Climate change alters flood magnitudes and mechanisms in climatically-diverse headwaters across the northwestern United States

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Abstract
Flooding caused by high streamflow events poses great risk around the world and is projected to increase under climate change. This paper assesses how climate change will alter high streamflow events by changing both the prevalence of different driving mechanisms (i.e. ‘flood generating processes’) and the magnitude of differently generated floods. We present an analysis of simulated changes in high streamflow events in selected basins in the hydroclimatically diverse Pacific Northwestern United States, classifying the events according to their mechanism. We then compare how the different classes of events respond to changes in climate at the annual scale. In a warmer future, high flow events will be caused less frequently by snowmelt and more frequently by precipitation events. Also, precipitation-driven high flow events are more sensitive to increases in precipitation than are snowmelt-driven high flow events, so the combination of the increase in both frequency and magnitude of precipitation-driven high flow events leads to higher flood likelihood than under each change alone. Our comparison of the results from two emissions pathways shows that a reduction in global emissions will limit the increase in magnitude and prevalence of these precipitation-driven events.

1. Introduction
The hydrology of river systems is expected to change under projected human-caused changes in air temperature and precipitation. Changes to high flows are of particular interest since they can lead to damaging flooding events (Smith and Katz 2013). A large body of literature assesses how high flows have changed in magnitude in observational records (Mallakpour and Villarini 2015, Matti et al 2017, Yuan et al 2018) as well as their response to projected climate change (Mantua et al 2010, Bürger et al 2011, Taye et al 2011, Köppl et al 2014, Vormoor et al 2015, Knighton et al 2017, Mandal and Simonovic 2017). A growing number of studies recognize the importance of incorporating upstream metrics and processes (e.g. temperature, snow-rain partitioning, soil moisture) into their assessments of changes in high flow magnitudes (Wasko and Sharma 2017, Yan et al 2019, Wasko and Nathan 2019, Davenport et al 2020) and the relative prevalence of different flood generating processes (FGPs; e.g. Berghuijs et al 2016, 2019). However, these studies were all based on the observational record which has limitations for extrapolating under a changing climate. First, applying historic relationships may not hold under a future climate that differs markedly from the observed climate. For example, Diffenbaugh (2020) showed that extrapolation based upon even the most recent historical records can be tenuous. Second, the dominant FGPs may change in an altered climate, particularly when warming causes a substantial change in precipitation phase. No study to date has explicitly calculated sensitivities of high flows, classified according to their dominant FGP, to changes in climate. Our study responds to the grand challenge posed by Sharma et al (2018) calling for a better understanding of the impacts of precipitation changes on floods.
Modeling studies can address changes in the FGP, allowing for a process-based analysis of projected changes in high flows. For example, Musselman et al (2018) examined changes in the rain-on-snow (ROS) FGP across the western U.S. due to projected climate change and calculated the change in ROS-generated rain and snowmelt water available for runoff. However, they highlighted as potential future work the use of a hydrologic model to account for the role that soil plays in changing high flows. Sharma et al (2018) also encouraged further evaluation of the role of the soil column in mediating extreme runoff, particularly under climate change.

This paper aims to understand how climate change will impact both the prevalence of different FGPs and the magnitude of high flows generated by these FGPs. Furthermore, this paper seeks to quantify the ‘sensitivity’ of extreme streamflow generated by distinct FGPs to changes in climate. The streamflow response to changes in temperature or precipitation has been called ‘sensitivity’ (Nijssen et al 2001, Vano et al 2012, Milly et al 2018) or ‘scaling’ (Wasko and Sharma 2017). In this paper we will use the term ‘sensitivity.’ Sensitivities are easy-to-interpret estimates of the response of a chosen variable (in our case streamflow) to climate change. Vano et al (2015) applied the sensitivity approach to annual streamflow across the Pacific Northwest (PNW). Their study provided first-order approximations of hydrologic impacts to aid in scenario selection for decision making. These model experiments did not evaluate sensitivities of extreme high flows. Expanding the sensitivity approach to encompass extreme events can aid in climate change planning for water resources management.

