Hydrological projections based on the coupled hydrological–hydraulic modeling in the complex river network region: a case study in the Taihu basin, China

Liu Liu and Zongxue Xu

ABSTRACT

Water resources in the Taihu basin, China, are not only facing the effects of a changing climate but also consequences of an intensive urbanization process with the abandonment of rural activities and the resulting changes in land use/land-cover. In the present work, the impact of climate change and urbanization on hydrological processes was assessed using an integrated modeling system, coupling the distributed hydrological model variable infiltration capacity and the hydraulic model ISIS, while future climate scenarios were projected using the regional climate model providing regional climate for impact studies. Results show a significant increasing trend of impervious surface area, while other types of land cover exhibit decreasing trends in 2021–2050. Furthermore, mean annual runoff under different future climate scenarios will increase, especially during flood seasons, consistent with the changes in precipitation and evapotranspiration for both spatial and temporal distribution. Maximum and mean flood water levels under two future scenarios will be higher than levels under the baseline scenario (1961–1990), and the return periods of storms resulting in the same flood water level will decrease significantly in comparison to the baseline scenario, implying more frequent occurrence of extreme floods in future. These results are significant to future flood control efforts and waterlog drainage planning in the Taihu basin.

Key words | climate change, flood, hydrological-hydraulic coupling model, Taihu, urbanization

INTRODUCTION

Climate change has significant impacts on hydrological, biological, and ecological systems including those on water availability and quality, floods, and droughts, which are all closely related to economic vitality and the quality of life. Natural and anthropogenic substances and processes that alter the Earth’s energy budget are drivers of climate change. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2013) confirms that warming in the climate system is unequivocal, with many of the observed changes unprecedented over decades to millennia, with each of the last three decades being successively warmer at the Earth’s surface than any preceding decade since 1850. The report also presents clear and robust conclusions in a global assessment of climate change science – not the least of which is that the science now shows with high certainty that human activity is the dominant cause of observed warming since the mid-20th century, implying that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. These facts indicate that future climate change will be of considerable global, national, and regional importance. Water is the single most important natural resource, and many societal and natural impacts of climate change will depend on the response of the hydrological cycle to anthropogenic warming (Marvel & Bonfils 2013). Changes in the global water cycle in response to the warming over
the 21st century will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase, although there may be regional exceptions. Understanding the potential effects of climate change on water cycle and hydrological regimes has thus become a priority area, both for research and for water and catchment management strategies (Jones & Woo 2002). Hydrologists and meteorologists have also realized that modeling the hydro-climatology for large river basins is ultimately crucial to understanding the basin-scale hydrological cycle and to managing water resources ultimately (Yu et al. 1999). The potential hydrological impacts of modeled climate change on hydrology and water resources have been studied by a number of researchers. For example, Miller et al. (2003) analyzed the hydrologic response due to temperature shifts and precipitation ratios based on two general circulation model (GCM) projections and a range of specified uniform changes in California, suggesting that the range of possible climate change responses is related to large-scale change and local characteristics. Liu Z. F. et al. (2010) applied the variable infiltration capacity (VIC) macro-scale hydrological model combined with the Delta method for constructing regional climate change scenarios to the headwater catchment of the Tarim River basin (TRB) in China. The results imply that water availability in the TRB would likely become more critical in the future. Bell et al. (2007) proposed a grid-based flow routing and runoff-production model, configured to employ the regional climate model (RCM) precipitation estimates as input to assess the effects of climate change on river flows in catchments across the UK, emphasizing the need to examine more than one set of current/future precipitation scenarios for flood impact studies. Up to date, involving an ensemble of climate model outputs to assess the effects of climate change and its surrounding uncertainties has become a hot issue due to increasing availability of ensemble outputs from GCMs and RCMs, which permit a more complete examination of the implications of climate uncertainties in hydrological systems (e.g., Wilby & Harris 2006; Nawaz & Adeloye 2006; New et al. 2007; Dessai & Hulme 2007; Christensen & Lettenmaier 2007; Manning et al. 2009).

