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# Parameterizing sub-surface drainage with geology to improve modeling streamflow responses to climate in data limited environments

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## Abstract

Hydrologic models are one of the core tools used to project how water resources may change under a warming climate. These models are typically applied over a range of scales, from headwater streams to higher order rivers, and for a variety of purposes, such as evaluating changes to aquatic habitat or reservoir operation. Most hydrologic models require streamflow data to calibrate subsurface drainage parameters. In many cases, long-term gage records may not be available for calibration, particularly when assessments are focused on low order stream reaches. Consequently, hydrologic modeling of climate change impacts is often performed in the absence of sufficient data to fully parameterize these hydrologic models. In this paper, we assess a geologic-based strategy for assigning drainage parameters. We examine the performance of this modeling strategy for the McKenzie River watershed in the US Oregon Cascades, a region where previous work has demonstrated sharp contrasts in hydrology based primarily on geological differences between the High and Western Cascades. Based on calibration and verification using existing streamflow data, we demonstrate that: (1) a set of streams ranging from 1st to 3rd order within the Western Cascade geologic region can share the same drainage parameter set, and (2) streams from the High Cascade geologic region, however, require a distinctive parameter set. Further, we show that a watershed comprised of a mixture of High and Western Cascade geology can be modeled without additional calibration by transferring parameters from these distinctive High and Western Cascade end-member parameter sets. Using this geologically-based parameter transfer scheme, our model predictions for all watersheds capture dominant historic streamflow patterns, and are sufficiently accurate to resolve geo-climatic differences in how these different watersheds are likely to respond to simple warming scenarios.





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## 1 Introduction

One of the key challenges in providing spatially distributed streamflow information is the limitation of data that is available for hydrologic model calibration and parameterization (Beven, 2001; Singh and Woolhiser, 2002; Wagener and Wheater, 2006). Implementing hydrologic models typically requires calibration of a number of drainage related parameters that cannot be directly measured (Beven, 2001). Most recent model-based studies of climate-warming impacts on hydrology within the Western US have used historic streamflow records for model calibration (Knowles and Cayan, 2002; Christensen et al., 2004; Hidalgo et al., 2009; Jung and Change, 2010; Null et al., 2010). Climate change impact assessments in the Western US address streamflow changes across multiple scales, ranging from impacts on larger-order streams that provide water supply to impacts on smaller headwater streams that support aquatic habitat. A diversity of stakeholders often needs information that includes estimates of both the distribution of headwater streamflow within a larger 3rd–4th order watershed and the discharge into larger (> 4th order) streams and reservoirs. To assess climate change impacts, estimates of how streamflow in these different sized basins responds to climate variability and change are needed (Farley et al., 2011). Particularly when assessments are focused on multiple streams, such as a population of low order stream reaches, long-term gage records may not be available for calibration. The limited availability of hydrologic data is further exacerbated by the steady decline in the USGS streamflow gauging network (USGS, 1999). Hydrologic modeling studies often assume that parameters used for a larger gaged watershed can be consistently applied to smaller sub-watersheds, or that parameters from neighboring watersheds can be used. However, calibration based on gauges from a larger order watershed does not necessarily apply to the diversity of lower order streams within that basin, or similarly, parameter transfer from neighboring watersheds may not be appropriate. In this paper we demonstrate the potential error in applying calibrated parameters across an entire watershed





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based solely on a larger order stream, and present a relatively simple strategy for parameter transfer based on geologic similarity.

Parameter transfer schemes, where parameters are assigned based on some readily measured watershed characteristics, offer one approach for assigning drainage parameters when estimates of streamflow across a range of watersheds are needed. In fact, when drainage parameters are assigned based on calibration of a larger watershed, streamflow estimates for nested subcatchments implicitly transfer parameters and assume similarity of those parameters across the larger basin. Studies on parameter transfer have used watershed size, elevation, and vegetation as a basis for transferring parameters between watersheds with varying degrees of success (e.g., Wagener and Wheater, 2006; van der Linden and Woo, 2003). These studies focus on overall model performance using different parameter schemes, but do not explicitly address implications for estimating climate change impacts. Evaluation of parameter transfer schemes, calibration approaches and model performance in general should ultimately reflect the context in which the model is being used. How good is good enough depends on the modeling goal. Here we evaluate parameter transfer approaches in the context of assessing climate change impacts on streamflow in the snow-dominated mountains of the Western Oregon Cascades.

We focus on the analysis of drainage parameter transfer in the context of snowmelt-dominated watersheds in the mountainous Western US and the use of hydrologic models to estimate how streamflow seasonality in these watersheds will respond to a warming climate. The hydrology of mountain regions throughout the globe is expected to be highly vulnerable to a warming climate (Barnett et al., 2005). In snow-dominated regions, warmer temperatures can reduce the amount of precipitation falling as snow and lead to earlier snowmelt, particularly at elevations where the majority of precipitation falls near 0 °C (Nolin and Daly, 2006). These changes in snow dynamics shift the timing of seasonal hydrographs, resulting in increased flow in winter and reductions during spring and summer (Knowles and Cayan, 2002; Barnett et al., 2005; Stewart et al., 2005). Process-based hydrologic models are one of the core tools used to project how water resources in these systems are likely to respond to climate variability and change. In this study, we investigate drainage parameter variation and its implication for hydrologic model-based estimates of seasonal streamflow responses to climate warming within the McKenzie River basin in Western Oregon. Our approach applies a process-based hydro-ecological model, the Regional Hydro-Ecologic Simulation System (RHESSys), and focuses on the estimation of seasonal streamflow response to climate change at multiple spatial scales. We propose an end-member mixing approach to parameter transfer where end-member sub-watersheds are defined based on geologic classification and used to estimate spatial patterns of drainage parameters. We then examine the utility of this parameter transfer strategy within the context of predicting inter-annual variation in seasonal streamflow patterns and streamflow response to climate warming in the snow-dominated watersheds of the Oregon Cascades.

## 2 Background

Ensemble climate model predictions for the mountain regions of the US Pacific Northwest (PNW) predict temperature increases of between 1 °C and 4 °C (Payne et al., 2004). Both empirical and model-based analyses in the PNW also link recent and projected future increases in air temperatures with reduced summer water availability (Tague et al., 2008; Hayhoe et al., 2004). This study focuses on tributaries of the McKenzie River, which is itself a tributary of the Willamette River in Oregon. The Willamette River basin is one of the largest river systems in Oregon, and drains 28 672 km$^2$ to its mouth at the Columbia River. The McKenzie River basin is one of several large tributaries of the Willamette that drains from the Cascade crest westward before joining the Willamette in its northward flow. The McKenzie River watershed, at 3463 km$^2$, accounts for approximately 12 % of the Willamette's total drainage. Streamflow within the McKenzie supports agriculture, aquatic biota, recreation, power generation, and municipal water supplies. Climate change impacts on the seasonality of flow, particularly reductions in summer flows when discharges are already low, will affect these water uses. Climate impact assessments for these multiple water uses will require estimates of the impact of climate variability and change in streamflow at multiple scales (Farley et al., 2011). For example, headwater reaches in the McKenzie support threatened fish species, such as Oregon Bull Trout and Chinook salmon (US EPA, 2003). At larger scales, flows are regulated by several large reservoirs primarily operated by the US Army Corps of Engineers within the McKenzie to provide power generation and flood protection.

