Potential natural vegetation dynamics driven by future long-term climate change and its hydrological impacts in the Hanjiang River basin, China

Fei Yuan, Liliang Ren, Zhongbo Yu, Yonghua Zhu, Jing Xu and Xiuqin Fang

ABSTRACT

Vegetation and land-surface hydrology are intrinsically linked under long-term climate change. This paper aims to evaluate the dynamics of potential natural vegetation arising from 21st century climate change and its possible impact on the water budget of the Hanjiang River basin in China. Based on predictions of the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (IPCC-SRES) A1 scenario from the PRECIS (Providing Regional Climates for Impact Studies) regional climate model, changes in plant functional types (PFTs) and leaf area index (LAI) were simulated via the Lund-Potsdam-Jena dynamic global vegetation model. Subsequently, predicted PFTs and LAIs were employed in the Xinanjiang vegetation-hydrology model for rainfall–runoff simulations. Results reveal that future long-term changes in precipitation, air temperature and atmospheric CO2 concentration would remarkably affect the spatiotemporal distribution of PFTs and LAIs. These climate-driven vegetation changes would further influence regional water balance. With the decrease in forest cover in the 21st century, plant transpiration and evaporative loss of intercepted canopy water will tend to fall while soil evaporation may rise considerably. As a result, total evapotranspiration may increase moderately with a slight increase in annual runoff depth. This indicates that, for long-term hydrological prediction, climate-induced changes in terrestrial vegetation cannot be neglected as the terrestrial biosphere plays an important role in land-surface hydrological responses.

Key words | climate change, evapotranspiration, LPJ-DGVM, runoff, vegetation, Xinanjiang hydrologic model

INTRODUCTION

Observational evidences from all continents reveal that ongoing climate change has a heavy impact on terrestrial hydrology, including increased runoff and earlier spring peak discharge in a significant number of glacier and snow-fed rivers as well as increased flood risk in many regions where annual precipitation tends to decrease (IPCC 2007). These effects will exacerbate current stresses on water resources arising from population growth, economic development and land-use change such as urbanization (IPCC 2007). Thus, in formulating guiding policies for climate change adaptation, it is essential to project hydrological effects under climate change and associated changes in terrestrial vegetation systems (Hickler et al. 2009).

Future long-term climate change may affect terrestrial hydrology in two ways: direct climate change impact and indirect vegetation impact. Due to direct climate change impact, changes in atmospheric forcing (mainly precipitation and air temperature) alter the input of land-surface hydrology and subsequently influence evapotranspiration and runoff.

Through indirect vegetation impact, the functioning, composition and spatiotemporal distribution of terrestrial
vegetation change gradually in response to long-term climate change (Roelandt 2001; Pompe et al. 2008) and CO₂ fertilization effect, and these vegetation alterations could further influence terrestrial hydrology. Recent warming has strongly affected global terrestrial vegetation, including such changes as leaf unfolding and poleward and upward shifts in plant ranges. According to satellite observations since the early 1980s, there has been a trend in various regions towards earlier ‘greening’ of vegetation in the spring linked to longer thermal growing seasons arising from recent warming (IPCC 2007). These vegetation changes potentially exert considerable effects on evapotranspiration and runoff in various ways, such as changing leaf area from which plants can intercept precipitation, modifying depth of soil from which plants can extract water and altering available energy by changing land-surface albedo (Gerten et al. 2004; Gedney et al. 2006).

Further, increasing CO₂ resulting from the combustion of fossil fuels tends to decrease stomatal conductance, potentially leading to lower transpiration and higher soil water content (Hickler et al. 2009). Free-air CO₂ enrichment (FACE) experiments (Ainsworth & Long 2005; Hickler et al. 2008) confirm that, at least in herbaceous vegetation and young forest stands, rising CO₂ increases vegetation productivity, potentially increasing leaf area from which water losses through transpiration occur. However, this CO₂ fertilization effect likewise depends on nutrient availability, either directly or via soil moisture conditions (Körner et al. 2007; Thornton et al. 2007). The physiological effect of increasing CO₂ concentration on plants has been identified as the chief cause of historical increases in continental-scale runoff (Gedney et al. 2006) and might lead to a further increase in continental runoff in various parts of the world under double-CO₂ emission scenarios (Gerten et al. 2004; Betts et al. 2007). A realistic assessment of spatiotemporal variation of terrestrial hydrologic elements under long-term climate change therefore requires that hydrological processes be linked with vegetation dynamics (Gerten et al. 2004).

Studies of future climate change impacts on terrestrial hydrology are typically based on macro-scale hydrological modeling driven by climate scenario simulations from general circulation models (GCMs) or regional climate models (RCMs) (Su & Xie 2003; Yuan et al. 2005; Jiang et al. 2007). However, transient vegetation change cannot be described by stand-alone macro-scale hydrological models; observed and remotely sensed vegetation or land-use data are usually employed as landcover status for the entire prediction period. These studies therefore cannot sufficiently capture hydrological effects resulting from variations in vegetation composition and distribution arising from long-term climate change (Gerten et al. 2004).

