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Selection of hydrologic modeling approaches for climate change assessment: A comparison of model scale and structures

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SUMMARY

A wide variety of approaches to hydrologic (rainfall–runoff) modeling of river basins confounds our ability to select, develop, and interpret models, particularly in the evaluation of prediction uncertainty associated with climate change assessment. To inform the model selection process, we characterized and compared three structurally-distinct approaches and spatial scales of parameterization to modeling catchment hydrology: a large-scale approach (using the VIC model; 671,000 km^2 area), a basin-scale approach (using the PRMS model; 29,700 km^2 area), and a site-specific approach (the GSFLOW model; 4700 km^2 area) forced by the same future climate estimates. For each approach, we present measures of fit to historic observations and predictions of future response, as well as estimates of model parameter uncertainty, when available. While the site-specific approach generally had the best fit to historic measurements, the performance of the model approaches varied. The site-specific approach generated the best fit at unregulated sites, the large scale approach performed best just downstream of flood control projects, and model performance varied at the farthest downstream sites where streamflow regulation is mitigated to some extent by unregulated tributaries and water diversions. These results illustrate how selection of a modeling approach and interpretation of climate change projections require (a) appropriate parameterization of the models for climate and hydrologic processes governing runoff generation in the area under study, (b) understanding and justifying the assumptions and limitations of the model, and (c) estimates of uncertainty associated with the modeling approach.

1. Introduction

The prediction and interpretation of uncertain hydrologic responses to climate change is a major challenge for water resource managers (Brekke et al., 2009). An important effect of climate change is modification of local and regional water availability due to the climate system's interaction with the hydrologic cycle (e.g., Bates et al., 2008). Studies of climate change impacts on water resources in the Pacific Northwest (PNW) suggest changes will occur in the magnitude and timing of runoff (e.g., Chang and Jung, 2010; Elsner et al., 2010; Hamlet et al., 2010), the frequency and intensity of floods and droughts (e.g., Mote et al., 2003; Jung and Chang, 2011b), water temperature (Mantua et al., 2010; Chang and Lawler, 2011), nutrient and sediment loading (Praskievicz and Chang, 2011), and quantity of water available for human use (e.g., IPCC, 2007; Mote et al., 2003). These hydrologic changes, in turn, influence various aspects of water resource management, including municipal, irrigation, and industrial supply, hydropower generation, flood management, channel morphology, and aquatic habitat conservation. Some of these effects may not necessarily be negative, but need to be evaluated because of the socio-economic importance of water (Jiang et al., 2007).

Downscaled General Circulation Model (GCM) simulations are frequently used within a hydrologic model to predict how the changes to climate affect the water balance and water-related sectors using a variety of approaches and scales of analysis (e.g., Wilby et al., 2009). Large uncertainties are inherent in the predictions, depending on GCM structure and parameterization, downscaling procedure, greenhouse gas (GHG) emission scenario, hydrologic model used, and hydrologic model parameters (e.g., Maurer, 2007; Surfleet and Tullos, 2012; Xu et al., 2005; Im et al., 2010). The effect on hydrologic predictions using different GCMs, downscaling techniques, and GHG emission scenarios have received considerable attention (e.g., Maurer, 2007; Wood et al., 2004; Maurer and Duffy, 2005). However, fewer studies (e.g., Jiang et al., 2007; Najafi et al., 2011) have focused on differences in uncertainties of

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predictions associated with the various hydrologic modeling approaches, though uncertainty should be considered in the selection of hydrologic models.

The choice of the hydrologic model may depend on a number of selection criteria, including the character (e.g., relevant spatial and temporal scale, acceptable level of error and uncertainty for alternative screening vs. detailed design) (e.g., Clark et al., 2008) of the water resource management issue. In addition, the scale of variability in physical characteristics (e.g., land use, elevation, geology) that influences important hydrological processes (e.g., evapotranspiration, snow accumulation and melt, or groundwater recharge and discharge) can be a principle factor in selecting hydrologic models. Finally, aspects of the individual models may influence its appropriateness for an application, including ease of use that includes pre- and post-processing, hardware requirements, rigor and comprehensiveness of modeled processes, availability and quality of required data, adaptability of source code, model availability, and cost (Singh, 1995).

In the PNW, several different hydrologic modeling approaches have been conducted for climate impact assessment. When continental scale information for a variety of climate predictions were needed, the VIC macroscale ($\sim$5–6 km grid cells) hydrologic model was applied (Nijssen et al., 1997; Hamlet and Lettenmaier, 1999; Elsner et al., 2010). If there is complexity and differences in hydrologic processes across the study area, but representation of small-scale spatial differences is not needed, then use of basin scale or regional parameters may be adequate (e.g., Chang and Jung, 2010; Jung and Chang, 2011a). If spatial heterogeneity in hydrogeology or subtle differences in hydrological processes over time have an important influence on runoff generation, then a site-specific modeling approach may be needed. For example, Tague et al. (2008) investigated the sensitivity of two Oregon Cascades basins, characterized by different geologic characteristics, under synthetic temperature warming scenarios using the Regional Hydro-Ecologic Simulation System (RHESSys). In urbanizing watersheds with multiple land use and water quality issues, Franczyk and Chang (2009) and Praskievicz and Chang (2011) used US EPA's physically-based model, BASINS-SWAT and BASINS-HSPF, respectively, in a site-specific approach.

