Chapter 7
Climate Change, Heavy Precipitation and Flood Risk in the Western United States

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Abstract Current flood management, including flood control structures, land use regulations, and insurance markets, is adapted to historic flood risks, often using data from the past 100 years. In places where climate change will increase the flood risk outside the historic exposure, current management practices may not be adequate and losses could become increasingly catastrophic. For planning purposes, communities require scenarios of likely future flood inundation, which requires modeling the combined effects of sea level rise and changing peak flows along the relevant rivers, which in turn are derived from climate models and downscaling methods. In many regions, including the western United States, extreme precipitation is projected to increase with climate change, and these changes would have substantial impacts on flood risk. Simulating the effects of climate change on extreme precipitation presents substantial modeling challenges due to the complex weather dynamics of these events. Downscaling methods are critical to adequately incorporate the effects of climate change on extreme events and to simulate the response of local flood risk to these changes at the spatial and temporal scales most relevant to assessing community-scale risks from flooding. Statistical and dynamical downscaling is discussed and the implications of these methods for flood risk projections is evaluated. A case study is presented that illustrates three primary pathways for climate change impacts on a flood plain (sea level rise, reduced snowpack and higher intensity precipitation extremes) and illustrates the importance of methodological choices.

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Introduction

Heavy rainfall during January 2009 cut off Interstate 5 and other major routes in Washington State, flooded major river drainages throughout the Pacific Northwest, and highlighted limitations in the ability of the Howard Hansen Dam in the Washington Cascades to protect $10–20 billion of assets and infrastructure and tens of thousands of people from flood risk (White et al. 2011). Rainstorms in France and Germany during May 2016 caused rivers to overflow their banks resulting in widespread flooding in Europe. Thousands of homes lost power, the River Seine overflowed in Paris threatening infrastructure and museums. The A.M. Best Company estimates insured losses from the floods at between EUR 0.9 billion and EUR 1.4 billion in France and around EUR 1.2 billion in Germany; especially in Germany, total economic losses were substantially higher. Given the probabilistic nature of rare events such as floods, it is not meaningful to ask whether climate change caused an event. Nevertheless, recent studies of extreme precipitation indicate a clear trend toward increased heavy precipitation in many regions worldwide (Easterling et al. 2000; Groisman et al. 2005) including much of the continental U.S. and parts of the West Coast (DeGaetano 2009; Mass et al. 2011). These trends are consistent with global projections of increased heavy precipitation with climate change (Tebaldi et al. 2006; Trenberth 2011). Positive trends are far from universal, however, and there is considerable uncertainty whether observed local changes are related to global climate change and will persist over the next few decades. In fact, natural variability is likely to continue to be a primary driver of local changes in the near term (Duliére et al. 2013).

Given the known link between human-induced climate change and heavy precipitation (Field et al. 2011; Hattermann et al. 2016) combined with uncertainty due to natural variability, recent events such as described above raise the critical question of whether floods are becoming more frequent as a result of climate change and whether society can expect flood risks to increase over the next few decades. Current flood management, including flood control structures, land use regulations, and insurance markets, is adapted to historic flood risks, often using data from the past 100 years. In places where climate change will increase the risk outside the historic exposure, current management practices may not be adequate and losses could become increasingly catastrophic.

Heavy precipitation in winter storms and snowmelt in spring are the primary causes of high flows and flood risk in much of the western United States (Neiman et al. 2008a). Flood risk is affected by a combination of factors, and modeling these processes requires high spatial resolution to represent the effects of mesoscale weather systems and terrain on extreme events and snowpack dynamics. A severe flooding event in Washington and Oregon in December 2007 illustrated the complex weather and climate factors typical of flood events in the western United States. A sequence of three storms hit the area over three days, the first two produced saturated soils and substantial snow cover in both the lowlands and mountains. The third storm was a so-called atmospheric river event popularly known as a “Pineapple Express”, a common winter storm system that directs warm, moist tropical air to the US West Coast resulting in substantial precipitation and snowmelt. This combination of antecedent conditions and a warm tropical weather event resulted in considerable flooding and mudslides across the region with six counties declared federal disaster areas. Thus, to adequately project future changes in the flood risk due to extreme weather events like those described above, sophisticated climate and hydrologic models must be used that can represent the influences of global climate change, extreme and localized weather systems, antecedent conditions of snow and soil moisture, the flow of water across the land surface and in rivers, and the hydraulic effects of sea-level rise. To this end, we have developed methods, described below, that are applicable at the geographic and temporal scales necessary to inform community planning and response to changes in flood risk. Here, we review several of the important climatic effects that must be considered, outline the methods for simulating flood risk, and provide some case examples where these have been applied. Our focus is on the western United States, but the approach could be generalized and applied in many places worldwide.

