Posted on Authorea 3 Dec 2019 — CC BY 4.0 — https://doi.org/10.22541/au.157541728.89075035 — This a preprint and has not been peer reviewed. Data may be preliminary.

# QUANTIFYING THE IMPACTS OF CLIMATE CHANGE AND LAND USE ON HYDROLOGICAL PROCESSES: A COMPARISON BETWEEN MOUNTAIN AND LOWLAND ARTIFICIAL WATERSHEDS

Zhen Cui[1], Jiacong Huang[1], Feng Tian[1], Junfeng Gao[2], Xuesong Wang[3], and Jun Li[3]

[1]Nanjing Institute of Geography and Limnology Chinese Academy of Sciences
[2]CAS
[3]Changzhou Hydrology and Water Resources Investigation Bureau

May 5, 2020

### Abstract

Mountain and lowland watersheds are two distinct geographical units. Understanding their hydrological processes in the context of future climate change and land use scenarios is important for watershed management. This study attempted to investigate hydrological processes and their driving factors for these two geographical units in Xitiaoxi watershed, east China, and quantify their differences through hydrological modelling. Hydrological processes in 24 mountain watersheds and 143 lowland watersheds were simulated based on a raster-based Xin'anjiang model and a Nitrogen Dynamic Polder (NDP) model, respectively. These two models were calibrated and validated with an acceptable performance (Nash-Sutcliffe efficiency coefficient of 0.81 and 0.50) in simulating discharge for mountain watersheds and water level for lowland watersheds. Based on the validated models, scenario analysis was conducted to evaluate the impacts of climate change and land use on hydrological processes. The simulation results revealed that climate change based on CMIP6 would cause a larger increase of annual runoff in the mountain watersheds than that in lowland watersheds, with the variation by 10 200% and 10 60% from 2015 to 2100 respectively. Land use change can cause a larger increase of annual runoff in lowland watersheds than that in mountain watersheds, with the variation by 3.9% and 0.6% respectively. We also found that land use change would enhance climate impacts on water balance in lowland watersheds, however, had insignificant effects in mountain watersheds. This study demonstrated that mountain and lowland watersheds are distinctly different in hydrological processes and their response to climate and land use change.

### Keywords

Hydrological processes; climate change; land use; mountain watersheds; lowland artificial watersheds.

## Introduction

It is widely recognized that hydrological processes and water balances between mountain and lowland watersheds are significantly different. Mountain watersheds with sharp wet-dry seasonal transitions and steep gradients in temperature and precipitation with elevation make the difficulties lie in quantifying the hydrologic change by integrating the temporal and spatial distribution of water resources (Bales et al., 2006; de Jong et al., 2005). Previous studies simulated this relatively natural regions based on the supply (precipitation)-demand (potential evapotranspiration)-storage (water storage in the soil) hypothesis (Milly, 1994). However, their adjacent downstream areas where slope are flat or gentle ([?]25) have dissimilar hydrological processes relative to upstream. Streamflow shows crossed, looped and human intervening, needing another hydrological regime to explain. Few studies have been conducted to quantify these differences of hydrological characteristics between mountain and lowland watersheds (Berihun et al., 2019; Weingartner et al., 2007).

Climate and landscape characteristics are the primary factors determining watershed hydrological processes (Berihun et al., 2019). Their influences vary with different watershed characteristics and the agro-ecological settings. For example, 1) *climate and farming controls water sources.*Precipitation is the main source for runoff generation in mountain watersheds, whereas irrigation is another important water source for lowland watersheds (e.g. accounting for 27% in Lake Taihu Basin, China (Huang et al., 2018a). 2) *Slope is not the driving force for streamflow.* In lowland watersheds, the target water levels human required regulate the flow direction. 3)*Alternative combination of land use options generates huge discrepancy in hydrological processes* . Polder is the main geographic unit of lowland watersheds. More than half of the total area are covered by farmland and surface water (Vermaat & Hellmann, 2010). The water storages such as ponds can increase the retention time of surface runoff by 6 months within polders (Cui et al., 2019). Moreover, large area of paddy lands will produce irrigation-related evaporation enhancement. 4) *Water conservancy facilities hinder the natural flow exchange* . Pumping stations commonly existed in lowlands interfere with the hydrological connections between polders and their receiving water body (Hesse et al., 2008), for example, inducing 8.6% reduction of annual runoff to surrounding rivers (Yan et al., 2018). In conclusions, predicting the responses of hydrological processes under future climate change and land use scenarios is favorable for applying sustainable land and water managements to adapt these impacts, in return resulting to an increase in available water. However, the research of individual and synergetic influence of climate change and land use on hydrological processes with various watershed characteristics is still limited (Gusarov, 2019).

The process-based models were widely employed to predict contributions of driving factors on streamflow variation via physical process simulations (Chen et al., 2019; Li et al., 2015; Wang et al., 2019). However, most models (e.g. SWAT, HSPF, Xin'anjiang and MIKE-SHE) were suitable for freely draining areas with sloping surfaces, and not designed for lowland polders with shallow groundwater (Hesse et al., 2008; Yan et al., 2016). They failed to reflect the complicated water management operation, especially lacking the irrigation and drainage processes simulation in crop fields (Salmon et al., 2015). For example, water conservancy facilities like dikes dramatically influence in simulating the quick return flow process through drainage systems (Tsuchiya et al., 2018). Moreover, pumping stations result in multiple drainage outlets within polders. More importantly, many existing models fail to accurate consider the characteristics of paddy field and ponds. For example, Soil Water Atmosphere Plant Model (SWAP) treats paddy fields as upland areas, which actually are the depression areas (Utset et al., 2007). Others set ponds and paddy lands as reservoirs (Xie & Cui, 2011). However, water balance of reservoir is calculated in volume, while paddy fields calculates water balance in depth (Tsuchiya et al., 2018). Up to now, the simulation methods aimed to modeling the hydrological processes in lowland artificial watersheds are the simplifications of real situations, inducing that not all the vital processes are taken into account (Lai et al., 2016; Su & Luo, 2019).

In our study area, there are two typical hydrological systems: mountain watersheds and lowland artificial watersheds. Aimed to identify the relative contributions of climatic and land use to streamflow varying with different watershed characteristics, we used the developed raster-based Xin'anjiang model to clarify the mechanism of runoff generation within mountain areas, and polder areas were treated separately which used Nitrogen Dynamic Polder (NDP) model to simulate the artificial drainage and natural flow components (Huang et al., 2018a). As changes in land use and climate are expected to intensify in future, it is a task and challenge to identify further hydrological responses considering these changes, for devising sustainable land and water management strategies. The modelling approach in this study is transferable to other watersheds.

# Material and methods

## Study area

The study area (Xitiaoxi Watershed) was located within Lake Taihu Basin in eastern China (Fig. 1). The watershed included 24 mountain sub-watersheds (30°23'N˜30°45'N and 119°14'E˜119°48'E), and 143 lowland artificial sub-watersheds (30°45'N˜31°5'N and 119°48'E˜120°9'E). The elevations range from 0 m (lowland) to 1576 m (mountain) above sea level.

