

Applying Climate Change Models to Risk Assessment and Flood
Hazard Scenario Modeling in Snohomish County

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Abstract

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This thesis analyzes and evaluates the utility of using HAZUS-MH, hazard modeling and loss estimation software used by the United States Federal Emergency Management Agency (FEMA), to estimate future losses from climate change influenced flood events under different greenhouse gas emissions scenarios. Current FEMA flood scenario techniques involve generating probabilities for floods for return intervals of 10, 20, 50, 100 and 500 years. These flood return intervals are typically based on historical record, which does not factor changes in climate into future estimates of risk. However, this thesis has integrated projected future flood return intervals and river discharges from the University of Washington's Climate Impacts Group. This is done so that future flood return intervals and river discharges, which show an increase in flood frequency and magnitude in the future due to climate change, can be modeled.

When climate change is factored into flood modeling, the areas of greatest future risk in a community can be identified. The particular community used as a case study in this thesis is the City of Sultan and surrounding Urban Growth Area. To quantify the difference in exposure and risk, the 5 different scenarios used in this thesis are calculated at 100 year flood return interval periods: the first scenario as the FEMA baseline with no climate data added, the other scenarios use climate projections for 2040 and 2080. These scenarios use existing data incorporated into HAZUS-MH to create river hydrology, depth grids and loss-estimates to building stock and social capital in the present day and in the future using population growth projections. The risk and exposure of each scenario is presented and compared, which ultimately leads to estimates that the designated Sultan Urban Growth Area will incur increased risk and loss in the future as floods become more frequent due to climate change. These results show that current 100 year floodplain boundaries may not adequately inform communities about the potential flood risk in the future due to climate change, and should change how urban planners decide to prepare communities for flooding hazards as the effects of climate change influence river systems.

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1.0 INTRODUCTION

Flooding is a problem that will only increase with time as the atmosphere warms due to increased greenhouse gas emissions. These changes in climate will significantly impact the natural and built environment in the twenty-first century.¹ Communities at risk for flooding are able to identify areas of risk using historical records and flood maps prepared by the Federal Emergency Management Agency (FEMA) through the use of HAZUS-MH loss estimation software. However, the current mapping process that FEMA uses only incorporates historical flood data to predict future flooding. When only historical flood data is used in current flood mapping techniques, it doesn't factor in the probable increase in flood frequency and magnitude due to climate change. By incorporating climate change models into the current flood mapping process, HAZUS-MH's usefulness as a tool to predict future flood losses due to climate change can be assessed.

Using climate change models to predict future floods improves flood hazard mapping techniques, which communities can then identify areas at the greatest risk for flooding in the future as well as the present. There are many avenues that cities can take to improve their resiliency to floods and other natural hazards; this thesis focuses on flood hazard mapping. Flood hazard mapping is the process by which FEMA and communities identify probable flood depths and damage in the floodplain. When these floodplain maps are created using historical flood data, they may under-represent the risk and exposure to flood-prone communities in the future.

In creating scenario models of future flood extents, urban planners can better decide what areas are more likely to flood and parcels that are more susceptible to flood damage.² This can help influence how a city grows as well as

¹ IPCC, "Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change" (Cambridge University Press, 2013), 120.

² Christopher Burton and Susan L. Cutter, "Levee Failures and Social Vulnerability in the Sacramento-San Joaquin Delta Area, California," *Natural Hazards Review* 9, no. 3 (August 2008): 144, doi:10.1061/(ASCE)1527-6988(2008)9:3(136).

prevent loss of life and structures, or social and built capital. Factoring in climate change will help communities plan for the future and rethink development in areas that are not prone to flooding now but may be in the future. Improved modeling techniques and more comprehensive datasets can increase the accuracy of flood hazard scenarios, which leads to better decision making.

1.1 PURPOSE

The purpose of this thesis is to assess the utility of HAZUS-MH loss estimation software as a tool to help predict future flooding exposure and vulnerability due to climate change. This has implications for riverine floodplain management and planning. Future projections of flood risks using climate models are needed in order to improve mitigation actions.³ Incorporating climate change models into HAZUS-MH, such as demonstrated in this paper, may serve to highlight and drive solutions to the increased effects of flooding due to climate change.

1.2 RESEARCH QUESTIONS

The main focus of this paper is to assess the capability of HAZUS-MH as a tool to incorporate climate change models into flood hazard modeling and estimate future vulnerability to built and social capital. In order to do this, these questions need to be answered:

- What is the present estimated level of exposure to built and social capital from the known frequency and magnitude of flood events in the region?
- How can the influence of climate change on flooding events be incorporated into HAZUS-MH scenario models?
- What is the change in exposure and risk to built and social capital based on future predictions of flood events influenced by climate change?

³ Yves Trambly et al., "Flood Risk under Future Climate in Data Sparse Regions: Linking Extreme Value Models and Flood Generating Processes," *Journal of Hydrology* 519, Part A (November 27, 2014): 549, doi:10.1016/j.jhydrol.2014.07.052.

1.3 METHODOLOGY

In order to assess HAZUS-MH as a tool to estimate future climate change flooding scenarios in this thesis, a case study region was selected. The chosen study area is the City of Sultan in the Skykomish River Valley. This region was selected because of available building inventory, river hydrology, and topographic data. Once the study region was delimited, available topographical maps from the United States Geological Survey and Puget Sound LiDAR Consortium were downloaded and incorporated into the HAZUS-MH software. In addition to this, built capital inventory from FEMA was uploaded into the HAZUS-MH database.

Once the initial study region was in place, flood return periods and estimated future river discharges were calculated from the Climate Impacts Group (CIG) future riverine condition data for the Skykomish River. HAZUS-MH then turned the inputs from the CIG into stream hydrology models and flood depth grids, which can show the exposure and vulnerability of the study region when faced with projected flooding.

Finally, the output from HAZUS-MH was adjusted on a percentage basis to account for future growth in both population and land use. This percentage was determined by official projections through the State of Washington Office of Financial Management.^{4 5}

1.4 ASSUMPTIONS & LIMITATIONS

This thesis only considered riverine conditions for the City of Sultan and surrounding growth boundaries. Larger boundaries would increase exponentially the amount of computational power needed to perform an accurate scenario model. Natural capital was not taken into account. In addition to this, the updated

⁴ ECONorthwest, “City of Sultan Preliminary Population Forecast” (ECONorthwest, June 2010), 10, http://ci.sultan.wa.us/wp-content/uploads/City_Hall/City_Departments/Community_Development/Long_Range_Planning/Draft_GSP_Chapters-Agency_Review_Version/Appendix_H-City_of_Sultan_Preliminary_Population_Forecast.pdf.

⁵ Snohomish County Tomorrow, “2013-2014 Growth Monitoring Report” (Snohomish County Tomorrow Steering Committee Review, October 22, 2014), 50, <http://snohomishcountywa.gov/DocumentCenter/View/20484>.

building inventory largely consisted only of residential homes, not downtown businesses and industry. These values were taken from the default statewide database. Many of the more advanced parameters, such as flood warning systems and response times, age and income modifiers, evacuation zones, agricultural crop prices, rental income, and business inventory also used default state values instead of specific region values, as they were unobtainable for this study. Modeling the BNSF and US-2 embankment protecting downtown was also impossible using 10-meter digital elevation models and the river discharge method, so this study assumes a worst-case scenario of embankment failure. Lastly, the future land use and population results cannot be directly modeled in the program, so current land use and social capital exposure and vulnerabilities were adjusted using future population projections, assuming evenly distributed growth within the Urban Growth Area.

1.5 THESIS OUTLINE

Section 1 introduces the research focus and purpose of this thesis. Section 2 outlines the relevant literature corresponding to flooding in the Pacific Northwest, how climate change will impact flooding, the role of mapping in planning for floods, and an overview of the HAZUS-MH loss estimation software and its limitations. Section 3 goes into detail about the study region, the Skykomish River Valley and the methods used to create the region in HAZUS-MH. Section 4 shows the results and analysis of the HAZUS-MH flooding scenarios. Section 5 discusses the implications of the results and assesses HAZUS-MH as a tool to model future flooding scenarios due to climate change. Finally, Section 6 explains the final conclusions of this thesis.

2.0 LITERATURE REVIEW

This section contains an overview of the relevant literature regarding flood hazard mapping in the Pacific Northwest. There are four different categories: flooding in the Pacific Northwest, impacts to flooding from climate change, the role of mapping in planning for flood hazards, and an overview of the HAZUS-MH software.

2.1 FLOODING IN THE PACIFIC NORTHWEST

Riverine flooding has always posed a risk to the built environment in the Pacific Northwest. In the earliest days of human habitation, floods were seen as a natural process that replenished natural systems, such as wildlife habitat and aquifers. Floods, or when rivers overflow their established stream banks to spread water across their floodplain, are essential to the natural environment and keeping a robust ecosystem thriving. Key contributing factors in identifying the scope of the local flood hazard are the size of the watershed, development within the watershed affecting storm water runoff, soil characteristics, topographic characteristics influencing the direction and flow of floodwaters, and regional climate.⁶ Flooding in the Pacific Northwest is usually the result of warm, moist subtropical southwesterly airflow interacting with the coastal and Cascade Mountains of Washington and Oregon.⁷ When a flood occurs, it carries sediment downstream which can create new channels and corridors, leading to new habitat, as well as carry important natural resources to replenish existing floodplain areas with fertile soil and new seedlings. The cottonwood tree uses floods as a primary

⁶ James. Schwab, *Planning for Post-Disaster Recovery and Reconstruction*, Report (American Planning Association. Planning Advisory Service); No. 483/484 (Chicago, IL: American Planning Association, 1998), 209.

⁷ Brian A. Colle and Clifford F. Mass, "The 5–9 February 1996 Flooding Event over the Pacific Northwest: Sensitivity Studies and Evaluation of the MM5 Precipitation Forecasts," *Monthly Weather Review* 128, no. 3 (March 1, 2000): 5, doi:10.1175/1520-0493(2000)128<0593:TFFEOT>2.0.CO;2.

method for reproduction, and depends on periodic floods to sustain its lifecycle. These natural functions are critical to sustain a healthy ecosystem.⁸

However, the current urban setting has developed since then, and floods are now viewed as a major hazard to people and the built environment, or social and built capital. In the last fiscal year, from October 2013 through September 2014, there were 69 claims of flood damage in Washington totaling over \$3,109,494.⁹ The most recent large scale flooding event occurred in late January and early February of 1996. Eight people were killed, over thirty thousand residents were displaced from their homes, and over \$500 million in property damage was estimated.¹⁰ This is mainly attributed to development situated on floodplains near large river systems, such as the Columbia, Willamette, Green, Skagit, and Snohomish river basins. Urban growth usually occurs and continues in these floodplains because original settlements were made along riverbanks to facilitate trade and a fresh source of water. The flat, arable land that typifies a floodplain is also prime real estate. The amount of damage caused by flood disasters in the US is steadily increasing as more development occurs in the floodplain.¹¹

Most of the types of floods that occur in this region are slow and prolonged, brought about by increased rainfall and snowmelt in the Cascade mountain range. This had the advantage of typically being clean water from glacier melt or rainfall and gives populations in the path of such flooding ample time to evacuate the area. Residents of Snoqualmie, one of the most flooded towns in the Pacific Northwest, typically have a period of one to three days to evacuate their homes.¹² This allows residents to pack up important belongings and relocate during the event of a flood, and gives them time to move hazardous

⁸ Bob Freitag, Susan M. Bolton, and Frank Westerlund, *Floodplain Management : A New Approach for a New Era* (Washington DC, USA: Island Press, 2009), 63.

⁹ Federal Emergency Management Agency, "Fiscal Year Statistics by State," 2015, <http://www.fema.gov/policy-claim-statistics-flood-insurance/policy-claim-statistics-flood-insurance/policy-claim-13-0#>.

¹⁰ Colle and Mass, "The 5–9 February 1996 Flooding Event over the Pacific Northwest," 5.

¹¹ Slobodan P. Simonovic, *Floods in a Changing Climate: Risk Management*, International Hydrology Series (Cambridge: Cambridge University Press, 2012), 10.

¹² National Oceanic and Atmospheric Administration, "Pacific Northwest Flood Event of Jan 15-19, 2011," 2011, http://www.nwrfc.noaa.gov/floods/jan_2011/january2011floodReport.pdf.

chemicals, such as gasoline or bleach, to a second story or otherwise out of the reach of floodwaters.

There are three general strategies for dealing with floods as a hazard: retreat, accommodate or protect. Retreat is used when an area is at such a great risk that continued habitation will likely result in loss of life and property. This can occur in small scales, such as relocating a family whose home was destroyed during a flood and where a new channel was created, to much larger scales, where entire towns are moved to prevent damage from frequent flooding.¹³

Accommodating the effects of a flood is a method whereby the built environment is constructed in such a way to minimize the risk of a flood while not altering the natural process. One of the prominent examples of this is in the City of Snoqualmie, where homes are typically elevated. Elevating a home exposes less of its contents to floodwater, which results in less damage to the property and less debris downstream.

The protect strategy was generally the go-to method to prevent change to the built environment in the past. This strategy typically involves large infrastructure projects, including hardening or armoring riverbanks to prevent a river from eroding its banks, large levee systems to prevent floodwaters from overtopping into developed areas,¹⁴ and hydroelectric dams to regulate seasonal floods and stabilize downstream water levels while at the same time generate electricity for use. While initially effective, using large structural approaches to protect development from flooding typically reduces the frequency of flood events. However, this approach also guarantees not only a large amount of resources devoted in the future to maintaining the infrastructure, but also that the failure of these structures will result in a higher magnitude of damage that could've been otherwise avoided.¹⁵

¹³ King County, Washington, "Flood Buyout and Elevation Programs," *Flooding Services*, 2015, <http://www.kingcounty.gov/environment/waterandland/flooding/buyout.aspx>.

¹⁴ US Army Corp of Engineers, "Final Startup Levee Notice of Preparation" (USACE, April 2012), <http://www.nws.usace.army.mil/Portals/27/docs/environmental/resources/Final%20Startup%20NOP%20April%202012.pdf>.

¹⁵ Freitag, Bolton, and Westerlund, *Floodplain Management*, 95.

Flooding is a natural process that is essential to ecosystem services. However, increased development in floodplains surrounding river systems exposes the built environment to increased risk from floods. This is continuing to be a major problem as the urban fabric continues to grow to accommodate population growth. There are several current strategies to minimize the effects of flooding.

2.2 IMPACTS TO FLOODING FROM CLIMATE CHANGE

Climate change will have impact to riverine systems and how they function. Currently, the Pacific Northwest region experiences an average of 66 inches rainfall per year, however due to increased moisture in the atmosphere climate projections show a range of -5% to +14% increase of rainfall by 2050.¹⁶ On average, the number of days with more than 1 inch of rain is projected to increase by 13% (+/- 7%) for the 2050's, relative to 1971-2000.¹⁷ Preliminary results suggest an increase in the number of heavy rain events occurring in the early fall.¹⁸ Increased rainfall leads to more flooding, especially in areas where the soil is already saturated or impervious surfaces, such as asphalt and concrete, divert an increased amount of water into a smaller area of soil, particularly in areas with unstable slopes or disturbed vegetation.¹⁹ Climate change simulations suggest more extreme storms in the early fall and general increases in flood intensity in the Pacific Northwest by the middle of the century.²⁰ Extreme

¹⁶ Meghan M. Dalton editor et al., *Climate Change in the Northwest : Implications for Our Landscapes, Waters, and Communities*, National Climate Assessment Regional Technical Input Report Series (Washington ; Covelo ; London: Island Press, 2013), 33.

¹⁷ Ibid., 38.

¹⁸ Eric P. Salathe et al., "Estimates of Twenty-First-Century Flood Risk in the Pacific Northwest Based on Regional Climate Model Simulations," *Journal Of Hydrometeorology* 15, no. 5 (2014): 1896, doi:10.1175/JHM-D-13-0137.1.

¹⁹ Oregon Department of Land Conservation and Development, "The Oregon Climate Change Adaptation Framework," 2010, http://www.oregon.gov/ENERGY/GBLWRM/docs/Framework_Final_DLCD.pdf.