Climatic Drivers of Flood Risk

Snowpack Effects

The timing of streamflow in mountainous rivers and streams is strongly controlled by the temperature and the seasonality of precipitation across the watershed that supplies the river. Basin temperature affects the geographic and elevational distribution of snow, and the proportion of winter precipitation falling as snow or rain within a river basin has a strong effect on streamflow. Especially in the Western US (Elsner et al. 2010), this temperature control on snowpack has become a critical means to categorize different rivers according to the seasonal timing of streamflow. Generally speaking, warmer river basins are found at lower elevations and along the coasts while cold basins drain the highest peaks of the Cascade, Sierra, and Rocky mountain ranges. For *rain dominant river basins*, the basin is generally too warm to accumulate snowpack and streamflow is coincident with precipitation. Typically, this results in a single maximum of streamflow and flood risk coincident with the heaviest rainfall in fall. In colder *snow dominant basins*, winter precipitation accumulates as snowpack, and streamflow peaks in spring and summer when the snowpack melts. In these basins, heavy fall precipitation events are essentially absorbed into the snowpack, reducing flood risks. Floods may occur, however, when snowpack melts rapidly into the river during spring. Intermediate temperatures result in transitional *mixed rain-snow basins,* which experience two peaks, corresponding to the fall rain-driven flow and the spring melt. Apart from any changes in precipitation, the effects of temperature can have profound impacts on flow characteristics and the risk of high flows by reducing the flow from melting snow and increasing the rain-driven flow (Hamlet et al. 2013). In addition to the shift towards higher flows in winter, rain-driven flow is more subject to intense precipitation events, resulting in an additional increase in flood risk (Tohver et al. 2014).

Heavy Precipitation

In the words of the Intergovernmental Program on Climate Change (IPCC), evidence for a warming trend in global temperatures is now “unequivocal” (IPCC 2007). The observational evidence for changes in the frequency, duration, and intensity of extreme precipitation events, however, suggest that increases are “likely”, indicating relatively lower confidence that changes have already occurred. At a regional scale, observational and modeling evidence suggest that a trend toward increased precipitation in the western US is only recently emerging (Duliére et al. 2013). The reduced confidence in extreme precipitation trends relative to temperature trends stems from the small number of extreme events in the historical record and the influence of natural variability on short-term trends in extreme events (see for example, Warner et al. 2012). Therefore, it is difficult to attribute recent trends at a single location to an anthropogenic influence on the climate. However, research suggests that over large regions, which aggregate many individual weather events and improve statistical sampling, the observed trend to more frequent extreme events can be statistically attributed to the warming of the climate system with increased greenhouse gas emissions (Min et al. 2011). For example, a study including the entire region of the United Kingdom found that local trends may be detectable at that geographical scale in the next 20 years (Fowler and Wilby 2010). Furthermore, there are strong theoretical reasons to expect increases in heavy precipitation in a warming climate, since warmer air will be able to transport more water vapor into storm systems, following the Claussius-Clapeyron scaling of the saturated vapor pressure with temperature (Pall et al. 2007). Thus, warming would tend to increase the moisture available for precipitation in extreme events (Trenberth 2011) and the intensity of both wet and dry extremes (Held and Soden 2006).

As with the December 2007 event described above, heavy precipitation along the west coast of North America depends on well-known weather patterns (Colle and Mass 1996; Garvert et al. 2007) associated with atmospheric river events (Neiman et al. 2011; Warner et al. 2012). Atmospheric rivers are storm systems that produce an intense stream of warm moist air flowing to the east from the subtropics to the mid-latitudes. They form over the ocean all around the globe in both north and southern hemispheres and produce heavy precipitation along the west coasts of major continents. Atmospheric rivers are controlled by the large-scale circulation patterns in the atmosphere, occurring along waves in the mid-latitude jet stream. Projected changes in the jet stream (Chang 2007; Salathé 2006; Ulbrich et al. 2008) or atmospheric rivers themselves (Leung and Qian 2009; Neiman et al. 2008a, b) would therefore have substantial implications for future extreme precipitation events. In particular, climate models project an increased risk for more frequent extreme precipitation in the western US by the second half of the 21st century (Avise et al. 2009; Fowler et al. 2007) with more intense atmospheric rivers along the west coast (Dettinger 2011) and local intensification in areas of complex terrain (Salathé et al. 2010).