The mountain watersheds are located at southwest of the study area, with areas of 1,367 km2. River Xitiaoxi contributed 27.7% of the water resources in Lake Taihu (Chen et al., 2019). Annually average precipitation is 1465.8 mm (Chen et al., 2019). Forestlands account for 74% of the mountain watersheds, following 15% paddy lands, 4% residential areas and small areas of surface water and grasslands.

The lowland watersheds (polders) are located at the northeast with a total area of 743 km2. To develop agriculture and protect villages from floods, these polders are enclosed by dikes. Therefore, water exchange between rivers and polders are manually controlled by pumps. The main cultivate land (69%) is paddy field with rice–wheat rotation, other land use types of polder systems contain dry lands (14%), ponds (6%) and residential areas (11%). During rice seasons (from May to Nov.), supplementary water source from surrounding rivers need to pour into paddy lands for irrigation. Meantime, artificial drainage is closed, and excess runoffs are delivered into ponds for keeping the soil moisture saturation. In case that the water level of ponds is too high to harm the crop growth during heavy rainfall events, pond water will be exported into surrounding rivers by pumps. During wheat season, runoff water would not kept in ponds due to its useless for wheat.

Fig. 1 Location of the study area (Xitiaoxi Watershed) with the distribution of hydrological and weathers stations.

## Data

The required dataset for these two models included meteorological and hydrological data, land use, and Digital Elevation Model (DEM). 1) Meteorological data were collected based on the national weather station (Huzhou: No.58450). The precipitation data were obtained from 13 automatic rain gauges (Fig. 1). The pan evaporation was substituted by the reference evapotranspiration (ET0) using Penman Equation. 2) Among hydrological data, daily water level was measured using a water level logger. The discharge for mountain watersheds was verified using the daily runoff data from 2009 to 2012 at the national station of Hengtangcun. 3) Land use and digital elevation model (DEM) with a spatial resolution of 30 m were obtained from the satellite image interpretation of 2010 and International Scientific and Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (*http://www.gscloud.cn*) respectively. Above-mentioned data were rescaled to an identical resolution of 100 m for hydrological modelling. We used DEM to delineate the boundaries of the mountain watersheds and to classify the slope.

Table 1 Data collected for the Xin'anjiang model and Nitrogen Dynamic Polder (NDP) model.

## Model description

Two hydrological models (Xin'anjiang and NDP) were used to simulate the hydrological processes in the mountain watersheds and lowland artificial watersheds, respectively, and to compare their different responses to climate and land use change. Xin'anjiang model, a widely used hydrological model for simulating streamflow in the humid and semi-humid regions in China, was used to simulate discharge for mountain watersheds at a daily time scale. NDP model was specially developed by Huang et al. (2018a) to describe the unique processes of hydrological and nitrogen dynamics in lowland polders. In this study, it was used to distinguish the water balance components in lowland watersheds.

### Raster-based Xin'anjiang model

The Raster-based Xin'anjiang model was developed based on the original Xin'anjiang model originally developed by Zhao (1984), incorporating the merits of the original conceptual rainfall-runoff model (Huang et al., 2018b). Its core concept was runoff formation on the repletion of storage capacity, which implied that the excess rainfall became the runoff until the soil water content of the aeration zone reached its field capacity (Yao et al., 2014). For each cell, the outflow was simulated based on four modules: evapotranspiration module, runoff generation module, runoff separation module and runoff routing module. Total runoff was separated into three components including surface, interflow, and groundwater runoff.

To develop the raster-based Xin'anjiang model for the mountain watersheds, the following inputs were required: 1) *initial data* : it included initial discharge of surface water, interflow and groundwater, tension water storage and free water storage. A spatial resolution of 100×100 m was used for the model. 2) *Forcing data* : weather conditions included the variables of sunshine hours, wind direction, wind speed, average air temperature, precipitation, maximum and minimum air temperature in a day. 3) *Boundary data* : the daily runoff and the locations of streamflows should be input. 4) *Model parameters* : there were 14 parameters in this model. Value ranges of these parameters as well as their calibrated values were given in Supporting Information.

### NDP model

The model was developed based on water balance equations in four land-use types (residential area, surface water area, paddy and dry land). It included the hydrological processes of precipitation, irrigation, evaporation, evapotranspiration, surface runoff, infiltration, water exchange between groundwater and surface water. Notably, water management modules describing the artificial drainage of polder systems were also included. Flood drainage, culvert drainage and seepage acted as outflow pathways to surrounding rivers.

The initial conditions of NDP included the areas of four land use types in each polder. In case that hydrological component was selected, the initial water level and land use types were required. Input data included time series meteorological data and parameters. NDP included 28 parameters in the water balance and water management modules, all the parameter values were obtained from previous studies in a typical polder located not far (about 38 km) from the study area (See Supporting Information).

## Forecasting hydrological response in the context of climate and land use change

The Scenario Model Intercomparison Project (ScenarioMIP) is the primary activity within Phase 6 of the Coupled Model Intercomparison Project (CMIP6) that will provide multi-model climate projections based on alternative scenarios of future emissions and land use changes produced with integrated assessment models. BCC-CSM2-MR configured for CMIP6 are used for generating precipitation and temperature for three developed alternative future societal development pathways (the SSPs) and emissions and land use scenarios based on RCPs (O'Neill et al., 2016). Historical simulations from 2000 to 2014 were as the reference period, and four distinct periods including 2029˜2032, 2049˜2052, 2069˜2072 and 2089˜2092 were chosen for future scenario runs representing the 2030s, 2050s, 2070s and 2090s, respectively. The predicted climate scenarios indicated a 3.45% increase in annual precipitation for the 2030s, a 7.54% increase for the 2050s, a 16.18% increase for the 2070s, and a 14.43% increase for the 2090s. Temperature outputs indicated a 0.98 °C increase for the 2030s, a 1.63 °C increase for the 2050s, a 2.39 °C increase for the 2070s and a 3.03 °C increase for the 2090s. Compared with BCC-CSM1.1m from CMIP5, BCC-CSM2-MR shows significant improvements in many aspects including the tropospheric air temperature and precipitation at global and regional scales in East Asia (Wu et al., 2019), which fit for our research.

Developed land use scenarios for the 2050s are all under the 'current rate' according to Chen et al. (2009). In mountain watersheds, the most frequent land use changes will occur in expanding 272.4% residential area at the expense of cultivate land and forest land by 86.5 km2 and 50.8 km2 respectively, following by the conversion between cultivate land and forest land. In lowland artificial watershed, converting 36.1%

(221.7 km2) cultivate land to residential land is overwhelming than other land-use conversion patterns (See Supporting Information).

# Results

## Model calibration and validation results

The raster-based Xin'anjiang model captured the seasonal trend of discharge and extreme flows in heavy rainfall events (Fig. 2). Discharge in Hengtangcun was well simulated with a correlation coefficient ($R2$ ) and Nash-Sutcliffe efficiency coefficient ($NS$ ) value of 0.90 and 0.81 in calibration period and with$R2$ and $NS$ value of 0.93 and 0.81 in validation period respectively. Several discharge peaks (e.g., on Aug. 10, 2009 and Jun. 14, 2011) were well described.