With the goal of facilitating discussion on hydrologic model selection and development for use in water resources planning and design, we undertook the comparison of three modeling approaches using identical climate forcing data. We differentiate the modeling approaches by the spatial scale of the model application (Large Scale, Basin Scale, or Site-Specific) (Fig. 1) the model used, and the quantification of uncertainty within the modeling approach.

(a) Large scale (LS) deterministic approach by the Variable Infiltration Capacity (VIC) model (Liang et al., 1994) for the Columbia River basin considering GCM uncertainty.
(b) Basin scale parameters and uncertainty (BSPU) effort using a surface runoff model, Precipitation-Runoff Modeling System (PRMS) (Leavesley et al., 1983), with GCM uncertainty cascaded through a parameter uncertainty assessment using existing parameter set ranges.
(c) Site-specific modeling with uncertainty (SSMU) effort with a coupled groundwater and surface-water flow model (GSFLOW) (Markstrom et al., 2008; Harbaugh, 2005) with GCM uncertainty cascaded through a parameter uncertainty assessm.

The objectives of this analysis are: (a) to compare fit to historic hydrologic observations across three hydrologic modeling approaches with varying model structures and spatial scales of parameterization; (b) examine differences in predictions of future hydrology from the three modeling approaches, and; (c) investigate the physical processes responsible for differences in predictions to facilitate discussion on hydrologic model selection and parameterization. Model simulation results are summarized into four classes of hydrologic responses (extreme peak flows events, extreme low flow events, average monthly flow, and snowmelt) that are generally relevant to water resources management.

2. Methods

2.1. Study areas, model comparison locations, and timeframes

The Santiam River Basin (SRB, 4700 km^2) is a tributary to the Willamette River Basin (WRB, 29,700 km^2), which is itself a tributary to the Columbia River Basin (CRB, 671000 km^2). Located on the western slopes of the Cascade Range in Oregon, USA (Fig. 1), the SRB is a valuable case study for model comparison because it is characterized by spatially heterogeneous hydrogeology, creating spatial variability in hydrologic response to changes in climate. The SRB varies from mountain terrain in high elevation alpine areas (3199 m) to low relief foothills to alluvial areas (50 m) that are hydrologically connected to the Willamette Valley. The land use classification within the basin is 80% forest, 15% agriculture, 2% urban, and 3% range (USGS, 2009). The soils in the SRB are classified (NRCS, 2007) as 80% in Hydrologic Group B, with moderate rates of water transmission (infiltration and drainage) and 20% in Hydrologic Group A, with slow rates of water transmission. Precipitation varies from rain at the basin outlet to primarily snow at higher elevations, with a mix of rain and snow between the two (Fig. 1). Furthermore, two hydrologically-distinct seasons exist in the basin, a wet season (November through April) during which approximately 85% of precipitation occurs, and a dry season (May through October) during which 15% of precipitation occurs (NRCS, 2011).

The runoff from the SRB is regulated by four flood control projects, Detroit and Big Cliff dams on the North Fork Santiam River and Foster and Green Peter Dams on the South Fork Santiam River. The high elevation areas of the Santiam River are composed of High Cascades geology where runoff is influenced by discharge from a substantial, deep groundwater aquifer and springs (Tague et al., 2008; Chang and Jung, 2010; Surfleet and Tullos, 2012). The lower alluvial section of the basin include areas of considerable recharge for groundwater associated with the Willamette Valley aquifer, where low flow streamflow is strongly affected by aquifer conditions (Lee and Risley, 2002). The remainder of the basin has Western Cascade geology, characterized by moderate to low hydraulic conductivities coupled with shallow soils that result in a rapid runoff response with little groundwater storage (Tague et al., 2008).

Our hydrologic model predictions were compared at four locations within the SRB (Fig. 1) with one additional location for historical streamflow only; South Santiam at Cascadia. The four locations were selected due to the availability of output from the LS model, proximity to a river gauging station, and spatial differences in basin characteristics affecting hydrologic response (Table 1). We summarized results of the model simulations for three time periods: historic (1960–2006), 2040s (2030–2059), and 2080s (2070–2099). These time periods, representative of the middle and the end of the21st century, were used to allow comparison to already completed VIC modeling (Hamlet et al., 2010). The VIC modeling used a 30 year time period that bracketed 2040 and 2080 to represent these respective time periods. The historical values for the BSPU and SSMU approaches were calculated from USGS streamflow data. We used the published values from the VIC modeling