For the McKenzie and other similar snow-dominated watersheds, a key hydrologic issue is how changing snow accumulation and snowmelt translate into changes in streamflow. There are two primary controls on this response: (1) how spatial patterns of snow accumulation and melt change and (2) how those changes in input translate into changes in streamflow behavior (Fig. 1). The latter is primarily controlled by subsurface drainage characteristics. Changes in evapotranspiration fluxes are a 3rd factor and can become increasingly important when climate change substantially alters vegetation structure through disturbances. A significant research focus in the Western US has been on improving models of snow accumulation and melt, as well as spatially explicit estimates of climate forcing functions (Daly et al., 1994). Translating these effects into streamflow change however, also requires adequate estimates of subsurface drainage characteristics. Our previous work has demonstrated that within the McKenzie, geologically mediated spatial differences in subsurface drainage characteristics can be a 1st order control on spatial patterns of streamflow response to warming (Tague and Grant, 2009). Subsurface drainage characteristics reflect both topography, which is relatively easy to parameterize given the widespread availability of DEM's, and effective subsurface conductivity of watersheds, where conductivity is a complex product of matric and macro pore flow rates and their distribution (Torch et al., 2009). In most hydrologic modeling studies, parameters associated with effective conductivity, such as hydraulic conductivity and macropore distributions, are calibrated or assumed to be spatially uniform. Given that subsurface drainage properties evolve through landscape evolutionary processes, one might expect that these parameters would vary across





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geological classification. Empirical studies and models based on streamflow patterns in the Oregon Cascades support this assertion (Tague and Grant, 2004, 2009).

Within the McKenzie River basin, sharp geologic contrasts exist between two largely contiguous geologic provinces: (a) the Plio-Pleistocene High Cascades (HC) to the east, and (b) the primarily Miocene Western Cascades (WC) to the west (Sherrod and Smith, 2000). Elevations range from 400 to 1800 m in the WC and from 1500 to over 3400 m at the summits of the large stratovolcanoes in the HC. Although the HC region has the highest elevations, much of the landscape is a broad constructional platform with relatively low relief; the WC is much steeper and more dissected. Young basaltic lava flows dominate the HC province while older lava flows and volcaniclastic rocks dominate the WC province. These distinctions drive hydrologic flowpath differences and residence times (Jefferson et al., 2006). The young lava flows in the HC have exceptionally high permeability with high vertical hydraulic conductivity, resulting in a greater portion of deep groundwater flow and large volume spring discharges. The high vertical conductivity allows recharge to quickly drain through the shallow and undeveloped soils and intersect large deep aquifers, where residence times can be on the scale of years or decades (Jefferson et al., 2006). In the WC, greater drainage efficiencies due to steep lateral hydraulic gradients and shallow bedrock and clay aquitards confine recharge to the shallow subsurface region, producing quicker transfer of recharge to streamflow (Tague and Grant, 2004). These differences in flowpaths, and therefore subsurface residence times, lead to distinctively different hydrologic regimes as characterized by higher baseflows, slower recessions, and muted flood peaks in HC watersheds (Tague and Grant, 2009). During winter storm and early spring snowmelt peaks, recharge in WC regions quickly enters streams, contributing a greater portion to flow than in HC regions. During summer periods, months after the last substantial precipitation has fallen, the groundwater storage in WC systems is largely depleted (Jefferson et al., 2006), and the pattern reverses as the majority of flow in the McKenzie originates from slow-draining HC aquifers (Tague and Grant, 2004).





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Given these geologic distinctions, we hypothesize that geologic classification should be a good indicator of drainage parameters for hydrologic models. To assess whether geology can be used as an effective parameter transfer approach, we compare the estimated parameters using model calibration against streamflow across a range of scales for WC watersheds, and compare with parameters estimated for HC watersheds. We then investigate the implications of using a "generalized" WC and HC parameter set for predicting streamflow responses to warming and test model performance for a watershed that includes both HC and WC geology, where spatial patterns of drainage parameters within the watershed are assigned based on these generalized values derived from calibration of end member WC and HC watersheds. We then explore how model assessments of climate warming impacts on streamflow seasonality respond to these strategies for assigning drainage parameters.

## 3 Methods

RHESSys (Tague and Band, 2004) is a physically based, spatially distributed, hierarchical daily time-step model that couples watershed hydrology, vegetation growth, and soil biogeochemical cycling processes. It models both vertical and lateral hydrologic processes. RHESSys has been applied to a number of mountain catchments in the Western US, (Tague and Grant, 2009; Baron et al., 2000) and mountainous catchments in Europe (Zierl et al., 2006). Its physical treatment of rain and snow partitioning, snow melt, shallow and deep groundwater flow, and evapotranspiration make it a suitable tool for studying the impacts of global change on mountain hydrology. Details of RHESSys process representation are summarized in Tague and Band (2004).

RHESSys model inputs consist of meteorological time series data and GIS-based inputs of topography, soils, land-use, and land cover. For simplicity, we use data from a single meteorologic station as input. While this paper focuses on the role of subsurface drainage uncertainty, another key challenge in estimating streamflow in mountain environments is distributing meteorological and, in particular, precipitation data. For





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this study, we account for spatial variation in precipitation using a single meteorological station combined with widely available PRISM mean annual precipitation grids (Daly et al., 1994) to derive spatially variable estimates for daily precipitation data. For temperature, we also use the same meteorological station and adjust temperature input data based on standard elevational lapse rates. While additional meteorological stations are located within the watershed, long-term records at multiple meteorological stations are often unavailable. In contrast, approaches for interpolating climate data such as PRISM are available for wide geographic areas. Here we test how well streamflow characteristics can be predicted for different watersheds using commonly available datasets. Other GIS dataset, such as soils, land cover, and elevation, are obtained from the Oregon Geospatial Data Clearinghouse.

There are six hydrologic parameters that can be calibrated in RHESSys: two parameters control soil transmissivity ($K$ – saturated hydraulic conductivity at the surface, and $m$ – the decay of saturated conductivity with depth); two parameters control soil moisture holding capacity (po – pore size index, and pa – soil water potential at air entry); and two parameters control ground-water drainage (gw1 – the percentage of subsurface water that enters a deep groundwater storage, and gw2 – the rate of drainage from that compartment). The last two parameters are only included in parameterization if this deeper ground-water store is needed, i.e., for basins with HC geology (Tague and Grant, 2004). Where deep groundwater is not present, a simpler representation of subsurface drainage is obtained by setting gw1 to 0, thus using only a shallow subsurface flow representation in the watershed.