Recently, the potentially large effects of changes in vegetation structure and functioning when projecting future changes in hydrology have been addressed with the aid of dynamic global vegetation models (DGVMs) (Gerten et al. 2004, 2005; Betts et al. 2007; Hickler et al. 2009). Such DGVMs belong to biogeochemistry models with process-based representations of terrestrial vegetation dynamics and land–atmosphere carbon and water exchanges. They are generally able to simultaneously track transient changes in vegetation structure driven by climatic variability, together with water availability and atmospheric CO₂ content. Currently, DGVMs are widely used to study vegetation dynamics in response to environmental drivers globally (Gerten et al. 2005) or in continents or countries such as Europe (Morales et al. 2005), Africa (Delire et al. 2008; Scheiter & Higgins 2009), Sweden (Koca et al. 2006) and the US (Hickler et al. 2004; Bachelet et al. 2008). Within the DGVM framework, a large-scale hydrology parameterization is included through which evapotranspiration, infiltration, surface runoff and soil water gravity drainage are calculated in each computational grid cell.

DGVMs can therefore be adopted as a large-scale hydrological model, combined with climate simulations to explicitly explore possible vegetation-driven changes in terrestrial water balance in response to a warmer future climate. For example, the Lund-Potsdam Jena (LPJ) DGVM (Sitch et al. 2003) and Integrated Biosphere Simulator (IBIS) (Foley et al. 1996) have been employed for evaluating future global and continental water budgets under specific climate change scenarios (Gerten et al. 2004, 2005; Delire et al. 2008). Another option for assessing hydrological consequences resulting from environmental change is to drive DGVMs to produce a spatiotemporal distribution of vegetation and use this information to feed physically based distributed hydrological models for rainfall–runoff simulations. For example, LPJ-DGVM was
linked to the Yamanashi distributed hydrological model (YHyM) (Takeuchi et al. 1999) to quantify the evolution of vegetation cover and its hydrological impact on the Mekong River basin in the 21st century (Ishidaira et al. 2008).

Due to large regional differences in climate as well as economic and social development, China is facing a difficult outlook on water resources. This situation is especially true regarding water problems in north China where water supply per capita is less than half of that in Egypt (Varis & Vakkilainen 2001). To guide government policy for sustainable water resource utilization and development under future climate change, various studies have been conducted to predict possible hydrological responses to future climate change in river basins in China (Guo et al. 2002; Su & Xie 2003; Yuan et al. 2005). However, the important relationship between climate-driven vegetation dynamics and hydrology are seldom investigated explicitly.

The objectives of this paper are as follows: (a) to quantify the manner by which long-term climate change leads to possible changes in potential natural vegetation in the Hanjiang River basin (the main middle-route water source area of the South-to-North Water Diversion Project in order to alleviate water shortage in north China); and (b) to analyze the manner by which climate-driven vegetation dynamics influence terrestrial hydrology. To achieve these aims, LPJ-DGVM was used to simulate transitions in natural vegetation. Simulated plant functional types (PFTs) and leaf area indices (LAIs) were employed as input for the Xinanjiang vegetation-hydrology model (XVHM) for rainfall–runoff simulations.

MATERIAL AND METHODS

Study area

The Hanjiang River, located in central China, is the longest tributary in the middle reach of the Yangtze River. It has a total watercourse length of 1,577 km and a drainage area of 159,000 km² (Figure 1). Elevation within the watershed ranges from 20 m a.m.s.l. at the watershed outlet to 3,408 m a.m.s.l. at the top of the watershed divide. The watershed has a subtropical monsoon climate and is rich in water resources. Annual average precipitation is approximately 873 mm and average annual runoff is approximately 425 mm, of which 75% is concentrated from May to October.

The Danjiangkou Reservoir (Figure 1), situated in the upstream reaches of the Hanjiang River, has a volume of approximately $1.74 \times 10^{10}$ m$^3$ and total water surface area greater than 800 km$^2$. Due to its ample available water, the Hanjiang River was selected as the middle route in the South-to-North Water Diversion Project to alleviate water shortages in northern China around Beijing, Tianjin Municipality and Hebei Province. This middle route will transfer water from the Danjiangkou Reservoir along the Hanjiang River to north China. It is predicted that in the year 2050 approximately $1.30 \times 10^{10}$ m$^3$ of water can be diverted to Beijing and Tianjin as well as to other provinces such as Shanxi, Henan and Hebei in north China. The Hanjiang River basin has therefore become an important region for implementing the South-to-North Water Diversion Project, attracting a number of researchers to examine its water cycle under changing environmental conditions (Yuan et al. 2004).

The models

Two models were adopted to investigate possible natural vegetation changes arising from long-term climate change and its hydrological impacts: the Lund-Potsdam-Jena dynamic global vegetation model (LPJ-DGVM) and the Xinanjiang vegetation-hydrology model (XVHM).