All analyses are based on a large ensemble of climate change projections to provide a more robust analysis of changes in extreme events (van der Wiel et al 2019). Previous studies detail how modeling choices can strongly affect climate change projections of mean streamflow values (Velázquez et al 2013, Addor et al 2014, Alder and Hostetler 2019, Chegwidden et al 2019). Here we use multiple modeling set-ups to better understand the effect of modeling decisions on high flows.

Our study covers a variety of hydroclimatic regions in the Columbia River Basin (figure 1), which allows for the assessment of the effect of projected changes on different dominant FGPs. There is also a strong socioeconomic motivation for studying the Columbia River Basin, which is intensely managed by a variety of stakeholders with often competing interests. Operationally, the system of dams in the region prioritizes flood risk management under international treaty obligations that are under renegotiation at the time of this writing (Bankes 2012).

2. Methods

The methods here are built on Berghuijs et al (2016), Vano et al (2012, 2015), Musselman et al (2018), and Curry and Zwiers (2018). Berghuijs et al (2016) classified extreme flow events as originating from snowmelt, extreme precipitation, or excess soil moisture. We used similar flood classifications as Berghuijs et al (2016). Unlike their methods that related mean timing of floods to mean timing of upstream processes, we linked individual high flow events to upstream hydrologic conditions at or before each specific event. We based our classifications on a set of hydrologic simulations distributed across headwater basins and evaluated how these classifications change under climate change. We classified high flows according to their FGP, anticipating that different FGPs might respond differently to changes in climate.

2.1. Base dataset

We used a large ensemble of hydrologic and climate change simulations for the Pacific Northwestern United States spanning the years 1950 to 2099 (Chegwidden et al 2017) as our base dataset. As described in Chegwidden et al (2019) and River Management Joint Operating Committee (RMJOC; 2018), the simulations represent a multi-model ensemble of hydrologic projections, which is useful for representing uncertainty in projections of the hydrologic response to climate change (Velázquez et al 2013, Bosshard et al 2013, Vormoor et al 2015, Vano et al 2018). The climate projections from two representative concentration pathways (RCPs; mid-range greenhouse gas concentrations, RCP 4.5; high concentrations, RCP 8.5) and 10 global climate models (GCMs) were selected from the Coupled Model Intercomparison Project Phase 5 (Taylor et al 2012). Climate data were downscaled to the spatial resolution of the hydrologic models (~6 km) using the Multivariate Adaptive Constructed Analogs (MACA) downscaling method (Abatzoglou and Brown 2012). The four hydrologic models include three implementations of the Variable Infiltration Capacity model (i.e. VIC-P1, VIC-P2, VIC-P3) and one implementation of the Precipitation Runoff Modeling System (PRMS-P1). The resulting hydrologic simulations do not account for changes in land use or landcover, which can influence hydrologic extremes (Bronstert et al 2002, Blöschl et al 2007, Hurkmans et al 2009). Further details on the construction of the dataset can be found in the Supplementary Materials Section S2.1.

Most analyses to date have used gridded runoff fields taken directly from climate or hydrologic model simulations without routing this runoff through a stream network. We used routed streamflow instead to assess the aggregate impact at locations in the stream network. We analyze headwaters basins...
Figure 1. The 21 headwater study basins.

2.2. Study domain
We conducted our study across 21 headwater basins located in a variety of hydroclimates within the Pacific Northwestern United States (PNW, see figure 1). Broadly, this region is characterized by winter-dominant precipitation (Hamlet et al. 2013). The precipitation falls on regions of complex topography and temperature regimes, creating a spectrum of snow-rain partitioning across the region. The range of hydroclimates creates a variety of ways in which snow mediates the timing of runoff in the region.

