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POTENTIAL IMPACTS OF CLIMATE CHANGE ON URBAN FLOODING: IMPLICATIONS FOR TRANSPORTATION INFRASTRUCTURE AND TRAVEL DISRUPTION

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Abstract

Climate change in the Pacific Northwest of America is likely to bring more frequent, heavier winter precipitation as temperature rises. These changes in precipitation patterns have significant implications in hydrology and socioeconomic sectors that could be affected by changes in hydrology. Transportation infrastructure and travel patterns are also vulnerable to potential changes in runoff regimes and stream geomorphology. The 2006 and 2007 winter storms resulted in massive flooding, causing several major road failures in Oregon. While the probability of these extreme events is projected to rise under the global warming scenarios, there is no study investigating this issue in Oregon.

The objectives of the project are threefold. First, we investigate the changes in the frequency and magnitude of winter runoff under climate change scenarios. Second, we determine the probability of road closure for representative road bridges under climate change scenarios. Third, we quantify these changes on transportation chokepoints related to flooding.

We examined two representative urban streams in the Portland Metro area. Johnson Creek and Fanno Creek were chosen because both creeks have historical flow data and exhibit high flooding potential; each also has high road density with high traffic volume. The hydrological processes of the two watersheds, however, are different (Fanno – highly urbanized and steep slope; Johnson Creek – mixed land use with gentle slope); thus, each serves as a good model for other urban watersheds in Oregon.

We used the following methodology to conduct our analysis.

1) *Hydro-climate modeling*: We applied statistically downscaled climate change scenarios for our study sites to predict the anticipated changes in winter precipitation amount and intensity. The US Geological Survey PRMS hydrologic model, together with a statistical model, were used to estimate runoff changes and resultant changes in flood frequency.
2) *Stream geomorphology survey and hydraulic analysis*: We surveyed channel profiles, patterns, and dimensions at the multiple cross sections of our study sites. The surveyed data were used to calibrate US Army Corp of Engineers' HAC-RAS for hydraulic analysis to project future water levels and identify vulnerable bridges and roads under different discharge scenarios.
3) *Traffic analysis*: We used Metro's travel forecast model to determine the potential impacts of road failure and congestion resulting from flooding. The model served as a reasonable and accurate assessment of the outcomes due to traffic disruption.

Our results show that there is a nonlinear relation between precipitation change and urban flooding and that impacts on travel disruption are subject to local hydroclimate and watershed land use conditions. This study is one of few interdisciplinary attempts to assess potential impacts of climate change on the transportation sector. Such integrated knowledge and spatially-explicit modeling is essential for establishing proactive flood and transportation management planning and policies under increasing climate uncertainty.

Introduction

The December 2007 storms amplified the ongoing flood risk in the Pacific Northwest (PNW). The problem has been cited as one of the worst cases of floods in the region. Many buildings and roads were closed as a result of prolonged and intense precipitation that brought severe floods. Flooding not only damaged various infrastructures but also disrupted freight and personal travel in the region. Flooding has become a persistent problem in recent years as more extreme weather events occur and development along the floodplain intensified. For example, in the city of Vernonia, the US Geological Survey recently revised a floodplain map, showing expanded floodplains into higher elevations. Flooding risk could increase in the future as a result of potential changing climate worldwide (Huntington 2006; Chang and Franczyk 2008). The stationarity assumption may not hold true in new infrastructure design and management (Milly et al. 2008). However, there is no quantitative study that investigates how future climate changes will affect flood frequency and its impacts on transportation infrastructure in the PNW.

While there is a growing body of literature on simulating future floods under climate change scenarios around the world (Ashley et al. 2005; Cameron 2004; Leander and Buishand 2007; Mazzarella and Rapetti 2004), there are only a few studies assessing potential consequences of climate change on the transportation sector in North America (NRC 2008). These studies include regional economic impacts as a result of changing transportation modes in Northern Canada (Lonergan et al. 1993) and flood risk mapping for vulnerable roads and the cost of travel disruption in the Boston Metropolitan area (Suarez et al. 2005). A unique feature of this study is to consider projected changes in land use and transportation demand as well as climatic conditions into the urban transportation modeling system. By incorporating broad environmental and socioeconomic scenarios, we will be able to discern the relative impacts of global warming on the transportation system as a result of additional riverine flooding.