The first model, LPJ-DGVM (Sitch et al. 2003), is a coupled biogeography-biogeochemistry model with process-based representations of large-scale terrestrial vegetation dynamics and land–atmosphere carbon and water exchanges.
Key ecosystem processes described in the model are seasonal vegetation growth, primary production, plant water productivity, mortality, carbon allocation and resource competition. To account for variations in structure and function among potential natural plants, 10 PFTs are determined by physiological, morphological, phenological, bioclimatic and fire-response attributes. Seasonal phenology of natural vegetation is dynamically simulated according to the variation of temperature and soil moisture (Sitch et al. 2005). Biomass production is calculated through a coupled photosynthesis–water balance scheme, which explicitly considers mutual dependence of transpiration and carbon uptake (Gerten et al. 2005).

A number of studies (Lucht et al. 2002; Gerten et al. 2004; Liang & Xie 2006) reveal that LPJ-DGVM is capable of generating reasonable global or regional vegetation dynamics. Gerten et al. (2004) demonstrated that LPJ-DGVM is capable of reproducing rational global runoff and evapotranspiration distribution. In this study, the model employed is LPJ V.1.2 in Fortran programming language, including core parameterization schemes of vegetation dynamics (Sitch et al. 2003) and updated hydrology of Gerten et al. (2004). The program was obtained from the website of the Potsdam Institute for Climate Impacts Research, Germany (http://www.pik-potsdam.de/research/cooperations/lpjweb/lpj-lpjml-versions).

Meanwhile, XVHM (Yuan & Ren 2009) is a modified version of the conceptual Xinanjiang rainfall–runoff model developed by Zhao (1992). It has been successfully and widely applied for flood forecasting, water resources estimation, design flood and field drainage and water quality accounting. This spatially distributed conceptual hydrological model is characterized by the concept of saturation runoff formation on repletion of soil moisture storage. It employs a runoff parameterization scheme similar to the original Xinanjiang model to calculate overland flow, interflow and base flow on each grid cell. The Muskingum–Cunge method (Cunge 1969) is utilized to route runoff from each grid cell to the watershed outlet. To consider the effects of land-surface characteristics on hydrological processes, XVHM employs the two-source evapotranspiration scheme (Mo et al. 2004; Yuan et al. 2008) to calculate canopy transpiration on dry vegetation canopy, evaporation of intercepted water on wet vegetation canopy and soil evaporation for various vegetation types. The kinematic wave method was adopted to describe the effects of vegetation on overland flow movement while the Manning roughness coefficient, which accounts for overland flow velocity, was assigned according to various vegetation types. In previous studies, XVHM has been employed to study the effects on land-use/cover change and climate change on water balance in the Hanjiang River basin (Yuan & Ren 2008, 2009).

Data

Basic forcing data for LPJ-DGVM consist of monthly gridded climatological data (0.5° × 0.5° grids) such as precipitation, air temperature and cloudiness and annual atmospheric CO₂ concentration. A monthly gridded climate dataset was derived from outputs of regional climate model Providing Regional Climates for Impacts Studies (PRECIS) (Met Office 2002). PRECIS consists of climate simulations of baseline (1961–1990) and future scenarios A1 (1991–2100), which are among future emission storylines in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) (IPCC 2001). These PRECIS outputs contain daily precipitation, daily maximum and minimum air temperature and daily cloud cover over 0.5° × 0.5° grids covering the whole Hanjiang River basin. Compared with the baseline years (1961–1990), PRECIS predicts an increase of 5.1 °C in the basin-averaged annual air temperature in the IPCC-SRES A1 scenario by the end of the 21st century. Further, basin-averaged annual precipitation also tends to increase under the IPCC-SRES A1 scenario. However, the Mann–Kendall trend test (Mann 1945; Kendall 1975) was conducted on monthly precipitation time series for 1991–2100 under the IPCC-SRES A1 scenario (Figure 2). This scenario demonstrates that precipitation remarkably increases during the period January–May, while it is inclined to drop during July–October. However, this decreasing trend is not significant. This PRECIS-simulated dataset was also used as atmospheric forcing for XVHM.

To calibrate and validate XVHM, observed meteorological data records at 15 stations and monthly streamflow data at the Baihe hydrological station within the Hanjiang River basin (Figure 1 and Table 1) were adopted. Other data used for LPJ-DGVM and XVHM simulations (e.g. soil texture and topography) are listed in Table 1.
Simulation design

Two sets of simulations were run in this study with the following objectives in mind: (1) to simulate potential natural vegetation variations in the baseline years (1961–1990) and in the 21st century (1991–2100) by using LPJ-DGVM with PRECIS-simulated climatology; and (2) to simulate the manner by which natural vegetation dynamics in the 21st century affects terrestrial water balance by XVHM, with LPJ-predicted vegetation information and PRECIS climate simulation results. Both simulations were performed over 0.5° × 0.5° grids covering the entire Hanjiang River basin (106°–114.5° E and 30°–34.5° N).