Fig. 2 Daily observed and simulated discharge at Hengtangcun station during model calibration (2009-2011) and validation periods (2012).

Simulated water level from NDP model has been verified using data from a typical polder close to the study area, which performances were acceptable with the $NS$ value of 0.73 and 0.50 for the calibration and validation periods (Huang et al., 2018a). More details can be found in the Supporting Information.

## The different hydrological responses to climate change and land use between mountain and lowland artificial watersheds

We compared the simulated hydrological processes between mountain and lowland artificial watersheds under current and each future climatic and land use conditions. To quantify the influence of future climate change, we changed temperature and precipitation parameters corresponding to climate change scenarios from CMIP6 for the 2030s, 2050s, 2070s and 2090s, and kept the other parameters of the two models unchanged. To quantify the influence of future land use, we evaluated discharge variations for the 2050s under the developed land use scenarios with the current change rate, using the identical climate data from 2009 to 2012.

### Hydrological responses to climate variability

Monthly discharge and evaporation calculated from the 2009-2012 basic data were used to compare the different hydrological responses to climate variability between mountain and lowland artificial watersheds. Fig. 3(a) showed the slope (4.75) of evaporation-temperature linear correlation in lowland watersheds was larger than in mountain watersheds (2.61), accounting for the same growth in temperature would cause larger evaporation increment in lowland. Fig. 3(b) showed an$R2$ of 0.65 in mountain watersheds was larger than that in lowland watersheds (0.12). This may because precipitation was the unique water resource in mountain watersheds while irrigation also controlled discharge in lowland artificial watersheds.

Fig. 3 The linear correlation of evaporation-temperature (a) and discharge-precipitation (b) in mountain watersheds (blue points) and lowland artificial watersheds (orange points).

In case that temperature and precipitation changed simultaneously in future climate change scenarios, the mean annual runoff change was more significant in mountain (10˜200%) than in lowland (10˜60%) (Fig. 4). In terms of season, autumn and winter were significantly related to the increment in mountain watersheds, and summer and autumn (rice seasons) had a largest contribution in lowland watersheds. The $R2$between precipitation variability and mean annual runoff change was 0.78 in mountain, comparing to 0.96 in lowland. The$R2$ between annual average temperature and runoff variability was negligible (0.05) in mountain comparing with that (0.33) in lowland. Therefore, the dominated factor for runoff variation under climate change scenarios was precipitation.

Fig. 4 The annual and seasonal runoff variation under future climate scenarios. RCP2.6_20, RCP4.5_20, RCP8.5_20 were the simulations for the 2030s; RCP2.6_40, RCP4.5_40, RCP8.5_40 were the simulations for the 2050s; RCP2.6_60, RCP4.5_60, RCP8.5_60 were the simulations for the 2070s; RCP2.6_80, RCP4.5_80, RCP8.5_80 were the simulations for the 2090s.

### Hydrological responses to land use

In order to learn the hydrological processes response to the different land use conditions, we subdivide the mountain watersheds into several sub-watersheds based on DEM, and the lowland artificial watersheds into several polders based on satellite images. Different metrics and thresholds have been used to characterize discharge regimes (Berihun et al., 2019). The annual mean runoff coefficient (α) is the average value of the ratio of annual runoff depth to annual precipitation depth. In lowland artificial watersheds, discharge is the total amount of seepage, culvert drainage and flood drainage, excluding the inflowing irrigation. A higher value of α correlates with the difficulty in absorption of precipitation by soil. The coefficient of variation (CV) is the ratio of standard deviation to average value. Here it estimates the variation extent of daily discharge in each sub-watershed (polder) as results of different land use conditions.

It can be found that α in mountain watersheds (0.41) was generally larger than that in lowland watersheds (0.36). It had a relatively weak negative correlation with the ratio of cultivate land in mountain ($R2$ =-0.28), compare to the relatively strong negative correlation in lowland ($R2$ =-0.85). In addition, the CV of discharge was generally larger in lowland watersheds (2.39) than in mountain watersheds (1.02), which was positively related to the ratio of cultivate land in the former ($R2$ =0.55) while negatively related to the ratio in the latter ($R2$ =-0.37). This is probably because in lowland artificial watersheds, the surface runoff flowing in or out of the cultivate land were controlled by pumping stations, generating sharper discharge hydrograph with higher peak-values and lower minimum-values (Yan et al., 2018). In terms of the ratio of water area, the CV of discharge had a negative relation ($R2$ =-0.83) with it in lowland watersheds comparing to non-significance in mountain watersheds, partly accounting for the capacity of regulating flow of ponds in polders. With respect to the ratio of residential area, we found that α having an extremely strong positive correlation ($R2$ =0.99) with it in lowland. The other result like α and CV value of discharge in mountain watersheds were positively correlated to the slope ($R2$ =0.73 and 0.82 respectively), implying that sloping regions more likely lead to the productions and variations of surface runoff (Fig. 5).

Fig. 5 The description of discharge characteristics and the land use conditions in mountain watersheds and lowland artificial watersheds respectively (Left); The different responds of surface runoff to the ratio of land use types and slope classes between mountain watersheds and lowland artificial watersheds (Right).

Note: α: the annual mean runoff coefficient; CV: the coefficient of variation of surface runoff; Farm: cultivated land; W: water area; R: residential area; For: forest land; G: grass land.

Monthly and annual runoff variations between two watersheds were compared to evaluate the different effects of future land use conversions. For the 2050s, keeping the current rate of land use change, the most dramatic variations of annual runoff in mountain watersheds were found under the scenarios of converting cultivate land, forestland or grassland into residential area (increasing 7.8%, 3.5% and 1.7% respectively). Moreover, under the above three scenarios, seasonal runoff showed increasing trend especially in May. The most significant changing of annual runoff in lowland artificial watersheds was found in the scenarios of converting cultivate land into residential area or into water area (increasing 22.0% and 2.1% respectively). The seasonal runoff showed a dramatic increase except in winter (from Dec. to Feb.) when converting cultivate land into residential area. It showed a slight increasing trend except in summer when converting cultivate land into water area because of the reduced irrigation. Overall, the effects of land use change on runoff were generally more significant in lowland artificial watersheds than that in mountain watersheds (Fig. 6).

Fig. 6 The different effects of land use conversions on monthly (a, b) and annual (c, d) runoff between mountain watersheds (a, c) and lowland artificial watersheds (b, d). The value of (c) and (d) represents annual runoff in X axis to that in Y axis.

Note: Farm: cultivated land; For: forest land; G: grass land; R: residential area; W: surface water area.

### Water balance at mountain and lowland artificial watersheds under future scenarios

Land use change scenarios were generated along the same storylines as climate change scenarios based on RCP 2.6 for the 2050s to assess the additive impacts of the two stressors. In mountain watersheds, climate changes itself led to an increase by 0.7 mm and 312.9 mm in annual evaporation and annual runoff respectively, probably due to the increment in rainfall. When combined with land use change, the water balance components varied slightly on the whole. Therefore, water balance in mountain watersheds were more sensitive to climate change. The land use change had weak enhancing effects on climate impacts (Mountain: S1, S2, S3 in Fig. 7).