RHESSys was calibrated independently for seven gaged watersheds in the upper McKenzie basin, including two HC watersheds and five WC watersheds (Table 1, Fig. 2). The two HC watersheds are McKenzie River at Clear Lake (CLR) and Horse Creek near McKenzie Bridge (HORSE). The five WC watersheds are Budworm Creek near Belknap Springs (BUD) and Lookout Creek (HJA), along with three subwatersheds within the Lookout Creek drainage (Mack Creek, W2, and W8). The number of HC watersheds considered was limited by the availability of gaged watersheds



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with predominately HC geology in their drainage area. All seven watersheds were calibrated for two water years, following a single year of spin-up. All watersheds were run across the same 1500 randomly generated parameter sets by sampling from a uniform random distribution within realistic ranges for each of the six parameters. For 300 of 1500 parameter sets, we set gw1 equal to 0 in order to run a simpler (and more parsimonious) model. Realistic ranges for each parameter were set based on RHESSys parameter libraries. We used two performance metrics, the Nash Sutcliffe Efficiency (NSE) and the NSE of log-transformed flow (NSElog), to evaluate the parameter sets.

For each watershed, we compared the number of acceptable parameter sets as well as sensitivity of model performance to each parameter. We examine how acceptable parameter values differ between HC watersheds and WC watersheds relative to comparisons of acceptable parameter sets within WC watersheds alone. The parameter sets are considered acceptable if the NSElog value $> 0.5$; we also consider a more stringent criteria $> 0.8$. We then define our generalized HC parameter sets as those that are acceptable for both of the two HC watersheds and our generalized WC parameter sets as those that are acceptable for all of the five WC watersheds. To test model performance, we selected four calibrated parameter sets from the generally acceptable dataset and ran RHESSys for all years for which streamflow is available ($> 25$ water years for most watersheds).

To assess the use of geologic classification as a method for assigning hydrologic parameters, we apply RHESSys to the South Fork McKenzie (SF) watershed (comprised of both HC and WC geology, Table 1, Fig. 2). We use an end-member mixing approach, where drainage parameters within SF are assigned based on drainage parameters for "pure" WC and HC watersheds. The pure "WC" and "HC" parameters are the generally acceptable drainage parameters from the calibrations of HC and WC described above. Thus, for the portion of SF with HC geology (approximately 64 percent of the drainage area), we use parameter sets that had acceptable performance from the CLR and Horse calibrations. For the WC portion (36 percent), we use parameter sets that had acceptable performance across all five WC watersheds.





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NSE is a commonly used performance metric and values about 0.5 are often considered acceptable. Nonetheless, assessing how "good" is "good enough" depends on the application of the hydrologic model. For this study, we base our assessment of "good enough" on the ability of the model to capture changes in seasonality of streamflow with climate warming. In climate change assessment within the Western US, a frequently used measure of streamflow change with warming is the spring fraction of total annual streamflow. Studies have shown that as snowpacks decline, the late spring and early summer fraction of total annual flow also declines (Regonda et al., 2005; Stewart et al., 2005). To examine whether model performance for the SF watershed using the generalized parameter sets is "good enough", we examine the correlation between observed and modeled spring fraction of flow. We define spring as April–June. We then simulate the response of SF and other watersheds to both 2 °C and 4 °C warming scenarios (using one of the best performing parameter sets) and assess whether predicted changes are small or large relative to error in predicting historic streamflow response to inter-annual climate variability. We apply a uniform temperature increase to historic meteorologic forcing data to generate the warming scenarios. Predicted future warming scenarios in the PNW range between one and eight degrees (Mote and Salathe, 2010). We acknowledge that a uniform warming scenario is simplistic and actual climate warming will be more temporally complex; we use it here, however, to assess the sensitivity of modeled streamflow to changes in temperature, given different assumptions about drainage parameters.

## 4 Results

Figure 3 illustrates the cumulative performance across parameter values for each of our six calibration parameters within each of the seven calibration watersheds. Following Thorndahl et al. (2008), we examine model sensitivity to specific parameters by comparing this cumulative performance distribution with the cumulative distribution of parameter values. Sensitivity to a particular parameter is demonstrated by a shift





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of the cumulative distribution of NSE or NSElog for that parameter relative to its cumulative distribution within the calibration set (shown in Fig. 3 as a solid black line). Results were similar using the NSE performance metric so only NSElog results are shown. The greatest difference in acceptable parameter distributions occurs between HC and WC sites; this difference is present for all parameters. Relative to the WC watersheds, the HC watershed CLR shows improved performance for higher values of gw1, lower values of gw2, higher values of $m$, and lower values of $K$, which is reasonable for a slower draining system with greater proportions of infiltrated water connecting to a deeper groundwater reservoir. The HC also shows slightly different responses to air entry pressure (pa) and pore size index (po). All sites show a strong sensitivity to $m$ (e.g., cumulative distribution of NSElog across $m$ parameter shows the greatest departure from the distributions of parameters within the calibration data set). For the $m$ parameter, there are also differences within the WC sites, particularly for W2. Higher values of $m$ show improved performance in W2 relative to other WC sites. The distinctive calibrated parameters for W2 relative to other WC watersheds may suggest actual difference in drainage characteristics. We note, however, that parameters associated with W2 may alternatively reflect potential errors in stream gage measurement since previous hydrologic analysis in W2, using a water-balance approach, suggests that approximately 20 % of streamflow may be lost as deep groundwater and not captured by the gage (Waichler et al., 2005).

Table 2 summarizes the number of acceptable parameter sets for each watershed. The watersheds differ in terms of the percentage of parameter sets that achieved an acceptable level of performance, where acceptable was defined as NSElog > 0.5. HJA had the highest (72 percent) number of parameters that achieved acceptable performance, while HORSE had the lowest (2 percent). There were 173 parameter sets that were acceptable for all WC sites (10 percent of parameters; based on NSElog > 0.5 criteria). None of the parameter sets that achieved acceptable performance for the WC sites also achieved acceptable performance for the HC sites. In other words, the set of acceptable parameters for the WC sites were mutually exclusive of those for the





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HC site. Within the WC sites, however, there was substantial, although not complete, overlap of acceptable parameter sets.

There was some variation in overall performance in the calibration period between different sites. In general, sites with a larger number of acceptable parameters had higher overall performance. To try to further constrain parameter values, we consider a more stringent criteria, defined as NSElog > 0.8 (Table 2). Using these more stringent criteria, there remain 17 parameter sets that are acceptable across for BUD, HJA, MACK, and W8 sites. However, W2 parameter sets do not overlap with the other sites if these more stringent criteria are used. This difference in W2 performance reflects its differing sensitivity to the *m* parameter as discussed above.