²⁰ Salathe et al., "Estimates of Twenty-First-Century Flood Risk in the Pacific Northwest Based on Regional Climate Model Simulations," 1896.

participation events also have the potential to cause localized flooding due partly to inadequate capacity of storm drain systems.²¹

In addition to increased rainfall, increased temperatures will also affect river floods. Instead of snowpack accumulating during the winter months and releasing water during the summer months, warmer temperatures will result in less snowpack and more rainwater and possible flooding, especially during the winter and spring months (see Figure 2.1).²² In addition to increasing peak flows, the timing of such will be earlier in the year. For some watersheds, such as the Sultan, Cedar, Tolt and Green River are predicted to see peak streamflows 4 to 9 weeks earlier by the 2080s relative to today.²³ Earlier peak streamflows coincide with increased rainfall and will likely increase the magnitude of yearly flooding events. In climates where seasonal snow storage and melting plays a significant role in annual runoff, the hydrologic regime is directly affected by changes in temperature.²⁴

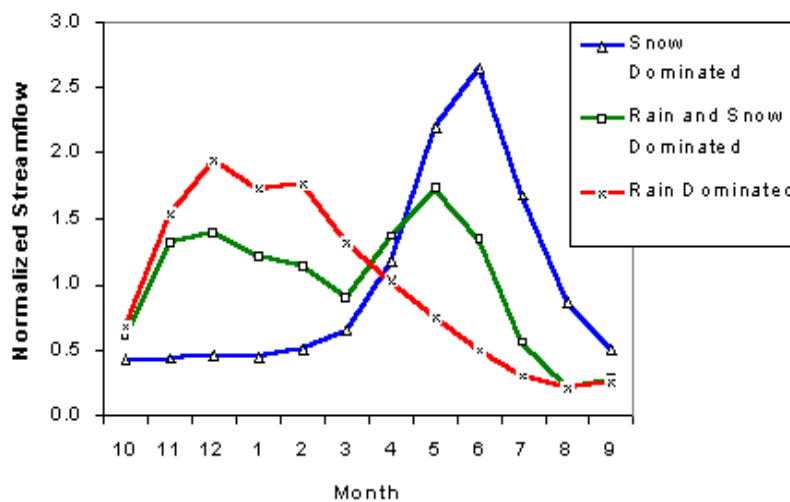


Figure 2.1 Seasonal hydrologic response for three types of Pacific Northwest Rivers (normalized monthly average streamflow).²⁵

²¹ Meghan M. Dalton editor et al., *Climate Change in the Northwest*, 45.

²² Freitag, Bolton, and Westerlund, *Floodplain Management*, 26.

²³ M. M. Elsner et al., "Implications of 21st Century Climate Change for the Hydrology of Washington State," *Climatic Change* 102, no. 1–2 (2010): 257, doi:10.1007/s10584-010-9855-0.

²⁴ Slobodan P. Simonovic, *Floods in a Changing Climate: Risk Management*, 26.

²⁵ Climate Impacts Group, "Seasonal Hydrologic Responses," *Types of Pacific Northwest Rivers*, accessed April 3, 2015, <http://ces.washington.edu/cig/data/index.shtml>.

When moving from just a rain and snow dominated system to a purely rain-dominated system, the amount of water discharged by rivers and streams increases in the winter months. This is compounded by most soils being more saturated during the wintertime because of increased rainfall, as opposed to summer floods when there is not as much rain to saturate the soil. Projections indicate that snowmelt dominant and mixed rain-snow watersheds will gradually trend towards mixed rain-snow and rain-dominant, respectively.²⁶

This kind of rain-dominated system can have disastrous results for floodplains that are used to experiencing snow-dominated summer flows. Climate simulations show substantial increases and more variability in flood intensity, particularly in rain-dominant and mixed-snow basins, and an increased range of uncertainty in projected flood risk.²⁷ A simulation for the Skagit river basin shows a projected increase in the 100 year floodplain by 24% by the 2080's, and that current water management practices can only mitigate 7% of this projected increase.²⁸ However, moving from a mixed-snow system to a completely rain dominated system can also decrease the magnitude of peak flood events, as the highest magnitude floods are caused by compounding heavy rain and snow melting events.²⁹ This does not negate the increased frequency of flood events as a system moves into a rain dominated system, however.

Climate change can also indirectly affect river systems through sea level rise. Higher sea level can increase the extent and depth of flooding by making it harder for floodwaters in rivers and streams to drain into the ocean or Puget Sound. Initial research on this issue suggests that the amount of area flooded in

²⁶ Meghan M. Dalton editor et al., *Climate Change in the Northwest*, 44.

²⁷ Salathe et al., "Estimates of Twenty-First-Century Flood Risk in the Pacific Northwest Based on Regional Climate Model Simulations," 1882.

²⁸ Se-Yeun Lee and Alan F. Hamlet, "Skagit River Basin Climate Science Report: A Summary Report Prepared for Skagit County and the Envision Skagit Project by the Department of Civil and Environmental Engineering and the Climate Impacts Group at the University of Washington," 2011, 172, <http://www.skagitcounty.net/EnvisionSkagit/Documents/ClimateChange/Complete.pdf>.

²⁹ Christopher G. Surfleet and Desirée Tullós, "Variability in Effect of Climate Change on Rain-on-Snow Peak Flow Events in a Temperate Climate," *Journal of Hydrology* 479 (February 4, 2013): 25, doi:10.1016/j.jhydrol.2012.11.021.

the Skagit River watershed would increase by up to 74% by the 2080s when accounting for the combined effects of sea level rise and larger floods.^{30 31}

Increased flooding in rivers is just one of the side effects of climate change. The opposite of flooding, minimum flows, will occur as well during the summer months in newly formed mixed rain/snow and rain dominated watersheds. Minimum flows from rivers tax hydroelectric dam electricity generation, stress the reliability of water infrastructure and force public water suppliers to invest in capital improvements to acquire, treat and distribute water from new sources to assure adequate availability of drinking water.³²

Climate change will have an increased effect on flooding by affecting seasonal rainfall values and more frequent extreme participation events, changing systems traditionally dominated by snow into more rain dominated systems, and the timing of earlier peak flows to coincide with wetter times of the year. All of these effects due to climate change will increase the frequency and magnitude of future flooding in the Pacific Northwest.

2.3 ROLE OF MAPPING IN PLANNING FOR FLOOD HAZARDS

The National Flood Insurance Program (NFIP) is a program designed in 1968 to provide affordable flood insurance to homeowners. Over 20,000 communities are currently participating in the program.³³ This program targets three areas of flood management – insurance, regulation and mapping.³⁴ While insurance and regulation deal with economics and land use, flood hazard mapping deals with hazard identification. This is crucial to the NFIP, as knowing where

³⁰ Climate Impacts Group, “State of Knowledge Report - Climate Change Impacts and Adaptation in Washington State: Technical Summaries for Decision Makers,” 2013, <http://cse.washington.edu/cig/reports.shtml>.

³¹ Joseph Johnston Hamman, “Effects of Projected Twenty-First Century Sea Level Rise, Storm Surge, and River Flooding on Water Levels in Puget Sound Floodplains and Estuaries” (Thesis, University of Washington, 2012), 56, <https://digital.lib.washington.edu/researchworks/handle/1773/20735>.

³² Meghan M. Dalton editor et al., *Climate Change in the Northwest*, 49.

³³ National Flood Insurance Program, *Myths and Facts about the National Flood Insurance Program* (Washington, DC: Federal Emergency Management Agency, 2010), 2, http://www.fema.gov/media-library-data/20130726-1620-20490-5675/f002_myths_facts_0210.pdf.

³⁴ Freitag, Bolton, and Westerlund, *Floodplain Management*, 199.

flooding is going to occur is one of the first steps of managing the flood hazard risk. The cornerstone of the NFIP mapping process is the Flood Insurance Rate Maps (FIRMs). These maps are the product of rigorous analysis and contain information such as illustrations of the 100 year floodplain boundary, the actual elevation the floodwaters are expected to reach during a 100-year flood, and often include the area expected to be inundated during a 500-year event.³⁵ Mapping flood boundaries for communities in flood zones allows them to assess their vulnerability. Assessing vulnerability means taking stock of the degree to which human life and property are exposed to damage from a flood; in other words, how much damage and loss of life could the community conceivably suffer.³⁶

One current problem with many flood hazard maps is that there are limited financial resources at FEMA to map the entire country. Many cities and even regions still use flood maps that are over 30 years old to conduct hazard policy, however there are current modernization efforts currently underway.³⁷ Without up-to-date maps, the areas of greatest risk may not be accurate.

In addition to this, the NFIP and FIRMs do not address flood effects over time, including results from increased development and its cumulative effects, land-use and land-cover changes and climate change.³⁸ By not modeling future conditions, flood hazard maps are effectively rendered obsolete even before they are adopted. Rivers are dynamic systems, and only using static maps to base flood management policy and planning decisions lacks foresight. This can be addressed by requiring future conditions floodplain maps. The NFIP should require regulation to these future-conditions maps; many communities currently manage their floodplains using such future-conditions maps, even though they are not required.³⁹

³⁵ Freitag, Bolton, and Westerlund, *Floodplain Management*, 202.

³⁶ Schwab, *Planning for Post-Disaster Recovery and Reconstruction*, 86.

³⁷ Doug Bellomo, Andrea Ryon, and Fernando Pasquel, "FEMA Flood Map Modernization Program," in *World Environmental and Water Resources Congress 2010* (American Society of Civil Engineers), 2, accessed May 14, 2015, <http://ascelibrary.org/doi/abs/10.1061/41114%28371%29229>.

³⁸ Freitag, Bolton, and Westerlund, *Floodplain Management*, 205.

³⁹ *Ibid.*, 206.

Risk assessments of areas with similar riverine systems show that climate change affects flood boundaries and future conditions. These assessments have been undertaken to better understand climate change-cause flood impacts on municipal infrastructure and provide a measurement of risk as the basis for the development of climate change adaptation options.⁴⁰ By doing this, maps of high-priority areas of infrastructure risk can be created to aid in future climate change adaptation planning decisions.⁴¹

Many of these options to map flood hazard zones are undertaken by large governmental organizations, but new techniques can also aid smaller communities that lack the resources needed to properly assess their vulnerability. Integration of local knowledge and the use of flood hazard mapping can be an effective and interactive tool to assess local vulnerabilities. It can be useful not only in mitigation aspects but also in planning all stages of hazard management including preparedness, response and recovery, while actively involving the local community in the decision making process.^{42 43}

Flood hazard mapping is a tool used by the NFIP to assess the greatest areas of risk. By knowing where the areas of greatest risk occur, communities can properly assess what is most vulnerable. Current mapping techniques and methodologies do not account for future conditions due to climate change, and other flood mapping efforts have shown that climate change does affect flood hazard zones in the future. Flood hazard mapping should include future-conditions, such as the changing effects of climate, but also land-use and local knowledge, which will improve the flood mapping process and allow communities to more accurately plan for future development and mitigate the risks from flood hazards.

⁴⁰ Slobodan P. Simonovic, *Floods in a Changing Climate: Risk Management*, 54.

⁴¹ Ibid.

⁴² Bijay Kumar Singh, "Flood Hazard Mapping with Participatory GIS The Case of Gorakhpur," *Environment and Urbanization Asia* 5, no. 1 (March 1, 2014): 162, doi:10.1177/0975425314521546.

⁴³ Robert C. Freitag et al., "Whole Community Resilience: An Asset-Based Approach to Enhancing Adaptive Capacity Before a Disruption," *Journal of the American Planning Association* 80, no. 4 (October 2, 2014): 334, doi:10.1080/01944363.2014.990480.

2.4 HAZUS-MH

HAZUS-MH (named for HAZards United States – Multi-Hazard) is a software package released by FEMA that combines the power of Geographic Information Systems (GIS) with hazard identification, risk assessment and loss-estimation capabilities. It can currently model three different types of hazards: floods, earthquakes and hurricanes. The flood module was originally released in 2004 and continually updated, most recently in May of 2015 to version 2.2.⁴⁴

The HAZUS-MH flood module is primarily used for flood extent analysis and loss-estimation. For the purposes of this thesis, HAZUS-MH is used to incorporate adjusted river discharges from climate model projections into the flood extent analysis and resulting loss-estimation. While other GIS products are powerful tools in their own right, only HAZUS-MH has the ability to cohesively generate outcomes in the intent of the thesis, such as showing what areas of Sultan are at the greatest risk of flooding due to climate change.

In addition to the software itself, HAZUS-MH also has a data management counterpart, called the Comprehensive Data Management System, or CDMS. The CDMS function is to keep a repository of buildings, or building stock, for every state in the United States. FEMA releases datasets of each state that have general building and population data from the US Census, as well as information about transportation and utility infrastructure, vehicles and essential facilities: police and fire stations, hospitals and schools.

This system can also be updated with user defined facilities or updates to each specific state dataset. If no updates to the dataset are performed, this is deemed a Level 1 Analysis using HAZUS-MH, where the building inventory remains on the default setting. A more in-depth Level 2 or 3 analyses require more comprehensive building information, as the software models can only be as accurate as the data used in the study. Data updated to the CDMS can involve building frame type, height above grade, assessed value, content value, etc. This

⁴⁴ Philip Schneider and Barbara Schauer, "HAZUS—Its Development and Its Future," *Natural Hazards Review* 7, no. 2 (2006): 40, doi:10.1061/(ASCE)1527-6988(2006)7:2(40).

helps the HAZUS-MH software more accurately model flood damage to these buildings.

Using the data from the CDMS, HAZUS-MH is able to more accurately predict the exposure and damage to structures and the surrounding area. Exposure and damage are defined in financial terms; this aids in comparing results to reported financial losses from historical flood events. Each building occupancy type is handled differently in HAZUS-MH,

For residential occupancy, HAZUS calculates the content value of to be 50% of the building cost. For all other occupancies, the building value could be multiplied by 50-150% to determine content value (see HAZUS Technical Manuals). The previous calculations refer only to inventory base data, not the calculated losses. To calculate losses, HAZUS-MH uses depth damage curves. Depth-damage curves are contained in HAZUS-MH and come from various data sources. For each census block an appropriate damage curve is assigned for each occupancy type and water depths are used to determine the associated percent damage. The percent damage is multiplied by the replacement value (i.e. building value, content value, etc.) to determine the full dollar loss. Shelter estimations are determined based on flood depth, individuals or households within a census block, population of a census block, number of census blocks affected, and restricted ingress/egress areas due to flooding. Debris is calculated based on flood depth and calculates debris generated from buildings and contents, not roads or utilities. More information on the HAZUS-MH calculations and depth curves can be found in the HAZUS User and Technical Manuals.⁴⁵

Using these algorithms can provide a consistent methodology to compare flood scenarios across a wide range of geographies and urban context. There are certain limitations of the HAZUS-MH software that impact this thesis described further in this chapter. Despite these limitations, HAZUS-MH is the most promising flood loss-estimation software to be able to use in adaptation and climate change

⁴⁵ FEMA Region X Mitigation, "HAZUS Analysis for the Green River Valley," October 6, 2009, 9, <http://your.kingcounty.gov/dnrp/library/water-and-land/flooding/green-river-valley-hazus-report-1009.pdf>.

scenarios.⁴⁶ HAZUS-MH produces output in the forms of financial damage to built capital and shelter requirements, as well as stream reaches and depth grids. Depth grids are files that contain the heights of floodwaters in the study region. The loss estimation data can be shown in both table and spatial form. Tabular data makes it easy to compare total social and built capital loss across specific categories, while spatial representation of that data allows easy identification of areas of concern. These maps can help communities assess which areas are at the greatest risk of flooding. HAZUS-MH has been successfully used to model riverine flood exposure and vulnerability in scenarios including dam failures⁴⁷, levee setbacks⁴⁸ and failures⁴⁹, and general floodplain use.⁵⁰

2.4.1 *Natural Capital Exposure*

Currently, HAZUS-MH models a wide variety of damage to built capital (structural damage, content replacement value, etc.) as well as social capital (temporary shelter needs, loss of life). However, HAZUS-MH does not currently incorporate methods to assess damage to natural capital, including habitat destruction, streambank erosion, destruction of flora and fauna, etc. Even though HAZUS-MH is unable to model these effects, flooding is a natural and necessary system process that while on the surface appears destructive can have multiple positive effects for the watershed it is located in.⁵¹

⁴⁶ James Banks, Janey Camp, and Mark Abkowitz, "Adaptation Planning for Floods: A Review of Available Tools," *Natural Hazards* 70, no. 2 (2014): 1335, doi:10.1007/s11069-013-0876-7.

⁴⁷ FEMA Region X Mitigation, "HAZUS Analysis for the Green River Valley," 39.

⁴⁸ Jennifer Dierauer, Nicholas Pinter, and Jonathan W. F. Remo, "Evaluation of Levee Setbacks for Flood-Loss Reduction, Middle Mississippi River, USA," *Journal of Hydrology* 450–51 (July 11, 2012): 1–8, doi:10.1016/j.jhydrol.2012.05.044.

⁴⁹ Burton and Cutter, "Levee Failures and Social Vulnerability in the Sacramento-San Joaquin Delta Area, California," 136.

⁵⁰ Xiaomin Qiu, Shuo-sheng Wu, and Yan Chen, "Effects of Threshold Drainage Area and Study Region Size on HAZUS Flood Analysis," *Cartography and Geographic Information Science* 37, no. 2 (January 1, 2010): 93–104, doi:10.1559/152304010791232172.

⁵¹ Freitag, Bolton, and Westerlund, *Floodplain Management*, 63.

2.4.2 *Building Stock*

While there is plenty of data on the residences of Sultan, very little information was available on civic, commercial or industrial structures in the Urban Growth Area. This includes essential facilities such as police stations, fire stations, hospitals, emergency centers and schools. For the purposes of this thesis, these building categories were modeled using the default Washington State database. Further study by individually rating each essential facility and incorporating other building parcel data would improve the loss estimation process.