In lowland artificial watersheds, the water input was larger than water output in summer, opposite to autumn, which related to the special water management and drainage rhythm of polders. As to evaporation component, it sharply declined by 266.6 mm when combining the effect of land use change, mainly due to the absence of rice evapotranspiration (Evaporation: S1, S2 in Fig. 7). Irrigation showed a decrease of 77.5 mm when rising 24.4% of annual precipitation (Irrigation: S0, S1 in Fig. 7), and decline became more apparent with the cultivate land shrinking (Irrigation: S1, S2 in Fig. 7). Pump drainage notably increased by 213.8 mm in response to the increment in precipitation (Pump: S0, S1 in Fig. 7), and when combining land use change, the capacity of retaining water of increased ponds can mitigate 57.2 mm of flood discharge (Pump: S1, S2 in Fig. 7). Culvert drainage increased by 25.8 mm with precipitation (Culvert: S0, S1 in Fig. 7). Moreover, cultivate land shrinking was direct to the reduction of water holding, consequently the culvert drainage increased another 111.7 mm (Culvert: S1, S2 in Fig. 7). Seepage increased abruptly by 138.6 mm under future land use change scenarios (Seepage: S1, S2 in Fig. 7). In summary, the land use change had strong combined effects on climate factors in lowland artificial watersheds.

Fig. 7 Water balance simulations of mountain and lowland artificial watersheds under climate change and land use scenarios for the 2050s. S0: Historical climate scenario + a baseline land use scenario. S1: RCP2.6 climate scenario + a baseline land use scenario. S2: RCP2.6 climate scenario + developed land use scenario for the 2050s.

# Discussion

## Model performance

Sensitive parameters determined the model performance. Their initial ranges were referred to Zhao et al. (2011) and the optimum parameter sets were obtained from the simulation results with the maximum *NS* value. Compared with previous case studies in Xitiaoxi watershed for mountain hydrology modeling by Chen et al. (2019), the *NS* value and *R2* value of daily flows at the Hengtangcun (Fig. 2) implied that the simulation results by Xin'anjiang model were "very good" during the calibration and validation periods. According to Moriasi et al. (2007), streamflow simulations were regarded as satisfactory for SWAT when *NS* [?]0.5.

In lowland artificial watersheds, the NDP model considered the dominating mechanisms affecting polder water balance. They were artificial drainage, the water interactions among surface water and groundwater, as well as soil water in farmlands (Huang et al., 2018a). The *NS*values of water level were above 0.5 during the calibration and validation periods. This model fit was acceptable compared with the surveying watershed modeling cases using 257 models (Wellen et al., 2015). Our study area was close to the case study by Huang et al. (2018a) in space and under the unified polder-controlled strategy by Taihu Basin Authority of Ministry of Water Resources. Therefore, these similarities between the hydrological conditions in the previously modelled data and the current hydrological year being modelled can illustrate the significance and reliability of the model fits.

## The different responses of hydrological processes to climate change and land use

Our study found that climate and land use change can cause higher surface runoff, which was consistent with previous study by Berihun et al. (2019). However, Berihun did not summarize the differences of hydrological responses between his three study watersheds with different biophysical characteristics, which was the key augmentations of our study. Wang et al. (2019) found that the corresponding sensitivity of streamflow to changes in climatic conditions and human activities varying from watershed to watershed. Therefore, it was important to analyze the hydrological processes and their driving factors at watershed scales.

In our study, climate change played a more critical role on the hydrological process in mountain watersheds than in lowland artificial watersheds. The variation of mean annual discharge resulting from climate change mainly due to the precipitation factor during the study period across two watersheds ($R2$ =0.78 in mountain, $R2$ =0.96 in lowland). In mountain watersheds, the annual average discharge would increase 10˜200% from 2015 to 2100 under three climate scenarios (RCP2.6, RCP4.5 and RCP8.5 from CMIP6), comparing to 10˜60% in lowland watersheds. In terms of seasonal discharge variation, it showed remarkable change during autumn and winter in mountain watersheds as their small base values. However, rice seasons were the "hot moments" of flood in lowland artificial watersheds.

Land use played a more critical role on the hydrological process in lowland artificial watersheds than in mountain watersheds. Converting cultivate land to residential land made a significant improvement on annual average discharge comparing to other land use scenarios, with an increment of 22.0% in lowland and 7.8% in mountain respectively, under the same conversion rate of 36.1%. In terms of the "hot moments" of flood under land use conversion scenarios, in lowland watersheds, the effect of converting cultivate land to residential land on seasonal runoff variation was more than 20.0% in the whole year expect winter. Moreover, when converting cultivate land to water area, seasonal runoff increased more than 10.0% in rice seasons especially during irrigation periods. In mountain watersheds, urban expansion from other land use types such as forestland and grassland caused seasonal runoff increasing especially in May, during the crops and plants growth seasons when consuming a lot of water. Another found in mountain watersheds was that runoff showed a positive correlation with the slope, implicating that the weak water storage capacity of sloping regions lead to more frequent rainstorm-runoff processes.

Land use can enhance climatic impact on hydrological process in lowland artificial watersheds, comparing to the non-significant tendency in mountain watersheds. For the 2050s, climate change would cause an increasing annual runoff by 312.9 mm and 349.7 mm in mountain and lowland watersheds, respectively. When combined with land use change, annual runoff increased another 55.1 mm and 269.3 mm in mountain and lowland watersheds, respectively.

## Implication for water managements

As land use and climate changes are expected to be intensive in future, many regions in the world may suffer from frequent droughts and floods. The relative effects of climate change and human activity vary among different watersheds as well as different periods (Ye et al., 2013). However, the effects of climate change and land use are always underestimated or overestimated by different methods, interfering decision makers to manage water resources in a sustainable way (Wang et al., 2019).

In our study, increased precipitation and temperature under future climate conditions would cause higher streamflow especially in mountain watersheds, which seems to have slight impact on evaporation. Therefore, floods in sloping regions may become more frequent under future climate effects, leading to more severe flood disasters. The major effects of land use change on hydrological processes for the 2050s will happen when the urban area expanding rapidly at the expense of cropland. Cropland is an important land use type in lowland artificial watersheds, for the disappearance of its water retention capacity will destroy flood prevention by polders. Moreover, pumping stations setting for cropland can increase the hydraulic retention time in lowland watersheds. The "hot moments" of flood in lowland artificial watersheds would be rice reasons when converting cropland to residential area, comparing with crop growing seasons in mountain watersheds without pumps. To sum up, precisely forecasting the mountain torrents during rainstorms, controlling urban expansion and maintaining the cropland area of polders could be potential strategies for flood prevention and water resources protection in highland-lowland watersheds.

