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Streamflow simulation using a water-balance model with annually-resolved inputs

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SUMMARY

Availability of long-term information on the variability of water resources in a given area is particularly important for sustainable resource management. Developing watershed simulation models that can be run using annually-resolved proxy climate data provides a way to improve reconstructions of hydrological parameters over multi-century time scales. Through the addition of a snowmelt modeling component, we enhanced a simple water-balance model to simulate streamflow at seasonal resolution. The model was calibrated to the upper Meadow Valley Wash, Nevada, USA, using USGS gage number 09417500 streamflow records. PRISM data at 2.5 arc-min resolution were used to reconstruct streamflow at the seasonal timescale (October through May) from 1896 to 2008, with and without a temperature-index snowmelt component. Best-fit model simulations had an R^2 of 0.81 against stream gage observations. Average predicted seasonal streamflow during calibration was 0.81 cm with a standard deviation of 0.35 cm, compared to the observed average seasonal streamflow of 0.76 cm and standard deviation of 0.48 cm. Despite some shortcomings for this watershed, the model approach has promise for providing scenario-based estimates of hydrologic variability in semi-arid mountain environments.

Introduction

Monitoring historic water resource variability is of particular importance in the semi-arid western United States, where an already rapidly growing population is expected to increase at twice the population growth rate of the United States over the next 30 years. Temporary groundwater and surface water shortages have already been identified in areas such as the Sacramento and San Joaquin basin, Ogallala Aquifer, and Colorado River basin, in part due to the increasing demand for water from a growing population (Gleick, 1990). A costly infrastructure of aqueducts, reservoirs, and pumps has been developed here and in other semi-arid regions to import water from distant sources because local water supplies cannot meet demands. As the number of people supported from the Colorado River is projected to grow from approximately 25 million in 2005 to 38 million by 2020, the demand for expensive water projects to sustain this population increase will only continue to expand (Pulwarty et al., 2005).

Simultaneous to the expected escalation in water demand, water resource supplies in the western United States are predicted to diminish as a result of climate change. Some climate trends that could potentially lead to a reduction in water supplies have already been observed or are projected for the future. Global net radiation increased by 1.6 W/m^2 from 1750 to 2005 (Bates et al., 2008). Assuming current carbon emission levels remain constant, climate models for the western United States predict the average annual air temperature will increase by 1–2 °C from now until 2050 (Barnett et al., 2004). These trends are expected to lead to higher evapotranspiration rates and thus less available water in the west (Barnett et al., 2004; Bates et al., 2008).

Some of the specific effects that climate change is anticipated to have on western water resource supplies are alarming, particularly in the Colorado River basin. Basin-wide runoff is projected to decrease by 30% because of the anticipated increase in air temperature and evapotranspiration (Pulwarty et al., 2005). Reservoir levels are predicted to drop by an average of one-third and subsequent releases from reservoirs are expected to fall by 17% from their current state by 2050 (Barnett et al., 2008). Total mean annual flow and basin storage are projected to decrease by 14% and 36%, respectively, from 2010 to 2039. Perhaps as soon as 2025, water supplies may fail to meet the requirements of the 1922 Colorado Compact for the Lower Colorado River Basin states 40% of the time (Christensen et al., 2004). Longer-term water resource modeling is thus essential to ensure the amount of available water resources from this region can support the future population.

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Quantifying long-term variations in water resources at annual resolution has been achieved in a number of studies by developing proxy tree-ring records of hydro-climatic variables such as streamflow (Meko et al., 2001; Woodhouse et al., 2006), precipitation (Gray et al., 2004; Haston and Michaelsen, 1997), and drought (Cook et al., 2004; Meko et al., 1980). Such reconstructions have provided a measure of the historic range of variability (HRV) for these variables dating back hundreds or even thousands of years depending on the tree species being used in the reconstruction. Because instrumental climate records often span less than 100 years, the use of tree-rings to extend these records is useful to quantify the climatic HRV, thereby providing for more sound management decisions when planning for droughts, future water supplies, or the potential impacts of climate change (Hughes and Graumlich, 1996).

