Title: The impacts of climate change and land cover transition on the hydrology in the upper Yellow River basin, China

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• In the study area, observed seasonal and annual streamflow have changed.

• Precipitation, evapotranspiration, rainfall runoff, baseflow affected streamflow.

• Snowmelt is important in April or May, but not important for annual streamflow.

• Climate change impact is important in the entire study area.

• Land cover change effect varied spatially and temporally due to human activity.
The impacts of climate change and land cover transition on the hydrology in the upper Yellow River basin, China

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Abstract

Observed streamflow over the past decades in the upper Yellow River Basin (UYRB) was examined for changes in hydrological regime. The modified Variable Infiltration Capacity (VIC) model was employed to better understand climate change impact and long-term and recent land cover change impact as it relates to the “Grain for Green Project” and “Three Rivers Source Region Reserve” on water resources by examining mechanisms behind observed streamflow changes.

Analysis has shown that UYRB hydrological regimes have undergone changes over the past decades as reflected by a decrease in wet and warm season streamflow, annual streamflow. Progressively more streamflow has been generated in the early part of the year (compared to the latter part), consequently leading to the earlier occurrence of the day representing the midpoint of yearly mass flow. VIC simulations suggest that these changes in observed streamflow were due to the combined effects of changes in precipitation, evapotranspiration (ET), rainfall runoff, and baseflow and were caused primarily by climate change above the Tang Nai Hai (TNH) hydrometric station. Below TNH where human activity is relative intense, land cover change impacts become important. Changes in snowmelt runoff were negligible over the past decades. Owing to this, snowmelt runoff appears to play only a minor role in the hydrology of the region. The conservation programs were shown to start to exhibit some positive impacts on water resources in the UYRB.

Keywords: Hydrological processes; Hydrological modeling; Climate change and land cover change impacts; the Upper Yellow River Basin;
1. Introduction

The Yellow River Basin, considered the cradle of Chinese civilization, originates in the Tibetan Plateau, flowing through the Loess Plateau and the North China Plain, eventually emptying into the Bohai Sea to the east of China. It supports 30% of China’s population (Huang et al., 2009) and 13% of China’s total cultivated area (Cai and Rosegrant, 2004). Its headwater is situated in the Bayan Har mountain range in southern Qinghai Province in the northern Tibetan Plateau region (Figure 1). The upper Yellow River Basin (UYRB) above the Tang Nai Hai (TNH) hydrometric station contributes approximately 35% of the total annual discharge in disproportion to its 15% area of the entire Yellow River Basin (Hu et al., 2011). Fragile and unique temperate, alpine, and wetland ecosystems within the UYRB rely on its available water resources. Thus, understanding UYRB hydrological processes, especially in the context of global climate change and increased human activity, is necessary for informed current and future sustainable management of its water resources.

Streamflow, being an integrated component of hydrology in a basin, and changes in streamflow reflect the combined effects of climate, vegetation, and soil (Rodriguez-Iturbe et al., 2001). It is important to understand how climate, land cover/use change will impact streamflow and, hence, available water resources on a basin scale.

A number of observational studies have shown that streamflow measured at TNH decreased over the past decades (Cao et al., 2006; Tang et al., 2008; Hu et al., 2011). Cao et al. (2006) found that TNH annual discharge exhibited a statistically
non-significant decreasing trend between 1956 and 2000. Seasonally, except for increases detected in April, May, and June, all other months exhibited decreases in discharge. *Hu et al.* (2011), who analyzed TNH streamflow for a prolonged period of time (1959–2008), found that decreasing TNH streamflow was associated with decreasing wet season (from May to September) precipitation and rising temperatures. They speculated that the source region catchment was largely undisturbed by human activity, which led the authors to conclude that decreasing streamflow was predominantly caused by climate change. Few studies examined streamflow changes at the other hydrometric stations of the UYRB and it is unclear whether or not their findings can be applicable to all sub-basins of the UYRB.

Like elsewhere on Earth, climate change is taking place in the Yellow River Basin as reported by *Wang et al.* (2001), *Fu et al.* (2004), *Yang et al.* (2004), *Xu et al.* (2007), *Zhao et al.* (2007), *Tang et al.* (2008), *Zhang et al.* (2008), and *Hu et al.* (2011). These cited studies consistently describe basin-wide temperature increases, tempo-spatial variations in changes to precipitation, and decreases in water resources in the Yellow River Basin. Based primarily on statistical trend analyses of observed climatology, many of these studies speculated that changes in water resources have resulted from climate change, especially changes in precipitation and temperature increases. Lacking in these studies are detailed analyses and the quantification of the water balance change resulted from climate change and its relation to streamflow.

Snow has been widely recognized as an important component of water resources in cold regions and water resources are greatly affected by changes in snow.
As suggested by Barnett et al. (2005) and Stewart (2009), snowpack changes in a warming climate were altering hydrological cycles and water availability. Clearly, the validity of this assertion relies on several factors, such as the proportion of snow to total precipitation, seasonal cycles of storm occurrences, elevation, and air temperature. As an example, in the Pacific Northwest (PNW) of the United States of America where major storm systems occur in winter and where winter average air temperature is roughly 0.5°C (Mote and Salathe, 2010; Gao et al., 2011), rising temperatures in the past have greatly affected winter snow-rain partitioning (Hamlet et al., 2005), resulting in a transition from nival to pluvial hydrological regimes for low to midrange elevation basins (Cuo et al., 2009). Similar transitions are also projected for PNW highland basins in the mid-twenty-first century as global warming progresses (Cuo et al., 2011).

