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

S. PRASKIEVICZ*
Department of Geography, University of Alabama, Tuscaloosa, Alabama, USA

ABSTRACT

Anthropogenic climate change is likely to have significant impacts on river systems, particularly on rivers dominated by seasonal snowmelt. In addition to altering the timing and magnitude of streamflow, climate change can affect the energy available to transport sediment, as well as the availability of sediment to be transported. These hydrologic changes are sensitive to local climate, which is largely controlled by topography, but climate models cannot resolve processes at these scales. Here, I investigate impacts of climate change on streamflow and suspended-sediment transport for three snowmelt-dominated rivers in the interior Pacific Northwest – the Tucannon River in Washington and the South Fork Coeur d'Alene and Red rivers in Idaho – using downscaled climate simulations from regional climate models (a range of three models plus an ensemble average) to drive a basin-scale hydrologic model. The results indicate that climate change is likely to amplify the annual cycle of river discharge, producing higher winter discharge (increases in ensemble mean January discharge ranging from 4.1% to 34.4% for the three rivers), an earlier spring snowmelt peak (by approximately one month), and lower summer discharge (decreases in ensemble mean July discharge ranging from 5.2% to 47.2%), relative to a late 20th-century baseline. The magnitude of the largest simulated flood under the ensemble-average climate change scenario increases by 0.6–41.6% across the three rivers. Simulated changes in suspended-sediment transport generally follow the changes in streamflow. These changes in discharge and sediment transport will likely produce significant impacts on the study rivers, including changes in flooding, physical habitat, and river morphology.

KEY WORDS: climate impacts; modelling; Pacific Northwest; streamflow; sediment transport; snow and ice

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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). Changes in precipitation are likely to exhibit significant spatial variability, and there is great uncertainty associated with future changes in precipitation because of different parameterizations of the relevant processes among different climate models.

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 supplement 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 50 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.

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

*Correspondence to: S. Praskievicz, Department of Geography, University of Oregon, 1251 University of Oregon, Eugene, Oregon 97403-1251, USA. E-mail: spraskievicz@ua.edu

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 affect a variety of socially and ecologically significant aspects of river systems, including river morphology, water quality, and physical habitat.

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, high-resolution (at least 15-km) climate models are needed. This resolution is finer than that of all general circulation models (GCMs) and most regional climate models (RCMs) (Buytaert *et al*., 2010). Climate model output must therefore be dynamically or statistically downscaled, which contributes significant uncertainty to the process of modelling 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 the 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 snowmelt-dominated rivers using basin hydrologic models (e.g. Pfister *et al*., 2004; Hay and McCabe, 2010; Vicuña *et al*., 2011; Jung *et al*., 2012; Ligare *et al*., 2012; Shrestha *et al*., 2012; Wu *et al*., 2012; Cuo *et al*., 2013; Ficklin *et al*., 2013a; 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 modelling 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.

METHODS

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 1). I chose these rivers in part because all three have United States Geological Survey (USGS) or United States Forest Service (USFS) stream gauges 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. Differences in basin physiography control differences in climate and hydrology among the three basins (Figure 2, Table I). The mean elevation of the Tucannon River Basin is 911 m, compared with 1245 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 higher-elevation basins (annual mean temperatures of 8.2