Given that climate conditions (mainly precipitation and air temperature) and atmospheric CO2 content are major determinants of plant growth (Scheiter & Higgins 2009),
simulations of potential natural vegetation dynamics in the 21st century were performed in two ways as described in Table 2. First, to account for the effects of climate condition changes on vegetation biogeography, LPJ-DGVM was driven by PRECIS-simulated climatology for 1991–2100 under IPCC-SRES A1; atmospheric CO₂ concentration was maintained at 1960s levels (317.2 ppm) for the entire simulation period (Scheme Clim in Table 2). Second, to quantify the CO₂ fertilization effect on vegetation, Scheme CO₂ (Table 2) was employed to run LPJ-DGVM with CO₂ concentration data under IPCC-SRES A1 scenario and climatic forcing equivalent to that of the baseline years (1961–1990).

The LPJ-DGVM was first run for 1000 years with PRECIS-simulated 1961–1990 climatology from an initial condition of bare ground to reach an approximate equilibrium of vegetation cover. From there, the model was driven for the baseline and the 21st century runs. This model outputs the spatiotemporal distributions of major PFTs and their cover ratios, together with LAIs at each grid cell. These vegetation variables were mainly analyzed at three time segments in the 21st century: 2020s (average of 2011–2040), 2050s (average of 2041–2070) and 2080s (average of 2071–2100). These figures were compared with those of the baseline run (1961–1990).

Subsequently, XVHM was employed to perform hydrological simulations in the 21st century with LPJ-simulated vegetation information (e.g. simulated PFTs and their coverage ratios and LAIs) as its input. To test sensitivity of hydrological elements to climate-driven vegetation change, two hydrological simulation schemes were adopted (Table 3). The scheme Hydro-with-veg assumes that vegetation dynamically varies in response to long-term climate change. It feeds XVHM with LPJ-simulated annual PFT cover percentage and monthly LAIs during 1991–2010. As the current version of XVHM does not consider the CO₂ physiological effect on evapotranspiration, LPJ-simulated vegetation information in the vegetation simulation Scheme Clim (Table 1) were used as XVHM inputs in this study. Another hydrological simulation scheme, Hydro-without-veg, neglects the possible variations in natural vegetation resulting from long-term climate change. It assumes that spatial distribution of PFTs in 1991–2100 is time-invariant, equivalent to that during the baseline years (1961–1990). Annual water budgets in these two hydrological simulation schemes were analyzed and compared.

Prior to running XVHM, three types of parameters must be determined. Vegetation-related parameters such as minimum stomatal resistance, canopy albedo, monthly roughness length, monthly zero-plane displacement, vegetation height and maximum leaf width were derived from the land data assimilation system (LDAS; http://ldas.gsfc.nasa.gov/gldas/GLDASmapveg.php). Soil parameters such as effective porosity, field capacity and wilting point soil moisture content for each soil texture class were determined through monthly streamflow curve and free water storage curve, as well as maximum free water storage, were determined through monthly streamflow simulation at the Baihe streamflow station. The station is situated in the upper reach of Hanjiang River and controls a drainage area of 59,115 km² (Figure 1). Yuan & Ren (2009) proved that XVHM effectively simulates monthly streamflows at the Baihe station, with Nash–Sutcliffe coefficients of 0.866 and 0.915 in the calibration (1961–1976) and

### Table 2 | Methods for simulating potential natural vegetation dynamics during 1991–2100

<table>
<thead>
<tr>
<th>Simulation schemes</th>
<th>Climate conditions</th>
<th>CO₂</th>
</tr>
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<tbody>
<tr>
<td>Scheme Clim</td>
<td>PRECIS-simulated climatology in 1991–2100 under IPCC-SRES A1</td>
<td>1960s level (317.2 ppm)</td>
</tr>
<tr>
<td>Scheme CO₂</td>
<td>Repeatedly using PRECIS-simulated climatology in baseline (1961–1990)</td>
<td>CO₂ concentration under IPCC-SRES A1</td>
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</table>

### Table 3 | Methods for hydrological simulation in 1991–2100

<table>
<thead>
<tr>
<th>Simulation schemes</th>
<th>Inputs of XVHM</th>
<th>Climatology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro-without-veg</td>
<td>LPJ-simulated mean annual PFT cover percentage and mean monthly LAIs during 1961–1990 (baseline)</td>
<td>PRECIS-simulated daily climatology in 1991–2100 under IPCC-SRES A1</td>
</tr>
</tbody>
</table>
validation periods (1977–1986), respectively. Thus, calibrated hydrologic parameters were transferred to all grid cells covering the entire Hanjiang River basin.

RESULTS

Present-day potential natural vegetation

According to LPJ-DGVM simulation in the baseline years (1961–1990), the four major natural vegetation types in the Hanjiang River basin are as follows: temperate needle-leaved evergreen PFT, temperate broad-leaved evergreen PFT, temperate broad-leaved deciduous PFT and temperate herbaceous PFT occupying 12.9, 3.4, 69.7 and 14%, respectively, of the total basin (Figure 3). Temperate needle-leaved evergreen PFT is mainly distributed in mountainous upper and lower reach regions (Figure 3(a)); temperate broad-leaved deciduous PFT is dominant in the low-elevation region (Figure 3(c)); temperate broad-leaved evergreen PFT merely appears in the southern part of the basin where local climate is warmer (Figure 3(b)); and temperate herbaceous PFT is distributed across the entire watershed as the major understory vegetation (Figure 3(d)). These features basically concur with the potential natural vegetation zonality in central China indicated by Wu (1980).