2.4.3 *Accuracy of HAZUS Algorithms*

The algorithms used in HAZUS-MH are constantly evolving, as refinement occurs after each natural hazard allows programmers and engineers to better model real life in a closer fashion. While the default settings are adequate for this thesis' purpose, a better understanding of these settings can allow for greater accuracy depending on knowledge of the study region, including but not limited to flood warning systems and response times, age and income modifiers, evacuation zones, building restoration timelines, agricultural crop prices, rental income and business inventory. In addition to this, the flood analysis performed at the census block level can be inaccurate when faced with large block sizes. HAZUS-MH applies a weighting methodology to assume a uniform distribution of census demographics and structures across the census block. This type of approach generally produces conservative loss estimates (often overestimating what the true losses might be).⁵²

⁵² Federal Emergency Management Agency, "Guidance for Flood Risk Analysis and Mapping," Guidance Document, May 2014, 3, http://www.fema.gov/media-library-data/1406747117351-744b6bd203c18ada4806ad4e90c18b81/Flood_Risk_Assessment_Guidance_May_2014.pdf.

2.4.4 *Temporal Data*

The temporal CIG data used in this thesis was primarily intended to model flood return intervals in the future due to climate change. While the data is being used for that purpose in this thesis, the HAZUS-MH software cannot directly model future flood return interval scenarios. To circumvent this limitation, flood magnitudes were extrapolated from the CIG data to simulate the projected future peak discharges at the 100-year return period for each scenario.

2.4.5 *Flood Extents*

Currently, the HAZUS-MH flood module can only model levees and embankments when using flood return intervals. Since this thesis uses the peak discharge method of modeling future flood scenarios, the US 2 and BNSF railroad embankments that protect part of downtown Sultan cannot be modeled directly in the scenarios. Because of this, the modeled scenarios in this report will assume a worst case scenario of these embankments failing during extreme flood events.

2.4.6 *Computational Power*

One of the largest limitations of this study is the raw computational power needed by HAZUS-MH to accurately create and model flood scenarios. The amount of time needed to generate river hydrology and depth grids from 3 meter LiDAR data is exponentially longer than with the 10 meter USGS National Elevation Database. The increase in modeling time from days to weeks or even months was evident after a couple of trial runs using different sets of elevation data. This combined with access to only one personal workstation and the propensity of HAZUS-MH to become unstable in the middle of the modeling process limited this thesis to using fast and stable methods. This problem can be corrected with multiple workstations and a longer thesis timeline.

2.4.7 *Future Social and Built Capital*

HAZUS-MH cannot directly apply damage to building inventory and population that has yet to arrive in the study region. To account for this, final population and building inventories took existing data and used a simple projection percentage based on Washington State GMA targets for 2040 population and housing inventory.^{53 54}

⁵³ ECONorthwest, “City of Sultan Preliminary Population Forecast,” 10.

⁵⁴ Snohomish County Tomorrow, “2013-2014 Growth Monitoring Report,” 50.

3.0 CASE STUDY

The Skykomish River Valley is a region of Western Washington that experiences flooding on a regular basis. Situated in Snohomish County, the Skykomish River starts in the Cascade Mountains while both the north and south forks converge just outside of the town of Gold Bar. From there, the 29 mile main reach of the river continues past the town of Sultan, population 4662.⁵⁵ ⁵⁶ Later on the Skykomish River joins the Snoqualmie River past Monroe which forms the Snohomish River and drains into Puget Sound (see Figure 3.1).

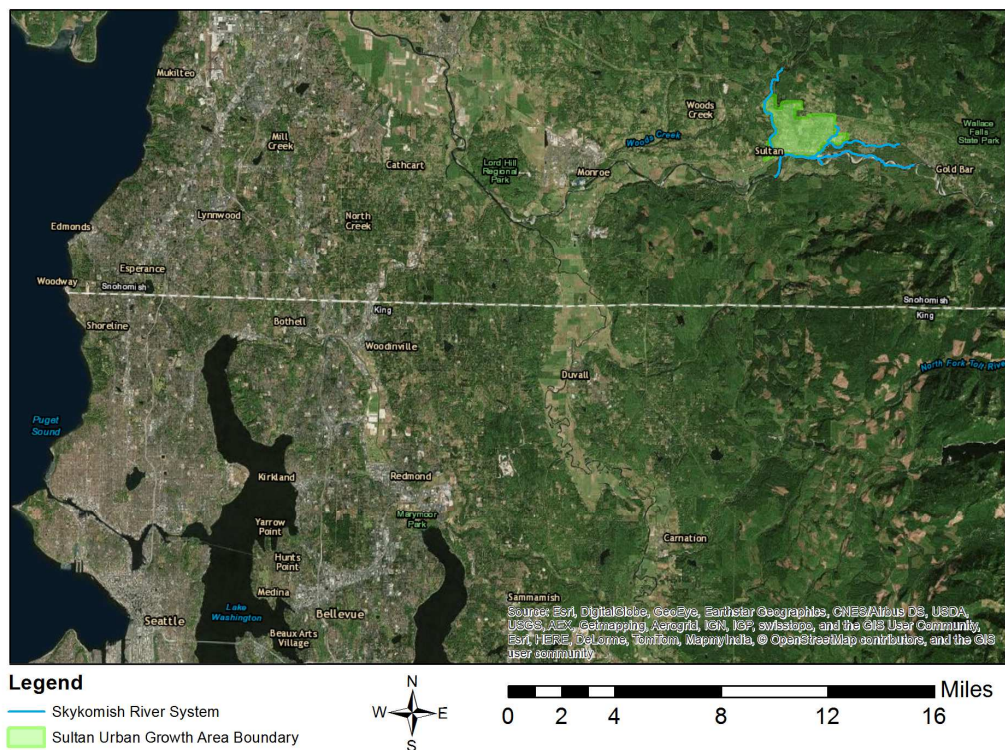


Figure 3.1 Overview of the Study Region

⁵⁵ U. S. Census Bureau, “American FactFinder,” accessed May 22, 2015, <http://factfinder.census.gov/faces/nav/jsf/pages/index.xhtml>.

⁵⁶ United States Geological Survey, “National Hydrography Dataset,” *U.S. Geological Survey - National Hydrography Dataset*, accessed May 20, 2015, <http://viewer.nationalmap.gov/viewer/nhd.html?p=nhd>.

3.1 OVERVIEW OF STUDY REGION

The town of Sultan floods on a frequent basis, which has happened at least 10 times since 1980, with the most recent peak floods occurring in 2006.⁵⁷ The 2006 flood pushed the river gage past 114,000 cubic feet per second (cfs), eclipsing the previous record of 102,000 cfs set in 1990.⁵⁸ The floodwaters caused millions of dollars of damage to 174 homes and 24 businesses in Snohomish County.⁵⁹ While there are smaller levees in the area, they are frequently eroded by high velocity floodwaters and overtop during increasingly stronger flooding events.⁶⁰

HAZUS-MH shows the city of Sultan and its surrounding Urban Growth Area (UGA) contains 1,678 households in the study region comprising a population of 4,948. It also shows an exposure value of \$678 million, or the replacement value in today's dollars of all the buildings and contents. There are 1,807 buildings in the study region, 1,778 of those are labeled as residential. This closely reflects the totals from the census data, allowing for the difference between the population of the city limits of Sultan and the outlying UGA boundary.

Sultan's development trends show a steady increase of population since 1980, when there was a population of 1,578. The growth rate of 3.7% from 1980 to 2009 (population 4,555) was higher than the Snohomish County average of 2.6% during the same timeframe.⁶¹ Because of this, future population projections and targets were set at a high level, with Sultan expecting to nearly double in population by 2040.⁶² However, this has not been the case. Since 2010, Sultan has

⁵⁷ City of Sultan, Washington, "Flood Information," accessed May 22, 2015, <http://ci.sultan.wa.us/flood-information/>.

⁵⁸ United States Geological Survey, "USGS Flood Update for Western Washington," *USGS Washington Water Science Center*, accessed April 13, 2015, <http://wa.water.usgs.gov/news/2006/news.newhiflo.Nov06.htm>.

⁵⁹ Brian Alexander, "More than \$45 Million in Damage Reported by Counties after Flood - Snohomish, King Totals Could Rise Estimates Will Help Determine Federal Aid," *Seattle Times, The (WA)*, November 18, 2006, Fourth edition.

⁶⁰ US Army Corp of Engineers, "Final Startup Levee Notice of Preparation."

⁶¹ ECONorthwest, "City of Sultan Preliminary Population Forecast," 4.

⁶² Snohomish County Tomorrow, "2013-2014 Growth Monitoring Report," 50.

remained nearly flat in both population and housing units constructed. Much of this can be attributed to the economic recession starting in 2009. Sultan has only gained one housing unit and 14 people since 2010.⁶³

3.1.1 *Current Designated Urban Growth Areas*

The Washington State Growth Management Act (GMA) requires communities that plan under the law to designate urban growth areas sufficient to permit the growth that is projected in their area for a twenty year period.⁶⁴ While the GMA is a great tool for allowing communities to develop urban centers and reduce sprawl, there can be problems when this development intersects with a floodplain. This type of clashing does happen on a regular basis, as usually the best sites for development has traditionally been on flat land in floodplains created by rivers and glaciers. Fortunately, the GMA also protects the 100-year floodplain from development, as long as it meets strict guidelines, such as not decreasing flood storage, increase storm water runoff, discharge pollutants or increase hazards to people and property.⁶⁵ The entire study region is the Urban Growth Area of the City of Sultan.

3.1.2 *Impact to Future Growth*

The GMA already incorporates flood hazards into development regulations. This is a great step, however with the 100-year floodplain projected to change in the coming century, development should change along with it. If the 100-year floodplain remains static because future climate projections are not taken into account, development today could be underwater in the future. The odds of a 100-year flood happening in any given year is 1%, however those odds will only increase over time, and not just due to climate change. What does change the odds is development in the watershed, especially in the floodplain itself. Increasing impervious surface, building obstructions to the flow of water

⁶³ Snohomish County Tomorrow, “2013-2014 Growth Monitoring Report,” 50.

⁶⁴ Washington State Legislature, *Growth Management Act, RCW*, vol. 36.70a.110, 1990, <http://apps.leg.wa.gov/rcw/default.aspx?cite=36.70a.110>.

⁶⁵ *Ibid.*

along the riverbank, or allowing sedimentation through streambank erosion all contribute to an escalation of the probabilities of flooding, and thus change 100-year floodplains into 80-year or 50-year floodplains. Changing the landscape changes the probabilities.⁶⁶ Since the entire study region is an urban growth area, careful monitoring of development in and close to the 100-year floodplain needs to be monitored.

3.1.3 *Study Region Topography Mapping*

The first step in creating a flood analysis report in HAZUS is to define a topographical study region. The City of Sultan was selected because of the intersection of available building inventory data from FEMA and river data from the Climate Impacts Group (CIG). The CIG dataset also included the Sauk, Stillaguamish and Snohomish rivers, but the corresponding analysis would have been at Level 1 due to a lack of targeted building inventory surrounding those rivers. Building data for the town of Sultan, combined with riverine data for the Skykomish River made it a perfect candidate for this thesis.

The borders of the study region were determined by Sultan's Urban Growth Area boundaries. While it is possible to select census tracts, the rural nature of the river valley included some very large tracts, which slows down processing time in future hydrological modeling. The current study region boundary (Figure 2) was chosen as the smallest boundary that could adequately include all the relevant drainage basins and watersheds, while maintaining the census block structure. Only by modeling the relevant watersheds and drainage basins can HAZUS accurately model flooding events.⁶⁷

Light Detection and Ranging, or LiDAR, is currently the highest resolution topographic imaging data available. The Puget Sound LiDAR Consortium keeps a repository of high-resolution LiDAR DEMs (Digital Elevation Models) on their website. The LiDAR file intended to be used for this

⁶⁶ Schwab, *Planning for Post-Disaster Recovery and Reconstruction*, 210.

⁶⁷ Qiu, Wu, and Chen, "Effects of Threshold Drainage Area and Study Region Size on HAZUS Flood Analysis," 103.

thesis is a 3 meter resolution bare earth elevation grid from Snohomish County Information Services that runs the length of the main stem of the Skykomish River.⁶⁸ 3 meter resolution means that every “square” in the topographic file is 3 meters by 3 meters.

Having a 3 meter resolution DEM exponentially increases the processing time for all future HAZUS-MH scenario modeling processes. In addition to this, HAZUS-MH requires enough of a geographic extent to properly calculate stream networks and river hydrology, even if it lies outside the study area boundaries. In order to try and combat both of these problems, the LiDAR DEM was combined with a larger extent of a lower resolution DEM using the mosaic function. The resulting DEM was intended to combine the hyper accuracy of LiDAR with the watershed extents of the full region. However, this mosaic did not significantly decrease the processing time over previous LiDAR datasets and was eventually eschewed for another DEM.

The other topographical dataset used in this thesis is from the United States Geological Survey (USGS) National Elevation Dataset. While HAZUS can automatically include 30 meter resolution topographical maps; that level of resolution is insufficient for this thesis’ hydrological modeling purposes. Instead, higher resolution maps with 10 meter squares were incorporated into the HAZUS-MH study region. The DEM in Figure 3.2 is the final topographic map used in the flood analysis. It covers all the watersheds that drain into the main reach of the Skykomish River.

⁶⁸ Puget Sound LiDAR Consortium, “Snohomish County LiDAR,” *Snohomish County LiDAR*, accessed April 13, 2015, http://pugetsoundlidar.ess.washington.edu/lidardata/restricted/nonpslc/snohomish_misc/index.html.

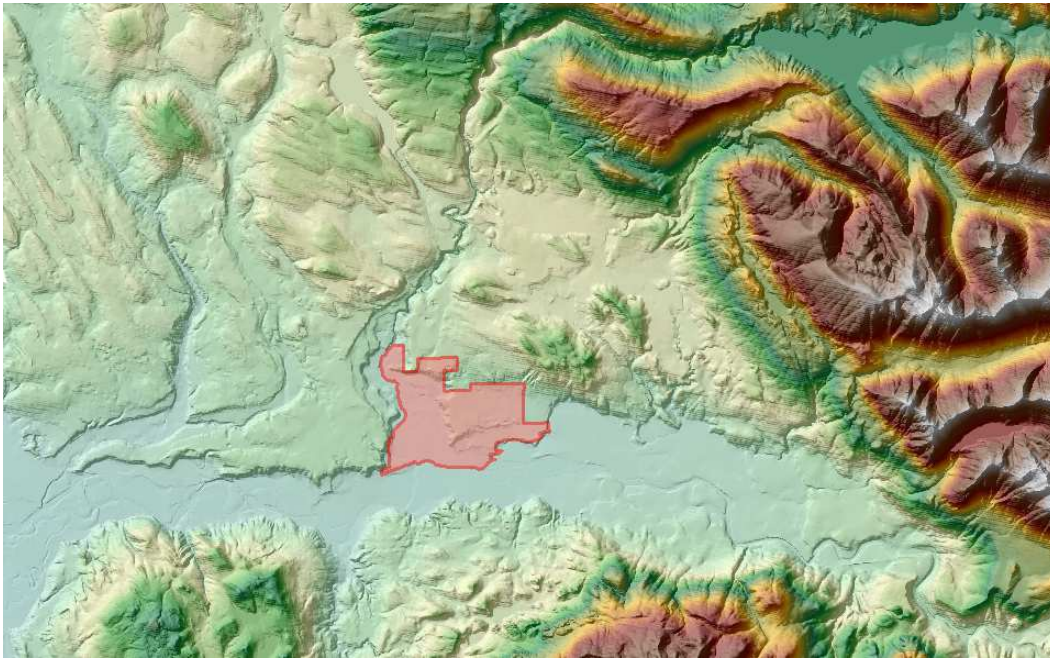


Figure 3.2 USGS 10m Digital Elevation Model

Once the study region was delimited, available topographical maps from the United States Geological Survey were downloaded and incorporated into the HAZUS-MH software. In addition to this, built capital inventory from FEMA was uploaded into the HAZUS-MH database.

3.1.4 *Built Capital Inventory*

The CDMS system previously discussed in Chapter 2.4 is primarily used to input local data into statewide datasets, increasing the accuracy of local hazard scenarios. The Sultan city building data received from FEMA for this thesis was mostly in the form that the CDMS could interpret. However, the data was only tied to census tracts, not the smaller census block level. This data was altered by spatially joining the building stock to their respective census blocks, and then fed into the CDMS for the local data update. This allows HAZUS-MH to use specific local building data when running flood scenarios, which increases the accuracy of the damage output.

3.2 CLIMATE IMPACTS GROUP FUTURE RIVERINE CONDITIONS MODELING

The Climate Impacts Group is an entity housed within the University of Washington College of the Environments. Since 1995 they have provided scientific understanding, projections, models and adaptation guidance needed to help decision makers prepare for a manage the impacts of climate variability and change.⁶⁹ Their data and hydrological model runs were used to further shape the study region profile for HAZUS-MH.

3.2.1 *Climate Models*

The climate scenarios the CIG used to run their flood return interval models are called Representative Concentration Pathway CO₂ – Equivalent Emissions Scenarios. All these scenarios assume continued growth in atmospheric levels of greenhouse gases for the next few decades. Figure 3.3 shows the equivalent CO₂ concentration, in parts per million (ppm), for each greenhouse gas scenario. CO₂-Equivalent is a measure of the global warming potential of all greenhouse gases – this is equivalent to listing the total change in energy balance, in W/m², due to all the greenhouse gas emissions, but is referenced to the commonly more cited atmospheric CO₂ concentration.⁷⁰ As the CO₂ concentration climbs higher, more heat is trapped by the sun which increases the overall energy in the system.