There are parameter sets that have gw1 set to 0 within those that are acceptable for BUD, HJA, MACK, and W8 using these more stringent criteria. We consider these sets to be preferable, given that they result in a simpler (more parsimonious) model because the deeper groundwater store is not used. It is worth noting that none of the acceptable parameter sets for the HC watershed have gw1 set to 0. Thus, for the HC watershed a deeper groundwater store must be included based either on the initial or more stringent criteria for parameter selection.

For validation, we randomly selected four parameter sets from those that were considered acceptable for WC and then HC sites, using the more stringent selection criteria. For BUD, HJA, MACK, and W8, we use parameter sets that met the more stringent criteria for all sites and two that did not include a deeper groundwater store (gw1 was set to 0). We consider these parameters to be examples of WC end-member parameter sets. We exclude W2 calibrations from developing the end-member WC parameter set because of their deviation from other WC watersheds and the evidence of observation error as the cause of this difference as noted above. For W2, we selected parameters that met the more stringent criteria for W2 and the initial criteria for all WC sites. For Horse and CLR, we randomly selected four parameter sets that met the more stringent criteria for both of those sites and consider these parameters to be examples of HC end-member parameters. Table 3 summarizes one of the parameter sets selected.





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Table 4 summarizes model performance for a 7-yr evaluation period that is common across all watersheds (except HORSE, which had very few years of overlap) and for a longer period using the full streamflow record available for each watershed. As expected, all watersheds show some degradation in performance over the evaluation periods relative to the two-year period used for calibration. Nonetheless, all watersheds show at least reasonable performance for the common evaluation and longest evaluation periods, with NSElog above 0.6 and NSE above 0.4 in most cases. Watersheds do differ in terms of long-term performance, with Horse and CLR showing lower NSElog values than other watersheds. We note that Horse and CLR are located farthest from the meteorologic station and thus are most susceptible to errors in spatial interpolation of precipitation.

Streamflow predictions for SF (Fig. 4), using a set of parameters transferred using the geologic end-member mixing described above, show good correspondence between observed and modeled flows. Based on our initial model implementation using this approach, streamflow predictions were consistently 20 percent lower than observed streamflow across all parameter sets. The long-term bias of 20 percent in total streamflow likely reflects a bias in input rather than drainage parameters, which tend to influence the hydrograph shape. Error in precipitation input estimates is not surprising given that precipitation inputs are based on a meteorologic station more than 27 km from SF. Although PRISM was also used to scale precipitation from the meteorologic site, PRISM grids are also relatively coarse (200 m). Since the focus of this paper is on drainage parameters, we simply applied a 20 percent increase in precipitation input to the model to account for the difference. We note, however, that the necessity of post-hoc precipitation adjustment illustrates the sensitivity to precipitation interpolation (or downscaling for GCM inputs), which is an ongoing area of research. Performance metrics for sixteen combinations of parameters (four different examples of HC end-member parameters paired with four examples of WC end-member parameters), after this precipitation adjustment, are summarized in Table 4.





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Model results for SF show relatively minor degradation in performance relative to the other watersheds that used calibrated parameters. For the common evaluation period, NSE for calibrated watersheds ranges from 0.59 to 0.69 and NSElog from 0.68 to 0.75. Performance measures for SF are within or even better than these ranges. For the longest evaluation period, SF produces performance metrics within the ranges produced by the watersheds for the calibration period. Figure 5 shows modeled streamflow for SF for one water year, using a parameter set based on our geologic end-member mixing approach. We compare this prediction to predictions using only WC or HC parameters. When SF is run as an all WC watershed, winter peaks are over predicted and summer flows under predicted. When SF is run as an all HC watershed the opposite bias occurs. Thus, when WC parameters are used for SF, we get a reasonable NSE (0.71), but a much low NSElog (0.28). When HC parameters are used for SF, we get a reasonable NSElog (0.83), but a lower NSE (0.65). Using a combination of HC/WC in the end-member mixing approach substantially improves performance and obtains high NSE and NSElog performance measures (0.83, 0.9, respectively).

If end-member drainage parameters are used, all sites show statistically significant ($p$-value $< 0.001$) relationships between observed and modeled estimates of inter-annual variation in spring fraction of annual flow (Fig. 6). Correlation coefficients of the relationship between observed and modeled inter-annual variation in spring flow fraction range from 0.6 to 0.9. Lowest correlations occur for CLR. Good correlation between observed and modeled estimates of inter-annual variation in spring fraction of annual flow suggest that the model captures historic driven climate variation in the seasonality of flow for all sites.

For most sites, model estimates of long-term means of spring fraction were not significantly different from observed values (Fig. 7a). The exception is W2, where modeled means of spring fraction were significantly higher than observed values. As noted above, W2 model results tend to over-estimate flow in general and may reflect stream gage limitations. Over estimation of spring fraction by the model would therefore be expected given that more flow occurs during the spring. Interestingly, W2 shows the highest correlation between historic inter-annual variations in observed versus modeled spring fraction (Fig. 6) – again suggesting that the model captures response to climate variation but that there is an overall bias in estimates of the volume of flow.

Finally, we test whether model estimates of spring fraction of flow for warming scenarios are significantly different from baseline estimates. For the 2 °C warming scenario (T2), CLR, HJA, MACK, and SF show statistically lower spring fractions. For the 4 °C warming scenario (T4), all watersheds except the more rain-dominated W2 show significant reductions (Fig. 7a). For the SF watershed, changes in streamflow with warming are large relative to model error. Further, we show that for the SF watershed, changes in spring fraction of flow are substantially different across different assumptions regarding drainage parameters (Fig. 7b). Simulations using the HC end-member watersheds show the least reduction in spring fraction of flow with warming, and also show almost no difference between T2 and T4 warming scenarios. If WC end-member parameters are used, the reduction in spring fraction of flow is greater, more variable from year to year, and shows a greater decline with more warming. Using the combined end-member approach, changes in seasonality with warming are intermediate between those found using the WC end-member and HC end-members alone. In this case, there is a moderate, though still, substantial reduction in spring fraction of flow with 2 °C warming, but with high inter-annual variation.

## 5 Discussion

Comparison of drainage parameter sensitivity across multiple watersheds provides insight into underlying hydrologic behavior of these watersheds, and provides a basis for deciding whether or not hydrologic parameters might be readily transferred from one watershed to another. For sites within the WC geologic region, parameter sensitivity was similar across scales ranging from a 4th order (HJA) to a 3rd order (MACK) to a 1st order (W8) watershed. However, W2 was an exception. As noted above, its parameters may also account for under representation of subsurface flow by the stream



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gage. W2 differs somewhat from W8 in receiving a higher proportion of rain versus snow events (Perkins and Jones, 2008) and parameter differences may be compensating for differences in snow accumulation and melt. We note, however, that HJA includes rain-dominated elevations and performs well with parameters from W8, which is usually snow dominated. Parameter sensitivity for HC sites was clearly distinctive from WC sites and is consistent with the interpretation presented in other modeling and empirical analyses (Tague et al., 2008; Jefferson et al., 2008) that suggest HC geology supports a slower draining, deeper groundwater system. Thus, if we remove W2 from our list of watersheds, we have two sets of parameters that correspond to end-members associated with mappable geologic regions.