Here, LPJ simulation results represent potential natural vegetation, ignoring direct anthropogenic effects such as agricultural practices in the Hanjiang River basin. According to University of Maryland land cover data (Global Land Cover Facility 1997), the Hanjiang River basin is significantly influenced by agricultural management with croplands occupying almost the entire lower reach region and majority of river valley areas of the upper and middle reach areas (Figure 4(a)). To validate the performance of LPJ-DGVM in simulating potential natural vegetation, LPJ-simulated present-day potential natural vegetation data were converted to the same format as that of the global potential vegetation dataset (GPVD) developed by Ramankutty & Foley (1999). Spatial distribution of LPJ-simulated dominant natural vegetation types in the baseline years (Figure 4(b)) is in basic agreement with that of the GPVD (Figure 4(c)).

Figure 3 | Distribution of LPJ-simulated PFTs in the baseline years (1961–1990).
LPJ and GPVD potential natural vegetation datasets both indicate that temperate broadleaf deciduous forest is the predominant natural vegetation type, occupying the majority of the basin. In these two datasets, temperate broadleaf evergreen forest is distributed in the most southern part of the basin where the climate is warmer, although LPJ underestimates this forest type. Both LPJ and GPVD demonstrate the appearance of mixed forest in the headwater region, but LPJ does not display this forest type in the northeastern region of the basin. This discrepancy of the spatial pattern of mixed forest and temperate broadleaf evergreen forest is partly a consequence of the fact that these two forest types have a limited extent, which makes it difficult to capture their spatial distribution accurately in a low-resolution model such as LPJ-DGVM. These simulation results are in accordance with modeling works by Liang & Xie (2006) and Sun et al. (2007). In summary, LPJ-DGVM is capable of providing reasonable estimates of potential PFT distribution in the Hanjiang River basin.

**Changes in potential natural vegetation in the 21st century**

**Effect of changes in climate conditions**

Numerical simulation Scheme Clim reveals that the percentage of forest cover in the Hanjiang River basin is predicted to decrease gradually in the 21st century as compared with the baseline years (Figure 5). Although annual precipitation in the whole basin is predicted to rise during 1991–2100, precipitation is predicted to decrease during the months of July to October; this time is the main growing season for the majority of natural vegetations in the Hanjiang River basin (Yuan & Ren 2009). During the growing season, plants generally tend to consume a greater amount of soil.
water to maintain growth and physiological demand. Reduced summer/autumn precipitation in 1991–2100 would therefore lead to a deficit of soil moisture in the plant-growing season. Meanwhile, as air temperature increases, atmospheric demand for evapotranspiration is enhanced, resulting in deteriorated soil moisture deficit that could further threaten the survival of forest PFTs. For example, the year 2071 is predicted to be considerably drier and warmer with an annual air temperature of 20.1 °C, annual precipitation of 771.1 mm and associated forest cover expected to be at 48.6%. This figure is the lowest predicted forest cover in the 21st century. With reduced forest PFTs, herbaceous PFT tends to increase gradually in the Hanjiang River basin (Figures 5 and 6(d)).

Degradation of forest PFTs in the 21st century is predicted mainly to involve temperate needle-leaved evergreen and temperate broad-leaved deciduous forests. Compared with the baseline years (1961–1990), percentages of these two forest PFTs at the end of the 21st century are considerably reduced in almost the entire watershed (Figures 6(a) and (c)). However, temperate broad-leaved evergreen PFT tends to expand northwards (Figure 6(b)) with a cover ratio of 3.4% in the baseline years increasing to 4.2% in 2080s. This figure may be attributed to the fact that the establishment of temperate broad-leaved evergreen PFT strongly depends on air temperature, and that increased air temperature may promote growth of this PFT.

A comparison of LPJ-simulated basin-averaged monthly LAIs in the baseline years (1961–1990) 2020s, 2050s and 2080s is presented in Figure 7. This comparison reveals that forest PFTs with denser canopies would be gradually succeeded by herbaceous PFT with sparser canopies. Basin-averaged monthly LAIs in the 21st century would therefore also decrease by degrees.

In summary, numerical simulation Scheme Clim indicates that if the CO₂ fertilization effect is neglected, increased annual air temperature and reduced summer/autumn precipitation are the main driving forces of vegetation change in the 21st century.