To date, there have been limited but mixed reports concerning the role of snow in hydrology as well as the impacts of snow change on UYRB streamflow. Lan et al. (1999) reported on the importance of snowmelt in the UYRB, especially during springtime when snowmelt accounts for nearly 40% of total runoff. However, Immerzeel et al. (2010) found that during 2000–2007 meltwater derived from snow and ice played only a modest role in mean annual streamflow across the upstream region of the Yellow River Basin (elevation greater than 2000 m). To what degree does snowmelt contribute to UYRB water resources certainly merits further investigation.

Besides climate change, human activity should also influence UYRB water
resources and hydrology. This appears to be especially true considering that human intrusion within this particularly harsh but pristine environment has increased in recent decades. As an example, Li and Liu (2004) and Dong et al. (2005) reported widespread grassland degradation in the UYRB during 1980s and 1990s and attributed the degradation to intensification of human activity such as overgrazing and caterpillar fungus digging. The recognition of human disturbance to the local ecosystem led to the implementation of “Grain for Green Project” (GGP) ecosystem restoration initiative in 2000. The Grain for Green Project aims to turn previously cultivated and grazed land back into forests and pastures by providing subsidies to farmers and nomads in the form of grain and cash. Later, in 2005, Qinghai provincial and China central governments also launched an eco-environmental protection project and established the Three Rivers Source Region Reserve (TRSRR), comprised of the headwaters of the Yellow River, the Yangtze River, and the Mekong River that lie side by side in southern Qinghai Province. These efforts represent an intensive human intervening aimed to ameliorate ecosystem degradation. However, it is unknown to what extent has the intensive intervening influenced water resources in the region.

A few studies have examined impacts of both climate change and land cover change on UYRB hydrology. For example, Zhao et al. (2009) used sensitivity-based analysis and a dynamic water balance model to study impacts of climate change as manifested by precipitation and potential evapotranspiration (ET) change and impacts of vegetation change, respectively, on streamflow at the Jimai, Tang Nai Hai, and Lan Zhou hydrometric stations in the UYRB in 1956–2000. Their results showed that
vegetation change played a secondary role in affecting changes in streamflow at Tang Nai Hai while both climate change and vegetation change were important factors at Lan Zhou. On the other hand, Zheng et al. (2009) applied the concept of climate elasticity to assess impacts of climate and land surface changes on UYRB streamflow from 1960 to 2000, showing that land use changes played a more important role in reducing streamflow during the 1990s. Inconsistencies between these studies stem from the different methods, time periods, and base scenarios used. None of them examined the influences of the recent large-scale human intervening on streamflow. This study, by applying a physically-based macro hydrological model to the UYRB accompanied with rigorous calibration and validation processes, aims to identify changes in observed streamflow at several locations and to explore causes of streamflow changes by examining climate and land cover change impacts. Furthermore, this study will reveal the contribution of snowmelt on streamflow.

2. Study area

The UYRB, situated above Jingyuan County, Gansu Province (JYR, 36°45’ N, 104°45’ E, 1400 m above mean sea level), was the area investigated in this study (Figure 1). Previous studies focused mainly on the Yellow River Basin above TNH where population density is low (6 /km² based on the 2003 census data). This study also includes areas below TNH and above JYR where two economic centers, Xining City and Lanzhou (LZH) City are located. In total, about 5.8 million people live in the two cities and the surroundings.
According to a 90-m elevation map, UYRB elevation ranges between 1400 m and 6300 m and drops off from the southwest to the northeast. The TNH hydrometric station (35°30’ N, 100°9’ E, 2700 m) is located just above the Longyang Gorge Reservoir (0.247 km³ water storage capacity) in Qinghai Province. The Ji Mai (JMA, 33°46’ N, 99°39’ E, 3955 m), Tang Ke (TAK, 33°25’ N, 102°28’ E, 3435 m), and Ma Qu (MAQ, 33°58’ N, 102°5’ E, 3435 m) hydrometric stations are located upstream of TNH. Streamflow measured at TNH and the area above had not been affected by dams or major irrigation diversions and as a consequence is largely reflective of natural conditions. Between TNH and JYR, where LZH gauge is located (36°04’ N, 103°49’ E, 1600 m), human activities, such as irrigation diversions and damming, are relatively intense. Areas of contribution for JYR, LZH, TNH, MAQ, TAK, and JMA are approximately 240,000 km², 220,000 km², 120,000 km², 109,000 km², 7,800 km², and 57,000 km², respectively.