The success of parameter transferability based on this mappable HC/WC classification depends on: (a) whether the HC/WC geologic classification resolves dominant spatial differences in subsurface drainage behavior; (b) whether the model representation of spatial differences in snow accumulation and melt is adequate and not implicitly corrected for by drainage parameters; and (c) whether spatial variation in other inputs, including meteorologic forcing, is adequately represented. For the SF, the necessity of adjusting incoming precipitation magnitudes suggest that the third condition is not met and more sophisticated schemes for interpolating precipitation data are needed. The relatively strong performance of SF once precipitation magnitudes (but not timing) were adjusted suggests that conditions (a) and (b) can be met within the larger McKenzie River basin. For SF and other watersheds, model performance measured as NSE or NSElog was within the range commonly reported in other model-based studies within the Western US (e.g., Hay and Clark, 2003; Franz et al., 2008; Graves and Chang, 2007).

Ultimately, the evaluation of model performance depends upon the use of that model. Here we evaluate model performance relative to an assessment of the impact of simple climate warming on seasonality of streamflow. Specifically, we examined model estimates of the spring fraction of annual flow. For most study sites, our model estimates of mean spring fraction of flow and its inter-annual variation were not significantly





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different from observed given historic climate forcing. What is particularly encouraging is that the SF watershed shows no degradation in performance relative to calibrated watersheds (based on predictions of spring fraction of flow).

Results of warming scenarios show that geology and snow vs. rain are both important factors in the sensitivity of watersheds to warming. For all snow-dominated sites, a warming of 4 °C led to a statistically significant reduction in spring fraction. For the rain-dominated site it did not. For the 2 °C warming scenario, higher and more snow-dominated watersheds, such as W8, did not show a significant reduction in spring fraction. In contrast, larger watersheds, such as HJA and MACK, that comprise a larger elevation range and include elevations typically at the boundary between rain-dominated and snow-dominated did show a reduction in spring fraction for the 2 °C warming scenario. These modeled spatial differences in the sensitivity of streamflow to warming are consistent with both empirical and model-based literature that demonstrate a linkage between reductions in spring fraction of flow, elevation, and warming for snow-dominated regions in the Western US (Stewart et al., 2005; Nolin and Daly, 2006). In addition to variation in the sensitivity of spring fraction to warming across snow-to-rain transitions, geologic differences are also important. Using the end-member drainage parameters from the WC for the SF watershed resulted in greater and more variable estimates of the reductions in spring fraction of flow with warming relative to estimates using HC drainage parameters, suggesting that greater drainage rates associated with WC geology enhance the sensitivity of the spring fraction of flow to warming. These results are consistent with our earlier model-based analysis that demonstrated that greater subsurface drainage rates in snow dominated catchments in the Western US tended to increase spring sensitivity to warming and decrease summer streamflow sensitivity (Tague and Grant, 2009). We note that differences in SF response across drainage parameters are solely due to the effect of subsurface effective conductivity/drainage rates since all other factors, including topography and changes in snow accumulation and melt, are held constant across the warming scenarios (Fig. 7b). These differences in response of SF watershed as a function of drainage parameters highlight the importance of accounting for geologically based differences in drainage rates in addition to topographic differences. Further, the emergence of end-member parameters that are consistent with mappable geologic classifications points to an approach for accomplishing this in the face of limited stream gage data.

These findings have broad implications for the use of distributed hydrologic models as a means of predicting downscaled streamflow response to climate warming, as is becoming increasingly common (Hamlet and Lettenmaier, 1999; Payne et al., 2004; Christensen et al., 2004; VanRheenen et al., 2004; Wood et al., 2004). Our results show that if predictions are needed in basins where calibrations have not been explicitly conducted, great caution needs to be exercised if these uncalibrated basins reflect different geologies than those where calibrated parameters were derived. Furthermore, in basins with mixed lithologies, which are the norm for larger watersheds, calibrated parameters need to be developed across the full range of drainage efficiencies and cannot be confidently applied simply based on basin proximity.

## 6 Conclusions

The hydro-climatic setting in the McKenzie River watershed offers an illustrative example that may reflect other similar mountain systems, where spatial patterns of snow accumulation and melt are super-imposed on geologically mediated differences in subsurface drainage and storage. In these settings, modeling the spatial response of streamflow to predicted climate change requires disentangling the spatial interaction between the static differences in subsurface drainage properties and the dynamic transition between rain and snow. To estimate how these systems will respond to climate variability and change, process-based modeling must represent the natural physical processes controlling runoff and capture relevant spatial differences in climate inputs and soil/drainage parameters. For climate inputs, limited spatial coverage by meteorologic stations with long-term records leads to the use of interpolation schemes, such as PRISM, to account for spatial difference in climate inputs. Continued improvements





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in estimates of precipitation and temperature spatial-temporal patterns, both for retrospective and future analysis, are a critical research area. Limited spatial coverage of gaged streams to calibrate drainage parameters, however, is also an important factor and necessitates a strategy for drainage parameter transfer. In this paper, we demonstrate a successful drainage parameter transfer approach based on end-member parameter sets associated with mapped geologic classes. Streamflow estimation using this geologic end-member approach to transfer parameters was sufficient to capture historic climate variability for a set of watersheds that cross a range of scales from 1st to 4th order streams, including one watershed that comprised a mixture of geologic classes from both end-members. Model error using this geologic end-member approach to assign drainage parameters was also small relative to changes in seasonal streamflow patterns associated with simple warming scenarios. For watersheds with a mixture of geology, assigning uniform parameters results in substantial degradation in flow, but perhaps more importantly, leads to substantially different estimates of the impact of warming on flow seasonality. These results argue for the importance of accounting for drainage parameter heterogeneity and offer a method for doing so.

Our geologic end-member approach could be used to model the full distribution of hydrologic responses to climate warming within the McKenzie and potentially adapted for other areas of the mountainous Western US. The need for this type of multi-scale modeling and parameterization approach is particularly important in assessments of climate change impacts on aquatic habitat, where the spatial patterns and diversity of hydrologic response within river basins may be important drivers of habitat quality and sensitivity to environmental change.

While the McKenzie watershed incorporates sub-watersheds with sharply contrasting hydrogeological terrains, it is by no means unique. Similar differences in drainage efficiencies would be expected in watersheds drained by both karstic and non-karstic lithologies, deeply weathered versus unweathered intrusive or sedimentary bodies, or glaciated versus non-glaciated terrain. Parameterization schemes for hydrologic





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models along the lines that we have outlined here offer a useful means of characterizing and interpreting the hydrologic differences among these varied settings.

