Hydrological Modelling and Integrated Water Resources Management in Ungauged Mountainous Watersheds
(Proceedings of a symposium held at Chengdu, China, November 2008). IAHS Publ. 335, 2009.

Evaluating the hydrological responses to climate change over a large basin with a hydrological–vegetation coupling model

XINGGUO MO, SUXIA LIU & ZHONGHUI LIN
Key Laboratory of Water Cycle & Related Land Surface Processes, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
moxg@igsnrr.ac.cn

Abstract A physically-based distributed hydrological–vegetation coupling model, VIP, is developed to predict the responses, i.e. the relative changes, of hydrological processes to climate change in the Wuding River basin, one of the largest tributaries to the middle Yellow River, located in the Loess Plateau. It is found that the discharge is sensitive to climate change scenarios, and the response amplitudes are quite different at sub-basins. The response of discharge ranges from 11% to 25% under the scenarios of ±10% precipitation variations and 1°C temperature increment, showing that precipitation amplifies stream runoff change, but the warming mitigates the responses of runoff. Regressive analysis shows that better correlation exists between the responses of runoff and the annual runoff (basin area), with the Pearson coefficient (r) being from 0.35 to 0.61, than the correlation between the response of runoff and annual precipitation with r being from 0.29 to 0.43. It is illustrated that considering precipitation processes other than just the annual precipitation, and running the ecohydrological model at as small as a daily scale and coupling with vegetation dynamics, are crucial in exploring the responses of hydrological processes to climate change.

Key words distributed ecohydrological model; streamflow; evapotranspiration; climate change; Loess Plateau

INTRODUCTION

Climate change has gained considerable attention over the last decade, due to the concerns of unfavourable impacts on water resources, agriculture and ecosystems, as well as human welfare. According to the IPCC Fourth Assessment Report (IPCC, 2007), global mean temperature has risen approximately 0.74°C in the last 100 years. Global climate models (GCMs) predict temperature increases of 1.1–6.4°C over the period 1990–2100. Climate change is expected to considerably impact the surface hydrological processes with variabilities in different regions (Caballero *et al.*, 2007). Many studies show that there will be an alteration of seasonal variations with winter flow increasing and summer flow decreasing (Miller *et al.*, 2003; Drogue *et al.*, 2004). An alteration of precipitation regime will have a greater impact on discharge magnitude, whereas air warming will affect the seasonal flow evolution (McCabe & Hay, 1995; Zierl & Bugmann, 2005).

The distributed models, which describe the spatial patterns of various inputs and boundary conditions, such as topography, vegetation, land use, soil characteristics, rainfall and other meteorological driving forces, are taken as valuable tools for prediction of the hydrological responses under climate change. So far, most of the hydrological models do not embed vegetation dynamics as a component (Cayrol *et al.*, 2000), with few exceptions such as RHESSys (Tague & Band, 2004), TOPOG (Silberstein *et al.*, 1999), SWIM (Krysanova *et al.*, 1998, 1999). Further, only some studies use such kinds of coupling models to explore the impacts of climate change on hydrological processes. Hence, combining vegetation dynamics with a process-based hydrological model to investigate the interactions between vegetation, hydrology and climate still poses challenges.

In this study, a distributed hydrological–vegetation dynamic coupling model is designed to simulate the hydrological responses to climate changes in the Wuding River basin, a large basin on the Loess Plateau. Through evaluating the responses of hydrological processes (streamflow and ET, etc.) to climate change at the basin scale, the study will provide a scientific basis to decision makers for sound management of soil and water.

THE VIP DISTRIBUTED ECO-HYDROLOGICAL MODEL

The model used here is called VIP (Vegetation Interface Processes) model (Mo & Liu, 2001; Mo *et al.*, 2005b, 2009). It was developed under the support of geographical information data. Its ecological and hydrological processes are coupled by a one-dimensional soil–vegetation–atmosphere transfer (SVAT) scheme, a distributed runoff routing scheme and a vegetation dynamic scheme. The model framework is introduced briefly as following:

Water budget

Water budget in a grid can be described as,

$$P = E_v + E_g + R + \Delta S \tag{1}$$

where P is the precipitation; E_v and E_g are the canopy transpiration and soil evaporation, respectively; R is the runoff of overland and groundwater; ΔS is the storage change. The unit of all these variables is mm.