# Conclusions

The sensitivity of hydrologic process and water balance to changes in climatic and land use conditions varied from watershed to watershed. In our study, two hydrological models fitted for mountain and lowland artificial watersheds respectively were applied in Lake Taihu basin to evaluate the seasonal and annual characteristics of hydrological variables and their driving factors, which were not fully understood in previous studies. We found that climate change caused a larger increase of annual runoff in mountain watersheds than that in lowland artificial watersheds, which opposite to the influence of land use change. The scenario of converting cultivate land to residential land increased the discharge mostly comparing to other land use scenarios. In addition, these variations were most notable in May in mountain watersheds, comparing to rice seasons in lowland artificial watersheds. Runoff variation in mountain watersheds were most attributed to climate change. However, the influence of land use change was equally important in the lowland artificial watersheds. Land use change can enhance climate impacts on water balance in lowland artificial watersheds. This study improved our understandings on the different hydrological responses to single and synergetic changes in climate and land use varying watershed characteristics, and can thus support water managers to project the future variation of hydrology and water resources in management practice.

# Acknowledgments

The project was financially supported by Youth Innovation Promotion Association CAS (2019313), National Natural Science Foundation of China (41971138), Major Science and Technology Program for Water Pollution Control and Treatment of China (2017ZX07301-001-02) and China Postdoctoral Science Foundation (2019M651891). The authors would like to thank China Meteorological Data Sharing Service System for providing the measured data for model development.

# Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

# References

Bales, R. C., Molotch, N. P., Painter, T. H., Dettinger, M. D., Rice, R., & Dozier, J. (2006). Mountain hydrology of the western United States. *Water Resources Research, 42* (8).*http://dx.doi.org/10.1029/2005wr004387*

Berihun, M. L., Tsunekawa, A., Haregeweyn, N., Meshesha, D. T., Adgo, E., Tsubo, M., . . . Ebabu, K. (2019). Hydrological responses to land use/land cover change and climate variability in contrasting agro-ecological environments of the Upper Blue Nile basin, Ethiopia. *The Science of the total environment, 689* , 347-365.*http://dx.doi.org/10.1016/j.scitotenv.2019.06.338*

Chen, Y., Xu, C. Y., Chen, X. W., Xu, Y. P., Yin, Y. X., Gao, L., & Liu, M. B. (2019). Uncertainty in simulation of land-use change impacts on catchment runoff with multi-timescales based on the comparison of the HSPF and SWAT models. *Journal of Hydrology, 573* , 486-500. *http://dx.doi.org/10.1016/j.jhydrol.2019.03.091*

Chen, Y., Yin, X. Y., & Chen, S. (2009). Land use/cover forcasting of catchment and its landscape ecological effects: a case study of Xitiaoxi catchment in the upper reaches of Taihu Basin *Resources and Environment in the Yangtze Basin (in Chinese), 18* (8), 765-770.

Cui, Z., Huang, J. C., Tian, F., & Gao, J. F. (2019). Modeling the response of river nutrient conditions to land use changes in lowland artificial watersheds (polders). *Ecological Engineering, 135* , 98-107. *http://dx.doi.org/10.1016/j.ecoleng.2019.05.012*

de Jong, C., Whelan, F., & Messerli, B. (2005). Preface: The importance of a hydrological research framework for water balance studies in mountain basins. *Hydrological Processes, 19* (12), 2323-2328. *http://dx.doi.org/10.1002/hyp.5886*

Gusarov, A. V. (2019). The impact of contemporary changes in climate and land use/cover on tendencies in water flow, suspended sediment yield and erosion intensity in the northeastern part of the Don River basin, SW European Russia. *Environmental Research, 175* , 468-488. *http://dx.doi.org/10.1016/j.envres.2019.03.057*

Hesse, C., Krysanova, V., Pazolt, J., & Hattermann, F. F. (2008). Eco-hydrological modelling in a highly regulated lowland catchment to find measures for improving water quality. *Ecological Modelling, 218* (1-2), 135-148. *http://dx.doi.org/10.1016/j.ecolmodel.2008.06.035*

Huang, J. C., Arhonditsis, G. B., Gao, J. F., Kim, D. K., & Dong, F. F. (2018a). Towards the development of a modeling framework to track nitrogen export from lowland artificial watersheds (polders). *Water Research, 133* , 319-337. *http://dx.doi.org/10.1016/j.watres.2018.01.011*

Huang, J. C., Zhang, Y. J., Huang, Q., & Gao, J. F. (2018b). When and where to reduce nutrient for controlling harmful algal blooms in large eutrophic lake Chaohu, China? *Ecological Indicators, 89* , 808-817. *http://dx.doi.org/10.1016/j.ecolind.2018.01.056*

Lai, Z. Q., Li, S., Lv, G.-N., Pan, Z. R., & Fei, G. S. (2016). Watershed delineation using hydrographic features and a DEM in plain river network region. *Hydrological Processes, 30* (2), 276-288. *http://dx.doi.org/10.1002/hyp.10612*

Li, Z. F., Luo, C., Xi, Q., Li, H. P., Pan, J. J., Zhou, Q. S., & Xiong, Z. Q. (2015). Assessment of the AnnAGNPS model in simulating runoff and nutrients in a typical small watershed in the Taihu Lake basin, China. *Catena, 133* , 349-361. *http://dx.doi.org/10.1016/j.catena.2015.06.007*

Milly, P. C. D. (1994). CLIMATE, SOIL-WATER STORAGE, AND THE AVERAGE ANNUAL WATER-BALANCE. *Water Resources Research, 30* (7), 2143-2156. *http://dx.doi.org/10.1029/94wr00586*

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the Asabe, 50* (3), 885-900.

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., . . . Sanderson, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development, 9* (9), 3461-3482. *http://dx.doi.org/10.5194/gmd-9-3461-2016*

Salmon, J. M., Friedl, M. A., Frolking, S., Wisser, D., & Douglas, E. M. (2015). Global rain-fed, irrigated, and paddy croplands: A new high resolution map derived from remote sensing, crop inventories and climate data. *International Journal of Applied Earth Observation and Geoinformation, 38* , 321-334. *http://dx.doi.org/10.1016/j.jag.2015.01.014*

Su, B. L., & Luo, Y. X. (2019). Modelling hydrological processes and nutrient retention in plain polders. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques, 64* (7), 835-844.*http://dx.doi.org/10.1080/02626667.2019.1601728*

Tsuchiya, R., Kato, T., Jeong, J., & Arnold, J. G. (2018). Development of SWAT-Paddy for Simulating Lowland Paddy Fields. *Sustainability, 10* (9).*http://dx.doi.org/10.3390/su10093246*

Utset, A., Velicia, H., del Rio, B., Morillo, R., Centeno, J. A., & Martinez, J. C. (2007). Calibrating and validating an agrohydrological model to simulate sugarbeet water use under mediterranean conditions. *Agricultural Water Management, 94* (1-3), 11-21.*http://dx.doi.org/10.1016/j.agwat.2007.07.007*

Vermaat, J. E., & Hellmann, F. (2010). Covariance in water- and nutrient budgets of Dutch peat polders: what governs nutrient retention? *Biogeochemistry, 99* (1-3), 109-126.*http://dx.doi.org/10.1007/s10533-009-9395-8*

Wang, F. Y., Duan, K. Q., Fu, S. Y., Gou, F., Liang, W., Yan, J. W., & Zhang, W. B. (2019). Partitioning climate and human contributions to changes in mean annual streamflow based on the Budyko complementary relationship in the Loess Plateau, China. *Science of the Total Environment, 665* , 579-590.*http://dx.doi.org/10.1016/j.scitotenv.2019.01.386*