⁶⁹ Climate Impacts Group, “Connecting Science and Decision-Making to Develop Climate Resilience,” *CIG Fact Sheet*, accessed May 5, 2015, http://cses.washington.edu/cig/files/CIG_factsheet_2014.pdf.

⁷⁰ Climate Impacts Group, “CIG Datasets,” *CIG Datasets and Other Data Sources*, accessed April 3, 2015, <http://cses.washington.edu/cig/data/index.shtml>.

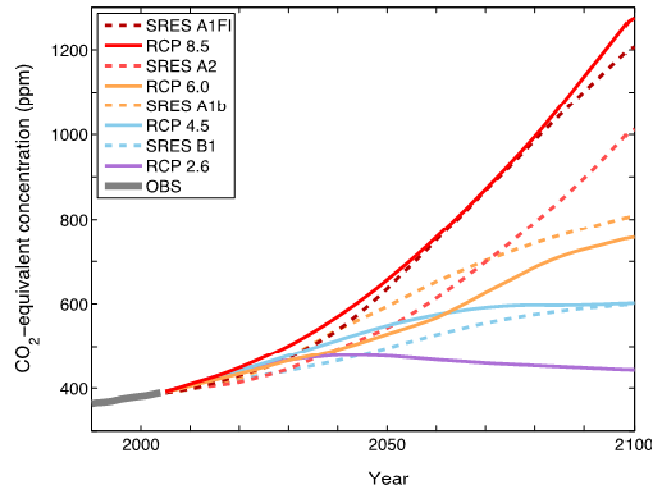


Figure 3.3 Climate Scenarios showing increased greenhouse gas concentration in parts per million (ppm). Source: CIG

The two specific ones used to model flood return intervals are the RCP 4.5 and 8.5 scenarios. RCP 4.5 shows a moderate increase and stabilization in greenhouse gas emissions (climate change effects are lower), while RCP 8.5 shows a steady and compounding increase over time (climate change effects are greater). RCP 8.5 is generally described as the “business as usual” approach, where no actions to mitigate greenhouse gases are performed.

3.2.2 Return Periods

The CIG was able to model future flood return intervals for the Skykomish River. These flood return interval models estimate the likelihood of certain magnitude of flooding in any given year. For instance, a 100-year flood return period means that there is a 1% chance of that flood happening in a given year; a 5-year flood means there is a 20% chance in any given year, etc. The CIG modeled future flood return intervals estimate the frequency at which four magnitudes of floods (10, 20, 50 and 100-year floods) will occur in the future. For example, their models estimate that the current 100-year flood will occur on average every 30 years in 2040. This “new normal” would already be a problem by itself, but floods in the future will also increase in magnitude as well as frequency.

3.2.3 Flood Magnitude

To accurately model the future flood discharge rates, the CIG calculated the change in peak discharge from historical flows on the Skykomish River using 10 Global Climate Models. These percentage changes in flow were applied to the effective Flood Insurance Study historical peak discharge rate of 129,500 cubic feet per second (cfs) at the start of the modeled reach.⁷¹ The median change in flow was used instead of the average, as the median flows were less biased by the undersampled distributions. The resulting cfs for each scenario in this report can be found in Table 1. The complete, unaltered dataset is found in Appendix A - Climate Impacts Group Riverine Model Data and the methodologies on how that data was derived can be found in Appendix B - Climate Impacts Group Riverine Model Methodologies.

| Scenario | Average % Change | Median % Change | CFS at Skykomish & Wallace Confluence |
|------------------|------------------|-----------------|---------------------------------------|
| 1 (Baseline) | - | - | 129,500 |
| 2 (RCP 4.5 2040) | 67.80% | 47.93% | 191,563 |
| 3 (RCP 4.5 2080) | 55.00% | 52.25% | 197,164 |
| 4 (RCP 8.5 2040) | 27.01% | 18.65% | 153,652 |
| 5 (RCP 8.5 2080) | 87.97% | 78.80% | 231,546 |

Table 1 Future 100-Year Peak Discharge

3.3 STREAM HYDROLOGY

Once the proper flood peak discharge rates were calculated, then the stream network for the study region had to be created. HAZUS-MH calculates stream hydrology by assessing the topographical data in the study region. Higher resolution data provides a more accurate stream network. Using the USGS 10

⁷¹ Snohomish County Department of Public Works, Surface Water Management Division, “Upper Skykomish River Flood Insurance Study Technical Support Data Notebook” (Snohomish County Department of Public Works, Surface Water Management Division, September 29, 2010), 26, <http://wa-snohomishcounty.civicplus.com/DocumentCenter/View/6668>.

meter topography, HAZUS was able to calculate a stream network very close to the actual stream reaches. When choosing a threshold drainage setting when building the stream network, the optimum (most closely reflecting reality) setting for a small county sized region is at 2.00 square miles.⁷² For the purposes of this thesis, this setting was used, because it was able to model the main Skykomish River reaches relatively accurately without the increase in processing time that a lower square mileage would have incurred. Also, the Sultan River was not modeled because of the Culmback dam regulating all water flows downstream.⁷³ The resulting river reaches are shown in Figure 3.4.

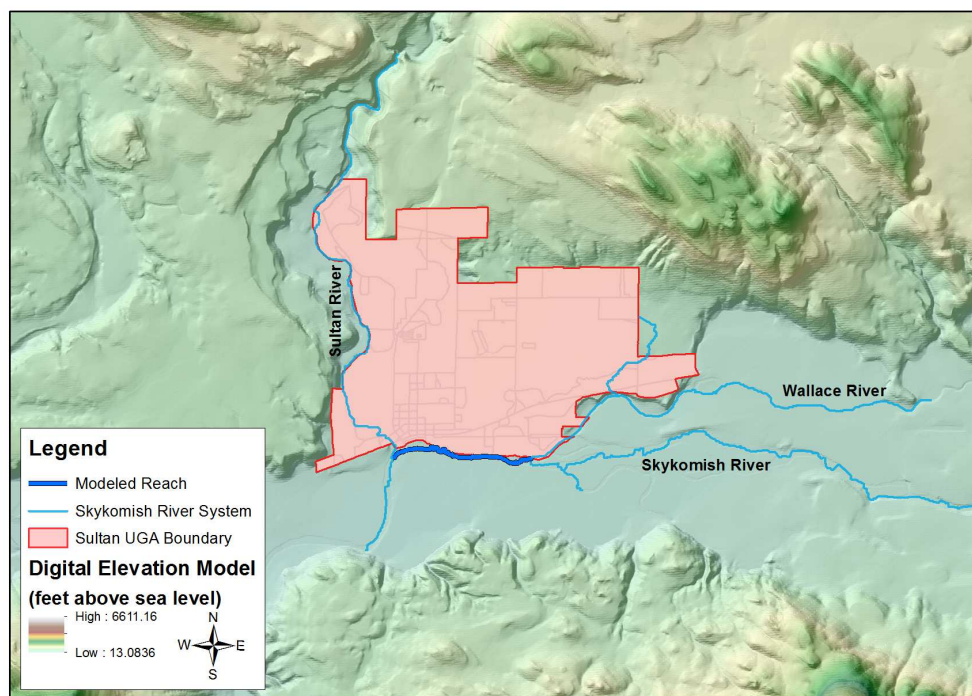


Figure 3.4 Computed River Reaches

⁷² Qiu, Wu, and Chen, “Effects of Threshold Drainage Area and Study Region Size on HAZUS Flood Analysis,” 102.

⁷³ Lynn Thompson, “FEMA’s New Flood Maps Go Too Far, Some Cities Say,” *The Seattle Times*, March 7, 2010, <http://www.seattletimes.com/seattle-news/femas-new-flood-maps-go-too-far-some-cities-say/>.

3.4 DEPTH GRIDS

Flood depth grids are the final result after HAZUS-MH takes the selected stream reach hydrology and combines them with the requested discharge rate of the river. Depth grids can also be produced for a specific major event, such as for a burst dam, levee or historical flood event. Each depth grid is unique to the river discharge chosen. For this thesis, there were a total of 5 scenarios modeled, each with a specific discharge rate used in Table 1.

In addition to this, HAZUS-MH requires the use of Manning's Equation to calculate the velocity of a unit mass of floodwater to the friction slope.⁷⁴ This is the "roughness" of a streambank. The computed n-values from the proposed FIS changes recommended by Northwest Hydrological Consultants for that stretch of river (Skykomish River downstream of Wallace River to Sultan River) were used.⁷⁵ For more information on how the depth grids are calculated, please refer to the HAZUS-MH Technical Manuals.⁷⁶

⁷⁴ Federal Emergency Management Agency, "Multi-Hazard Loss Estimation Methodology, Flood Model, Hazus-MH Technical Manual" (Federal Emergency Management Agency, January 29, 2015), 4-49, http://www.fema.gov/media-library-data/20130726-1820-25045-8292/hz mh2_1_fl_tm.pdf.

⁷⁵ Snohomish County Department of Public Works, Surface Water Management Division, "Upper Skykomish River FIS," 11.

⁷⁶ Federal Emergency Management Agency, "Flood Model Technical Manual."

4.0 RESULTS

This section contains an overview of the results the risk and exposure output produced by the HAZUS-MH software. Each of the five scenarios has 2 maps broken down by census block that shows direct building economic loss (the full replacement value of the structure and contents inside), and displaced population. Damaged residential buildings (total count and substantially damaged), and debris generated (from structures, foundations and finish materials) are also presented at the end of the section.

The baseline flood event is the current standard FEMA 100-year floodplain scenario. The standard 100-year floodplain is how most National Flood Insurance Program boundaries are regulated. Scenarios 2 through 5 were all generated under the assumption of evenly distributed growth conforming to an annual average growth rate of 2.2%.⁷⁷ The 2010 shows Sultan as having a population of 4,651⁷⁸, so these scenarios are using projected population targets of 8,935 in 2040 and 21,336 in 2080. The increase in growth from 2010 to 2040 and 2010 to 2080 is 92.1% and 358.74%, respectively. These percentages were used to modify the raw HAZUS-MH output for each future scenario. All maps show the City of Sultan Urban Growth Area (UGA) and flood extent for each scenario. Any parcels or census blocks outside of the UGA were not considered, as the population projections would not apply.

Both RCP 4.5 and 8.5 scenarios in 2040 show an increase in risk and exposure over the baseline 100-year flood scenario, and both 2080 scenarios show a much higher increase over their 2040 counterparts.

4.1 SCENARIO 1 – BASELINE 100 YEAR FLOOD EVENT

The baseline scenario maps shown here show a limited amount of flooding in the Sultan downtown area, but a moderate amount of risk in the two census

⁷⁷ Snohomish County Tomorrow, “2013-2014 Growth Monitoring Report,” 50.

⁷⁸ U. S. Census Bureau, “American FactFinder.”

blocks closest to the Skykomish River, just east of downtown. These parcels are mostly residential homes and constitute the bulk of the displaced population, debris and economic loss that occurs. Just north of downtown and south of the elementary school there is also a large residential neighborhood that suffers some damage, but will have to have a moderate amount of people evacuate their homes. While the majority of the Urban Growth Area is untouched by the modeled flood, it is important to remember that the riverfront and downtown areas of Sultan are some of the most dense areas of the UGA and important to the fabric of the community.

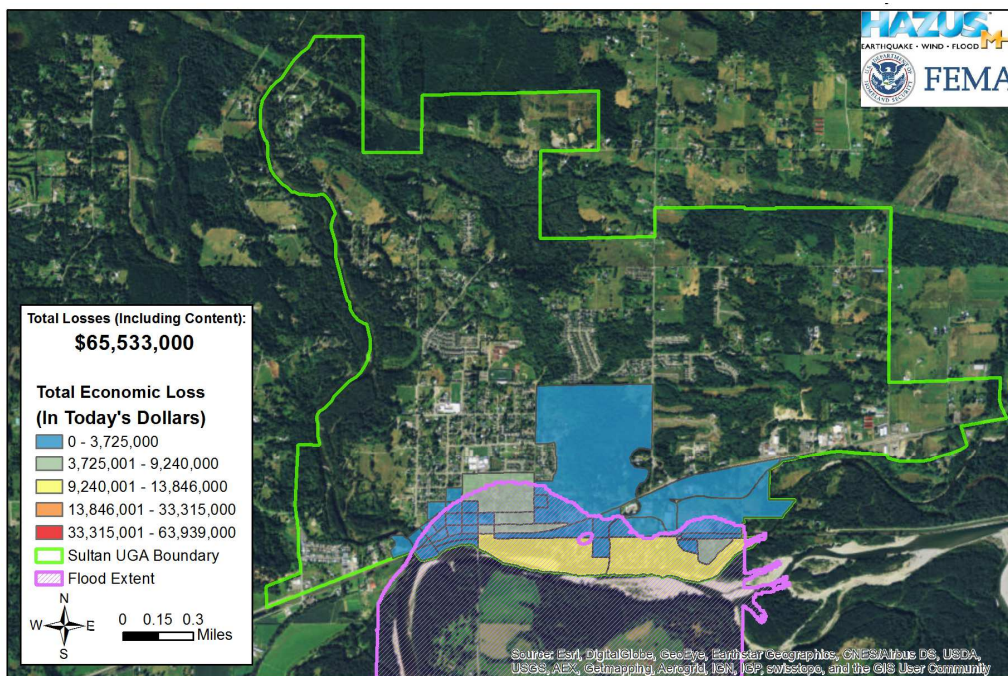


Figure 4.1 Direct Building Economic Loss – Baseline

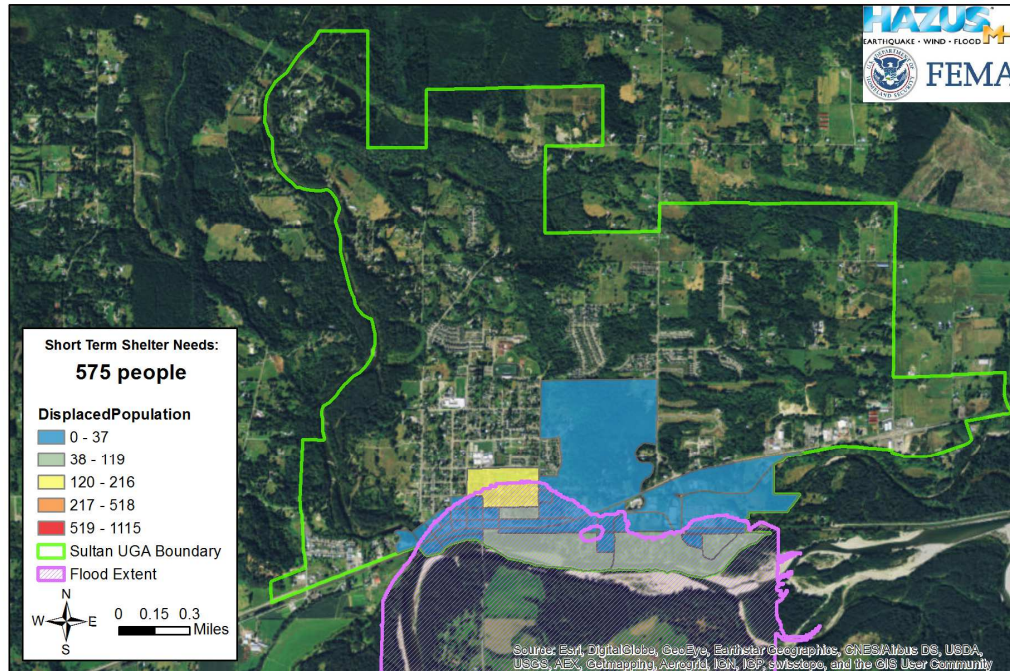


Figure 4.2 Displaced Population/Shelter Needs – Baseline

4.2 SCENARIO 2 – RCP 4.5 100 YEAR FLOOD EVENT IN 2040

Scenario 2 is the first of the modeled climate scenarios, which uses the “low emissions” RCP 4.5 climate model. The results show an increase in every category over the baseline scenario. This is compounded by the projected increase in urban growth of 92.1% between 2010 and 2040. The downtown again shows a couple of census blocks of concern near Main Street, especially close to the elementary school, but the primary focus is the residential areas east of downtown closest to the riverbank.

