# A HIERARCHICAL MODELING APPROACH TO SIMULATING THE GEOMORPHIC RESPONSE OF RIVER SYSTEMS TO CLIMATE CHANGE

by

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# A DISSERTATION

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# DISSERTATION APPROVAL PAGE

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## DISSERTATION ABSTRACT

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Title: A Hierarchical Modeling Approach to Simulating the Geomorphic Response of River Systems to Climate Change

Anthropogenic climate change significantly affects water resources. River flows in mountainous regions are driven by snowmelt and are therefore highly sensitive to increases in temperature resulting from climate change. Climate-driven hydrological changes are potentially significant for the fluvial geomorphology of river systems. In unchanging climatic and tectonic conditions, a river's morphology will develop in equilibrium with inputs of water and sediment, but climate change represents a potential forcing on these variables that may push the system into disequilibrium and cause significant changes in river morphology. Geomorphic factors, such as channel geometry, planform, and sediment transport, are major determinants of the value of river systems, including their suitability for threatened and endangered species and for human uses of water.

This dissertation research uses a hierarchical modeling approach to investigate potential impacts of anthropogenic climate change on river morphology in the interior Pacific Northwest. The research will address the following theoretical and methodological objectives: 1) Develop downscaled climate change scenarios, based on regional climate-model output, including changes in daily minimum and maximum

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temperature and precipitation. 2) Estimate how climate change scenarios affect riverdischarge and suspended-sediment load, using a basin-scale hydrologic model.3) Examine potential impacts of climate-driven hydrologic changes on stream power and shear stress, bedload sediment transport, and river morphology, including channel geometry and planform.

The downscaling approach, based on empirically-estimated local topographic lapse rates, produces high-resolution climate grids with positive forecast skill. The hydrologic modeling results indicate that projected climate change in the study rivers will change the annual cycle of hydrology, with increased winter discharge, a decrease in the magnitude of the spring snowmelt peak, and decreased summer discharge. Geomorphic modeling results suggest that changes in reach-averaged bedload transport are highly sensitive to likely changes in the recurrence interval of the critical discharge needed to mobilize bed sediments. This dissertation research makes an original contribution to the climatechange impacts literature by linking Earth processes across a wide range of spatial scales to project changes in river systems that may be significant for management of these systems for societal and ecological benefits.

This dissertation includes unpublished co-authored material.

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### CHAPTER I

### INTRODUCTION

Anthropogenic climate change is expected to significantly affect water resources [Kundzewicz et al., 2007; Jiménez Cisneros, et al., 2014]. General circulation models (GCMs), which simulate energy and moisture fluxes for the earth's atmosphere and oceans, project increasing temperatures and changing precipitation patterns on a global scale as a result of increasing atmospheric concentrations of greenhouse gases [Kirtman et al., 2013]. Increases in evaporation rates and atmospheric water-vapor content are likely to intensify the global hydrological cycle [Huntington, 2006].

Because of their coarse spatial resolution of several degrees of latitude and longitude, GCMs cannot resolve regional factors that affect climate locally and so cannot be used to project climate change in any particular location, such as a river system [Maraun et al., 2010]. Moreover, river systems are affected not only by climate, but also by watershed characteristics such as basin physiography, geology, vegetation, and land use [Hamlet and Lettenmaier, 2007; Adam et al., 2009; Cuo et al., 2009; Elsner et al., 2010]. Developing projections of climate-change impacts on river systems is important, because it is at the local scale that adaptation takes place. Many aspects of river systems, such as flooding, water supply, water quality, and species habitat, are potentially sensitive to climate change, and managers therefore need to adapt their practices in order to maintain the benefits provided by river systems as the climate changes [Milly et al., 2008]. Local projections of climate change are therefore critical, but they are much more uncertain than global-scale changes.

In this dissertation, I have developed and applied a hierarchical modeling approach to simulate impacts of climate change on river systems. The conceptual framework is a hierarchy of nested Earth systems across a wide range of spatial scales (Figure 1.1). At the broadest scale, the climate system consists of the global circulation of energy and moisture, superimposed on regional factors, notably topography. Together, these global and regional factors determine the regional climate. This regional climate, along with watershed characteristics such as geology and land cover, comprise the hydrologic system, which is described by basin-scale river discharge and suspendedsediment transport. Finally, inputs of water and sediment to a river reach, along with local factors such as water-surface slope, determine the energy available for erosion and transport of sediment, as well as the supply of sediment available for transport. This balance between energy and sediment availability affects erosion and deposition within the reach and consequently characteristics of river morphology, such as channel geometry and planform. The system hierarchy therefore ranges in scale from global climate, to regional climate, to basin-scale hydrology, to reach-scale morphology.

# 1.1. Overall Objectives

This dissertation has three main objectives:

- Develop downscaled climate change scenarios, based on regional climate-model output, including changes in daily minimum and maximum temperature and precipitation (Chapter II).
- 2. Estimate how climate change scenarios affect river discharge and suspendedsediment load, using a basin-scale hydrologic model (Chapter III).



Figure 1.1. Conceptual framework of hierarchy of Earth systems.

3. Examine potential impacts of climate-driven hydrologic changes on stream power and shear stress, bedload sediment transport, and river morphology, including channel geometry and planform (Chapter IV).

My study area includes three rivers in the interior Pacific Northwest: the Tucannon River in southeastern Washington and the South Fork Coeur d'Alene and Red rivers in Idaho. I chose these rivers based on three major criteria. First, all three have a strong snowmelt signal in their annual hydrographs, meaning they are likely to be sensitive to increased temperature associated with climate change and its attendant impacts on snowpack accumulation and melt. Second, all three are undammed alluvial rivers, which means that they are likely able to develop a geomorphic response to climate-driven hydrological changes in the decadal timeframe of the study. Third, gaging station records of discharge and suspended sediment are available for all three rivers, which is necessary for model calibration and validation.

The study objectives are achieved through a hierarchy of models that corresponds to the hierarchy of Earth systems. Ultimately, the modeling hierarchy is driven by output from GCMs, but because of these models' coarse resolution, I began with regional climate model (RCM) output from the North American Regional Climate Change Assessment Program (NARCCAP). These RCMs are higher-resolution (~50-km) physical models with the boundary conditions provided by GCMs [Mearns et al., 2007]. Because even these higher-resolution models are still coarse relative to the size of my study basins, I further downscaled the RCM output using an elevational adjustment method based on local topographic lapse rates estimated from a high-resolution climate grid. I used the resulting high-resolution (800-m) downscaled RCM outputs to generate daily climate-change scenarios for my study basins.

After generating the downscaled climate-change scenarios, I used them to drive the basin-scale hydrologic model Soil and Water Assessment Tool (SWAT). This model uses the Soil Conservation Service curve number method to simulate river discharge as a function of the input climate data and watershed characteristics, namely land cover, soils, and slope [Neitsch et al., 2011]. SWAT also simulates basin-scale suspended-sediment load using the Modified Universal Soil Loss Equation (MUSLE). I first calibrated and validated SWAT for discharge and suspended sediment on my three study rivers and then used the daily timeseries produced from the elevationally-adjusted RCM outputs to run

the model. The results were 30-year simulations of discharge and suspended-sediment load under baseline climate and projected future climate change.

I then used the SWAT-simulated changes in daily discharge and suspendedsediment load from Objectives 1 and 2 to examine impacts of climate change on reachscale river morphology. This part of the project required data on the topography and sediment grain-size distributions of the study reaches, which I obtained through fieldwork on all three rivers. I used three modeling systems to assess the impacts of climate change on geomorphic processes. First, I used the Hydrologic Engineering Center River Analysis System (HEC-RAS) one-dimensional hydraulic model to examine changes in the energy available to do geomorphic work as expressed by the variables stream power and shear stress [USACE, 2010]. Next, I used sediment transport formulas, as implemented in the Bedload Assessment of Gravel-bed Streams (BAGS) software, to determine changes in reach-averaged bedload transport [Pitlick et al., 2009]. Finally, I used the Cellular Automaton Evolutionary Slope and River (CAESAR) model to simulate changes in erosion and deposition within the reach and to qualitatively assess potential patterns of changes in channel geometry and river planform resulting from climate change [Coulthard et al., 2002].

# 1.2. Outline of Dissertation Chapters

This dissertation is organized in three main chapters, which approximately correspond to each of the three objectives listed above. Each chapter, however, has its own independent objectives while still fitting into the larger dissertation. Below is a brief description of the objectives and methods of each chapter:

# Chapter II: Hydrologic modeling using elevationally adjusted NARR and NARCCAP regional climate-model simulations: Tucannon River, Washington

This chapter roughly corresponds to Objective 1 of the dissertation, which is to generate downscaled climate-change scenarios for the study basins. Because I first had to develop and validate the lapse-rate downscaling method, however, the chapter is limited to one study basin (the Tucannon River) and only deals with retrospective rather than future climate-change model output. In the chapter, I estimated local topographic lapse rates for the northwestern United States and used them to elevationally adjust two types of RCM output: the North American Regional Reanalysis (NARR), a retrospective dataset produced by running a regional weather forecasting model constrained by observations; and the NARCCAP baseline simulations, which are produced by a range of RCMs under the boundary conditions of different GCMs with observed forcings for a historic period. Because I applied the elevational adjustment to retrospective model runs, I could compare the resulting downscaled model output to station data to calculate forecast skill and thereby validate the method. I then used the entire range of elevationally-adjusted NARR and NARCCAP baseline model output to run the calibrated and validated SWAT model for the Tucannon River. The overall purpose of the chapter was to demonstrate that the elevationally-adjusted RCM output could be used to run a hydrologic model. This chapter was co-authored with Dr. Patrick Bartlein.

Chapter III: Impacts of projected climate changes on streamflow and sediment transport for three snowmelt-dominated rivers in the interior Pacific Northwest

This chapter corresponds to Objective 2 of the dissertation, which is to simulate changes in discharge and suspended-sediment transport under climate change for all three rivers. I used the elevational-adjustment method described in Chapter II to produce downscaled climate-model output for both the baseline and the future NARCCAP period, which is based on a greenhouse gas forcing. I then extracted timeseries from the downscaled climate-model output to produce daily climate timeseries for the baseline and future period for all three basins. I calibrated the SWAT model for both discharge and suspended-sediment load on all three rivers using observed gaging station records. I then selected three of the NARCCAP model combinations that represented a range of climate changes in the basin. I also created an ensemble average using a stochastic weather generator based on monthly parameters from all modeling combinations. I used these four climate change scenarios to run the calibrated SWAT model for each basin to project changes in both discharge and suspended-sediment load resulting from climate change.

# Chapter IV: A hierarchical modeling approach to simulating the geomorphic response of river systems to climate change

This chapter corresponds to Objective 3 of the dissertation, which is to simulate the reach-scale geomorphic response of the study rivers to the hydrological changes examined in Chapter III. I modified the hydrological timeseries resulting from Chapter III to make them compatible with the geomorphic models used in Chapter IV. I also did fieldwork to obtain the topographic and sediment grain-size distribution data needed for geomorphic modeling. I then used HEC-RAS to simulate changes in stream power and shear, BAGS to calculate changes in reach-averaged bedload transport, and CAESAR to examine spatial patterns of erosion and deposition within each reach and their potential consequences for channel geometry and planform.

## CHAPTER II

# HYDROLOGIC MODELING USING ELEVATIONALLY ADJUSTED NARR AND NARCCAP REGIONAL CLIMATE-MODEL SIMULATIONS: TUCANNON RIVER, WASHINGTON

This chapter was co-authored with my adviser, Dr. Patrick Bartlein, who contributed substantially to this work by coding the programs used in the analysis (which I subsequently modified with his assistance) and also by providing substantial feedback on the interpretation of results and helping to revise the text and figures. I performed the actual analysis and wrote the manuscript.

## 2.1. Introduction

Anthropogenic climate change is likely to result in significant changes to global water resources and their management through intensification of the global hydrological cycle, with more energy available for evaporation and increased latent heat exchange contributing to the intensification of global circulation (Huntington, 2006; Kundzewicz et al., 2007; Milly et al., 2008) and an increase in atmospheric moisture content (Santer et al., 2007). In snowmelt-dominated systems, higher temperatures will result in more winter precipitation falling as rain rather than snow, with hydrologic consequences including increased winter discharge, a shift in the spring snowmelt peak to earlier in the season, and decreased summer discharge (Stewart et al., 2004; Day, 2009; Adam et al., 2009). Hydrologic modeling studies have found that such climate-driven increases in seasonal hydrological variability are likely in snowmelt-dominated river systems, including in mountainous basins of western North America (Merritt et al., 2006; Graves

and Chang, 2007; Young et al., 2009; Hay and McCabe, 2010; Jung et al., 2012; Shrestha et al., 2012; Ficklin et al., 2013).

One of the major sources of uncertainty in using hydrologic models to project future climate change impacts arises in the downscaling of climate projections from General Circulation Models (GCMs) to a spatial resolution more relevant for hydrological applications. GCMs are based on the physics of energy, mass, and momentum transfer between the atmosphere and ocean (Meehl et al., 2007). The controls of these models, such as the atmospheric concentration of greenhouse gases, can be altered to predict the resulting changes in climate. While GCMs adequately represent large-scale or global-average conditions, their coarse resolution of several degrees of latitude and longitude limits their application to any specific location. Hydrological variables are especially sensitive to both spatial and temporal scale (Prudhomme et al., 2002; Fowler and Kilsby, 2007; Kundzewicz et al., 2007). The climate-change scenarios generated by GCMs must therefore be downscaled to be relevant to hydrological applications.

One emerging approach is dynamic downscaling, in which a regional climate model (RCM) is driven by lateral boundary conditions furnished by the output from a (global) general circulation model (GCM) (Hewitson and Crane, 2006; Goderniaux et al., 2009; Dadson et al., 2011; Pielke and Wilby, 2012). The GCM simulations are of two types: 1) reanalysis simulations, in which the GCM is constrained by observational data (e.g., Saha et al., 2010); or 2) climate-change simulations in which only the boundary conditions for the GCM are prescribed. RCMs are sophisticated in their representation of physical processes, but the input datasets are large, and the simulations are

computationally intensive. Furthermore, climate-change scenarios generated by RCMs are still constrained by the model's resolution, which is often in the range of 50 km (Christensen and Christensen, 2003; Rasmussen et al., 2012). This scale, although much finer than that of a GCM, still significantly smoothes topography, which can be especially problematic for simulation of orographic precipitation and the detailed spatial patterns of temperature, snowmelt, soil moisture, etc.

The alternative to dynamic downscaling is statistical downscaling, in which an empirical relationship is established between the model output and observed data at a station, and this relationship is used to generate climate-change scenarios for the station (Xu, 1999; Teutschbein, et al. 2011; Nasseri et al., 2013). For example, a relationship can be established between coarse-scale variables from a climate model, such as surface pressure, with station data, such as temperature. While this approach is simpler and less computationally intensive than dynamic downscaling, it depends on the assumption that predictor variables in the GCM or RCM dataset are well-correlated with meteorological data at a station and that this relationship will remain constant in the future. This assumption is likely to be violated as climate changes.

Downscaling methods for hydrological applications thus face a unique set of challenges. For example, in some regions and for some types of climate change impacts, the seasonal variation of precipitation is as important as the annual average (Maraun et al., 2010). For many hydrological applications, extreme events may be of more interest than annual or seasonal values, and these are difficult to estimate either dynamically or statistically (Katz et al., 2002). In some cases, the spatial distribution of precipitation within a basin can significantly affect the performance of hydrologic models, but fully

distributed precipitation scenarios are difficult to generate (Segond et al., 2007). The requirements of hydrological climate change impact studies therefore require special care to be taken in the selection of downscaling techniques. Regardless of the method chosen, downscaling introduces an additional set of uncertainties into the climate impact modeling process (Praskievicz and Chang, 2009).

In mountainous regions, where topography exerts a strong orographic control on temperature and precipitation, elevation can be used as an auxiliary variable to generate downscaled climate change scenarios for the purpose of modeling the hydrologic impacts of climate change. This elevational adjustment can be accomplished through the use of local topographic lapse rates. These lapse rates, not to be confused with "free air" environmental lapse rates – the decrease in temperature with increasing altitude in the free atmosphere as pressure decreases, or with adiabatic lapse rates in rising (or sinking) air parcels – are the changes in a target climate variable (e.g., temperature or precipitation) with elevation. Topographic lapse rates, commonly used in glaciology and mountain climatology, vary seasonally and spatially (Barry, 1992; Rolland, 2003; Chung and Yun, 2004; McVicar et al., 2007; Huang et al., 2008; Fridley, 2009; Im et al., 2010; Hwang et al., 2011; Tobin et al., 2011). Here, we use local topographic lapse rates to adjust regional climate-model data, including both reanalysis data from the North American Regional Reanalysis (NARR) and baseline climate projections from the North American Regional Climate Change Assessment Program (NARCCAP), according to local topography. We then use the resulting "elevationally-adjusted" high-resolution climate projections to simulate discharge in a snowmelt-dominated mountainous basin using the Soil and Water Assessment Tool (SWAT) basin-scale hydrologic model.

### 2.2. Methods

# 2.2.1. Study Site

The Tucannon River heads in the Blue Mountains and flows for 113 km to its confluence with the Snake River (Figure 2.1). The basin area is 820 km<sup>2</sup>, and elevations range from 244 to 1890 m, with an average basin elevation of 911 m. The basin has a semiarid continental climate. At the town of Pomeroy, located in the basin at an elevation of 566 m, average monthly temperatures range from just above 0°C in January to over 21°C in July (WRCC, 2011) (Figure 2.2). Annual precipitation is approximately 400 mm, with a pronounced winter maximum and summer minimum. Average monthly discharge ranges from less than 2 m<sup>3</sup>s<sup>-1</sup> in August to nearly 9 m<sup>3</sup>s<sup>-1</sup> in May (USGS, 2011). The basin is composed of Columbia River Basalts overlain by alluvial deposits (Covert et al., 1995). Land use in the basin is primarily agricultural (approximately 37%, mostly wheat) and rangeland (35%), with the remainder as forested uplands (Covert et al., 1995). The Tucannon River Basin was chosen for this study for the following reasons: 1) The basin exhibits a range of elevations with topographic complexity and a strong orographic influence on temperature and precipitation. 2) The Tucannon River has a long record of discharge and sediment-yield data from United States Geological Survey (USGS) gaging stations that can be used for hydrologic model calibration and validation. 3) This study is the first stage of a larger project examining the impacts of climate change on river morphology in the Tucannon River Basin (Praskievicz, 2014a; Praskievicz, 2014b).



Figure 2.1. Location and topography of the Tucannon River Basin.



**Figure 2.2.** (a) Climagraph for Pomeroy, Washington, 1971-2000. Data source: WRCC (2011). (b) Hydrograph for Tucannon River at Starbuck, Washington, 1971-2000. Data source: USGS (2011).

## 2.2.2. Regional Climate-Model Datasets

We used two regional climate-model datasets in this analysis. The first is the North American Regional Reanalysis (NARR), based on a regional weather forecasting model initialized from observed climate and the boundary conditions provided by the National Centers for Environmental Prediction (NCEP) Reanalysis (Mesinger et al., 2006). The NARR datasets have a spatial resolution of 32 km and a temporal resolution of 3 hours; the data period is 1979-2012 (NCEP, 2013). Because they are constrained by actual observations, reanalysis datasets may be compared on a day-to-day or month-tomonth basis with the observed data for the Tucannon. We therefore used NARR to evaluate our elevational adjustment method and to test whether the regional reanalysis would yield similar hydrological results to station data when used to drive the SWAT model.

We also used baseline projections from the North American Regional Climate Change Assessment Program (NARCCAP), which has two phases. In phase I, the NARCCAP team used a series of RCMs to simulate climate using boundary conditions from the NCEP Reanalysis. In phase II, the team used a series of RCMs driven by a set of GCMs, with a spatial resolution of 50 km and a temporal resolution of 3 hours for the output (Mearns et al., 2012). The major purpose of NARCCAP phase I was to compare the response of the different RCMs to the same forcing for present-day conditions, while our objective here is to apply the downscaling method to different climate scenarios, and so we chose to use only NARCCAP phase II RCM-GCM combinations. The baseline period is from 1968-1998, and the models were also run for a future period of 2038-2068 with anthropogenic greenhouse gas forcing from the Intergovernmental Panel on Climate

Change (IPCC) Special Report on Emissions Scenarios (SRES) A2 scenario. In this study, we used a set of ten RCM-GCM combinations for the NARCCAP baseline period: CRCM-CCSM, CRCM-CGCM3, ECP2-GFDL, HRM3-GFDL, HRM3-HADCM3, MM5-CCSM, RCM3-CGCM3, RCM3-GFDL, WRF-CCSM, and WRF-CGCM3 (for details on the models, see Mearns et al., 2007). Because the GCM simulations that drive the NARCCAP simulations are constrained only by large-scale boundary conditions (solar radiation, atmospheric composition, etc.), the simulations should be comparable with observations only in a statistical sense (e.g., long-term means) before bias-correction. By comparing the hydrological results from the SWAT model run using the baseline projections, we were able to evaluate the sensitivity of the hydrologic model to the different realizations of the climate provided by the various NARCCAP modeling combinations.

# 2.2.3. Local Topographic Lapse Rates

We used the Parameter-elevation Regressions on Independent Slopes Model (PRISM) datasets to calculate the local topographic lapse rates for elevational adjustment of the regional climate-model data. The PRISM datasets are available as monthly timeseries and long-term means on an 800-m climate grid and are based on station data and regressions of climate variables against elevation, aspect, proximity to water bodies, and other topographic variables, with the primary controls on climate being elevation along topographic facets depending on slope orientation (PRISM Climate Group, 2011). Although the PRISM dataset is based on interpolations between stations with topographic variables as co-variates, we derived lapse rates indirectly from the PRISM data in order to isolate the climatic effects of elevation alone. We calculated local topographic lapse

rates for maximum and minimum temperature and precipitation from the 1971-2000 monthly long-term means and the PRISM digital elevation model (DEM). In a spatial domain covering the Pacific Northwest of the United States, we looped over each monthly grid and collected all the cells within a defined search window around each target cell. Elevation and the target climate variable for the points within the search radius were related to one another through singular value decomposition (SVD) regression (Press, 1992), in which a local trend surface was fitted using second-order polynomials of latitude and longitude, with elevation as a linear covariate. Weighted regression was used, with weights defined as the inverse-square-distance of each point from the center of the search window. When evaluated at the grid point in the center of the window, the trend-surface regressions yield the local topographic lapse rate as the coefficient of elevation. The procedure was repeated for each grid cell in the domain, climate variable, and month of the year. The estimated monthly lapse-rate values have very smooth seasonal cycles, which allowed us to interpolate daily values of lapse rates for the downscaling of the RCM data. We experimented with different search-window sizes for each target variable and identified those that yielded lapse-rate patterns that appeared to correspond most closely to real topographic features (80 km for maximum temperature and 20 km for minimum temperature and precipitation).

# 2.2.4. Elevational Adjustment of Regional Climate-Model Data

We elevationally adjusted the regional climate-model data by interpolating the RCM output to the RCM grid and adding or subtracting the local topographic lapse rates calculated from PRISM on a cell-by-cell basis. First, we converted NARR and NARCCAP 3-hourly datasets to daily values, so that they could be used as daily input to the SWAT hydrologic model, taking care to define the local day (0900 to 0600 UTC the following day) appropriately for the longitude of the basin. We created maximum and minimum temperature grids from the NARR and NARCCAP average temperature datasets by extracting the highest and lowest 3-hourly temperature from each local 24-hour day. We also aggregated 3-hourly precipitation to daily by summing the values over each local day. Then, we regridded the NARR and NARCCAP data to the resolution of the PRISM grid through bilinear interpolation and applied the daily interpolated lapse rate correction using the elevations of the RCM and PRISM grid points. Finally, we extracted daily time series of the target climate variables – for NARR and the baseline NARCCAP projections – for the grid point that contains the Pomeroy, Washington, weather station, located in the Tucannon River basin, to use as input to SWAT.