Effect of CO₂ fertilization

As indicated by numerical simulation Scheme CO₂ under the environment of elevated atmospheric CO₂, forest cover is predicted to increase gradually while grassland is seen to decrease considerably in the 21st century (Figures 8 and 9). Increased CO₂ tends to favor carbon assimilation by directly enhancing photosynthesis and improving water-use efficiency; it eventually affects both ecosystem functioning and structure. Relative to temperate herbaceous PFT, temperate needle-leaved evergreen forest PET generally consumes a greater amount of water to maintain its growth and physiological demand. Given increased CO₂ in the atmosphere and constant
climate conditions as the baseline years, temperate forest PFTs in the 21st century therefore may undergo less soil water deficit, facilitating growth and survival. It may succeed in competing with temperate herbaceous PFT for larger living spaces.

In the 21st century, basin-averaged monthly LAI increased remarkably compared with the baseline simulation (Figure 10). This phenomenon may possibly be attributed to two causes: (1) rise in atmospheric CO₂ resulting in changes in plant physiological structure such as
information demonstrate that 21st century vegetation dynamics would further influence the regional water balance significantly.

In the case of no climate-driven vegetation change (Hydro-without-veg), changes in the hydrological cycle are largely determined by changes in precipitation and air temperature. Due to an ongoing increase in annual precipitation and annual mean air temperature in the 21st century, annual total evapotranspiration would increase considerably (Table 4). As forest cover is maintained at a high and invariable percentage (86%) within the entire prediction period, all evapotranspiration components would increase and constitute a stable proportion of total evapotranspiration (approximately 27.2–27.5% for plant transpiration, 25.1–27.8% for interception evaporation and 47.5–53.5% for soil evaporation). Further, as an increase in annual evapotranspiration offsets an increase in annual precipitation, annual runoff is predicted to decrease slightly by the end of the 21st century (Table 4).

However, if climate-induced vegetation dynamics were considered (Hydro-with-veg), the variation in regional water balance would be controlled by both changes in atmospheric forcing and alteration in vegetation. As forest cover continues to degrade in the warmer 21st century, plants will transpire less water into the atmosphere because of lower LAIs and less available energy at the canopy surface. Evaporative loss of
intercepted canopy water likewise tends to decrease on account of reduced canopy interception capability. However, soil evaporation will rise remarkably as the canopy becomes sparser and more solar energy reaches the soil surface (Table 4). As total evapotranspiration records a lower increase compared with precipitation, annual runoff represents a minor increase by the end of the 21st century (Table 4).
Annual runoff depths calculated through the two hydrological simulation schemes in three time segments (2020s, 2050s and 2080s) were compared (Figure 11). In the simulation Hydro-with-veg, the percentage of forest covers in 2020s is 82.8% (merely 3.2% lower than that in Hydro-without-veg). This factor does not influence evapotranspiration regime and runoff intensively. Thus, calculated annual runoff series in the 2020s in both hydrological simulations are in fair agreement with each other. However, on account of the much warmer and drier summer climate in 2050s and 2080s, forest covers in Hydro-with-veg would experience more obvious degradation. In the 2050s and 2080s, total evapotranspiration in Hydro-with-veg is therefore lower than that for Hydro-without-veg. As a result, runoff depth in Hydro-with-veg becomes higher compared with that in Hydro-without-veg, especially in the 2080s when forest degradation is most obvious.

The above two hydrological simulations demonstrate that considering future changes in vegetation may have significant impacts on terrestrial hydrology and, occasionally, even produce distinct runoff prediction results. As terrestrial vegetation changes dynamically in response to climate change, land-surface characteristics such as albedo, available land-surface energy, LAIs and interception capability will be altered considerably. This change will affect the evapotranspiration regime and its components and, finally, modify runoff volume. Climate-driven vegetation change could therefore be a necessary element that should be represented explicitly in long-term hydrological prediction.

Table 4 | Calculated hydrological variables in the two hydrologic simulation schemes

<table>
<thead>
<tr>
<th>Fractional forest cover and hydrological variables</th>
<th>Hydro-without-veg (simulation without vegetation change)</th>
<th>Hydro-with-veg (simulation with vegetation change)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2020s</td>
<td>2050s</td>
</tr>
<tr>
<td>Fractional forest cover (%)</td>
<td>86.0</td>
<td>86.0</td>
</tr>
<tr>
<td>Mean annual precipitation P (mm)</td>
<td>912.0</td>
<td>924.1</td>
</tr>
<tr>
<td>Mean annual total evapotranspiration AE (mm)</td>
<td>522.1</td>
<td>543.5</td>
</tr>
<tr>
<td>Mean annual canopy transpiration EC (mm)</td>
<td>142.9</td>
<td>143.5</td>
</tr>
<tr>
<td>Mean annual evaporation of intercepted water on canopy EI (mm)</td>
<td>131.1</td>
<td>137.7</td>
</tr>
<tr>
<td>Mean annual soil evaporation ES (mm)</td>
<td>248.1</td>
<td>262.3</td>
</tr>
<tr>
<td>Mean annual runoff depth R (mm)</td>
<td>389.9</td>
<td>380.6</td>
</tr>
</tbody>
</table>
DISCUSSION AND CONCLUSIONS

This paper aims to evaluate the possible effect of 21st century climate change on the evolution of potential natural vegetation and its subsequent impact on the water budget in the Hanjiang River basin, which is a particularly important region for implementing the South-to-North Water Diversion Project in China. The LPJ dynamic global vegetation model was selected to investigate the manner by which change in climate conditions or rising atmospheric CO2 concentration affects spatiotemporal distribution of PFTs and LAIs.

