction section, i.e.,Water abstractions increased from 2.2 mm during 1956-1983 to 13.4 mm during 1984-2005.*

Page 7797, line 19, should be Eq. (16)?

Page 7797, line 21, should be Eq. (17)?

Response: *Eq. (14) and (15) have changed to Eq. (16) and (17).*

Page 7798, line 14, the interpolation method should be clarified.

Response: *The interpolation method have been clarified in section 2.2.*

Page 7799, line 13, "estimated" should be "improved"

Response: *Page 7799 line 13, "estimated" have replaced by "improved".*

Page 7799, line 19-24, weird sentence.

Response: *Page 7799, line 19-24, the sentence have been modified.*

Page 7800, line 13-16, weird sentence.
Response: *Page 7800, line 13-16, the sentence have been modified.*

Page 7800, line 28, where is table 2?
Response: *Page 7800, line 28, table 2 have been replaced by table 1.*

Page 7801, line 2-6, weird sentence.
Response: *Page 7801, line 2-6, the sentence have been modified.*

Page 7801, line 9-10, based on the analysis results, the impact of increasing forestlands from 71.9% in 1998 to 73.8% in 2008 accounts for 36% to 58% of decline in water yield in table 1. Thus, the positive effects of land use were neglected in discussion section, which should be proper addressed.
Response: *According to the comment, we added a sentence on Page 7801 to discuss the positive effects of land use on water yield over Miyun reservoir. Considering forestland is only one type of land use, and is not account for behalf of the land use change, we also added a sentence to remind readers about the conclusion.*

Page 7802, line 6, the temperature data were not discussed in this paper. The "global warming" should be replaced by "climate change".
Page 7802, line 7, delete "resulting in"
Page 7802, line 9, the "global warming" should be replaced by "climate change".
Response: *all these have been changed/deleted.*

Page 7802, line 11-15, how to consider the climate change in designing management strategies? The groundwater withdrawal had not been mentioned in manuscript, did you mean increase the groundwater abstraction instead of direct diverting the water from surface water for irrigation?
Response: *Future climate change should be considered in designing watershed management strategies. For example, according to IPCC, trends of precipitation and air temperature are needed to consider in designing watershed management strategies. "ground water withdrawal" was replaced by "drinking water management". We rewrote the sentence to make it clearer.*

Figure 1, I can only see 3 meteorological stations in the map, can you add one map to indicate the location of 7 meteorological stations at the regional scale?
Response: *Figure 1, as the table above, latitude and longitude of 7 meteorological stations were described.*

Figure 2, the Ep in Jan/Feb/Nov/Dec are larger than zero in the figure when the temperature in the below table are negative. If you insist on these values in winter, please address them as "estimated potential evapotranspiration" in caption.

Response: *Figure 2 (should be Figure 3), the response lie in the paragraph below the table of this document.*

Figure 3, the six categories were used in the text, why you only use four?
Response: *Figure 3 (should be Figure 4), four categories were used in the Figure due to the flowing reasons. First, land use(others) including water area, residential area, and bare area, account for very small proportion of total area. Second, the manuscript focused on* E_p*. Land use(others) including water area, residential area, and bare area account for very small proportion of total* E_p*.*

Figure 9, the dashed line can’t be seen, the "measured evapotranspiration" in caption should be deleted.
Response: *Figure 9, “the dashed line” have been replaced by “the thin line”. “the solid line” have been replaced by “the bold line”. “measured evapotranspiration” have been deleted.*

POINT by POINT RESPONSE to Reviewer #2

Anonymous Referee #2

General comment:

The work presented here certainly lies within the scope of HESS and contributes to the body of hydrological literature. However, I still would like to present my critics on the paper, serving as further improvement to bring the paper into publishing level or lastly helps to appear in HESS. The paper presents the impacts of land use change and climate variation on annual inflow into Miyun reservoir, China. The paper tried to disentangle the contribution of the changes on streamflow due to land use and climate variation. Three models, the annual water balance model, the Climate Elasticity Model, and simple empirical rainfall runoff model were used. Furthermore, break points in time series were detected using sequential Mann-Kendall and double mass analysis. The main concern in this research is that the methodology employed is not add new ideas or techniques to investigate the impacts of land use/ land cover and climate variation on streamflow. Past researches also used the same methodology in different part of the world (e.g. Yang and Yang, 2011; Zhang et al., 2008; Li et al., 2009). Though the CEM and empirical rainfall-runoff models gave comparable results, both methods lacks physical basis. The coefficients in both models are not explicitly accounted the vegetation or other physiographic characteristics of the catchment. Besides, the results need further interpretations or discussions with respect to past work on the same catchment or in different parts of the Globe. The discussion part is only emphasis on the qualitative aspects of uncertainty analysis. The quantitative values of the uncertainty analysis would support your results or increases the degree of belief of the model results. In general, most of the statistical test like the Mann-Kendall test is prone to give biased results unless the data set is of good quality. Consequently, revising the data analysis part is vital to see the quality of the hydro-meteorological data, which was not presented clearly in the manuscript.