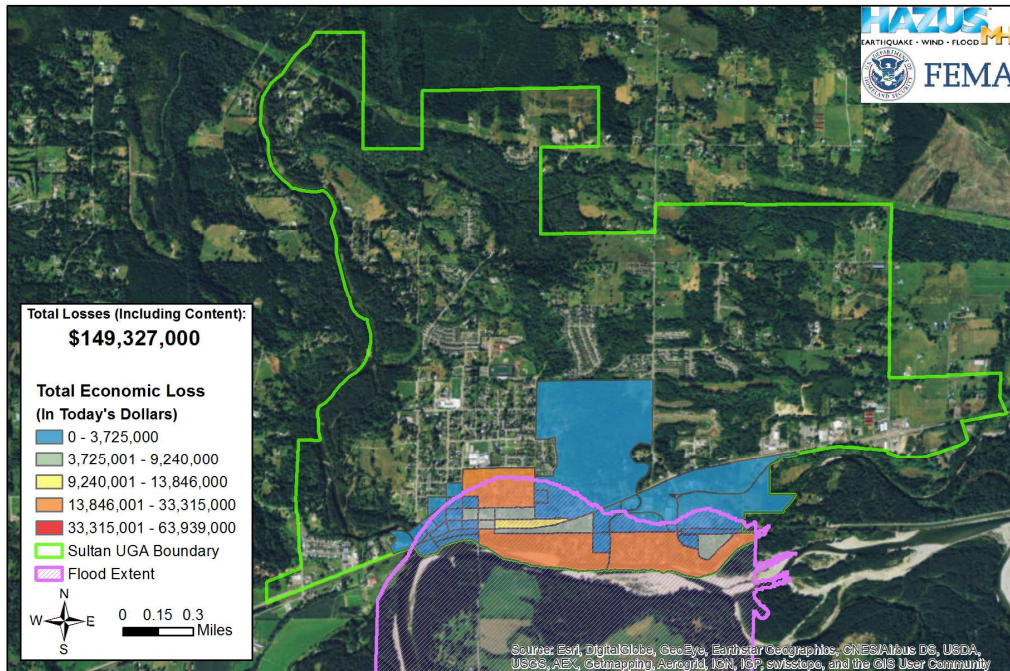


Figure 4.3 Direct Building Economic Loss – RCP 4.5 in 2040

In both the total economic loss (built capital) and displaced population (social capital) maps, it is not difficult to see how the assumed increase in growth affects the resulting risk and exposure, even in just thirty years.

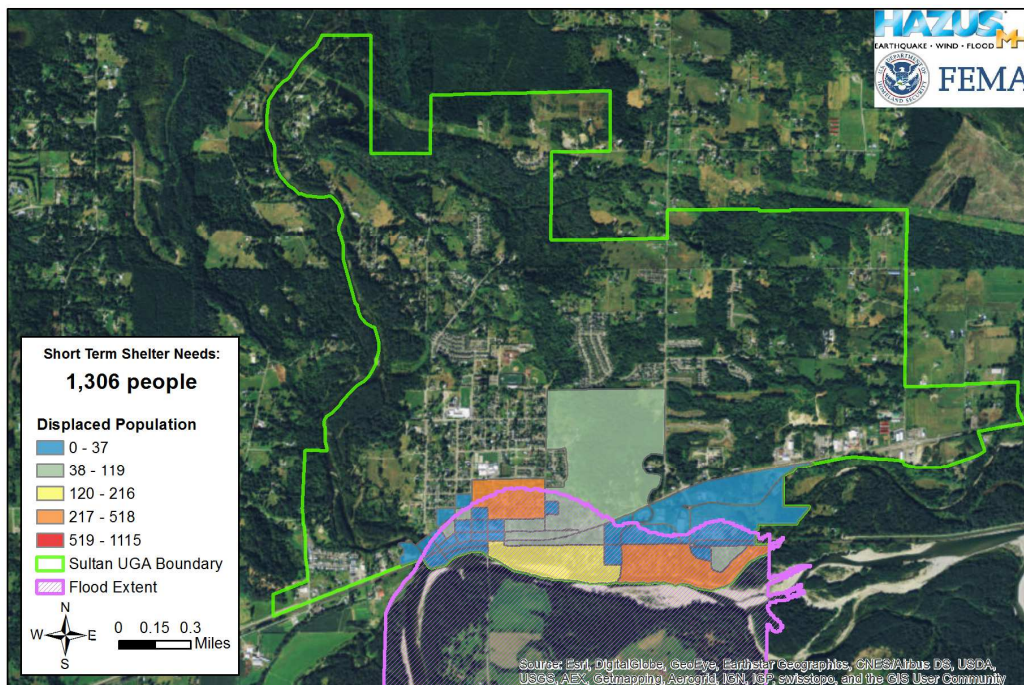


Figure 4.4 Displaced Population/Shelter Needs – RCP 4.5 in 2040

4.3 SCENARIO 3 – RCP 4.5 100 YEAR FLOOD EVENT IN 2080

Scenario 3 is just like the previous scenario, using the “low emissions” RCP 4.5 climate model. However, this is now estimating the risk and exposure of the same study area in 2080, after a projected 358% increase in urban development and population. The actual flood depths and extents are just marginally higher than the 2040 scenario, because under this climate model, the amount of carbon in the atmosphere has stabilized by 2080. However, despite the same intensity of the flood, the risk and exposure is much greater due to the projected growth inside of the UGA. Total economic losses are projected to be approximately six times the current FEMA baseline 100-year flood. In addition to increasing risk and exposure downtown, several sections with previously minor damage are turning into moderate or heavy areas of concern.

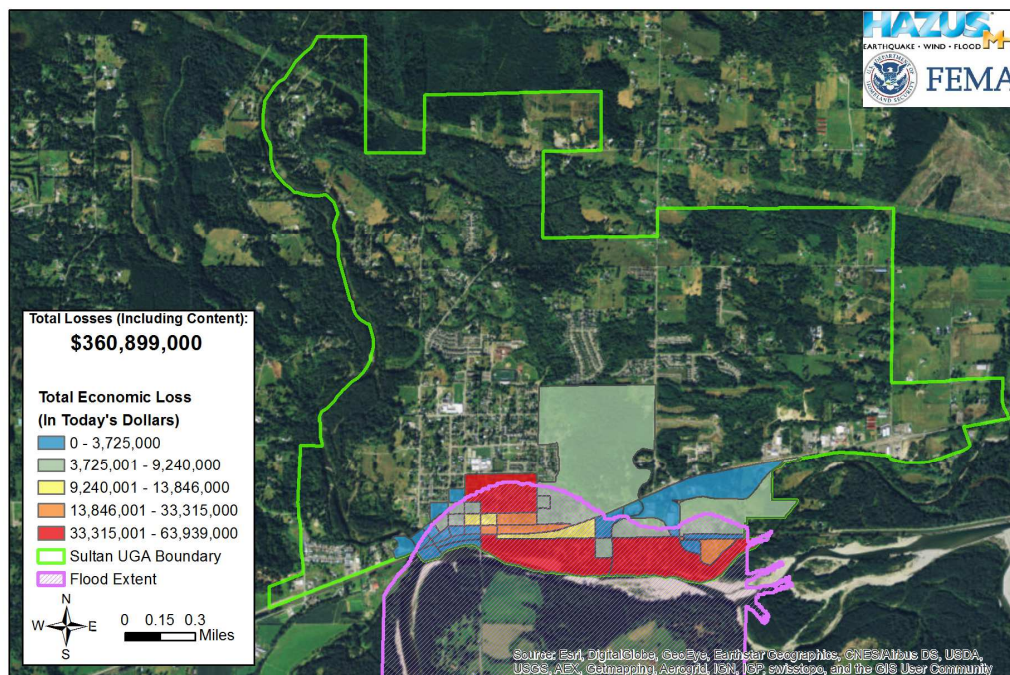


Figure 4.5 Direct Building Economic Loss – RCP 4.5 in 2080

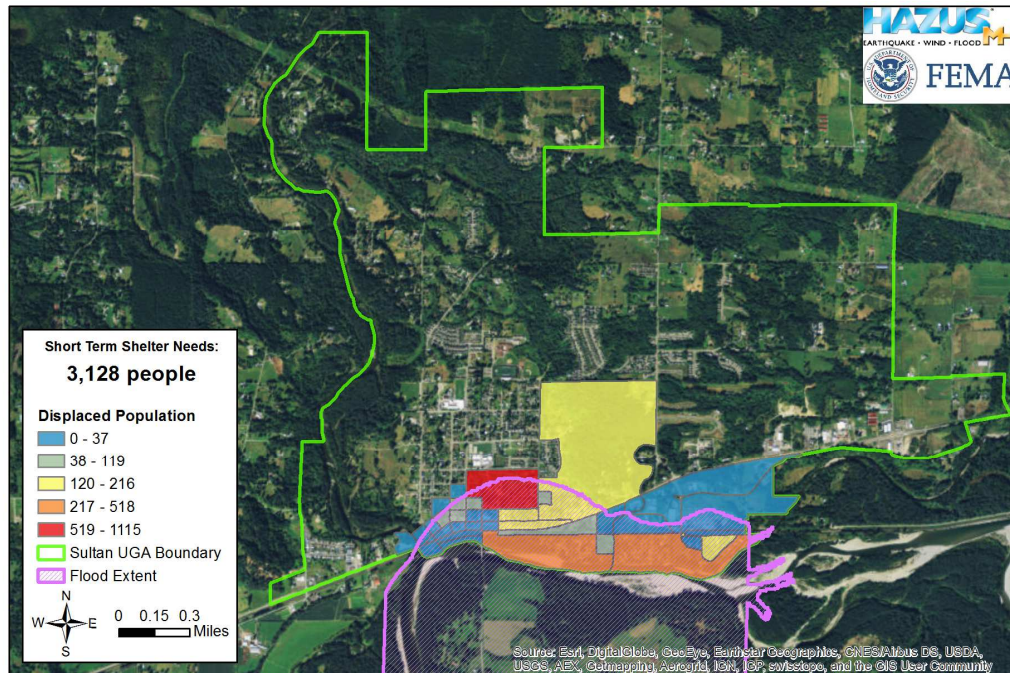


Figure 4.6 Displaced Population/Shelter Needs – RCP 4.5 in 2080

4.4 SCENARIO 4 – RCP 8.5 100 YEAR FLOOD EVENT IN 2040

Scenario 4 is the first scenario using the RCP 8.5 climate model, or “business as usual” in 2040. In this event, carbon emissions have not been curtailed. However, this scenario shows a similar amount of risk and exposure to Scenario 2 – RCP 4.5 in 2040. The reason for this is that there is already a certain amount of climate change “in the pipeline” and even if policies were put into place to curb greenhouse gas emissions, a certain amount of climate change will happen regardless. By 2040 there will not have been enough time elapsed to prevent a certain amount of temperature and precipitation increase.

Because of this, the output in Scenario 4 looks similar to Scenario 2, where the downtown of Sultan is experiencing moderate floods but the main areas are the residential homes closest to the Skykomish riverbank.

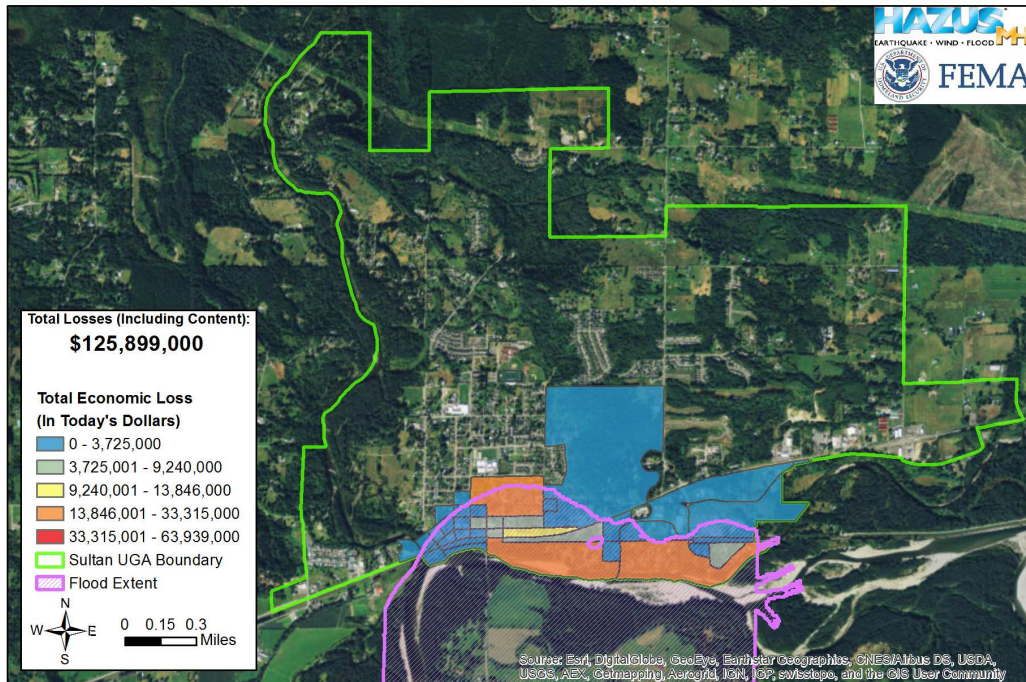


Figure 4.7 Direct Building Economic Loss – RCP 8.5 in 2040

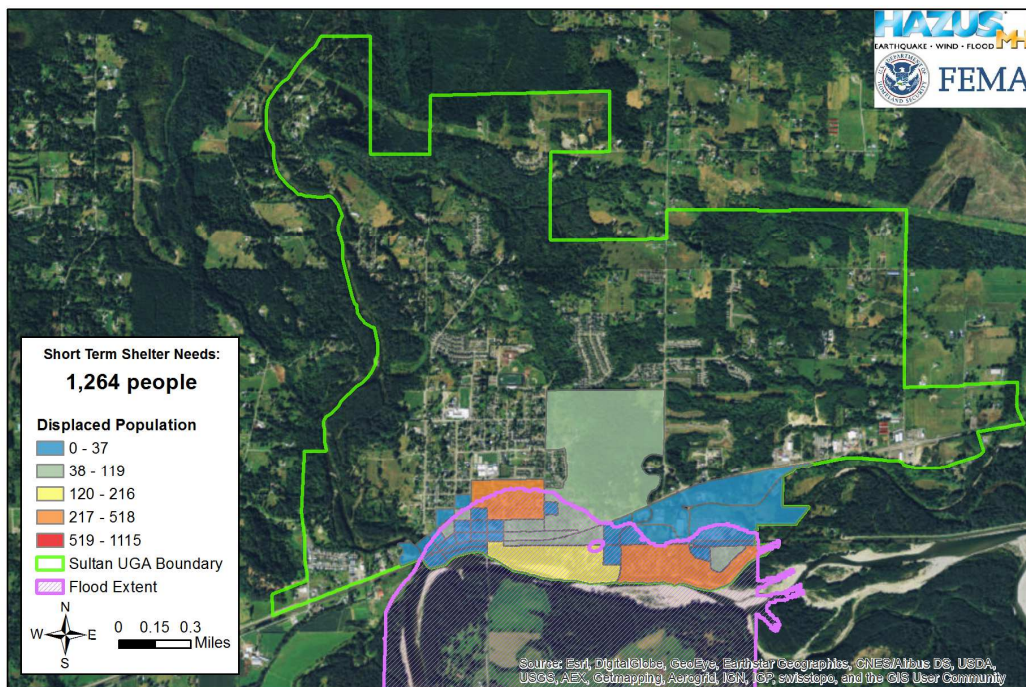


Figure 4.8 Displaced Population/Shelter Needs – RCP 8.5 in 2040

4.5 SCENARIO 5 – RCP 8.5 100 YEAR FLOOD EVENT IN 2080

Scenario 5 is the last scenario modeled in this thesis. While in 2040 the RCP 8.5 “business as usual” approach did not significantly change the risk and exposure compared to its RCP 4.5 counterpart, here in 2080 the increased greenhouse gas emissions and resulting climate change are starting to affect more of the Sultan UGA. In this scenario, there is the highest flood depth and extent, and shows the greatest amount of risk and exposure. Downtown Sultan is experiencing moderate to heavy flooding, and parcels other than the riverbank homes are experiencing the consequences of a changing climate. The projected total economic losses are triple that of Scenario 4, which occurs just 40 years earlier.