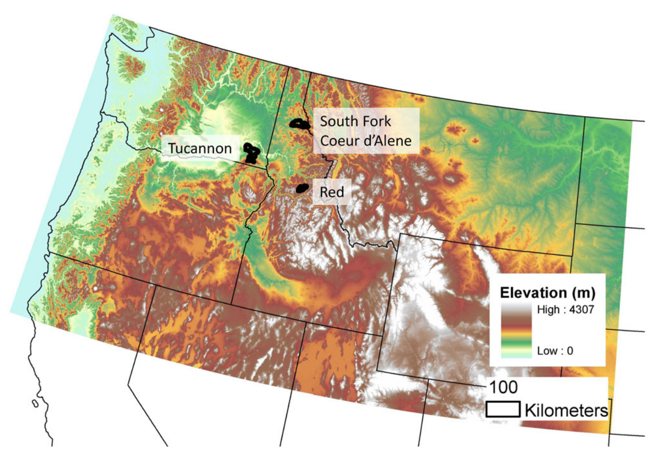

Figure 1. Locations of Tucannon, South Fork Coeur d'Alene, and Red river basins. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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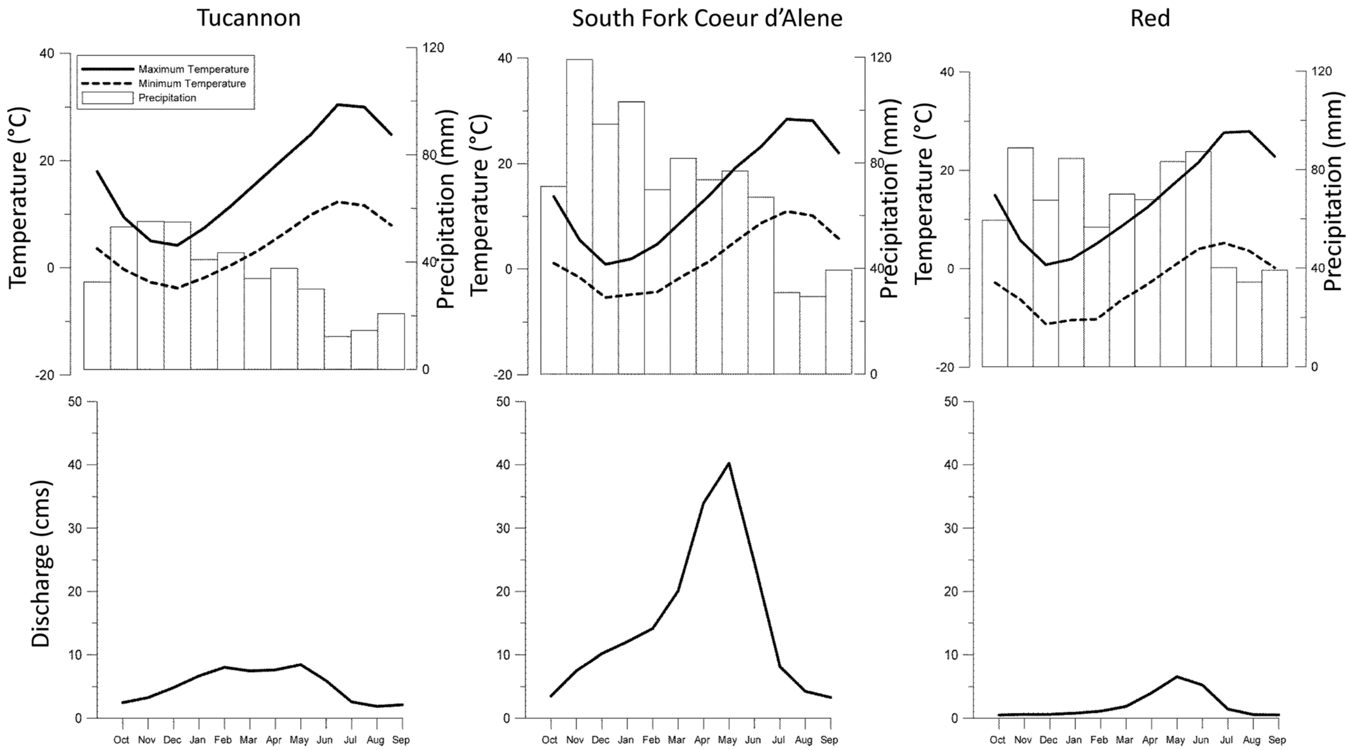

Figure 2. The 1980–2010 annual (water-year) climagraphs for (a) the Tucannon River Basin (Pomeroy, Washington, weather station); (b) South Fork Coeur d'Alene River Basin (Kellogg, Idaho, weather station); (c) Red River Basin (Elk City, Idaho, weather station); annual (water-year) hydrograph for (d) the Tucannon River (USGS gauge 13344500, Starbuck, Washington); (e) the South Fork Coeur d'Alene River (USGS gauge 12413470, Pinehurst, Idaho); and (f) the Red River (USFS gauge at Red River Ranger Station, Idaho). Data sources: NCDC (2014) and USGS (2014)

and 5.4 °C and average annual precipitation of 71.4 and 64.9 cm for the South Fork Coeur d'Alene and Red river basins, respectively). 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.