A number of observational and modeling studies find that, at both regional and global scales, total precipitation responds less to anthropogenic climate change than does heavy precipitation (Allen and Ingram 2002; Fowler et al. 2010; Frei and Schär 2001). For example, regional climate model simulations of total precipitation in current and future climate of the western US (Duliére et al. 2013) show inconsistent responses to climate change among three different climate models and across the western U.S. (Fig. 1, top row). However, for precipitation on days exceeding the historic 95th percentile, a more robust increase is found (Fig. 1, bottom row), and all three models show an increase over most of the western U.S. These results suggest that (1) processes strongly linked to climate change (e.g. thermodynamic processes such as moisture convergence, adiabatic lapse rate, large-scale circulation patterns) result in heavier precipitation during rainy events, (2) these effects are robustly simulated across the climate models, and (3) natural climate variability (e.g. El Niño, PDO) has a greater effect on the total annual precipitation. This natural variability will likely continue as in the past, dominating any trends in

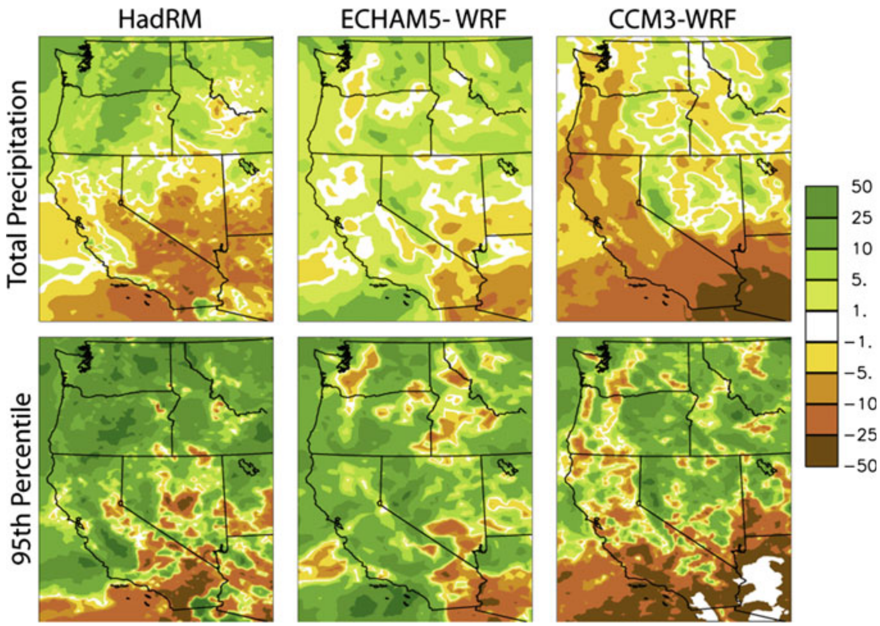

Fig. 1 Percent change from 1970–1999 to 2030–2059 in precipitation on all days (top row) and for days exceeding the historic daily 95th percentile (bottom row). Each column shows results for one of three regional climate model simulations. *Source* authors own

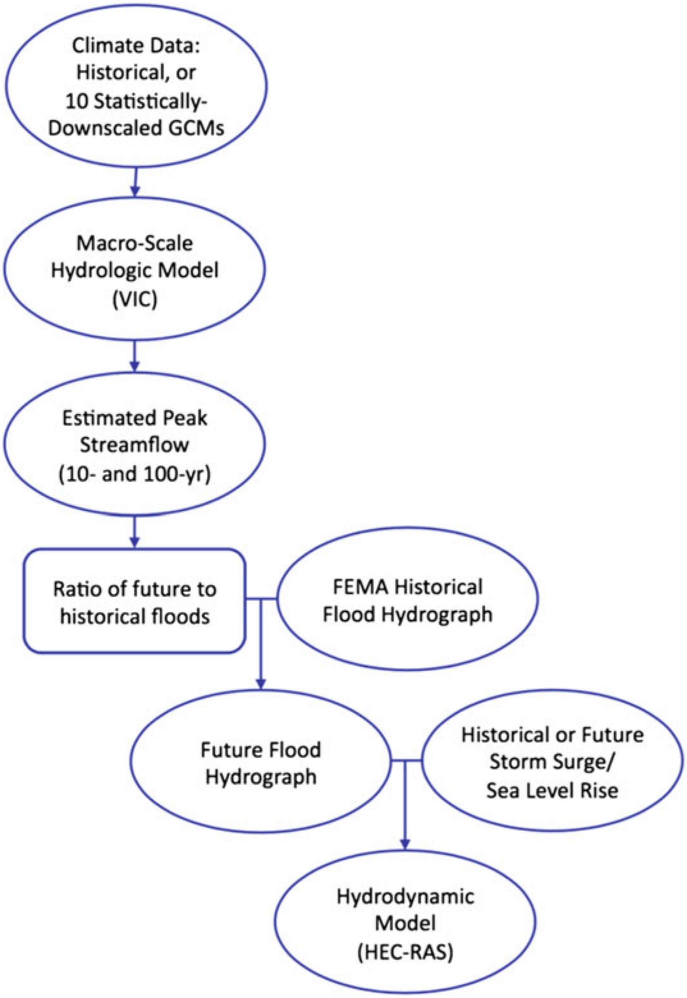

Fig. 2 Flow chart for modeling procedure. *Source* authors own

annual total precipitation (Mote and Salathé 2010). Similarly, Warner et al. (2015) found increases in winter mean precipitation off the west coast of the United States at a rate of about 5% per degree Celsius and changes of 10% or more per degree for atmospheric river events. The natural year-to-year variability in precipitation would overwhelm the modest increase in winter mean precipitation, and this change would not be discernible over the next century. The larger sensitivity of rainfall in atmospheric rivers, however, would emerge from natural variability in a few decades (Fig. 2).