The choice of a model for a particular study depends on many factors, i.e., the purpose of the study and model, and the data availability dominating the decision process (Liu Z. F. et al. 2010). This study aims to assess the effects of climate change and human activities on a macro-scale basin. Thus, the VIC model (Liang et al. 1994, 1996), a macro-scale hydrological model that has been widely used at large scales, was selected for this study. In addition, to study the response of flooding, a hydraulic model (ISIS) was applied to simulate the Taihu Lake water levels.

The Taihu basin, located in the Yangtze River Delta, east China, is typical of many areas in China that are highly vulnerable to natural disasters due to their rapid economic and social development. In recent years, the Taihu basin has suffered great changes in rainfall–runoff characteristics due to climate change and urbanization. The frequent occurrence of extreme flood events in the basin has also received significant attention from both the local and central Chinese governments, especially two major flood events in 1991 and 1999 where water levels exceeded historical records and inflicted severe damage on local people’s property and safety (Wu & Guan 2000; Ou & Wu 2001). Because of the special natural topography and great anthropogenic activities in the Taihu basin, it is of great importance for officials to understand and prepare to address the effects of climate change and land use/cover change. The distributed hydrological model L-THIA, and the conceptual hydrological models LASCAM, STREAM, and HEC-HMS (Wu et al. 2006; Zhang et al. 2006; Li et al. 2007; Wan et al. 2007) have been applied to investigate the impact of climate change on runoff and water resources in the Taihu basin, mostly focusing on runoff simulation and the impact of land use/cover change (LUCC) on streamflow. Wang et al. (2000) analyzed the flood generating process in the Taihu basin according to a numerical model of river network unstable flow. Gao (2002) discussed the flood response to land use change in the Taihu basin and indicated that the increase of land use for construction purposes would result in serious damage. However, acceleration of the hydrological cycle induced by climate change and intensive urbanization will result in more frequent occurrence of extreme events, which could not be effectively reflected in previous studies. The expected impact of climate change, together with the current challenges for sustainable development in the Taihu basin, provide an ideal opportunity for a holistic, inter-regional integrated assessment to underpin future water resources management policy and practice.
Therefore, it is vital to set a new course for future water resources management and to adapt to regional environmental changes.

In this study, a combined scenario analysis technique including the variable infiltration capacity-three layer model, the hydraulic model ISIS, and the RCM providing regional climate for impacts studies (PRECIS) will be used to investigate the hydrological responses, including runoff and evapotranspiration in the Taihu basin along with the Taihu Lake water levels, to climate change and intensive urbanization. The Xitiaoxi catchment located at the southwest part of the Taihu basin was selected to calibrate the VIC model. The results of this study could be used to provide technical support for flood control and drought relief in urban planning and construction in the Taihu basin, especially during future global change.

MATERIALS AND METHODS

Study area

The Taihu basin (Figure 1), located at 30°5′–32°8′ and 119°8′–121°55′, belongs to the subtropical monsoon climate zone, one of the most vulnerable climate zones in the world. The drift of the monsoon rain belt has a significant effect on droughts and floods in the basin. Influenced by the monsoon climate, the annual precipitation is 1,400 mm, mostly during the summer (from June to August); the annual mean air temperature ranges from 14.9 to 16.2°C with a zonal distribution decreasing from south to north; the annual snowfall ranges between 4.5 and 10.8 days and shows an increasing trend from northeast to southwest. The northern and southern floodplains are covered with dense river networks and occupy roughly 80% of the total area in the basin, while other areas are composed of hills or mountains. The frequent typhoon storm surges, floods, and droughts faced by the Taihu basin are an integrated consequence of its complicated climate, land use and cover change, special geographic location, and topography.

The Xitiaoxi catchment is located at the southwestern part of the Taihu basin. It is one of the most important tributaries upstream of the Taihu Lake, supplying 27.7% of the water to the lake. The drainage area controlled by the Hengtangcun gauging station is 1,355 km² (Figure 1). The elevation varies significantly from 2 m to 1,574 m, with the highest elevation in the southwest and the lowest elevation in the northeast.
The catchment is characterized by a subtropical monsoon climate, with an average annual temperature and precipitation of 15.5°C and 1,465.8 mm, respectively. The dominant land uses are forest and arable land, while urban areas account for around 9.2% of the entire catchment.