SWAT calibration and validation

I simulated daily discharge and suspended-sediment load on the study rivers using 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

Table I. Study basin characteristics

Variable	Tucannon	South Fork Coeur d'Alene	Red
Drainage area (km^2)	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)

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, 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 gauges on each river, evaluating fit using the Nash–Sutcliffe efficiency criterion (NSE; Nash and Sutcliffe, 1970) and percent bias. The longest available continuous periods of gauging station records were used for calibration and validation. For discharge, at least 6 years of both calibration and validation data were used on all three rivers, but only 1 year each of continuous suspended-sediment data were available for the calibration and validation periods (Table II).

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 III). These projections are based on NARCCAP, which includes output from a total of 10 combinations of six RCMs driven by a set of four GCMs, for two periods: a baseline period of 1968–1998 and a future climate change period of 2038–2068 under the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios 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 projections to 800 m by elevationally adjusting the NARCCAP grid using empirically estimated local topographic lapse rates. I then bias-corrected the resulting elevationally adjusted 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). The lapse rate downscaled climate projections were found to have positive forecast skill relative to interpolated RCM output and other reference climatologies, and hydrologic modelling results using the lapse rate downscaled climate more closely reproduced observed gauging station records than those using the interpolated RCM output (Praskievicz and Bartlein, 2014).

Figure 3 shows the range of relative changes in maximum and minimum temperature and precipitation for the three basins among all 10 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 modelling 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. From the full suite of 10 GCM–RCM

Table II. Calibration and validation statistics

River	Variable	Calibration time period	Validation time period	Calibration NSE	Validation NSE	Calibration bias (%)	Validation bias (%)
Tucannon	Streamflow	1980–1985	1974–1979	0.64	0.51	4.1	−12.3
South Fork Coeur d'Alene	Streamflow	1991−2000	2001−2010	0.62	0.62	3.6	10.8
Red	Streamflow	1980–1989	1990–1999	0.62	0.50	−3.1	12.7
Tucannon	Suspended sediment	1963	1964	0.49	0.10		
South Fork Coeur d'Alene	Suspended sediment	1993	1994	0.36	0.26	−31.1 27.6	−87.3 74.9
Red	Suspended sediment	1980	1981	0.45	0.31	−33.8	−72.4

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Table III. Hydrologic modelling results[a]

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

[a]Simulated changes are for future period (2038–2068) relative to baseline (1968–1998).

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'; ECP2-GFDL, UC San Diego/Scripps Experimental Climate Prediction Center Regional Spectral Model forced by Geophysical Fluid Dynamics Model GCM), the one with the largest temperature increase ('hot'; CRCM-CGCM for the Tucannon River, OURANOS/UQAM Canadian Regional Climate Model forced by Coupled Global Climate Model; CRCM-CCSM for the South Fork Coeur d'Alene and Red Rivers, CRCM forced by Community Climate System Model), and the one with the largest decrease in precipitation ('dry'; HRM-GFDL, Hadley Centre Regional Model forced by GFDL). 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 10 NARCCAP GCM–RCM combinations.

RESULTS

SWAT calibration and validation

After adjustment of the model parameters, the calculated NSE values and percent bias indicate moderately high goodness-of-fit for discharge on all three rivers for the calibration and validation periods (Nash and Sutcliffe, 1970; Figure 4, Table II). NSE values across the three rivers range from 0.62 to 0.64 in the calibration period and from 0.50 to 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 to 0.45 in the calibration period and from 0.26 to 0.40 in the validation period (Figure 5, Table II). NSE compares the model residual variance with 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 suspended-sediment transport incorporates the uncertainty of the simulated discharge, simulating sediment transport is more complicated than simulating discharge, and there is uncertainty in the gauging 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.