The entire UYRB is situated within a semiarid region with an approximate total annual precipitation of 500 mm and an approximate annual mean air temperature of 0.7°C. Large systems that control the weather and climate are the subtropical westerly jet stream, the El Niño–Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Arctic Oscillation (AO) in the winter and ENSO, the subtropical westerly jet stream, the East Asian summer monsoon, and the South Asian summer monsoon in summer (Cuo et al., 2012).

UYRB land cover is dominated by temperate and alpine grasslands and alpine meadows (Zhou et al., 1987). The geological feature of the study area is principally
characterized by Triassic flysche sandstone. In general, UYRB soil is poorly
developed and relatively young when considering its overall lifespan. Sand is the
main component of soil texture in the region (FAO, 2008). Fine, medium, and coarse
gravel are also common to this region. Soil textures in the top 1 m are primarily sandy
loam in the west and loam in the east (FAO, 2008).

3. The Variable Infiltration Capacity (VIC) model

The Variable Infiltration Capacity model (VIC, Liang et al., 1994, 1996) was
employed for this study to investigate and understand impacts of climate change and
land cover transition on UYRB hydrology. VIC is a macroscale physically-based
hydrological model developed to solve water and energy balances as a whole. It has
been applied in many parts of the world in a range of climate conditions and
resolutions (Abdulla and Lettenmaier, 1997; Lohmann et al., 1998b; Matheussen et al.,
2000; Durre et al., 2000; Nijssen et al., 2001; Rhoads et al., 2001; Christensen et al.,
2004; Su et al., 2005; Haddeland et al., 2006; Adam et al., 2007; Wen et al., 2011).
VIC has been demonstrated to perform especially well in simulating streamflow in
humid environments (Abdulla and Lettenmaier, 1997). One of its appealing features
relevant to the current study is its capacity to simulate cold region hydrology by
incorporating mechanisms of frozen soil and snow accumulation and ablation
(Cherkauer and Lettenmaier, 1999; Cherkauer et al., 2003).

The infiltration rate for VIC is specified as a power function of the maximum
infiltration capacity and basin saturation area, and is controlled by an empirical
parameter (Zhao et al., 1980). Hence, changes in the infiltration rate provide
indication of soil moisture spatial variability. For VIC, baseflow responds both
linearly and nonlinearly to soil moisture changes depending on bottom layer soil
moisture conditions and flow rates, which are realized using the empirical Arno model
conceptualization (Todini, 1996). VIC solves both energy and water balances for
individual cells of a grid that represents a watershed. The streamflow routing model
developed by Lohmann et al. (1998a) can be launched after VIC concludes energy
and water balance calculations for a watershed. Input data for VIC include
meteorological forcing data, vegetation and soil characteristic parameters. For this
study, a modified version of VIC (v4.1.1) was used that also takes into account UYRB
irrigation practices as well as being able to distinguish between snowmelt and rainfall
surface runoff from which to investigate hydrological dynamics of this particular
region.

Land cover and land use are represented by land cover/use class IDs, areal
fractions, vegetation root zone depths, and root zone fractions of individual cells.
Other land cover parameters involved in water and energy balances such as leaf area
index (LAI), stomatal resistance, etc., are specified for each land cover/use class and
referenced by class IDs. When irrigated cropland is present within a cell, irrigation
timing (at a monthly time step) and the amount of water required are also listed for the
cell. Land cover/use classes, areal fractions of classes, root zone and other
characteristics involved in the energy and water balances for certain locations
represented by grid cells will be different under different land cover scenarios. Such
differences will cause hydrological processes to change in areas of interest, for which
VIC can be used to simulate and investigate.

According to the Qinghai Local Disaster Classifications (Government Document ID: DB63), when soil moisture is reduced to 60% below field capacity, the soil is considered to be under a drought condition and irrigation is required. However, in the northern Tibetan Plateau region, irrigation is not a major agricultural practice. This is especially true throughout Qinghai Province where 80% of the UYRB is situated, for which approximately only one-third of the total agricultural land (~5333 km²) is irrigated. Nevertheless, the effect of irrigation on hydrological processes needs to be considered in view of the GGP and other conservation projects. For this study, irrigation and its effects are accounted for in VIC through the modifications discussed below.

Irrigation in the UYRB usually takes place during the months of February, March, and June. To model irrigation, a scheme is employed that combines irrigation timing, surface runoff, and soil moisture redistribution, depending on the ratio of soil moisture to field capacity. Specifically, during these irrigation months, a comparison is first made between the previous 10 day averaged top root zone soil moisture or accumulated 10 day precipitation and 60% field capacity in the top root zone for grid cells that contain irrigated cropland. If the 10 day averaged soil moisture or total precipitation is less than 60% of field capacity, the amount of water equivalent to 60% of field capacity is extracted from surface runoff (that would have been routed to stream channels) and is added to the top root zone soil moisture. The added top zone
soil water content would then be fully involved in the processes of soil evaporation, runoff generation, and root zone soil water flux. The remaining surface runoff would subsequently be routed to the stream channel. Note that the 60% threshold and irrigation months are set as input parameters and therefore can be conveniently adjusted if required.