Weingartner, R., Viviroli, D., & Schadler, B. (2007). Water resources in mountain regions: a methodological approach to assess the water balance in a highland-lowland-system. *Hydrological Processes, 21* (5), 578-585.*http://dx.doi.org/10.1002/hyp.6268*

Wellen, C., Kamran-Disfani, A. R., & Arhonditsis, G. B. (2015). Evaluation of the Current State of Distributed Watershed Nutrient Water Quality Modeling.*Environmental Science & Technology, 49* (6), 3278-3290.*http://dx.doi.org/10.1021/es5049557*

Wu, T. W., Lu, Y. X., Fang, Y. J., Xin, X. G., Li, L., Li, W. P., . . . Liu, X. H. (2019). The Beijing Climate Center Climate System Model (BCC-CSM): the main progress from CMIP5 to CMIP6. *Geoscientific Model Development, 12* (4), 1573-1600.*http://dx.doi.org/10.5194/gmd-12-1573-2019*

Xie, X. H., & Cui, Y. L. (2011). Development and test of SWAT for modeling hydrological processes in irrigation districts with paddy rice. *Journal of Hydrology, 396* (1-2), 61-71.*http://dx.doi.org/10.1016/j.jhydrol.2010.10.032*

Yan, R. H., Gao, J. F., & Huang, J. C. (2016). WALRUS-paddy model for simulating the hydrological processes of lowland polders with paddy fields and pumping stations.*Agricultural Water Management, 169* , 148-161.*http://dx.doi.org/10.1016/j.agwat.2016.02.018*

Yan, R. H., Li, L. L., & Gao, J. F. (2018). Modelling the regulation effects of lowland polder with pumping station on hydrological processes and phosphorus loads. *Science of the Total Environment, 637* , 200-207.*http://dx.doi.org/10.1016/j.scitotenv.2018.04.389*

Yao, C., Zhang, K., Yu, Z. B., Li, Z. J., & Li, Q. L. (2014). Improving the flood prediction capability of the Xinanjiang model in ungauged nested catchments by coupling it with the geomorphologic instantaneous unit hydrograph. *Journal of Hydrology, 517* , 1035-1048.*http://dx.doi.org/10.1016/j.jhydrol.2014.06.037*

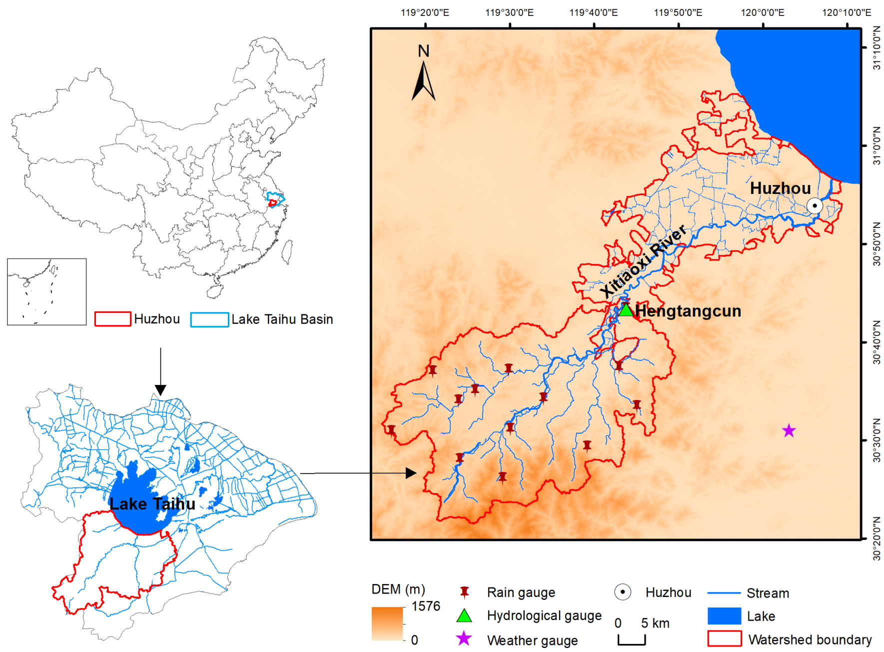
Ye, X. C., Zhang, Q., Liu, J., Li, X. H., & Xu, C. Y. (2013). Distinguishing the relative impacts of climate change and human activities on variation of streamflow in the Poyang Lake catchment, China. *Journal of Hydrology, 494* , 83-95.*http://dx.doi.org/10.1016/j.jhydrol.2013.04.036*

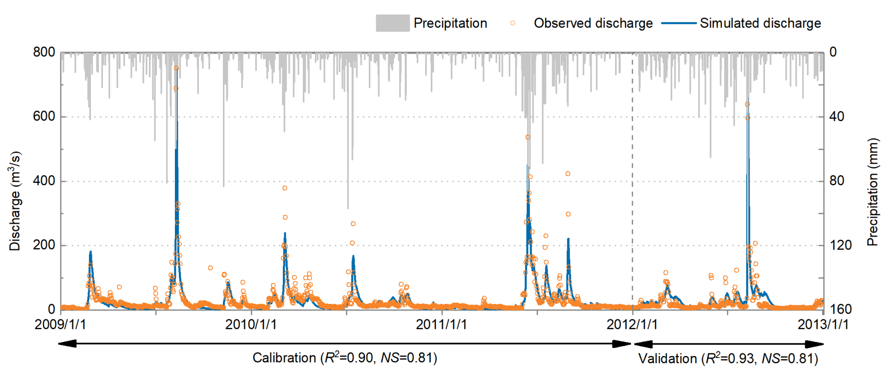
Zhao, G. J., Hormann, G., Fohrer, N., Gao, J. F., Li, H. P., & Tian, P. (2011). Application of a Simple Raster-Based Hydrological Model for Streamflow Prediction in a Humid Catchment with Polder Systems. *Water Resources Management, 25* (2), 661-676.*http://dx.doi.org/10.1007/s11269-010-9719-4*

