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A distributed scheme developed for eco-hydrological modeling in the upper Heihe River

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Modeling the hydrological processes at catchment scale requires a flexible distributed scheme to represent the catchment topography, river network and vegetation pattern. This study has developed a distributed scheme for eco-hydrological simulation in the upper Heihe River. Based on a 1 km × 1 km grid system, the study catchment is divided into 461 sub-catchments, whose main streams form the streamflow pathway. Furthermore, a 1 km grid is represented by a number of topographically similar "hillslope-valley" systems, and the hillslope is the basic unit of the eco-hydrological simulation. This model is tested with a simplified hydrological simulation focusing on soil-water dynamics and streamflow routing. Based on a 12-year simulation from 2001 to 2012, it is found that variability in hydrological behavior is closely associated with climatic and landscape conditions especially vegetation types. The subsurface and groundwater flows dominate the total river runoff. This implies that the soil freezing and thawing process would significantly influence the runoff generation in the upper Heihe basin. Furthermore, the runoff components and water balance characteristics vary among different vegetation types, showing the importance of coupling the vegetation pattern into catchment hydrological simulation. This paper also discusses the model improvement to be done in future study.

distributed scheme, catchment discretization, streamflow pathway, hillslope parameterization, the upper Heihe River

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Water shortage is a serious problem to society and a major cause for the degradation of eco-environment in the inland river basins of northwest China. The inter-annual and intra-annual variabilities of river runoff generated from the cold high mountainous regions have great impact on the socio-economic development in the middle reach and the eco-system of downstream in these arid inland river basins. Catchment hydrology depends on climate condition, topography, soil and land cover. The latter is determined primarily by the vegetation pattern. Climate forcing is the common controlling factor on catchment hydrological processes and vegetation pattern, while there are also their mutual interactions. Therefore, in order to simulate and predict the river runoff variation under changes in climate and land use/cover, it is important to develop an eco-hydrological model.

Hydrological models have been used widely for water resources assessment, especially for studying the impact of climate change (Oki et al., 2001; Doll et al., 2003; Xu et al., 2008; Cong et al., 2009; Ma et al., 2010). Arnell (1999)

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used a daily water balance model for investigating the impact of climate change on global water resources. Middelkoop et al. (2001) compared a water balance model and a physically-based hydrological model for water resources assessment in the Rhine basin. It has been found that physically-based model did a better job than water balance model. Examples of attempts made for better understanding of the impacts of land use/cover change on water and energy fluxes include the application of the Simple Biosphere model 2 (SiB2) to the Chao Phraya River basin (Kim et al., 2005), application of the Community Land Model version 3 (CLM3) to analyze the hydro-climatic trends in the Mississippi River basin (Qian et al., 2007), and the development of a distributed biosphere hydrological model by fully coupling SiB2 into a geomorphology-based hydrological model (GBHM) (Wang et al., 2009). Among others, the latter model improved the land surface representation in the distributed hydrological model, benefiting streamflow prediction as well as providing water and energy fluxes estimation. Their study showed the potential of GBHM to couple with land surface processes.

Modeling the mutual interaction of catchment hydrological and vegetation dynamic processes requires a flexible distributed modeling scheme to represent the catchment topography, river network and vegetation pattern. Therefore, development of an appropriate distributed modeling scheme is the first important step in eco-hydrological model development. Most existing distributed hydrological models commonly use a grid system to discretize the catchment. In order to represent the catchment topography appropriately, the grid system needs to be of fine spatial resolution. However, large size grid systems are usually used in practice especially for large scale hydrological modeling. By introducing a sub-grid parameterization scheme, Yang et al. (2004) proposed a large scale distributed hydrological model (named GBHM2) and used it for water resources assessment in the Yangtze River (Xu et al., 2008) and the Yellow River basins (Cong et al., 2009). This model used a grid system of large size (e.g. 5–10 km) to discretize the study basin and a sub-grid parameterization scheme to represent the landscape, which is similar to parameterization within a flow-interval used in GBHM1 (the first version of geomorphology-based hydrological model) (Yang et al., 1998, 2002). The modeling scheme used in GBHM (both the version 1 and 2) focused on effective representation of the hillslope and hillslope geometry for runoff generation. However it lacked consideration of the vegetation pattern and was inadequate to represent the catchment river networks.

Based on the hydroclimatic observations, the basic characteristics of the river runoff in the upper Heihe River and its variations in the past decades have been analyzed in several studies. The spatial variation of river runoff in the upper Heihe basin depends on the complex climate and topography conditions (Kang et al., 2008). The temporal variation of river runoff is highly influenced by the climate variability and land use/cover change. In order to have a full picture of the hydrological characteristics, several studies focused on the hydrological modeling in the Heihe River basin. Examples include the development of a distributed hydrological model in the upper Heihe River basin (Chen et al., 2004), application of the WEP (water and energy transfer processes) model to the whole Heihe River basin (Jia et al., 2006), development of a heat and water coupling hydrological model in a small experimental catchment of the upper Heihe River (Wang et al., 2010; Zhang et al., 2013), and the application of the SWAT model to the Heihe River basin (Zang and Liu, 2013; Yin et al., 2014). Due to the complexity of eco-hydrological processes in the upper Heihe River, research is still continuing for developing a sophisticated eco-hydrological model. For better simulation of the hydrological processes in cold regions, Zhou et al. (2014) developed a modular model, in which several cold region hydrological process modules were linked to build an appropriate hydrological model.