**Hydrological modeling**

The VIC model (Liang *et al.* 1996; Liang & Xie 2001; Xie *et al.* 2003) was selected to simulate upland inflows which would be coupled with the hydraulic model as discharge boundaries in this study.

The observed daily data series from eight rain gauging stations located in or around the Xitiaoxi catchment provided by the Taihu Basin Authority (TBA) were selected; each set included precipitation, maximum and minimum air temperature ($T_{\text{max}}$ and $T_{\text{min}}$) over the period 1990–2000. In addition, daily data series from seven national meteorological stations with daily series surrounding the Taihu basin, each containing precipitation, $T_{\text{max}}$ and $T_{\text{min}}$ from 1961 to 1990, were provided by the National Climate Centre of China. Observed discharge data at the Hengtangcun station, which is the outlet of the Xitiaoxi catchment, were also available for the period 1990–2000. The location of these stations is shown in Figure 1.

In this study, as the entire Taihu basin including the upland Xitiaoxi catchment belongs to a rainy, mid-latitude climate where it seldom snows (Huang 2008), the VIC model was run at a resolution of 5 km × 5 km in the water-balance mode without snowmelt modeling to calibrate these parameters based on the daily discharge data from the Hengtangcun gauging station over the period of 1 January 1990 to 31 December 1997. Validation of the model was then conducted with the daily discharge data from the same station from 1 January 1998 to 31 December 2000. The simulated runoff within each grid was routed to the outlet through the unit hydrograph method for overland flow and the linear Saint-Venant method for channel flow, which was developed by Lohmann *et al.* (1998). The following three criteria were selected for model calibration: relative error, deterministic coefficient ($R^2$), and Nash–Sutcliffe efficiency coefficient ($E_{\text{n}}$).

As shown in Table 1, the relative errors ($E_r$) of the mean annual runoff in the Hengtangcun gauging station are 0.77 and 3.43%, respectively, both of which are smaller than 5%. Both deterministic coefficients and Nash–Sutcliffe efficiency coefficients are greater than 0.75, no matter which temporal scale is used. Figure 2 shows that monthly

<table>
<thead>
<tr>
<th>Period</th>
<th>$E_r/%$</th>
<th>$R^2$</th>
<th>$E_{\text{n}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yearly</td>
<td>Daily</td>
<td>Monthly</td>
</tr>
<tr>
<td>Calibration (1990–1997)</td>
<td>0.77</td>
<td>0.760</td>
<td>0.826</td>
</tr>
<tr>
<td>Validation (1998–2000)</td>
<td>3.43</td>
<td>0.854</td>
<td>0.916</td>
</tr>
</tbody>
</table>

![Figure 2](https://iwaponline.com/jwcc/article-pdf/6/2/386/375764/jwc0060386.pdf)
hydrographs of observed and simulated discharge fit well, implying a good agreement between observed and simulated discharge. In this study, because of limited observed discharges from other catchments and the fact that the entire Taihu basin is within the same climate zone (rainy and mid-latitude climate), it was assumed that the hydrological process and its related parameters were similar within the same climate zone and that parameters calibrated in the Xitiaoxi catchment were transferrable to the entire basin. This assumption was proved to be suitable in the Taihu basin by Liu L. et al. (2010).

Framework of hydrological–hydraulic modeling system

Regarding the different characteristics of rainfall–runoff between floodplain and mountainous areas, conceptual and distributed hydrological models are adopted for runoff yields, respectively, combined with a hydraulic model for flow routine in the floodplain. As shown in Figure 3(a), the mountainous area is divided into nine sub-catchments based on the locations of the inflows from the mountain to the floodplain for application in the VIC model at a resolution of 1 km × 1 km, while the floodplain comprises 16 districts in which the underlying surface is generalized into four types (e.g., water, paddy, dryland, and impervious surface) for runoff simulation (Ou et al. 2001). A conceptualized river network was proposed in this study for hydrodynamic modeling in the floodplain due to the complexity of the actual river network, which consists of 795 reaches, 2,394 river cross sections, and 198 flood cells (Figure 3(a) and 3(b)). Furthermore, 19 inflow nodes from the western mountains to the floodplain were extracted to combine nine upland sub-catchment VIC models with the floodplain hydraulic model (ISIS).