Response: *Indeed, CEM and empirical Rainfall-runoff models are statistical models. Both models lacks physical basis. However, statistical model is often applied to evaluate the impact of climate change on annual streamflow in a long period of time. In the section of introduction, some past works in different parts of the globe were cited and discussed. Certainly, it is important to quantitatively evaluate the uncertainty analysis. But it is hard to carry out the uncertainty analysis in a few days. Furthermore, 3 models were employed in the form of effect range to increase the degree of belief. The quality of data set is vital for statistical test. Therefore, the quality of the hydro-meteorological data has been presented clearly in section 2.2.*

Specific comment:

Abstract:

The abstract is well written except that on Line 20 onwards, i.e. the last paragraph should be modified as uncertainty analysis has not done.

Response: *On line 20, "forestlands" has been replaced by "forestland". "rates" has been deleted. Although uncertainty analysis has not been evaluated quantitatively, qualitative aspect also supported the result to some extent.*

Introduction

Overall, the introduction provide information about different past researches on the area but lacks to provide the current state of arts how different researches in different parts of the world are conducted with regard to impacts of land use and climate variation on streamflow. Please enrich the literature review in the introduction part a bit. On page 7788, Line 15 mentioned literature is worked out in MYRC. Please discuss at least the unique part of your study next to this paragraph. On page 7789, the results provided to meet the third objective is speculative.

Response: *In page 7787, 3 literatures have been added to state hydrological impact of land use and climate change in different parts of the world. In the end of the paragraph on page 7788, line 15, the unique part of our study has been inserted. On page 7789, line 5, "Our objectives are to" was replaced by "This study attempts to".*

Material and Methods

On page 7790 under 2.2 the hydro-meteorological data, nothing is mentioned about the data quality. Assessing the quality of hydro-meteorological data is a key task before making any analysis about hydrological variability/changes. Please re-do the data quality under this section. Page 7791, before applying directly the Mann-Kendall test, the assumption inherent for the null hypothesis is that a data series is serially independent and identically distributed with no trend. Hence, The MK test should be applied to serially independent or uncorrelated data (Helsel and Hirsch, 1992). To correct the data for serial correlation, the procedure of trend free pre-whitening (TFPW), should be applied (e.g. Yue et al., 2002 and 2003; Tekleab et al., 2013). Re-evaluating the data for serial correlation could potentially change your trend results OR YOUR REFERENCE AND EVALUATION PERIODS.

Response: *On page 7790 under 2.2, about the hydro-meteorological data, some statements have been added to clarify the data quality in the end of line 13. For page 7791, in this study, the sequential version of Mann-Kendall test (Sneyers, 1975), not Mann-Kendall trend test (Mann, 1945), was applied to detect the break points. The sequential version of Mann-Kendall test is used to test assumptions about the start of a trend within the sample $X_1, \ldots, X_n$ from set of random variable X based on rank series of progressive and retrograde rows of the sample (Yang and Tian, 2009). It is also a non-parametric assessment which is not disturbed by few outliers and not complied with distribution test (Zhang and Wang, 2007). Moreover, the Double Mass Curve, combined with the historical record of water abstraction (Ma et al., 2010), were also employed to detect the break points of streamflow.*

Results

Page 7795, the descriptions given under sub-title "Land use change and its major driving factors" are not results rather you provided information about the land use changes over time. In order to accept this section as a result, clear methodology about land use change classification should be provided under methodology section. I think this section has to be removed and the information can be described in the discussion section. Page 7796, Line 1-10, the description is about the method. I see structural problem (mixing results with methodology). Page 7797 what does it tells the elasticity coefficients ε_1 and ε_2 provided 2.12 and -2.25? The error of data, combined with uncertainty of model structure, increased uncertain to attribution of land use change. This statement is not clear and needs paraphrasing.

Response: *According to the comment, section 3.1 have been removed and the information have been described in the discussion section. Consequently, Figure numbers from Figure 4 to Figure 9 have been modified. Page 7796, line 1-10, the sentence have been simplified and modified. Page 7797, line 8-9, the sentence have been paraphrased.*

Technical correction:

Page 7793, Line 7, what is this correction factor K how the value is set? Line 8, the average daily temperature expressed (◦)? ◦C, or ◦F ??

Page 7793 correct equation 13.

Response: *Page 7793, line 7, " , K is the correction factor. " has been replaced by ". K is the calibration coefficient, which is set as 1.2 (Lu et al., 2005). " Line 8, " ° " has been replaced by " ℃". Equation 13 is correct.*

Page 7794, Line 17 the word ”hydrometeological” should be corrected as hydrometeorological.

Response: *Page 7794, "hydrometeological" has been replaced by "hydrometeorological".*

Page 7796, Line 15, 17 and 18, and throughout the manuscript, watershed and catchment are interchangeably used. Choose either catchment or watershed consistently throughout the manuscript.

Response: *Page 7796, line 15, 17, 18, "watersheds" changed to "catchments", and "watershed" changed to "catchment".*

Page 7797, Line19, the coefficients should be computed from Eqn. 16 NOT Eqn. 14??

Response: *Page 7797, line 19 and line 21, Eq. (14) and Eq. (15) were replaced by Eq. (16) and Eq. (17), respectively.*

Page 7799, line 27, calibration and validation phases.... Phases shall be replaced by periods.