Distinguishing between snowmelt runoff and rainfall runoff is based on the amount of inflow to root zones in a time step. For example, if snowmelt and runoff production takes place in a time step where no rainfall is present, surface runoff would then be considered as snowmelt runoff only. If snowmelt and rainfall both take place in a time step, then surface runoff would then be adjusted by the ratio of snowmelt inflow to the total soil moisture from which total surface runoff is generated. If no snowmelt is present, runoff would then be produced by rainfall only.

4. Data

4.1 Forcing data and streamflow

This study used a gridded historical dataset at 0.25° × 0.25° resolution generated for the northern Tibetan Plateau (Cuo et al., 2012) to drive VIC simulations. The dataset contained daily precipitation, 2 m temperature maxima and minima, and 10 m wind speed from 1957 to 2009. Gridded data were created from observations taken from 81 meteorological stations situated within the northern Tibetan Plateau using the Synographic Mapping System (SYMAP, Shepard, 1984) and elevation-based gridding processes to account for changes in temperature, wind speed, and warm and wet
season precipitation over varying elevations (Cuo et al., 2012). Station observations were obtained from the China Meteorological Administration and the Qinghai Institute of Meteorology and are fully quality controlled. In order to examine impacts of climate change on UYRB water resources, two sets of climate forcing data representing climate conditions for the beginning and ending of the period between 1957 and 2009 were also generated, using the gridded data. These two sets of data are referred to as “climate 1957” and “climate 2009,” respectively, and were created as follows: first, linear monthly trends in precipitation, temperature maxima and minima, and wind speed were calculated for the period between 1957 and 2009; second, the pivotal year 1957 (or 2009) was chosen as the baseline upon which trends were removed from (or added to) daily time series using a linear relationship to generate climate 1957 (or 2009).

Daily streamflow data for JMA (1959–2009), TAK (1981–2009), MAQ (1960–2009), TNH (1956–2009) and LZH (daily: 1956-1997; monthly: 1956-2000) were originally obtained from the Hydrological Bureau of the Ministry of Water Resources of China. TNH measurements were used to calibrate VIC while model validation was carried out at JMA, TAK, MAQ and TNH. The choice of TNH as the calibration site was the result of (a) the comparatively little human activity that took place upstream of TNH, (b) that it possessed the longest streamflow measurement record available and (c) that it covers the largest area suitable for macro-scale modeling.
4.2 Vegetation and soil data

For this study, VIC vegetation and soil parameters were adopted from ftp://ftp.hydro.washington.edu/pub/HYDRO/models/VIC/Veg/veg_lib and http://www.hydro.washington.edu/Lettenmaier/Models/VIC/Documentation/SoilPara m.shtml, respectively. Soil textures were obtained from FAO (2008).

The land cover map for 1994 (hereafter referred to as “land cover 1994”) was downloaded from http://www.glcf.umd.edu/data/landcover/. This global land cover classification dataset was compiled in 1998 using imagery from Advanced Very High Resolution Radiometer (AVHRR) satellites acquired between 1981 and 1994 (Hansen et al., 2000). Evaluations of land cover data using field measurements obtained by United States of America and European food and agricultural agencies have shown to be of good quality throughout most parts of the world except for Africa where data quality appeared to be relatively inferior (Hansen et al., 2000).

Since reliable land cover data during late 1950s and early 1960s do not exist, we constructed land cover 1960s using land cover 1994 based on previous finding that the major land cover change in the UYRB and the surroundings between the 1960s and the 1990s has been grassland degradation (Chen and Liu, 2007; Dong et al., 2005; Li and Liu, 2004, Fu et al., 2007). The construction of land cover 1960s involved several steps. First, the population of the UYRB was obtained for 1960 and 1994 based on census data from the China National Bureau of Statistics for 1964, 1990 and 2000 (http://www.stats.gov.cn/tjb/zkpf/zkpsb). Second, the population ratio between 1960 and 1994 was computed and a scaling factor was obtained by one minus the
population ratio. Third, the areal coverage for all land cover types except for grassland and forest in land cover 1994 was multiplied by the scaling factor and the portion was assigned as grassland for the 1960s. The converted land is about 10% of the whole UYRB area.

For this study, cropland was divided into irrigated and non-irrigated cropland using an elevation threshold of 2700 m. This was based on the fact that irrigated cropland is usually distributed alongside river banks in the UYRB where elevation is lower than 2700 m. Table 1 provides land cover types, percentage coverage, and cell numbers of each classification over the study area for land cover 1994. Dominant UYRB land cover types are grassland and shrubland (Table 1), followed by cropland and woodland.

5. Analysis

Long-term Mann-Kendall trends in monthly and annual streamflow, monthly to annual flow ratios, and day representing the midpoint of yearly mass flow were examined to detect changes in observed streamflow over the past decades. The monthly to annual flow ratio and day representing the midpoint of yearly mass flow, computed following Stewart et al. (2005), represented contributions of monthly flow to the annual total and the overall distribution of flow during a one-year period, respectively. The mechanisms behind streamflow changes were explored through the examination of VIC simulated water balance terms under two climate (climate 1957 and 2009) and two land cover scenarios (land cover 1960s and 1994).
Historical daily meteorological forcing data and land cover 1994 were used during calibration. VIC was calibrated using daily TNH streamflow measurements from 1987 to 1997. Daily and monthly streamflow measurements for JMA, TAK, MAQ, and TNH were also employed to validate VIC. Snow estimates from satellites were used to evaluate VIC simulated snow cover.