Because climate models, including those used to generate NARR and NARCCAP datasets, usually produce output that is biased in a systematic way, it is common practice to identify those biases and correct them (Berg et al., 2012). We used a simple scaling approach in which we calculated, for each climate variable, the daily climatology (i.e. the long-term mean over a baseline period) for observed station data at Pomeroy (1968-2010) and for the extracted NARR (1979-2010) and NARCCAP (1968-1998) timeseries. We then decomposed the NARR and NARCCAP timeseries into the daily climatology component and a daily anomaly component, then applied the anomaly to the observed (Pomeroy) climatology. Although the base periods of the climatologies were different for NARR and NARCCAP, this is unlikely to be a problem because there is no reason to assume that the biases for NARR and NARCCAP would be the same. Because the NARCCAP models are based on a 365-day calendar (except for HRM-HADCM3, which

has a 360-day calendar), we linearly interpolated values for missing model days to match the number of days in the actual calendar year.

For precipitation, an additional bias is well-known in climate models, in which daily precipitation is simulated as "drizzly." That is, climate models simulate low amounts of precipitation occurring nearly every day, and their precipitation totals on wet days are correspondingly too low, because the cloud formation processes that influence sub-grid parameterization of precipitation are not well-understood (Hanel and Buishand, 2010; Lindau and Simmer, 2013). We addressed this problem by applying a precipitation filter to the daily data. In our extracted NARR and NARCCAP timeseries, we determined a threshold amount of precipitation that must occur in order for the day to be considered a wet day. We iteratively evaluated different threshold values, and chose 0.5 mm because that value resulted in the number of wet days in the model being most similar to the actual number of wet days from observed station data. We then applied this threshold so that days with simulated precipitation less than 0.5 mm were reassigned to 0 mm, and the anomaly-based multiplicative bias correction was then applied to the precipitation timeseries (Räty et al, 2014). For comparison, we also experimented with a method in which the precipitation on days below the threshold was accumulated and added to the next wet day above the threshold. This filtering method, when used to produce precipitation timeseries to drive the SWAT hydrologic model, resulted in noticeable but small differences in simulated annual discharge from that simulated using the standard filtering method. This discrepancy likely occurs because the concentration of precipitation to the end of dry periods results in higher amounts of immediate runoff rather than evapotranspiration or infiltration. For this reason, we chose to use the standard

filtering/bias-correction approach to generating timeseries for hydrologic modeling, rather than adding the accumulated precipitation to the next wet day. The consequence of this approach is that the total water volume (precipitation depth over the basin area) of the drizzle is not included in the water input to the basin. However, relative to the size of the bias corrections, this volume is negligible.

To verify the local topographic lapse-rate downscaling method, we calculated skill scores of the elevationally-adjusted, bias-corrected, and (in the case of precipitation) filtered climate timeseries from NARR relative to observed station data. Such a comparison to observed data is appropriate for NARR, which is constrained by observations, but not for NARCCAP, in which variability is determined by model physics only. We obtained observed daily maximum and minimum temperature and precipitation data for Pomeroy from the National Climatic Data Center (NCDC, 2013) and calculated skill scores as:

(1) SS = 1-(MSEforecast/MSEref)

where SS is the forecast skill, MSEforecast is the mean square error of the forecast climatology (in this case, the downscaled and bias-corrected timeseries), and MSEref is the mean square error of a reference climatology. We used three reference climatologies:

• A simple bilinear interpolation of the NARR data to the PRISM grid, without topographic correction

• An average climatology, based on the observed long-term mean of the observed values for the study period

• A persistence climatology, based on lagged values of daily observations

Negative skill scores indicate that the reference climatology is more predictive than the forecast climatology, while a skill score of 1.0 would indicate that the forecast climatology predicts actual climate perfectly.

# 2.2.5. Hydrologic Modeling

After generating the downscaled and bias-corrected climate timeseries for Pomeroy, we used these timeseries, as well as the observed timeseries for Pomeroy, to drive the Soil and Water Assessment Tool (SWAT), a basin-scale semi-distributed hydrologic model developed by the United States Department of Agriculture that simulates runoff depth as a function of climatic, topographic, soil, and land cover input data using the Soil Conservation Service curve number method (Neitsch et al., 2011). The watershed is first delineated into sub-basins based on flow direction and accumulation derived from a DEM, and then each sub-basin is further subdivided into hydrologic response units, each of which has a curve number determining its runoff response rate based on its unique combination of land use, soil, and slope (Gassman et al., 2007). Daily weather datasets are specified at one or more stations, and these datasets can be distributed spatially through lapse rates of temperature and precipitation for userdefined elevation bands.

Because this model uses many adjustable empirically derived parameters that describe the overall structure of a basin, we first calibrated and cross-validated it using a split sample of observational discharge records from a USGS gage on the Tucannon River at Starbuck, Washington, with one-half of the record used for calibration and the

other for validation (both halves alternately being used for calibration and validation), evaluating fit using the Nash-Sutcliffe efficiency (NSE) criterion (Nash and Sutcliffe, 1970). We used the SWAT Calibration and Uncertainty Program (SWAT-CUP), which, through a variant of Latin Hypercube Sampling, varies sensitive model parameters within a defined range, producing an estimate of best-fit parameters and a 95-percent uncertainty envelope after multiple iterations (Abbaspour et al., 2007). After calibration, we ran SWAT with the observed, NARR (interpolated and bias-adjusted), and baseline NARCCAP (interpolated and bias-adjusted) data to examine the variations in simulated discharge among the different input timeseries.

# 2.3. Results

# 2.3.1. Local Topographic Lapse Rates

Figure 2.3 shows the monthly local topographic lapse rates for maximum and minimum temperature and precipitation. The maximum temperature lapse rates are mostly negative, with temperatures decreasing with increasing elevation, which is the expected relationship. In the winter months, positive lapse rates in some valleys in the northeastern part of the study region indicate the presence of temperature inversions. A narrow band of positive lapse rates can also be seen along the coast in the summer, when temperatures increase with distance from the ocean. Overall, maximum temperature lapse rates are less spatially variable in summer than in winter. The minimum temperature lapse rates, which were created from a smaller search window of 20 km, are more spatially variable than those for maximum temperature, and the winter temperature inversions are more pronounced. Precipitation lapse rates are mostly positive, with
precipitation increasing with increasing elevation, but with some areas of negative lapse rates on the leeward side of mountain ranges. Overall, the pattern of local topographic lapse rates appears climatically reasonable, particularly in the interior mountains of the Pacific Northwest, the area of focus for this study (Figure 2.4).



**Figure 2.3.** Northwest U.S. topographic lapse rates, calculated from the 1971-2000 PRISM long-term mean, for (a) January maximum temperature, (b) July maximum temperature, (c) January minimum temperature, (d) July minimum temperature, (e) January precipitation, and (f) July precipitation.



**Figure 2.4.** Pomeroy, Washington, temperature and precipitation lapse rates, calculated from the 1971-2000 PRISM long-term mean.

#### 2.3.2. Elevational Adjustment of Regional Climate-Model Data

Figure 2.5a-b shows NARR average temperature for a typical January and July day (January 1<sup>st</sup> and July 1<sup>st</sup>, 2005). With the relatively large grid cells of the NARR data, only the largest topographic features, such as the Cascade Mountains and the Snake River Plain, are resolved. In Figure 2.5c-d, the NARR datasets have been bilinear-interpolated to the PRISM grid without lapse-rate correction. These maps appear smoother than the raw NARR grid, but there is no additional apparent spatial variability of climate. In Figure 2.5e-f, the elevational adjustment based on the lapse rates has been applied. In comparison to the "raw" or bilinearly interpolated data, the elevationally-adjusted datasets exhibit finer-scale spatial variability, including the resolution of some individual topographic features such as major mountain peaks and river valleys.



**Figure 2.5.** Average temperature for the northwest U.S., for (a) January 1<sup>st</sup>, 2005, uncorrected NARR, (b) July 1<sup>st</sup>, 2005, uncorrected NARR, (c) January 1<sup>st</sup>, 2005, bilinear interpolation of NARR, (d) July 1<sup>st</sup>, 2005, bilinear interpolation of NARR, (e) January 1<sup>st</sup>, 2005, lapse-rate-corrected NARR, and (f) July 1<sup>st</sup>, 2005, lapse-rate-corrected NARR.

Mean monthly maximum and minimum temperature and precipitation, including the observed station data for Pomeroy and the NARR data extracted for the grid cell that contains Pomeroy, can be seen in Figure 2.6 for the time period 1979-1998, which is the



**Figure 2.6.** Observed, bilinear interpolation of NARR (NARR Interp), lapse-ratedownscaled NARR (NARR-DS), and lapse-rate-downscaled and bias-corrected NARR (NARR DS-BC, the final version of the timeseries used for hydrologic modeling), Pomeroy, Washington, 1979-1998, for (a) maximum and minimum temperature and (b) precipitation.

period of overlap between the observed climate data (1948-2008), observed discharge data (1914-2013), NARR (1979-2010), and NARCCAP baseline (1968-1998). For all three climate variables, the initial uncorrected NARR bilinear interpolation is systematically biased relative to the observed station data. For example, the uncorrected NARR underestimates maximum temperature and overestimates minimum temperature, yielding a smaller temperature range than that of the station data. The NARR timeseries that have been elevationally adjusted using lapse rates are less biased than the uncorrected NARR because they are systematically offset by the lapse rates. Finally, the downscaled and bias-corrected NARR timeseries are very close to the observed station data, as they might be expected to be, given the nature of the bias adjustment. The magnitude of the bias adjustments is smaller than the differences in output among the different climate models, which provides support for the assumption that the adjustments are conservative and are likely to remain relatively constant as climate changes.

Table 2.1 shows skill scores of the lapse-rate-downscaled and bias-corrected maximum and minimum temperature and precipitation for Pomeroy, relative to the reference climatologies of the uncorrected NARR bilinear interpolation, average climatology, and persistence. For all three climate variables, the skill scores are positive relative to all three reference climatologies, which indicates that the downscaling method produces estimates with less error than the naïve reference methods. The downscaling and bias correction method shows greater skill for temperature, particularly maximum temperature, than for precipitation. The positive and generally high skill scores for all climate variables indicate that the elevational adjustment method performs adequately for the Pomeroy station.

**Table 2.1.** Skill scores for maximum and minimum temperature and precipitation at Pomeroy, Washington, 1979-1998, relative to reference climatologies of bilinear interpolation of NARR, average climatology, and persistence. Higher positive scores indicate greater forecast skill.

Reference Climatology	Maximum Temperature	Minimum Temperature	Precipitation
Interpolated NARR	0.40	0.42	0.02
Climatology	0.61	0.41	0.21
Persistence	0.18	0.26	0.52

Given that the elevational adjustment method produces good results for the target station over the study period, we applied the lapse-rate downscaling and bias correction to the ten NARCCAP baseline scenarios of maximum and minimum temperature and precipitation. The results for the 1980-1998 period at Pomeroy, along with the observed station data and downscaled and bias-corrected NARR, can be seen in Figure 2.7. The temperature timeseries for NARR and NARCCAP are nearly indistinguishable from the observed station data. Precipitation varies much more among the different timeseries, which is to be expected given the difficulty of simulating precipitation in global and regional climate models. The peaks of precipitation generally increase toward the end of both the observed and simulated timeseries, because of some wet years in the late 1990s. Overall, the general pattern of all climate variables is well-simulated by the elevationallyadjusted regional climate-model data.



**Figure 2.7.** Observed, NARR, and ten NARCCAP baseline scenarios for Pomeroy, Washington, 1979-1998 (a) monthly maximum temperature, (b) long-term mean monthly maximum temperature, (c) monthly minimum temperature, (d) long-term mean monthly minimum temperature, (e) monthly precipitation, and (f) long-term mean monthly precipitation.

# 2.3.3. Hydrologic Modeling

Figure 2.8 shows the calibration and validation of the SWAT hydrologic model for the Tucannon River Basin, with a cross-validation in order to ensure that the model is not overfitted to the calibration year. The model achieves a Nash-Sutcliffe efficiency of 0.64 for the calibration period of 1980-1985 and 0.51 for the validation period of 1974-1979 (Table 2.2). The Nash-Sutcliffe value compares the residual variance to the data variance. The Nash-Sutcliffe values calculated for the calibration and validation periods indicate a moderately good fit that allows the model to be used for comparing discharge simulated by the different climate timeseries. The fit of the validation data is lower in part because of an apparent overestimation by the model in one year (1977). This discrepancy, however, corresponds with a shift in the USGS rating curve after a major flood in January 1976 (USGS, 2011).



**Figure 2.8.** Observed and simulated discharge for the Tucannon River at Starbuck, Washington, for (a) calibration for 1974-1979, (b) validation for 1974-1979, (c) calibration for 1980-1985, and (d) validation for 1980-1985.

Input Timeseries	Nash-Sutcliffe Efficiency	Annual Average Discharge Error (%)
Observed (calibration 1974-1979)	0.51	5.0
Observed (calibration 1980-1985)	0.64	4.1
Observed (validation 1974-1979)	0.51	-12.3
Observed (validation 1980-1985)	0.48	-3.3
NARR	0.41	8.7
NARCCAP MM5-CCSM	0.07	-7.8
NARCCAP WRF-CCSM	0.15	-11.0
NARCCAP WRF-CGCM3	0.18	-1.38
NARCCAP RCM3-CGCM3	0.10	4.0
NARCCAP RCM3-GFDL	0.30	-3.5
NARCCAP CRCM-CCSM	0.37	-16.8
NARCCAP ECP2-GFDL	0.37	-8.2
NARCCAP HRM3-GFDL	0.34	-16.4
NARCCAP HRM3-HADCM3	0.28	-21.8

**Table 2.2.** Goodness-of-fit statistics comparing discharge simulated by SWAT, using the different input climate timeseries, to observed discharge at the Starbuck, Washington, USGS gage. NARR and NARCCAP statistics are for the period 1980-1989, because of missing observed gaging station data from 1990-1994.

Figure 2.9 shows the monthly timeseries and long-term mean monthly values of observed discharge for the study period (1980-1998), along with discharge simulated using observed climate, elevationally-adjusted NARR data, and the ten elevationally-adjusted NARCCAP baseline scenarios. Although there is some variation in discharge among the different climates, probably due in part to uncertainty in the estimated parameters of the hydrologic model and partly to the variation in precipitation among the

climate timeseries, the general pattern of discharge is similar. In particular, the discharge simulated by observed climate (NSE = 0.64, annual average discharge error = 4.1%) and by NARR (NSE = 0.41, annual average discharge error = 8.7%) is more similar to the observed discharge than that of the NARCCAP scenarios (Table 2.2). Of the NARCCAP scenarios, the best-fitting is ECP2-GFDL (NSE = 0.37, annual average discharge error = -8.2%), and the worst-fitting is MM5-CCSM (NSE = 0.07, annual average discharge error = -7.8%). This variability in simulated discharge indicates the sensitivity of the hydrologic model to the input climate timeseries, and in particular to the variability in precipitation among the different climate models.



**Figure 2.9.** Observed discharge data and simulated discharge data, based on observed climate, NARR, and ten NARCCAP baseline scenarios, for the Tucannon River at Starbuck, for (a) mean monthly discharge from 1980-1998 (note that observed gaging station data are missing from 1990-1994), and (b) long-term mean monthly discharge from 1980-1989 (the longest period within the study timeframe for which observed gaging station data are complete).

#### 2.4. Discussion

#### 2.4.1. Local Topographic Lapse Rates

The local topographic lapse rates calculated for this study are useful both for what they reveal about the climate of the northwestern United States and for their application as a means of elevationally adjusting regional climate-model data. The local topographic lapse rates for Pomeroy are similar in magnitude and seasonal pattern to those calculated for Italy (Rolland, 2003), China (McVicar et al., 2007), and Yellowstone National Park (Huang et al., 2008), with the maximum temperature lapse rates ranging from approximately  $-3.0^{\circ}$ C/km in winter to  $-7.2^{\circ}$ C/km in summer, and minimum temperature lapse rates ranging from about -0.6°C/km in winter to -3.0°C/km in summer (Figure 2.4). As in previous studies, lapse rates are higher in the summer, probably because large-scale subsidence limits convection, and so the dry adiabatic lapse rate is likely to apply more frequently whenever air is ascending. Also, because of warmer temperatures, summer relative humidity is lower and the amount of cooling needed to reach saturation is greater. Minimum temperature lapse rates are less extreme and more spatially variable, possibly because they are more susceptible to local topographic factors such as cold-air drainage. Our study, unlike most other research on topographic lapse rates in mountain environments, also includes a precipitation lapse rate, which ranges from approximately 0.4 mm/km in summer to 3.8 mm/km in winter. Changes in precipitation with elevation are especially important for hydrologic modeling of mountainous basins. Our study is innovative in calculating local topographic lapse rates for a large region using a gridded climate dataset and for using these lapse rates as a downscaling method for regional climate-model data. This approach could be applied in other mountainous regions and

other types of climate-model output to examine the role of circulation patterns in determining the direction and magnitude of local topographic lapse rates. This method is limited, however, to regions in which high-resolution gridded climate observations such as PRISM are available, excluding its application to many remote and less-developed parts of the world. To address this problem, future research could focus on using satellitebased precipitation grids in order to derive lapse rates for regions in which station data are unavailable.

# 2.4.2. Elevational Adjustment of Regional Climate-Model Data

This study uses local topographic lapse rates to elevationally correct regional climate-model output. The initial uncorrected regional climate datasets were seen to be biased relative to observed station data (Figure 2.6). This problem of regional model bias is beginning to be widely recognized in the literature (Racherla et al., 2012; Kerr, 2013). In particular, RCMs are typically evaluated on the basis of their average climatology, which is well-simulated because these models include topographic features that are not resolved by GCMs. When these models are evaluated on their ability to resolve dynamic changes in climate and to reproduce past climates, however, they tend to perform poorly, particularly when the nested regional model does not include feedback to the driving global model (Racherla et al., 2012). The approach taken in this study ameliorates this regional modeling problem by elevationally adjusting and bias-correcting the RCM output. The result is a grid with both high spatial and temporal resolution that reproduces actual past climates, for particular locations, with a higher degree of fidelity than the RCM alone can achieve. Until the regional models improve, this solution can be useful for applications that involve the simulation of highly local climates, as is required in

hydrologic modeling of mountainous basins. We plotted values of NARCCAP biases for the first half of the NARCCAP period (1968-1983) and the second half (1984-1998), and found no significant difference in the biases between these two time periods. Given this apparent lack of trend, it is reasonable to assume that the bias is stationary, at least within the observational period. One limitation of this study, however, is that we evaluated the forecast skill of our elevational adjustment method relative to a naïve bilinear interpolation in order to establish that incorporating elevation adds skill beyond that from increasing spatial resolution. In future research, it would be useful to compare our elevational-adjustment method to more sophisticated downscaling techniques such as Bias Correction and Spatial Downscaling (BCSD) (Wood et al., 2002; Wood et al., 2004; Wood et al., 2005) and Constructed Analogs (CA) (Maurer and Hidalgo, 2008).

# 2.4.3. Hydrologic Modeling

We find that elevationally adjusted data from a regional climate model, when used to drive a hydrologic model, can produce results that are similar to those obtained using observed climate, albeit with some variability between the observed and simulated discharge (Figure 2.9). There are two likely sources of this variability. The first is uncertainty in the parameters of the hydrologic model. In particular, the accumulation and melting of snow is highly sensitive to a few model parameters (Pederson et al., 2013). The Tucannon River Basin is a relatively low-elevation basin with a bimodal annual hydrograph that includes both a winter rainfall peak and a later spring snowmelt peak. This means that the Tucannon River is highly sensitive to climate change, because a small increase in winter temperature will cause a significant decrease in snowpack. It also means, however, that the hydrology of the basin is especially difficult to model, given

that so much of the basin's area lies near the rain-snow transition threshold. Because such transitional basins are the most sensitive to climate change impacts, yet the most difficult to model (Elsner et al., 2010), future research should prioritize development of more sophisticated snow accumulation and snowmelt parameters in hydrologic models.

Another source of variability in simulated discharge among the different input timeseries is variability in the simulated (NARR and NARCCAP) climates themselves. Although both maximum and minimum temperatures in the elevationally-adjusted and bias-corrected NARR and NARCCAP baseline scenarios are very close to observed station data, substantial variability exists in the precipitation timeseries. This variability is the result of the inherent difficulty of modeling precipitation, which is often generated by stochastic processes that are too fine in spatial or temporal resolution to be resolved by existing models (Maraun et al., 2010). The impact of this variability can be seen in the hydrologic modeling results, in which the relatively low-precipitation WRF-CCSM scenario generates substantially less discharge than the wetter scenarios.

The difference in NSE values of discharge simulated by the best-fitting NARCCAP scenario (ECP2-GFDL, NSE = 0.37) and the worst-fitting NARCCAP scenario (MM5-CCSM, NSE = 0.07) is 0.30, which is less than the difference from perfect NSE (NSE = 1) of 0.36 for the calibration period (NSE = 0.64) or 0.49 for the validation period (NSE = 0.51). The implication is that, in this study, discharge is more sensitive to uncertainty in the hydrologic model than to uncertainty in climate. This result suggests that the topographic correction method used in this study may be applied in other types of climate analysis, such as temperature- or moisture-sensitive weathering processes or species ranges, or for hydrologic modeling of future climate change. More

work is needed, however, to further test the method and establish that it does not introduce significant additional uncertainty, before it can be reliably used in other types of applications.

#### 2.5. Conclusion

Here, we generate local topographic lapse rates and use them to elevationally adjust regional climate-model output for use in modeling the hydrology of a mountainous basin. Evaluation of the method indicates that this lapse-rate-based approach performs well and is appropriate for generating high-resolution climate timeseries for regions in which a strong orographic control on climate exists. Hydrologic modeling of the Tucannon River demonstrates that the elevationally adjusted regional climate-model data can produce discharge that is similar to observed, albeit with some variability resulting from uncertainty in precipitation and in hydrologic-model parameters. This approach can be used for elevationally adjusting reanalysis data using lapse rates – estimated from interpolated climate grids like PRISM or from satellite measurements – to simulate hydrology in remote basins that lack weather stations, or to downscale regional paleoclimate models or RCMs driven by future climate change scenarios to simulate the impacts of climate change on hydrology in mountainous basins.

In Chapter II, I developed and validated a method for elevationally adjusting RCM output using local topographic lapse rates. The resulting downscaled RCM grids are necessary for producing the baseline and future NARCCAP timeseries that serve as input to the SWAT hydrologic model. This chapter bridges the climatic and hydrologic systems in my modeling hierarchy, because it focuses on downscaling regional climate

projections to the basin hydrology scale. In Chapter III, I will use SWAT, driven by the downscaled RCM output from Chapter II, to simulate changes in basin-scale discharge and suspended-sediment load resulting from climate change on all three of my study rivers.

#### CHAPTER III

# IMPACTS OF PROJECTED CLIMATE CHANGES ON STREAMFLOW AND SEDIMENT TRANSPORT FOR THREE SNOWMELT-DOMINATED RIVERS IN THE INTERIOR PACIFIC NORTHWEST

### 3.1. Introduction

Anthropogenic climate change is expected to significantly affect water resources [Kundzewicz et al., 2007]. At the global scale, higher temperatures are likely to increase evaporation and precipitation rates globally through an acceleration of the hydrologic cycle, with additional regional differences in future precipitation changes related to changes in the general circulation of the atmosphere [Trenberth, 1999; Oki and Kanae, 2006; Giorgi et al. 2011; Kirtman et al., 2013].