A major research plan entitled "Integrated research on the eco-hydrological process of the Heihe River Basin" was launched by the National Natural Science Foundation of China in 2010. The general scientific target of this research plan is to establish the watershed ecology, hydrology and social economy coupled models for better understanding of the water resources formation and transformation mechanisms in inland watersheds (Cheng et al., 2014). As one of the integrated research projects, the present study selected the upper part of the Heihe River basin as the study area and aimed to develop a distributed eco-hydrological model for high cold maintain regions in China. With the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) providing new opportunity for the eco-hydrological model development (Li et al., 2013), the major objective of this study is to develop a distributed scheme for representing the topography and vegetation pattern and improving the river network representation based on the model structure of GBHM.

1 Study catchment and data used

The Heihe River basin is the second largest inland river basin in China. The upper Heihe River, located above 2000 m elevation, accounts for 20% of the total basin areas, while it provides 70% of the river flow to the middle and lower reach. Runoff from the upper Heihe River maintains the agricultural production in the middle reaches and the ecological health in the lower reach (Cheng et al., 2006).

The catchment upstream of the Yingluoxia Hydrological Station forms the major part of the upper Heihe basin, and was selected as the study area. It has a drainage area of 10009 km^2 according to the Hydrological Year Book. The two major tributaries originate from the Qilian Mountain in the east and the west, respectively and flow in opposite directions. They join the main channel at the Huangzangsi from where the main river flows to the north and discharges into the Zhangye Plain from Yingluoxia (Figure 1). This is catchment located in the high cold mountains with elevation between 2100–5200 m. The annual precipitation varies in the range 200–500 mm with more than 60% concentrated in the summer. The major land cover types are alpine meadow, grassland, shrub land, sparse vegetated land and forest (Figure 2).

The basic data used in this study including hydro-climate data and vegetation data are provided by the Cold and Arid Regions Science Data Center at Lanzhou (http://westdc.westgis.ac.cn). Meteorological data which includes daily precipitation, temperature, wind speed, sunshine hour, and humidity, are acquired from the data center of the China Meteorological Administration (http://cdc.cma.gov.cn). Daily river discharge data are obtained from the Hydrology and Water Resources Bureau of Gansu Province. Digital elevation data, with a spatial resolution of 90-m, are downloaded from the SRTM Database (Jarvis et al., 2008). Vegetation map of the study area is obtained from the China Vegetation Map (Hou, 2001) with a resolution of 1 km × 1 km. Soil map of the study area is obtained from the 1:1000000 soil map of the Heihe river basin that is produced by the second national soil survey (Shi et al., 2004).

2 A distributed scheme for eco-hydrological modeling

2.1 Analysis of catchment landscape characteristics

The landscape of a catchment can be represented mainly by its topography, land cover (vegetation type) and soil type mainly. The topography controls the stream network and influences the spatial distribution of vegetation and soil in the catchment. The geomorphological characteristic represented by the stream network can be considered as an integrator of the topography, land cover and soil and which is widely used in catchment hydrological studies (Yang et al., 2000).

To analyze the catchment landscape characteristics, this study starts with stream network generated by the digital elevation model (DEM) of 90 m × 90 m resolution (90 m DEM) from which the catchment boundary is extracted. The catchment area derived from the DEM is in agreement with that published (10009 km^2) in the Hydrological Year Book. According to Horton-Strahler classification system the stream network has 5 orders. To keep the 5-order channel network, the minimum threshold area for dividing into sub-catchments is 10 km^2. The total number of sub-catchments is 461, and the mean drainage area of each sub-catchment is 21.7 km^2. Figure 3 shows the stream network and the sub-catchments of the study area derived from the 90-m DEM.