As a representative sample, we distributed the 21 headwaters basins among three different hydroclimatic regions: (1) temperate: seven basins in lowland, historically rain-dominant regions, (2) transition: seven basins on the leeward side of the Cascade Range, characterized as basins where precipitation is projected to transition from snow to rain under climate change, and (3) montane: seven high-elevation basins in the Rocky Mountains where snow is generally less at risk under a changing climate (Hamlet et al. 2013, Chegwidden et al. 2019).

2.3. Classifying annual maxima by flood generating process (FGPs)
Our analyses focus on annual maximum flow (AMF) from 1951–2099. We calculated AMF as the highest daily flow to occur in any given water year (WY, October 1—September 30). We specifically selected AMF as opposed to other high flow metrics to create a single value for each year in the study period. As if often done in the literature, we will use the term ‘flood’ when discussing high flow, although we recognize that a river’s AMF will not necessarily exceed its banks. Bankfull flow can be approximated by the one-to two-year return flow, and so the AMF is reasonably representative of flood stage.

We based our FGP classification generally on (Berghuijs et al. 2016) but modified the classification scheme to better suit our objectives. We determined the FGP directly for each AMF event, which is in contrast to Berghuijs et al. (2016) who inferred FGP by aligning the mean timing of streamflow events with the mean timing of precipitation and snowmelt events. Determining the FGP accounts for potential changes in upstream climate and hydrologic states, which is important in a climate change study.

We first collated the AMFs with their corresponding basin-average states and processes (i.e. precipitation and snowmelt) for each model simulation during the period (1950–2099). We then classified each AMF according to its dominant FGP via a decision tree.
The definitions of each FGP and the classification tree are outlined fully in section S2.3. The FGP classes were: (1) Precipitation driven, (2) snowmelt driven, (3) Rain-on-snow (ROS) driven, (4) Other. We limited our analyses to a small number of classes to create a sufficiently large sample size for each classification in our sensitivity analysis (section 2.4). While many hydrologic events result from a diversity of upstream processes (e.g. rain-on-snow at high elevations combined with rain at low elevations), we identified a single, dominant FGP for each high flow event. Accordingly, we selected small headwater basins so that a single upstream FGP was likely to be dominant. We then identified how these FGPs changed under climate change.

For regional analyses, we calculated the portion of events for all simulations at all sites in each region caused by each FGP for each year. This paper does not focus on the ‘Other’ class as it played a minor role overall in our study basins.

2.4. Calculating sensitivities

Vano et al (2012) estimated sensitivities of annual streamflow to changes in annual temperature and precipitation. We instead estimated sensitivities of high flows to changes in annual temperature and precipitation and took the additional step of calculating sensitivities of high flow conditional upon their FGPs.

For each location, we calculated the ensemble’s projected sensitivities to changes in annual temperature and precipitation according to the methods described in Section S2.4 of the Supplementary Materials. Changes in climate were calculated as changes in mean annual precipitation and temperature over the control (WY 1970–1999; ‘1980s’) and future (WY 2070–2099; ‘2080s’) periods for the area upstream of each streamflow location for the years classified by each FGP.

We purposefully base our analyses on annual changes in temperature and precipitation for three reasons. First, we want to provide a first-order understanding of the sensitivity of high streamflow to climate change to support stakeholders with limited access to computing resources or costly modeling studies. These first-order understandings also align well with the existing sensitivity literature which is often with respect to mean annual changes. A similar approach was used by Curry and Zwiers (2018) to investigate linear relationships between high flows and hydroclimate predictors based on the observational record. Second, we reiterate the reasoning of Curry and Zwiers (2018) that the annual precipitation signal is less variable than the daily extremes and thus the sensitivity approach is more robust when calculated upon the annual values.

3. Results and discussion

3.1. High flows will increase in magnitude with smaller subbasins experiencing larger increases

As detailed in Queen et al (2019), AMFs are projected to increase across the PNW at almost all locations under any scenario, in general agreement with Tohver et al (2014). Projected changes in AMFs from all 396 streamflow locations in the Chegwidden et al (2019) ensemble are shown in figure S1 in the supplementary materials (available online at stacks.iop.org/ERL/15/094048/mmedia). As AMF magnitude (and, by proxy, basin size) decreases, the increases in AMF grow larger. The contrast between small and large basins aligns with the suggestion from Sharma et al (2018) that extremes will intensify more strongly in headwater basins. The significance of headwaters basins as being most susceptible to changes in flooding further motivates our focus on smaller basins in this study.