Climate change impacts: river discharge

Figure 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

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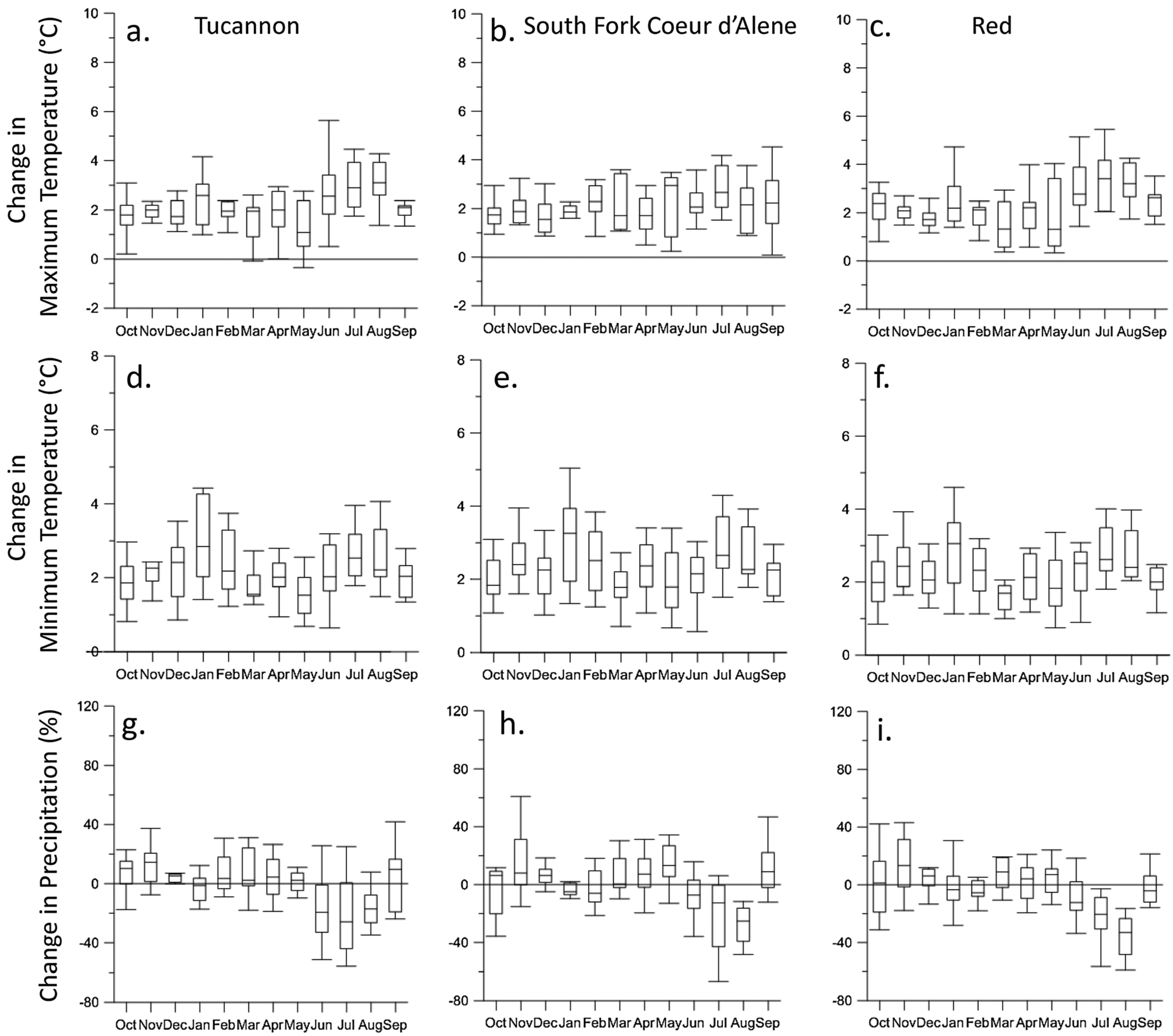

Figure 3. Boxplot summarizations of the relative changes for the NARCCAP future climate period (2038–2068) relative to the baseline period (1968–1998) for 10 NARCCAP GCM-RCM combinations. (a) Change in mean monthly maximum temperature for Tucannon River Basin; (b) change in mean monthly maximum temperature for South Fork Coeur d'Alene River Basin; (c) change in mean monthly maximum temperature for Red 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 precipitation for Tucannon River Basin; (h) change in mean monthly precipitation for South Fork Coeur d'Alene River Basin; and (i) change in mean monthly precipitation for Red River Basin. Note: Whiskers extend from minimum to maximum values

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 6, Table III). 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