Future changes in basin hydrology will result from the superimposition of these global and regional climatic changes on watershed characteristics, such as topography, soils, and land use/land cover. One of the most robust patterns of change can be found in mountainous river basins, such as those in the western United States, in which the accumulation of winter snowpack and its melting in the spring and summer supplements river discharge during the dry summers [Mote et al., 2003]. Because of the snowpack influence on the annual hydrograph, these rivers are expected to be highly sensitive to increases in temperature, particularly during winter and spring. The impacts of climate change on the hydrology of these rivers may therefore be amplified relative to the regional changes in temperature and precipitation. Some climatic and hydrologic trends have already been observed in these basins. Over the past fifty years, peak spring runoff

in snowmelt-dominated and transient basins in the western United States has been occurring earlier, because of decreasing snowpack and increasing spring temperatures [Stewart et al., 2004; Regonda et al., 2005; Barnett et al., 2008]. Such trends are likely to continue throughout the twenty-first century with ongoing anthropogenic climate change.

Aspects of basin physiography may also affect the relative sensitivity of a river to climate-driven hydrologic changes. Hamlet and Lettenmaier [2007] divided western U.S. basins into three categories of potential response to climate change. Cold, snow-dominated basins that have temperatures far enough below the rain-snow transition are unlikely to shift to frequent winter rainfall as a result of projected climate change. Warm, rain-dominated basins are relatively unaffected by snow, and their climate change response is therefore more sensitive to changes in precipitation amount and evapotranspiration, which are more uncertain and spatially variable than changes in temperature. The type of basin most likely to experience significant climate change impacts is the transient basin, which has average winter temperatures near freezing [Adam et al., 2009; Cuo et al., 2009; Elsner et al., 2010]. A small increase in temperature in these basins can therefore result in the transition of precipitation from snow to rain, with consequent effects on winter runoff and spring/summer snowmelt.

In addition to changes in the mean annual hydrograph, transient and snowmeltdominated basins are vulnerable to changes in extreme events. For example, these rivers are susceptible to the risk of a particularly severe type of flood that results from intense rainfall on a snowpack. These rain-on-snow events generate river discharge not only from rainfall, but also from the melting snow. Because a small increase in temperature can change the form of precipitation from snow to rain, these events may become more

frequent and severe as a result of climate change [Leung et al., 2004; Surfleet and Tullos, 2013]. Large floods may be produced that exceed the magnitude of equivalent recurrence interval floods from the historic record. Because of the sensitivity of mean and extreme hydrology in transient and snowmelt-dominated basins to small changes in temperature resulting from elevation differences, the topography of these basins must be explicitly incorporated into projections of future climate change.

Hydrologic changes in mountainous river basins may also affect sediment transport. Because the amount of sediment transported by a river depends on stream power, or the amount of energy available for geomorphic work, which is determined in part by the river discharge, increased river discharge will result in increased sediment transport, assuming additional sediment supplies are available. Changes in runoff and river discharge resulting from climate change could therefore influence the amount of sediment transport and thus the geomorphic characteristics of rivers, because channel geometry adjusts to inputs of water and sediment [Orr and Carling, 2006; Lane et al. 2007; Whitehead et al., 2009]. Any increase in large floods that results in more frequent overbank flows could rework the floodplain and change the river planform [Eaton and Lapointe, 2001; Schmidt et al., 2001; Fuller et al., 2003]. The erosion, transport, and deposition of sediment affects a variety of socially and ecologically significant aspects of river systems, including river morphology, water quality, and physical habitat.

Although river discharge and suspended-sediment transport are highly correlated, the relationship is not always straightforward. Sediment rating curves may change for different times within a storm and locations within a watershed [Guo and Wood, 1995]. Marcus [1989] found that the faster velocity of flood waves relative to streamflow can

result in variations in the relationship between discharge and suspended-sediment concentration through time. In addition to the energy available for transport, which is determined by hydraulic conditions, suspended-sediment transport is also affected by the supply of sediment, which varies spatially and temporally [Gao, 2008]. Although any changes in suspended-sediment transport resulting from climate change may be expected to generally co-vary with changes in river discharge, the nature and magnitude of the changes may vary seasonally and with location in the watershed.

Although mountainous areas are likely to be highly sensitive to hydrological impacts of climate change, the spatial scale of climatic processes relevant to these systems is not well-resolved with existing climate models. Salathé et al. [2007] found that, in order to simulate the land-surface and topographic characteristics that control mesoscale climate changes in the Pacific Northwest, including regionally significant changes to the surface radiation budget related to snow cover and cloudiness, highresolution (at least 15-km) climate models are needed. This resolution is finer than that of all GCMs and most RCMs [Buytaert et al., 2010]. Climate-model output must therefore be dynamically or statistically downscaled, which contributes significant uncertainty to the process of modeling impacts of climate change on hydrology [Fowler et al., 2007; Chen et al., 2011; Teutschbein et al., 2011; Ghosh and Katkar, 2012]. Furthermore, downscaling approaches depend on the assumption that relationships between the predictor and response variables are stationary, which may not be the case in the context of climate change [Raje and Mujumdar, 2010]. The approach presented here contributes to understanding of hydrological impacts of climate change in mountain regions by using

downscaled climate grids that are on a scale closer to that of the processes controlling mountain climatology and hydrology.

A number of studies have simulated the impacts of climate change on snowmeltdominated rivers using basin hydrologic models [e.g., Pfister et al., 2004; Caballero et al., 2007; Graves and Chang, 2007; Hay and McCabe, 2010; Vicuña et al., 2011; Jung et al., 2012; Laghari et al., 2012; Ligare et al., 2012; Shrestha et al., 2012; Wu et al., 2012; Cuo et al., 2013; Ficklin et al., 2013; Ragettli et al., 2013]. Most of these studies, however, have used climate change projections that are relatively coarse in spatial resolution and therefore do not explicitly consider the role of topography in controlling hydrologic impacts of climate change in mountainous regions. Furthermore, few existing hydrologic modeling studies have simulated impacts of climate change on sediment transport in snowmelt-dominated basins. Here, I use the Soil and Water Assessment Tool (SWAT) basin-scale hydrologic model, driven by downscaled regional-scale climate projections from the North American Regional Climate Change Assessment Program (NARCCAP), to simulate impacts of climate change on both river discharge and suspended-sediment transport for three snowmelt-dominated rivers in the interior Pacific Northwest.

3.2. Methods

#### 3.2.1. Study Area

The study basins are the Tucannon River in southeastern Washington and the South Fork Coeur d'Alene and Red rivers in Idaho (Figure 3.1). I chose these rivers in part because all three have United States Geological Survey (USGS) or United States Forest Service (USFS) stream gages with at least several years of both discharge and suspended-sediment records, which are required for set-up and implementation of the hydrologic model. The rivers are all undammed, which means their hydrological responses to changes in climate will not be limited by operational hydrological actions. Finally, all three rivers are located in mountainous areas in which a significant snowpack accumulates, which means they are likely to be sensitive to increased temperatures associated with climate change.



Figure 3.1. Locations of Tucannon, South Fork Coeur d'Alene, and Red river basins.

The study rivers are part of the larger Columbia River Basin, located in the interior Pacific Northwest between the Cascade Range to the west and the Rocky Mountains to the east. Differences in basin physiography control differences in climate and hydrology among the three basins (Figure 3.2, Table 3.1). The Tucannon River heads

in the Blue Mountains, but the lower part of the basin is on the relatively low-elevation Columbia Plateau. The mean elevation of the Tucannon River Basin is 911 m, compared to 1245 m and 1639 m for the South Fork Coeur d'Alene and Red river basins, respectively. Consequently, the Tucannon River Basin has higher temperatures (annual mean of 10.4°C) and lower precipitation (annual average of 35.7 cm) than the two higherelevation basins (annual mean temperatures of 8.2°C and 5.4°C and average annual precipitation of 71.4 cm and 64.9 cm for the South Fork Coeur d'Alene and Red river basins). Although the annual hydrographs of the South Fork Coeur d'Alene and Red rivers both exhibit a distinct peak in May, indicating the dominance of late-spring snowmelt, the Tucannon River's annual hydrograph is bimodal, with a rainfall-generated peak in January, followed by a snowmelt peak in May. The Tucannon River therefore exemplifies the transient basin, in which hydrology is likely to be especially sensitive to climate change, while the South Fork Coeur d'Alene and Red rivers are dominated by snowmelt.



**Figure 3.2.** 1980-2010 annual (water-year) climagraph for (a) the Tucannon River Basin (Pomeroy, Washington, weather station); (b) South Fork Coeur d'Alene River Basin (Kellogg, Idaho, weather station); (c) Red River Basin (Elk City, Idaho, weather station); annual (water-year) hydrograph for (d) the Tucannon River (USGS gage 13344500, Starbuck, Washington); (e) the South Fork Coeur d'Alene River (USGS gage 12413470, Pinehurst, Idaho); (f) the Red River (USFS gage at Red River Ranger Station, Idaho). Data sources: NRDC (2013) and USGS (2013).

Variable	Tucannon	South Fork Coeur d'Alene	Red
Drainage area (km <sup>2</sup> )	1116	743	99
Minimum elevation (m)	244	665	1281
Maximum elevation (m)	1890	2081	2261
Mean elevation (m)	911	1245	1639
Mean annual temperature (°C)	10.4	8.2	5.4
Mean January temperature (°C)	0.2	-1.4	-4.2
Mean July temperature (°C)	21.4	19.7	16.4
Mean annual precipitation (cm)	35.7	71.4	64.9
Mean January precipitation (cm)	54.9	103.1	84.6
Mean July precipitation (cm)	12.2	31.0	40.1
Mean annual discharge (cms)	5.1	15.2	2.0
Mean annual discharge for highest- discharge month (cms)	8.47 (May)	40.2 (May)	6.6 (May)
Mean annual discharge for lowest- discharge month (cms)	1.9 (August)	3.3 (September)	0.5 (October)

Table 3.1. Study Basin Characteristics

### 3.2.2. SWAT Calibration and Validation

I simulated discharge and suspended-sediment load on the study rivers using the Soil and Water Assessment Tool (SWAT), a basin-scale semi-distributed hydrologic model developed by the United States Department of Agriculture that simulates runoff depth as a function of climatic, topographic, soil, and land cover input data using the Soil Conservation Service curve number method [Neitsch et al, 2011]. In applications of SWAT, a watershed is first delineated into sub-basins based on flow direction and accumulation derived from a digital elevation model (DEM), and then each sub-basin is further subdivided into hydrologic response units (HRUs), each of which has a curve number determining its runoff response rate based on its unique combination of land cover, soil, and slope [Gassman et al., 2007]. In addition to river discharge, SWAT also simulates suspended-sediment load, using the Modified Universal Soil Loss Equation (MUSLE) [Neitsch et al., 2011]. Although MUSLE was originally developed for agricultural watersheds, its soil and topographic parameters (rainfall erosivity, soil erodibility, slope and length) should be broadly applicable. Because SWAT uses many empirically-derived adjustable parameters that describe the overall structure and processes within a basin, I first calibrated and validated it using a split sample of observed discharge and suspended-sediment records from gages on each river, evaluating fit using the Nash-Sutcliffe efficiency criterion (NSE) [Nash and Sutcliffe, 1970]. The longest available continuous periods of gaging station records were used for calibration and validation. For discharge, at least six years of both calibration and validation data were used on all three rivers, but only one year each of continuous suspended-sediment data was available for the calibration and validation periods (Table 3.2).

River	Variable	Calibration time period	Validation time period	Calibration NSE	Validation NSE
Tucannon	Streamflow	1980-1985	1974-1979	0.64	0.51
South Fork					
Coeur d'Alene	Streamflow	1991-2000	2001-2010	0.62	0.62
Red	Streamflow	1980-1989	1990-1999	0.62	0.50
	X7 ' 1 1	Calibration	Validation	Calibration	Validation
River	Variable	time period	time period	NSE	NSE
Tucannon	Suspended sediment	1963	1964	0.49	0.10
South Fork Coeur d'Alene	Suspended sediment	1993	1994	0.36	0.26
Red	Suspended sediment	1980	1981	0.45	0.31

Table 3.2. Calibration and Validation Statistics

Two types of climate data can be used as input to SWAT. The first option is to use explicit daily (or hourly) temperature and precipitation timeseries from a weather station. The second option is to specify average monthly values of temperature and precipitation (and related statistics such as wet-day frequency, maximum half-hour rainfall, solar radiation, relative humidity, and wind speed) and use SWAT's WXGEN stochastic weather generator to create synthetic daily timeseries based on these average values. The weather generator uses a first-order Markov chain to incorporate system memory conditioned on the occurrence of precipitation on the previous day, generates precipitation amounts on wet days using an exponential distribution, and estimates daily maximum and minimum temperature using a weakly stationary generating process [Arnold et al., 2011]. To drive SWAT, I used both explicit (downscaled) daily timeseries from individual climate models and synthetic timeseries produced by the weather generator using average monthly values from ensemble-averages of climate-model output. The individual daily timeseries should contain realistic day-to-day variability in weather, while the ensemble-average-based timeseries should provide an across-model "consensus" of simulated climate change. (It would be nonsensical to create daily ensemble averages to do this, unless each regional climate model used an identical daily sequence of global-model forcing.)

# 3.2.3. Climate Change Impacts

To simulate changes in river discharge and suspended sediment resulting from climate change, I ran the calibrated SWAT model using baseline and future climate simulations for each basin (Table 3.3). These projections are based on the North American Regional Climate Change Assessment Program (NARCCAP), which includes output from a total of ten combinations of six RCMs driven by a set of four General Circulation Models (GCMs), for two time periods: a baseline period of 1968-1998, and a future climate change period of 2038-2068 under the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) A2 greenhouse gas forcing [Mearns et al., 2007]. The NARCCAP projections include daily maximum and minimum temperature and precipitation on a 50-km grid, but I downscaled these

NARCCAP Scenario	RCM	RCM Modeling Group	GCM	GCM Ensemble Member Used
CRCM-CCSM	Canadian Regional Climate Model/le Modèle Régional Canadien du Climat	OURANOS/UQAM	Community Climate System Model	b30.030e (ctl), b30.042e (fut)
CRCM-CGCM	Canadian Regional Climate Model/le Modèle Régional Canadien du Climat	OURANOS/UQAM	Third Generation Coupled Global Climate Model	CGCM #4
ECP2-GFDL	Experimental Climate Prediction Center Regional Spectral Model	University of California, San Diego/Scripps Institution of Oceanography	Geophysical Fluid Dynamics Laboratory GCM	20C3M, run2; sresa2, run1
HRM3-GFDL	Hadley Regional Model 3	Hadley Centre	Geophysical Fluid Dynamic Laboratory GCM	20C3M, run2; sresa2, run1
HRM3- HadCM3	Hadley Regional Model 3	Hadley Centre	Hadley Centre Coupled Model, Version 3	Custom run for NARCCAP
MM5-CCSM	MM5 - PSU/NCAR Mesoscale Model	Iowa State University	Community Climate System Model	b30.030e (ctl), b30.042e (fut)
WRF-CCSM	Weather Research and Forecasting Model	Pacific Northwest National Laboratory	Community Climate System Model	b30.030e (ctl), b30.042e (fut)
WRF-CGCM	Weather Research and Forecasting Model	Pacific Northwest National Laboratory	Third Generation Coupled Global Climate Model	CGCM #4
RCM-CGCM	Regional Climate Model Version 3	University of California, Santa Cruz	Third Generation Coupled Global Climate Model	CGCM #4
RCM-GFDL	Regional Climate Model Version 3	University of California, Santa Cruz	Geophysical Fluid Dynamics Laboratory GCM	20C3M, run2; sresa2, run1

# Table 3.3. NARCCAP GCM and RCM Characteristics<sup>a</sup>

<sup>a</sup>Data source: UCAR (2013).

projections to 800 m by elevationally adjusting the NARCCAP grid using empiricallyestimated local topographic lapse rates. I then bias-corrected the resulting elevationallyadjusted NARCCAP projections by applying the average daily anomaly relative to observed station climatologies. For details on the lapse-rate downscaling procedure, see Praskievicz and Bartlein [2014].

Figure 3.3 shows the range of relative changes in maximum and minimum temperature and precipitation for the three basins among all ten NARCCAP GCM-RCM combinations. The future changes in climate projected by NARCCAP are similar across all three study basins. The mean increases in maximum temperature across the three basins range from 1.8 to 2.4°C in January and 2.8 to 3.5°C in July. For minimum temperature, the mean increases are 2.9 to 3.8°C in January and 2.7 to 2.8°C in July. The mean changes in precipitation include slight decreases in January winter precipitation and more extreme decreases in summer precipitation, ranging across the three basins from -2.8% to -1.0% in January and -17.1% to -20.3% in July. While all the NARCCAP modeling combinations indicate increases in both maximum and minimum temperature for all months in all three basins, the projections for precipitation vary more among the different GCM-RCM combinations. For example, in the Tucannon River Basin, projected changes in precipitation among the different models range from -15.0% to +17.8% in January and from -49.2% to +26.2% in July. This variability among models is unsurprising, given the differences in parameterizations that control precipitation among the models.



**Figure 3.3.** Boxplot summarizations of the relative changes for the NARCCAP future climate period (2038-2068) relative to the baseline period (1968-1998) for ten NARCCAP GCM-RCM combinations. (a) Change in mean monthly maximum temperature for Tucannon River Basin; (b) change in mean monthly maximum temperature for South Fork Coeur d'Alene River Basin; (c) change in mean monthly minimum temperature for Tucannon River Basin; (d) change in mean monthly minimum temperature for Tucannon River Basin; (e) change in mean monthly minimum temperature for South Fork Coeur d'Alene River Basin; (f) change in mean monthly minimum temperature for Red River Basin; (g) change in mean monthly minimum temperature for Red River Basin; (g) change in mean monthly precipitation for Tucannon River Basin; (h) change in mean monthly precipitation for South Fork Coeur d'Alene River Basin; (i) change in mean monthly precipitation for Red River Basin; (i) change in mean monthly precipitation for Red River Basin; (i) change in mean monthly precipitation for Red River Basin; (i) change in mean monthly precipitation for Red River Basin; (i) change in mean monthly precipitation for Red River Basin. Note: whiskers extend from minimum to maximum values.

From the full suite of ten GCM-RCM combinations in NARCCAP, I selected three for simulating river discharge and suspended-sediment load in each basin: the GCM-RCM combination with the smallest temperature increase in each basin ("cool"), the one with the largest temperature increase ("hot"), and the one with the largest decrease in precipitation ("dry") (Table 3.4). Selecting these extremes allows for the simulation of a wide range of possible future climate change impacts on basin hydrology and sediment transport. Using all ten NARCCAP GCM-RCM combinations would have been redundant, since many of the projected climate changes projected by the different models are similar to one another (being driven by the same GCM simulations), so using the most divergent model combinations simplifies the analysis while still allowing the widest range of variability among the different projections to be examined. For each of the three selected NARCCAP GCM-RCM combinations, I ran the SWAT model using both the NARCCAP baseline (1968-1998) and future (2038-2068) projections. In order to simulate the impacts of the mean climate changes projected by NARCCAP, I also created an ensemble climate projection by calculating the long-term monthly means of maximum and minimum temperature and precipitation averaged across all ten NARCCAP GCM-RCM combinations. I used these long-term monthly means to create synthetic daily timeseries using SWAT's WXGEN stochastic weather generator. The synthetic daily timeseries simulated by the weather generator, forced by the long-term monthly means of maximum and minimum temperature and precipitation averaged across all ten NARCCAP models for the baseline and future periods, provided an ensemble climate change projection to drive SWAT.

River	"Cool" Scenario	"Hot" Scenario	"Dry" Scenario
Tucannon	ECP2-GFDL (+1.5°C annual temperature)	CRCM-CGCM (+3.4° annual temperature)	HRM-GFDL (-18.1% annual precipitation)
South Fork Coeur d'Alene	ECP2-GFDL (+1.7°C annual temperature)	CRCM-CCSM (+3.5°C annual temperature)	HRM-GFDL (-18.4% annual precipitation)
Red	ECP2-GFDL (+1.8°C annual temperature)	CRCM-CCSM (+4.1°C annual temperature)	HRM-GFDL (-19.0% annual precipitation)

**Table 3.4.** Extremes of NARCCAP Model Combinations Selected for Hydrologic

 Modeling

#### 3.3. Results

# 3.3.1. SWAT Calibration and Validation

After adjustment of the model parameters, the calculated NSE values indicate moderately high goodness-of-fit for discharge on all three rivers for the calibration and validation periods [Nash and Sutcliffe, 1970] (Figure 3.4, Table 3.2). NSE values across the three rivers range from 0.62-0.64 in the calibration period and 0.50-0.62 in the validation period. For suspended-sediment load, the model fit was lower, with NSE values for the three rivers ranging from 0.36-0.45 in the calibration period and from 0.26-0.40 in the validation period (Figure 3.5, Table 3.2). NSE compares the model residual variance to the data variance, with a value of 1 indicating a perfect model fit, any positive value indicating a better fit than the mean of the observed data, and a value of approximately 0.6 considered adequate for daily discharge. The better model performance for river discharge is to be expected, given that the simulated suspendedsediment transport incorporates the uncertainty of the simulated discharge, simulating



**Figure 3.4.** Observed and simulated monthly discharge for (a) the Tucannon River in the calibration period (1980-1985); (b) the Tucannon River in the validation period (1974-1979); (c) the South Fork Coeur d'Alene River in the calibration period (1991-2000); (d) the South Fork Coeur d'Alene River in the validation period (2001-2010); (e) the Red River in the calibration period (1980-1989); (f) the Red River in the validation period (1990-1999).



**Figure 3.5.** Observed and simulated daily suspended-sediment load for (a) the Tucannon River in the calibration period (1963); (b) the Tucannon River in the validation period (1964); (c) the South Fork Coeur d'Alene River in the calibration period (1993); (d) the South Fork Coeur d'Alene River in the validation period (1994); (e) the Red River in the calibration period (1980); (f) the Red River in the validation period (1981).

sediment transport is more complicated than simulating discharge, and there is uncertainty in the gaging station records of suspended-sediment load. Except for some missing peaks in sediment load during the validation period on the South Fork Coeur d'Alene River, the model's simulated sediment transport peaks approximate the observed timing and magnitude well. Given that the NSE values indicate relatively good model performance for both variables, simulation of future climate change impacts on river discharge and suspended sediment for the three rivers is warranted.