Response: *Page 7799, line 27, “phases” has been replaced by “periods”.*

Page 7811, the catchment areas provided under in figure 1 caption is inconsistent with the area mentioned on page 7789 Line 15.

Response: *Page 7811, On page 7789 Line 15, drainage area is about 15380km^2, including Zhangjiafen catchment (8762 km^2) , Xiahui catchment (5891 km^2) and surrounding area of Miyun reservoir.*

Pages 7816, the dashed lines described in figure 6 are confusing. Replaced the dotted horizontal lines with dashed bold horizontal lines represent critical values at the 95% confidence.

Response: *Page 7816, According to the comments, dashed lines have been replaced as followed.*

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Marked-up manuscript version showing the changes made in our manuscript

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 associate environmental variables using the long-term historical hydrometeorology and remote sensing based land cover records. To effectively quantify the different impacts of the climate variation and land cover 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

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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 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 cause of hydrologic change at the same time.
Miyun reservoir provides 70% of 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 and climate was also a influential factor (Ma et al., 2010). Now, 18 reservoirs were built in the catchment , whose total storing capacity is 0.214

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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 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) considered 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 separate 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. 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 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.

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 Miyun reservoir, and 3) provide suggestion to watershed management for the studied watershed.

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.

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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 received 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 Heibei 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). Land use was regrouped into six categories, i.e., water area, bare area, 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_p was calculated using Hamon method (Hamon, 1963; Lu et al., 2005) as described in section 2.4.1. All the hydrometeorological data are collected in accordance with international standards. For Abnormal data were replaced by the values obtained from Kriging interpolation using nearby weather stations. Mean hydrometeorological values for the entire catchment are 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, potential evapotranspiration (E_p) in summer, 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 is the curve through the points given two cumulative records. A break in this 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:

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

（1）

Where r_i is as following:

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

（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:

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

（3）

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

（4）

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

（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

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($u_{0.05}$) lies within ±1.96 at a significance level (α = 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.

$$Q = P - E_a \pm \Delta\delta$$

（6）

$$E_a = \frac{1+\omega\frac{E_p}{P}}{1+\omega\frac{E_p}{P}+\frac{P}{E_p}} \times P$$

（7）

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

（8）

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

（9）

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

（10）

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

（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). ω is the plant-available water coefficient that varies in soil water use for transpiration. For MYRC, ω 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

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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).

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

(12)

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

(13)

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

(14)

$$d\overline{Q}_{tot} = d\overline{Q}_{c\lim} + d\overline{Q}_{lan}$$

(15)

Where ε_1 and ε_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. ΔP_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 ($\overline{Q_e}$). $d\overline{Q}_{clim}$ 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.

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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).

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

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

Here, Q_i (mm yr^{-1}) and P_i (mm yr^{-1}) are the annual observed streamflow and precipitation, respectively. σ_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 average simulated 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_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.

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In the Miyun Reservoir catchment, forestlands accounted for above 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, grass

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3.2 AWB model results

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 $E_a = P-Q$ 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 results

Based on Eq. (12) and data in the period of 1961-1983, ε_1 and ε_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 results

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, and 22% lower during the period of 2000-2008.

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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, artificial 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 dranage area of 15,380 km^2 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 the one hand, due to the growth of population (Figure 2) and development of industry and agriculture, the annual direct abstraction of water from 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 closedown of water-based industries were carried out to reduce water consumption that might compensate the streamflow decline trend and improve 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 cover, 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

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Hamon method recommended by the Food and Agriculture Organization of United Nations (FAO) was used to calculate E_p (Hamon, 1963). model parameter (ω) 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, whose correlation coefficients are 0.78 and 0.80 during calibration and validation phases, respectively. The error of data, 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 BCZ catchment (65.2 km^2) and 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 $d\bar{Q}_{clim}$ 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) only accounts rainfall as the only climate 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 $d\bar{Q}_{clim}$ 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 reservoir was characterized with thin soils on a rocky mountain environment(< 30 cm) (He *et al.*, 2010). Therefore, instead of storing large amounts of rainfall in the soil, more rainfall transformed into streamflow, which was another reason differentially estimating the impact of climate change on inflow into MYRC.

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

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streamflow decline for 1984-1999 and the 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 seen global warning and climate change will 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, would make 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 native 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 are necessary to deal with water shortages including vegetation restoration and water allocation.

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 landcover 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 student 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 management such as converting marginal croplands to natural grasslands 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 sceanario analysis to examine the tradeoffs of water management options in terms of impacts of hydrologic impacts under future climate change condistions.