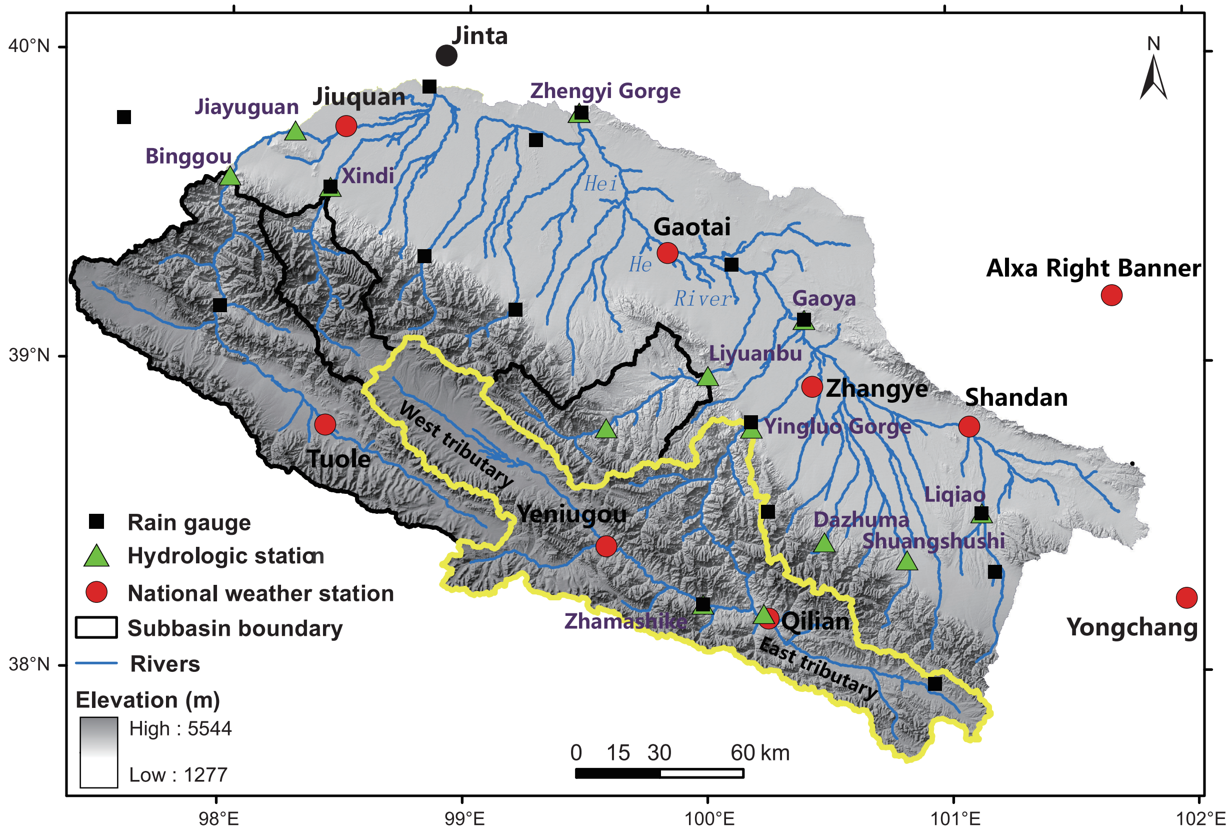

Figure 1 Study area and locations of hydrological stations, rain-gauges and meteorological stations.

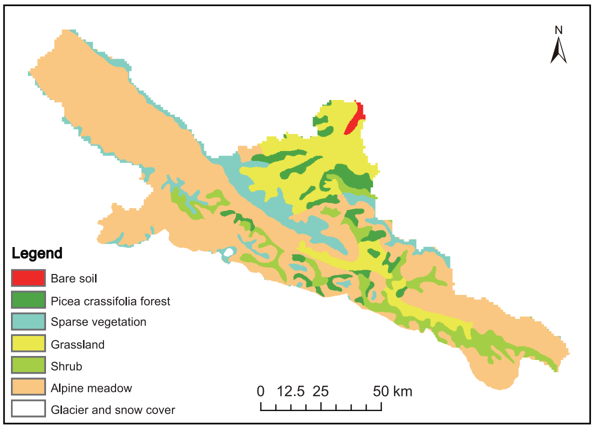

Figure 2 Vegetation map of the study catchment.

Table 1 illustrates the vegetation distribution in different regions of the catchment. It can be observed that the distribution of vegetation changes with elevation. The bare soil is mainly located in the lowland regions below the elevations of 2500 m. The Alpine meadow, sparse vegetation and glacier are located mainly in the high mountain regions with elevations higher than 3300 m. The thick leaf spruces (*Picea crassifolia*) are mainly located in the elevation range of 2500–3300 m, and majority of shrubs is located in the elevations above 3300 m. Grassland is distributed more evenly compared to other species, mainly located in elevations below 2500 m. This highlights the importance in considering the spatial pattern of vegetation in the eco-hydrological model.

2.2 Catchment discretization and water flow pathway

The grid system is convenient for utilizing the available geographical information and for model application. Based on a grid system, the essential principle for catchment discretization in distributed hydrological modeling is to maintain appropriate water flow pathway. From a finer resolution DEM, we can derive relative accurate river network. However this spatial scale is too small for the distributed hydrological modeling especially for large river basins. Therefore selection of an appropriate grid size is necessary for discretizing the study catchment and for deriving the river network with sufficient accuracy.