The processes described above consider heavy precipitation at a very large, continental scale. However, the flooding from heavy precipitation impacts very small regions, often along only a few rivers and a few cities or counties. Mountainous terrain can produce localized intensification of precipitation, for example as air is lifted over windward slopes or converges in the lee of mountains with important implications for municipal agencies managing the flooding impacts of heavy precipitation. Alterations in heavy precipitation events associated with climate change include (1) the temporal and spatial extent of heavy precipitation, (2) the temperature anomaly and freezing level associated with storms, (3) the likelihood of storms occurring with specific antecedent conditions (e.g. high soil moisture or snow cover), and (4) the orientation of storms relative to local terrain. From the local perspective, these effects could have profound implications for the flood risks from extreme events that go beyond simple changes in the amount of rainfall, requiring an integrated approach to precipitation and surface hydrology.

Since shifts in the intensity and frequency of heavy precipitation or changes in storm characteristics (e.g. physical extent, duration, tracking relative to terrain) can have a substantial effect on streamflow and flood risk, changes in extreme events would have greater impacts in many regions than changes in total precipitation. The regional climate scenarios discussed here have been specifically designed to represent the response of the local flood risk to these changes at the spatial and temporal scales most relevant to assessing community-scale risks from flooding and to guide decision making in the face of these risks.

Methodological Approaches

To develop estimates of future flood risk from the information provided from global climate models, a number of additional modeling steps must be taken. The objective is to develop scenarios of future risk of flooding using the same parameters and nomenclature used by communities in planning for flood events today. Global climate models (GCMs) are the primary tool for simulating the future climate. Due to the computational constraints of simulating the global coupled atmosphere-ocean-land system, however, global models typically use a grid spacing of 100–200 km or more. While adequate to represent the climate system dynamics responsible for global climate change, information not produced at the spatial scale of the impacts of climate change, typically under 10 km. Thus, the information provided by the global models must be regionalized or downscaled to project the implications of changes in the large-scale environment on local conditions. We have conducted studies of flood risk and climate change using two methods to downscale the information from Global Climate Models, (1) statistical downscaling methods (Tohver et al. 2014) (see http://www.hydro.washington.edu/2860/) and a (2) dynamical downscaling using the Weather Research and Forecasting regional climate model (WRF) (Duliére et al. 2013) Both methods produce consistent high-resolution regional climate data, specifically for precipitation and temperature, which are used to model snowpack and river flows. Data from both products are used in parallel for projecting future flood risks in order to maximize the advantages of the two approaches, as discussed below. Our research has shown that regional climate models project very different future flooding scenarios than statistical downscaling, (Salathé et al. 2010, 2014). The fundamental reason for this difference is that statistical downscaling methods are designed to preserve the rate of change of temperature and precipitation simulated by the global model. Dynamical downscaling, by contrast, represents weather processes that are not resolved by the global models, which could create strong local differences with the global model result. Given the uncertainties in projecting the future climate and limitations of our current state of knowledge, it is not clear which of these approaches provides the best practice in a given application. However, by using both approaches and understanding where and why they diverge, one can gain important insight into the weather and hydrologic processes that contribute to future flood risks.

To generate quantitative flood risk scenarios, the downscaled daily temperature and precipitation projections are used as input to a distributed hydrologic model to simulate daily surface runoff and resulting streamflow volumes. The resulting regional climate and hydrologic scenarios have since been adopted by researchers at the USACE, USFS, and other regional agencies for assessing future flood risks and vulnerabilities (see, for example, Hamlet et al. 2013; Rybczyk et al. 2016).