#### 3.3.2. Climate Change Impacts: River Discharge

Figure 3.6 shows the simulated annual hydrographs and relative changes in discharge for the three rivers under the three baseline and future NARCCAP GCM-RCM combinations and ensemble average. Under the projected future climate change, all three rivers show a similar general response of increased winter discharge, a decrease in the magnitude of the spring snowmelt peak and its shift to earlier in the season by approximately one month, and decreased summer discharge (Figure 3.6, Table 3.5). Although the magnitude of relative changes in river discharge is greatest for the South Fork Coeur d'Alene and Red rivers, possibly because of generally greater warming in the driving climate-change scenarios at higher elevations, these snowmelt-dominated rivers maintain their spring snowmelt peak in the future scenarios, albeit with a reduction in the magnitude of the peak. The Tucannon River, the lowest-elevation of the three basins, is projected to experience a shift in its hydrologic regime. Under the current climate, the Tucannon River's annual hydrograph has a winter rainfall peak and a spring snowmelt peak, but in the future climate-change simulation the snowpack accumulation diminishes to the point that the spring snowmelt peak no longer occurs. The Tucannon River is therefore projected to shift its hydrologic regime from its current transient state to a system characterized by a single winter-rainfall peak under climate change. The increase



**Figure 3.6.** (a) Simulated monthly baseline (1968-1998) and future (2038-2068) discharge on the Tucannon River; (b) change in simulated discharge for the future period (2038-2068) relative to baseline (1968-1998) on the Tucannon River; (c) simulated baseline (1968-1998) and future (2038-2068) discharge on the South Fork Coeur d'Alene River; (d) change in simulated discharge for the future period (2038-2068) relative to baseline (1968-1998) on the South Fork Coeur d'Alene River; (e) simulated baseline (1968-1998) on the South Fork Coeur d'Alene River; (e) simulated baseline (1968-1998) and future (2038-2068) discharge on the Red River; (f) change in simulated baseline (1968-1998) and future (2038-2068) discharge on the Red River; (f) change in simulated baseline (1968-1998) and future (2038-2068) discharge on the Red River; (f) change in simulated baseline (1968-1998) and future (2038-2068) discharge on the Red River.
Table 3.5.	Hydrologic	Modeling	Results

Tucannon	ECP2-GFDL	CRCM- CGCM	HRM- GFDL	Ensemble
Change in mean annual discharge (%)	-1.3	-10.5	-15.0	-4.3
Change in mean January discharge (%)	+13.0	+36.6	+1.1	+16.3
Change in mean July discharge (%)	-2.4	-20.5	-9.7	-5.2
Change in mean annual suspended-sediment load (%)	-1.1	-15.2	-12.8	-18.4
Change in mean January suspended-sediment load (%)	-21.6	+7.6	-23.6	-14.0
Change in mean July suspended-sediment load (%)	-59.6	-29.6	+98.3	-5.4
South Fork Coeur d'Alene	ECP2-GFDL	CRCM- CCSM	HRM- GFDL	Ensemble
Change in mean annual discharge (%)	-14.9	-5.7	-8.1	-8.9
Change in mean January discharge (%)	+21.3	+94.7	+39.2	+4.1
Change in mean July discharge (%)	-29.8	-40.7	-28.6	-31.7
Change in mean annual suspended-sediment load (%)	+0.5	-12.8	+8.9	-18.3
Change in mean January suspended-sediment load (%)	+94.3	+91.2	+79.2	+88.2
Change in mean July suspended-sediment load (%)	-59.8	-63.4	-73.4	-72.2
Red	ECP2-GFDL	CRCM- CCSM	HRM- GFDL	Ensemble
Change in mean annual discharge (%)	-6.5	+6.0	-21.5	-6.5
Change in mean January discharge (%)	+13.7	+68.5	+20.9	+34.4
Change in mean July discharge (%)	-56.7	-9.9	-68.2	-47.2
Change in mean annual suspended-sediment load (%)	-1.9	-8.5	-14.5	-8.4
Change in mean January suspended-sediment load (%)	-5.7	-12.2	-23.9	-13.8
Change in mean July suspended-sediment load (%)	-4.3	-27.7	-42.8	-25.5

<sup>a</sup>Simulated changes are for future period (2038-2068) relative to baseline (1968-1998).

in winter discharge for the "hot" scenario (CRCM-CCSM) is even higher on the South Fork Coeur d'Alene and Red Rivers (+70.8% and +94.7%, respectively) than on the Tucannon River.

Simulated changes in discharge vary among the different NARCCAP model combinations, because of the moderate differences in temperature among the different models and the more substantial differences in precipitation, including in the sign of future precipitation change. For all three rivers, the most extreme changes in annual discharge are for the "dry" climate change scenario (HRM-GFDL), because this scenario provides the least amount of incoming precipitation. The most extreme changes in January discharge, however, are for the "hot" scenario (CRCM-CGCM for the Tucannon River and CRCM-CCSM for the other two rivers). This result indicates that, while changes in precipitation determine impacts on the annual water budget, the winter discharge of the study rivers is strongly controlled by temperature, as would be expected for snowmelt-dominated rivers.

In addition to the simulated changes in mean hydrology, the modeling results also indicate changes in the frequency of flood events of varying magnitudes (Figure 3.7). Simulated bankfull discharge (recurrence interval of 2 years) for the study rivers under the ensemble climate-change scenario increases in the future period relative to baseline, with increases ranging from +10.1% for the South Fork Coeur d'Alene River to +48.8% for the Tucannon River. This increase could result from the higher proportion of winter precipitation occurring as rain under future climate change. The largest simulated floods also increase for the ensemble future period relative to baseline, with the magnitude



**Figure 3.7.** Flow duration curves for simulated ensemble baseline (1968-1998) and future (2038-2068) discharge on (a) the Tucannon River; (b) the South Fork Coeur d'Alene River; (c) the Red River.

of the increase ranging from +0.6% for the Tucannon River to +41.6% for the South Fork Coeur d'Alene River. These particular floods are rare rain-on-snow events, for which the necessary conditions are likely to become increasingly common under climate change. Intermediate-magnitude floods vary among the different rivers in the direction of simulated future change. For example, the 10-year flood increases in the ensemble future period on the Red River (+4.5%) and the Tucannon River (+43.1%), but decreases on the South Fork Coeur d'Alene River (-2.7%). Similarly, the magnitude of the 100-year flood increases in the ensemble future period for the Red River (+2.5%), but decreases for the Tucannon River (-15.1%) and the South Fork Coeur d'Alene River (-0.2%).

The variability in changes in simulated flood magnitudes may be attributed to the interactions of changes in temperature and precipitation, the relative importance of which varies among the different models. For example, on the South Fork Coeur d'Alene River, the simulated magnitude of the 100-year flood increases under the "hot" CRCM-CCSM future scenario (+46.9%), but decreases under the "dry" HRM-GFDL future scenario (-7.2%). This result indicates that future changes in flood magnitude are strongly controlled by the nature of the climate change scenario. The changes in simulated discharge are strongly controlled by how precipitation changes in the future period. In the warmest scenarios, the change in winter precipitation from snow to rain is the most significant effect, resulting in larger floods. In the driest scenarios, in contrast, the decreased annual precipitation results in lower flood magnitudes. Because there is substantial variation among different climate models regarding future changes in precipitation, a wide range of possible changes in flood magnitude is possible.

## 3.3.3. Climate Change Impacts: Suspended Sediment

The simulated impacts of projected future climate change on suspended-sediment load generally follow the patterns of simulated changes in discharge (Figure 3.8, Table 3.5). In the future scenarios for all rivers, simulated annual and summer suspendedsediment load decreases, because of decreased discharge in the summer. The change in winter suspended-sediment load varies among the different scenarios, because winter sediment transport is dependent not only on discharge but also on snow cover and soil temperature. Sediment supply, such as from mass-wasting events, is also an important control on suspended-sediment transport, but such processes are not explicitly represented in SWAT. On the Tucannon River, the simulated future suspended-sediment load decreases under the "dry" scenario (HRM-GFDL), because the reduced precipitation leads to less runoff available to erode and transport sediment. For the "hot" scenario (CRCM-CGCM), however, the simulated future winter suspended-sediment transport increases, because the effect of increased winter temperature is more important than any changes in precipitation. Increased winter temperature can result in more sediment being exposed at the surface and available for transport, because of both decreased snow cover and greater extent of unfrozen ground. These effects are both explicitly incorporated into SWAT, which modifies the sediment transport equation to account for decreases in the erosive potential of precipitation and discharge when snow cover is present in an HRU [Neitsch et al., 2011].



**Figure 3.8**. (a) Simulated monthly baseline (1968-1998) and future (2038-2068) suspended-sediment load on the Tucannon River; (b) change in simulated suspended-sediment load for the future period (2038-2068) relative to baseline (1968-1998) on the Tucannon River; (c) simulated baseline (1968-1998) and future (2038-2068) suspended-sediment load on the South Fork Coeur d'Alene River; (d) change in simulated suspended-sediment load for the future period (2038-2068) relative to baseline (1968-1998) on the South Fork Coeur d'Alene River; (e) simulated baseline (1968-1998) and future (2038-2068) suspended-sediment load on the Red River; (f) change in suspended-sediment load for the future period (2038-2068) relative to baseline (1968-1998) and future (2038-2068) suspended-sediment load on the Red River; (f) change in suspended-sediment load for the future period (2038-2068) relative to baseline (1968-1998) and future (2038-2068) suspended-sediment load on the Red River; (f) change in suspended-sediment load for the future period (2038-2068) relative to baseline (1968-1998) and future (2038-2068) suspended-sediment load on the Red River; (f) change in suspended-sediment load for the future period (2038-2068) relative to baseline (1968-1998) on the Red River.

The impact of discharge on suspended-sediment load can be seen when the two variables are plotted against one another (Figure 3.9). As expected (owing to the dependence of sediment transport on discharge, both in nature and the model), there is a strong and nearly linear relationship between discharge and suspended-sediment load in both the baseline and future periods. It is possible that some of the association between discharge and suspended-sediment load is an artifact of the model calculating suspended-sediment transport as a function of discharge. I performed an analysis of covariance (ANCOVA) to test differences in the slope of the regression line of the discharge-sediment relationship between the future and baseline periods and found no significant difference for the Tucannon River (baseline slope = 176.7, future slope = 152.9, p>0.05) or the Red River (baseline slope = 11.5, future slope = 10.7, p>0.05), but the difference for the South Fork Cocur d'Alene River (baseline slope = 9.0, future slope = 4.4, p<0.001) was significant. A power function describes the relationship between discharge and suspended-sediment loads well in both the baseline and future periods.



**Figure 3.9.** Simulated monthly discharge and suspended-sediment load for the ensemble baseline (1968-1998) and future (2038-2068) periods for (a) the Tucannon River; (b) the Red River.

### 3.4. Discussion

### 3.4.1. Climate Change Impacts: River Discharge

The major hydrological impact of climate change simulated for the river basins in this study is a change in the annual cycle, with an increase in winter discharge resulting from more winter precipitation occurring as rain rather than snow, resulting in less snowpack accumulation and consequently in an earlier and lower-magnitude spring snowmelt peak and decreased summer discharge. This pattern of hydrological response to climate change has been projected in modeling studies of other snowmelt-dominated rivers, including the Adour-Garonne River Basin in France [Caballero et al., 2007], the Upper Clackamas River in Oregon [Graves and Chang, 2007], the Yukon River in Alaska [Hay and McCabe, 2010], the Limarí River in Chile [Vicuña et al., 2011], and the Mono Lake Basin in California [Ficklin et al., 2013]. Here, the Tucannon River Basin, the lowest-elevation of the three study basins, is characterized by a transient hydrological regime that, according to modeling results, is likely to shift to a rainfall-dominated regime under projected climate change. Other modeling studies have also found greater sensitivity to climate-change impacts in transient than in snowmelt- or rainfall-dominated river systems [Pfister et al., 2004; Hamlet and Lettermaier, 2007]. There is, however, variability in the response that arises from the different ways that hydrologic models parameterize snowpack accumulation and melt, as well as uncertainty in parameter values. Jung et al. [2012] simulated impacts of climate change on a rainfall-dominated and a snowmelt-dominated river basin in Oregon using the Precipitation Runoff Modeling System (PRMS) and found that discharge simulations in the snowmeltdominated basin were more sensitive to hydrologic model parameter uncertainty than

were simulations of discharge in the rainfall-dominated basin. Because of the importance of transient and snowmelt-dominated river systems for supplying year-round water to semi-arid and arid regions such as the western United States, and the likely sensitivity of such river systems to climate change, improving snowpack parameterizations should be a high priority for future development of hydrologic models.

The projected increased amplitude in the annual cycle resulting from climate change has major implications for river management. Climate change represents a significant challenge to traditional water management, which bases planning and infrastructure design decisions on the assumption of a stationary climate [Milly et al., 2008; Stakhiv, 2011]. In addition, the interactions of climate change with land-use change and other human impacts can amplify or mediate hydrologic impacts in complex ways [Praskievicz and Chang, 2011; Nolin, 2012]. Here, modeling results suggest that climate change will contribute to both an increase in large floods and a decrease in summer discharge. This increased seasonality in an already highly seasonal hydrological regime may lead to challenges in managing water for both human and ecological uses.

3.4.2. Climate Change Impacts: Suspended Sediment

The simulation results for the study rivers project changes in suspended-sediment load that generally track changes in discharge under climate change, with increased winter and decreased summer suspended-sediment load. However, the simulated changes in suspended-sediment transport vary widely among the different driving climate change scenarios. This sensitivity of suspended-sediment transport to choice of climate change scenario, particularly to differences in precipitation among different climate models, has

also been found in other modeling studies of basin-scale sediment transport, including in Denmark [Thodsen et al., 2008], New Zealand [Gomez et al., 2009], and Laos [Shrestha et al., 2013]. Because detachment of soil and erosion in mountainous basins is affected not only by the amount of runoff, but also by the length of time that sediment is available to be transported from snow-free and unfrozen ground, sediment transport in these basins may be especially sensitive to climate change.

As with climate-driven changes in river discharge, changes in suspendedsediment load can have implications for management of river systems. In excessive amounts, suspended sediment can be considered a water pollutant, with negative consequences (e.g., increased turbidity) that leads to increasing costs of drinking water treatment; binding of nutrients, metals, and other pollutants to the sediment particles; and infilling of spawning gravels and smothering of eggs of vulnerable fish species such as salmonids. Climate change can potentially lead to an increase in flood events that flush large quantities of suspended sediment into river systems, especially in combination with deforestation and other direct human impacts, which have been found to be more significant than climate in determining sediment fluxes [Ward et al., 2009; Naik and Jay, 2011; Gao et al., 2013; Lopez et al., 2013; Ma et al., 2013]. Although these processes are not directly simulated by SWAT, rivers dynamically adjust their channels and floodplains to inputs of water and sediment, so changes in these driving variables may also affect geomorphic characteristics such as channel geometry and planform.

Here, I have examined the influence of climate change alone on suspendedsediment transport, in order to isolate the climate-change signal, but in fact many additional factors affect sediment fluxes. Some of the other anthropogenic controls on suspended-sediment transport include dam and reservoir construction, land-use change, mining, and agricultural activities [Walling and Fang, 2003]. Because suspendedsediment transport is a function of climatic, geomorphic, and ecological processes, climate change could result in feedback responses that affect suspended-sediment transport in complex ways. For example, climate change is expected to increase the frequency and severity of mass-wasting events, because of more intense precipitation and rain-on-snow events in mountainous watersheds [Crozier, 2010]. In fluvial systems, such mass-wasting events could include undercutting and failure of river banks during extreme floods. This increased occurrence of mass wasting could result in additional sediment supply and increased sediment transport. Another example of a synergistic response is that of wildfire. Drier conditions associated with climate change are likely to increase the frequency and severity of wildfires, which can result in increased sediment yield from burned areas [DiBiase and Lamb, 2013]. Further research is needed to illuminate how climate change may affect disturbance frequency and severity, sediment supply, and sediment transport.

## 3.5. Conclusion

Here, I have used the SWAT basin-scale hydrologic model, driven by downscaled climate projections, to simulate impacts of future climate change on streamflow and suspended-sediment load for three snowmelt-dominated rivers in the interior Pacific Northwest. The overall projected impacts include changes in the annual cycle of river discharge, an increase in the magnitude of the largest floods, and variable changes in suspended-sediment load resulting from differences both in energy available for transport and sediment availability in the winter and spring. These hydrological changes could

have significant impacts on processes governing hazards, water supply, water quality, fluvial geomorphology, and species habitat, all of which are relevant to managing rivers for societal and ecological values.

In Chapter III, I used the SWAT hydrologic model to simulate impacts of projected climate change on both basin-scale discharge and suspended-sediment load for all three of my study rivers. This chapter corresponds to the hydrologic system level of my modeling hierarchy. These projections of climate-driven hydrological changes are needed as input to the geomorphic models that I will apply next. In Chapter IV, I will use the hydrological change scenarios from Chapter III, along with field-derived topographic and sediment grain-size distribution data, to simulate changes in stream power and shear using HEC-RAS, changes in reach-averaged bedload transport using BAGS, and changes in the spatial patterns of erosion and deposition – which may affect channel geometry and planform – using CAESAR.

## CHAPTER IV

# A HIERARCHICAL MODELING APPROACH TO SIMULATING THE GEOMORPHIC RESPONSE OF RIVER SYSTEMS TO CLIMATE CHANGE

## 4.1.Introduction

Anthropogenic climate change is expected to affect the hydrology of river systems [Matalas, 1997; Kundzewicz et al., 2007]. Snowmelt-dominated rivers are likely to be especially sensitive to climate change impacts, with increased seasonality of discharge resulting from higher winter temperatures, including increased winter discharge, a decrease in the spring snowmelt peak and its shift to earlier in the season, and decreased summer discharge [Christensen et al., 2004; Vanrheenen et al., 2004; Graham et al., 2007; Elsner et al., 2010; Lespinas et al., 2010; Vicuña et al., 2011; Ficklin et al., 2013; Praskievicz, 2014]. Research on the impacts of climate change on water resources has generally followed a progression, from examining historical data for hydrological trends, to modeling potential future impacts of climate on hydrology, to investigating how these projected hydrological changes may affect other aspects of river systems, such as ecosystems, economics, and water resource management [Vicuña and Dracup, 2007]. Sediment-transport dynamics and river morphology are important components of river systems, because of their impacts on water quality, hazards, species habitat, and aesthetics. The role of past climatic forcings on modern landscapes has been investigated for various regions and time periods [Tebbens et al., 1998; Carignano, 1999; Blum and Törnqvist, 2000; Grove, 2001; Lewis et al., 2001; Maas and Macklin, 2002; Candy et al., 2004; Wallinga et al., 2004; Thomas et al., 2007; Persico and Meyer, 2009;

van Balen et al., 2010; Olszak, 2011; Layzell et al., 2012; Hall and Peterson, 2013]. Landscape evolution models have been widely used to quantify the role of climatic and other forcings on landform development over geological timescales [Istanbulluoglu, 2009; Tucker and Hancock, 2010]. There is little existing research, however, on how future climate change is likely to affect sediment transport and river morphology at the reach scale, because of the difficulty in bridging the scales between global climate change and highly local geomorphic processes, as well in detecting a signal from relatively nearterm climate change on slow-responding geomorphic variables. Moreover, the geomorphic response of rivers to climatic forcings may be mediated or amplified by characteristics of the river system, such as geology and land use [Phillips, 2010; Li et al., 2011]. This lack of research on the geomorphic implications of well-studied hydrological changes is a major gap in understanding how climate change will affect river systems.

Because rivers adjust their morphology to their discharge and sediment regime, changes in hydrology or sediment transport associated with climate change may be expected to cause geomorphic change. A much-debated but widely-recognized theory in fluvial geomorphology is that rivers develop channels that are of a sufficient size to convey the water and sediment that the river transports at bankfull stage, with discharge typically equivalent to the one- to two-year recurrence-interval flood [Wolman and Miller, 1960]. Any change in this typical discharge or sediment load will cause disequilibrium in the system, and the river will adjust to the new regime through aggradation or degradation [Lane, 1955; Schumm, 1969]. This process of adjustment is likely to be nonlinear, however, because sediment fluxes and morphological adjustment are highly sensitive to thresholds of critical discharge [Meyer-Peter and Müller, 1948].

While the qualitative patterns of river response to change have been explored [Dust and Wohl, 2012], a number of geomorphic variables can also be quantified to provide a more robust assessment of the response of river systems to changes in discharge or sediment regime. The three main categories of quantitative assessment that will be discussed here are shear stress as described by energy-conservation hydraulic models, bedload transport formulas, and cellular-automata models. Taken together, these approaches can help determine how hydrological changes affect the amount of energy available to erode and transport sediment, the amount of sediment that is transported as bedload given the available supply, and the spatial distribution of erosion and deposition within a river reach and consequent changes in channel geometry and planform.

Energy-based approaches such as stream power and boundary shear stress are useful for determining whether a hydrological change will result in more or less energy being available for sediment transport. Stream power is a basic measure of a river's capacity to do geomorphic work and is calculated as [Bagnold, 1966]:

(1) 
$$\omega = \rho g Q S$$

where  $\omega$  is stream power (W/m<sup>2</sup>),  $\rho$  is the density of water (g/m<sup>3</sup>), g is acceleration due to gravity (N), Q is discharge (m<sup>3</sup>/s), and S is slope (m/m). Since slope is a relatively slowly-changing response variable, it can be assumed to remain fairly constant over the decadal timescales of interest here, so changes in stream power associated with anthropogenic climate change are likely to linearly scale with discharge.

The boundary shear stress, or the force the river applies to bed sediments, can be calculated as [Leopold et al., 1964]:

(2) 
$$\tau_0 = \rho g h S$$

where  $\tau_0$  is the average boundary shear stress, *h* is average depth, and *S* is the watersurface slope. Differing levels of discharge interact differently with bedforms and could greatly affect water-surface slope. River discharge also determines the depth, but the relationship is nonlinear and depends on the local rating curve for a particular river. Boundary shear stress can therefore be expected to increase with increased discharge, but the rate of increase will depend on local channel geometry.

Approaches based on shear stress and stream power are useful for determining whether a given change in discharge affects the river's capacity to do geomorphic work. In order to determine how much geomorphic work is actually accomplished, however, these energy calculations must be combined with data on characteristics of the sediment supply. A large variety of sediment transport formulas have been developed, mainly based on empirical observations from field and flume experiments [e.g., Meyer-Peter and Müller, 1948; Parker, 1990; Wilcock and Crowe, 2003]. Two that will be discussed here were developed for bedload transport in gravel-bed streams and are based on surface sediment grain-size distributions, rather than grain-size distributions for the substrate beneath the armor layer, as implemented in the United States Forest Service Stream Systems Technology Center's Bedload Assessment in Gravel-bedded Streams (BAGS) software.

The first sediment transport formula is that of Parker [1990]:

(3) 
$$W_i^* = \{11.9(1-0.853/\phi)^{4.5}\}$$
  
 $\{0.00218 \exp[14.2(\phi-1)-9.28(\phi-1)^2]\}$   
 $\{0.00218\phi^{14.2}\}$   
 $\phi_{50} < 1.0$ 

where  $W_i^*$  is a dimensionless transport parameter for grain size *i* and  $\varphi$  is a parameter calculated from an nested set of equations, namely a hiding function that accounts for size-dependent differences in the mobility of grains, a sorting function that accounts for changes in the mean grain size with increased shear stress and transport, and a function that calculates the transport stage in terms of the Shields stress (for details, see Parker [1990]). Like other sediment-transport formulas, this formula relates the shear stress generated by a given discharge to the critical stress needed to mobilize sediment grains of a given size. The dimensionless transport parameter  $W_i^*$  is a ratio that determines the proportion of each grain size class that is mobilized, based on the relation of available stress to critical stress, and therefore determines the overall transport rate by summing across the size classes.

The second surface-based gravel-bed sediment transport formula discussed here is that of Wilcock and Crowe [2003]:

(4) 
$$W_i^* = \{0.002\varphi^{7.5}\}$$
  $\varphi < 1.35$ 

$$\{14(1-0.894/\varphi^{0.5})^{4.5}\}$$
  $\varphi \ge 1.35$ 

Similar to the Parker [1990] formula, the Wilcock and Crowe [2003] formula includes functions for hiding effects and the Shields stress, but it also includes a function that accounts for the effect of sand on gravel transport.

These sediment-transport formulas calculate the amount of sediment that is transported as bedload through a river reach, given the discharge regime, channel geometry, slope, and surface sediment grain-size distribution. In order to find out whether changes in discharge and sediment regime may cause changes in river morphology, patterns of erosion and deposition within the reach must be spatially explicit. There are a number of modeling approaches to accomplish this, but the focus here is on the Cellular Automaton Evolutionary Slope and River (CAESAR) model. CAESAR uses inputs of river discharge and a surface grain-size distribution to erode and transport sediment using the Wilcock and Crowe [2003] formula on a cell-by-cell basis for a digital elevation model (DEM) of the river reach [Coulthard et al., 2002]. Through this spatially explicit geomorphic modeling, changes in discharge and sediment regime can be related to potential patterns of change in channel geometry, such as widening, narrowing, deepening, or filling; and to changes in river planform, such as sinuosity, meander amplitude, or avulsions.