A previous study suggested that an appropriate threshold area for extracting the stream network from DEM was around 1 km^2 (Yang et al., 2001). This implies that an appropriate DEM resolution for extracting river network should be no larger than 1 km × 1 km. In this study a 1 km × 1 km resolution DEM (1-km DEM) is resampled from the 90-m DEM. As shown in Figure 4, from the 1-km DEM we obtain a very close stream network and similar partition of

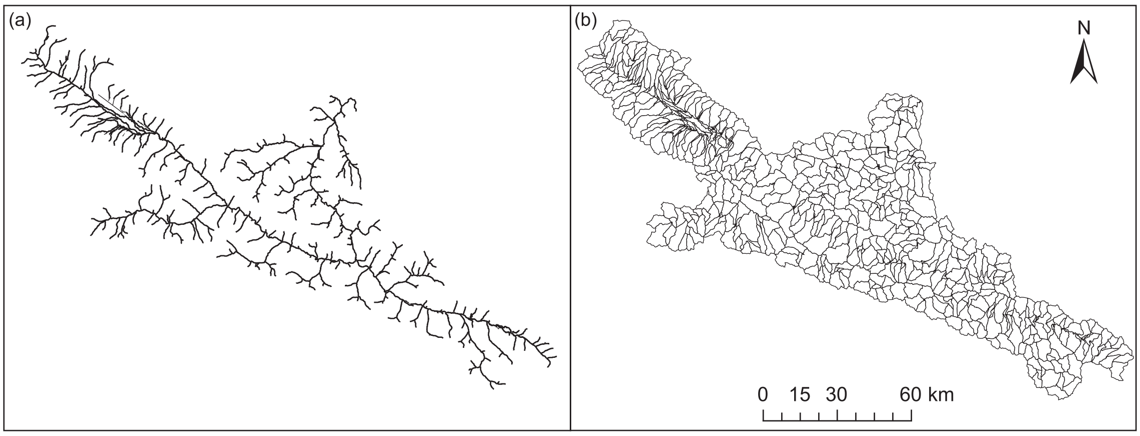

Figure 3 Stream network and sub-catchments derived by the 90-m DEM.

Table 1 Area fraction of each vegetation type within different elevation ranges

Vegetation type	Area fraction (%)		
	< 2500 m	2500–3300 m	> 3300 m
Bare soil	93.3	6.5	0.2
Thick leaf spruce	1.2	67.1	31.7
Shrub	0.2	29.0	70.8
Grassland	46.4	34.2	19.4
Alpine meadow	2.5	3.3	94.2
Sparse vegetation	0.0	0.4	99.6
Glacier and snow cover	0.0	0.0	100.0

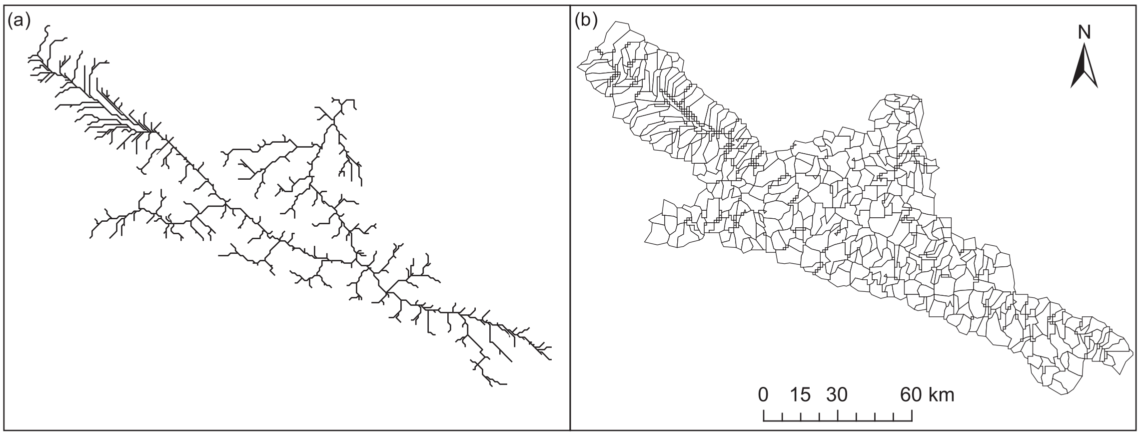

Figure 4 Stream network and sub-catchments derived by the 1-km DEM.

sub-catchments as those extracted from the 90-m DEM. The difference in drainage area of the catchment derived from the 90-m and 1-km DEMs is less than 1%. This means that the catchment and streamflow pathway can be appropriately derived from the 1-km DEM. Therefore, a 1 km × 1 km grid system is suggested to discretize the study catchment and the river network extracted from the 1-km DEM is used to represent the streamflow pathway. By the stream network, 461 sub-catchments are connected successively, and Horton-Strahler ordering system is used to build the streamflow sequence.

In a sub-catchment the streamflow pathway is simplified by using a single main channel that has the maximum flow length of this sub-catchment. The runoff generated from each grid over the sub-catchment is assumed to be the lateral inflow of the main channel, which flows into the main channel at the flow distance of this grid (Figure 5). Each 1 km × 1 km grid is represented by a number of topographically similar "hillslope-valley" systems. The water flow pathways on a hillslope include surface, sub-surface and groundwater. The hillslope is the basic unit of eco-hydrological simulation, which is also the common scale in field experiments.