The delta approach was utilized for examining the responses of water balances to changes in temperature, precipitation and wind speed to better understand climate change impact. Delta values were the mean monthly changes in each variable between climate 2009 and 1957. For example, to examine temperature sensitivity, the mean changes in monthly temperature between climate 2009 and 1957 were added to the daily temperature in climate 1957, while keeping precipitation and wind speed in climate 1957. Likewise, precipitation and wind speed were perturbed in the same way. The response of water balance terms to changes in temperature, precipitation and wind speed can then be obtained by investigating the differences in water balance terms between the perturbed runs and the control runs.

More than 50 year climate records were applied to represent climate change impacts on hydrology. It was assumed that when climate gradually changes over a long period of time, the beginning and ending conditions represent the beginning and ending status of changes. For this study, the beginning (1957) and the ending (2009) of climate records were chosen to represent both historical and current climate conditions. Two simulations were subsequently carried out using climate 1957 and climate 2009 alongside land cover 1994 as a way to isolate impacts of climate change.
on water balances and streamflow.

Land cover 1960s and 1994 were used to study long term and recent land cover change impacts on streamflow. Recent land cover change was assumed to be the result of the GGP and TRSRR implemented in Qinghai Province. To isolate long term and recent land cover change effects from climate change effects, two simulations were conducted using land cover 1960s and land cover 1994 alongside historical climate records. Both simulations were compared to observations for the same time period, i.e., simulations using land cover 1960s (1994) were compared to streamflow observations beginning in 1960 (1994). It was assumed that observed streamflow reflects the influence from both climate and land cover change, and the simulations with land cover fixed only contain the climate change impacts. The residuals between the observations and the simulations represent the isolated land cover change impacts for the study period (Bowling et al. 2000; Cuo et al., 2009). Here, only streamflow was examined in the analysis as other water balance terms were not observed.

6. Results

6.1 Trends in observed streamflow

Trends in observed streamflow for all five stations are provided in Figure 2. Most monthly trends were negative above TNH, with statistically significant negative trends were found in June, July, September, and October for TAK and January through March for MAQ. Compared to other months, JMA, TAK, MAQ and TNH stations experienced noticeably large negative trends between July and October,
although these trends were not statistically significant except for TAK. Relatively
large but statistically insignificant positive trends were noted only in June for JMA,
MAQ, and TNH. LZH experienced significantly negative trends in June–October.
During December through May, however, statistically significant positive trends were
noted for LZH, which was not the case at the other stations. All stations reported
negative annual trends, and they are statistically significant for TAK, MAQ and LZH
(Figure 2).

The monthly to annual streamflow ratio (Figure 3) showed small trends that to a
large extent followed patterns of monthly streamflow for all stations. Negative trends
primarily occurred between July and October, the wet season, with September
exhibiting the largest or nearly the largest trends for all stations (statistically
significant at TAK and LZH). Positive trends predominantly occurred during the dry
season between November and June (with most statistically significant trends noted
for TAK and LZH). June corresponded to the largest positive trends for all stations
except TAK where a small negative trend was detected (Figure 3). Such distributions
in ratios appear to suggest that despite negative trends in monthly streamflow at most
stations as shown in Figure 2, positive contribution to annual streamflow have been
progressively on the rise in the early part (compared to the middle part). This is also
consistent with decreasing trends for days representing the midpoint of observed mass
flow (which occurred progressively earlier) for all five stations (lower right panel in
Figure 3), possibly indicating changes in the UYRB hydrological regime.
6.2 Calibration and validation of VIC

Figure 4 provides observed and VIC simulated daily and monthly streamflow for 1987 - 1997 (calibration period so as to cover the 1994 land cover period) and for 1977 - 1987 (validation period) for TNH (statistics provided in Table 2). Simulations during the calibration period captured the observed evolution and magnitude reasonably well for both daily and monthly time scales. Rising limbs of daily hydrographs and baseflow were simulated especially well. Both observations and simulations also exhibited generally decreasing trends in TNH streamflow between 1987 and 1997. Deficiencies in VIC simulations included overestimation of descending limbs for 1990, 1992, 1994, 1995, and 1997, and mismatched peak flows for 1989, 1992, 1993, 1995, and 1997, which was most likely due to errors in extreme precipitation in the forcing data. During the calibration period, mean model bias was 4% for both daily and monthly streamflow (Table 2). Correlation coefficients (R), root mean square errors (RMSE), and Nash-Sutcliffe (NS) coefficients for daily series within the calibration period were 0.86, 246.1 m³s⁻¹, and 0.74, respectively. At a monthly time step, statistics slightly improved (Table 2). Table 3 lists calibrated parameters and their values.

During the validation period, rising limbs and baseflow were also simulated well (Figure 4). Peak flow simulations improved during the validation period in comparison to the calibration period. Mean model bias was −1% for both daily and monthly time series, and R, RMSE, and NS measurements were 0.89, 295.5 m³s⁻¹, and 0.80, respectively, for daily streamflow (Table 2). The slightly better statistical values
on monthly streamflow were due to the smoothing out of daily variability.