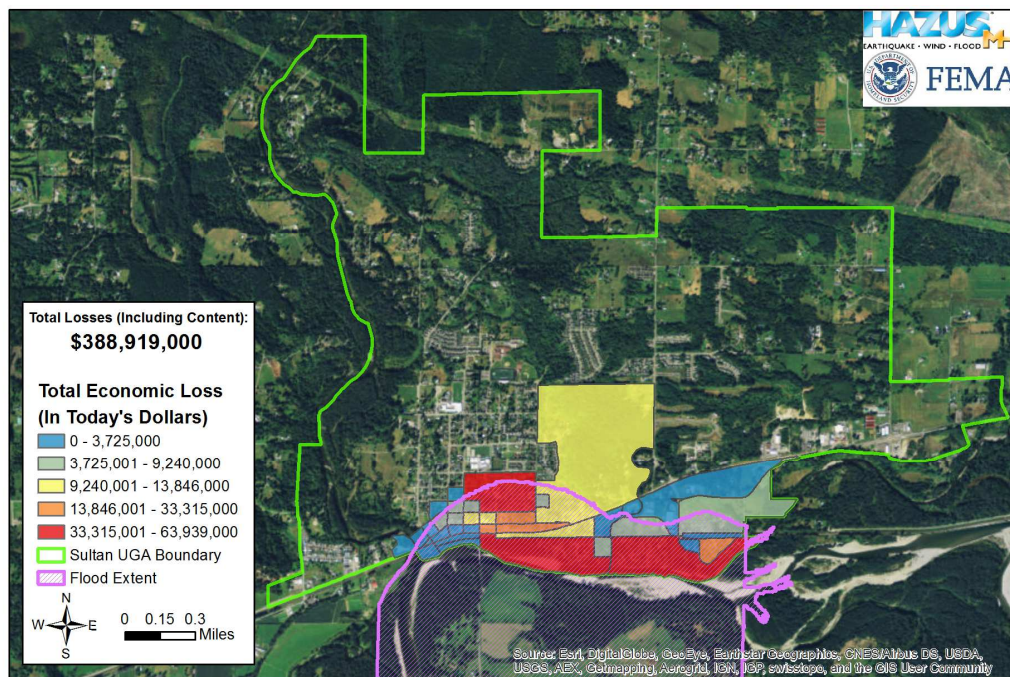


Figure 4.9 Direct Building Economic Loss – RCP 8.5 in 2080

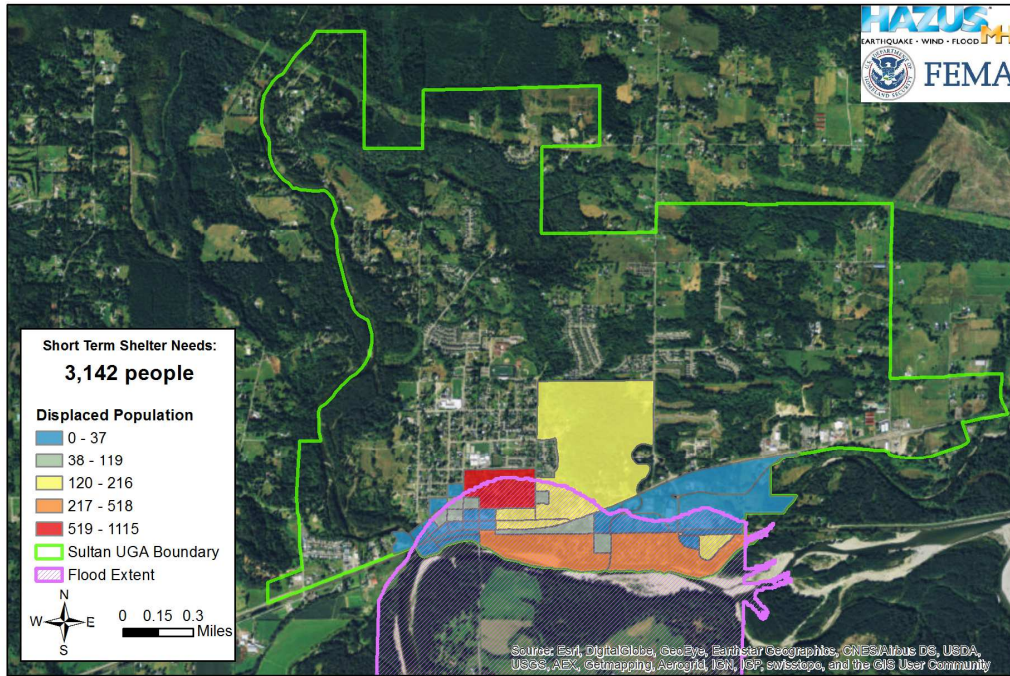


Figure 4.10 Displaced Population/Shelter Needs – RCP 8.5 in 2080

5.0 DISCUSSION

Risk assessment and hazard identification are a couple of first steps needed in helping communities properly prepare for a hazard. By showing which areas in the UGAs of Sultan that are at greater risk when factoring in climate change can lead to improved decision making when planning for future growth inside flood-prone areas. However, for the purposes of this thesis the scenario results will be used to prove that the HAZUS-MH software can be used as a tool to model future climate change scenarios.

5.1 RISK AND EXPOSURE

Table 2 provides a comparison between each scenario in the categories measured. Figure 5.1 and 5.2 show graphically the comparisons between each scenario. When looking at the scenario comparison table and figures, it is not difficult to see that the increased effects of climate change have a drastic effect of the built and social capital of the Sultan UGA.

| | Total Direct Building Economic Loss | Total Residential Buildings Damaged | Substantially Damaged Buildings | Total Debris Generated (tons) | Displaced Population |
|--------------------------------------|---|--|---------------------------------------|--|-------------------------|
| Scenario 1 (Baseline 100yr flood) | \$65,533,000 | 156 | 79 | 2080 | 699 |
| Scenario 2 (RCP 4.5 2040) | \$149,327,000 | 355 | 240 | 6318 | 1527 |
| Scenario 3 (RCP 4.5 2080) | \$360,899,000 | 849 | 583 | 15726 | 3652 |
| Scenario 4 (RCP 8.5 2040) | \$125,889,000 | 327 | 171 | 4845 | 1500 |
| Scenario 5 (RCP 8.5 2080) | \$388,919,000 | 885 | 656 | 20120 | 3672 |

Table 2 Summary of Comparisons between Flood Scenarios

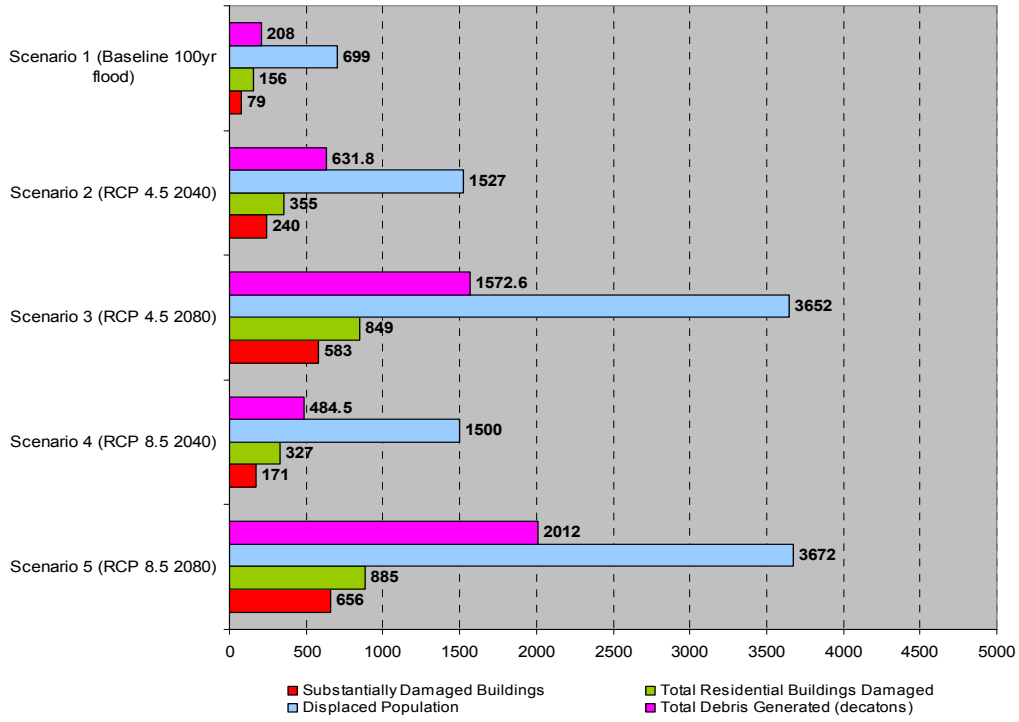


Figure 5.1 Displaced Population, Debris Generated and Substantially Damaged Buildings Comparison

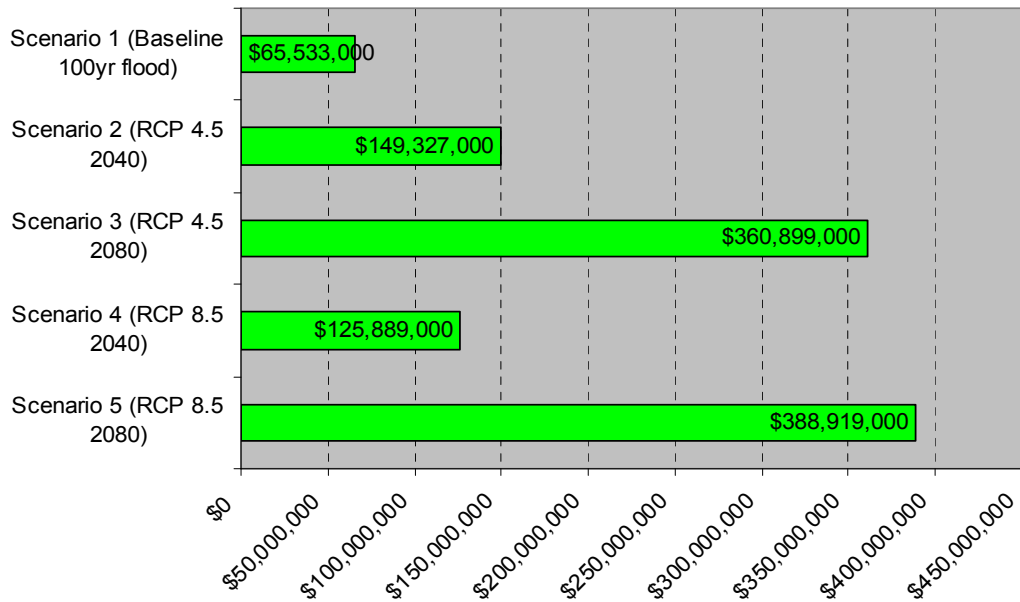


Figure 5.2 Total Direct Building Economic Loss Comparison

The baseline 100-year flood scenario is the least damaging of all the scenarios, as it has the lowest exposure of built and social capital. As the amount of exposure climbs in future climate scenarios, the amount of risk increases substantially. In this instance, urban growth in the floodplain is the single biggest factor contributing to the risk to built and social capital. The location of this growth is critical. In all the HAZUS-MH scenarios, there are only a portion of census blocks out of the many in Sultan that are actually at risk for flooding. Outside of the core downtown parcels, all of them are located on the riverbank on the other side of the railroad embankment, with a large portion occurring in small residential neighborhoods east of downtown.

When comparing the RCP 4.5 and 8.5 scenarios together in 2040, the risk and exposure is much closer between them than with the same RCP scenarios in 2080. There is a \$24 million dollar difference in damage between the two RCP scenarios in 2040, and a \$28 million difference between the RCP 8.5 “business as usual” scenarios in 2040 and 2080. This proves that HAZUS-MH software in this case can be used to evaluate risk due to climate change scenarios by incorporating climate data and future population projections, provided the population projections are reasonable and evenly distributed over the study area.

5.2 FLOOD EXTENTS AND MAGNITUDE

Initially the expectation was that the increased rainfall in the system due to climate change would create larger flood extents and higher magnitude floods. This is true to some extent, however the HAZUS-MH scenarios show only marginal increases in flood extents and depths. This is likely due to climate change lessening the amount of heavy rain events onto large snowpack deposits. As the climate moves closer to a rain dominated system, these higher magnitude rain and snow combination floods will most likely occur less often.⁷⁹ The resulting values of the highest peak above flood stage and modeled flooded extent are in Figure 5.3. Most of the peak flood depths appeared away from the City of

⁷⁹ Surfleet and Tullos, “Variability in Effect of Climate Change on Rain-on-Snow Peak Flow Events in a Temperate Climate.”

Sultan and formed further downstream, outside the study region. Shown below are the peak flood depths closest to the study region, at the confluence of the Wallace and Skykomish rivers.

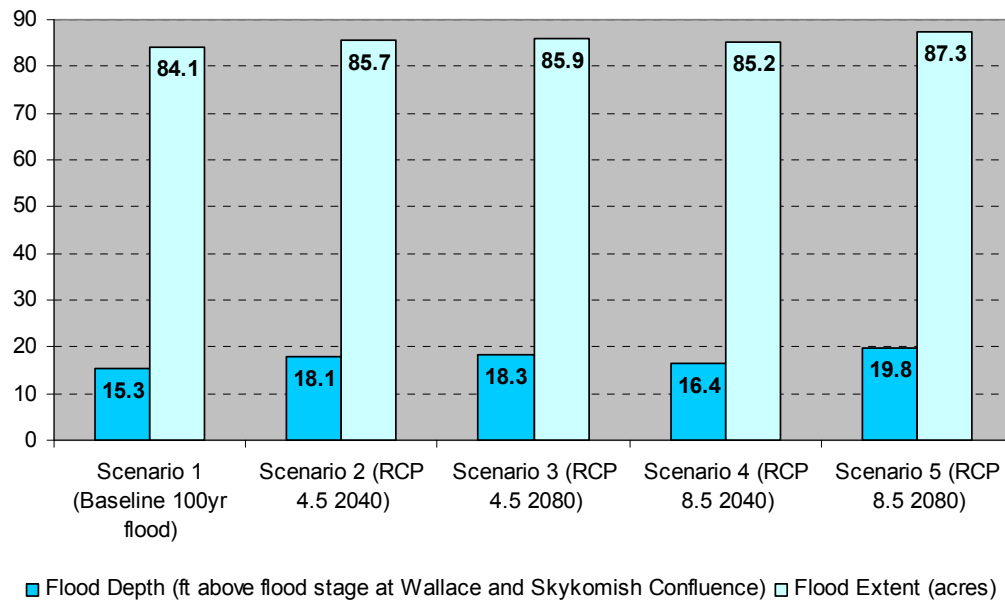


Figure 5.3 Flood Depth and Extent Comparison

5.3 FREQUENCY OF FLOOD EVENTS

While the extent of the peak floods might not change all that much, the frequency of flood events will. While this thesis is primarily concerned with the evaluation of HAZUS-MH as a tool to model future scenarios due to climate change, the CIG data used in this report also shows that the likelihood of the types of flooding events modeled previously will increase in frequency in the future.⁸⁰ Having a peak flow event that causes \$65 million worth of damage that happens every 100 years is nothing when compared to an annualized loss of \$15 million because of the increased frequency of smaller 10 year floods. HAZUS-MH can model these smaller floods in addition to the peak flood events and provide communities with a better understanding of the challenges they face every year,

⁸⁰ Climate Impacts Group, "CIG Datasets."

not just “when the big one” hits. The modeled 100 year baseline flood in this report will occur on average every 38 years under the RCP 4.5 scenario and every 17 years under the RCP 8.5 scenario model in 2080.

6.0 CONCLUSIONS

HAZUS-MH is a powerful tool capable of modeling future flood scenarios that are influenced by climate change. This can be possible by getting the specific local data that HAZUS-MH needs to model flood scenarios. By doing so, the HAZUS-MH flood scenarios estimate a rising amount of economic and social capital lost over time as the frequency and magnitude of flooding increases as a result of climate change.

This thesis selected the Sultan Urban Growth Area as the case study region. This area was selected because of the available building inventory, river hydrology and topographical data. By showing the differences between the baseline scenario using historical flood data and future scenarios using climate data, the change in risk due to climate change can be estimated. The current risk and exposure to the Sultan UGA using the baseline 100 year flood scenario is estimated to be almost 700 people and \$66 million dollars in built capital at risk. These exposure levels are contingent on the magnitude of the baseline flood being at 129,500 cubic feet per second at the confluence of the Wallace and Skykomish rivers which occurs on average once every 100 years. The baseline scenario areas of concern are riverbank properties in the eastern portion of the Sultan UGA, and any businesses and homes clustered south of Main Street/US-2 in Sultan.

HAZUS-MH can also estimate future risk and exposure by taking climate change into account. This is possible by focusing on a suitable study region, using up-to-date digital elevation models, local building inventory, census data and using climate scenarios to estimate future peak flows for future flood return intervals. These discharge rates and flood return intervals were applied in conjunction with evenly distributed population growth targets to create plausible estimates of future flood risk in the Sultan UGA.

The amount of total economic loss, residences destroyed, debris and displaced populations in 2040 and 2080 all increase when compared to the baseline 100-year flood scenario. The increase in exposure and risk to the Sultan

UGA built and social capital is facilitated by the increased frequency of flood events due to moving to a rain dominated system, and the projected increase in growth of built and social capital in or near the floodplain. These scenarios also show a large amount of debris being generated by the parcels upstream from Sultan, which would be a concern for the downtown area and any towns further downstream, mainly the city of Monroe. However, the flood extents of future scenarios do not show much increased area despite the magnitude of peak flood events increasing.

These results show that current 100 year floodplain boundaries may not adequately inform communities about the potential flood risk in the future due to climate change. While the baseline 100-year flood may have a tolerable level of risk in the present day, the increased magnitude and frequency of estimated future floods should concern the City of Sultan and any property owners with built and social capital near the banks of the Skykomish River.

While the National Insurance Flood Program does help communities insure properties and regulate development in the floodplain, it might be prudent for the community of Sultan to look at a phased retreat approach of properties at the greatest risk of flood damage. This would ensure that as higher magnitude floods become more frequent due to climate change, the loss of life and property can be prevented, as well as the social and economic hardships that occur after severe flooding.

The accuracy of these scenarios can be increased by incorporating LiDAR digital elevation models, updated building inventories, using regional parameter values instead of state values, more refined population growth estimation methods and embankments not currently modeled in the HAZUS-MH program. As the HAZUS-MH software program evolves, it may be possible in the future for the program to accurately model the loss of natural capital as well. In addition to this, newer discharge numbers can be incorporated as more studies are done to estimate how the hydrology and climate will change in the future. Any further research into incorporating climate change into flood hazard mapping should take these variables into account when the relevant information becomes available.