3.2. High flows will shift from snowmelt-driven to precipitation-driven

Snow accumulations are projected to decrease throughout the 21st century with projections of increased temperatures (Elsner et al 2010, Hamlet et al 2013, Gergel et al 2017, Chegwidden et al 2019). Accordingly, the overall role of snow in the hydrology of extreme events is projected to diminish, thus affecting the distribution of FGPs.

Changes in dominant FGP over time demonstrate the changing role that different processes play in the generation of AMF (figure 2). Figure 2(a) shows that in the 20th century AMFs in temperate basins were mostly precipitation driven, with about 25% caused either by snowmelt or rain-on-snow (though mostly snowmelt). By the 2080s under RCP 8.5, ROS-driven AMFs nearly disappear and snowmelt-driven AMFs account for only about 5% of the total.

The transition basins will experience a large shift from snowmelt to precipitation-driven AMFs (figure 2(b)). In the 20th century, precipitation is responsible for only 13% of AMFs but by the end of the 21st century it is responsible for 50% of AMFs. Transition basins also experience a small reduction in the frequency of AMFs caused by ROS (23% to 18%). When compared to the results for RCP 4.5 shown in figure S2, we see that emission mitigation has its greatest impact in transition basins, where mitigation could reduce the share of precipitation-driven AMFs from 50% to 35% by the 2080s.

Our findings contrast with those of Musselman et al (2018) who found that, based on one set of simulations from one high-resolution climate model, ROS incidence would decrease at low elevation basins in the PNW but increase in higher elevation basins. In our study, we see a near disappearance of ROS
AMFs in the temperate (lower elevation) region, and a small decrease in higher elevation regions (figure 3(c)), likely owing to the overall reduction in snow presence. Besides climate model differences, a key distinction between our studies is that the analysis here addressed all FGPs but only for AMF, while Musselman et al. (2018) investigated ROS events only but for all event magnitudes. Changes in smaller magnitude ROS events are not captured by our analyses, which focus on the mechanisms behind the largest events.

As noted in the Introduction, the choice of hydrologic model can substantially impact model results. Figure 3 shows the proportion of AMFs triggered by each of the three major FGPs for each of the three hydro-climatic regions and separated by hydrological models. The control and future (RCP 8.5) periods are shown with open circles and filled triangles, respectively. Simulations from every GCM-hydrologic model-headwater basin permutation are then plotted on the ternary graphs. The results from the four different models are shown in different colors, with the marginal distributions of control (dashed lines) and future (solid lines) displayed along the axes of the ternary diagrams. The mean behavior of the four different hydrologic model results is shown in the differently colored bold circles and triangles with connecting lines.

Generally, the hydrologic models agree on their patterns of shifting from snow-driven to precipitation-driven AMF, as seen by the shift of every circle (control) toward the lower right part of the plot for its corresponding triangle (future) in the mean. Nevertheless, we note several nuances. First, there can be a large spread in the FGP partitioning depending on the region. For example, in the montane region while the means of the different hydrologic models are very tightly clustered, the spreads of the simulations are wide. The transition region shows the greatest hydrologic model diversity, with PRMS behaving markedly differently from the three VIC implementations with more precipitation- and ROS-driven AMFs at the expense of snowmelt events.
We also note that hydrologic models can have a strong impact on the attribution of the process causing the AMF. For example, in every region the PRMS implementation consistently exhibits fewer snowmelt and ROS AMFs in favor of precipitation-driven events. This is a result of a simpler elevation representation in PRMS compared to VIC which allows for high elevation snowfall in regions of complex topography. As another example, the VIC-P1 simulations in the temperate region show more snowmelt-driven AMFs, due to a less flashy hydrograph in those simulations, decreasing the peak of the precipitation events causing the snowmelt peak to be the year’s highest event. Broadly, however, the relative behaviors of the models are preserved under climate change: the relative positions of each marker on the ternary plot is consistent in control and future periods. For example, the PRMS simulations show less snow in all regions in the control period and continue to in the future.

