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# Mountain-river runoff components and their role in the seasonal development of desert-oases in northwest China

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ABSTRACT

The paper examines the role of mountain runoff in the seasonal growth of oasis vegetation in the hyper-arid region of northwest China. Central to this examination is the development of a simple hydrologic model that relates hydrologic inflows and outflows estimated from remote sensing data (e.g., evapotranspiration, precipitation, snow accumulation, and snowmelt) to the calculation of runoff over a ten-year period (2000–2009). Modeled runoff is shown to reproduce the seasonal trends in hydrometric data fairly well, yielding $R^2$'s of 0.75 and 0.66 for stations in the upper reaches of the Shiyang and Hei River systems. Greater than 90% of the runoff from the Qilian Mountains to the oases occurs during the May–September period. Considerable discrepancy between modeled and observed runoff exists in the lower reaches of the rivers, where significant amounts of river water (>45%) are routinely extracted for cropland irrigation. Along the river systems, where water extraction and inflow of glacial meltwater are minor, model calculations replicate observed water yields much more closely. Analysis of seasonal trends in the contribution of snowmelt and rainfall to the return flow, reveals snowmelt as having the greatest influence in initiating the oasis growing period during the March-to-May period of each year.



## 1. Introduction

Permanence of vegetation cover at the base of mountain ranges in northwest (NW) China is fundamental to the long term ecological integrity of lowland oases (Ji et al., 2006). Desert-oases in the region account for little more than 5% of the total landbase (Han and Meng, 1999; Li et al., 2006), yet support about 95% of the region's growing population (Chu et al., 2005). In the shadow of the Qinghai-Tibetan Plateau, NW China is one of the driest places on earth (Huo et al., 2007). The amount of convective precipitation induced locally (at the scale of individual oases) is normally insufficient to satisfy the demand for water by existing lowland vegetation. Fate of this vegetation depends to a large measure on the availability of substantial amounts of precipitation-water generated in the mountains as a result of orographic processes (Bourque and Hassan, 2009).

Water recycles in these hydrologically-closed (endorheic) basins through three main mechanisms, namely through: (i) the loss of oasis surface water to the atmosphere by evapotranspiration (ET) and horizontal wind advection; (ii) the production of in-mountain precipitation by orographic lifting of moistened desert air and condensation of water vapor; and (iii) the return of liquid water to the base of the mountains and oases by downslope, surface and shallow-subsurface flow (Bourque and Hassan, 2009; Bourque and Matin, 2012). In general, water not used by the lowland vegetation or by humans flows to terminate in the deserts due to excessive evaporation (Li et al., 2013).

Associated river basins are economically very important (Chen et al., 2003), but at the same time, extremely sensitive to hydro-meteorological and climate variability (Meybeck, 2003). Monitoring and forecasting of water yield and generation of river runoff is crucial to the sustainable management of these basins.

Conceptual hydrological models use simple mathematical equations to describe basic hydrological processes of river basins (Aghakouchak and Habib, 2010) and are based on a schematic understanding of hydrological features (Pechlivanidis et al., 2011). By using simpler equations, conceptual models overcome some of the limitations in physically-based models (Elshorbagy et al., 2010).

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Their simplicity, however, has resulted in some opposition from hydrologists because of the lack of causal description of physical relationships (Elshorbagy et al., 2009). In spite of this opposition, when implemented with prudence and an excellent understanding of the interactions among the different variables, conceptual models are convenient tools in modeling hydrological systems. Popular conceptual models varies in terms of spatial representation, number of calibration parameters, and level of process description. In simplifying calculations, semi-distributed models, such as TOPMODEL (Beven and Kirkby, 1979), HBV (Lindstrom et al., 1997), and SWAT (Arnold et al., 2012), partition river basins into homogenous response units (sub-catchments) according to the region's topography, landuse, and other land-surface features. TOPMODEL and SWAT require the calibration of 11 parameters and HBV, the calibration of 17 parameters in their basic use. The distributed model, variable infiltration capacity model (VIC), partitions the watershed into equal grid areas and requires the calibration of 17 parameters.

Few attempts have been made to implement hydrological models in simulating river runoff in NW China. Chen et al. (2003) implemented a distributed model for a mountainous region of the Hei River basin. In their work, the study area was sub-divided into 103 sub-basins; each sub-basin providing a new background for the calculation of water balances at the sub-basin scale. Excess water in each sub-basin (i.e., water beyond the water-holding capacity of sub-basins) was treated as runoff and was passed on to a neighboring sub-basin in a downstream direction. The model required that 27 parameters be calibrated. Kang et al. (1999) implemented the HBV model with some modification. Using precipitation and temperature as basic input, the model generated monthly ET and surface runoff. Vertical modification in precipitation and temperature fields was calculated from altitudinal gradients and atmospheric lapse rates estimated from meteorological data acquired from the Zhangye (reference station) and surrounding climate stations. Zhao and Zhang (2005) employed the VIC-3L model for the headwaters of the Hei River basin. VIC-3L is a grid-based model (Liang et al., 1996) that generates surface runoff depth within individual grid cells. Surplus water is routed in the model according to a unit-hydrograph method (Nijssen et al., 1997); a unit hydrograph is the direct runoff resulting from one unit of effective rainfall (Rakhecha and Vijay, 2009). Input data to the model were interpolated from daily precipitation and temperature data observed at several climate stations. Jia et al. (2009) implemented a distributed water- and energy-balance model to investigate the hydrological cycle in the upper and middle reaches of the Hei River basin. Model simulations were performed with daily precipitation and temperature input data at 1-km grid resolution generated with Thiessen polygons and adjusted locally according to elevation.