Statistical Downscaling

The statistical downscaling method used in Tohver et al. (2014) is based on a gridded historical time series of temperature and precipitation from 1916 to 2006. In this dataset, station observations were interpolated onto a 0.0625-degree (1/16-degree) grid with elevational corrections applied to account for the effects of topography (Elsner et al. 2010; Hamlet et al. 2013). Since there are relatively few station observations in areas of high terrain, simple interpolation between stations would produce inaccurate results if the stations are at a lower elevation than the area between them. Daly et al. (1994) developed a sophisticated empirical model of the effects of topography—slope, aspect, and elevation—on the variation in temperature and precipitation with elevation, which is applied in the interpolation process to better represent temperature and precipitation in mountainous regions. To represent future climate conditions based on a global climate model simulation, the historic observations at each grid cell are perturbed to reflect the shift in the monthly-mean probability distribution projected by the global model for that location. Thus, the downscaled climate change scenarios repeat the historic sequence of daily weather, but with the projected future monthly statistics. In this approach, both the mean and higher moments of the observed data change in response to monthly GCM projections, and these changes vary spatially. Although the downscaling represents changes projected by the GCM, the future daily time series behavior and cross correlations of precipitation and temperature, and also the size, location, and inter-arrival time of storms match those in the historical record. As a result, a winter storm event or summer dry spell in the future will have the same location, spatial extent, and duration as its occurrence in the historical record, but the intensity of individual events are scaled to match the change in the monthly values projected by the GCM simulations. These limitations reflect the current lack of confidence in the ability of most global climate models to adequately simulate current and future daily weather statistics such as the time between storms, and until recently, most global modeling centers provided only monthly-mean climate data. Therefore, to aggregate the results from as many global models as possible in an even-handed way, the downscaling is based upon the change in monthly-mean climate, with the historic daily variability preserved. A smaller set of global models do adequately simulate daily weather statistics, and these may be selected for more detailed downscaling using a regional climate model as described below.

By design, the statistical method does not represent all the mechanisms that could affect hydrologic processes in the future. In particular, the characteristics of intense weather events could change in ways the global model does not simulate due to regional-scale atmospheric processes such as deep convection triggered by the terrain. For example, for a north-south oriented mountain range exposed to mid-latitude westerly winds, such as the Cascade Range of Washington and Oregon, precipitation may increase more on the western side than on the eastern side due to the higher intensity of rainfall on the windward slopes and the suppression of precipitation by the rain shadow. Statistical downscaling, therefore, produces regional scenarios of climate change that incorporate primarily the continental-scale and seasonal changes in temperature and precipitation, but not the effects of smaller scale weather processes and terrain interactions. With regard to changing flood risk, for the western U.S., the consensus of global models indicates a shift to more autumn precipitation and warmer autumn temperatures during the next century. The downscaling method allows a detailed simulation of the regional impacts of these shifts in the climate with the greatest confidence.

Regional Climate Model

The dynamical downscaling used for the case studies we discuss here were performed for a northwestern U.S. geographical domain using the Weather and Research Forecasting (WRF) community mesoscale model (Salathé et al. 2008, 2010; Zhang et al. 2009). The domain covers the northwestern U.S. encompassing Washington, Oregon, Idaho, northern California, and southern British Columbia with a spatial resolution of 12 km. Global climate model results obtained from several research centers are used to provide boundary conditions for the regional simulation (please refer to Salathé et al. (2010) for technical details of the regional modeling methods). This kind of simulation, where a coarse-resolution global model is used as input to a high-resolution regional model, is frequently referred to as dynamically downscaling the global model. The dynamical downscaling is performed for several global climate model simulations from the Climate Model

Intercomparison Projects (CMIP3 and CMIP5) (Meehl et al. 2007; Taylor et al. 2011). The Climate Model Intercomparison Project is an organized effort of the international climate modeling community under the World Climate Research Programme (WCRP) beginning in 1995. The project established a standard experimental protocol for studying the output global climate models and to support the Intergovernmental Panel on Climate Change assessments. Nearly all climate modeling centers around the world participate and perform climate simulations of the historic climate and projections of the future climate using common standards and data processing. Future climate projections are performed for a number of scenarios of future climate emissions reflecting a range of greenhouse gas emission pathways. CMIP3 and CMIP5 produced a large ensemble of climate model simulations that could be quantitatively compared against each other and against observations in order to select the most appropriate models for climate impacts studies (Mote and Salathé 2010; Rupp et al. 2013).

Although the regional climate model represents important terrain features and the mesoscale structure of storms that control flooding in rivers better than global models, deficiencies in both the global forcing fields and the regional model remain and introduce biases in the simulated climate variables (Christensen et al. 2008; Wood et al. 2004). Furthermore, to obtain acceptable hydrologic simulations, the simulated temperature and precipitation require additional downscaling from the 12 km WRF grid to the 0.0625-degree (approximately 6-km) grid used for hydrologic modeling as described in detail in Salathé et al. (2014). Briefly, the bias correction is based on a mapping between simulated and observed probability distribution functions to remove bias, while largely preserving local climate signals and time series behavior in the simulation. These steps remove systematic bias in simulated meteorological variables resulting from combined bias in the large scale forcing and WRF simulations.

Hydrologic Model

In order to simulate surface runoff and associated flow in the streams and rivers that collect runoff, the projected climate scenarios are used as input to a surface hydrologic model. In our work, we have used the Variable Infiltration Capacity (VIC) model (Liang et al. 1994) implemented 0.0625-degrees (Elsner et al. 2010). VIC is a macro-scale, fully-distributed hydrologic model that solves the water and energy balance at each model grid cell, producing (among other water balance variables) daily time step runoff and baseflow at each model grid cell. A separate streamflow routing model (Lohmann et al. 1996), is used to generate daily time step streamflows at various river locations from the simulated runoff and baseflow. The VIC model requires daily inputs of total precipitation, maximum and minimum air temperature, and mean wind speed.