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**Table 1.** Watershed characteristics.

| Watershed (WS) | Abbreviation | Drainage ($km^2$) | Elevation (m) | Geology |
|---|---|---|---|---|
| Budworm Creek | BUD | 7.77 (54.5) | 619–1626 | WC |
| Lookout Creek | HJA | 62.4 | 428–1620 | WC |
| Mack Creek | MACK | 5.8 | 758–1610 | WC |
| Watershed 2 | W2 | 0.60 | 548–1070 | WC |
| Watershed 8 | W8 | 0.22 | 993–1170 | WC |
| Clearlake | CLR | 239.3 | 924–2019 | HC |
| Horse Creek | HORSE | 387.5 | 439–3152 | HC |
| Southfork | SF | 538.7 | 530–2044 | 36 % WC; 64 % HC |





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**Table 2.** Number of acceptable parameters sets for each watershed.

| WS | Initial Criteria (NSElog > 0.5) | Stringent Criteria (NSElog > 0.8) |
|---|---|---|
| CLR | 17 (3 %) | 0 |
| HORSE | 11 (2 %) | 0 |
| BUD | 266 (44 %) | 20 (3 %) |
| HJA | 431 (72 %) | 185 (31 %) |
| MACK | 404 (67 %) | 152 (25 %) |
| W2 | 327 (55 %) | 126 (21 %) |
| W8 | 376 (63 %) | 111 (19 %) |





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**Table 3.** Example of an acceptable parameter set across common geologic watersheds.

| WS | $m$ | $K$ | pa | po | gw1 | gw2 |
|---|---|---|---|---|---|---|
| CLR | 5.1 | 34 | 0.9 | 1.6 | 0.3 | 0.6 |
| HORSE | 5.1 | 34 | 0.9 | 1.6 | 0.3 | 0.6 |
| BUD | 0.8 | 58 | 1.8 | 1.1 | 0 | 0 |
| HJA | 0.8 | 58 | 1.8 | 1.1 | 0 | 0 |
| MACK | 0.8 | 58 | 1.8 | 1.1 | 0 | 0 |
| W8 | 0.8 | 58 | 1.8 | 1.1 | 0 | 0 |
| W2 | 1.8 | 249 | 1.8 | 1.3 | 0.2 | 0.6 |





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**Table 4.** Model performance across four chosen parameters.

| WS | Calibration (WY 1999–2000) | | Evaluation (longest period) | | | Evaluation (WY 1980–1986) | |
|---|---|---|---|---|---|---|---|
| | LogNSE | NSE | LogNSE | NSE | Eval. Period | LogNSE | NSE |
| CLR | 0.51–0.67 | 0.30–0.68 | 0.61–0.68 | 0.55–0.56 | WY 70-06 | 0.54–0.62 | 0.50–0.53 |
| HORSE | 0.50–0.62 | 0.46–0.65 | 0.52–0.59 | 0.40–0.48 | WY 62-69 | NA | NA |
| BUD | 0.80–0.83 | 0.62–0.68 | 0.68–0.75 | 0.40–0.45 | WY 79-86 | 0.67–0.74 | 0.40–0.44 |
| HJA | 0.82–0.91 | 0.72–0.82 | 0.68–0.82 | 0.47–0.60 | WY 58-05 | 0.70–0.80 | 0.49–0.62 |
| MACK | 0.85–0.91 | 0.60–0.70 | 0.68–0.76 | 0.41–0.49 | WY 80-06 | 0.56–0.69 | 0.40–0.53 |
| W2 | 0.83–0.91 | 0.51–0.61 | 0.69–0.75 | 0.36–0.44 | WY 58-06 | 0.66–0.74 | 0.31–0.43 |
| W8 | 0.88–0.89 | 0.60–0.66 | 0.74–0.75 | 0.35–0.37 | WY 64-05 | 0.69–0.72 | 0.39–0.46 |
| SF | NA | NA | 0.75–0.80 | 0.58–0.66 | WY 58-88 | 0.68–0.75 | 0.59–0.69 |





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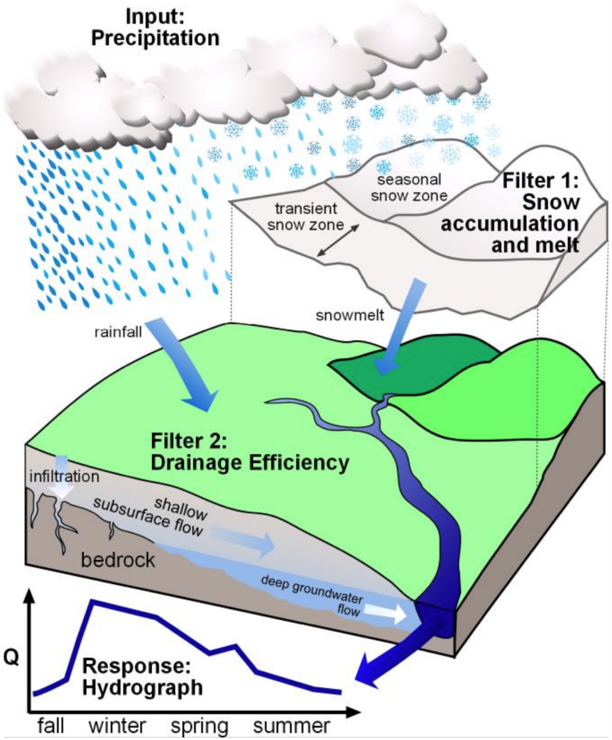


**Fig. 1.** Landscape responses to precipitation inputs – as a series of filters (Tague and Grant, 2009).





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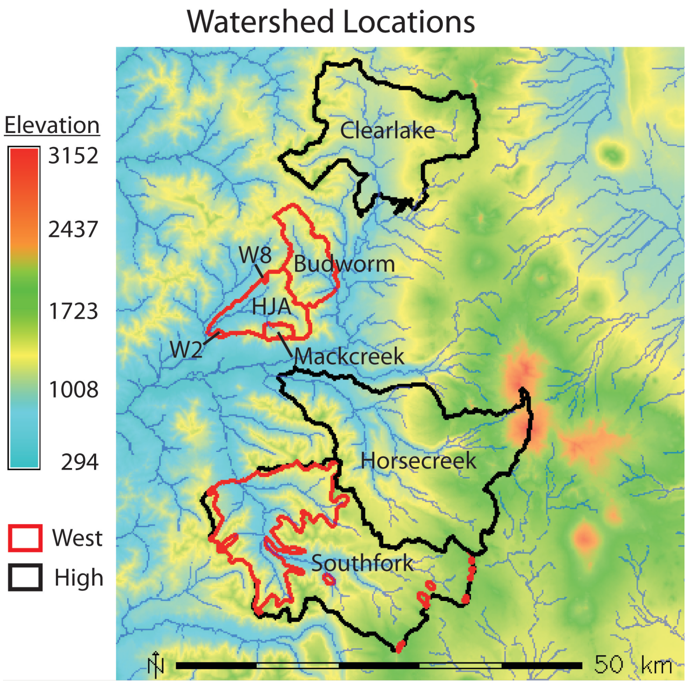