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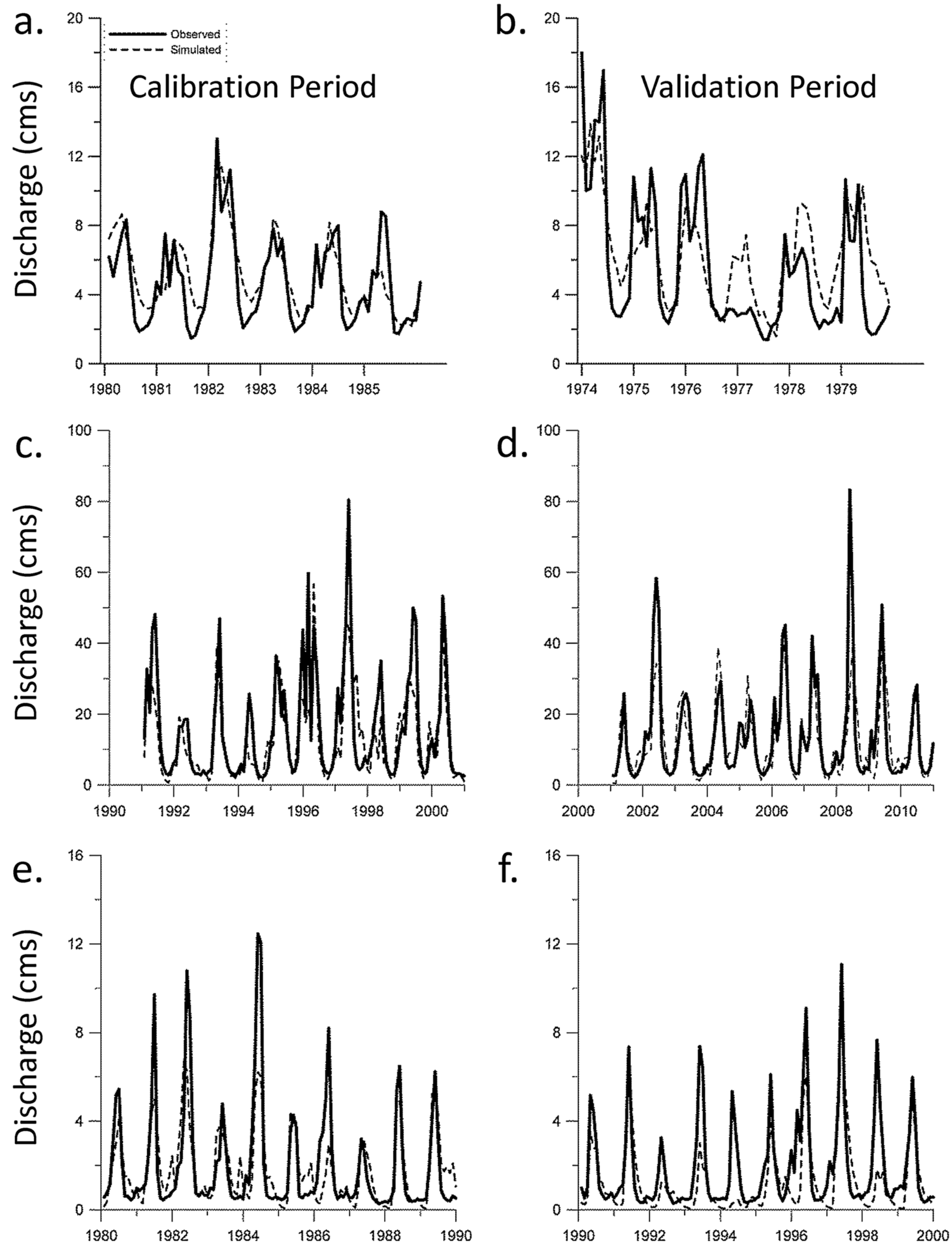

Figure 4. Observed and simulated monthly discharges for (a) the Tucannon River in the calibration period (1980–1985); (b) the Tucannon River in the validation period (1974–1979); (c) the South Fork Coeur d'Alene River in the calibration period (1991–2000); (d) the South Fork Coeur d'Alene River in the validation period (2001–2010); (e) the Red River in the calibration period (1980–1989); and (f) the Red River in the validation period (1990–1999)

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 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