The issues discussed above regarding rain and snow effects on river flow are important in understanding the uncertainties in hydrologic simulations. For rain-dominant basins, uncertainties in simulated hydrologic extremes are mostly related to uncertainties in simulated precipitation, which is obtained from the statistical downscaling or regional climate model. in regions where snow is an important part of the hydrologic cycle, however, uncertainties are related to the simulated temperature and to the snow pack simulation from the hydrologic model.

Case Study: Inundation Scenarios and Decision Support

Over the past decade, numerous studies have estimated changes in river flooding, sea level rise, and storm surge; however, few studies have quantified their combined impacts on flood risk. Here we present a case study that assessed the impacts of sea-level rise, storm surge and changing peak streamflows on flood inundation in the lower Snohomish River (for more information, refer to the project report, https://cig.uw.edu/wpcontent/uploads/sites/2/2014/11/FinalReport_CIG_TNC_Snohomish-20141209.compressed.pdf). Flood risk in the lower Snohomish River, located in the Puget Sound Region of Washington State, is impacted from the downstream marine boundary by storm surge and sea level rise (SLR), and from the upstream freshwater boundary by seasonal changes in river flow and hydrologic extremes. Building on previous work on the nearby Skagit River basin (Hamman et al. 2016), we developed projections of changing inundation in the lower Snohomish based on changes in these two boundary forcings. Results from this work have been incorporated into a decision support tool developed by The Nature Conservancy (TNC), designed to support multi-objective floodplain management by partners across Puget Sound. The goal of multi-objective floodplain management is to coordinate flood loss reduction measures with other community needs and goals for the floodplain; it depends on communication between different parties and on the technical and financial help from government agencies and private organizations.

For planning purposes, communities require scenarios of likely future flood inundation—that is, the areas physically covered by flood waters. Producing these scenarios required modeling the combined effects of sea level rise and changing peak flows along the relevant rivers, which in turn are derived from climate models and downscaling methods described above. Thus, we used a chain of computational models to incorporate all these effects as shown in the flow chart in Fig. 3. The climate data, storm surge, and sea-level rise inputs used depends on the climate change scenario and downscaling method selected. By adjusting these inputs, we generate multiple inundation results to provide a range of scenarios for planning.

Regional climate scenarios used in this study follow the methods described above, resulting in future projections of temperature, precipitation, and streamflow. To simulate the resulting changes in flood inundation in the lower Snohomish River, we coordinated with WEST Consultants, who developed a one-dimensional unsteady-flow hydraulic model for the lower Snohomish River using the US Army Corps of Engineers Hydrologic Engineering Center's River Analysis System

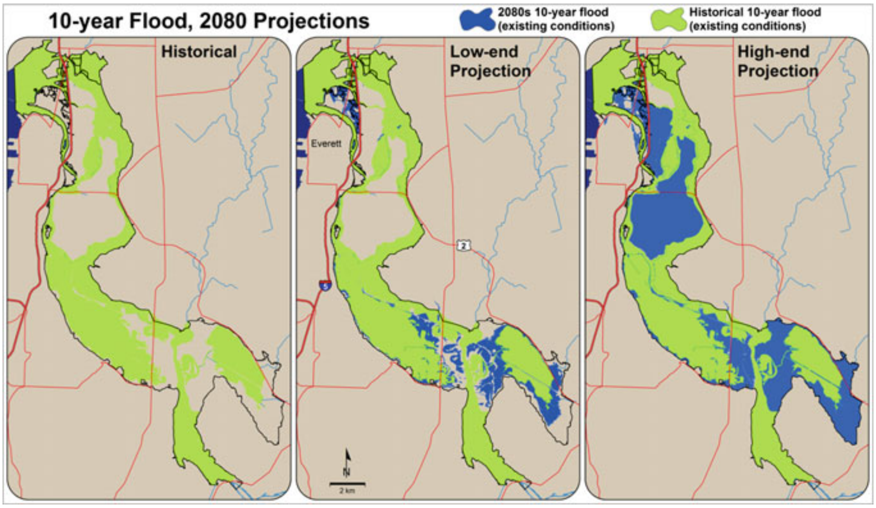

Fig. 3 10-year flood inundation simulated for historic conditions and projected 2080s climate. Green areas are inundated during historical 10-year flood events. Blue areas are flooded in addition during projected future 10-year events based on a low-end and high-end climate projection. *Source* authors own

(HEC-RAS) model. Projections of changing storm surge, SLR, and riverine flooding provided boundary conditions for the hydraulic model, which was used to estimate the combined effects of sea level rise and changing peak flows on flood inundation.