The ISIS model developed by Halcrow (http://www.halcrow.com/isis/), supported by the China–UK cooperation project, was applied to the floodplain in the Taihu basin for the simulation of floods in combination with the conceptualized river network and hydraulic engineering (as shown in Figure 3). In this study, the ISIS model for the Taihu basin consists of 22 inflow boundaries (19 nodes are western upland inflow nodes and the remaining three are fixed discharge inflow nodes) and 42 water level boundaries. The floodplain was represented by ISIS flood cell units, each covering an area of roughly 100 km², connected to the channel system by overbank spill units (weir equations representing flow over the flood banks). The flood control projects in the model contained 111 sluice gates and their corresponding pumps. According to the available data, most recent river conditions, sluice gates, and tide levels have been encoded in this hydraulic model.

Figure 3 | (a) Nine sub-catchments in the upland. (b) Conceptualized rivers, sections, and flood cells.
Upland inflows and net rainfall in the floodplain

As mentioned previously, the Xitiaoxi catchment is located in the western upland, within the same climate zone as all nine sub-catchments and with very similar physical characteristics (soil/relief/geology). Therefore, it was feasible to transfer the soil parameters calibrated in the Xitiaoxi catchment to the nine sub-catchments. The regionalized depth-duration-frequency statistics were then applied to produce the required inflows for all modeled return period events. At a resolution of 1 km × 1 km, the VIC model coupled with the Dag Lohman routing scheme was applied to the nine sub-catchments from 1998 to 1999. Simulated outflows were then split into 19 boundary nodes extracted from the ISIS model correspondingly as upland inflows into the floodplain based on the locations of these nodes and 3-month discharge series (from June 1999 to August 1999) supplied by TBA. Comparisons between simulated and observed discharges at the 19 nodes were conducted to investigate the adaptability of the VIC model to the upland. Results at eight representative nodes are given in Figure 4. As shown, most simulated peak values fit well with observation, while there was a small difference between simulated and observed peak times, which is, however, still within a reasonable range coinciding with the actual situation during the 1999 flood occurring at the end of June.

To satisfy the demands of future scenario analysis, the net rainfall calculation must take land use and cover change into consideration. The soil conservation service (SCS) method using the curve number (CN) was selected as the analytical method as it was easy to apply and included an integrated parameter for land use and cover. The CN values of the four underlying types (water, paddy, dryland, and impervious surface) in the floodplain were obtained by comparing the soil type classification of the SCS with that of the TBA. The net rainfall in each rainfall district was calculated based on the interpolation of the daily precipitation series from seven meteorological stations surrounding the Taihu basin into 16 districts in the floodplain. It was assumed that the net rainfall in each flood cell was equal to the value in the rainfall district in which the flood cell belongs. The net rainfall in the 16 districts from June 1999 to August 1999 was simulated to provide inputs for the ISIS flood cells. Relative errors of the total net rainfall for the 5 months compared with the observed data; all are within ±7%, implying that the net rainfall calculation scheme proposed is appropriate for this study.

Coupled model verification

Based on the simulated upland inflows and floodplain net rainfall, the ISIS model was calibrated using the daily data for the flood of 1999 (from June to August). The observed water levels in the Taihu Lake and channel system were used for comparison with simulated levels and to define the water level at the start of the simulation. The ISIS model was run for the period from June 1999 to August 1999 through a process of adjusting the assumed values in the model (e.g., sluice gate operation rules, pumping abstraction rates, and rules). The simulated and observed water levels at six key locations (Taihu Lake, Changzhou, Wuxi, Suzhou, Ganlu, and Jiaxing) were compared with each other, and the results are shown in Table 2.