Common to all of these applications is the engagement of some form of numerical interpolation in generating the required input data. As the models are complex, model calibration (given the appropriate information) frequently relies on adjusting a large number of model parameters, usually by trial and error. In general, as the number of model parameters increases, the statistical stability of model predictions deteriorates (Xing et al., 2008). Also, the spatial unit of calculation is often large, e.g., at the sub-basin scale or at coarse grid resolutions ($\geq$1-km resolution). Depending on the sensitivity of parameters, calibration error in these models can often lead to incorrect results; this is particularly the case in areas with highly variable landcover and topography, such as in NW China. Lack of computing resources may also limit the application of these complex models, especially when spatial resolutions are refined or the models are applied to large computational domains (Kishtawal et al., 2003).

Quality of the output from hydrological models is always determined by the quality of input data used in model calibration, initialization, and simulation. In sparsely-gaged river basins, application of distributed models may suffer some uncertainty, due to error introduced in the input data as a result of spatial interpolation. In regions, where landcover and topographic variation is high, calibrated remote sensing (RS)-data can help improve model-output quality (Schultz, 1993). Various RS-sensors deployed over the last few decades have proven effective either at directly estimating specific hydrologic variables or by capturing land surface and atmospheric properties that can be subsequently used to estimate components of the water cycle (Pietroniro and Leconte, 2005; Schmugge et al., 2002). At present, means to determine river runoff directly from RS-data are lacking. However, earlier studies have shown that the use of RS-data as input in distributed hydrological models can enhance our modeling capabilities of surface runoff (Immerzeel et al., 2008; Liu et al., 2012; Qin et al., 2008; Schultz, 1996; Shelp et al., 2011).

In this study, we develop and implement a monthly distributed hydrological model to estimate surface runoff and river-water yields at moderate spatial resolution (250-m resolution) for two data-sparse, endorheic river basins in NW China over a 10-year period (2000–2009). Considering that most of the liquid water generated in these river basins contributes to surface and subsurface flow with much less to recharging groundwater, we assume that a simple water-balance model, with fewer parameters than most existing hydrological models (two, overall), is sufficiently robust to produce acceptable evaluations of river runoff, when high-quality input data (i.e., rasterized hydrological components generated from RS-data) are used in model simulation.

## 2. Study area

The study area consists of the Shiyang and Hei River basins in westcentral Gansu, NW China (Fig. 1). The Shiyang River basin is an endorheic river basin (Li et al., 2013) located in the eastern Hexi Corridor. The Shiyang River network originates from the Qilian Mountains and flows about 300 km northeastward (Gao et al., 2006) before terminating in the Minqin-lake district (Li et al., 2007). The total basin area is roughly 49,500 km$^2$. Elevation in the Shiyang River basin varies from 1284–5161 m above mean sea level (AMSL), with a mean elevation of 1871 m AMSL. The Shiyang River network has eight main branches, including the Xida, Donga, Xiying, Jinta, Zamusi, Huangyang, Gulang, and Dajing Rivers (Li et al., 2013; Wonderen et al., 2010).

The Hei River network also originates in the Qilian Mountains, northwest of the main source of the Shiyang River, and flows northwestward through the oases and terminates in the desert lakes (Akiyama et al., 2007). The Hei River basin, with a land surface area of approximately 128,000 km$^2$, is the second largest endorheic river basin in NW China (Gu et al., 2008). The Hei River basin includes the Zhangye sub-basin, with a total land area of about 31,100 km$^2$. Elevation in the Zhangye sub-basin varies from 1287–5045 m AMSL, with a mean elevation of 2679 m AMSL (Fig. 1).

The study area overlaps four distinct ecoregions (Olson et al., 2001). The northern part, noted for its arid to semi-arid conditions, includes a portion of the Badain Jaran and Tengger deserts and oases in the southwestern portions of the Alashan Plateau. The Liangzhou Oasis, to the south, and the Minqin Oasis, to the north, are two important oases in the Shiyang River basin (Li et al., 2007), whereas the Zhangye Oasis is the main oasis in the Zhangye sub-basin. Spring wheat is the main food crop grown in these oases, which is usually supported by irrigation (Zhao et al., 2005). In the deserts, salt-tolerant, xerophytic shrub species, i.e., saxaul