If the CO2 fertilization effect is neglected, increased annual air temperature and reduced summer/autumn precipitation in the 21st century would lead to forest degradation and grass succession, thereby reducing basin-averaged LAIs. Under conditions in which only the CO2 fertilization effect is considered, herbaceous PFT would be gradually succeeded by forest PFTs which enhances mean monthly LAIs in the 21st century. This situation indicates that future long-term climate change may generate pronounced changes in natural vegetation and intensively impact vegetation biogeography in the Hanjiang River basin in the 21st century.

Subsequent hydrological simulations based on the XVHM with LPJ-simulated vegetation information reveal that 21st century vegetation dynamics will significantly influence regional water balance. Due to predicted forest degradation and grassland succession in the 21st century, plant transpiration and evaporative loss of intercepted canopy water will tend to drop while soil evaporation may rise sharply. As a result, total evapotranspiration would rise moderately with a slight increase in annual runoff. Nevertheless, when vegetation is assumed not to change within the entire prediction period, the rise in evapotranspiration due to ongoing warming in the 21st century would offset precipitation increase, resulting in a minor decrease in annual runoff.

This phenomenon implies that long-term hydrological simulations are greatly affected by whether or not climate-driven vegetation change is taken into account. It likewise raises the following question for hydrometeorology researchers: ‘Should hydrological predictions under various climate change scenarios necessarily include and analyze future possible vegetation variation associated with climate change?’ The answer resulting from this study is a definite yes.

Projections of climate-induced vegetation dynamics and their hydrological impact are influenced by various sources of uncertainties. These factors include uncertainty in anthropogenic greenhouse emission scenarios and atmospheric forcing in response to a given level of greenhouse emission arising from missing or mis-parameterized physical processes in GCMs or RCMs (Cubasch et al. 2001). Here, only PRECIS-simulated climatology under economy-oriented IPCC-SRES A1 greenhouse emission scenario was adopted for numerical simulation and analysis. To include multiple climate change situations in the future, sensitivity analysis should be conducted to reveal how DGVMs and hydrologic models respond to various greenhouse emission scenarios and process-based parameterizations.

Another major source of uncertainty exists in the representation of ecological and hydrological processes in the equations of DGVMs and hydrologic models resulting from limited knowledge of underlying processes or neglect of some important processes. For instance, both LPJ-DGVM and XVHM use the bottom drainage parameterization to describe water recharge from unsaturated zone to aquifer, but they omit the capillary rise of phreatic water that is generally the predominant hydrological process in dry season in the study area and, to some extent, determines soil water availability for vegetation species distribution. Such important hydrological processes should be adequately considered in ecological models and hydrological models.

In addition, nutrient cycling affects carbon uptake by the terrestrial biosphere and influences plant production and vegetation transition in response to variations in temperature and precipitation (Thornton et al. 2007; Wang & Houlton 2009), but nutrient cycling is neglected in LPJ-DGVM and most dynamic global vegetation models. Models lacking an explicit representation of the nitrogen cycle may overestimate the amount of carbon that terrestrial ecosystems can uptake, hence exaggerating plant growth (Hungate et al. 2003; Moorcroft 2006).

Thornton et al. (2007) simulated that carbon–nitrogen cycle coupling reduces the global terrestrial carbon uptake
response to elevated atmospheric CO₂ concentration by 74%, relative to a carbon-only model. However, Sokolov et al. (2008) found that global warming may enhance nitrogen availability through mineralization of organic matter by increasing the decomposition of detritus; the elevated nitrogen availability may, in turn, alleviate the nitrogen limitations on plant productivity in nitrogen-constrained ecosystems, amplifying the CO₂ fertilization effect. Gerber et al. (2010) concluded that carbon–nitrogen interactions are weak when the coupled carbon–nitrogen model system approaches equilibrium. Many simulated features of the carbon cycle, such as primary productivity and carbon inventories, are similar to simulations that only include carbon cycle. Although previous research results vary, it may be of extreme importance to include nitrogen cycling in process-based DGVM to account for this possible bias in future studies.

Our basic knowledge about CO₂ fertilization effect is based on enclosed open-top chamber experiments that revealed that photosynthesis in C₃ plant could be enhanced by 60% due to the increase in CO₂ concentrations of about 300 ppmv, resulting in substantial increases in net primary productivity (NPP) (Norby et al. 1999). However due to the ‘chamber effect’, the applicability of chamber experiments is questioned. Large-scale FACE experiments were therefore carried out to overcome the recognized problems of small-scale experiments (Hendrey et al. 1999; Norby et al. 1999). They generally confirmed the enhancement of NPP due to enriched CO₂ (Ainsworth & Long 2005; Norby et al. 2005) and demonstrated that ‘the responses of forest NPP is highly conserved across a wide range of productivity, with a stimulation at the median of 23 ± 2%’ (for approximately 550 ppmv CO₂; Norby et al. 2005; Hickler et al. 2008).