Most of the simulated maximum water levels coincided with observed values with absolute errors ranging between ±10 cm, except for the simulation results at Wuxi station, which had an absolute error of −13 cm, and Jiaxing, which had an error of −27 cm. The simulation effect was the best for the Taihu Lake level, for which the absolute error was only −5 cm. In addition, the simulated peak time at six stations agreed well with observations, most of which were 2 days ahead of the observed peak time; the result at Changzhou station, however, lagged by 2 days, and the peak time at Taihu Lake occurred 5 days in advance. Evidence from the comparison of water levels suggested that the ISIS model developed for the Taihu basin was able to generate results with sufficient accuracy for future scenario analysis on water level prediction.

IMPACT ASSESSMENT

Climate change scenarios

Four scenarios, developed in the IPCC Special Report on Emissions Scenarios, are adopted in PRECIS to describe emission scenarios in the future. These scenarios are labeled
Table 2 | Comparison between observed and simulated maximum water levels from June 1999 to August 1999

<table>
<thead>
<tr>
<th>Locations</th>
<th>Observed (m)</th>
<th>Time (month–day)</th>
<th>Simulated (m)</th>
<th>Time (month–day)</th>
<th>Absolute error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taihu Lake</td>
<td>4.96</td>
<td>7–8</td>
<td>5.01</td>
<td>7–3</td>
<td>−0.05</td>
</tr>
<tr>
<td>Changzhou</td>
<td>5.47</td>
<td>6–28</td>
<td>5.39</td>
<td>6–30</td>
<td>+0.08</td>
</tr>
<tr>
<td>Wuxi</td>
<td>4.73</td>
<td>7–1</td>
<td>4.86</td>
<td>6–30</td>
<td>−0.13</td>
</tr>
<tr>
<td>Suzhou</td>
<td>4.49</td>
<td>7–1</td>
<td>4.52</td>
<td>6–30</td>
<td>−0.03</td>
</tr>
<tr>
<td>Ganlu</td>
<td>4.44</td>
<td>7–1</td>
<td>4.51</td>
<td>6–30</td>
<td>−0.07</td>
</tr>
<tr>
<td>Jiaxing</td>
<td>4.51</td>
<td>7–2</td>
<td>4.58</td>
<td>6–30</td>
<td>−0.27</td>
</tr>
</tbody>
</table>

Figure 4 | Comparison between observed and simulated discharge from June 1999 to August 1999.
A1, A2, B2, and B1 in the order of decreasing emissions. Details about PRECIS can be found in Jones et al. (2004), but PRECIS was first introduced into China by the Chinese Academy of Agricultural Sciences in 2003 with the aim of developing high resolution regional climate change scenarios. PRECIS outputs have been successfully used to generate climate change scenarios in China in the 21st century (Xu et al. 2005). Xu & Jones (2004) validated the adaptability of PRECIS in China; their results indicate that PRECIS could successfully simulate the spatiotemporal distribution of maximum and minimum air temperatures in China, while the simulated precipitation was greater than observation, and the capacity of PRECIS to simulate extreme precipitation was strong. In the current study, the PRECIS outputs, including daily precipitation, daily maximum and minimum air temperature during the baseline period (1961–1990) and future periods (2021–2050) under the A2 and B2 scenarios, were obtained from the Chinese Academy of Agricultural Sciences at a 50 km × 50 km resolution and re-gridded to a 5 km × 5 km grid resolution to generate the forcing data for the VIC model. The A2 scenario describes a world in which economic development is primarily regionally oriented and technological change is more fragmented and slower than described by other scenarios, while the B2 scenario describes a world in which the emphasis is focused on local solutions to economic, social, and environmental sustainability. Liu et al. (2011) investigated the simulation efficiency of PRECIS in the Taihu basin, indicating that PRECIS could be used to generate the climate change scenarios for the Taihu basin. Absolute changes for $T_{\text{max}}$ and $T_{\text{min}}$ and percentage changes in seasonal mean precipitation over the period 2021–2050 in the study area are shown in Figure 5, which shows warmer and wetter conditions for the study area in 2021–2050 compared with conditions in 1961–1990.