As an upstream boundary condition for simulating current climate conditions, we used existing hydrographs representing the historical 10- and 100-year flood events. These were developed for a Flood Insurance Study (FIS) for Federal Emergency Management Agency (FEMA) Region 10. We then developed projected future flood events by scaling these historical hydrographs. The scaling factors were determined using the ratio of simulated future to historical flow intensities at the corresponding return periods. The future flood events were simulated using the methods described in the previous section: temperature and precipitation are obtained from both the statistical downscaling and regional climate model (WRF) and streamflow from the VIC hydrologic model.

For flood statistics, we extracted the 1-, 3-, 5-, and 7-day consecutive highest flows for each year and ranked the values by flow magnitude. A quantile was assigned to each value using an unbiased quantile estimator (Maidment 1993). These were fit to a Generalized Extreme Value (GEV) Distribution using L-moments (Hosking and Wallis 1993; Wang 1997). For historical as well as two future time periods, we estimated flood magnitudes with 10-year (Q10), 50-year (Q50) and 100-year (Q100) return frequencies from the fitted GEV distributions. These are defined based on the probability that peak flows exceed a certain threshold on any given year. Sometimes referred to as the "Annual Chance of Exceedance" (ACE), the 3 return frequencies correspond to an ACE of 10, 2, and 1%, respectively.

The ratios of future to historical flood events at a given return interval are used to scale observationally-based hydrographs of historical extreme flows. The resulting maximum, median and minimum change projected for the Snohomish River by all ten GCMs is listed in Table 1. Note that there is some tendency towards larger changes for the longer period flows (e.g.: 7-day relative to 1-day), especially for the 50- and 100-year events, although the differences are small compared to the range among models.

The lower, marine boundary condition to the model is determined by total water levels associated with sea level rise, tides, and surge. It is possible that climate change may affect extremes in surface pressure, winds, or circulation due to changes in storm frequency and strength. Hamman et al. (2016) evaluated this possibility, using regional climate model simulations (Salathé et al. 2010, 2014) and a regression model trained on regional variations in sea level pressure and sea surface temperature associated with the El Niño Southern Oscillation (ENSO). Their results, consistent with the findings of Stammer and Hüttemann (2008),

Table 1 Ratio of future to historical floods for the Snohomish River for 1-day, 3-day, 5-day and 7-day consecutive highest flows with a return frequency of 10-year (Q10), 50-year (Q50) and 100-year (Q100) for the 2040s and 2080s. These correspond to the 10, 2, and 1% ACE, respectively. Citation needed!

Time periods	Return interval	Ratio of future to historical peak flow				
			1-Day	3-Day	5-Day	7-Day
2040s	Q10 (10%ACE)	Max	1.60	1.61	1.65	1.65
		Mean	1.25	1.27	1.29	1.29
		Min	1.06	1.08	1.09	1.09
	Q50 (2%ACE)	Max	1.49	1.47	1.51	1.54
		Mean	1.15	1.17	1.20	1.22
		Min	1.01	1.03	1.04	1.04
	Q100 (1%ACE)	Max	1.44	1.41	1.45	1.49
		Mean	1.10	1.12	1.16	1.18
		Min	0.96	0.97	1.03	1.02
2080s	Q10 (10%ACE)	Max	1.78	1.79	1.83	1.82
		Mean	1.40	1.42	1.43	1.43
		Min	1.16	1.18	1.20	1.20
	Q50 (2%ACE)	Max	1.64	1.63	1.64	1.66
		Mean	1.27	1.30	1.31	1.33
		Min	1.04	1.08	1.10	1.12
	Q100 (1%ACE)	Max	1.57	1.56	1.56	1.59
		Mean	1.22	1.25	1.26	1.28
		Min	0.98	1.04	1.06	1.08

suggest that climate change has very little influence on storm surge. Thus, we incorporated the effects of storm surge using the most recent 50-years of hourly observations from Seattle. From these data, we estimate the 10, 50, and 100-year surge values (relative to MHHW) using the same approach described above for peak flows.

Sea Level Rise (SLR) projections were taken from the recent synthesis of projections for the West Coast by the National Research Council (NRC 2012). Among projections of global sea level rise, the NRC projections are within the range of other recent projections—higher than the projections of the recent Intergovernmental Panel on Climate Change (IPCC 2013) report, but lower than those of Vermeer and Rahmstorf (2009). For consistency with the time periods used for the study, the sea level projections were interpolated to 2045 and 2085 using a quadratic fit. The resulting SLR projection for the 2040 s are 3.7 in (low) 5.3 in (medium) 7.3 in (high), and for the 2080 s 9.8 in (low) 16 in (medium) 22 in (high). Subsiding land motion in this location increases the actual sea-level rise, and we accounted for this effect using an estimate of −1 mm/yr for Anacortes, WA (NRC 2012).