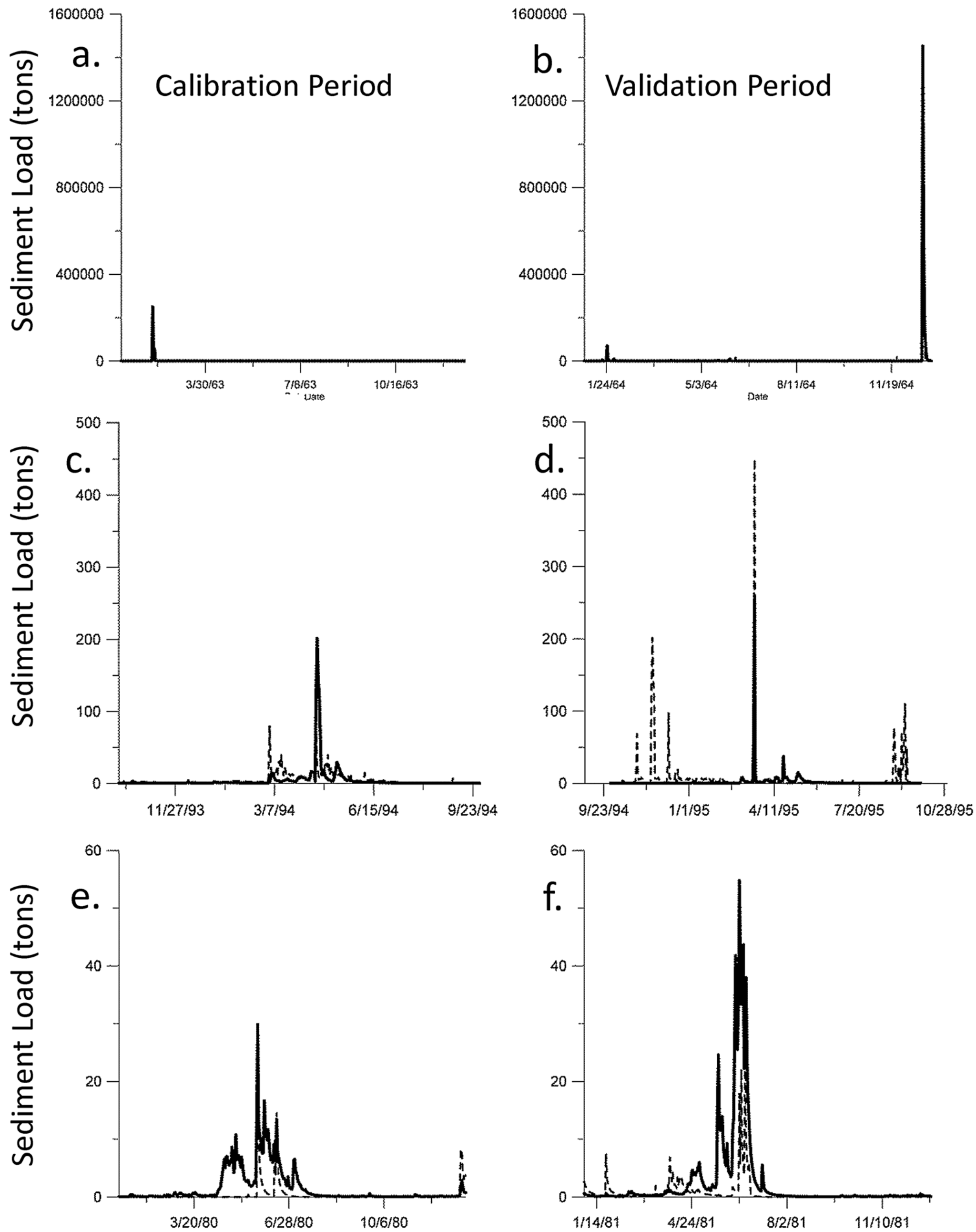

Figure 5. Observed and simulated daily suspended-sediment loads for (a) the Tucannon River in the calibration period (1963); (b) the Tucannon River in the validation period (1964); (c) the South Fork Coeur d'Alene River in the calibration period (1993); (d) the South Fork Coeur d'Alene River in the validation period (1994); (e) the Red River in the calibration period (1980); and (f) the Red River in the validation period (1981)

'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.