Here, I develop and apply a hierarchical modeling approach to investigate potential climate change impacts on the geomorphology of three snowmelt-dominated rivers in the interior Pacific Northwest. First, I created downscaled climate change scenarios for my study rivers using an approach based on local topographic lapse rates [Praskievicz and Bartlein, 2014]. Then, I used a basin-scale hydrologic model, driven by the downscaled climate-change scenarios, to simulate changes in river discharge and suspended-sediment loads [Praskievicz, 2014a]. These simulated changes in discharge and suspended-sediment transport are used in a hierarchy of three reach-scale

geomorphic models to investigate their impacts on the capacity to do geomorphic work, the rate of bedload transport, and channel morphology.

4.2. Methods

#### 4.2.1. Study Area

I selected three study rivers to develop and apply the hierarchical modeling framework: the Tucannon River in southeastern Washington and the South Fork Coeur d'Alene and Red rivers in Idaho (Figure 3.1). All three are snowmelt-dominated rivers located in the mountains of the interior Pacific Northwest. I chose these rivers because they all have gaging station records of discharge and suspended-sediment load, and all three are undammed and gravel-bedded alluvial rivers with active bars, which means they have the potential to respond geomorphically to climate-driven changes in the hydrological regime on decadal timescales.

On each river, I selected one study reach (length 300-500 m) located in the immediate vicinity of the gaging station, because proximity to the gaging station ensures that inputs of water and sediment to the reach are consistent between the hydrologic and geomorphic models, and also because such a reach is likely to be fairly representative of the river system. The Tucannon River reach, located just above the river's mouth on the Snake River, is multiple-threaded, with numerous gravel bars and secondary channels. The single-thread South Fork Coeur d'Alene reach, located higher up in its watershed, is the highest-energy of the three reaches, with the steepest slope and coarsest substrate. Finally, the Red River reach is a single-threaded meandering channel with fine-grained

cohesive banks, located on a broad floodplain in a mountain meadow. Images and characteristics of the study reaches can be seen in Figure 4.1 and Table 4.1.



**Figure 4.1.** Photos of (a) Tucannon River reach; (b) South Fork Coeur d'Alene River reach; (c) Red River reach; aerial images of (d) Tucannon River reach; (e) South Fork Coeur d'Alene River reach; (f) Red River reach. Photo credits for d-f: <a href="http://www.arcgis.com/features/">http://www.arcgis.com/features/</a>

River	Reach- average bankfull width (m)	Reach- average bankfull depth (m)	Reach- average width-depth ratio	Reach slope	Reach sinuosity	D50 (mm)	D90 (mm)
Tucannon	21.53	0.60	52.02	0.0085	1.40	20.23	40.02
South Fork Coeur							
d'Alene	19.57	0.61	38.99	0.0132	1.31	30.83	58.95
Red	15.20	0.83	19.18	0.0065	1.69	24.63	40.78

Table 4.1. Characteristics of the study reaches.

## 4.2.2. Field Data Collection

I conducted fieldwork on all three river reaches to obtain basic topographic and sediment data for use in geomorphic modeling. I used a Topcon Real-Time Kinematic Global Positioning System (RTK-GPS) to survey elevations on a series of river crosssections and banktops, with a maximum point spacing of 2 m both along and between the cross-sections. On the Tucannon and South Fork Coeur d'Alene rivers, the survey was restricted to the bankfull width. On the Red River, which has a more extensive floodplain, the cross-sections were expanded to approximately 100 m out from each bank. Surveying the outer floodplain was not feasible for the Tucannon and South Fork Coeur d'Alene rivers, because of dense vegetation that impeded GPS signals in the former and a steep bedrock outcrop along the right bank of the latter. I later used the survey points to create triangular irregular networks (TINs) of each reach, which I then manually edited for quality control and converted to 2-meter digital elevation models (DEMs) using natural-neighbor interpolation (Figure 4.2). In the field, I also did a Wolman [1954] pebble count, measuring the b-axis diameter of at least 300 bed and bar grain samples from each reach using a gravelometer. I used these samples to generate a sediment grain-size distribution for each reach (Figure 4.2).



**Figure 4.2.** Tucannon River (a) DEM; (b) count-based sediment grain-size distribution; South Fork Coeur d'Alene River (c) DEM; (d) count-based sediment grain-size distribution; Red River (e) DEM; (f) count-based sediment grain-size distribution.

## 4.2.3. Climate and Hydrological Change Scenarios

The experimental design for this project uses a hierarchical series of linked models across a broad range of spatial scales to simulate impacts of climate change on basin hydrology and reach-scale river morphology. At the broadest scale, the project is driven by downscaled climate-model output for a 30-year baseline period and a 30-year future climate change period. I used a watershed hydrology model to simulate river discharge and suspended-sediment transport at the basin scale for the two climate periods. I then used three reach-scale geomorphic models to simulate bedload transport and river morphology using discharge and suspended-sediment load simulated by the hydrologic model for the two climate periods. Each geomorphic model was run for baseline conditions and then again for future conditions, with the difference in output illustrating the impact of climate change on sediment transport and channel geometry.

To simulate the potential geomorphic response of the study rivers to climate change, I needed to develop climate change scenarios with high spatial and temporal resolution for the study area and to use these scenarios to generate hydrological timeseries for the study reaches. For the baseline period of 1968-1998 and the future period of 2038-2068 under the Intergovermental Panel on Climate Change (IPCC) A2 emission scenario, I used output from ten realizations of regional-climate-model (RCM) output from the North American Regional Climate Change Assessment Program (NARCCAP) [Mearns et al., 2007], elevationally adjusted using local topographic lapse rates, to generate high-resolution (800-m) daily climate change scenarios for the northwestern United States. Details on the climate-change-scenario downscaling procedure can be found in Praskievicz and Bartlein [2014]. I also used the statistics of the ten downscaled baseline and future datasets to create an ensemble-average daily timeseries using a stochastic weather generator, which was necessary because daily outputs from different climate models cannot be averaged without smoothing out variability. I then used three of these climate change scenarios (the "cool" scenario with the least average annual temperature increase, ECP2-GFDL; the "hot" scenario with the

greatest average annual temperature increase, CRCM-CGCM for the Tucannon River and CRCM-CCSM for the other two rivers; and the "dry" scenario with the greatest decrease in annual precipitation, HRM-GFDL), plus the ensemble average, to simulate basin-scale discharge and suspended-sediment load in the baseline and future climate change periods for the three rivers with a watershed hydrology model [Praskievicz, 2014]. The result was eight 30-year daily timeseries of discharge and suspended-sediment load for each river, four each for the baseline and future periods, consisting of output from three individual climate-model simulations and from the weather-generator-produced ensemble average.

Although the original climatic and hydrologic change scenarios were for the entire 30-year NARCCAP future period, for geomorphic modeling I sampled a subset of 5 years of simulated daily discharge and suspended-sediment load from both the baseline and future periods for each of the three NARCCAP model-output sets and the ensembleaverage simulations for each river. The samplers were designed so that the peak flow of each truncated 5-year timeseries was the 10-year flood. This was done in order to reduce the runtime of the geomorphic modeling, especially when running the computationally intensive CAESAR model. The original 30-year timeseries were fit to a Weibull distribution so that flood recurrence intervals could be calculated. Climate-change impacts on river morphology were assessed by comparing pairs (baseline versus future) of geomorphic-model simulations.

Figure 4.3 shows the characteristics of the climate and hydrologic change scenarios used in this study. The climate change scenarios included increases in both maximum and minimum temperature, with average annual temperature increases ranging from 1.5°C in the coolest scenario to 4.1°C in the warmest, and seasonally variable

changes in precipitation, with annual precipitation decreasing from 18.1% to 19.0% across the scenarios. The hydrologic changes, averaged over the entire 30-year timeseries, are characterized by an amplified annual cycle of discharge, with increases in winter discharge for the ensemble scenario ranging from 4.1% to 34.4% for the three rivers, and decreases in summer discharge ranging from 5.2% to 47.2%.



**Figure 4.3.** Changes in total precipitation over five-year simulation period for three NARCCAP GCM-RCM future climate change scenarios relative to baseline (snow estimated as precipitation occurring on days when temperature is below freezing; ensemble average not shown because it is based on monthly values) for (a) Tucannon River Basin; (b) South Fork Coeur d'Alene River Basin; (c) Red River Basin; changes in SWAT-simulated discharge of varying recurrence intervals over-five-year simulation period for three NARCCAP GCM-RCM climate change scenarios and ensemble average relative to baseline for (d) Tucannon River; (e) South Fork Coeur d'Alene River; (f) Red River.

For the Tucannon River, the five-year subset timeseries used for geomorphic modeling include generally increased discharge for small to moderate floods (recurrence interval of 2-20 years, ensemble baseline magnitude of 0.5  $m^3/s$  to 10.1  $m^3/s$ , ensemble future magnitude of 0.8  $\text{m}^3$ /s to 12.1  $\text{m}^3$ /s) and consistent decreases for larger floods (50-100 year, ensemble baseline magnitude of  $14.2 \text{ m}^3/\text{s}$  to  $26.1 \text{ m}^3/\text{s}$ , ensemble future magnitude of 16.2  $\text{m}^3$ /s to 23.9  $\text{m}^3$ /s) across the climate change scenarios. For the South Fork Coeur d'Alene River, nearly all climate change scenarios produce decreased flows of all recurrence intervals (ensemble baseline magnitude ranging from 4.9  $m^3/s$  to 37.7  $m^3/s$ , future ensemble magnitude ranging from 5.7  $m^3/s$  to 35.9  $m^3/s$ ). For the Red River, the ensemble-average and "hot" CRCM-CCSM scenarios produce increased discharge for all recurrence intervals (ensemble baseline magnitude ranging from  $0.7 \text{ m}^3$ /s to 9.6  $m^3/s$ , ensemble future magnitude ranging from 0.8  $m^3/s$  to 10.6  $m^3/s$ ), while the "cool" ECP2-GFDL and "dry" HRM-GFDL scenarios produce decreased discharge for all recurrence intervals. The ensemble-average results are not necessarily intermediary among the other three scenarios, because the ensemble was created from a total of ten climate models. The three rivers respond differently to the same climate change scenarios. The most consistent change is a decrease in floods of most recurrence intervals for the "dry" HRM-GFDL scenario on all three rivers.

## 4.2.4. Geomorphic Modeling

My general approach to simulating the geomorphic response of the study rivers to the climate-driven hydrological changes was to apply a hierarchy of geomorphic models (Figure 4.4). First, I simulated changes in reach-averaged stream power and shear resulting from changes in discharge, using the United States Army Corps of Engineers Hydrologic Engineering Center River Analysis System (HEC-RAS). Second, changes in the force applied to the bed by discharge, in combination with the known sediment grainsize distribution of the bed, would cause changes in reach-averaged bedload transport, which I estimated using the Parker [1990] and Wilcock and Crowe [2003] sediment transport formulas from BAGS. Finally, I used the CAESAR model to explore potential spatial patterns of erosion and deposition that could lead to changes in channel geometry and planform. Because observed data on bedload transport were unavailable for my study rivers, I also compared the bedload transport rates simulated by BAGS and CAESAR in order to independently test the models.



**Figure 4.4.** Conceptual diagram of hierarchical geomorphic modeling process.

## 4.2.4.1. HEC-RAS Stream Power and Shear

HEC-RAS is a one-dimensional hydraulic model that simulates a river reach as a series of cross-sections [USACE, 2010]. I imported my field-measured cross-sections into HEC-RAS and used the steady flow analysis to input flows of varying recurrence intervals (2-year, 10-year, 20-year, 50-year, and 100-year), derived from a Weibull

distribution fit to the SWAT-simulated baseline and future ensemble-average timeseries on each river. Because changes in stream power and shear are directly dependent on changes in discharge, I did the HEC-RAS analysis for the ensemble-average timeseries only. The steady flow analysis yields estimates of stream power and shear for each crosssection under each flow level. I averaged the cross-sectional estimates for each reach and examined changes in these energy variables in the future relative to baseline climate periods.

## 4.2.4.2. BAGS Bedload Transport

BAGS is a program that automates the calculation of several bedload transport formulas for gravel-bedded streams using data on reach bankfull width, slope, sediment grain-size distribution, and a discharge record [Pitlick et al., 2009]. The two formulas I used are the Parker [1990] and Wilcock and Crowe [2003] formulas, because they are based on surface-sediment grain-size distributions, which is what I measured in the field. I calculated the average bankfull width and slope from my survey points and input the field-measured sediment grain-size distributions and the SWAT-simulated 5-year daily discharge records (sampled from the longer 30-year timeseries) for the baseline and future periods for the three climate models and the ensemble average. I then compared the resulting reach-averaged bedload transport calculated for the baseline and future periods using the Parker [1990] and Wilcock and Crowe [2003] formulas.

## 4.2.4.3. CAESAR Erosion and Deposition

CAESAR is a cellular-automaton landscape-evolution model that routes discharge and sediment of different size classes through a high-resolution DEM of a study reach

and calculates sediment transport among cells [Coulthard et al., 2002; Van De Wiel et al., 2007]. I used as input to CAESAR the DEMs and sediment grain-size distributions created from field measurements and the SWAT-simulated 5-year daily ensemble baseline and future discharge and suspended sediment data. In order to speed up model computations, I subset the timeseries by removing days with flows at the 10% flow exceedance level or below, assuming that little geomorphic work would be accomplished at these low flows [Nash, 1994]. I modified the timeseries further for use in CAESAR by matching the recurrence interval of highest flows in each year in the baseline and future time periods. That is, if the highest flow in the baseline period occurred in the first year and had a recurrence interval of 10 years, I would input the 10-year flood of the future period in the first year of the future period. This modification ensured that the 5-year periods sampled were representative of the complete 30-year timeseries and that the baseline and future periods were comparable to one another in terms of the relative magnitude and timing of peak events. After modification, the highest flow of the baseline and future timeseries for all three rivers had a recurrence interval of 10 years, and it occurred in the second year of the timeseries.

Finally, because observed bedload transport data were unavailable, I initialized the model by first running it through the entire timeseries using only the discharge and suspended-sediment fraction simulated by SWAT. I then took the resulting bedload transport in each grain-size class for each timestep and used it as input for the next run of CAESAR. This step was to ensure that the bedload transport simulated by CAESAR was consistent with both the discharge and existing sediment grain-size distribution. I analyzed changes in reach-averaged sediment transport for the future relative to baseline

period from this final pair of model runs and compared it to the transport simulated by BAGS. I also created DEMs of difference (DODs) by subtracting the end-of-run DEM from the baseline period from that of the future period, in order to examine the spatial patterns of simulated erosion and deposition within the reach and therefore to qualitatively assess whether the climate-driven hydrological changes would be likely to lead to changes in channel geometry and planform.

#### 4.3. Results

## 4.3.1. HEC-RAS Stream Power and Shear

Reach-averaged stream power and shear simulated by HEC-RAS for the future ensemble-average climate relative to the baseline climate are directly proportional to differences in discharge. This result is expected for these energy variables, because they are scaled with discharge in the case of stream power and depth in the case of shear. I calculated changes only for the ensemble-average baseline and future climates (Table 4.2). On the Tucannon River, stream power and shear increase for small and medium floods in the future scenario, with maximum increases in shear of 75.2% for the 2-year recurrence interval flood and an increase in stream power of 79.2% for the 10-year flood. For the 100-year flood, there is a decrease of 8.5% in shear and 12.9% in stream power. On the South Fork Coeur d'Alene River, simulated stream power and shear increase for only the smaller floods, with an increase in shear of 11.3% and in stream power of 18.5% for the 2-year flood. For larger floods, the stream power and shear decrease, for example by 7.3% for shear and 11.0% for stream power for the 50-year flood. Finally, on the Red River, there is an increase in simulated stream power and shear for floods of all recurrence intervals in the future ensemble period, with the largest increases (3.1% for shear and 3.6% for stream power) occurring during the 20-year flood. The overall pattern for the three rivers is an increase in the capacity to do geomorphic work in the ensemble future scenario, except for the larger floods on the Tucannon and South Fork Coeur d'Alene rivers, which decrease in magnitude under the ensemble future scenario because of reduced precipitation and snowmelt and therefore lower stream power and shear. The smaller floods on all three rivers increase because of higher temperatures causing more winter precipitation to occur as rain rather than snow, therefore immediately generating runoff rather than being stored in the snowpack.

	Flow recurrence	Change in shear	Change in stream
River	interval (years)	stress (%)	power (%)
Tucannon	2	75.2	76.0
rucumon	10	73.9	79.2
	20	21.9	35.2
	50	15.6	25.0
	100	-8.5	-12.9
South Fork Coeur	2	11.3	18.5
d'Alene	10	1.4	1.9
	20	-3.6	-5.4
	50	-7.3	-11.0
	100	-6.7	-4.6
Red	2	3.0	3.4
1100	10	1.2	0.8
	20	3.1	3.6
	50	1.1	1.2
	100	1.4	1.7

**Table 4.2.** Changes in simulated shear stress and stream power.

The climate changes explain the differences among rivers (Figure 4.3). The Tucannon, the river with the greatest increases in discharge and consequently in stream

power and shear for small-to-moderate recurrence intervals, experiences the smallest decrease in average annual precipitation (-2.8%), accompanied by a decrease in the proportion of precipitation that falls as snow rather than rain (-34.1%). This translates to large increases in the discharge of 2- and 10-year events, modest increases for 20- and 50-year events, and small decreases for 100-year events. The South Fork Coeur d'Alene River, which experiences the greatest decreases in discharge, has the greatest decrease in average annual precipitation (-6.9%), as well as the greatest decrease in the snow-to-rain ratio (-40.2%). This translates to small increases in the discharge of 2- and 10-year events, and small decreases in the discharge of larger events. On the Red River, which experiences moderate increases in discharge, there is a large precipitation decrease (-6.5%), but a smaller decrease in the snow-to-rain ratio (-4.9%). The simulated changes in discharge appear to follow an elevational gradient, in which the lower-elevation Tucannon River experiences modest increases in discharge, because there is less precipitation than for the other two basins (for both the baseline and future conditions) but more of it arrives as rain; the higher-elevation South Fork Coeur d'Alene experiences decreased discharge, because there is a more substantial reduction of precipitation (between baseline and future conditions); while the highest-elevation Red River experiences the least amount of change, because the current snowpack hydrology is mostly maintained. In general, discharge increases more for the Tucannon than for the other two rivers, because although precipitation decreases for all three rivers, winter precipitation actually increases, which on the lower-elevation Tucannon River means more winter rainfall.

## 4.3.2. BAGS Bedload Transport

Sediment-transport formulas estimate fluxes of sediment by comparing the shear stress generated by discharge to the critical shear stress needed for transport of grains of a given size. A similar value to the critical shear stress is the reference shear stress, the amount of shear stress needed to achieve a small but measurable amount of sediment transport; in BAGS, this is defined as a dimensionless transport parameter of 0.002 [Wilcock et al., 2009]. BAGS uses this reference shear stress, which is slightly larger than the critical shear stress, because in practice it is difficult to determine whether or not transport is actually occurring, since bedload movement is a stochastic process. The critical discharge needed to attain this reference shear stress can be compared to a discharge timeseries in order to determine how often significant bedload transport occurs on a particular river. In other words, the number of days on which discharge exceeds the critical threshold can be considered the duration of bedload mobilization. Figure 4.5a-c shows the changes in the number of days the critical discharge needed to mobilize the D50 and D90 grains is met or exceeded, as simulated by the Parker [1990] sediment transport formula in BAGS, for the future climate change scenarios and the ensemble average, relative to baseline.



**Figure 4.5.** Changes in the duration of simulated  $D_{50}$  and  $D_{90}$  critical discharge for three NARCCAP future climate change scenarios and ensemble average relative to baseline, for (a) Tucannon River; (b) South Fork Coeur d'Alene River; (c) Red River; relative changes in bedload transport simulated by the Parker [1990] and Wilcock and Crowe [2003] formulas for three NARCCAP future climate change scenarios and ensemble average relative to baseline, for (d) Tucannon River; (e) South Fork Coeur d'Alene River; (f) Red River.

On the Tucannon River, in the ensemble baseline scenario, the critical discharge needed to mobilize the D50 grains ( $1.6 \text{ m}^3/\text{s}$ ), as calculated from the Parker [1990] sediment transport formula, has a recurrence interval of 3.3 years and the D90 critical discharge ( $1.9 \text{ m}^3/\text{s}$ ) has a recurrence interval of 4.0 years (Figure 4.5a). These recurrence intervals are comparable to thresholds of bedload transport initiation on other gravel-bed rivers [Emmett and Wolman 2001]. In the ensemble future scenario, the recurrence

interval of this critical discharge decreases to 2.5 years for D50 and 2.9 years for D90. In other words, in the ensemble future scenario, the bed sediments of the Tucannon River are expected to be mobilized more often than in the baseline scenario. Bed mobilization is also expected to increase in the "hot" CRCM-CGCM future scenario. In the "cool" ECP2-GFDL future scenario, simulated bed mobility decreases, because of the projected decrease in larger floods on the Tucannon River (Figure 4.3). In the "dry" HRM-GFDL scenario, simulated bed mobility also decreases because of decreased discharge for most recurrence intervals.

On the South Fork Coeur d'Alene River, the critical discharge needed to mobilize the D50 grains  $(1.9 \text{ m}^3/\text{s})$  has a recurrence interval of 1.1 years and the D90 critical discharge (2.8 m<sup>3</sup>/s) has a recurrence interval of 1.3 years. The duration of these critical flows is projected to decrease under all future climate change scenarios, so the bed mobility of the South Fork Coeur d'Alene River is expected to decrease (Figure 4.5b). This result can be explained by the projected discharge decrease for most recurrence intervals in all the climate change scenarios (Figure 4.3).

On the Red River, in the ensemble baseline scenario, the critical discharge for D50 grains  $(1.9 \text{ m}^3/\text{s})$  has a recurrence interval of 5.0 years and the critical discharge for D90 grains  $(2.6 \text{ m}^3/\text{s})$  has a recurrence interval of 6.7 years. In the future ensemble scenario, the duration of critical discharge is projected to decrease for D50 and increase for D90 grains (Figure 4.5c). The discharge magnitude-frequency curves for this scenario indicates increased discharge for most recurrence intervals (Figure 4.3). In contrast, the remaining scenarios show decreases in D50 and D90 critical discharge duration, with

decreased bed mobility. This result is also consistent with the projected hydrological changes, with these scenarios including decreases in effective discharge.

After the changes in critical flows needed to mobilize bed sediment are calculated, the sediment transport formulas in BAGS can be used to estimate changes in reach-averaged total bedload transport resulting from climate change. Figure 4.5d-f shows the simulated future changes in total transport relative to baseline for the three climate change scenarios and ensemble average, calculated using the Parker [1990] and Wilcock and Crowe [2003] sediment transport formulas in BAGS. For the Tucannon River, sediment transport increases for the ensemble average and "hot" CRCM-CGCM scenario. This change is consistent with the climate change scenarios, in which total precipitation over the study period decreases most substantially for the HRM-GFDL scenario, but temperatures increase most for the CRCM-CGCM scenario, which provides more winter precipitation as rainfall. Similarly, on the South Fork Coeur d'Alene and Red rivers, all scenarios produce decreased sediment transport because precipitation decreases in the future period for all scenarios. The simulated changes in sediment transport are also consistent with the results of the critical discharge analysis (Figure 4.5a-c). On the Tucannon River, simulated bedload transport increases for the ensemble average and "hot" CRCM-CGCM scenarios, the scenarios in which the duration of critical discharge increases, but decreases for the remaining scenarios in which critical discharge duration decreases. Similarly, on the South Fork Coeur d'Alene River, simulated future bedload transport decreases under all scenarios, consistent with decreased duration of critical discharge and decreased bed mobility for all scenarios. This consistency indicates that, as expected, changes in the duration of the critical discharge
needed to mobilize bed sediments are the primary drivers of changes in reach-averaged sediment transport.