Model statistics were reasonably satisfactory for JMA, TAK, and MAQ throughout the validation period considering that VIC was not calibrated specifically for these stations (Table 2). For JMA and TAK, capturing streamflow from smaller sub-basins (see Fig. 1), simulated streamflow exhibited the lowest NS among all stations. This was likely due to the coarse resolution (0.25 by 0.25 degrees) represented by VIC. On the other hand, the model captured temporal variability of observed streamflow for JMA and TAK reasonably well as reflected by the high R in excess of 0.68 for both daily and monthly time series. For MAQ, the model exhibited rather similar statistics to those for TNH (Table 2). The good performance of the VIC at MAQ and TNH implies that the model in its current settings can be used to study streamflow in un-gauged basins of similar physical properties.

In order to evaluate the performance of VIC in simulating snow, MODIS snow cover data (MODIS/Terra Snow Cover L3 monthly 0.05 degree Grid MYD10CM) for 2003–2009 and Northern Hemisphere 25-km EASE-Grid Weekly Snow Cover and Sea Ice Extent Version 3 data for 1972–2006 (Armstrong and Brodzik, 2005) were used. The intention of using both EASE-Grid and MODIS snow measurements was to not only include as many sources of snow data as possible but also to extend the period of UYRB snow cover estimation so that long-term VIC simulations could be evaluated. Figure 5 provides satellite estimated and VIC simulated mean annual and monthly snow cover for the area above JYR. Agreement between MODIS estimations and VIC simulated annual snow cover over the short overlapping period was evident.
EASE-Grid annual snow exhibited noticeable underestimation when compared to MODIS measurements and VIC simulations. Caution had to be taken when interpreting mean monthly snow cover because a different time period was used for EASE-Grid estimation. However, Figure 5 demonstrates that VIC simulations satisfactorily captured seasonal cycles in both satellite estimations. Overestimation was detected in VIC for January, February, November, and December when compared to MODIS measurements. During warmer months (May to September), VIC simulated snow cover was smaller than MODIS estimations but matched EASE-Grid snow data reasonably well. Differences between model simulated and satellite estimated monthly snow cover did not exceed 15% for any given month. Nevertheless, it was understood that both satellite estimations and VIC simulations contained large uncertainties concerning snow cover, making further improvements to the approach necessary.

The above analyses suggest that in general VIC performance was reasonable in resolving observed UYRB streamflow and snow cover. The following sections will use the VIC to explore possible mechanisms behind observed streamflow changes.

6.3 Climate change scenarios

Figure 6 shows annual precipitation, annual mean temperature (average of maximum and minimum temperature), and wind speed for the historical period (1957–2009), climate 1957, and climate 2009 for the area above JYR. Figure 6 reveals that in general linear trends occurred in annual precipitation and annual mean
temperature for the historical period. Annual precipitation increased by approximately 20 mm for climate 2009 compared to climate 1957 while annual mean temperature rose by approximately 1.6°C for climate 2009 compared to climate 1957. Wind speed exhibited an abrupt change around 1969 (owing to the extensive anemometer upgrade that took place across China at that time). It decreased nearly linearly after that point in time. Wind speed on average decreased by 0.3 m s\(^{-1}\) for climate 2009 compared to climate 1957. F-tests showed that trends in annual mean temperature and wind speed were statistically significant at \(\alpha=0.05\). Figure 6 further demonstrates that temperature and precipitation in climate 1957 and climate 2009 well represented the beginning and end status of the gradual climate change that occurred between 1957 and 2009.

In order to examine the effect of abrupt wind speed change around 1969, an adjusted wind speed time series was created by adding the monthly averaged differences between pre-1969 and 1969 - 1970 to the daily pre-1969 wind speed. The linear monthly trends existed in 1957-1968 wind speed were remained in the adjusted time series. Post-1969 wind speed data were not changed.

VIC simulations driven by the wind speed-adjusted and the original forcing data were compared and the differences in water balance terms were computed. Results indicated that among the various water balance terms, only ET was affected the most and the differences in ET were less than 8 mm in annual averages for all sub-basins. Monthly averaged water balance terms were hardly affected by the adjustment due to the short record of 1957-1969 compared to 1969-2009. We concluded that the wind speed abrupt change around 1969 had negligible effects on the simulated annual and
seasonal water balances and thus the original wind speed was used in subsequent analysis.

6.4 Response to climate variable changes

In order to understand climate change impact, it is necessary to investigate how water balance terms in sub-basins respond to changes in temperature, precipitation and wind speed separately as shown in Fig. 6. Table 4 presents the relative changes in water balance terms after temperature, precipitation and wind speed were perturbed. It is clear that increased temperature reduced available water resources and increased ET consumption (Table 4), in consistent with the findings by Yang et al. (2011) who reported that increased ET corresponded to increased temperature over the Tibetan Plateau in recent decades. On the other hand, increased precipitation and decreased wind speed resulted in more available water. Table 4 also revealed that over the UYRB temperature changes impacted water balance terms the most, followed by precipitation changes and the least by wind speed changes. Among the sub-basins, the impacts from temperature increase appeared to be more or less uniform especially for baseflow and ET; while precipitation changes affected water balance more for JMA than for other sub-basins, due to spatially varied precipitation changes as reported by Cuo et al. (2012).