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	
					$d\overline{Q}_{land}$	$d\overline{Q}_{clim}$	$d\overline{Q}_{land}$	$d\overline{Q}_{clim}$	$d\overline{Q}_{land}$	$d\overline{Q}_{clim}$
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%)

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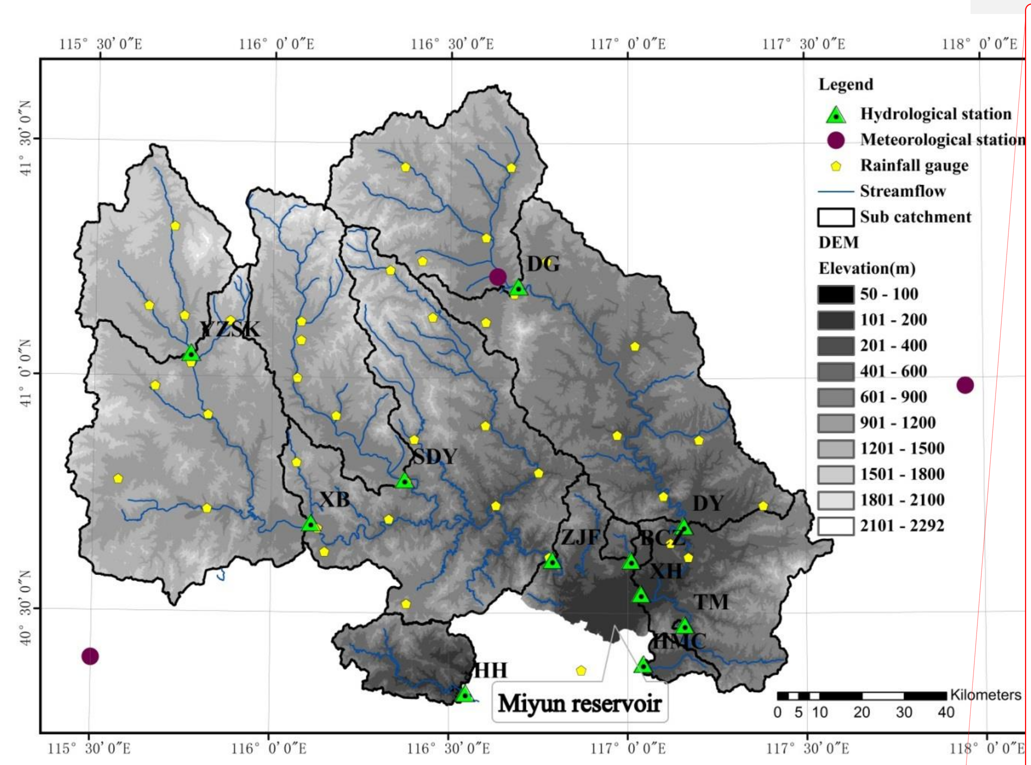
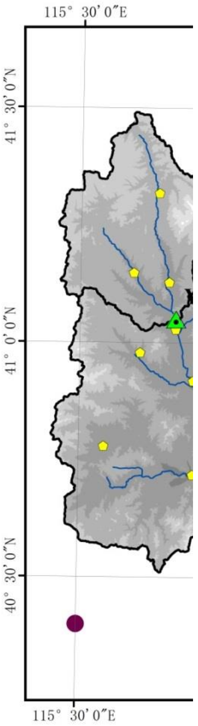


Figure 1. Information of Miyun reservoir catchment and sub catchments including YZSK(Yunzhoushuiku, 1193km^2), XB(Xiabao,3960km^2), SDY(Sandaoying, 1536 km^2), ZJF(Zhangjiafen, 8762 km^2), DG(Dage, 1660 km^2), DY(Daiying, 4634 km^2), XH(Xiahui,5891 km^2), HH(Huaihe, 486 km^2), HMC(Hongmenchuan, 111 km^2),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



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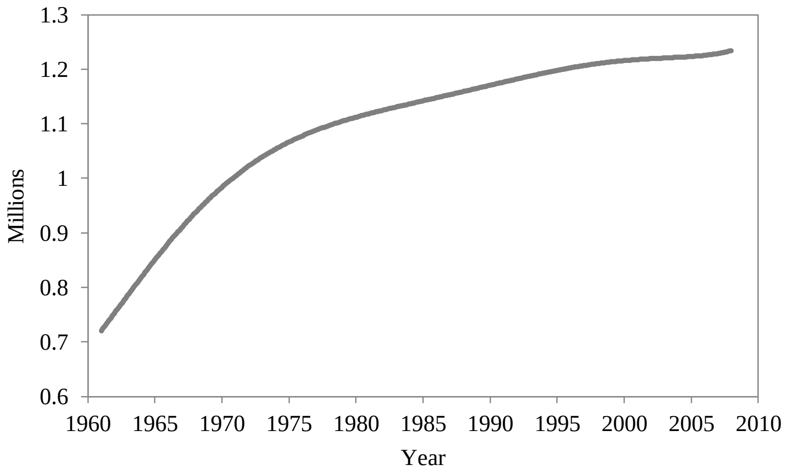
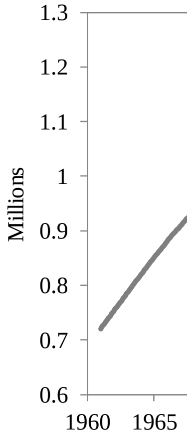


Figure 2. Change in the population of 4 main counties located in Hebei province from 1961 to 2007.