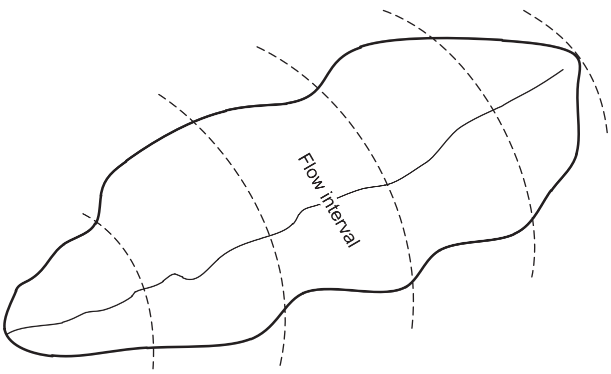

Figure 5 Flow interval and main channel representing flow pathway of a sub-catchment.

2.3 Hillslope parameterization

Regional similarity is commonly observed in landscape. Hillslope gradient of the hillslope-valley system is taken as the average slope of the same 1 km × 1 km grid that is estimated by the 90-m DEM. A hillslope-valley system (Figure 6) is assumed to be symmetrical, and the hillslope length is estimated as:

$$l = A/2L, \tag{1}$$

where l is the hillslope length (m); A is the area of a 1-km grid (km^2); L is the total length of the rivers in a 1 km × 1 km grid estimated by the 90-m DEM (m).

Hillslope aspect has a significant impact on solar radiation and therefore on vegetation distribution. Estimation of surface solar radiation over a complex terrain is not an easy task. A recent study used a relatively simple method proposed by Allen et al. (2006) on a DEM based radiation model (Chen et al., 2013) to estimate the daily extra-terrestrial solar radiation by taking into account the slope gradient and slope aspect in the form:

$$R_a = \frac{G_{sc}}{d^2}\int_{\varpi_1}^{\varpi_2} \cos\theta \,\mathrm{d}\varpi, \tag{2}$$

where R_a is the incident solar radiation, G_{sc} is the solar constant, d is the relative earth-sun distance, ϖ is the hour angle, ϖ_1, ϖ_2 are the beginning and ending sun-hour angles, and $\cos\theta$ is calculated as:

$$\begin{aligned}\cos\theta = {} & \sin(\delta)\sin(\phi)\cos(\beta) - \sin(\delta)\cos(\phi)\sin(\beta)\cos(\gamma) \\ & + \cos(\delta)\cos(\phi)\cos(\beta)\cos(\omega) \\ & + \cos(\delta)\sin(\phi)\sin(\beta)\cos(\gamma)\cos(\omega) \\ & - \cos(\delta)\sin(\phi)\sin(\gamma)\sin(\omega).\end{aligned} \tag{3}$$

In eq. (3) δ is the declination of the earth, ϕ is the latitude, β is the slope angle and γ is the slope aspect angle.

Using the available data, the downward shortwave radiation on the ground surface is calculated as (Maidment, 1993):

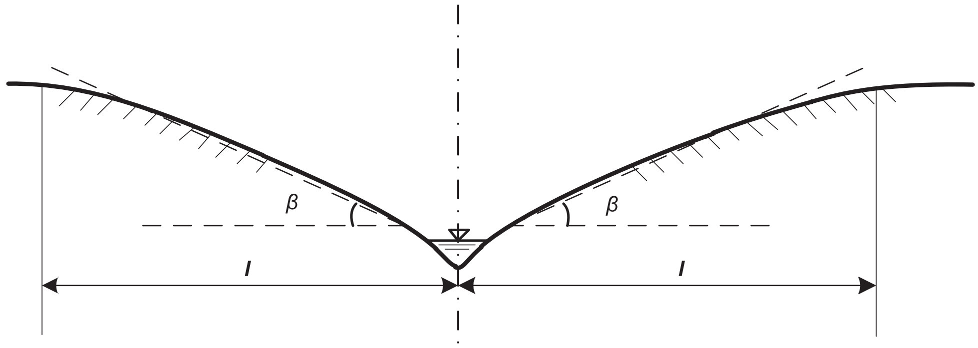

Figure 6 Hillslope-valley system used for sub-grid topographical parameterization.

$$S_t = \left(a_s + b_s \frac{n}{N} \right) R_a. \quad (4)$$

In eq. (4) S_t is the downward shortwave radiation on the ground surface; n is the daily sunshine hour; N is the maximum possible daily sunshine hours; a_s and b_s are linear regression constants. Then the net radiation on the ground surface is calculated as:

$$R_n = (1-\alpha)S_t + L_n, \quad (5)$$

where R_n is the net radiation, S_t is the downward shortwave radiation on the ground surface; α is the surface albedo, and L_n is the net surface long wave radiation.

The net surface long wave radiation is calculated as:

$$L_n = -f\varepsilon'\sigma\left(T+273.16\right)^4. \quad (6)$$

In eq. (6) f is the cloud cover coefficient which is determined by the solar radiation on the ground surface and the clear-sky solar radiation; ε' is the air emissivity which is determined by the actual vapor pressure; σ is the Stefan–Boltzmann constant, and T is the air temperature.

Figure 7 shows the comparison of yearly-averaged daily net radiation with/without considering slope aspect impacts in the study catchment. The basin annual average value is 100.6/100.7 W m^{-2} with/without considering slope aspect impacts, but more heterogeneity is obtained by considering this factor.