6.5 Climate change impacts

Simulated differences in water balance terms between climate 2009 and climate
1957 for JMA, TAK, MAQ, TNH and LZH are provided in Figure 7. Because of the short observation period at TAK (1981 – 2009), JMA, MAQ, TNH and LZH were focused on to determine relationships between streamflow and water balance term changes. Terms examined included annual and monthly precipitation, ET, total surface runoff (runoff hereafter), baseflow, snowmelt runoff, and rainfall runoff. Except for TAK, all other basins exhibited increasing annual precipitation from 1957 to 2009, with JMA showing the largest increase (left panels in Figure 7). All basins showed increasing annual ET but decreasing annual runoff, annual baseflow, and annual rainfall runoff except for JMA. Reductions in annual baseflow were slightly larger than those in annual runoff for TAK, MAQ, and TNH. Annual snowmelt runoff exhibited negligible changes for all basins, giving rise to nearly identical changes in runoff and rainfall runoff. This indicates that UYRB rainfall runoff predominates changes in annual total surface runoff. ET changes far exceeded precipitation change for MAQ, TNH, and LZH, which, together with small decreases in runoff and baseflow, could explain large decreases in observed annual streamflow for MAQ, TNH and LZH (Figure 2). For JMA, on the other hand, large increases in ET and precipitation virtually canceled each other out, which is likely responsible for the small changes observed in annual streamflow for JMA (Figure 2).

Seasonally, water balance changes in the wet and warm season (May – September) dominated over those in the dry and cold season (October – April, right panels in Figure 7). Precipitation notably decreased between July and September after small increasing in the first half of the year (from January to June) for MAQ, TNH,
and LZH (Figure 8). For all basins, May through November corresponded to high ET. Runoff and rainfall runoff (identical in both magnitude and pattern for all seasons) exhibited decreasing trends between July and September for TAK, MAQ, TNH, and LZH, which are consistent with changes in precipitation. For JMA, changes in runoff and rainfall runoff virtually amounted to null. Little change was detected for seasonal snowmelt runoff between climate 2009 and climate 1957 indicating that the contribution of snow to streamflow change in the UYRB was little, differing from the Puget Sound basin situated in the PNW in the United States of America. Baseflow increased slightly in May and June and then decreased in the second half of the year with peaks occurring in September or October for all sub-basins. Such changes in baseflow and precipitation may explain the forward movement of the day representing the midpoint of yearly mass flow as it was identified in the observed streamflow (see Figure 3). As a further demonstration of this effect, the simulated VIC midpoint day of yearly mass flow occurred 7, 8, 8, 6, and 5 days earlier for climate 2009 than for climate 1957 at JMA, TAK, MAQ, TNH and LZH, respectively.

When comparing Figure 2 to Figure 7, it becomes clear that the large decreases in observed streamflow for JMA, MAQ, TNH and LZH that occurred between July and September were the result of increased ET and reduced precipitation. For June, statistically insignificant increases for JMA, MAQ, and TNH (Figure 2) was likely due to increased precipitation (Figure 7).

In January - May, observed streamflow exhibited negligible increases for JMA, but relatively large decreases for MAQ and TNH due to the change in baseflow
(Figures 2 and 7). For LZH, precipitation changes nearly canceled out ET changes in January – May (Figure 7), whereas observed streamflow still showed significant increases during the same time period (Figure 2), indicating that climate change alone could not explain observed streamflow changes.

In October, precipitation falls as snow in the most part of UYRB and it offered little contribution to overall streamflow. On the other hand, increased ET in October reduced baseflow, hence reducing streamflow. November saw slight decreases (increases) in precipitation (ET) in all basins while little change in precipitation and ET was measured in December (Figure 7). Consequently, observed streamflow for all sub-basins except LZH showed slight decreases in November and virtually no changes in December (Figure 2). For TAK, VIC simulated changes in water balance terms could explain the observed trends rather well (Figures 2 and 7). Unlike the other sub-basins, observed streamflow trends for LZH could not be accounted for by climate change scenarios, likely indicating the important influence of land cover change for LZH.

### 6.6 Land cover change impacts

Observed and simulated annual streamflow using historical climate record and land cover 1960s is shown in Figure 8. The similarity between observed and simulated streamflow for JMA, MAQ and TNH, and large difference for LZH indicates that land cover change impacts were small above TNH but large for LZH. Differences in land cover change impacts above and below TNH were likely related to
differences in population density: low density above TNH but much high density and hence intense water use activity below TNH. Differences between the simulations and the observations started to amplify for JMA, MAQ, TNH and LZH after 1980 when economy started to boost. Since 1980s, streamflow has been increasingly diverted to reservoirs or for irrigation, and much of the land in the lower reach has been transformed to residential area, cropland.