In an additional set of simulations we evaluated the impact of levee modifications. In consultation with staff at Snohomish County, we identified two alternative levee scenarios which we could model. The first involved removing the levees protecting Crabb and Beck dikes, which are near the upstream end of the model domain, near the city of Monroe, Washington. The second alternative involved breaching the levees protecting Spencer Island, allowing for the flooding of the island and providing storage area for excess flow volumes that would cause flooding elsewhere. We do not present maps of the results of these simulations since neither had an appreciable effect on flooding due to the lack of adequate storage to accommodate flood water. Although there are other options for providing flood storage, few are currently viable as options given current floodplain development and land use constraints.

Results from this study were incorporated into TNC's "coastalresilience" decision support web tool, which allows users to interactively explore the study results, along with numerous other spatial datasets. Figures 3 and 4 show screenshots of inundation maps as they are displayed in TNC's web tool. These maps illustrate changes both in depth and area. Changes in the depth of inundation, in contrast to areal extent alone, are notable for all scenarios. Projected changes in the areal extent of flooding are large for the 10-year flood, but quite small for the 100-year flood. This is not surprising, since the levees in the lower basin are primarily designed to mitigate 10-year events. This means that the historical 100-year flood, under present-day conditions, should already result in flooding that extends from valley wall to valley wall, which limits the potential changes in flood extent going into the future. In contrast, small changes in the volume of the 10-year flood may lead to large changes in the area inundated. As a result, we expect the area inundated to increase more for moderate flood events rather than for the most extreme events.

A primary goal of this study was to provide a proof-of-concept for incorporating climate change into flood risk assessment and planning. By using a hydraulic model

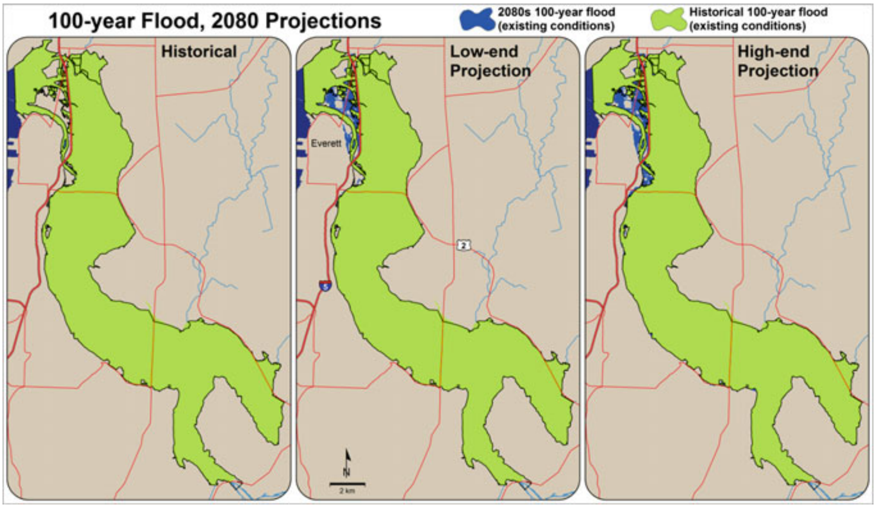

Fig. 4 As for Fig. 3, but for 100-year flood events *Source* authors own

that was essentially off-the-shelf, we were able to assess the combined impacts of SLR and streamflow on flooding at a relatively low cost. Having now established the methodology, this approach could be applied elsewhere in the region at a much lower cost.

Conclusions

The case study cited in this chapter focused on just three pathways for climate change impacts on floodplains: sea level rise, reduced snowpack and higher intensity precipitation extremes. These are key factors, but there are other mechanisms by which climate may impact flood risk such as vegetation loss due to wildfires or stream channel changes due to sediment transport and landslides. Climate change impacts on floodplains also extend beyond changes in flood risk discussed here but also include the impacts on riparian habitat, groundwater, saltwater intrusion, and water temperature. Thus, more work is needed to evaluate these risks and determine their relevance to managers, tribes, agriculture, and other key stakeholders.

Despite evidence that the response of extreme events to climate change is highly dependent on local processes that are not well represented in current global models, substantial fundamental questions remain unanswered. For example, regional climate models can be used to answer some of these questions, but the differences between global and regional simulations of extreme events have not been rigorously examined, and the suitability of regional climate models for specific applications is not well established. Important decisions with significant economic and societal implications will be made in the next few years based on our incomplete understanding of how climate change affects extreme events. In particular, we do not currently understand:

(1) The relative influences of climate variability and climate change on recent trends in heavy precipitation;
(2) The relative importance of large-scale and mesoscale processes on changes in the frequency, duration, and intensity of heavy precipitation; and
(3) The relative importance of precipitation, snowpack dynamics, and antecedent conditions in connecting climate change to flood risk.

These issues must be settled in order to better understand and project changes in extreme events a changing climate and to evaluate potential adaptation strategies.

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