Water cycle and energy transfer are coupled through ET (latent heat flux) process. Neglecting solar energy fixed by photosynthesis, energy balances in canopy and soil surfaces are expressed as,

$$C_v \frac{\partial T_v}{\partial t} = R_{nv} - H_v - LE_v \tag{2}$$

$$C_{m1} \frac{\partial T_g}{\partial t} = R_{ng} - H_g - LE_g - G \tag{3}$$

where C_v and C_{m1} are the bulk heat capacity of canopy and surface soil layer (J m^{-2} K^{-1}); T_v and T_g are the canopy and soil surface temperatures (K); R_n, H, LE and G are the net radiation, sensible, latent and soil heat fluxes (W m^{-2}), with subscript v and g referring to canopy and ground, respectively.

Overland runoff is estimated with a variable infiltration curve (Mo *et al*., 2005a), modified from Zhao (1992). The groundwater is divided into two layers and routed to the channel with the linear reservoir assumption. Routines of both overland and channel runoff are calculated with the kinematic wave equation.

Vegetation dynamics

The evolutions of foliage, stem and root biomass are expressed as:

$$\frac{dM_i}{dt} = a_i P_g - R_{g,i} - R_{m,i} - D_i \tag{4}$$

where M is the biomass of vegetation compartments (g m^{-2}); subscript $i = l$, s, r, representing the foliage, stem and root biomass of woody vegetation types, respectively; for herbaceous vegetation, $i = l$, r, representing foliage and root, respectively; P_g is the daily gross photosynthetic amount (g (CH_2O) m^{-2} day^{-1}; a is the allocation coefficient; R_m and R_g are the maintenance and growth respiration rates (g m^{-2} day^{-1}), respectively; D is the senescent rate (g m^{-2} day^{-1}); t is time (days).

The estimation of canopy photosynthesis is based on Farquhar's biochemical model. The canopy leaves are simplified into sunlit and shaded groups to account for their different photosynthetic responses to radiation and a multilayer scheme is designed to describe the radiation penetration in canopy. Leaf area index (*LAI*) is the key state variable linking the hydrological processes and vegetation dynamics. *LAI* is derived from the foliage biomass, M_l, and the specific leaf area, s (m^2 g^{-1}), namely:

$$LAI = sM_l \tag{5}$$

STUDY BASIN AND DATA

Study basin

The Wuding River, one of the largest tributaries in the middle reach of the Yellow River, is located on the Loess Plateau, covering an area of 30 261 km^2 (Fig. 1). The altitude in the basin ranges from 600 m to 1800 m with the main flatland being about 1200 m a.s.l. in the northwestern part. In its southern part, the geomorphologic characteristics consist of terraces, hill slopes and incised gullies. The main channel originates from Mount Baiyu, with a length of 491.1 km and a mean slope of 0.197%. The soil texture is distinguished as sandy loam, sandy silt, silt, sand and coarse sand, of which 55% is sandy silt. It belongs to the semi-arid climate zone. The annual precipitation amount is 376 ± 92 mm over the period from 1970 to 2000, most of which occurs in summer monsoon season, especially from July to August. The long-term mean stream flow over the period from 1970 to 2000 is about 30 m^3 s^{-1} at the basin outlet (Baijiachuan site).

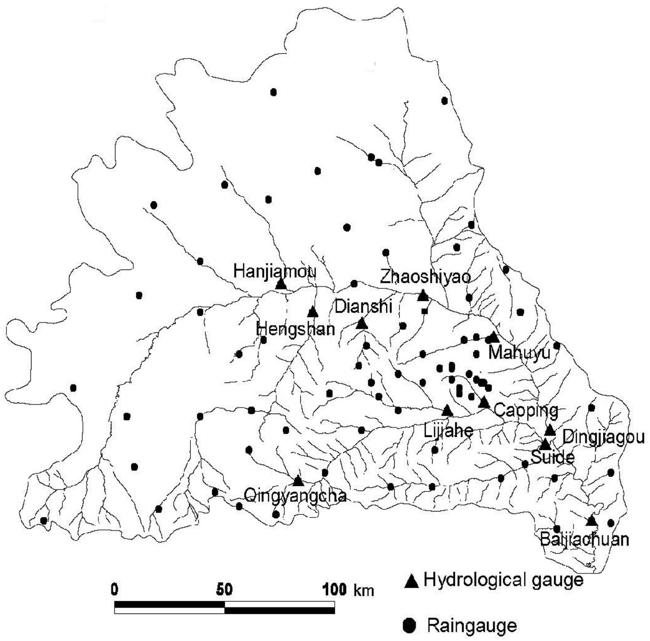

Fig. 1 Hydrological and rain gauges over the Wuding River basin.