The current flood mapping process only incorporates historical flood data into projections of future risk. This process can be improved by taking climate change into account when planning for future flood hazards. When mapping flood hazards, including climate change as an important factor is a crucial step towards creating solutions to complex hazard mitigation and urban planning problems in the future. The HAZUS-MH output shows not just an increase in damage and the location of built and social capital at risk, but also shows an increase in the need to prepare communities to adapt to the changing conditions in the future due to climate change.

BIBLIOGRAPHY

- Alexander, Brian. "More than \$45 Million in Damage Reported by Counties after Flood - Snohomish, King Totals Could Rise Estimates Will Help Determine Federal Aid." *Seattle Times, The (WA)*, November 18, 2006, Fourth edition.
- Banks, James, Janey Camp, and Mark Abkowitz. "Adaptation Planning for Floods: A Review of Available Tools." *Natural Hazards* 70, no. 2 (2014): 1327–37. doi:10.1007/s11069-013-0876-7.
- Bellomo, Doug, Andrea Ryon, and Fernando Pasquel. "FEMA Flood Map Modernization Program." In *World Environmental and Water Resources Congress 2010*, 2223–30. American Society of Civil Engineers. Accessed May 14, 2015. <http://ascelibrary.org/doi/abs/10.1061/41114%28371%29229>.
- Burton, Christopher, and Susan L. Cutter. "Levee Failures and Social Vulnerability in the Sacramento-San Joaquin Delta Area, California." *Natural Hazards Review* 9, no. 3 (August 2008): 136–49. doi:10.1061/(ASCE)1527-6988(2008)9:3(136).
- City of Sultan, Washington. "Flood Information." Accessed May 22, 2015. <http://ci.sultan.wa.us/flood-information/>.
- Climate Impacts Group. "CIG Datasets." *CIG Datasets and Other Data Sources*. Accessed April 3, 2015. <http://ces.washington.edu/cig/data/index.shtml>.
- . "Connecting Science and Decision-Making to Develop Climate Resilience." *CIG Fact Sheet*. Accessed May 5, 2015. http://ces.washington.edu/cig/files/CIG_factsheet_2014.pdf.
- . "Seasonal Hydrologic Responses." *Types of Pacific Northwest Rivers*. Accessed April 3, 2015. <http://ces.washington.edu/cig/data/index.shtml>.
- . "State of Knowledge Report - Climate Change Impacts and Adaptation in Washington State: Technical Summaries for Decision Makers," 2013. <http://ces.washington.edu/cig/reports.shtml>.
- Colle, Brian A., and Clifford F. Mass. "The 5–9 February 1996 Flooding Event over the Pacific Northwest: Sensitivity Studies and Evaluation of the MM5 Precipitation Forecasts." *Monthly Weather Review* 128, no. 3 (March 1, 2000): 593–617. doi:10.1175/1520-0493(2000)128<0593:TFFEOT>2.0.CO;2.
- Cummings, Christina A., Paul E. Todhunter, and Bradley C. Rundquist. "Using the Hazus-MH Flood Model to Evaluate Community Relocation as a Flood Mitigation Response to Terminal Lake Flooding: The Case of Minnewaukan,

North Dakota, USA.” *Applied Geography* 32, no. 2 (March 2012): 889–95. doi:10.1016/j.apgeog.2011.08.016.

Dierauer, Jennifer, Nicholas Pinter, and Jonathan W. F. Remo. “Evaluation of Levee Setbacks for Flood-Loss Reduction, Middle Mississippi River, USA.” *Journal of Hydrology* 450–451 (July 11, 2012): 1–8. doi:10.1016/j.jhydrol.2012.05.044.

ECONorthwest. “City of Sultan Preliminary Population Forecast.” ECONorthwest, June 2010. http://ci.sultan.wa.us/wp-content/uploads/City_Hall/City_Departments/Community_Development/Long_Range_Planning/Draft_GSP_Chapters-Agency_Review_Version/Appendix_H-City_of_Sultan_Preliminary_Population_Forecast.pdf.

Elsner, M. M., L. Cuo, N. Voisin, Js Deems, Af Hamlet, Ja Vano, Keb Mickelson, Sy Lee, and Dp Lettenmaier. “Implications of 21st Century Climate Change for the Hydrology of Washington State.” *Climatic Change* 102, no. 1–2 (2010): 225–60. doi:10.1007/s10584-010-9855-0.

Emery, Mary, and Cornelia B. Flora. “Appreciative Inquiry as a Visioning Process.” In *Community Vision Programs: Processes and Outcomes*, 135–55. Hoboken, NJ: Taylor & Francis, 2012.

Federal Emergency Management Agency. “Fiscal Year Statistics by State,” 2015. <http://www.fema.gov/policy-claim-statistics-flood-insurance/policy-claim-statistics-flood-insurance/policy-claim-13-0#>.

———. “Guidance for Flood Risk Analysis and Mapping.” Guidance Document, May 2014. http://www.fema.gov/media-library-data/1406747117351-744b6bd203c18ada4806ad4e90c18b81/Flood_Risk_Assessment_Guidance_May_2014.pdf.

———. “Multi-Hazard Loss Estimation Methodology, Flood Model, Hazus-MH Technical Manual.” Federal Emergency Management Agency, January 29, 2015. http://www.fema.gov/media-library-data/20130726-1820-25045-8292/hznh2_1_fl_tm.pdf.

FEMA Region X Mitigation. “HAZUS Analysis for the Green River Valley,” October 6, 2009. <http://your.kingcounty.gov/dnrp/library/water-and-land/flooding/green-river-valley-hazus-report-1009.pdf>.

Freitag, Bob, Susan M. Bolton, and Frank Westerlund. *Floodplain Management : A New Approach for a New Era*. Washington DC, USA: Island Press, 2009.

- Freitag, Robert C., Daniel B. Abramson, Manish Chalana, and Maximilian Dixon. "Whole Community Resilience: An Asset-Based Approach to Enhancing Adaptive Capacity Before a Disruption." *Journal of the American Planning Association* 80, no. 4 (October 2, 2014): 324–35. doi:10.1080/01944363.2014.990480.
- Hamman, Joseph Johnston. "Effects of Projected Twenty-First Century Sea Level Rise, Storm Surge, and River Flooding on Water Levels in Puget Sound Floodplains and Estuaries." Thesis, University of Washington, 2012. <https://digital.lib.washington.edu/researchworks/handle/1773/20735>.
- IPCC. "Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change." Cambridge University Press, 2013.
- King County, Washington. "Flood Buyout and Elevation Programs." *Flooding Services*, 2015. <http://www.kingcounty.gov/environment/waterandland/flooding/buyout.aspx>.
- Meghan M. Dalton editor, author Philip W. Mote editor, author Amy K. Snover editor, author Pacific Northwest Climate Impacts Research Consortium, author University of Washington. Climate Impacts Group, sponsoring body United States. National Oceanic and Atmospheric Administration. Office of Climate Observation. Climate Program Office, National Climate Assessment, et al. *Climate Change in the Northwest : Implications for Our Landscapes, Waters, and Communities*. National Climate Assessment Regional Technical Input Report Series. Washington ; Covelo ; London: Island Press, 2013.
- National Flood Insurance Program. *Myths and Facts about the National Flood Insurance Program*. Washington, DC: Federal Emergency Management Agency, 2010.
- National Oceanic and Atmospheric Administration. "Pacific Northwest Flood Event of Jan 15-19, 2011," 2011. http://www.nwrfc.noaa.gov/floods/jan_2011/january2011floodReport.pdf.
- Oregon Department of Land Conservation and Development. "The Oregon Climate Change Adaptation Framework," 2010. http://www.oregon.gov/ENERGY/GBLWRM/docs/Framework_Final_DLCD.pdf.
- Puget Sound LiDAR Consortium. "Snohomish County LiDAR." *Snohomish County LiDAR*. Accessed April 13, 2015. http://pugetsoundlidar.ess.washington.edu/lidardata/restricted/nonpslc/snohomish_misc/index.html.

- Qiu, Xiaomin, Shuo-sheng Wu, and Yan Chen. "Effects of Threshold Drainage Area and Study Region Size on HAZUS Flood Analysis." *Cartography and Geographic Information Science* 37, no. 2 (January 1, 2010): 93–104. doi:10.1559/152304010791232172.
- Salathe, Ep, Af Hamlet, Cf Mass, Sy Lee, M. Stumbaugh, and R. Steed. "Estimates of Twenty-First-Century Flood Risk in the Pacific Northwest Based on Regional Climate Model Simulations." *Journal Of Hydrometeorology* 15, no. 5 (2014): 1881–99. doi:10.1175/JHM-D-13-0137.1.
- Schneider, Philip, and Barbara Schauer. "HAZUS—Its Development and Its Future." *Natural Hazards Review* 7, no. 2 (2006): 40–44. doi:10.1061/(ASCE)1527-6988(2006)7:2(40).
- Schwab, James. *Planning for Post-Disaster Recovery and Reconstruction*. Report (American Planning Association. Planning Advisory Service) ; No. 483/484. Chicago, IL: American Planning Association, 1998.
- Singh, Bijay Kumar. "Flood Hazard Mapping with Participatory GIS The Case of Gorakhpur." *Environment and Urbanization Asia* 5, no. 1 (March 1, 2014): 161–73. doi:10.1177/0975425314521546.
- Slobodan P. Simonovic. *Floods in a Changing Climate: Risk Management*. International Hydrology Series. Cambridge: Cambridge University Press, 2012.
- Snohomish County Department of Public Works, Surface Water Management Division. "Upper Skykomish River Flood Insurance Study Technical Support Data Notebook," September 29, 2010. <http://wa-snohomishcounty.civicplus.com/DocumentCenter/View/6668>.
- Snohomish County Tomorrow. "2013-2014 Growth Monitoring Report." Snohomish County Tomorrow Steering Committee Review, October 22, 2014. <http://snohomishcountywa.gov/DocumentCenter/View/20484>.
- Surfleet, Christopher G., and Desirée Tullos. "Variability in Effect of Climate Change on Rain-on-Snow Peak Flow Events in a Temperate Climate." *Journal of Hydrology* 479 (February 4, 2013): 24–34. doi:10.1016/j.jhydrol.2012.11.021.
- S-Y, Lee, and A.F Hamlet. "Skagit River Basin Climate Science Report: A Summary Report Prepared for Skagit County and the Envision Skagit Project by the Department of Civil and Environmental Engineering and the Climate Impacts Group at the University of Washington," 2011.
- Thompson, Lynn. "FEMA's New Flood Maps Go Too Far, Some Cities Say." *The Seattle Times*, March 7, 2010. <http://www.seattletimes.com/seattle-news/femas-new-flood-maps-go-too-far-some-cities-say/>.

Tramblay, Yves, Ernest Amoussou, Wouter Dorigo, and Gil Mahé. "Flood Risk under Future Climate in Data Sparse Regions: Linking Extreme Value Models and Flood Generating Processes." *Journal of Hydrology* 519, Part A (November 27, 2014): 549–58. doi:10.1016/j.jhydrol.2014.07.052.

United States Geological Survey. "National Hydrography Dataset." *U.S. Geological Survey - National Hydrography Dataset*. Accessed May 20, 2015.
<http://viewer.nationalmap.gov/viewer/nhd.html?p=nhd>.

———. "USGS Flood Update for Western Washington." *USGS Washington Water Science Center*. Accessed April 13, 2015.
<http://wa.water.usgs.gov/news/2006/news.newhiflo.Nov06.htm>.

US Army Corp of Engineers. "Final Startup Levee Notice of Preparation." USACE, April 2012.
<http://www.nws.usace.army.mil/Portals/27/docs/environmental/resources/Final%20Startup%20NOP%20April%202012.pdf>.

U. S. Census Bureau. "American FactFinder." Accessed May 22, 2015.
<http://factfinder.census.gov/faces/nav/jsf/pages/index.xhtml>.

Washington State Legislature. *Growth Management Act. RCW*. Vol. 36.70a.110, 1990.
<http://apps.leg.wa.gov/rcw/default.aspx?cite=36.70a.110>.

APPENDIX A – CLIMATE IMPACTS GROUP

RIVERINE MODEL DATA

| Site ID | Average Period | Climate Scenario | Time Period | Hydrological Model Percentage Change in Flow Rate (ΔQ) by Climate Model | | | | | | | | | |
|-----------|----------------|------------------|-------------|---|---------|-------|----------|---------------|---------------|---------------|--------------|--------|-----------|
| | | | | bcc-csm1-1-m | CanESM2 | CCSM4 | CNRM-CM5 | CSIRO-Mk3-6-0 | HadGEM2-CC365 | HadGEM2-ES365 | IPSL-CM5A-MR | MIROC5 | NorESM1-M |
| SKYKOMISH | 1d | RCP 4.5 | 2040s | -4.2 | 49.1 | 48.5 | 34.6 | 25.2 | 49.1 | 80.3 | 127.4 | 33 | 127.2 |
| SKYKOMISH | 3d | RCP 4.5 | 2040s | 31.2 | 40.5 | 48.9 | 29.5 | 11.1 | 32.3 | 84.6 | 123.5 | 63.8 | 159.6 |
| SKYKOMISH | 5d | RCP 4.5 | 2040s | 48.2 | 40.2 | 58.8 | 45.6 | 3.7 | 36.9 | 74.8 | 105.6 | 58.2 | 164.7 |
| SKYKOMISH | 7d | RCP 4.5 | 2040s | 45.8 | 32.9 | 71.9 | 26.8 | 4.4 | 37.3 | 61.4 | 111.8 | 48.3 | 135.5 |
| SKYKOMISH | 1d | RCP 4.5 | 2080s | 219.1 | 0.1 | 53 | 56.9 | 55.4 | 96.5 | 62.1 | -16.5 | -21.2 | 84 |
| SKYKOMISH | 3d | RCP 4.5 | 2080s | 154.7 | 8.1 | 53 | 55.4 | 53.5 | 81.3 | 45.8 | -12.7 | 8.4 | 108.2 |
| SKYKOMISH | 5d | RCP 4.5 | 2080s | 123.2 | 21.6 | 68.3 | 52.9 | 49.6 | 78.4 | 40.4 | -17.4 | 23.1 | 126.1 |
| SKYKOMISH | 7d | RCP 4.5 | 2080s | 98.5 | 20.1 | 54.9 | 40.8 | 48.1 | 73.5 | 31.7 | -20.6 | 21.6 | 119.9 |
| SKYKOMISH | 1d | RCP 8.5 | 2040s | 41.1 | 4.2 | 2.6 | -10.3 | -3.6 | 32.8 | 86.3 | 69.1 | -18.7 | 2.1 |
| SKYKOMISH | 3d | RCP 8.5 | 2040s | 41.9 | 1.2 | 4.9 | -0.8 | -14.7 | 29 | 75.2 | 72 | 5.2 | 32.4 |
| SKYKOMISH | 5d | RCP 8.5 | 2040s | 62.7 | 18.8 | 14.7 | 12.7 | -6.6 | 24.9 | 55.2 | 67.2 | 10.4 | 65 |
| SKYKOMISH | 7d | RCP 8.5 | 2040s | 53.3 | 23.5 | 14 | 10.8 | 4.2 | 16.9 | 46.8 | 69.9 | -0.8 | 64.7 |
| SKYKOMISH | 1d | RCP 8.5 | 2080s | 356.1 | 101.1 | 143.2 | 106.5 | -20.9 | 107.4 | 31.9 | 16.3 | 40.3 | 56.1 |
| SKYKOMISH | 3d | RCP 8.5 | 2080s | 368.9 | 78.6 | 132.1 | 148 | -22.7 | 79.4 | 19.4 | 21.1 | 60.1 | 83.6 |
| SKYKOMISH | 5d | RCP 8.5 | 2080s | 315.6 | 95 | 104 | 136.4 | -26.9 | 79.1 | 17.3 | 6.2 | 51 | 102.4 |
| SKYKOMISH | 7d | RCP 8.5 | 2080s | 248.8 | 74.3 | 78.5 | 107.2 | -24.5 | 86.9 | 19.6 | 2.6 | 37.6 | 101.3 |