**Response of runoff in the Taihu basin**

The VIC model was driven using the PRECIS outputs of daily precipitation, daily maximum and minimum temperatures for the baseline period (1961–1990) to generate runoff in 1,452 grids that cover the entire Taihu basin at a resolution of 5 km × 5 km. Figure 6 shows the distribution of mean annual precipitation and runoff depth. Figure 6(a) implies
that the mean annual precipitation from 1961 to 1990 based on PRECIS was above 1,000 mm and exhibited a spatial distribution, i.e., the precipitation increased from north to south. Figure 6(b) indicates that the mean annual runoff differs from 252 to 727 mm, and its spatial distribution is consistent with that of precipitation. As shown, the mean annual runoff was larger in the mountainous area than that in the flat region, which is opposite to the distribution of evapotranspiration shown in Figure 6(c), further proving that it is feasible to use the VIC model coupled with PRECIS to assess the impact of climate change in the Taihu basin.

As shown in Figure 7(a), the mean annual precipitation in each grid under the A2 scenario tends to increase from 2021 to 2050 compared with the baseline period, ranging from 3 to 8%. The minimum increase occurs in the northeastern part of the Taihu basin close to the Yangtze River where the mean annual evapotranspiration exhibits a decreasing trend, causing a slight increase of runoff in roughly the same area shown in Figure 7(b) and 7(c), respectively. The maximum increase of precipitation occurs near Hangzhou city in the southern part of the basin where a decreasing trend of evapotranspiration is located, resulting in a significant increase in runoff. The spatial patterns of precipitation, evapotranspiration, and runoff simulated in this study are reasonable in terms of the hydrological cycle principle.

As shown in Table 3, the mean values for precipitation, runoff, and evapotranspiration exhibited only slight changes between 1961–1990 and 2021–2050, but the changes for intra-annual values were significant. Figure 5 shows the changes in seasonal values between these two periods. Runoff during the flood season from May to August exhibited an obvious increasing trend. However, the greatest increase in runoff occurred in November, the reason being that the precipitation simulated by PRECIS increased the most in November. PRECIS is more suitable for the simulation of extreme events compared with mean values (Xu & Jones 2004), which needs further improvement. The consistency between changes in precipitation and runoff indicates that runoff is mainly affected by precipitation, that is to say, precipitation is the leading factor of the runoff change in the Taihu basin. Overall, there are only a few differences in the changes in runoff under the A2 and B2 scenarios. The magnitude of these changes is slightly larger under the A2 scenario than that under the B2 scenario as a consequence of the changes in precipitation and
evapotranspiration, and the precipitation, runoff, and evapo-
transpiration changes under the B2 scenario (not shown
here) exhibit similar spatial distributions to those under
the A2 scenario.

Response of flood water level in Taihu Lake

The water level of Taihu Lake is the most important index of
the water regime in the Taihu basin as it has significant
effects on regional flood defense, water supply safety, eco-
logical environment maintenance, and water resources
management.

The flood of 1999 (maximum 30-day rainfall is
609.9 mm equal to 200-year return period event) was
selected as the classic event in this study to generate the
different scenarios of rainfall. Accordingly, the maximum
rainfall of 30 days for five return periods (50, 100, 200,
500, and 1,000 year) under the baseline, A2, and B2 scen-
arios were calculated by rescaling that of the 1999 event
by scaling factors. The VIC model was driven by rainfall
sets of five return periods under the three scenarios, respect-
ively, and outlet discharges of nine sub-catchments were
split into 19 nodes as the upland inflows into the floodplain
for the hydraulic model.