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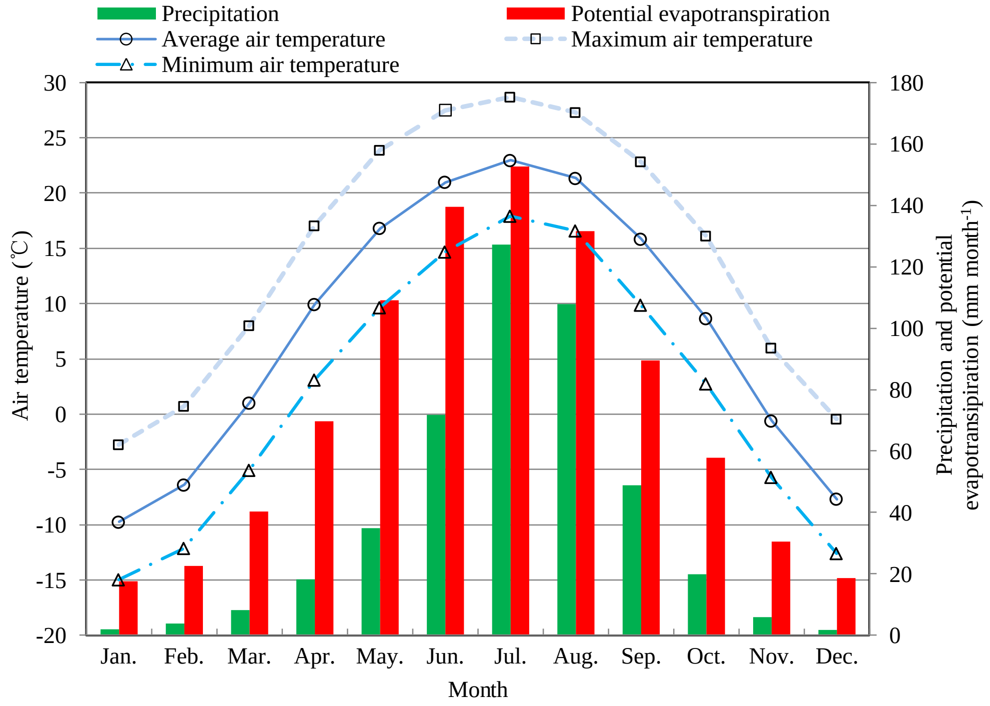
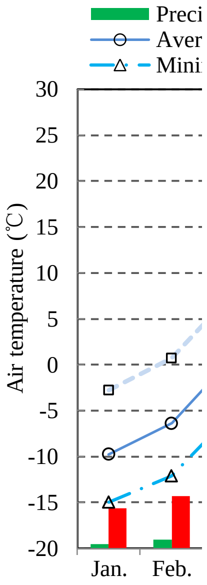


month	Average air temperature	Maximum air temperature	Minimum air temperature	Precipitation	Potential evapotranspiration
Jan.	-9.7	-2.8	-14.9	1.9	17.5
Feb.	-6.4	0.7	-12.1	3.8	22.6
Mar.	1.0	8.0	-5.1	8.1	40.4
Apr.	9.9	17.0	3.1	18.3	69.6
May.	16.8	23.9	9.6	34.9	109.0
Jun.	21.0	27.5	14.7	71.8	139.5
Jul.	23.0	28.7	17.9	127.1	152.7
Aug.	21.4	27.3	16.6	107.7	131.6



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Sep.	15.8	22.8	9.9	48.8	89.4
Oct.	8.7	16.1	2.8	19.9	57.8
Nov.	-0.6	6.0	-5.7	6.0	30.6
Dec.	-7.7	-0.5	-12.6	1.8	18.6