Studies on natural hazard impacts from future climate change have struggled to adequately assess impacts (Soleckie and Rosenzweig 2001). This is largely due to a lack of adequate data, difficulty in interpreting the existing multi-disciplinary data, the complexity of cascading effects resulting from flooding on the regional transportation systems (NRC 1999), and the focus on attempting to model only extreme events, which are inherently more difficult to predict and model (Pielke and Downton 2000; Changon 2003). With this study, we are focusing on the cumulative effects of a range of flood events, which are to likely increase in frequency as a result of climate. In addition, we modeled the short-term transportation impact from temporary flooding in a few local roadways.

Study Area

The Portland metropolitan area serves our study site (Figure 1). Johnson Creek and Fanno Creek were chosen because both creeks have historical flow data and exhibit high flooding potential; each also has high road density with high traffic volume. The hydrological processes of the two watersheds, however, are different (Fanno – highly urbanized and steep slope; Johnson Creek – mixed land use with gentle slope); thus, each serves as representative for other urban watersheds in Oregon. While the urban areas of Upper Fanno and Lower Fanno Creeks, and Lower Johnson Creek are 83%, 87%, 89% of respective watersheds, the urban areas of the Upper Johnson Creek watershed are only 40% of the watershed. A portion of Upper Johnson Creek has been incorporated into urban growth boundaries in 2002.

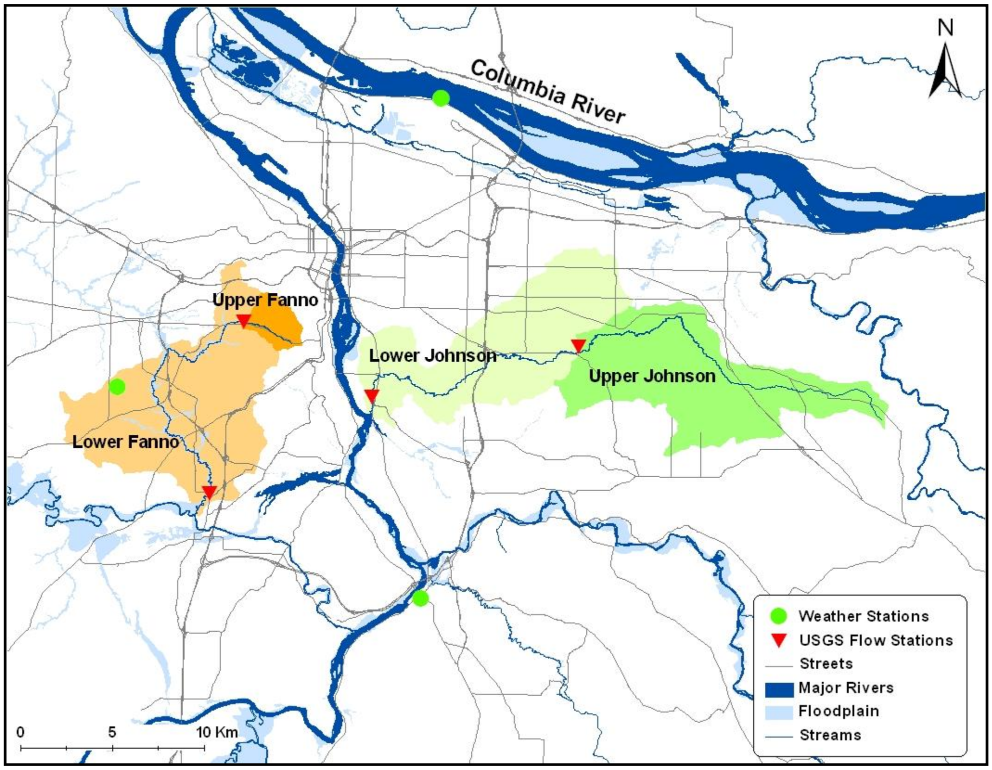

Figure 1. Study area: The Portland metropolitan area

Data and Methods

Hydroclimate modeling

We applied downscaled climate change scenarios for our study sites to predict the anticipated changes in winter precipitation amount and intensity. We used four representative climate change scenarios (CCSM-A1B, CCSM-B1, ECHAM5-B1, IPSL-B1) statistically downscaled at a spatial resolution of 1/16 degree for a period between 1960 and 2059. The years between 1960 and 1989 serve as reference period, while the years between 2030 and 2059 serve as future period representing the years around 2040s. These scenarios were obtained from the Climate Impact Group at the University of Washington (Salathe and Mote 2007). The precipitation and temperature data from the downscaled scenarios were compared with weather station data from PDX airport and Beaverton. When there are substantial biases in the downscaled data, we corrected the bias using quantile mapping. The bias-corrected data are then used as input to the hydrologic simulation model. Figure 2 shows changes in winter precipitation and temperature for the study area under the IPSL-B1 climate change scenarios.