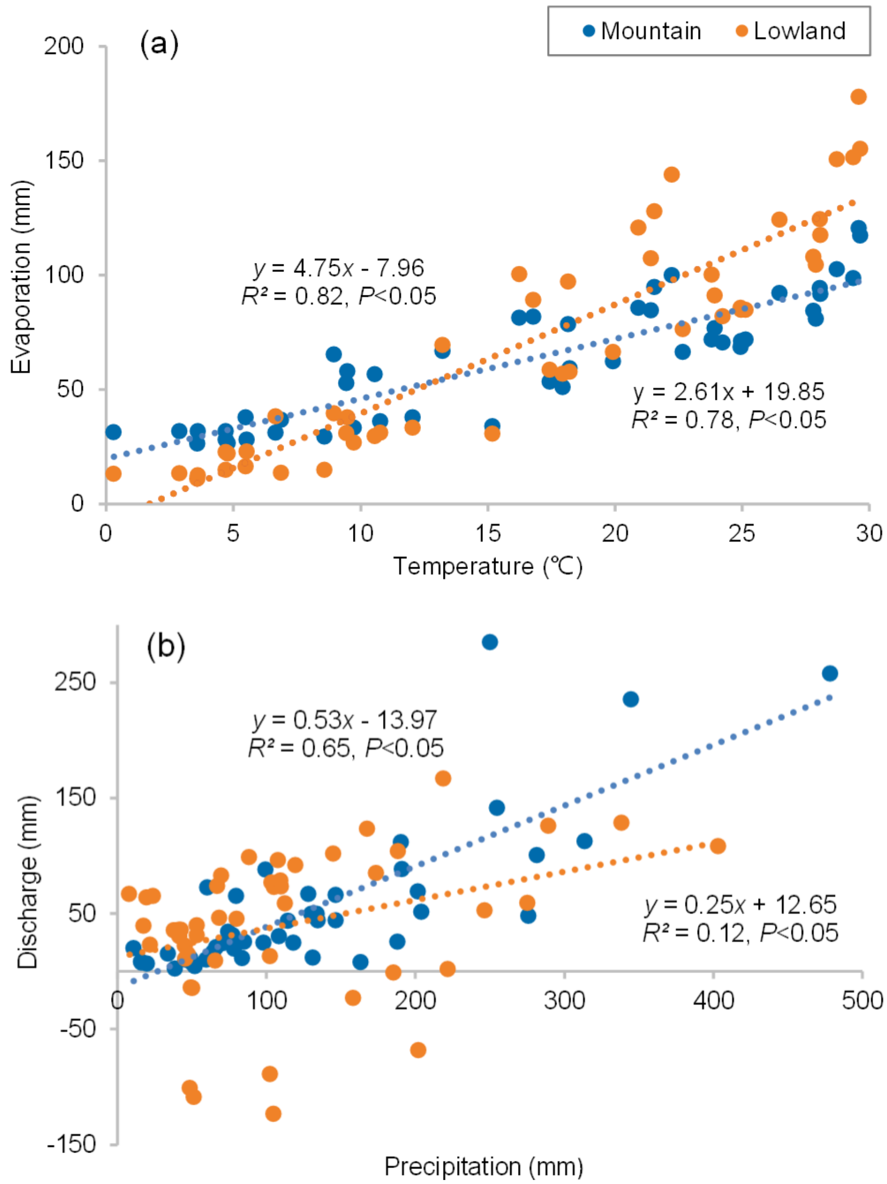
Zhao, R. J. (1984). *Water hydrological modelling - Xinanjiang Model and Shanbei Model* . Beijing: China Water Resources and Hydropower Press.

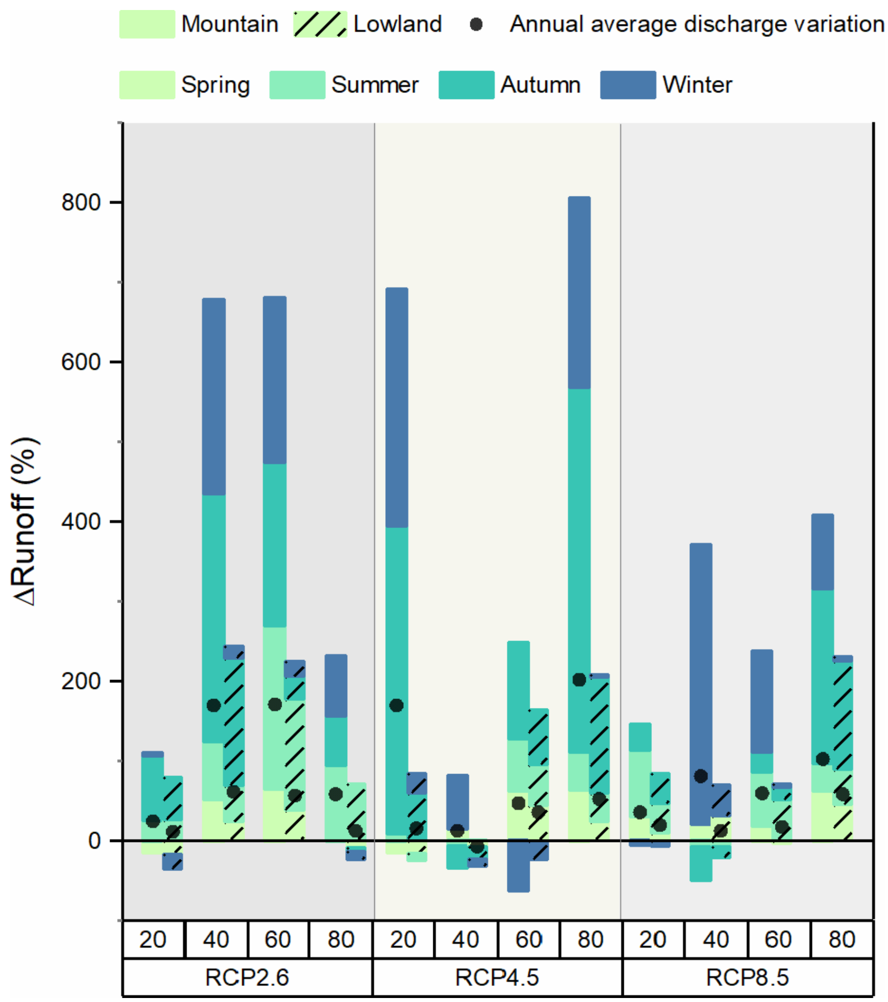
### Hosted file

`Tables.docx` available at https://authorea.com/users/287208/articles/411830-quantifying-the-impacts-of-climate-change-and-land-use-on-hydrological-processes-a-comparison-between-mountain-and-lowland-artificial-watersheds