3.3. Projected changes in high flows: precipitation-driven high flows will increase in magnitude more than snowmelt-driven AMFs

The changes in AMF for each FGP and their relationship to changes in climate are plotted in the scatter plots of figure 4. Each row corresponds to a different hydro-climatic region and each column corresponds to a different FGP. Every dot represents, for each (ensemble member-hydrologic model-basin) combination, the mean change in temperature and precipitation along the x- and y-axes, respectively, between control (1980s) and future (2080s) periods, with dots colored by the corresponding change in AMF magnitude. The mean changes in AMF for each FGP/region combination are shown in the upper left bar chart.

Grouping all hydro-climatic regions, precipitation-driven AMFs show the largest increases in flow magnitude, ranging between 29% and 36%. Increased AMF magnitude and increases in annual precipitation are connected because precipitation-driven AMFs are the result of fast-response runoff. With increased precipitation, soils become increasingly saturated, promoting fast-response flow so an individual precipitation event will be converted preferentially into runoff. ROS-driven AMFs show the smallest changes in magnitude (between −9 and +10%), likely because smaller snowpacks counteract the influence of elevated soil moisture that increases the magnitude of precipitation-driven AMFs.

Changes in snowmelt-driven AMFs depend highly on the hydroclimatic regime: while in the transition and montane regions we see average increases of 12% in magnitude, in temperate regions, AMFs increase by 33%. We can explain this difference using the same logic of the interpretation of the precipitation-driven AMFs above. The general pattern for a snowmelt-driven event includes a period of elevated soil moisture due to the melting of an upstream snowpack. Then, for any year’s AMF to satisfy the classification of snowmelt-driven, elevated streamflow due to snowmelt must follow a (series of) precipitation event(s) or warm period triggering intense melt. Because snow plays a smaller role in the temperate region, the AMFs are more likely caused by precipitation events, and thus the sensitivities of the temperate snowmelt-driven AMFs behave more similarly to the precipitation-driven floods. The snowmelt-driven floods in the transition and montane regions experience less of the influence of elevated precipitation and show smaller average increases in AMF (~12%).

3.4. Sensitivities of high flows to changes in climate: up to 2% increase in flood magnitudes in response to 1% increase in annual precipitation

The contours on the panels of figure 4 reflect the multilinear regression of changes in AMF (ΔAMF) on changes in mean annual temperature (ΔT) and annual precipitation (ΔP)

$$\Delta \text{AMF} = \beta_0 + \beta_1 \Delta T + \beta_2 \Delta P.$$  \hspace{1cm} (1)

The coefficients $\beta_1$ and $\beta_2$ for each FGP/region combination (see figure 4 panel titles) represent, respectively, the relative increase in AMF magnitude given a 1 °C increase in annual temperature and a 1% increase in annual precipitation. The contours in each panel represent the linear combination of the response in AMF magnitude over a range of changes in temperature and precipitation from equation (1). As a simple linear regression, equation (1) ignores interactions among predictor variables and non-linearities in the response of AMF to changes in climate, but aids in interpretability of the coefficients $\beta_1$ and $\beta_2$.