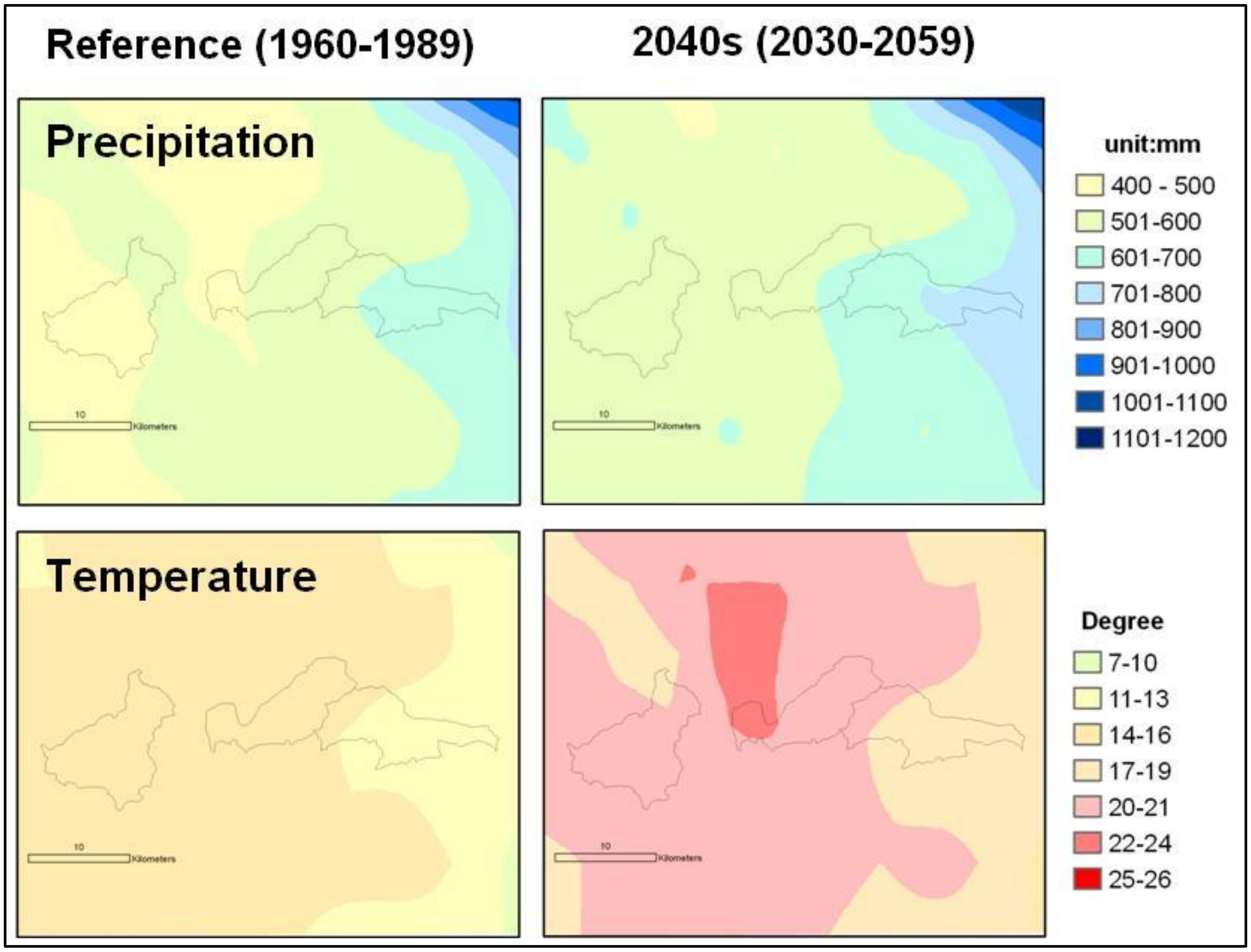

Figure 2. Changes in winter (December to February) precipitation and temperature under the IPSL-B1 climate change scenarios for the Portland metropolitan areas

The US Geological Survey PRMS watershed hydrologic model was used to simulate runoff changes and resultant changes in flood frequency. PRMS uses daily mean precipitation, temperature and streamflow to simulate daily streamflow conditions. PRMS is a physically-based watershed model that is ideal for simulating changes in flow under different environmental scenarios, including climate change.