**Fig. 2.** Map showing study watersheds (listed in Table 1) and geologic classification.



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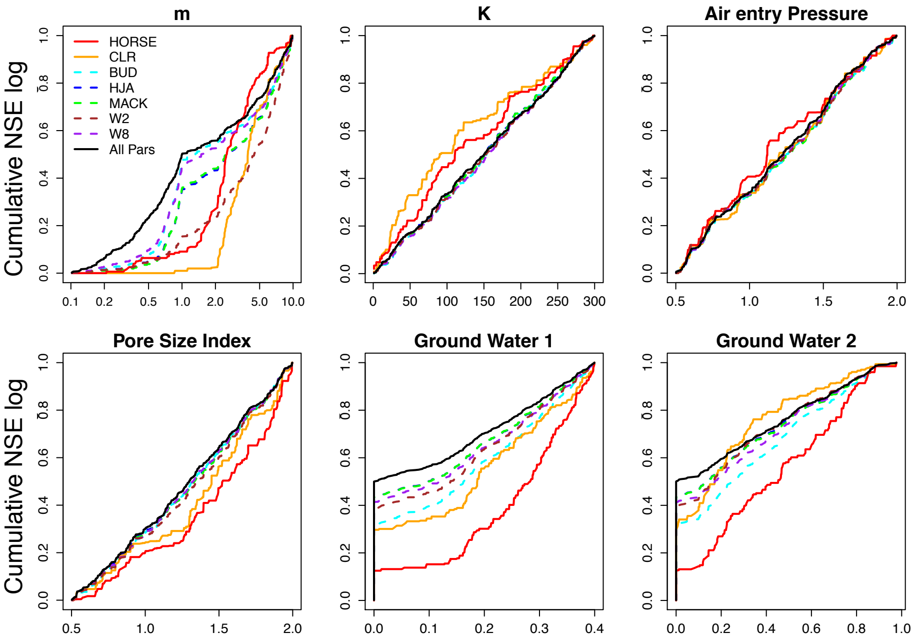


**Fig. 3.** Cumulative distribution of performance across parameter sets. Solid black line shows the original parameter distribution; colored lines show distribution of performance by parameter value for each watershed. Departures from the black line show preference for particular parameter values.





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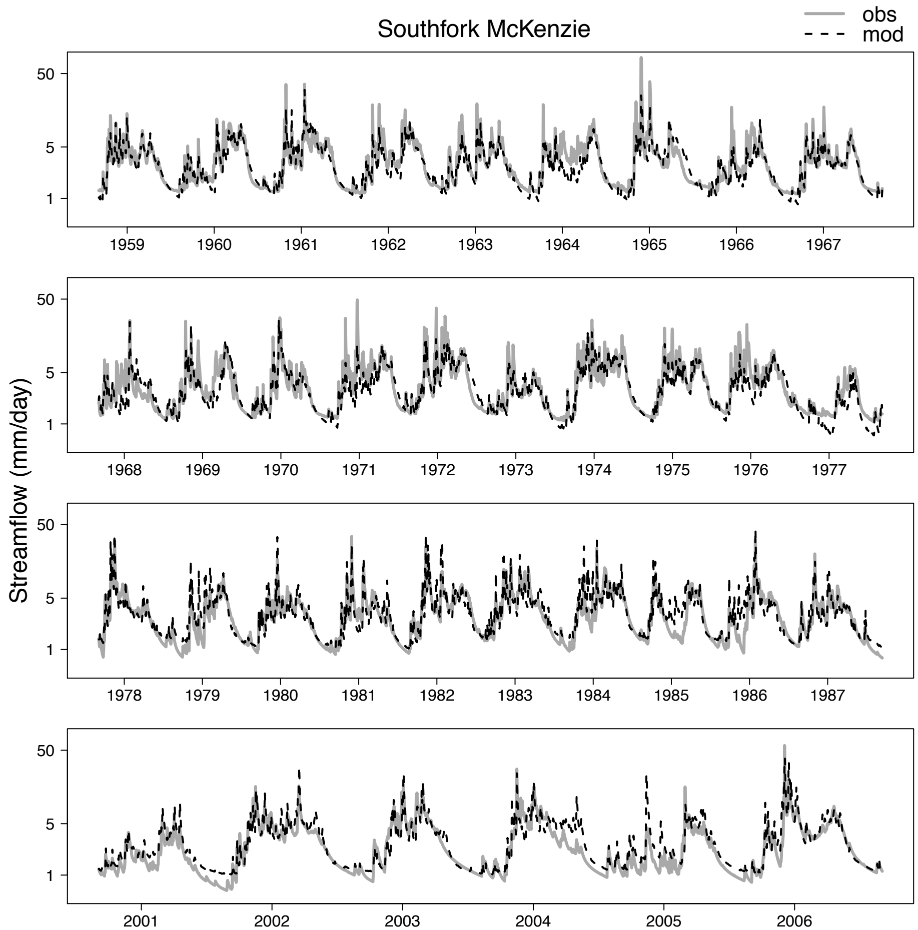


**Fig. 4.** Southfork watershed streamflow, modeled and observed. Modeled streamflows are generated using geologic end-members to assign soil drainage parameters.





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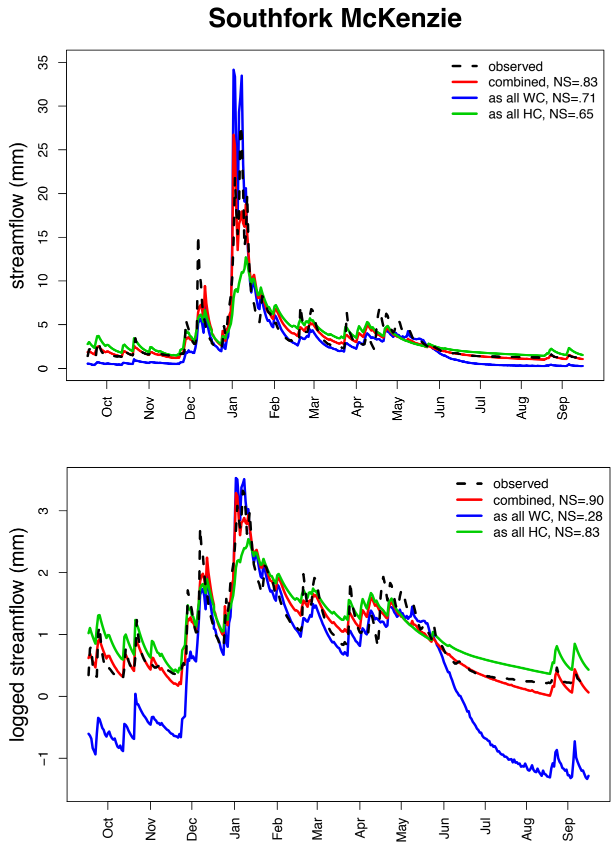


**Fig. 5.** Observed and modeled daily **(a)** streamflow and **(b)** log-transformed streamflow for Southfork McKenzie. Modeled streamflow estimates are shown for three parameter-transfer strategies including using only WC end-member parameters, only HC end-member parameters and combined strategy where parameters are varied spatially according to HC/WC geologic classification within the Southfork watershed.