Data

Based on the land use map published in 1990 (Wu *et al.*, 1990), the land use/cover patterns in the basin are classified into six types, namely, farmland, deciduous broadleaf forest, mixture forest, dwarf shrub, grassland and desert with ratios being 22.4%, 1%, 0.3%, 10%, 45% and 21.4%, respectively. The planted crops include maize, millet, sorghum, rice, soybean and some others. A DEM generated from contour with 1:250 000 scale is used to derive the channel pattern and flow directions of the whole basin with 1 km resolution.

Daily precipitation at 82 raingauges and meteorological data recorded at 16 climatic stations in and around the basin are used to interpolate the surface synoptic variables, which include daily atmospheric pressure, maximum and minimum air temperatures, humidity, wind velocity, precipitation and sunshine duration. Diurnal variation of air temperature and solar radiation are estimated with sine shape curves. Geographical information of vegetation types is incorporated to assign the land surface attributes spatially. Then the model is run with a 30-minute time step and 1-km spatial resolution.

Climate change scenarios

Climate change considerably affects the ecosystem water cycle and carbon assimilation processes. According to HadCM3 GCMs projections, the air temperature and precipitation over the Loess Plateau will increase about 1ºC and 10% in 2035, respectively. Under climate change, the temperature of the Wuding River basin will increase along with global warming, whereas precipitation is quite uncertain. Considering the uncertainty in the climate change scenarios, as well as the spatial variability of precipitation, we set 0.5°C and 1.0°C increments of air temperature, along with 10% increment/decrement of precipitation, respectively, as the climate change scenarios. Only sensitivities of the hydrological cycle to climate change in the Wuding River basin under air temperature increase and precipitation increase/decrease scenarios are analysed here.

RESULTS

Discharge validation

The predicted daily discharges from 1988 to 1997 are validated with the measurements at the basin and six sub-basin outlets (Fig. 2). The Pearson correlation coefficient is 0.70 between the two series. The absolute relative biases of annual discharge are less than 13% between the predicted and measured discharge, except for two years. For the six sub-basins, the mean absolute relative bias of annual discharge was 14% in 1988 (Fig. 3). In this kind of semi-arid basin, rainfall–runoff process is related to rainfall intensity, soil hydraulic conductivity, as well as vegetation condition. Bias in the runoff prediction may come from parameter uncertainty in the overland runoff generation scheme.

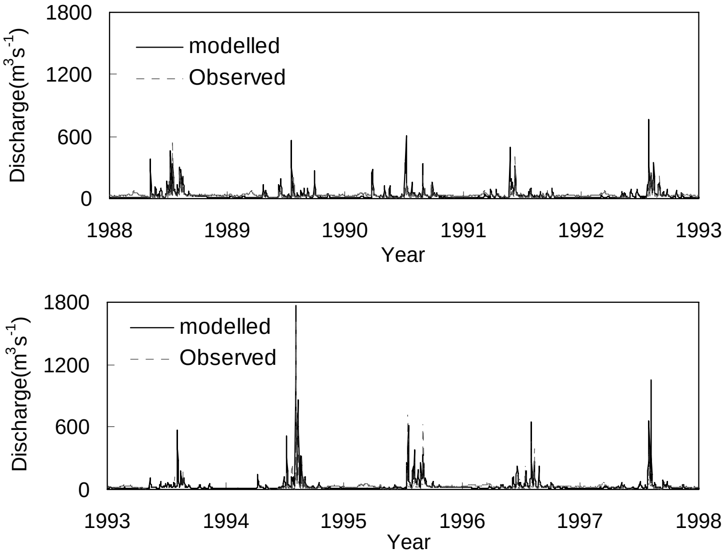

Fig. 2 Comparison of the observed and simulated daily stream discharge at the basin outlet from 1988 to 1997.

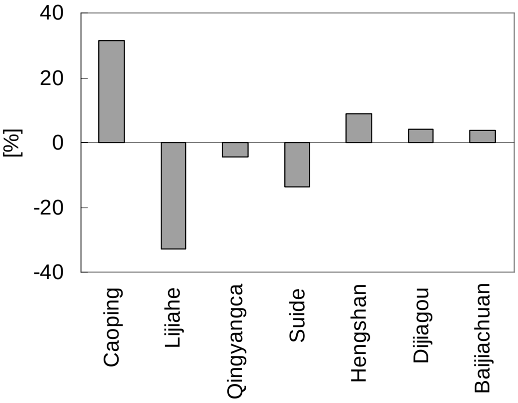

Fig. 3 Relative errors of the simulated annual discharges at the basin and its six sub-basin outlets in 1988.