Other landscape attributes for a hillslope, such as the mean elevation, vegetation and soil type, can be obtained from the 1 km resolution GIS of the study catchment. The vegetation distribution is adjusted by the hillslope aspect. In the study catchment, the thick leaf spruces are grown on the shaded slope rather than on the sunny slope. The vertical structure of the hillslope consists of vegetation canopy, land surface, subsurface soil layer, bedrock, and groundwater aquifer.

3 Model test using a simplified hydrological simulation

For model testing, we simply employ the hydrological simulations used by GBHM (Yang et al., 2002), which includes hillslope hydrological processes and flow routing in stream network.

Hillslope hydrological processes include glacier/snowmelt, canopy interception, evapotranspiration, infiltration, surface flow, subsurface flow and the exchange between the river and groundwater. Glacier/snowmelt is calculated using the temperature-index approach. The actual evapotranspiration is calculated from the potential evaporation by considering seasonal variation of LAI, root distribution and soil moisture availability. Infiltration and soil water flow in the vertical direction is simulated using the Richards equation. The surface runoff is from the infiltration excess or saturation excess and flows through the hillslope into the stream. The groundwater aquifer is treated as an individual storage corresponding to each grid. The exchange between the groundwater and the river water is calculated by Darcy's law. Flow routing in the river network is solved using the kinematic wave approach (Yang et al., 1998, 2000, 2002).

4 Result and discussion

4.1 Simulation of river flow hydrograph

In order to achieve the catchment hydrological state of equilibrium, a warm-up run is carried out from 1998 to 2006 and the model state variables are saved and used as the initial condition. Calibration and validation of the present model are based on the monthly and daily river discharge data observed on the west tributary and the main river. The period of 1999–2002 is selected as the calibration period and the period of 2003–2006 is used as the validation period. Nash-Sutcliffe efficiency coefficient (NSE) and the relative error (RE) are used to evaluate the model performance. The model parameters are specified using the available data in the same region and the related references. Two manually tuning parameters are the groundwater hydraulic conductivity and the degree-day factor of snow-melting. The groundwater hydraulic conductivity is sensitive for simulating the groundwater runoff (i.e., the base flow), and the degree-day factor is sensitive for simulating rising of the runoff in the

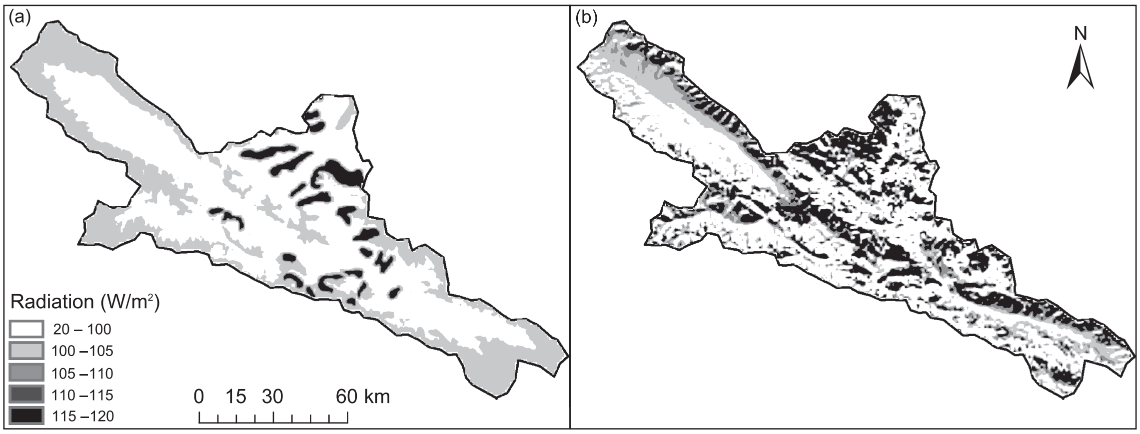

Figure 7 Annual-averaged daily net radiation in the study catchment. (a) Without consideration of slope aspect, (b) with the consideration of slope aspect.