Intensive human activities have greatly changed the
underlying features of the floodplain in the Taihu basin,
which results in significant changes of rainfall–runoff
characteristics. In this study, the land use changes aligned
with the A2 and B2 scenarios were obtained according to
socioeconomic scenarios (Penning-Rowsell et al. 2013). The
different scenarios of the Taihu Lake water level for five
return periods under three scenarios (baseline, A2, and
B2) were simulated in the ISIS model using the outputs
from the nine VIC models for the upland sub-catchments
and the calculated net rainfall from the 16 floodplain
districts.

The historical maximum water level of 5.08 m for Taihu
Lake occurred in the 1999 flood event (which TBA assigned
a rainstorm return period of 200 years). The results from
the current study (Table 4) suggest that the maximum water
level of the Taihu Lake would exceed the historical record
under the A2 scenario during a 100-year rainstorm
(5.13 m), and under the B2 scenario only a 50-year rain-
storm would be required to exceed the 1999 level.

Further indicators of the potential impacts of climate
change and urbanization were provided by comparing the
baseline scenario and the A2 and B2 scenarios outputs. A
1,000-year rainstorm under the baseline scenario (1961–
1990) is predicted to result in a maximum lake water level
of 5.25 m, which is equivalent to the level generated by a
200-year rainstorm under the A2 scenario (2021–2050).
Under the B2 scenario, the corresponding return period
would be less than 100 years. Thus, without changes in
flood management practices, the projections indicate that
extreme high water levels in Taihu Lake will occur more fre-
quently due to climate change and urbanization. The current
flood control standard of protection in most regions in the
Taihu basin is 1 in 20 years (with a higher standard in the
central and industrial zones ranging from 1 in 50 years to
1 in 1,000 years). It is thus clear that flood management is
likely to be an important challenge for sustainable develop-
ment in the Taihu basin in the future.

**DISCUSSION AND CONCLUSIONS**

In this study, the VIC model was coupled with the ISIS and
PRECIS RCMs to assess the effect of climate change and
urbanization on hydrological processes in the Taihu basin,
China. Outputs including daily precipitation, maximum
and minimum air temperatures from PRECIS under three
climate scenarios (baseline climate (1961–1990), future cli-
mate (2021–2050) under A2 and B2 scenarios) were input
to the VIC model to simulate the changes in runoff in the
Taihu basin. In addition, the response of flood risk to cli-
mate change was investigated in the Xitiaoxi catchment,
along with water levels in Taihu Lake.

<table>
<thead>
<tr>
<th>Return periods</th>
<th>Maximum water levels/m</th>
<th>Mean water levels/m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>A2</td>
</tr>
<tr>
<td>50</td>
<td>4.55</td>
<td>5.00</td>
</tr>
<tr>
<td>100</td>
<td>4.71</td>
<td>5.13</td>
</tr>
<tr>
<td>200</td>
<td>4.91</td>
<td>5.25</td>
</tr>
<tr>
<td>500</td>
<td>5.17</td>
<td>5.39</td>
</tr>
<tr>
<td>1,000</td>
<td>5.25</td>
<td>5.48</td>
</tr>
</tbody>
</table>
Results show that the discharge from the Hengtangcun gauging station at the outlet of the Xitiaoxi catchment will increase significantly during flood seasons in the future (2021–2050), and the magnitude of floods in the future (2021–2050) will be greater than that during the baseline period (1961–1990). The Taihu basin is represented by 1,452 cells with a spatial resolution of 5 km × 5 km and for each cell the response of runoff to climate change was assessed by the VIC model. From the limited observation of discharge in other catchments, and the fact that the entire Taihu basin is within the same climate zone, it was assumed that the hydrological process and its related parameters were similar in the same climate zone, and thus parameters calibrated in the Xitiaoxi catchment were used for the entire basin. The runoff simulation shows an increasing trend from 2021 to 2050 under climate change scenarios obtained by PRECIS, especially in the Zhexi region in the upper reaches of the Xiao River basin.