Table 3 CIG Percent Change in 100-Year Flood Return Period

| Site ID | Future | Ret. Per. | Scenario | Avg Period | 10 model projections, in order from lowest to greatest | | | | | | | | | |
|-----------------------|-----------|-----------|----------|------------|--|----|----|----|----|----|----|-----|-----|------|
| SKYKOMISH NR GOLD BAR | 2030-2059 | 100 | RCP 4.5 | 1d | 16 | 17 | 19 | 25 | 27 | 34 | 36 | 40 | 45 | 146 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 100 | RCP 8.5 | 1d | 19 | 23 | 26 | 50 | 83 | 84 | 91 | 119 | 344 | 2072 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 100 | RCP 4.5 | 3d | 12 | 15 | 17 | 17 | 22 | 26 | 27 | 37 | 50 | 66 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 100 | RCP 8.5 | 3d | 12 | 21 | 26 | 31 | 49 | 65 | 73 | 93 | 107 | 206 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 100 | RCP 4.5 | 5d | 9 | 14 | 16 | 17 | 17 | 18 | 21 | 28 | 45 | 84 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 100 | RCP 8.5 | 5d | 8 | 15 | 21 | 31 | 40 | 44 | 48 | 51 | 52 | 133 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 100 | RCP 4.5 | 7d | 9 | 15 | 16 | 17 | 18 | 19 | 23 | 40 | 41 | 81 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 100 | RCP 8.5 | 7d | 9 | 13 | 19 | 32 | 33 | 53 | 55 | 58 | 86 | 109 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 50 | RCP 4.5 | 1d | 10 | 11 | 11 | 15 | 15 | 17 | 19 | 19 | 25 | 52 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 50 | RCP 8.5 | 1d | 11 | 13 | 14 | 29 | 30 | 32 | 38 | 42 | 58 | 113 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 50 | RCP 4.5 | 3d | 9 | 10 | 10 | 10 | 13 | 15 | 18 | 21 | 23 | 30 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 50 | RCP 8.5 | 3d | 8 | 12 | 16 | 18 | 20 | 28 | 28 | 37 | 43 | 52 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 50 | RCP 4.5 | 5d | 7 | 8 | 10 | 10 | 11 | 13 | 14 | 19 | 27 | 29 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 50 | RCP 8.5 | 5d | 6 | 11 | 12 | 15 | 19 | 23 | 25 | 28 | 29 | 46 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 50 | RCP 4.5 | 7d | 7 | 9 | 10 | 11 | 11 | 14 | 15 | 26 | 27 | 29 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 50 | RCP 8.5 | 7d | 7 | 10 | 12 | 20 | 20 | 24 | 27 | 32 | 32 | 38 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 20 | RCP 4.5 | 1d | 5 | 6 | 6 | 7 | 8 | 8 | 8 | 9 | 13 | 16 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 20 | RCP 8.5 | 1d | 6 | 6 | 7 | 8 | 9 | 11 | 13 | 14 | 14 | 15 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 20 | RCP 4.5 | 3d | 5 | 5 | 5 | 6 | 6 | 7 | 7 | 11 | 12 | 15 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 20 | RCP 8.5 | 3d | 5 | 6 | 6 | 9 | 9 | 9 | 12 | 12 | 14 | 15 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 20 | RCP 4.5 | 5d | 4 | 5 | 6 | 6 | 6 | 7 | 8 | 10 | 11 | 16 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 20 | RCP 8.5 | 5d | 5 | 5 | 6 | 7 | 10 | 10 | 11 | 13 | 14 | 14 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 20 | RCP 4.5 | 7d | 4 | 5 | 6 | 6 | 6 | 8 | 9 | 11 | 14 | 15 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 20 | RCP 8.5 | 7d | 5 | 6 | 6 | 6 | 10 | 10 | 12 | 14 | 14 | 16 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 10 | RCP 4.5 | 1d | 3 | 3 | 4 | 5 | 5 | 5 | 5 | 5 | 7 | 8 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 10 | RCP 8.5 | 1d | 3 | 4 | 4 | 4 | 4 | 5 | 5 | 7 | 7 | 8 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 10 | RCP 4.5 | 3d | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 7 | 7 | 9 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 10 | RCP 8.5 | 3d | 3 | 3 | 4 | 5 | 5 | 5 | 5 | 6 | 7 | 8 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 10 | RCP 4.5 | 5d | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 7 | 7 | 10 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 10 | RCP 8.5 | 5d | 3 | 4 | 4 | 5 | 5 | 6 | 6 | 7 | 8 | 8 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 10 | RCP 4.5 | 7d | 3 | 4 | 4 | 4 | 4 | 5 | 5 | 8 | 8 | 9 |
| SKYKOMISH NR GOLD BAR | 2030-2059 | 10 | RCP 8.5 | 7d | 3 | 4 | 4 | 5 | 6 | 6 | 6 | 7 | 8 | 9 |

Notes:

Large return periods at the high end of the range are probably not accurate estimates, but do mean that those particular simulations indicate a decrease in flood probability

"NaN" values occur when the future projections do not include flows that reach the same magnitude as in the historical record

"Inf" values occur when there is an issue with the return period calculation.

Table 4 CIG Future Flood Return Interval Projections in 2040

| Site ID | Future | Ret. Perd. | Scenario | Avg Period | 10 model projections, in order from lowest to greatest | | | | | | | | | |
|-----------------------|-----------|------------|----------|------------|--|----|----|----|----|----|----|----|-----|------|
| SKYKOMISH NR GOLD BAR | 2070-2099 | 100 | RCP 4.5 | 1d | 7 | 12 | 17 | 18 | 22 | 24 | 24 | 98 | 336 | 5316 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 100 | RCP 8.5 | 1d | 4 | 6 | 10 | 11 | 13 | 15 | 24 | 25 | 48 | 1316 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 100 | RCP 4.5 | 3d | 7 | 7 | 16 | 19 | 21 | 24 | 27 | 48 | 53 | 350 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 100 | RCP 8.5 | 3d | 4 | 6 | 8 | 8 | 13 | 13 | 15 | 37 | 39 | 3740 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 100 | RCP 4.5 | 5d | 5 | 5 | 16 | 18 | 20 | 21 | 24 | 24 | 24 | 1914 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 100 | RCP 8.5 | 5d | 0 | 3 | 6 | 6 | 8 | 9 | 11 | 11 | 43 | 63 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 100 | RCP 4.5 | 7d | 0 | 5 | 6 | 19 | 20 | 22 | 22 | 22 | 22 | 25 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 100 | RCP 8.5 | 7d | 0 | 3 | 6 | 7 | 8 | 10 | 10 | 13 | 39 | 77 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 50 | RCP 4.5 | 1d | 5 | 7 | 9 | 9 | 9 | 14 | 16 | 18 | 59 | 167 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 50 | RCP 8.5 | 1d | 3 | 4 | 6 | 7 | 7 | 9 | 10 | 12 | 15 | 58 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 50 | RCP 4.5 | 3d | 5 | 5 | 9 | 10 | 10 | 12 | 15 | 18 | 18 | 55 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 50 | RCP 8.5 | 3d | 3 | 4 | 5 | 6 | 8 | 8 | 8 | 14 | 15 | 62 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 50 | RCP 4.5 | 5d | 4 | 5 | 10 | 10 | 10 | 11 | 11 | 11 | 16 | 104 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 50 | RCP 8.5 | 5d | 3 | 4 | 4 | 6 | 6 | 6 | 7 | 18 | 18 | 265 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 50 | RCP 4.5 | 7d | 4 | 5 | 10 | 10 | 10 | 11 | 12 | 13 | 15 | 350 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 50 | RCP 8.5 | 7d | 3 | 5 | 5 | 6 | 6 | 6 | 7 | 17 | 18 | 432 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 20 | RCP 4.5 | 1d | 4 | 4 | 4 | 4 | 4 | 5 | 7 | 9 | 9 | 15 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 20 | RCP 8.5 | 1d | 2 | 3 | 3 | 4 | 4 | 4 | 4 | 5 | 5 | 6 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 20 | RCP 4.5 | 3d | 3 | 4 | 4 | 4 | 5 | 5 | 6 | 6 | 9 | 10 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 20 | RCP 8.5 | 3d | 2 | 2 | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 5 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 20 | RCP 4.5 | 5d | 3 | 4 | 4 | 4 | 4 | 5 | 6 | 6 | 9 | 10 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 20 | RCP 8.5 | 5d | 2 | 3 | 3 | 3 | 4 | 4 | 4 | 5 | 7 | 7 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 20 | RCP 4.5 | 7d | 3 | 4 | 4 | 4 | 5 | 5 | 6 | 7 | 9 | 10 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 20 | RCP 8.5 | 7d | 2 | 3 | 3 | 3 | 4 | 4 | 5 | 5 | 7 | 8 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 10 | RCP 4.5 | 1d | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 5 | 6 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 10 | RCP 8.5 | 1d | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 10 | RCP 4.5 | 3d | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 6 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 10 | RCP 8.5 | 3d | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 10 | RCP 4.5 | 5d | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 6 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 10 | RCP 8.5 | 5d | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 10 | RCP 4.5 | 7d | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 6 |
| SKYKOMISH NR GOLD BAR | 2070-2099 | 10 | RCP 8.5 | 7d | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 4 |

Notes:

Large return periods at the high end of the range are probably not accurate estimates, but do mean that those particular simulations indicate a decrease in flood probability

"NaN" values occur when the future projections do not include flows that reach the same magnitude as in the historical record

"Inf" values occur when there is an issue with the return period calculation.

Table 5 CIG Future Flood Return Interval Projections in 2080

APPENDIX B – CLIMATE IMPACTS GROUP

RIVERINE MODEL METHODOLOGIES

Climate Projections and Downscaling

We used ten Global Climate Models (GCMs) drawn from the newly available Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012). Ten CMIP5 models were statistically downscaled using Multivariate Adaptive Constructed Analogues (MACA, Abatzoglou and Brown 2011), producing a gridded daily time series of temperature and precipitation at 1/16-degree resolution (about 5-7 km). The MACA downscaling was applied to the historical (1950-2005) and two future projections (2006-2009) for each GCM (i.e.: 3 time series per GCM). The two projections were taken from a low and a high Representative Concentration Pathway (RCP; Van Vuuren et al., 2011), named RCP 4.5 and 8.5, respectively.

Hydrologic Modeling, Streamflow Routing

The statistically downscaled meteorological data were used to drive the Variable Infiltration Capacity (VIC) macroscale model (version 4.1.2; Gao et al., 2010; Liang et al., 1994). To produce streamflow data at each site, VIC simulations of runoff and baseflow from each grid cell were post-processed using the RVIC streamflow routing model (<https://github.com/UW-Hydro/RVIC/wiki/RVIC-Wiki>). For the four sites that have more than 30 years of observed historical data during 1950-2005, streamflow simulations were bias corrected to match naturalized streamflow observations using a quantile mapping approach outlined by Snover et al. (2003) and Hamlet et al. (2003) as described in detail below.

Routed streamflows with and without bias-correction were then used to estimate flood magnitude for the 10-, 20-, 50- and 100-year return periods, using

the historical run for each GCM. To estimate flood magnitude for return intervals of 10-, 20-, 50- and 100-years, the maximum peak flows are extracted for each water year at each site to produce a time series of annual peak flows. Generalized Extreme Value (GEV) distributions are then fitted to these data using L-moments derived from probability weighted moments (Wang 1997; Hosking and Wallis 1993; Hosking 1990). Flood magnitudes for different return intervals from each GCM's historical run were then used to estimate the new return interval corresponding to the magnitude of historical peak flows. We also considered width of future flood hydrographs so results included for the 1-, 3-, 5-, and 7-day peak flows in each instance.

Bias Correction

A bias correction procedure was applied to remove systematic biases in the monthly time step streamflow simulation by using a quantile mapping technique (Snover et al., 2003; Hamlet et al., 2003). The mapping technique is based on a simple nonparametric lookup procedure and produces a one-to-one mapping between simulated and observed cumulative distribution functions for each calendar month, as shown in Figure 1. For example, if the “raw” simulated data for a particular month represents the estimated Xth quantile in the cumulative distribution function, then the Xth quantile is looked up in the observed distribution for the same period, and this quantile in the observed distribution becomes the bias corrected value for that month. For future simulations, the same quantile mapping is used, the assumption being that the bias structure of the hydrologic model is not altered by changes in temperature and precipitation in the driving data.

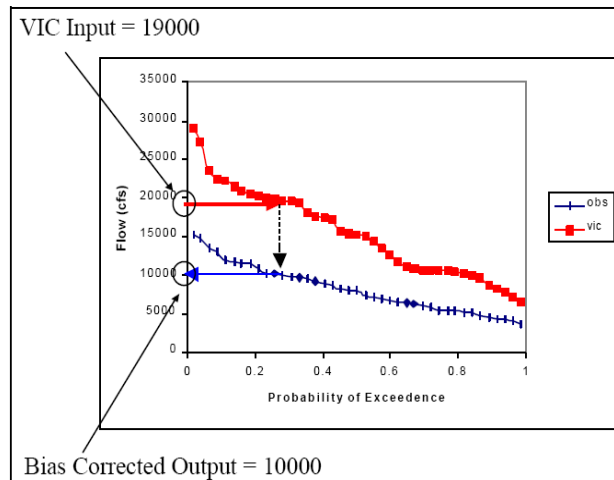


Figure 1. Schematic diagram showing the quantile mapping process (after Wood et al., 2001).

In the process of bias correcting individual months, annual streamflows (which hydrologic models usually simulate quite well) may be distorted somewhat. To remove this artifact of the monthly bias correction process, each month of the bias corrected simulation is adjusted to match annual runoff from the raw model results. Thus the bias corrected annual streamflow is exactly reproduced by the rescaled monthly values, but the relative "shape" of the monthly values is defined by the monthly quantile mapping procedure.

Figure 2 shows a monthly summary of the VIC simulations before and after bias correction at the Sauk River above Whitechuck near Darrington. The bias-corrected monthly values were then used to rescale the simulated daily flow sequences produced by the hydrologic model to estimate daily flows for both historical conditions and climate change scenarios.

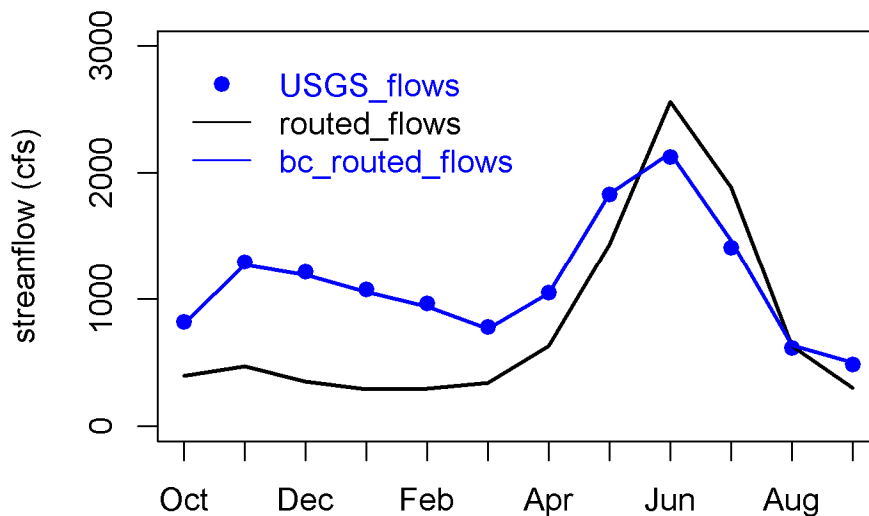


Figure 2. Comparison of long-term (Oct 1950 - Sep 2005) monthly mean observed and model simulated flows, both before (“routed_flows”) and after bias correction (“bc_routed_flows”) at the Sauk River above Whitechuck near Darrington.

References

- Abatzoglou, J.T., and T.J. Brown, 2011, A Comparison of Statistical Downscaling Methods Suited for Wildfire Applications, *International Journal of Climatology*, doi:10.1002/joc.2312.
- Gao, H., Tang, Q., Shi, X., Zhu, C., Bohn, T. J., Su, F., ... & Wood, E. F. (2010). Water budget record from Variable Infiltration Capacity (VIC) model. *Algorithm Theoretical Basis Document for Terrestrial Water Cycle Data Records*.
- Hamlet, A.F., Snover, A.K., and Lettenmaier, D.P., 2003, Climate Change Scenarios for Pacific Northwest Water Planning Studies: Motivation, Methodologies, and a User’s Guide to Application. Technical Document. *Center for Science in the Earth System, Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington*.
http://www.hydro.washington.edu/Lettenmaier/permanent_archive/hamlea/f/bams_paper/technical_documentation.pdf.
- Hosking, J.R.M., 1990. L-moments: analysis and estimation of distributions using linear combinations of order statistics. *J of the R Stat Soc, Series B*, 52,105-124.

- Liang, X., Lettenmaier, D.P., Wood, E.F., and Burges, S.J., 1994. A simple hydrologically based model of land surface water and energy fluxes for GSMs. *J. Geophys. Res.*, 99 (D7), 14415-14428.
- Snover, A.K., Hamlet, A.F., and Lettenmaier, D.P. (2003). "Climate-change scenarios for water planning studies: Pilot applications in the Pacific Northwest." *Bulletin of the American Meteorological Society*, 84 (11), 1513-1518.
- Taylor, K. E. et al., 2012. An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, 93(4), 485-498. doi:10.1175/BAMS-D-11-00094.1
- Van Vuuren, D. P. et al., 2011. The representative concentration pathways: An overview. *Climatic Change*, 109(1-2): 5-31.
- Wang, Q.J., 1997. LH moments for statistical analysis of extreme events. *Water Resour Res*, 33(12), 2841-2848.
- Wood, A. W., E. P. Maurer, A. Kumar, and D. P. Lettenmaier (2002), Long-range experimental hydrologic forecasting for the eastern United States, *J. Geophys. Res.*, 107(D20), 4429, doi:10.1029/2001JD000659.