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

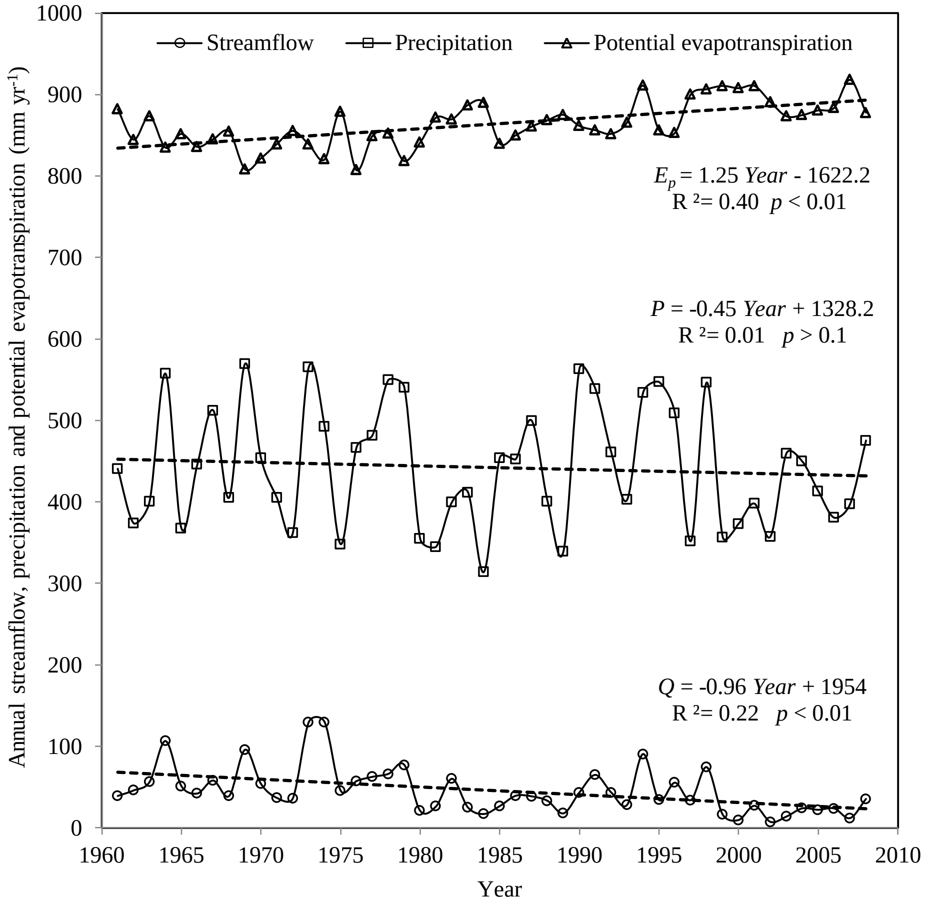

Figure 4. Evolution of streamflow (Q), precipitation (P), and potential evapotranspiration (E_p) of Miyun reservoir catchment over 1961-2008.The dashed lines are the fitted linear trend for variables.

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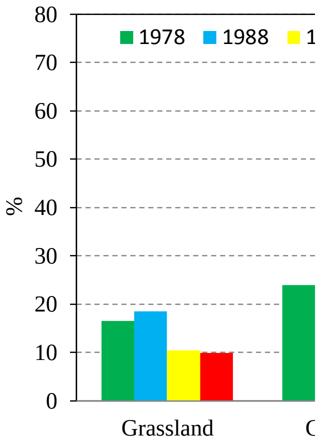

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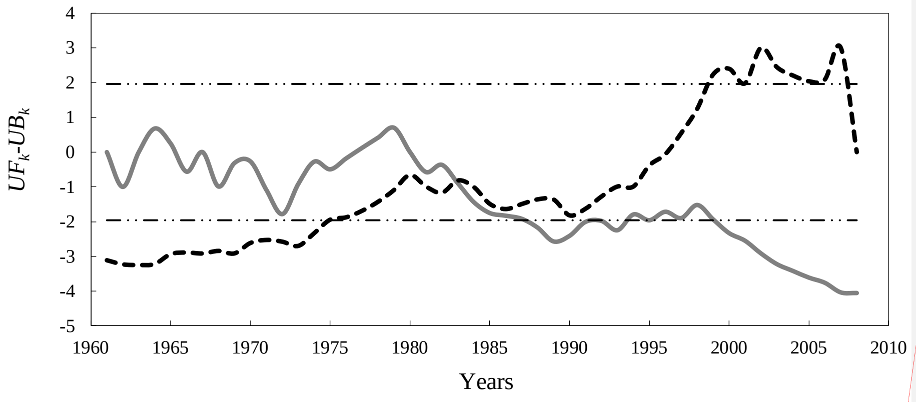

Fig. 5 The Sequential Mann-Kendall test for annual streamflow in Miyun reservoir catchment with forward-trend UF_k (solid line), and backward-trend UB_k (dotted line). Dashed bold horizontal lines represent critical values at the 95% confidence.

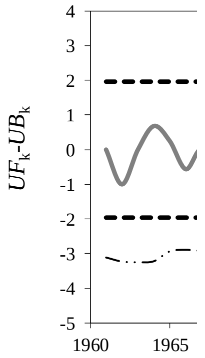

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Figure 6.

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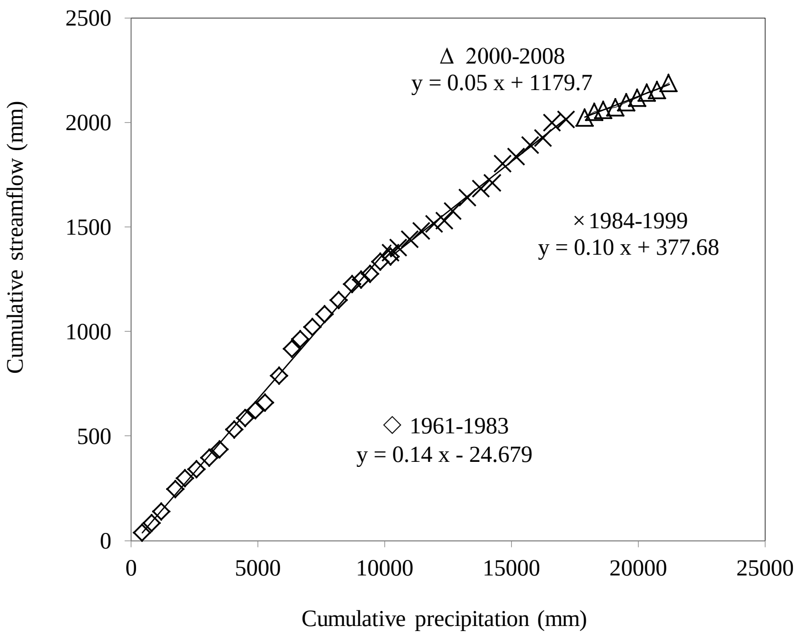
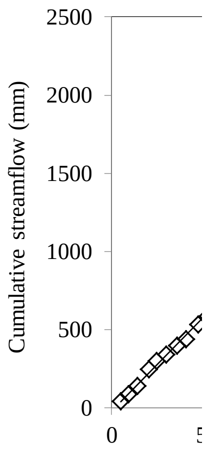


Figure 6. The Double Mass Curve showing the relations between cumulative streamflow and cumulative precipitation for Miyun reservoir catchment (1961-2008).