# 4.3.3. CAESAR Erosion and Deposition

I simulated the spatial patterns of erosion and deposition using CAESAR. First, since no bedload transport data were available for model calibration and validation, I compared the average bedload transport for each grain-size class simulated by CAESAR to that simulated by BAGS for the 5-year baseline ensemble average using the Wilcock and Crowe [2003] formula (Figure 4.6). Because sediment transport formulas are highly sensitive to slope, I used slope values derived from the DEM in CAESAR modeling to calculate the bedload transport in BAGS, so that the bedload transport would be consistent between the two models. Because CAESAR's sediment transport data are output as volumes and BAGS as load (mass per time), I converted the volumetric transport from CAESAR to mass using an estimated sediment bulk density of 2.1 metric tons per cubic meter [Wallick et al., 2012]. Given the uncertainty introduced by these parameters and the differences in how the two models represent channel geometry (BAGS with average reach width and slope, CAESAR with a DEM), the agreement between the different bedload rating curves is acceptable.



**Figure 4.6.** Observed sediment grain-size distribution and simulated average bedload transport by grain-size class from CAESAR and BAGS, using the Wilcock and Crowe [2003] sediment transport formula, for the 5-year baseline ensemble average, for the (a) Tucannon River; (b) South Fork Coeur d'Alene River; (c) Red River.

The spatial patterns of erosion and deposition after a five-year run of the ensemble-average baseline and future scenarios can be seen in Figure 4.7. The overall pattern for the Tucannon River is a shift in its main channel, with increased infilling of the thalweg in the future scenario. For the South Fork Coeur d'Alene River, the most striking change scouring of an existing pool at the upstream end of the reach. Finally, the simulated changes on the Red River are relatively small in magnitude and lack a coherent spatial pattern. Although this exploratory model run is too short to produce definitive conclusions about future spatial patterns of erosion and deposition within these river reaches, the results suggest that the morphology of the Tucannon and Red rivers is sensitive to changes in discharge and sediment transport and that there is potential for channel change associated with climate change. Another possibility is that the reaches are in a transient state and are still adjusting to past changes. In order to definitively link these simulated geomorphic changes to climate change, it would be necessary to examine their current trajectories under current climatic conditions for a longer time period.

These preliminary results indicate that changes could include net deposition on the Tucannon River, with the growth of an existing mid-channel bar resulting from increased input of sediment from upstream, and net erosion on the South Fork Coeur d'Alene River, which manifests as pool scour, because of increased bankfull flows under the ensemble-average climate change scenario. While these two higher-energy rivers show substantial changes in their morphology under the climate change scenario, the changes on the Red River are fairly minimal, probably because of its relatively low slope and steep, cohesive banks that limit lateral movement. This difference suggests that the geomorphic response of river systems to climate change may depend not only on the



**Figure 4.7.** Results from 5-year ensemble-average CAESAR simulation, for (a) Tucannon River baseline period; (b) Tucannon River future period; (c) Tucannon River DOD for future relative to baseline period; (d) South Fork Coeur d'Alene River baseline period; (e) South Fork Coeur d'Alene River future period; (f) South Fork Coeur d'Alene DOD for future relative to baseline period; (g) Red River baseline period; (h) Red River future period; (i) Red River DOD for future relative to baseline period; (b) Red River baseline period; (c) Red River baseline peri

driving climatic and hydrological changes, but also on how reach characteristics affect a

river's relative stability or mobility.

#### 4.4. Discussion

#### 4.4.1. Climate Change and Sediment Transport

Here, I found that the response of bedload transport to climate change is highly nonlinear and threshold-dominated. Much of the previous research on climate change impacts on sediment transport has focused on suspended sediment, most likely because it is easier to model at the basin scale and to directly associate with climate than is bedload transport. Several studies have simulated climate-driven changes in suspended sediment transport at the basin scale and found that, as might be expected, they closely follow patterns of changes in discharge, with suspended-sediment transport increasing in locations or seasons in which discharge is expected to increase as a result of climate change and decreasing when discharge is projected to decrease [Thodsen et al., 2008; Zhu et al., 2008; Ward et al., 2009; Praskievicz and Chang, 2011; Shrestha et al., 2013; Praskievicz, 2014]. Other research has focused on retrospectively linking changes in past sediment transport to changes in climatic regime [Inman and Jenkins, 1999; Dornblaser and Striegl, 2009]. Although these studies indicate that climate is an important driving factor in sediment transport, other research has found that direct human modification of the landscape, such as land-use change, have exerted a stronger control on observed changes in suspended sediment transport [Wang et al., 2007; Gao et al., 2013; Ma et al., 2013].

There is less research on the impacts of climate change on bedload transport. This study suggests that the process of bedload transport may be linked to climate change impacts, but there are some caveats. The first is that, unlike suspended sediment which can be transported even at relatively low discharge, significant mobilization of bed sediments occurs only during relatively infrequent large flow events. These events have a stochastic distribution for which climate and hydrologic models are limited in their prediction ability. In general, basin-scale suspended-sediment transport can be expected to correlate directly with discharge as a power function, but the threshold-initiated nature of bedload transport means that its response to climate change is likely to be highly nonlinear and dependent on changes in critical flows that may vary significantly depending on the local morphology.

Second, climate may have a more direct role in initiating suspended-sediment transport relative to bedload transport. In addition to its total amount, characteristics of precipitation, such as its intensity, the time between events, and its form (rain or snow) all directly impact sediment grains on the land surface through rainsplash erosion and overland flow. In contrast, sediment grains on the bed of a river are not directly mobilized by precipitation, but by discharge, which is precipitation mediated by hydrologic processes such as subsurface flow, hyporheic exchange, and snowmelt. These processes mean that there is greater temporal and spatial distance between the occurrence of precipitation and the initiation of movement of sediment grains. Moreover, temperature may affect the availability of sediment on the land surface more directly than sediment on the river bed, because the presence of snow or frozen ground can inhibit the mobilization of suspended sediment from the land surface. Basin-scale erosion and sediment delivery are important components of sediment transport, in addition to what is occurring within the river channels. Sediment supply was not explicitly incorporated into

the modeling process here, but the impact of climate change on sediment delivery to rivers is worthy of future research.

In addition to these possible reasons for non-straightforward relationships between climate and bedload transport in nature, there are some technical limitations of this modeling approach that make it difficult to directly link these processes. For example, many of the projected impacts of climate change on basin-scale discharge and suspended sediment transport are best described by seasonal changes. Because of the irregular frequency of bedload transport, however, it is more difficult to aggregate any changes into seasonal patterns. Bedload transport is a function of duration of critical discharge, whether that discharge occurs from a winter rainfall event or from spring snowmelt. The expected changes in seasonal hydrological variability resulting from climate change in snowmelt-dominated river systems do not, therefore, translate directly into impacts on bedload transport. These climate-driven hydrological changes would be expected to change the duration of critical discharge and thereby affect bedload transport and river morphology. Because this study used the total duration rather than seasonality of critical discharge, however, further research is needed to investigate how the seasonal timing of critical discharge events affects the river's geomorphic response. It is likely that climate-driven changes in the annual hydrograph, such as more frequent rain-on-snow floods and reduced spring snowmelt peak flows, would influence the magnitude and duration of critical discharge and therefore affect bedload transport and river morphology.

While climate change may not directly affect bedload transport as strongly as basin-scale suspended-sediment transport, land-use change is also likely to be less of a

driving factor in determining changes in bedload transport, except for activities that take place directly adjacent to rivers. A number of other direct human modifications of rivers can significantly affect bedload transport rates. An obvious example is the construction of dams, which can reduce rates of bedload transport by orders of magnitude. Less directly, human activities can increase the risk of mass-wasting events that may contribute large pulses of sediment to rivers. Climate change may also contribute to sediment delivery to rivers through mass wasting by increasing the frequency of rain-on-snow and other intense precipitation events [Miller and Benda, 2000].

Although the focus here has been primarily on the energy available to initiate bedload transport through climate-driven changes in discharge, bedload transport rates are affected by sediment supply as well. Climate change could potentially affect processes that affect sediment supply. For example, if climate change results in more wildfires because of drier conditions, sediment delivery to the channel would increase because of reduced slope stability [Reneau et al., 2007]. Fluvial wood is an important control on sediment transport and channel morphology in many river systems [Brooks and Brierly, 2002]. Post-fire, there could be an influx of downed wood to a river system, followed by a period of reduced wood supply during the revegetation process, both of which could affect bedload transport. Further research is needed to determine how climate change might affect processes that control sediment supply to a river.

# 4.4.2. Climate Change and River Morphology

Here, simulated river morphology was found to be sensitive to climate change for higher-energy rivers with unstable banks, which are able to adjust their channels to

altered inputs of discharge and sediment. Changes in precipitation amount resulting from climate change were found to be a major control on simulated changes in sediment transport and river morphology This dominance of precipitation changes was also found by Coulthard et al. [2012], who used CAESAR to simulate impacts of changing precipitation under climate change on discharge and sediment yield of a river in the United Kingdom and found that projected increased winter rainfall results in an increase in basin-average sediment yield, as simulated by running the model in catchment mode. Such increases in sediment yield could cause significant changes in the patterns of erosion and deposition within the channel and lead to morphological changes. When temperature changes are also taken into account, particularly in snowmelt-dominated river systems, the seasonality of changes in discharge affects changes in sediment transport and river morphology. Boyer et al. [2010] used the HSAMI hydrological model to simulate impacts of climate change on the hydrology and fluvial geomorphology of tributaries to the St. Lawrence River in Quebec and found that winter sediment transport may increase because of higher winter discharge and longer ice-free conditions, spring sediment transport may decrease because of lower spring snowmelt discharge, and the magnitude of rare large events that cause erosion and channel change may increase because of rain-on-snow and other large flood events. The net effect of these seasonal changes on river morphology may depend on whether the increase in winter discharge or decrease in spring discharge is more substantial, which may in turn be the result of absolute changes in precipitation rather than relative changes in its seasonal occurrence as rain or snow.

Whether net erosion or aggradation occurs in a river reach as a result of climate change, such geomorphic changes can potentially affect management of the river system for human and ecological uses. Where net erosion occurs, for example, incision can cause the river to become disconnected from its floodplain and widening can lead to bank instability and failure. Net aggradation, in turn, can have impacts on flooding. Lane et al. [2007] used a two-dimensional model to simulate impacts of climate change on sediment delivery and flood risk on the UK's River Wharfe and found that in-channel aggradation increases projected flood inundation extent. Similarly, Gomez et al. [2009], using the HydroTrend hydrologic model and the TUGS sediment transport model to simulate impacts of climate change on discharge and sediment transport on New Zealand's Waipaoa River, found that climate change may result in aggradation that could have significant negative consequences for flood control. Another example of potential negative consequences of the reduced channel capacity resulting from river aggradation was found by Bogen et al. [2012], who analyzed the effects of river aggradation resulting from influxes of sediment from receding glaciers on hydropower production in Norway and found that reservoir infilling could reduce the hydraulic head and subsequently the efficiency of hydropower generation facilities. In general, climate change that forces a river system out of equilibrium will cause adjustments that may be out of the range of historic conditions to which human and ecological systems have adapted.

Finally, a major limitation of the hierarchical modeling approach used in this study is that uncertainty from one model is propagated to the next. Uncertainty is introduced at each stage, from the driving greenhouse gas emissions scenario, the driving GCM and RCM simulations, lapse-rate downscaling, hydrologic modeling, to the geomorphic modeling. While I have reduced this uncertainty to the extent possible by using ensemble simulations and by validating each model, some amount of uncertainty is irreducible when modeling climate-change impacts. The results presented here should therefore not be interpreted as a specific prediction of how these particular rivers will change in the future. Nevertheless, the results are useful in generating a range of plausible responses to a given change in climate and in identifying variables of interest for future study. For example, bedload transport is highly sensitive to changes in the duration of the critical discharge needed to mobilize bed sediments. Although this sensitivity makes it difficult to generalize the geomorphic response of river systems to climate change, because the response is dependent on both the grain-size characteristics of a particular river reach and on how climate change affects the probability of occurrence of flows needed to initiate movement of those grains, critical discharge can be calculated from sediment and channel geometry data and examined under a range of possible future hydrologic regimes. Although the results from this exploratory study are not transferable to other systems, if the dependence on critical discharge is a general relationship, the methods employed here may be implemented to study the geomorphic response of other rivers to climate change.

Understanding the geomorphic response of river systems to climate change is critical for water-resource management, because many aspects of river systems are potentially affected by climate-driven geomorphic changes. For example, increased sediment loads can negatively affect water quality, both through increased turbidity from suspended sediment and through nutrients and heavy metals that bind to sediment particles in agricultural and mining areas [Murdoch et al., 2000]. Climate change can

increase the risk of flooding, mass wasting, bank failures, channel avulsions, and other geomorphic hazards that threaten lives and property [Evans and Clague, 1994]. Changes in sediment grain-size distribution and bedform morphology can affect sensitive aquatic species with specific physical habitat requirements, such as salmonids [Neupane and Yager, 2013]. Because climate-change adaptation takes place at the local scale, river managers need locally-specific projections of the hydrologic and geomorphic impacts of climate change in order to maintain the societal and ecological benefits of river systems.

# 4.5. Conclusion

Here I have used discharge and suspended-sediment load simulated by a basinscale hydrologic model driven by downscaled climate change scenarios to examine potential impacts of climate change on the sediment transport and morphology of three snowmelt-dominated alluvial rivers in the interior Pacific Northwest. Changes in the flow regime were dependent on changes in both temperature and discharge, with the largest increases in discharge for the lower-elevation Tucannon River and mostly decreases in discharge for the two higher-elevation rivers. In general, the ensemble climate change scenario produces changes in available stream power and shear that are consistent with projected changes in discharge, including increases in energy available to do geomorphic work except for the largest floods on the Tucannon and South Fork Coeur d'Alene rivers. Simulated changes in reach-averaged bedload transport vary among the different climate change scenarios with changes in the duration of critical discharge, with generally increasing bedload transport on the Tucannon River and decreasing bedload transport on the South Fork Coeur d'Alene and Red rivers. These results suggest that the geomorphic response to climate change is nonlinear and threshold-dependent, with bedload transport

decreasing in some cases because of a shorter duration of critical discharge. In addition to changes in the duration of the critical discharge, any changes in the magnitude of peak flows are also likely to alter bedload transport. Understanding the role of sediment transport and river morphology is an important, yet under-studied, aspect of climatechange impacts on river systems that should inform river management and adaptation.

In Chapter IV, I used a set of three reach-scale geomorphic models – HEC-RAS, BAGS, and CAESAR – to simulate potential impacts of climate-driven hydrological changes on stream power and shear, reach-averaged bedload transport, and spatial patterns of erosion and deposition. This chapter, corresponding to the geomorphic system level in my modeling hierarchy, represents the culmination of the dissertation through its linkage of the climatic and hydrologic systems in Chapters II and III to the geomorphic response of the study rivers. In the final concluding chapter, I will summarize the main findings of the dissertation and the broader impacts of this research.

#### CHAPTER V

#### CONCLUSION

This dissertation used a hierarchical modeling approach to simulate the impacts of global climate change on basin-scale hydrology and reach-scale river morphology. This research makes an original contribution to the climate-change impacts literature by linking models and processes that operate at very different spatial scales. The main objectives of the dissertation and the key findings from each chapter are summarized below.

- Develop downscaled climate change scenarios, based on regional climate-model output, including changes in daily minimum and maximum temperature and precipitation (Chapter II).
- 2. Estimate how climate change scenarios affect river discharge and suspendedsediment load, using a basin-scale hydrologic model (Chapter III).
- 3. Examine potential impacts of climate-driven hydrologic changes on stream power and shear stress, bedload sediment transport, and river morphology, including channel geometry and planform (Chapter IV).

Chapter II: Hydrologic modeling using elevationally adjusted NARR and NARCCAP regional climate-model simulations: Tucannon River, Washington

This chapter, corresponding roughly to Objective 1 of the dissertation and to the climate system level of the modeling hierarchy, focused on estimating local topographic lapse rates for the northwestern United States and using them to elevationally adjust the output from a range of RCMs. I then used the resulting downscaled climate grids to run the SWAT hydrologic model for the Tucannon River to evaluate the sensitivity of the hydrologic model to the input climate data. I found that the estimated local topographic lapse rates correspond well to the real scale of topographic features and observed spatial and seasonal climatic patterns. Skill scores indicated that elevationally adjusted regional reanalysis output has forecast skill relative to reference climatologies of simple bilinear interpolation of the reanalysis data, average climatology, or persistence. Hydrologic modeling simulations of the Tucannon River varied among the different input climate timeseries, but the amount of variability introduced by the climate timeseries was less than that resulting from hydrologic model uncertainty. These results suggest that elevational adjustment using local topographic lapse rates is a promising method for downscaling RCM output in mountainous basins for use in hydrologic modeling.

# Chapter III: Impacts of projected climate changes on streamflow and sediment transport for three snowmelt-dominated rivers in the interior Pacific Northwest

In this chapter, which corresponds to Objective 2 of the dissertation and to the hydrologic system level of the modeling hierarchy, I used the downscaling method from Chapter II to create scenarios of future climate change for all three study basins and simulated impacts on basin-scale discharge and suspended-sediment load using the SWAT hydrologic model. I found that the projected climate changes were likely to increase the seasonality of discharge in the study rivers, with increased winter discharge, a decrease in the magnitude of the spring snowmelt peak, and decreased summer discharge. Hydrologic simulations also indicated that climate change may cause an increase in the magnitude of the largest floods on the study rivers. The simulated changes

in suspended-sediment load generally followed changes in discharge linearly, but in transitional late-winter and early-spring months, increases in suspended-sediment load were amplified by greater extent of snow-free and unfrozen ground. The hydrologic modeling results indicate that the study rivers are likely to experience shifts in their hydrologic regime, from being mostly dominated by snowmelt to including a larger winter rainfall component in their annual hydrographs. This shift is significant given these rivers' already-significant seasonality of discharge.

# Chapter IV: A hierarchical modeling approach to simulating the geomorphic response of river systems to climate change

This chapter, which corresponds to Objective 3 of the dissertation and the geomorphic system level of the modeling hierarchy, focused on using the projections of climatic and hydrologic change from Chapters II and III to simulate the geomorphic response of river systems using a set of reach-scale geomorphic models. The changes in stream power and shear stress simulated by HEC-RAS were, as expected, directly related to changes in discharge, with scenarios of increased discharge producing increased energy to do geomorphic work and vice versa. The changes in reach-averaged bedload transport simulated by the BAGS sediment transport formulas, however, were highly dependent on changes in the recurrence interval of critical discharge needed to mobilize bed sediments. The CAESAR simulations resulted in spatially-coherent patterns of erosion and deposition that could result in changes in the morphology of the different rivers, including enlargement of secondary channels, channel widening, and expansion of meanders. Because the results indicate that climate-driven changes in bedload transport are highly nonlinear and dependent on thresholds, generalizing these results beyond these

specific rivers is difficult. My results suggest that the patterns of geomorphic response to climate change depend on both the driving hydrologic scenario, namely the recurrence interval of critical discharge, as well as characteristics of the individual river reach, in particular the typical grain size of bed sediments. Because these factors are specific to particular rivers, general statements about climate-change impacts on river morphology cannot be made based on this research, but the results are useful in identifying some of the factors that potentially control the geomorphic response of rivers to climate change.

# 5.1. Limitations

This dissertation was motivated by the need to develop projections of the impacts of global climate change on local river systems. Few existing studies have attempted to examine impacts of global climate change on such localized processes as reach-scale bedload transport and river morphology, but the hierarchical modeling approach used here was designed to link established models and datasets at different scales to explore cross-scale effects. The major limitation of this approach is that uncertainty is introduced at each step of the modeling hierarchy (Figure 5.1). The most effective method of constraining this uncertainty would be to use a Monte Carlo or other iterative procedure to generate a probability distribution of model results, but this step was beyond the scope of the dissertation, so I used simpler methods for uncertainty reduction. Uncertainty in greenhouse gas emissions, GCMs, and RCMs was already present in my initial NARCCAP dataset. My lapse-rate downscaling procedure introduced further uncertainty in the future climate change scenarios that were used in hydrologic modeling. Uncertainty in the hydrologic model, as well as the propagated uncertainty in future climate change, was carried forward into the geomorphic modeling. The geomorphic

modeling results are especially sensitive to uncertainty in the climatic and hydrologic scenarios upon which they are based, because bedload transport is a nonlinear process that is sensitive to thresholds. Although I attempted to reduce these cascading uncertainties by using a range of driving climate models and an ensemble average, and by validating the models by comparing to observed data before proceeding to the next level of the modeling hierarchy, some amount of uncertainty is inevitable in any modeling study of future climate-change impacts.



**Figure 5.1.** Sources of uncertainty in hierarchical modeling process and steps taken to reduce uncertainty.

Because of the uncertainty inherent in the process, the results of this research cannot be used to make specific predictions about how my particular study rivers will change in the future. For such a prediction to be made, there would need to be reliable information on how the atmospheric concentration of greenhouse gases will change in the future (emissions scenario uncertainty), how the global climate will respond to those concentrations (GCM uncertainty), how those global changes will affect the regional and local climate of the study watersheds (RCM and lapse-rate downscaling uncertainty), how the hydrologic system will respond to those climate changes (hydrologic model uncertainty), and how the geomorphic system will respond to those hydrological changes (geomorphic model uncertainty). Because the uncertainty arising from the emission scenario, GCMs, and RCMs are inherent in the NARCCAP datasets on which this research is based, these uncertainties are irreducible within this dissertation. The additional uncertainties that arose from my methods include uncertainties arising from the lapse-rate downscaling, hydrologic modeling, and geomorphic modeling.

Given an RCM output, my lapse-rate downscaling procedure projects how the climate simulated by the RCM manifests at local scales through observed relationships between elevation and climate. As with all statistical downscaling methods, this approach relies on the assumption that observed relationships between the predictor and response variables will remain constant in the future as climate changes. Although this assumption cannot be verified, the level of uncertainty originating from this step of the modeling process is likely to be fairly minimal, since the lapse-rate adjusted RCM outputs for the study area are very similar to observed station data and there is no indication that model bias changes over the course of the study period.

The next step of the modeling process, the hydrologic modeling, introduces additional uncertainty. The results of Chapter II suggest that hydrologic modeling uncertainty is greater than the uncertainty introduced by the different input climate timeseries. For these particular study rivers, hydrologic modeling is particularly sensitive to parameterizations of snowpack accumulation and melt. A great deal of the overall uncertainty of this project, therefore, can be attributed to uncertainty in how a given change in temperature and precipitation affects basin-scale hydrology. Nevertheless, the calibration and validation statistics indicate that the model performs relatively well, and the range of changes simulated by the different climate change scenarios can be considered a reasonable range of plausible future hydrologic responses.