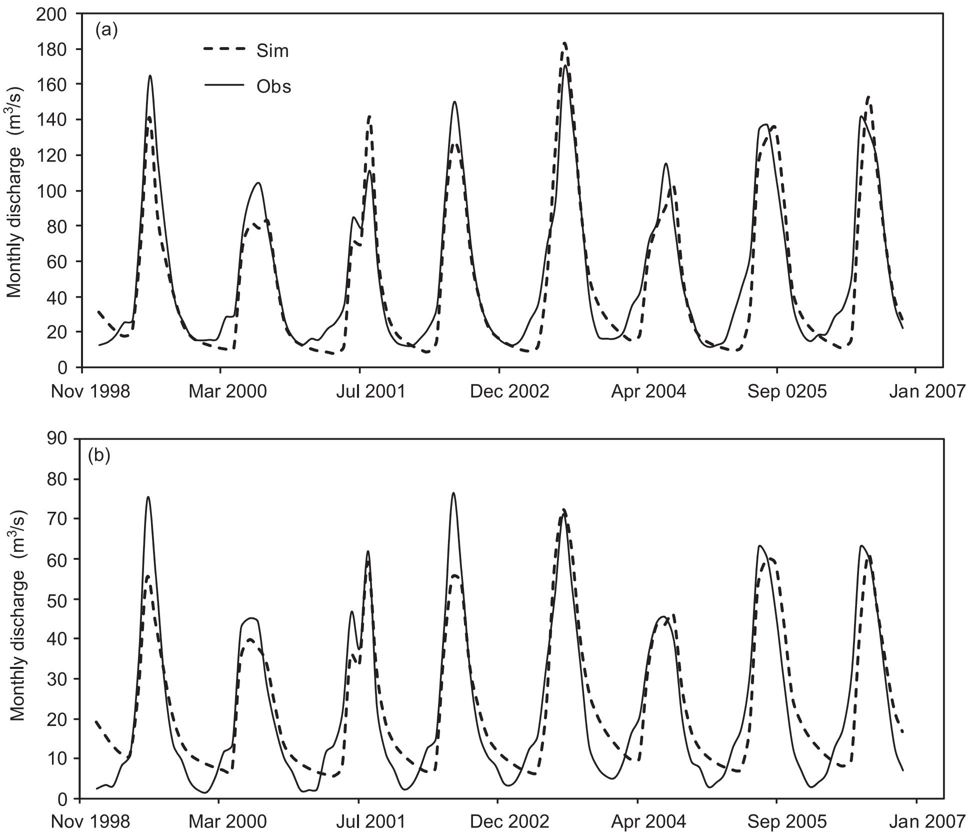

Figure 8 Monthly river discharge of the (a) Yingluoxia gauge and (b) Zhamashike gauge during the calibration period (1999–2002) and the validation period (2003–2006).

spring at daily scale.

As shown in Figure 8, comparison between the simulated and observed monthly discharges at the three hydrological stations shows that the proposed model had good performance. Table 2 summarizes the NSE and RE values for monthly and daily discharge at the three hydrological stations. The NSE values are larger than 0.77 and the absolute values of RE are smaller than 10% for both the calibration and validation periods for the monthly river discharge. The RE value has no change for the daily river discharge. The NSE value slightly decreases but is still larger than 0.65. These results show that the model has reasonable capacity to simulate the river discharge appropriately.

It can also be observed from Figure 8 that the model

Table 2 Model performance in the calibration and validation periods based on monthly/daily river discharge

Period	The Yingluoxia station (main river)		The Zhamashike station (west tributary)	
	NSE	RE (%)	NSE	RE (%)
Calibration: 1999–2002	0.89/0.80	−8.3/−8.3	0.84/0.69	1.3/1.3
Validation: 2003–2006	0.84/0.70	−5.7/−5.7	0.77/0.65	7.5/7.5

overestimates the runoff in winter and underestim ates in spring and early summer. This might be due to non-consideration of the soil freezing/thawing process. The degree-day factor of snow-melting model could also be a reason for this error, but it should not be the major reason because this parameter affects the snow-melting amount at a daily time scale rather than at a monthly time scale. This implies that the cryosphere hydrological processes should be improved in future studies.

4.2 Simulation of water balance and detailed components

The mean annual water balance of the 12-years from 2001 to 2012 is calculated from the simulated results. As shown in Table 3 it is observed that the annual precipitation is 402.4 mm, the annual total evapotranspiration is 220.3 mm and the annual runoff is 184.6 mm. It is estimated that subsurface storage (water storage in soil layer and groundwater aquifer) increases 5.4 mm and the glacier and snow cover decrease 7.9 mm. Table 3 illustrates that annual evapotranspiration is largely from soil evaporation which contributed 75% (164.1 mm) of the annual total (220.3 mm). Contributions from vegetation transpiration and canopy evaporation are estimated to be 20% (44.2 mm) and 5% (12.0 mm), respectively. Soil evaporation dominates the total actual evapotranspiration, this might be due to low vegetation coverage used in this simulation and low LAI values estimated from monthly NDVI data. From Table 3 we also can find that groundwater flow dominates the total runoff. The major reason could be the high permeability of the soil and groundwater aquifer. However the reality of evapotranspiration and runoff components should be validated carefully using the HiWATER observations (Li et al., 2013) in future study.

Table 4 shows the long term mean water balance and the detailed components for the west and east tributaries, and the main river section region, respectively. Runoff depth of the main river section is lower than that of the east and west tributaries. In the west and east tributaries, the groundwater runoff is much larger than the surface runoff. This spatial variability in hydrological behavior might be caused by the spatial heterogeneities in climate and landscape conditions. Climate over the high cold mountainous region has great spatial variability, which is a major uncertainty source of hydrological simulations. Similar to this spatial variability, the detailed water balance components for different land cover (vegetation) types show much higher variability, indicating the different eco-hydrological behaviors due to the vegetation differences.