Tree-ring reconstructions of streamflow are typically performed by using regression techniques to relate tree-ring chronologies to runoff during the available instrumental record. The same regression techniques are then used to reconstruct streamflow beyond the instrumental period (Loaiciga et al., 1993). This practice assumes the instrumental record is representative of the entire reconstructed period, and that changes to streamflow can only be induced by changes in climate. However, landscape-scale factors such as land use changes, wildfires, species invasions, or geomorphic processes (e.g., landslides) can lead to changes in stream runoff even when climate does not change. Such scenarios could be simulated in a watershed model that uses proxy-derived precipitation and/or temperature from annually or seasonally resolved paleorecords (such as tree-rings), and also includes one or more parameters to account for changes in runoff that may occur due to modifications in the above-mentioned landscape features (Saito et al., 2008). In order to achieve this objective, it is first necessary to develop and calibrate the streamflow prediction model using instrumental records. We currently use a modification of a simple water-balance model (Fiering, 1967; Sankarasubramanian and Vogel, 2002) to estimate historic streamflow and other hydrologic component fluctuations.

In this study we extended a previous version of our model (Saito et al., 2008) by using a seasonal (October to May) instead of an annual timescale. In addition, a snowmelt component was added because snowmelt is a critical aspect of watershed modeling throughout the western United States, where snowpack accounts for about 75% of the region's water supply (Williams and Tarboton, 1999). The model was applied to the upper Meadow Valley Wash watershed of the Colorado River basin in eastern Nevada. The study area receives a large proportion of its precipitation as snow during the winter, and although our analysis was restricted to instrumental records as input, this watershed is suitable for developing multi-century long proxy records of climate (Biondi and Strachan, 2009). Such records, in turn, could be used as input to simulate (hence reconstruct) streamflow while performing model experiments to estimate how basin runoff could vary over time with changes in fire regime, grazing, vegetation cover, or topographic features.

Materials and methods

Modeling approach

The watershed model (Fig. 1) consisted of surface, subsurface, and groundwater storages and the movement of water through each of the storages was assumed to be instantaneous. Input and output hydrologic variables linked the storages to one another. Seasonal precipitation and air temperature represented the only model inputs. Other variables determined by the model included surface runoff, infiltration, evapotranspiration, deep percolation, baseflow, groundwater flow, groundwater storage, snowmelt, and surface runoff. Four water-balance model parameters were used in model calculations, including: a = fraction of precipitation that becomes surface runoff; b = fraction of infiltrated water (or portion of water not becoming surface runoff) that evaporates; c = fraction of groundwater storage that becomes baseflow; d = fraction of groundwater storage that becomes groundwater flow. Three snowmelt parameters were used in the model to estimate snow

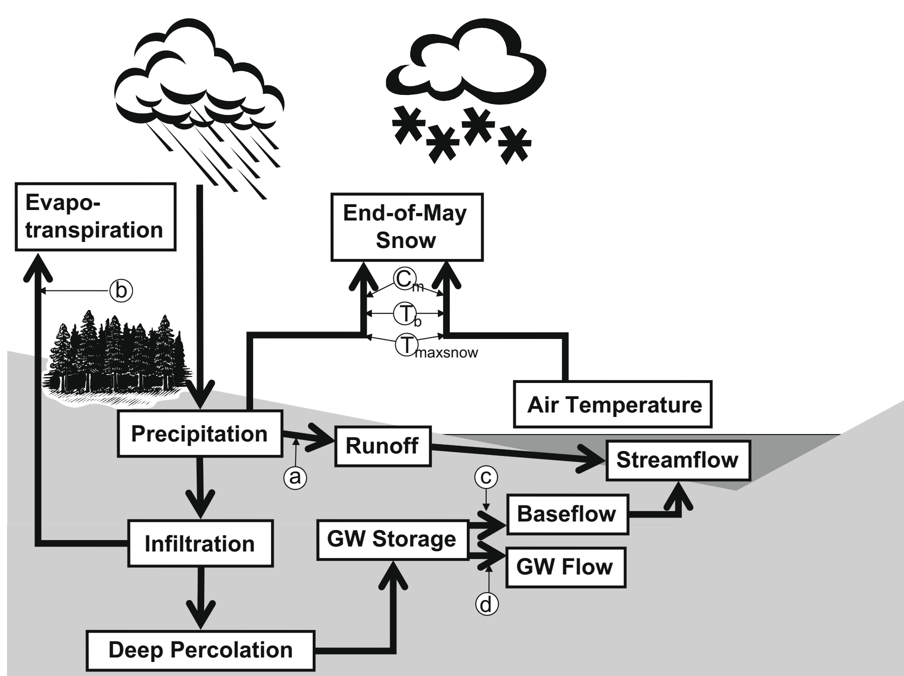

Fig. 1. Schematic of water-balance model showing variables (boxes) and parameters (circles) as well as relative locations of variables within the watershed. Large arrows indicate relative movement of water from one variable to another (GW = Groundwater). Small arrows indicate which variables the parameters are affecting.