Difference between observed and simulated streamflow after 2000 when conservation projects were implemented was visually similar to that in the 1980s and 1990s for JMA, MAQ and TNH (Figure 8), indicating that the conservation projects have yet to exert significant influences on annual streamflow. Simulations using land cover 1994 and historical climate records show the same results (not shown).

Trends of monthly streamflow residual (observation minus simulation) describe land cover change impacts over the past decades. A positive (negative) residual trend suggests positive (negative) land cover change impacts, as the observations and simulations both experience the same climate change and assuming a linear climate and land cover change relation.

Figure 9 presents the trends in residual for 1957-2009 (top four panels,) and 1994-2009 (bottom four panels), representing the long-term and recent land cover change impacts, respectively. Over the long-term, residual had been mostly decreasing in the warm season, indicating negative impacts of land cover change on streamflow. In the cold season for JMA, MAQ and TNH, residual had been mostly increasing from October through December but decreasing from January through
April. It seems that for JMA, MAQ and TNH, land cover change impacts are similar to climate change impacts in the warm season by reducing streamflow. For LZH, the trends were always the largest amongst the sub-basins and consistence was noted between residual trends (Figure 9) and observed trends (Figure 2) for both the monthly and annual time scales, further corroborating that land cover change impacts also play an important role for this sub-basin.

Differences were noted between the long-term and recent land cover change impacts (Figure 9), with more positive monthly and annual trends after 1994. This indicates that the GGP and TRSRR may have started to exert some positive effects on water resources in the region, although a longer time may be needed for the effects to fully emerge and be significant.

7. Discussions

Simulations using historical forcing records show that in November – April, streamflow is dominated by baseflow. In March and April (May) for TAK, MAQ, TNH and JYR (JMA), snow melt runoff is about 10-35% of the total month streamflow, which only accounts for about 5-13% of the total annual streamflow in the respective sub-basins. This is largely consistent with the findings by Lan et al. (1999) who showed that during late March – early June snow melt contributed less than 40% of the streamflow for TNH, and also corroborates Immerzeel et al. (2010), with an extended period of data. Snow melt contribution is only important during the melting season before the onset of the raining season when baseflow still dominates.
The major contributions to water resources in the UYRB are rainfall runoff and baseflow.

The limited melt water contribution in this region was most likely due to the reasons provided as follows. First, roughly 85% of annual precipitation takes place during the wet and warm season when average air temperature is approximately 9°C. Only 15% of annual precipitation is recorded in the dry and cold season. There are essentially no glaciers in the UYRB (Immerzeel et al., 2010). Second, during the wet and warm season, only 5% precipitation falls as snow. Thirdly, average air temperature remains −5°C in the dry and cold season, much lower than 1.6°C being the lower limit for rain to occur and 3.4°C being the upper limit for snow to occur (Cuo et al., 2012). The limited contribution can also be explained by the elevation-area relationship (Casola et al., 2009). According to Lan et al. (1999), in late April, snow covers areas with elevation above 4000 m, and average snow line is about 5000 m in the UYRB. Hypsometric analysis based on 1-km elevation map shows that about 34% of area in the UYRB has elevation above 4000 m, but areas with elevation greater than 5000 m are less than 1%. We argue that on top of the limited snow amount, areas to keep snow are also limited in the UYRB.

8. Conclusions

UYRB hydrological regimes have exhibited changes over the past decades as manifested by decreases in annual streamflow, a progressively greater overall streamflow during the early part of the year (compared to the latter part), and the
forward movement of the day representing the midpoint of yearly mass flow. These changes in observed streamflow were determined to be combined effects of changes in precipitation, ET, rainfall runoff, and baseflow caused primarily by climate change in the area above TNH. Snowmelt runoff plays only a minor role in UYRB hydrology. Below TNH where human activity is relative intense, land cover change impacts become important. The GGP and TRSRR have started to show positive effects on water resources in the UYRB.

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Zhou, X., Wang, Z., and Du, Q., 1987. Qing Hai Vegetation, Qing Hai Ren Ming Publisher, Xi Ning, Qing Hai, China.
Figure 1. Location and elevation of the upper Yellow River basin. Major rivers originating from the Tibetan Plateau are displayed in the top panel. Blue lines in the bottom panel represent the Yellow River channels while black line outlines the upper Yellow River basin. Triangles inside the basin denote the Ji Mai station (JMA), Tang Ke station (TAK), Ma Qu station (MAQ), and Tang Nai Hai station (TNH) in Qing Hai Province, and Lan Zhou station (LZH) in Gan Su Province. Triangle in the northeast of the basin represents the outlet of the upper Yellow River basin in Jing Yuan County, Gan Su Province (JYR).


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Table 1. Land cover types, areal percentage and cell numbers for land cover 1994 in the upper Yellow River basin.

<table>
<thead>
<tr>
<th>Land Cover (ID)</th>
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<th>Percent coverage (%) (cell numbers)</th>
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<td>Water (0)</td>
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<tr>
<td>Evergreen needle leaf (1)</td>
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Table 2. Statistics in the calibration and validation periods.

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<th>P_change (%)</th>
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