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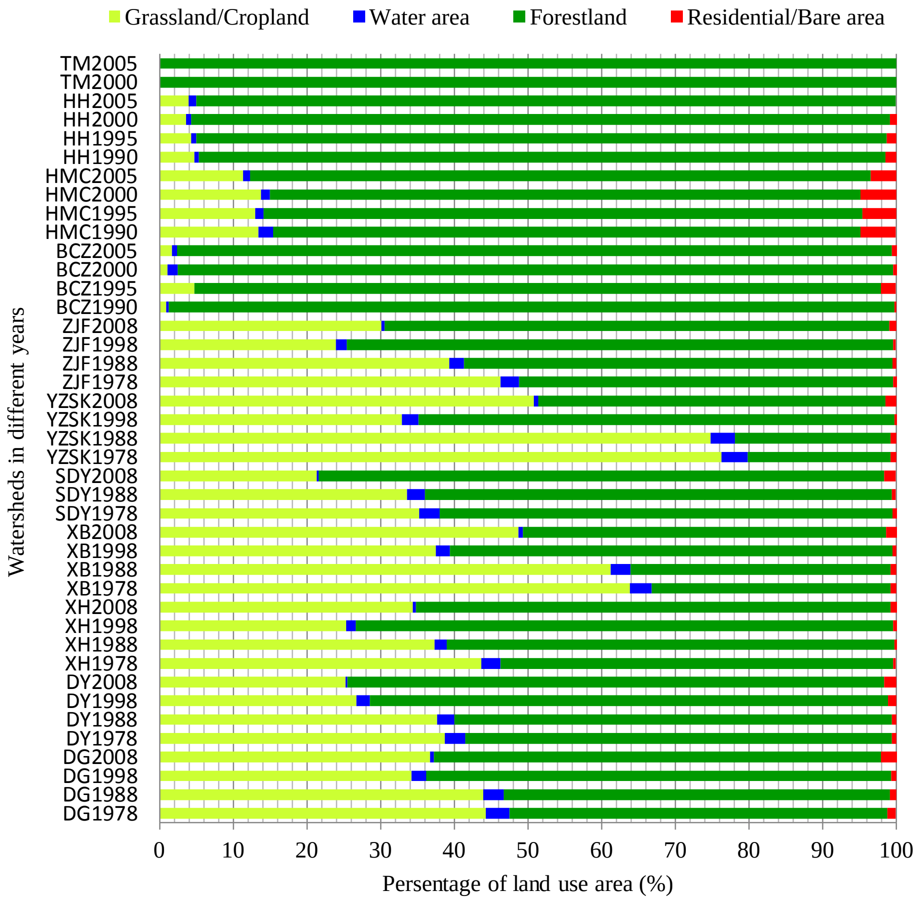

Figure 7. Land use composition of watersheds in different year used for annual water balance model building. For example, DG1978 refer to Dage Watershed in 1978. Data prior to 2001 was used for the model calibration. Data after 2001 was used for the model validation.

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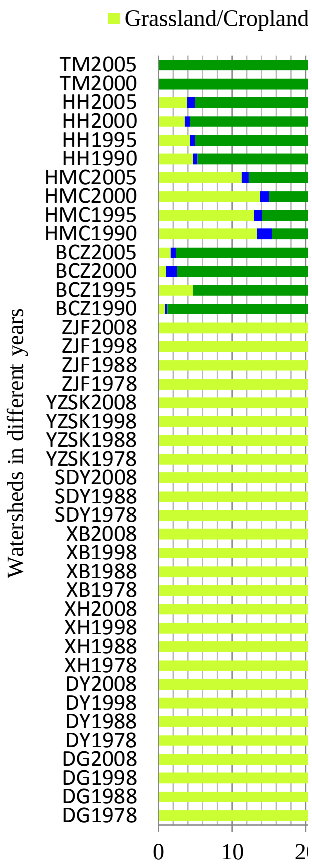