Climate change effects

From the model simulation, it shows that for +10% precipitation conditions, runoff will increase by 11–20%; while for –10% precipitation conditions, runoff will reduce by 13–22% in the basin and six sub-basins (Table 1). Without precipitation change, air warming will reduce the runoff. The predicted ranges of the responses, i.e. the relative change, of runoff to climate change are comparable to literature reports, such as Jones *et al.* (2006), which reported a 1% change of annual precipitation inducing 2.1–2.5% change of runoff in Australia basins. The stream runoff usually amplifies the effect of precipitation change, whereas the warming mitigates the runoff responses. This is also found from the analysis based on observed data (communication with the Bureau of Hydrology, Yellow River Conservancy Committee).

The simulation results also show that the responses of streamflow at the entire basin and sub-basin scale are quite different, which is largely conditioned by spatial variability of climatic and physiographical characteristics between the sub-basins (Drogue *et al.*, 2004). In our case, the response variability is mainly related to the difference in temporal precipitation series.

The mechanisms of the heterogeneous hydrological responses to climate change over the large basin can be explained as follows: (1) during dry seasons, higher temperature will enhance the land surface ET rate, then more soil moisture is depleted and the recharge to groundwater is reduced, and finally the streamflow becomes lower; (2) as the response of overland runoff to daily precipitation is nonlinear and also regulated by vegetation conditions, the same percentage increment of rainfall will result in quite varied runoff responses, e.g. the response magnitudes are diverse for two sub-basins with almost the same amount of annual precipitation.

Better correlation exists between the response and runoff depth on an annual scale (basin area), with the Pearson correlation coefficient being from 0.35 to 0.61, than the correlation between the response and precipitation, with the Pearson correlation coefficient being from 0.29 to 0.43, as shown in Table 2. In such a semi-arid basin, the precipitation amount in the specific storm events and soil moisture at the beginning of the rainy season, play a more critical role in shaping the flow than the rainfall total, as demonstrated by the simulation at a daily scale.

Table 1 Area, annual precipitation and runoff amounts in 1988 and the relative changes of the stream flow to climate changes (+0.5°C, +1.0°C temperature and ±10% precipitation change) over the entire basin and its six sub-basins (Baijiachuan is the basin outlet).

	Caoping	Lijiahe	Qingyangca	Hengshan	Suide	Dingjiagou	Baijiachuan
Area (km^2)	187	807	662	2415	3893	23422	29662
P (mm year^{-1})	503	435	434	423	444	419	424
Q (10^{4}m^3 year^{-1})	2.96	6.02	7.73	18.73	44.03	236.02	341.24
+0.5°C, +10%	0.19	0.15	0.13	0.16	0.15	0.18	0.19
+0.5°C, –10%	–0.20	–0.15	–0.13	–0.16	–0.17	–0.17	–0.20
+1.0°C,+10%	0.18	0.12	0.11	0.16	0.13	0.16	0.16
+1.0°C, –10%	–0.21	–0.17	–0.14	–0.16	–0.18	–0.18	–0.22

Table 2 The Pearson correlation coefficient between the responses and annual precipitation and between the responses and runoff amounts over the entire basin and its six sub-basins.

		Q (10^{4}m^3 year^{-1})	P (mm year^{-1})
Responses	dT=+0.5°C, dP=+10%	0.61	0.29
	dT=+0.5°C, dP=–10%	–0.51	–0.43
	dT=+1.0°C, dP=+10%	0.35	0.37
	dT=+1.0°C, P=–10%	–0.57	–0.39

In contrast, ET from the land surface is slightly intensified (about 2%) with 1°C air temperature increment, even though the precipitation is reduced by 10%, due to the extending growing period and water vapour deficit. Under the above climate change scenarios, the relative changes of ET are much less than that of runoff caused by the precipitation increment/decrement (not shown here).

DISCUSSION AND CONCLUSIONS

Climate changes the vegetation composition in the relative long term, which significantly influences the vegetation and hydrological processes. The climate change alters the vegetation density, resulting in hydrological processes modification. To exploit the hydrological mechanisms under climate changes, eco-hydrological models, which integrate vegetation dynamics, hydrological processes and the feedback of climate are effective tools.

The paper conducted a sensitivity analysis of hydrological processes to climate change by using the eco-hydrological VIP model. It shows that the streamflow is quite sensitive to precipitation change, whereas the sensitivities are quite different at sub-basin scale. The responses range from 11% to 25% under scenarios of ±10% precipitation change and 1°C temperature increments.