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 7, Table III). In the

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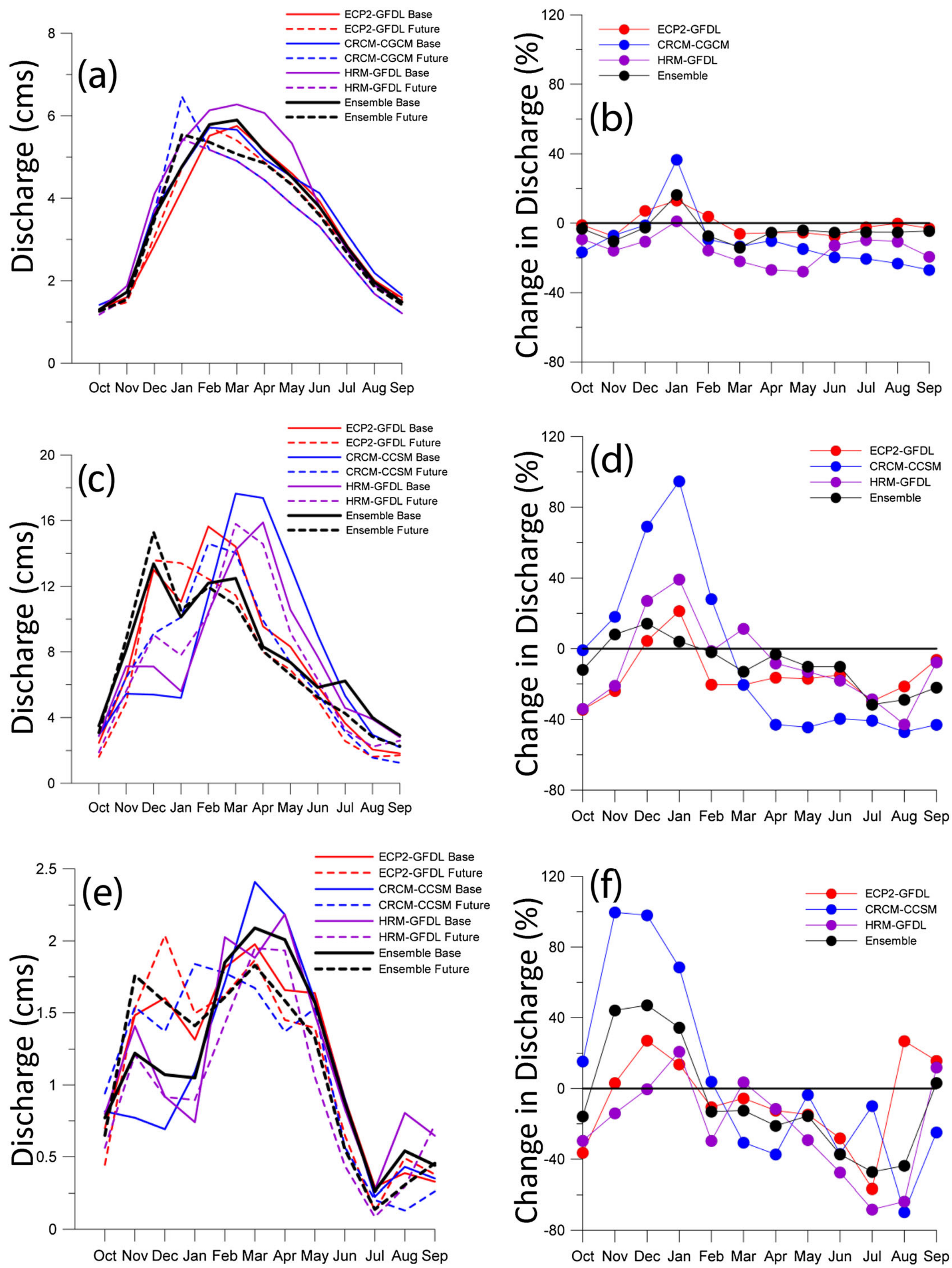