Heterogeneity of the soil and groundwater is one of the challenges to hydrological simulation in many watersheds, and it is especially important in the upper Heihe River. Therefore, future studies should focus on the hillslope subsurface parameterization, and the reality of runoff pattern needs to be validated using field experimental data.

4.3 Discussion on future model improvement

Major implications from the above hydrological simulation can be summarized as follows: (1) The soil freezing/thawing and snow/glacier melting processes are important in high cold mountainous regions. (2) Special attention should be paid to the subsurface parameterization of the hillslope for subsurface and groundwater flow dominant regions. (3) Partition of the precipitation into the evapotranspiration and runoff is controlled by the soil-vegetation-atmosphere interaction in which the vegetation pattern and vegetation growing are essential. Therefore, future improvements of this distributed eco-hydrological model should consider:

(1) Hillslope parameterization. Figure 6 gives the geometry of a hillslope, which is estimated from the DEM. In order to simulate the hillslope hydrology, parameterization of vegetation pattern along the hillslope (from the top to base), subsurface soil and bed rock, and vertical structure of the vegetation needs to be considered.

(2) Incorporation of hillslope hydrology with cryosphere processes. Simulation of the soil freezing/thawing and snow/glacier melting processes using more physically-based approach is needed.

Table 3 Long-term mean water balance and detailed components for the whole study catchment[a)]

Precipitation (mm/a)	Actual evapotranspiration (mm/a)			Runoff (mm/a)			Change in subsurface storage (mm/a)	Change in glacier and snow (mm/a)
	E_{canopy}	E_{tr}	E_s	R_s	R_{sub}	R_G		
402.4	12.0	44.2	164.1	12.9	26.1	145.6	5.4	−7.9

a) E_{canopy} means the canopy evaporation, E_{tr} means the vegetation transpiration, E_s means the soil evaporation, $E_{canopy} + E_{tr} + E_s = 220.3$ mm/a; R_s means surface runoff, R_{sub} means the subsurface runoff, R_G means the groundwater runoff, $R_s + R_{sub} + R_G = 184.6$ mm/a.

Table 4 Long-term mean water balances and detailed components for the west and east tributaries and the main river section

Precipitation (mm/a)	Actual evapotranspiration (mm/a)			Runoff (mm/a)			Change in subsurface storage (mm/a)	Change in glacier and snow (mm/a)
	E_{canopy}	E_{tr}	E_s	R_s	R_{sub}	R_G		
The West Tributary, $E_{canopy}+E_{tr}+E_s$ = 223.8 mm/a, $R_s+R_{sub}+R_G$ = 196.5 mm/a								
417.4	8.3	43.1	172.4	22.1	20.2	154.2	9.3	−12.2
The East Tributary, $E_{canopy}+E_{tr}+E_s$ = 198.4 mm/a, $R_s+R_{sub}+R_G$ = 187.3 mm/a								
383.3	17.9	45.8	134.7	6.6	35.9	144.8	0.2	−2.6
The Main River Section, $E_{canopy}+E_{tr}+E_s$ = 234.5 mm/a, $R_s+R_{sub}+R_G$ = 156.6 mm/a								
389.5	12.2	43.1	179.2	3.3	28.0	125.3	−1.2	−0.4

(3) Coupling of hillslope hydrology with vegetation pattern and growing process. It is necessary to couple the proposed model with a vegetation dynamics model for simulating the interaction between the hydrological processes and the vegetation growth.

(4) Incorporating flow routing with river ice hydraulics. Water freezing and thawing would change the river flow especially in winter and spring. Therefore it is necessary to consider river ice hydraulics in simulation of flow routing along the river network.

Field observed data, both onsite and remotely sensed, should be used for calibration and validation of the model. In addition to improvements in the model itself, careful attention should also be given to forcing data accuracy. Recent research in the Tibetan Plateau (Chen et al., 2013) could be taken as a base reference.

5 Summary and conclusion

A distributed scheme for eco-hydrological modeling in the upper Heihe River is proposed in this study. For testing a simplified hydrological simulation has been carried out in the study area, and based on the simulation results model improvement has been discussed. The major conclusions are:

(1) Stream network plays an important role as water flow pathways in catchment hydrology. The discretization scheme used in a distributed eco-hydrological model must maintain an appropriate stream network. For the upper Heihe River, a grid system of 1 km × 1 km is suggested for this task.

(2) In order to describe the topography, a sub-grid parameterization approach in which each 1 km × 1 km grid is represented by a number of topographically similar “hillslope-valley” systems, is introduced. The hillslope is considered as the basic simulation unit of the distributed eco-hydrological model.

(3) The test run shows that sub-surface and groundwater runoffs are the dominant components of total runoff. This implies that the sub-surface parameterization on the hillslope has significant effects on runoff simulation. Therefore soil freezing/thawing and snow/glacier melting processes need to be considered.

(4) The detailed water balance components show high variability in different land cover types. This result suggests that it is necessary to couple vegetation pattern and growing process for better simulation of the catchment hydrology.

In summary, results from the test run demonstrate the flexibility of this distributed modeling scheme and show clearly the future direction of model improvement.

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