In this study, NPP in the Hanjiang River basin was also simulated through LPJ-DGVM. It is predicted that mean annual NPP would rise from 492.7 g C m⁻² a⁻¹ in the baseline years (1961–1990 for 340 ppmv CO₂) to 624.9 g C m⁻² a⁻¹ in the 2080s (2071–2100 for 675 ppmv CO₂) with an increase of 26.8%, close to the mean NPP enhancement rate at temperate forest FACE experiments (25.7 ± 0.14%, Hickler et al. 2008). However, given that no FACE experiments have been carried out in the Hanjiang River basin and no NPP observation data are available, the results of the simulated NPP were not analyzed in this study. Moreover, the CO₂ physiological effect on water balance of the Hanjiang River basin was not considered in the hydrological modeling, which tends to limit the scope of the conclusions of this study. This was decided because (a) there are almost no data on the CO₂ fertilization effect in the study area, and (b) current XVHM does not include a parameterization scheme which accounts for the effect of rising CO₂ on plant transpiration. If the studied ecosystem acted as young temperate forests, the elevated CO₂ in the 21st century would enhance photosynthesis and increase water-use efficiency (Gerten et al. 2004). Less water would therefore be lost from plants and the situation of soil water stress would be mitigated, possibly leading to a greater increased annual runoff than predicted in this study.

Simulations presented in this study were of potential natural vegetation and its impact on terrestrial hydrology; these ignored direct anthropogenic effects such as land use or agricultural management. Agricultural and forest practices and human socioeconomic activities constitute an important factor which shapes species composition of terrestrial vegetation (Koca et al. 2006) and therefore influences land-surface hydrological processes. At present, crop cultivation remarkably reduces forest extent and results in expansive occupation of cropland in the middle and down reaches of Hanjiang River basin (Figure 4(a)).

In the future, these anthropogenic effects on carbon and water budgets of agricultural lands under climate change will be studied through the new LPJ model (LPJmL, Lund-Potsdam-Jena managed land). This model simulates transient changes in carbon and water cycles arising from land use, specific phenology and seasonal CO₂ fluxes of agriculture-dominated areas and production of crops and grazing land (Bondeau et al. 2007).

In this study, LPJ-DGVM provides simulation results on how changes in atmospheric CO₂ and climate conditions affect LAI. It is predicted that forest cover would replace grassland with increased LAIs due to the CO₂ fertilization effect in the absence of changes in climate conditions. Our simulations basically agree with FACE experiments. Ainsworth & Long (2005) analyzed the results of FACE experiments and concluded that, on average, LAI does not change remarkably with growth in elevated CO₂ but this response varies with functional type. As trees under enriched atmospheric CO₂ have increased stem diameter and plant height that allows for more leaves, the forest has
a 21% increase in LAI; herbaceous C3 does not show a significant change in LAI. Our simulations also show a much higher LAI increase in forests than herbaceous PFT (not analyzed in this study).

In addition, LPJ-DGVM includes the potential of vegetation to adapt to warmer and drier conditions by decreasing LAI to reduce water losses from ecosystems through evapotranspiration. In our simulation, this ‘ecosystem adaptation’ occurs. Under warmer and drier conditions in the 21st century, forest LAIs would decrease by degrees and forest PFTs would be gradually succeeded by herbaceous PFT. This potential ecosystem adaptation to warmer and drier conditions through reductions in leaf area and replacement with shrub vegetation may be a measure to reduce the vulnerability of terrestrial ecosystem to climate change (Hickler et al. 2009). However, this study only simulates LAI changes resulting from atmospheric CO2 increase or changes in climate conditions. Future studies with LPJ-DGVM should investigate how these two factors jointly affect LAI.

In this study, the influence of climate on vegetation and hydrology was evaluated through one-way coupling of RCM and DVGM with a hydrological model. This offline modeling methodology does not however account for the fact that land-surface vegetation and hydrology also significantly influence local climate. For example, it is widely acknowledged that regions marked by dense forest cover are generally humid in climate; here, forests tend to transpire more water into the atmosphere, thus enhancing near-surface air moisture (Betts et al. 1997). Such effects would, in turn, feed back to vegetation and the water cycle. Although valuable progress can be made with offline studies, a fully coupled climate–vegetation–hydrology modeling system would need to be established to represent feedbacks from climate, vegetation and land-surface hydrology (Foley et al. 1998).

Despite various uncertainties and biases, the methodology introduced in this paper can be adopted to examine possible future changes in watershed or regional hydrology, considering both changes in climate conditions and vegetation cover resulting from climate change. Particularly in long-term hydrological predictions under various climate change scenarios, changes in vegetation cover must be included as the terrestrial biosphere plays an important role in land-surface hydrological responses.

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REFERENCES


Bondeau, A., Smith, P., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C.,


Moorcroft, P. R. 2006 How close are we to a predictive science of the biosphere? Trends in Ecology and Evolution 21, 400–407.


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