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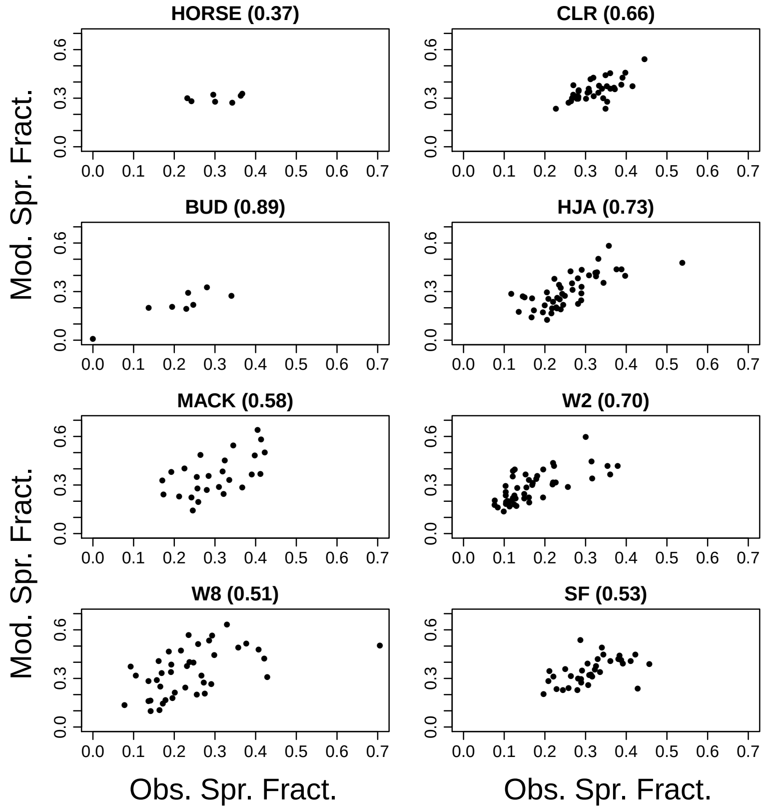


**Fig. 6.** Correlation between observed and modeled spring fraction of annual flow. Values in brackets are Pearson Correlation Coefficient – all were significant at 99 % confidence. Results are shown for a single acceptable parameter set and for all years with observed/modeled streamflow (available water years for each watershed are listed in evaluation column of Table 4).

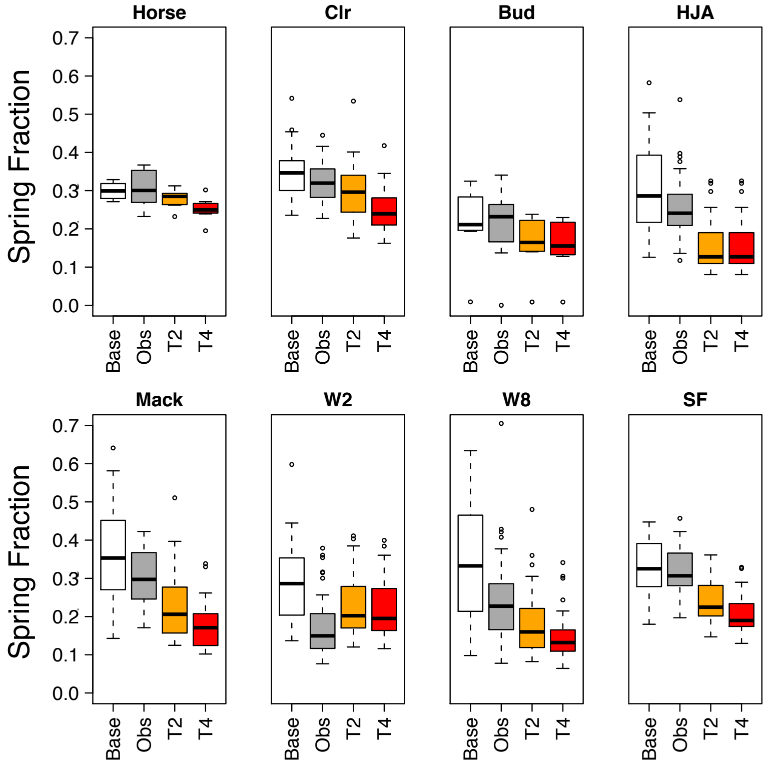


**Fig. 7a.** Variation in spring fraction of annual flow for modeled (white) and observed (grey) with historic climate (WY) and modeled results for a 2 °C (orange) and 4 °C (red) warming scenario. Results are shown for a single acceptable parameter set and for all years with observed/modeled streamflow (available water years for each watershed are listed in evaluation column of Table 4).





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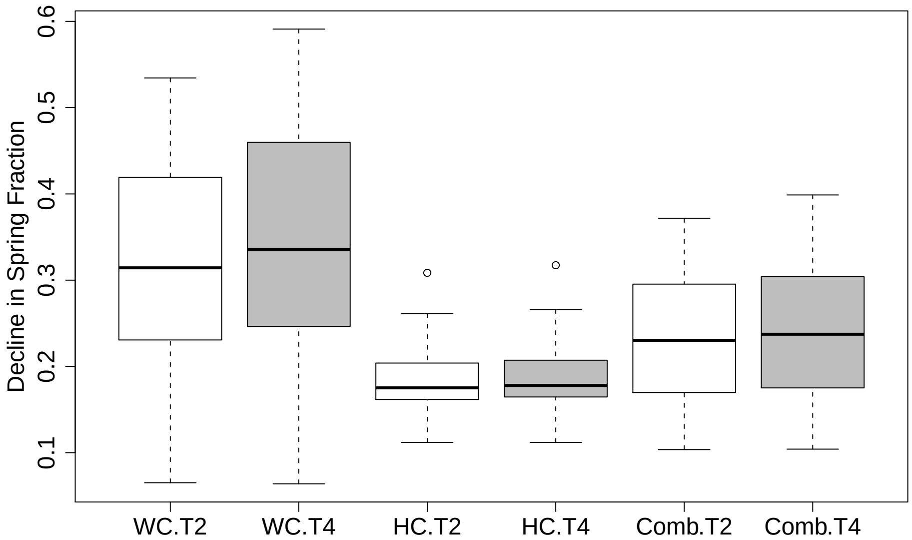


**Fig. 7b.** Change in modeled spring fraction of annual flow for 2 °C (white) and 4 °C (grey) warming scenarios in SF run as all WC, as all HC, and SF comprised of both HC and WC.



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