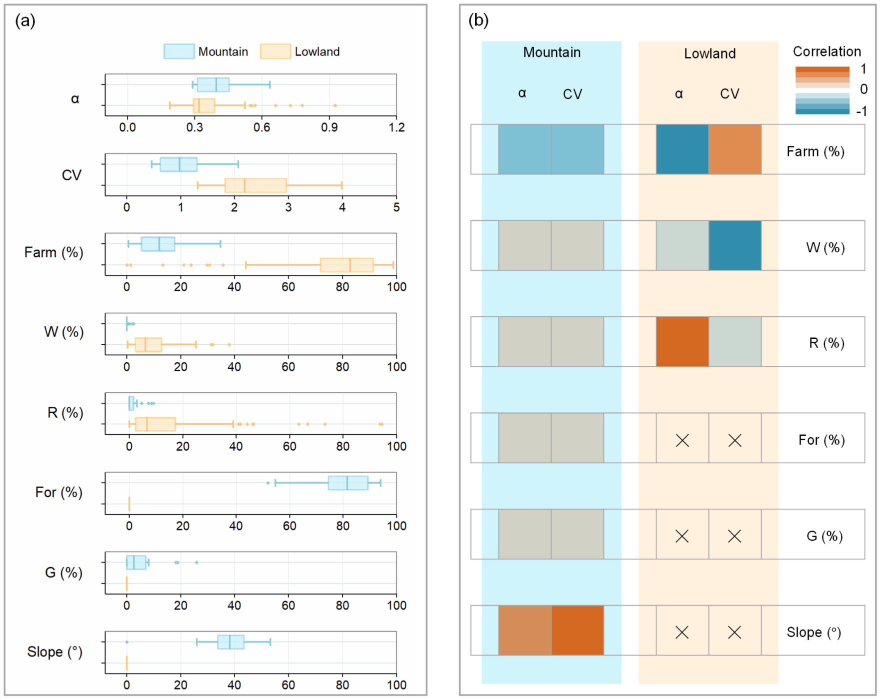


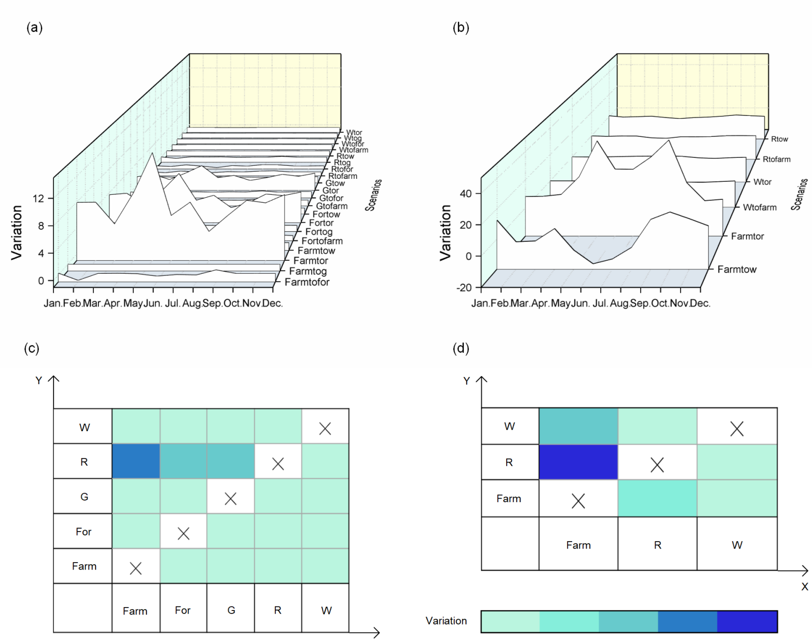



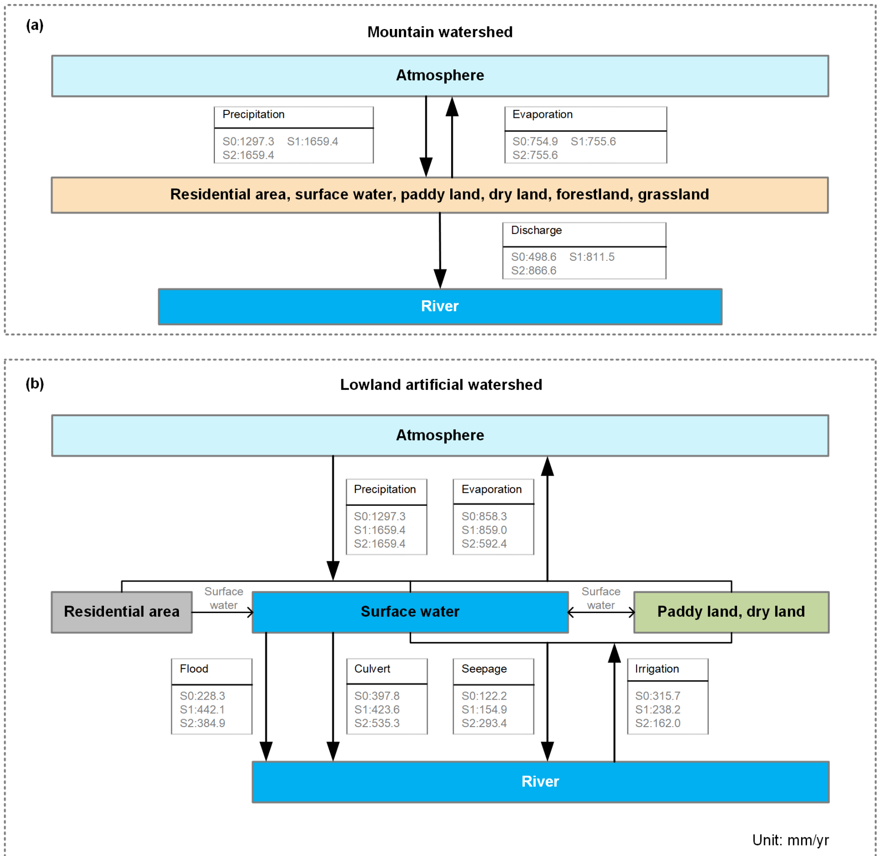

(a)
Mountain
Lowland
200
150
100
50
0
Evaporation (mm)
y = 4.75x - 7.96
R² = 0.82, P<0.05
y = 2.61x + 19.85
R² = 0.78, P<0.05
0
5
10
15
20
25
30
Temperature (℃)
(b)
250
150
50
-50
-150
Discharge (mm)
y = 0.53x - 13.97
R² = 0.65, P<0.05
y = 0.25x + 12.65
R² = 0.12, P<0.05
0
100
200
300
400
500
Precipitation (mm)



Mountain
Lowland
Annual average discharge variation
Spring
Summer
Autumn
Winter
ΔRunoff (%)
800
600
400
200
0
20
40
60
80
20
40
60
80
20
40
60
80
RCP2.6
RCP4.5
RCP8.5


(a)
Mountain
Lowland
α
CV
Farm (%)
W (%)
R (%)
For (%)
G (%)
Slope (°)
(b)
Mountain
Lowland
Correlation
1
0
-1
α
CV
Farm (%)
W (%)
R (%)
For (%)
G (%)
Slope (°)


(a)
(b)
Variation
Scenarios
Jan.Feb.Mar.Apr.MayJun. Jul.AugSep.Oct.Nov.Dec.
Rtow
Rtofarm
Wtor
Wtofarm
Farmtor
Farmtow
(c)
(d)
Y
X
W
R
G
For
Farm
Variation
0
0.5
1.0
5.0
10.0
>10.0 (%)


(a)
Mountain watershed
Atmosphere
Precipitation
S0:1297.3 S1:1659.4
S2:1659.4
Evaporation
S0:754.9 S1:755.6
S2:755.6
Residential area, surface water, paddy land, dry land, forestland, grassland
Discharge
S0:498.6 S1:811.5
S2:866.6
River
(b)
Lowland artificial watershed
Atmosphere
Precipitation
S0:1297.3
S1:1659.4
S2:1659.4
Evaporation
S0:858.3
S1:859.0
S2:592.4
Residential area
Surface water
Surface water
Surface water
Paddy land, dry land
Flood
S0:228.3
S1:442.1
S2:384.9
Culvert
S0:397.8
S1:423.6
S2:535.3
Seepage
S0:122.2
S1:154.9
S2:293.4
Irrigation
S0:315.7
S1:238.2
S2:162.0
River
Unit: mm/yr