Acknowledgements This study was jointly supported by the Natural Science Foundation of China grant (40671033, 40671032), the Chinese Ministry of Science and Technology for “863” agriculture high technology project (2006AA10Z228), the Chinese Ministry of Science and Technology for “973”projects (2009CB421307, 2010CB428400-4).

REFERENCES

Caballero, Y., Voirin-Morel, S., Habets, F., Noilhan, J., LeMoigne, P., Lehenaff, A. & Boone A. (2007) Hydrological sensitivity of the Adour-Garonne river basin to climate change. *Water Resour. Res.* **43**, W07448, doi:10.1029/-2005WR004192.

Cayrol, P., Kergoat, L., Moulin, S., Dedieu, G. & Chehbouni, A. (2000) Calibrating a coupled SVAT–vegetation growth model with remotely sensed reflectance and surface temperature – a case study for the HAPEX-Sahel grassland sites. *J. Appl. Met.* **39**, 2452–2472.

Drogue, G., Pfister, L., Leviandier, T. E. I., Idrissi, A., Iffly, J. F., Matgen, P., Humbert, J. & Hoffmann, L. (2004) Simulating the spatio-temporal variability of streamflow response to climate change scenarios in a mesoscale basin. *J. Hydrol.* **293**, 255–269.

IPCC (2007) The Physical Science Basis. Contribution of I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: *Climate Change 2007.* (ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller). Cambridge University Press, Cambridge, UK.

Krysanova, V., Muller-Wohlfeil, D. & Becker, A. (1998) Development and test of a spatially distributed hydrological/water quality model for mesoscale watersheds. *Ecol. Modelling* **106**, 261–289.

Krysanova, V., Wechsung, F., Becker, A., Poschenrieder, W. & Grafe, J. (1999) Mesoscale ecohydrological modelling to analyse regional effects of climate change. *Environ. Modeling & Assessment* **4**, 259–271.

Jones, R. N., Chiew, F. H. S., Boughton, W. C. & Zhang, L. (2006) Estimating the sensitivity of mean annual runoff to climate change using selected hydrological models. *Adv. Water Resour.* **29**(10), 1419–1429.

McCabe, G. J. & Hay, L. E. (1995) Hydrologic effects of hypothetical climate changes on water resources in the East River basin, Colorado. *Hydrol. Sci. J.* **40**, 303–318.

Miller, N. L., Bashford, K. E. & Strem, E. (2003) Potential impacts of climate change on California hydrology. *J. Am. Water Resour. Assoc.* **39**, 771–784.

Mo, X. & Liu, S. (2001) Simulating evapotranspiration and photosynthesis of winter wheat over the growing season. *Agric. For. Met.* **109**, 203–222.

Mo, X., Beven, K., Liu, S., Leslie, L.M. & de Roo, Ad (2005a) Long-term water budget estimation with the modified distributed model – LISFLOOD-WB over the Lushi basin, China. *Meteorol Atmos Phys.* **90**, 1–16.

Mo, X., Liu, S., Lin, Z., Xu, Y., Xiang, Y. & McVicar, T. R. (2005b) Prediction of crop yield, water consumption and water use efficiency with a SVAT-crop growth model using remotely sensed data on the North China Plain. *Ecol. Modelling* **183**, 310–322.

Mo, X., Liu, S., Chen, D., Lin, Z. & Zhao, W. (2009) Grid-scale effects on evapotranspiration and gross primary production estimation over a large loess plateau basin. *Hydrol. Sci. J.* **54**(1), 160–173.

Silberstein, R. P., Vertessy, R. A., Morris, J. & Feikema, P. M. (1999) Modelling the effects of soil moisture and solute conditions on long-term tree growth and water use: a case study from the Shepparton irrigation area, Australia. *Agric. Water Manage.* **39**, 283–315.

Tague, C. & Band, L. E. (2004) RHESSys: Regional hydro-ecologic simulation system: an object-oriented approach to spatially distributed modeling of carbon, water and nutrient cycling. *Earth Interactions* **8**, 1–42.

Wu, C. (1990) *1:1 000 000 Land Use Map of China*. Science Press, Beijing, China.

Zhao, R. J. (1992) The Xinanjiang model applied in China. *J. Hydrol.* **135**, 371–381.

Zierl, B. & Bugmann, H. (2005) Global change impacts on hydrological process in Alpine catchments. *Water Resour. Res.* **41**, W02028, doi: 10.1029 /2004WR003447.