The general expectation is that global warming will lead to an increase in evapotranspiration, a key component of the hydrologic cycle. However, as shown in Table 3, during 2021–2050, the evapotranspiration in the Taihu basin will decrease under the B2 scenario with only a slight increase under the A2 scenario which could be ignored compared to the great increase in temperature. Similar changing characteristics in the Yangtze River basin, to which the Taihu basin belongs, have already been found (Xu et al. 2006a, 2006b; Wang et al. 2007), which is that in a globally warming climate, rates of observed pan evaporation and estimated rates of fully physically based models of both potential evapotranspiration and crop reference evapotranspiration have declined over recent decades. Furthermore, this paradox of evapotranspiration has also been reported to be widespread in China, such as in the Haihe River basin (Zheng et al. 2009), the Yellow River basin (Liu & Zeng 2004; Liu Q. et al. 2010), the Tibet Plateau (Liu et al. 2011a), and the whole country (Liu M. et al. 2010; Liu et al. 2011b). Jhajharia et al. (2012, 2014) have also demonstrated that in spite of the warmer climate in India, the pan evaporation and reference evapotranspiration show a significantly decreasing trend. In order to confirm that the declining rate of evaporative demand is a globally widespread phenomenon and its attribution, McVicar et al. (2012) reviewed papers reporting trends in evapotranspiration from 148 regional studies over the world, advocating that in addition to considering air temperature trends, trends in wind speed, atmospheric humidity, and the radiative balance must also be considered to fully understand trends of evapotranspiration in a changing climate. More sophisticated exploitation on spatiotemporal characteristics of evapotranspiration in the Taihu basin should be studied in the future.

Water levels in Taihu Lake for five return periods under three climate change and urbanization scenarios (baseline, A2, and B2) were simulated using the ISIS model coupled with nine upland sub-catchment VIC models and a net rainfall from a 16-floodplain district calculation scheme. Both maximum and mean water levels in Taihu Lake under A2 and B2 scenarios from 2021 to 2050 will increase significantly compared with 1961–1990 levels and are associated with a greater increase under the B2 scenario. These results are similar to the changes in precipitation simulated by PRECIS. Changes in the maximum water levels in Taihu Lake under A2 and B2 scenarios have contrary trends with the return periods of rainstorms, in which maximum water levels will decrease with the increasing return periods, implying that the maximum water level in Taihu Lake in the future would be more sensitive to rainstorms with relative small return periods, especially to 50 and 100-year rainstorms, while being less sensitive to extreme events such as 1,000-year rainstorms. Similar results were obtained by Zhou et al. (2015), indicating that the urbanization in the Taihu basin increased peak discharge more than that of flood volume, and the change rate was found to be higher for small flood events than for large events. As for multi-peak flood events, urbanization caused a greater increase on former flood peaks than on the latter flood peaks. Zeng & Wang (2012) also demonstrated that the accelerating urbanization process in the Taihu basin had a significant influence on hydrological processes, which caused the increase of water stage, with the maximum of the increase being 4.6%.

The parameters in the VIC model were calibrated on the basis of climate zone and the spatial distribution characteristics of soil types. It is necessary to identify in detail their physical meanings, which could be done using remote sensing data to delineate the spatial distribution...
features of those parameters. The adaptability of the VIC model should be verified by more observed data to distinguish the impacts of dam operation and water diversion. In addition, a more comprehensive routing scheme should be developed that considers the effects of human activities on runoff in complicated river network regions. This is the first attempt that should be made in the future to improve the reliability of the conclusions obtained in this study.

PRECIS was validated using the data from 1961 to 1990 due to the limitations in available conditions and does not include the years of 1991 and 1999 during which two large floods occurred. The 1990s are also the period most associated with global warming. Today, the baseline period for climate models has already been extended to 2000. Therefore, the current work should be extended to include a validation period for PRECIS outputs that covers the period from 1990 to 2000 in order to improve the reliability of climate change prediction.

A broad-scale hydraulic model should be developed to meet the demands of future flood risk management. The development of ISIS in this study offers an important technical tool for a broad-scale hydraulic analysis, but it is still difficult to simulate the phenomena of overflow and intra-urban flooding. Thus, the third avenue of future investigation is for a more adaptable methodology combined with ISIS or for broad-scale hydraulic analysis, which should be investigated according to the available data and the demands for predicting future flooding.

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