Sensitivities are positive for annual precipitation for all FGP’s and regions. The region/FGP combinations with higher changes in AMF magnitude also have higher sensitivities. For example, precipitation-driven events in montane regions (average increase 28%; upper left panel) show a high flow sensitivity ($\beta_2$) of 1.67 %/% (bottom left panel) compared to the 1.40 %/% sensitivity of ROS-driven AMF in montane regions (which only increase on average by 9%). We note that the temperature sensitivity is more variable across FGP’s and regions, with the strongest coefficient being −2.0 %/°C. Because the units of changes in temperature [°C] and precipitation [%] are not directly comparable, we cannot say that one scenario is ‘twice as sensitive to changes in precipitation as changes in temperature.’ Nevertheless, we can conclude that increases in annual precipitation show a much stronger relationship with increases in AMF than changes in annual temperature. Comparing the slopes of the contours between panels in figure 4 allows us to see whether changes in AMF are more strongly related to temperature for one FGP
compared to another, or in one hydroclimate compared to another.

Changes in mean climate explain, at most, 49% of the variance in changes in AMF (as seen by the $R^2$ values in figure 4), leaving the majority of the variance unexplained. Still, we are able to derive useful first-order relationships between changes in high flows and changes in mean climate. For example, the sensitivity approach explains ~40% of the variance in montane regions and changes in snowmelt events. We also find that annual precipitation change is a stronger driver of changes in AMF than changes in annual temperature. For example, the montane region shows almost no temperature sensitivity, potentially because AMFs occur during wet, cold times of the year when ET is low and the changes in temperature are not sufficient to cause a large change in precipitation phase. The two sensitivity regressions with the strongest temperature components (see precipitation-driven events in temperate and transition basins) have among the lowest $R^2$ of those studied. The one example of a relationship with a stronger temperature sensitivity and an $R^2$ above 0.3 is snowmelt events in temperate basins.

4. Conclusions

While AMFs are projected to increase almost universally across the Pacific Northwest, there are distinct differences among flood generating processes (FGP). With reductions in snow, temperate and transition zones will experience AMFs which are precipitation-driven instead of snowmelt-driven. These precipitation-driven events show the greatest sensitivity in their magnitudes with changes in climate and will on average be 35% higher in magnitude. The reasoning behind this higher sensitivity is intuitive: precipitation-driven floods originate...
from fast-response runoff which has less opportunity to be delayed by other mediating processes like infiltration or evapotranspiration and sublimation. This supports Wasko and Nathan (2019) who found that while soil moisture trends can affect less extreme high flow events, higher flow events (including AMF) are mainly controlled by precipitation changes. By the end of the 21st century, ROS events will likely have greater magnitudes but will have a smaller role in controlling AMFs because of a reduced prevalence of ROS. The patterns of shifts from snow to precipitation-driven dominance are largely robust across hydrologic models, though the ability of the models to represent sub-grid scale snow processes, such as multiple elevation zones within each model grid cell, influences the rate of this shift. We also show that a simple linear regression of changes in high flows against changes in mean annual temperature and precipitation can explain about 40% of the variance in the high flow changes. This suggests that a simple linear relationship can provide a first-order analysis of changes in high flows. Further, because of the interpretability of the linear regression framework, we can deduce sensitivities of flood magnitudes ranging between 1% and 2% increases for every 1% increase in annual precipitation. We believe that these are the first published numerical estimates of flood magnitude sensitivity to changes in annual climate and contribute toward the grand challenge posed by Sharma et al (2018).

Finally, a comparison of the differences between the changes in prevalence of each FGP of RCP 4.5 and RCP 8.5 climate scenarios shows the potential for climate change mitigation to limit the risk of increased high flows. Based upon these analyses, a warmer world will experience increased precipitation-induced flooding, which also shows greater sensitivity to changes in climate. This finding presents two interrelated benefits of emissions mitigation: (1) we mitigate flood risk by preserving snowmelt-triggered floods which (2) have a lesser sensitivity to the warming that does occur.

Key points

- In a warmer world, snow will play a less important role in generating high streamflow events.
- Precipitation-driven high flow events show greater sensitivities to changes in climate than other kinds of floods.
- Carbon emissions mitigation would reduce flood risk by limiting the prevalence of precipitation-driven high flow events.

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Data availability statement

The data that support the findings of this study are openly available at the following DOI: https://doi.org/10.5281/zenodo.854763.

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