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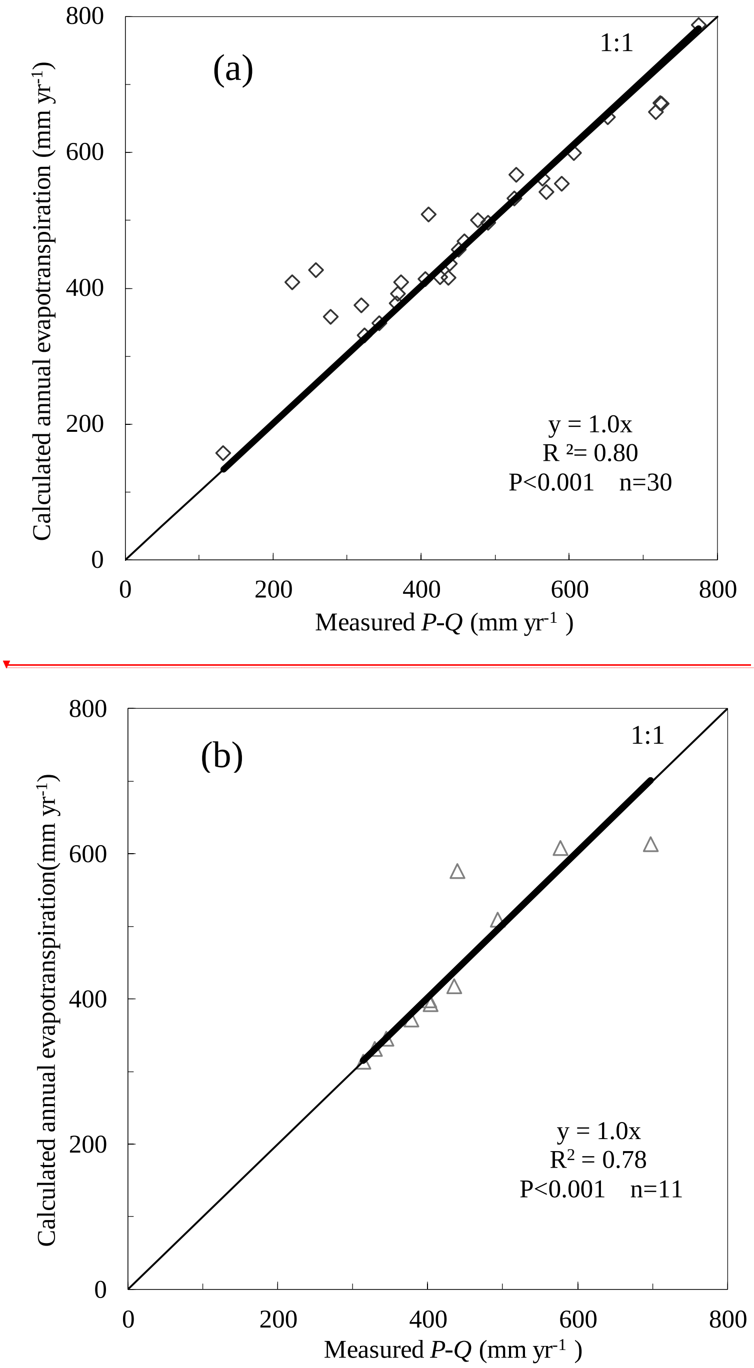
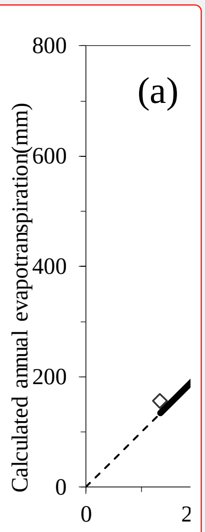


Figure 8. Scatter plots of calculated evapotranspiration using equation (7 & 8) against E_a = P-Q during calibration phase (a) and validation period (b). The thin line is the 1:1 line and the bold line is the line of best-fit provided by the equation.



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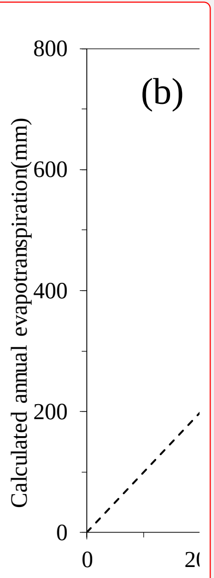

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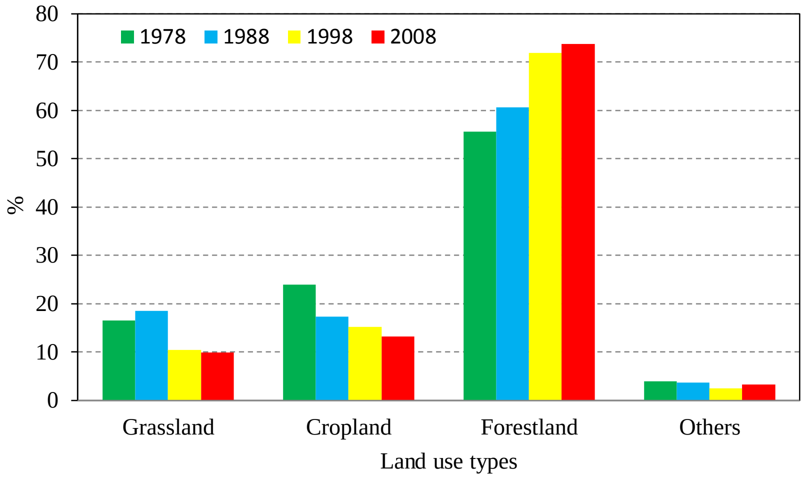

Land use types	1978	1988	1998	2008
Grassland	16.5	18.5	10.4	9.8
Cropland	23.9	17.3	15.2	13.1
Forestland	55.6	60.6	71.9	73.8
Others	3.9	3.6	2.5	3.2

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