Finally, probably the greatest source of uncertainty in this project comes from the geomorphic modeling. This uncertainty is unsurprising because, at highly local scales, processes are more noisy and sensitive to factors that may not be adequately sampled in the field or represented in models. This high level of uncertainty is probably responsible for the lack of existing research on how global climate change may affect reach-scale bedload transport and river morphology. The geomorphic modeling results are highly sensitive to the choice of input hydrologic change scenario, so the uncertainty from the hydrologic modeling results is amplified in the final stage of the project, and definitive statements about the specific geomorphic response of these river systems to climate change cannot be made. To quantify the uncertainty associated with climate and hydrologic change and with geomorphic characteristics, it would be necessary to simulate the impacts of a wider range of climate change scenario on a single river, or to simulate the impacts of a single climate change scenario on many more rivers with differing

hydrologic and geomorphic characteristics. Nevertheless, these results are useful in that they demonstrate that the most important factor influencing changes in bedload transport is how the duration of the critical discharge needed to mobilize bed sediments changes. This critical discharge can be calculated as a function of the sediment grain-size distribution and channel geometry of a particular river reach, and changes in this critical discharge resulting from a range of climate-change scenarios can be simulated. Although the results of this research cannot be generalized to other systems, if this sensitivity to critical discharge is a general relationship, the methods used in this dissertation can be applied to simulate impacts of climate change on the geomorphic response of other rivers.

#### 5.2. Implications

This research has broader implications that go beyond the particular projections of climate change impacts for my study rivers. First, I have developed and applied a novel method of downscaling RCM output based on local topographic lapse rates. Although the method needs more extensive validation before it is used in other applications, it is a promising technique in areas where topography exerts a strong control on climate. Because the lapse rates have a physical basis and appear to be stationary over time, this approach could potentially be used to elevationally adjust the output from RCMs in other regions in which high-resolution gridded climate data are available.

Beyond the methods developed in this dissertation, the results are significant in terms of management of river systems. Rivers in the mountains of the western United States are highly seasonal and dependent on snowmelt. My simulation results indicate that these snowmelt-dominated rivers are likely to experience increased winter discharge

and an increase in the magnitude of the largest floods. This increased winter discharge could lead to greater risk of flooding caused by heavy precipitation and rain-on-snow events. The decreased snowpack, in turn, causes a reduction in the magnitude of the spring snowmelt peak and summer discharge. Such decreased discharge during the growing season, when demand for water is highest in both human and ecological systems, could exacerbate water scarcity in a region in which there is already conflict among different water users. These changes in hydrologic regime may be a challenge for management of water infrastructure, such as dams and reservoirs, which were designed for a stationary hydrologic system.

Finally, any changes in bedload transport and reach-scale river morphology could have significant impacts on river systems. Aggradation of some river reaches could lead to decreased channel capacity and increased flood risk, while incision of other reaches could disconnect rivers from their floodplains (Lane et al., 2007; Gomez et al., 2009; Coulthard et al., 2012). Channel widening, bank erosion, and avulsions may endanger structures adjacent to rivers. Erosion and deposition within channels could lead to changes in the distribution of pools, riffles, side channels, and other features necessary for maintaining complex habitat for salmonids and other aquatic species. Changes in the frequency of critical discharge could over time change the sediment grain-size distribution of reaches and therefore their suitability for spawning and rearing habitat. Although there is irreducible uncertainty in projecting the impacts of global climate change on these highly local geomorphic processes, the hierarchical modeling approach presented here offers a framework for connecting processes across these very different scales.

# **REFERENCES CITED**

- Abbaspour, K.C., J. Yang, I. Maximov, R. Siber, K. Bogner, J. Mieleitner, J. Zobrist, and R. Srinivasan (2007) Modelling hydrology and water quality in the prealpine/alpine Thur watershed using SWAT, J. Hydrol., 333, 413-430, doi: 10.1016/j.jhydrol.2006.09.014.
- Adam, J.C., A.F. Hamlet, and D.P. Lettenmaier (2009), Implications of global climate change for snowmelt hydrology in the twenty-first century, Hydrol. Process., 23, 962-972, doi: 10.1002/hyp.7201.
- Arnold, J.G., J.R. Kiniry, R. Srinivasan, J.R. Williams, E.B. Haney, and S.L. Neitsch (2011), Soil and Water Assessment Tool: Input/Output File Documentation, Texas Water Resources Institute, College Station, TX.
- Bagnold, R.A. (1966), An approach to the sediment transport problem from general physics, United States Geological Survey Professional Paper 422-I, 1-37.
- Barnett, T.P., D.W. Pierce, H.G. Hidalgo, C. Bonfils, B.D. Santer, T. Das, G. Bala, A.W. Wood, T. Nozawa, A.A. Mirin, D.R. Cayan, and M.D. Dettinger (2008), Humaninduced changes in the hydrology of the western United States, Science, 319, 1080-1083, doi: 10.1126/science.1152538.
- Barry, R.G. (1992), Mountain Weather and Climate, Routledge, New York, NY.
- Berg, P., H. Feldmann, and H.-J. Panitz (2012), Bias correction of high resolution regional climate model data, J. Hydrol., 448-449, 80-92, doi: 10.1016/j.jhydrol.2012.04.026.
- Blum, M.D., and T.E. Törnqvist (2000), Fluvial responses to climate and sea-level change: A review and look forward, Sedimentology, 47, 2-48, doi: 10.1046/j.1365-3091.2000.00008.x.
- Bogen, J., T. Bønsnes, and G. Ragulina (2012), Impact of climate change on glacial sediment delivery to Norwegian rivers and consequences for hydropower operations, IAHS-AISH P., 356, 210-218.
- Boyer, C., D. Chaumont, I. Chartier, and A.G.Roy (2010), Impact of climate change on the hydrology of St. Lawrence tributaries, J. Hydrol., 384, 65-83, doi: 10.1016/j.jhydrol.2010.01.011.
- Brooks, A.P., and G.J. Brierly (2002), Mediated equilibrium: The influence of riparian vegetation and wood on the long-term evolution and behaviour of a near-pristine river, Earth Surf. Proc. Land., 27, 343-367, doi: 10.1002/esp.332.
- Buytaert, W., M. Vuille, A. Dewulf, R. Urrutia, A. Karmalkar, and R. Célleri (2010), Uncertainties in climate change projections and regional downscaling in the tropical Andes: Implications for water resources management, Hydrol. Earth Syst. Sc., 14, 1247-1258, doi: 10.5194/hess-14-1247-2010.

- Caballero, Y., S. Voirin-Morel, F. Habets, J. Noilhan, P. LeMoigne, A. Lehenaff, and A. Boone (2007), Hydrological sensitivity of the Adour-Garonne river basin to climate change, Water Resour. Res., 43, W07448, doi: 10.1029/2005WR004192.
- Candy, I., S. Black, and B.W. Sellwood (2004), Interpreting the response of a dryland river system to Late Quaternary climate change, Quaternary Sci. Rev., 23, 2513-2523, doi: 10.1016/j.quascirev.2004.06.009.
- Carignano, C.A. (1999), Late Pleistocene to recent climate change in Córdoba Province, Argentina: Geomorphological evidence, Quatern. Int., 57/58, 117-134, doi: 10.1016/S1040-6182(98)00054-8.
- Chen, J., F.P. Brissette, and R. Leconte (2011), Uncertainty of downscaling method in quantifying the impact of climate change on hydrology, J. Hydrol., 401, 190-202, doi: 10.1016/j.jhydrol.2011.02.020.
- Christensen, J.H., and O.B. Christensen (2003), Climate modelling: Severe summertime flooding in Europe, Nature, 421, 805-806, doi: 10.1038/421805a.
- Christensen, N.S., A.W. Wood, N. Voisin, D.P. Lettenmaier, and R.N. Palmer (2004), The effects of climate change on the hydrology and water resources of the Colorado River Basin, Climatic Change, 62, 337-363, doi: 10.1023/B:CLIM.0000013684.13621.1f.
- Chung, U., and J.I. Yun (2004), Solar irradiance-corrected spatial interpolation of hourly temperature in complex terrain, Agric. For. Meteorol., 126, 129-139, doi: 10.1016/j.agrformet.2004.06.006.
- Coulthard, T.J., M.G. Macklin, and M.J. Kirkby (2002), A cellular model of Holocene upland river basin and alluvial fan evolution, Earth Surf. Processes, 27, 269-288, doi: 10.1002/esp.318.
- Coulthard, T.J., J. Ramirez, H.J. Fowler, and V. Glenis (2012), Using the UKCP09 probabilistic scenarios to model the amplified impact of climate change on drainage basin sediment yield, Hydrol. Earth Syst. Sc. 16, 4401-4416, doi: 10.5194/hess-16-4401-2012.
- Covert, J., J. Lyerla, and M. Ader (1995), Initial Watershed Assessment: Tucannon River Watershed, Washington Department of Ecology Eastern Regional Office, Spokane, WA.
- Crozier, M.J. (2010), Deciphering the effect of climate change on landslide activity: A review, Geomorphology, 124, 260-267, doi: 10.1016/j.geomorph.2010.04.009.
- Cuo, L., D.P. Lettenmaier, M. Alberti, and J.E. Richey (2009), Effects of a century of land cover and climate change on the hydrology of the Puget Sound basin, Hydrol. Process., 23, 907-933, doi: 10.1002/hyp.7228.

- Cuo, L., Y. Zhang, Y. Gao, Z. Hao, and L. Cairang (2013), The impacts of climate change and land cover/land use transition on the hydrology in the upper Yellow River Basin, China, J. Hydrol., 502, 37-52, doi: 10.1016/j.jhydrol.2013.08.003.
- Dadson, S.J., V.A. Bell, and R.G. Jones (2011), Evaluation of a grid-based river flow model configured for use in a regional climate model, J. Hydrol., 411, 238-250, doi: 10.1016/j.jhydrol.2011.10.002.
- Day, C.A. (2009), Modelling impacts of climate change on snowmelt runoff generation and streamflow across western U.S. mountain basins: A review of techniques and applications for water resource management, Prog. Phys. Geog., 33, 614-633, doi: 10.1177/0309133309343131.
- DiBiase, R.A., and M.P. Lamb (2013), Vegetation and wildfire controls on sediment yield in bedrock landscapes, Geophys. Res. Lett., 40, 1093-1097, doi: 10.1002/grl.50277.
- Dornblaser, M.M., and R.G. Striegl (2009), Suspended sediment and carbonate transport in the Yukon River Basin, Alaska: Fluxes and potential future responses to climate change, Water Resour. Res. 45, W06411, doi: 10.1029/2008WR007546.
- Dust, D., and E. Wohl (2012), Conceptual model for complex river responses using an expanded Lane's relation, Geomorphology 139-140, 109-121, doi: 10.1016/j.geomorph.2011.10.008.
- Eaton, B.C., and M.F. Lapointe (2001), Effects of large floods on sediment transport and reach morphology in the cobble-bed Sainte Marguerite River, Geomorphology, 40, 291-309.
- Elsner, M.M., L. Cuo, N. Voisin, J.S. Deems, A.F. Hamlet, J.A. Vano, K.E.B. Mickelson, S.-Y. Lee, and D.P. Lettenmaier (2010), Implications of 21<sup>st</sup> century climate change for the hydrology of Washington State, Climatic Change, 102, 225-260, doi: 10.1007/s10584-010-9855-0.
- Emmett, W.W., and M.G. Wolman (2001), Effective discharge and gravel-bed rivers, Earth Surf Processes, 26, 1369-1380, doi: 10.1002/esp.303.
- Evans, S.G., and J.J. Clague (1994), Recent climatic change and catastrophic geomorphic processes in mountain environments, Geomorphology, 10, 107-128, doi: 10.1016/0169-555X(94)90011-6.
- Ficklin, D.L., I.T. Stewart, and E.P. Maurer (2013), Effects of projected climate change on the hydrology in the Mono Lake Basin, California, Climatic Change, 116, 111-131, doi: 10.1007/s10584-012-0566-6.
- Fowler, H.J., S. Blenkinsop, and C. Tebaldi (2007), Linking climate change modelling to impacts studies: Recent advances in downscaling techniques for hydrological modelling, Int. J. Climatol., 27, 1547-1578, doi: 10.1002/joc.1556.

- Fowler, H.J., and C.G. Kilsby (2007), Using regional climate model data to simulate historical and future river flows in northwest England, Climatic Change, 80, 337-367, doi: 10.1007/s10584-006-9117-3.
- Fridley, J.D. (2009), Downscaling climate over complex terrain: High finescale (<1000 m) spatial variation of near-ground temperatures in a montane forested landscape (Great Smoky Mountains), J. Appl. Meteorol. Clim., 48, 1033-1049, doi: 10.1175/2008JAMC2084.1.</p>
- Fuller, I.C., A.R.G. Large, and D.J. Milan (2003), Quantifying channel development and sediment transfer following chute cutoff in a wandering gravel-bed river, Geomorphology, 54, 307-323, doi: 10.1016/S0169-555X(02)00374-4.
- Gao, P. (2008), Understanding watershed suspended sediment transport, Prog. Phys. Geog., 32, 243-263, doi: 10.1177/0309133308094849.
- Gao, P., V. Geissen, C.J. Ritsema, X.-M. Mu, and F. Wang (2013), Impact of climate change and anthropogenic activities on stream flow and sediment discharge in the Wei River basin, China, Hydrol. Earth Syst. Sc., 17, 961-972, doi: 10.5194/hess-17-961-2013.
- Gassman, P.W., M. Reyes, C.H. Green, and J.G. Arnold (2007), The Soil and Water Assessment Tool: Historical development, applications, and future directions, Trans. Am. Soc. Agric. Biol. Eng., 50, 1211-1250.
- Ghosh, S., and S. Katkar (2012), Modeling uncertainty resulting from multiple downscaling methods in assessing hydrological impacts of climate change, Water Resour. Manag., 26, 3559-3579, doi: 10.1007/s11269-012-0090-5.
- Giorgi, F., E.-S. Im, E. Coppola, N.S. Diffenbaugh, X.J. Gao, L. Mariotti, and Y. Shi (2011), Higher hydroclimatic intensity with global warming, J. Climate, 24, 5309-5324, doi: 10.1007/s11269-012-0090-5.
- Goderniaux, P., S. Brouyère, H.J. Fowler, S. Blenkinsop, R. Therrien, P. Orban, and A. Dassargues (2009), Large scale surface-subsurface hydrological model to assess climate change impacts on groundwater reserves, J. Hydrol., 373, 122-138, doi: 10.1016/j.jhydrol.2009.04.017.
- Gomez, B., Y. Cui, A.J. Kettner, D.H. Peacock, and J.P.M. Syvitski (2009), Simulating changes to the sediment transport regime of the Waipaoa River, New Zealand, driven by climate change in the twenty-first century, Global Planet. Change, 67, 153-166, doi: 10.1016/j.gloplacha.2009.02.002.
- Graham, L.P., J. Andréasson, and B. Carlsson (2007), Assessing climate change impacts on hydrology from an ensemble of regional climate models, model scales and linking methods: A case study on the Lule River basin, Climatic Change, 81, 293-307, doi: 10.1007/s10584-006-9215-2.

- Graves, D., and H. Chang (2007), Hydrologic impacts of climate change in the Upper Clackamas River Basin, Oregon, USA, Climate Res., 33, 143-157, doi: 10.3354/cr033143.
- Grove, A.T. (2001), The "Little Ice Age" and its geomorphological consequences in Mediterranean Europe, Climatic Change, 48, 121-136, doi: 10.1023/A:1005610804390.
- Guo, J., and W.L. Wood (1995), Fine suspended sediment transport rates, J. Hydraul. Eng., 121, 919-922.
- Hall, S.A., and J.A. Peterson (2013), Floodplain construction of the Rio Grande at El Paso, Texas, USA: Response to Holocene climate change, Quaternary Sci. Rev., 65, 102-119, doi: 10.1016/j.quascirev.2012.11.013.
- Hamlet, A.F., and D. P. Lettenmaier (2007), Effects of 20<sup>th</sup> century warming and climate variability on flood risk in the western U.S., Water Resour. Res., 43, W06427, doi: 10.1029/2006WR005099.
- Hanel, M., and T.A. Buishand (2010), On the value of hourly precipitation extremes in regional climate model simulations, J. Hydrol., 393, 265-273, doi: 10.1016/j.jhydrol.2010.08.024.
- Hay, L.E., and G.J. McCabe (2010), Hydrologic effects of climate change in the Yukon River Basin, Climatic Change, 100, 509-523, doi: 10.1007/s10584-010-9805-x.
- Hewitson, B.C., and R.G. Crane (2006), Consensus between GCM climate change projections with empirical downscaling: Precipitation downscaling over South Africa, Int. J. Climatol., 26, 1315-1337, doi: 10.1002/joc.1314.
- Huang, S., P.M. Rich, R.L. Crabtree, C.S. Potter, and P. Fu (2008), Modeling monthly near-surface air temperature from solar radiation and lapse rate: Application over complex terrain in Yellowstone National Park, Phys. Geogr., 29, 158-178, doi: Huang, S., Rich, P.M., Crabtree, R.L., Potter, C.S., Fu, P., 2008. Modeling monthly near-surface air temperature from solar radiation and lapse rate: Application over complex terrain in Yellowstone National Park. Phys. Geogr. 29, 158-178.
- Huntington, T.G. (2006), Evidence for intensification of the global water cycle: Review and synthesis, J. Hydrol., 319, 83-95, doi: :10.1016/j.jhydrol.2005.07.003.
- Hwang, T., C. Song, J.M. Vose, and L.E. Band (2011), Topography-mediated controls on local vegetation phenology estimated from MODIS vegetation index, Landscape Ecol., 26, 541-556, doi: 10.1007/s10980-011-9580-8.
- Im, E.-S., E. Coppola, F. Giorgi, and X. Bi (2010), Validation of a high-resolution regional climate model for the alpine region and effects of a subgrid-scale topography and land use representation, J. Climate., 23, 1854-1873, doi: 10.1175/2009JCLI3262.1.

- Inman, D.L., and S.A. Jenkins (1999), Climate change and the episodicity of sediment flux of small California rivers, J. Geol. 107, 251-270, doi: 10.1086/314346.
- Istanbulluoglu, E. (2009), Modeling catchment evolution: From decoding geomorphic processes signatures toward predicting impacts of climate change, Geography Compass, 3, 1125-1150, doi: 10.1111/j.1749-8198.2009.00228.x.
- Jiménez Cisneros, B.E., T. Oki, N.W. Arnell, G. Benito, J.G. Cogley, P. Döll, T. Jiang, and S.S. Mwakalila (2014), Freshwater resources, in Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by P. Kabat and Z. Kundzewicz, pp. 1-76, Cambridge University Press, Cambridge, UK.
- Jung, I.-W., H. Moradkhani, and H. Chang (2012), Uncertainty assessment of climate change impacts for hydrologically distinct river basins, J. Hydrol., 466, 73-87, doi: 10.1016/j.jhydrol.2012.08.002.
- Katz, R.W., M.B. Parlange, and P. Naveau (2002), Statistics of extremes in hydrology, Adv. Water Resour., 25, 1287-1304, doi: 10.1016/S0309-1708(02)00056-8.
- Kerr, R.A. (2013), Forecasting regional climate change flunks its first test, Science, 339, 638, doi: 10.1126/science.339.6120.638.
- Kirtman, B., S.B. Power, J.A. Adedoyin, G.J. Boer, R. Bojariu, I. Camilloni, F.J. Doblas-Reyes, A.M. Fiore, M. Kimoto, G.A. Meehl, M. Prather, A. Sarr, C. Schär, R. Sutton, G.J. van Oldenborgh, G. Vecchi, and H.J Wang (2013), Near-term climate change: Projections and predictability, in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, pp. 953-1028, Cambridge University Press, Cambridge, UK.
- Kundzewicz, Z.W., L.J. Mata, N. Arnell, P. Döll, P. Kabat, B. Jiménez, K. Miller, T. Oki, Z. Şen, and I. Shiklomanov (2007), Freshwater resources and their management, in Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, pp. 174-210, Cambridge University Press, Cambridge, UK.
- Laghari, A.N., D. Vanham, and W. Rauch (2012), To what extent does climate change result in a shift in Alpine hydrology? A case study in the Austrian Alps, Hydrol. Sci. J., 1 57, 103-117, doi: 10.1080/02626667.2011.637040.
- Lane, E.W. (1955), Design of stable channels, T. Am. Soc. Civ. Eng. 120, 1234-1260.

- Layzell, A.L., M.C. Eppes, B.G. Johnson, and J.A. Diemer (2012), Post-glacial range of variability in the Conejos River Valley, southern Colorado, USA: Fluvial response to climate change and sediment supply, Earth Surf. Proc. Land., 37, 1189-1202, doi: 10.1002/esp.3253.
- Lane, S.N., V. Tayefi, S.C. Reid, D. Yu, and R.J. Hardy (2007), Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment, Earth Surf. Proc. Land., 32, 429-446, doi: 10.1002/esp.1404.
- Leopold, L.B., M.G. Wolman, and J.P. Miller (1964), Fluvial Processes in Geomorphology, W.H. Freeman, San Francisco, CA.
- Lespinas, F., W. Ludwig, and S. Heussner (2010), Impact of recent climate change on the hydrology of coastal Mediterranean rivers in Southern France, Climatic Change, 99, 425-456, doi: 10.1007/s10584-009-9668-1.
- Leung, L.R., Y. Qian, X. Bian, W.M. Washington, J. Han, and J.O. Roads (2004), Midcentury ensemble regional climate change scenarios for the western United States, Climatic Change, 62, 75-113, doi: 10.1023/B:CLIM.0000013692.50640.55.
- Lewis, S.G., D. Maddy, and R.G. Scaife (2001), The fluvial system response to abrupt climate change during the last cold stage: The Upper Pleistocene River Thames fluvial succession at Ashton Keynes, UK, Global Planet. Change, 28, 341-359, doi: <u>http://dx.doi.org/10.1016/S0921-8181(00)00083-7</u>.
- Li, Z., W.-Z. Liu, X.-C. Zhang, and F.-L. Zheng (2011), Assessing the site-specific impacts of climate change on hydrology, soil erosion and crop yields in the Loess Plateau of China, Climatic Change 105, 223-242, doi: 10.1007/s10584-010-9875-9.
- Ligare, S.T., J.H. Viers, S.E. Null, D.E. Rheinheimer, and J.F. Mount (2012), Nonuniform changes to whitewater recreation in California's Sierra Nevada from regional climate warming, River Res. Appl., 28, 1299-1311, doi: 10.1002/rra.1522.
- Lindau, R., and C. Simmer (2013), On correcting precipitation as simulated by the regional climate model COSMO-CLM with daily rain gauge observations, Meteorol. Atmos. Phys., 119, 31-42, doi: 10.1007/s00703-012-0215-7.
- Lopez, S.R., T.S. Hogue, and E.D. Stein (2013), A framework for evaluating regional hydrologic sensitivity to climate change using archetypal watershed modeling, Hydrol. Earth Syst. Sc., 17, 3077-3094, doi: 10.5194/hess-17-3077-2013.
- Ma, X., X. Lu, M. van Noordwijk, J. Xu, and J. Li (2013), Climate change, vegetation restoration and engineering as a 1:2:1 explanation for reduction of suspended sediment in southwest China, Hydrol. Earth Syst. Sc. Disc., 10, 12417-12451, doi: 10.5194/hessd-10-12417-2013.