Figure 6. (a) Simulated monthly baseline (1968–1998) and future (2038–2068) discharges on the Tucannon River; (b) change in simulated discharge for the future period (2038–2068) relative to baseline (1968–1998) on the Tucannon River; (c) simulated baseline (1968–1998) and future (2038–2068) discharges 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) and future (2038–2068) discharges on the Red River; and (f) change in simulated baseline (1968–1998) and future (2038–2068) discharges on the Red River. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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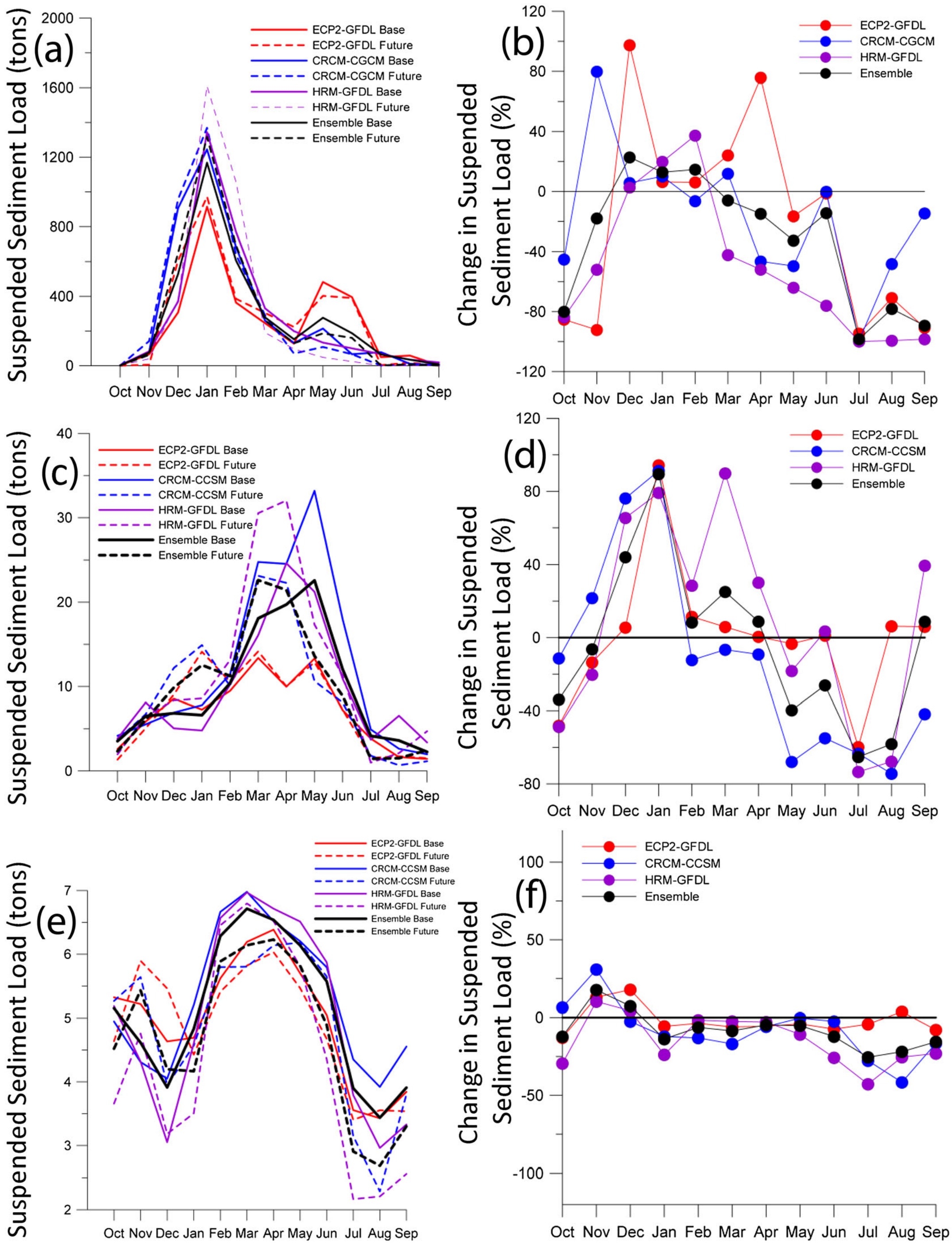

Figure 7. (a) Simulated monthly baseline (1968–1998) and future (2038–2068) suspended-sediment loads on the Tucannon River; (b) change in simulated suspended-sediment load for the future period (2038–2068) relative to baseline (1968–1998) on the Tucannon River; (c) simulated baseline (1968–1998) and future (2038–2068) suspended-sediment loads 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 loads on the Red River; and (f) change in suspended-sediment load for the future period (2038–2068) relative to baseline (1968–1998) on the Red River. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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future scenarios for all rivers, simulated annual and summer suspended-sediment 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).

DISCUSSION

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 modelling studies of other snowmelt-dominated rivers, including 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*., 2013a). Here, the Tucannon River Basin, the lowest elevation of the three study basins, is characterized by a transient hydrological regime that, according to modelling results, is likely to shift to a rainfall-dominated regime under projected climate change. Other modelling 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 Lettenmaier, 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 snowmelt-dominated river basin in Oregon using the Precipitation Runoff Modelling System and found that discharge simulations in the snowmelt-dominated 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, modelling 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.

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 loads. 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 modelling 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 suspended-sediment load can have implications for management of river systems. In excessive amounts, suspended sediment can be considered a water pollutant,

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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 suspended-sediment 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 suspended-sediment 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). An additional potential feedback relates to changes in watershed biomass production resulting from changes in temperature and precipitation, which could in turn affect sediment yield (Ficklin *et al*., 2013b). Further research is needed to illuminate how climate change may affect disturbance frequency and severity, sediment supply, and sediment transport.

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.

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