- Maas, G.S., and M.G. Macklin (2002), The impact of recent climate change on flooding and sediment supply within a Mediterranean mountain catchment, southwestern Crete, Greece, Earth Surf. Processes 27, 1087-1105, doi: 10.1002/esp.398.
- Maraun, D., F. Wetterhall, A.M. Ireson, R.E. Chandler, E.J. Kendon, M. Widmann, S. Brienen, H.W. Rust, T. Sauter, M. Themel, V.K.C. Venema, K.P. Chun, C.M. Goodess, R.G. Jones, C. Onof, M. Vrac, and I. Thiele-Eich (2010), Precipitation downscaling under climate change: Recent developments to bridge the gap between dynamical models and the end user, Rev. Geophys., 48, 2009RG000314, doi: 10.1029/2009RG000314.
- Marcus, W.A. (1989) Lag-time routing of suspended sediment concentrations during unsteady flow, Geolg. Soc. Am. Bull., 101, 644-651, doi: 10.1130/0016-7606(1989)101<0644:LTROSS>2.3.CO;2.
- Matalas, N.C. (1997), Stochastic hydrology in the context of climate change, Climatic Change, 37, 89-101, doi: 10.1023/A:1005374000318.
- Maurer, E.P., and H.G. Hidalgo (2008), Utility of daily vs. monthly large-scale climate data: An intercomparison of two statistical downscaling methods, Hydrol. Earth Syst. Sc., 12, 551-563, doi: 10.5194/hess-12-551-2008.
- McVicar, T.R., T.G. Van Niel, L. Li, M.F. Hutchinson, X. Mu, and Z. Liu (2007), Spatially distributing monthly reference evapotranspiration and pan evaporation considering topographic influences, J. Hydrol., 338, 196-220, doi: 10.1016/j.jhydrol.2007.02.018.
- Mearns, L.O., et al. (2007), The North American Regional Climate Change Assessment Program Dataset, National Center for Atmospheric Research Earth System Grid data portal, Boulder, CO, data last accessed 2014-01-31. http://www.narccap.ucar.edu/.
- Mearns, L.O., R. Arritt, S. Biner, M.S. Bukovsky, S. McGinnis, S. Sain, D. Caya, J. Correia, D. Flory, W. Gutowski, E.S. Takle, R. Jones, R. Leung, W. Moufouma-Okia, L. McDaniel, A.M.B. Nunes, Y. Qian, J. Roads, L. Sloan, and M. Snyder (2012), The North American Regional Climate Change Assessment Program: Overview of Phase I results, B. Am. Meteorol. Soc., 93, 1337-1362 doi: 10.1175/BAMS-D-11-00223.1.
- Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.j>
  Weaver, and Z.-C. Zhao (2007), Global climate projections, in Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, (Eds.), pp. 747-845, Cambridge University Press, Cambridge, UK.

- Merritt, W.S., Y. Alila, M. Barton, B. Taylor, S. Cohen, and D. Neilsen (2006), Hydrologic response to scenarios of climate change in subwatersheds of the Okanagan basin, British Columbia, J. Hydrol., 326, 79-108, doi: 10.1016/j.jhydrol.2005.10.025.
- Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, P.C. Shafran, W. Ebisuzaki, D. Jovic, J. Woollen, E. Rogers, E.H. Berbery, M.B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, and W. Shi (2006), North American regional reanalysis, B. Am. Meteorol. Soc., 87, 343-360, doi: 10.1175/BAMS-87-3-343.
- Meyer-Peter, E., and R. Müller (1948), Formulas for bed-load transport, Proceedings of the 2<sup>nd</sup> Meeting of the International Association for Hydraulic Structures Research, 39-64.
- Miller, D.J., and L.E. Benda (2000), Effects of punctuated sediment supply on valleyfloor landforms and sediment transport, Geol. Soc. Am. Bull., 112, 1814-1824, doi: 10.1130/0016-7606(2000)112<1814:EOPSSO>2.0.CO;2.
- Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer (2008), Stationarity is dead: Whither water management?, Science, 319, 573-574, doi: 10.1126/science.1151915.
- Mote, P.W., E.A. Parson, A.F. Hamlet, W.S. Keeton, D. Lettenmaier, N. Mantua, E.L.
   Miles, D.W. Peterson, D.L. Peterson, R. Slaughter, and A.K. Snover (2003),
   Preparing for climatic change: The water, salmon, and forests of the Pacific
   Northwest, Climatic Change, 61, 45-88, doi: 10.1023/A:1026302914358.
- Murdoch, P.S., J.S. Baron, and T.L. Miller (2000), Potential effects of climate change on surface-water quality in North America, J. Am. Water Resour. As., 36, 347-366, doi: 10.1111/j.1752-1688.2000.tb04273.x.
- Naik, P.K., and D.A. Jay (2011), Distinguishing human and climate influences on the Columbia River: Changes in mean flow and sediment transport, J. Hydrol., 404, 259-277, doi: 10.1016/j.jhydrol.2011.04.035.
- Nash, D.B. (1994), Effective sediment-transporting discharge from magnitude-frequency analysis, J. Geol., 102, 79-95.
- Nash, J.E., and J.V. Sutcliffe (1970), River flow forecasting through conceptual models. Part I: A discussion of principles, J. Hydrol., 10, 282-290.
- Nasseri, M., H. Tavakol-Davani, and B. Zahraie (2013), Performance assessment of different data mining methods in statistical downscaling of daily precipitation, J. Hydrol., 492, 1-14, doi: 10.1016/j.jhydrol.2013.04.017.
- National Centers for Environmental Prediction (NCEP) (2013), North American Regional Reanalysis Homepage, data last accessed 2013-06-13. <u>http://www.emc.ncep.noaa.gov/mmb/rreanl/</u>.

- National Climatic Data Center (NCDC) (2013), Online Climate Data Directory, data last accessed 2013-06-13. <u>http://www.ncdc.noaa.gov/oa/climate/climatedata.html</u>.
- Neitsch, S.L., J.G. Arnold, J.R. Kiniry, and J.R. Williams (2011), Soil and Water Assessment Tool: Theoretical Documentation, Texas Water Resources Institute, College Station, TX.
- Neupane, S., and E.M. Yager (2013), Numerical simulation of the impact of sediment supply and streamflow variations on channel grain sizes and Chinook salmon habitat in mountain drainage networks, Earth Surf. Proc. Land., 38, 1822-1837, doi: 10.1002/esp.3426.
- Nolin, A.W. (2012), Perspectives on climate change, mountain hydrology, and water resources in the Oregon Cascades, USA, Mt. Res. Dev., 32, S35-S46, doi: 10.1659/MRD-JOURNAL-D-11-00038.S1.
- Olszak, J. (2011), Evolution of fluvial terraces in response to climate change and tectonic uplift during the Pleistocene: Evidence from Kamienica and Ochotnica River valleys (Polish Outer Carpathians), Geomorphology, 129, 71-78, doi: 10.1016/j.geomorph.2011.01.014.
- Oki, T., and S. Kanae (2006), Global hydrological cycles and world water resources, Science, 313, 1068-1072, doi: 10.1126/science.1128845.
- Orr, H.G., and P.A. Carling (2006), Hydro-climatic and land use changes in the River Lune catchment, north west England, implications for catchment management, River Res. Appl., 22, 239-255, doi: 10.1002/rra.908.
- Parker, G. (1990), Surface-based bedload transport relation for gravel rivers, J. Hydraul. Res. 28, 417-436.
- Pederson, G.T., J.L. Betancourt, and G.J. McCabe (2013), Regional patterns and proximal causes of the recent snowpack decline in the Rocky Mountains, U.S. Geophys. Res. Lett., 40, 1-6, doi: 10.1002/grl.50424.
- Persico, L., and G. Meyer (2009), Holocene beaver damming, fluvial geomorphology, and climate in Yellowstone National Park, Wyoming, Quaternary Res. 71, 340-353, doi: 10.1016/j.yqres.2008.09.007.
- Pfister, L., J. Kwadijk, A. Musy, A. Bronstert, and L. Hoffmann (2004) Climate change, land use change and runoff prediction in the Rhine-Meuse basins, River Res. Appl. 20, 229-241, doi: 10.1002/rra.775.
- Phillips, J.D. (2010), Amplifiers, filters and geomorphic responses to climate change in Kentucky rivers, Climatic Change 103, 571-595, doi: 10.1007/s10584-009-9775z.
- Pielke, R.A., and R.L. Wilby (2012), Regional climate downscaling: What's the point?, Eos, 93, 52-53, doi: 10.1029/2012EO050008.

- Pitlick, J., Y. Cui, and P. Wilcock (2009), Manual for Computing Bed Load Transport Using BAGS (Bedload Assessment for Gravel-bed Streams) Software, United States Department of Agriculture Forest Service Rocky Mountain Research Station Stream Systems Technology Center, Fort Collins, CO.
- Praskievicz, S. (2014a), Impacts of projected climate changes on streamflow and sediment transport for three snowmelt-dominated rivers in the interior Pacific Northwest, Water Resour. Res., in preparation.
- Praskievicz, S. (2014b), A hierarchical modeling approach to simulating the geomorphic response of river systems to climate change, J. Geophys. Res.-Earth, in preparation.
- Praskievicz, S., and P. Bartlein (2014), Hydrologic modeling using elevationally adjusted NARR and NARCCAP regional climate-model simulations: Tucannon River, Washington, J. Hydrol., in press.
- Praskievicz, S., and H. Chang (2009), A review of hydrological modelling of basin-scale climate change and urban development impacts, Prog. Phys. Geog., 33, 650-671, doi: 10.1177/0309133309348098.
- Praskievicz, S., and H. Chang (2011), Impacts of climate change and urban development on water resources in the Tualatin River Basin, Oregon, Ann. Assoc. Am. Geogr., 101, 249-271, doi: 10.1080/00045608.2010.544934.
- Press, W.H. (1992), Numerical Recipes in FORTRAN: The Art of Scientific Computing, Cambridge University Press, New York, NY.
- PRISM Climate Group (2011), PRISM Products Matrix, data last accessed 2011-09-01. http://www.prism.oregonstate.edu/products/matrix.phtml?view=data.
- Prudhomme, C., N. Reynard, and S. Crooks (2002), Downscaling of global climate models for flood frequency analysis: Where are we now?, Hydrol. Process., 16, 1137-1150, doi: 10.1002/hyp.1054.
- Racherla, P.N., D.T. Shindell, and G.S. Faluvegi (2012), The added value to global model projections of climate change by dynamical downscaling: A case study over the continental U.S. using the GISS-ModelE2 and WRF models, J. Geophys. Res., 117, D20118, doi: 10.1029/2012JD018091.
- Ragettli, S., F. Pellocciotti, R. Bordoy, and W.W. Immerzeel (2013), Sources of uncertainty in modeling the glaciohydrological response of a Karakoram watershed to climate change, Water Resour. Res., 49, 6048-6066, doi: 10.1002/wrcr.20450.
- Raje, D., and P.P. Mujumdar (2010), Constraining uncertainty in regional hydrologic impacts of climate change: Nonstationarity in downscaling, Water Resour. Res., 46, W07543, doi: 10.1029/2009WR008425.

- Rasmussen, S.H., M.B. Butts, S.M. Lerer, and J.C. Refsgaard (2012), Parameterisation and scaling of the land surface model for use in a coupled climate-hydrological model, J. Hydrol., 426-427, 63-78, doi: 10.1016/j.jhydrol.2012.01.014.
- Räty, O., J. Räisänen, and J.S. Ylhäisi (2014), Evaluation of delta change and bias correction methods for future daily precipitation: Intermodel cross-validation using ENSEMBLES simulations, Clim. Dynam., 42, 2287-2303, doi: 10.1007/s00382-014-2130-8.
- Regonda, S.K., B. Rajagopalan, M. Clark, and J. Pitlick (2005), Seasonal cycle shifts in hydroclimatology over the western United States, J. Climate, 18, 372-384, doi: 10.1029/2009WR008425.
- Reneau, S.L., D. Katzman, G.A. Kuyumjian, A. Lavine, and D.V. Malmon (2007), Sediment delivery after a wildfire, Geology, 35, 151-154, doi: 10.1130/G23288A.1.
- Rolland, C. (2003), Spatial and seasonal variations of air temperature lapse rates in alpine regions, J. Climate, 16, 1032-1046, doi: 10.1175/1520-0442(2003)016.
- Saha, S., S. Moorthi, H.L. Pan, X.R. Wu, J.D. Wang, S. Nadiga, P. Tripp, R. Kistler, J. Woollen, D. Behringer, H.X. Liu, D. Stokes, R. Grumbine, G. Gayno, J. Wang, Y.T. Hou, H.Y. Chuang, H.M.H. Juang, J. Sela, M. Iredell, R. Treadon, D. Kleist, P. Van Delst, D. Keyser, J. Derber, M. Ek, J. Meng, H.L. Wei, R.Q. Yang, S. Lord, H. Van den Dool, A. Kumar, W.Q. Wang, C. Long, M. Chelliah, Y. Xue, B.Y. Huang, J.K. Schemm, W. Ebisuzaki, R. Lin, P.P. Xie, M.Y. Chen, S.T. Zhou, W. Higgins, C.Z. Zou, Q.H. Liu, Y. Chen, Y. Han, L. Cucurull, R.W. Reynolds, G. Rutledge, and M. Goldberg (2010), The NCEP climate forecast reanalysis system, B. Am. Meteorol. Soc., 91, 1015-1057, doi: 10.1175/2010Bams3001.1.
- Santer, B.D., C. Mears, F.J. Wentz, K.E. Taylor, P.J. Gleckler, T.M.L. Wigley, T.P. Barnett, J.S. Boyle, W. Brüggemann, N.P. Gillett, S.A. Klein, G.A. Meehl, T. Nozawa, D.W. Pierce, P.A. Stott, W.M. Washington, and M.F. Wehner (2007), Identification of human-induced changes in atmospheric moisture content, P. Natl. Acad. Sci., 104, 15248-15253, doi: 10.1073/pnas.0702872104.
- Schmidt, J.C., R.A. Parnell, P.E. Grams, J.H. Hazel, M.A. Kaplinski, L.E. Stevens, and T.L. Hoffnagle (2001), The 1996 controlled flood in Grand Canyon: Flow, sediment transport, and geomorphic change, Ecol. Appl., 11, 657-671, doi: 10.1890/1051-0761(2001)011[0657:TCFIGC]2.0.CO;2.

Schumm, S.A. (1969), River metamorphosis, J. Hydraul. Eng. – ASCE 95, 255.

Segond, M.-L., H.S. Wheater, and C. Onof (2007), The significance of spatial rainfall representation for flood runoff estimation: A numerical evaluation based on the Lee catchment, UK, J. Hydrol., 347, 116-131, doi: 10.1016/j.jhydrol.2007.09.040.

- Shrestha, B., M.S. Babel, S. Maskey, A.van Griensven, S. Uhlenbrook, A. Green, and I. Akkharath (2013), Impact of climate change on sediment yield in the Mekong River basin: A case study of the Nam Ou basin, Lao PDR, Hydrol. Earth Syst. Sc., 17, 1-20, doi: 10.5194/hess-17-1-2013.
- Shrestha, R.R., Y.B. Dibike, and T.D. Prowse (2012), Modeling climate change impacts on hydrology and nutrient loading in the Upper Assiniboine catchment, J. Am. Water Resour. As., 48, 74-89, doi: 10.1111/j.1752-1688.2011.00592.x.
- Salathé, E.P., P.W. Mote, and M.W. Wiley (2007), Review of scenario selection and downscaling methods for the assessment of climate change impacts on hydrology in the United States Pacific Northwest, Int. J. Climatol., 27, 1611-1621, doi: 10.1002/joc.1540.
- Stakhiv, E.Z. (2011), Pragmatic approaches for water management under climate change uncertainty, J. Am. Water Resour. As., 47, 1183-1196, doi: 10.1111/j.1752-1688.2011.00589.x.
- Stewart, I.T., D.R. Cayan, and M.D. Dettinger (2004), Changes in snowmelt runoff timing in western North America under a "business as usual" climate change scenario, Climatic Change, 62, 217-232, doi: 10.1023/B:CLIM.0000013702.22656.e8.
- Surfleet, C.G., and D. Tullos (2013), Variability in effect of climate change on rain-onsnow peak flow events in a temperate climate, J. Hydrol., 479, 24-34, doi: 10.1016/j.jhydrol.2012.11.021.
- Tebbens, L.A., A. Veldkamp, and S.B. Kroonenberg (1998), The impact of climate change on the bulk and clay geochemistry of fluvial residual channel infillings: The Late Weichselian and Early Holocene River Meuse sediments (The Netherlands), J. Quaternary Sci. 13, 345-356, doi: 10.1002/(SICI)1099-1417(199807/08)13:4<345::AID-JQS384>3.0.CO;2-B.
- Teutschbein, C., F. Wetterhall, and J. Seibert (2011), Evaluation of different downscaling techniques for hydrological climate-change impact studies at the catchment scale, Clim. Dynam., 37, 2087-2105, doi: 10.1007/s00382-010-0979-8.
- Thodsen, H., B. Hasholt, and J.H. Kjærsgaard (2008), The influence of climate change on suspended sediment transport in Danish rivers, Hydrol. Process., 22, 764-774, doi: 10.1002/hyp.6652.
- Thomas, M.F., J. Nott, A.S. Murray, and D.M. Price (2007), Fluvial response to late Quaternary climate change in NE Queensland, Australia, Palaeogeog. Palaeocl., 251, 119-136, doi: 10.1016/j.palaeo.2007.02.021.
- Tobin, C., L. Nicotina, M.B. Parlange, A. Berne, and A. Rinaldo (2011), Improved interpolation of meteorological forcings for hydrologic applications in a Swiss Alpine region, J. Hydrol., 401, 77-89, doi: 10.1016/j.jhydrol.2011.02.010.

- Trenberth, K.E. (1999), Conceptual framework for changes of extremes of the hydrological cycle with climate change, Climatic Change, 42, 327-339, doi: 10.1023/A:1005488920935.
- Tucker, G.E., and G.R. Hancock (2010), Modelling landscape evolution, Earth Surf. Proc. Land., 35, 28-50, doi: 10.1002/esp.1952.
- United States Army Corps of Engineers (USACE) (2010), HEC-RAS River Analysis System: User's Manual, USACE Institute for Water Resources Hydrologic Engineering Center, Davis, CA.
- United States Geological Survey (USGS) (2011), USGS Surface-Water Monthly Statistics for the Nation, data last accessed 2011-09-01. <u>http://waterdata.usgs.gov/nwis/monthly/?referred\_module=sw</u>.
- Van Balen, R.T., F.S. Busschers, and G.E. Tucker (2010), Modeling the response of the Rhine-Meuse fluvial system to Late Pleistocene climate change, Geomorphology, 114, 440-452, doi: 10.1016/j.geomorph.2009.08.007.
- Van De Wiel, M.J., T.J. Coulthard, M.G. Macklin, and J. Lewin (2007) Embedding reach-scale fluvial dynamics within the CAESAR cellular automaton landscape evolution model, Geomorphology, 90, 283-301, doi: 10.1016/j.geomorph.2006.10.024.
- Vanrheenen, N.T., A.W. Wood, R.N. Palmer, and D.P. Lettenmaier (2004), Potential implications of PCM climate change scenarios for Sacramento-San Joaquin River Basin hydrology and water resources, Climatic Change, 62, 257-281, doi: 10.1023/B:CLIM.0000013686.97342.55.
- Vicuña, S., and J.A. Dracup (2007), The evolution of climate change impact studies on hydrology and water resources in California, Climatic Change, 82, 327-350, doi: 10.1007/s10584-006-9207-2.
- Vicuña, S., R.D. Garreaud, and J. McPhee (2011), Climate change impacts on the hydrology of a snowmelt driven basin in semiarid Chile, Climatic Change, 105, 469-488, doi: 10.1007/s10584-010-9888-4.
- Wallick, J.R., S.W. Anderson, C. Cannon, and J.E. O'Connor (2012), Channel change and bed-material transport in the Lower Chetco River, Oregon, United States Geological Survey, Reston, VA.
- Walling, D.E., and D. Fang (2003), Recent trends in the suspended sediment loads of the world's rivers, Global Planet. Change, 39, 111-126, doi: 10.1177/0309133308094849.
- Wallinga, J., T.E. Törnqvist, F.S. Busshers, and H.J.T. Weerts (2004), Allogenic forcing of the late Quaternary Rhine-Meuse fluvial records: The interplay of sea-level change, climate change and crustal movements, Basin Res., 16, 535-547, doi: 10.1111/j.1365-2117.2004.00248.x.
- Wang, H., Z. Yang, Y. Saito, J.P. Liu, X. Sun, and Y. Wang (2007), Stepwise decreases of the Huanghe (Yellow River) sediment load (1950-2005): Impacts of climate change and human activities, Global Planet. Change 57, 331-354, doi: 10.1016/j.gloplacha.2007.01.003.
- Ward, P.J., R.T. van Balen, G. Verstraeten, H. Renssen, and J. Vandenberghe (2009), The impact of land use and climate change on late Holocene and future suspended sediment yield of the Meuse catchment, Geomorphology, 103, 389-400, doi: 10.1016/j.geomorph.2008.07.006.
- Western Regional Climate Center (WRCC) (2011), Western U.S. Climate Historical Summaries, data last accessed 2011-09-01. http://www.wrcc.dri.edu/Climsum.html.
- Whitehead, P.G., R.L. Wilby, R.W. Battarbee, M. Kernan, and A.J. Wade (2009), A review of the potential impacts of climate change on surface water quality, Hydrol. Sci. J., 54, 101-123, doi: 10.1623/hysj.54.1.101.
- Wilcock, P.R., and J.C. Crowe (2009), Surface-based transport model for mixed-size sediment, J. Hydraul. Eng. – ASCE 129, 120-128, doi: 10.1061/~ASCE!0733-9429~2003!129:2~120!.
- Wilcock, P., J. Pitlick, and Y. Cui (2009), Sediment Transport Primer: Estimating Bed-Material Transport in Gravel-Bed Rivers, United States Department of Agriculture Forest Service Rocky Mountain Research Station Stream Systems Technology Center, Fort Collins, CO.
- Wolman, M.G. (1954), A method of sampling coarse river-bed material, T. Amer. Geophysical Union, 35, 951-956.
- Wolman, M.G., and J.P. Miller (1960), Magnitude and frequency of forces in geomorphic processes, J. Geol., 68, 54-74.
- Wood, A.W., A. Kumar, and D.P. Lettenmaier (2005), A retrospective assessment of National Centers for Environmental Prediction climate model-based ensemble hydrologic forecasting in the western United States, J. Geophys. Res., 110:D04105, doi: 10.1029/2004JD004508.
- Wood, A.W., L.R. Leung, V. Sridhar, and D.P. Lettenmaier (2004), Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs, Climatic Change, 62:189-216, doi: 10.1023/B:CLIM.0000013685.99609.9e.
- Wood, A.W., E.P. Maurer, A. Kumar, and D.P. Lettenmaier (2002), Long range experimental hydrologic forecasting for the eastern United States, J. Geophys. Res., 107:4429, doi: 10.1029/2001JD000659.

- Wu, H., J.S. Kimball, M.E. Elsner, N. Mantua, R.F. Adler, and J. Stanford (2012), Projected climate change impacts on the hydrology and temperature of Pacific Northwest rivers, Water Resour. Res., 48, W11530., doi: 10.1029/2012WR012082.
- Xu, C.-Y. (1999), From GCMs to river flow: A review of downscaling methods and hydrologic modeling approaches, Prog. Phys. Geog., 23, 229-249, doi: 10.1177/030913339902300204.
- Young, C.A., M.I. Escobar-Arias, M. Fernandes, B. Joyce, M. Kiparsky, J.F. Mount, V.K. Mehta, D. Purkey, J.H. Viers, and D. Yates (2009), Modeling the hydrology of climate change in California's Sierra Nevada for subwatershed scale adaptation, J. Am. Water Resour. As., 45, 1409-1423, doi: DOI: 10.1111/j.1752-1688.2009.00375.x.
- Zhu, Y.-M., X.-X. Lu, and Y. Zhou (2008), Sediment flux sensitivity to climate change: A case study in the Longchuanjiang catchment of the upper Yangtze River, China, Global Planet. Change, 60, 429-442, doi: 10.1016/j.gloplacha.2007.05.001.