The PRMS model parameters are derived from the literature (Laenen and Risley 1997), relevant GIS layers (e.g., geology, land cover, and soils), and the channel survey data.

Stream geomorphology survey and hydraulic analysis

In order to evaluate future flooding impacts at actual road crossings, we surveyed several stream cross-sections, gathered discharge information, and conducted a hydraulic analysis using HEC-RAS. The output of this effort is a water surface elevation at each location for a given discharge; that is, we can determine the particular discharge that floods the road. We surveyed channel geometry at the five cross sections of our study sites and determine the discharge necessary to produce a flood at each cross-section using the U.S. Army Corps of Engineers HEC-RAS discharge model. Each road was rated as either an arterial or major arterial and also served as a bus line. Four of the five locations have a history of flooding the road during large storm events. The other bridge site is a rather large span with no history of flooding; this site was selected as a possible example of a correctly sized structure with respect to climate-change induced flooding. All sites are located between USGS gauging stations.

We measured a channel morphological feature of interest, including the top of the stream channel, bankfull positions, the water surface and the thalweg position. Along this reach we also determined channel slope and roughness, which is used for modeling stream discharge. In this manner, we were able to determine the discharge necessary to induce floods of varying magnitudes. Each surveyed reach were tied to a precisely surveyed elevation benchmark allowing us to construct a GIS model depicting the water flow from the stream channel to the roadways during flood events.

The stream channel data, both geometry and flow data, were analyzed in HEC-RAS to determine water surface elevations for a given discharge. HEC-RAS is a one-dimensional steady flow model that calculates water surface height as a function of discharge, channel geometry, and energy losses due to friction (Manning's equation) and the expansion/contraction of flow through between cross-sections. We conducted a combined steady flow analysis using the bridge routine. This routine allows us to enter the bridge geometry the location of any pillars s a barrier to flow and also to define areas of ineffective flow. We established values for Manning's N based on field observation for both in channel on over-bank flow.

Transportation Impacts Methodology

Metro's regional travel model is the analytical tool for the measuring the potential disruption and costs of flooding on the transportation system. The model produces current and forecasted travel volumes based on land use assumptions. The current model uses 2005 as the base year and 2035 as the forecasted year. For travel forecasting purposes, land use assumptions are divided into geographical areas called transportation analysis zones (TAZs). The TAZ is the "unit geography" for travel within the demand model. Households and employment estimates are assigned to each TAZ. All the trips generated by the land use elements are aggregated and analyzed at the TAZ level.

The travel model estimates the number of trips that will be made, the distribution patterns of the trips throughout the region, the likely mode used for the trip and the actual roadways and transit lines used for auto, truck and transit trips. Traffic volume projections from these simulations help assess transportation system performance and identify future road and transit needs. Due to the macroscopic nature of the regional model, the model does not effectively analyze walking, biking or local street traffic volumes at detailed analysis levels. Also, the model assumes perfect knowledge by the traveler and may underestimate the traffic impacts of a road closure.

The traffic analysis began with the identification of transportation network links that are expected to flood based on the findings from the climate and hydrological analysis. Initial one-hour mid-day and two-hour pm peak traffic assignments were run using EMME^3 software to establish baseline traffic volumes and link volume/capacity for 2005 and 2035. Traffic assignments were then rerun with the flooded network links removed for both the Fanno Creek and Johnson Creek study areas. Using this output, a flood area of influence, comprised of TAZ clusters, was identified for each study area. Transportation evaluation measures were produced for each flood area of influence area that included vehicle miles traveled, vehicle hours and vehicle hours of delay for the one-hour mid-day and two-hour pm peak travel periods.

Results And Discussion

Changes in runoff

We estimated the changes in flood frequency with different recurrence intervals by the peakFQ program developed by US Geological Survey (Flynn et al., 2006). The PeakFQ provides estimates of instantaneous annual-maximum peak flows having recurrence intervals of 2, 5, 10, 25, 50, and 100 years based on flood-frequency analyses recommended in Bulletin 17B (IACWD, 1982). With this method, we constructed annual peak flows using daily discharge simulated by the PRMS results for 1960-1989 and for 2030-2059 at the four study areas.

As shown in Table 1, there are different patterns in changes in flood frequency across the four sites. Flood frequency is projected to increase mostly in highly urbanized watersheds such as Upper Fanno, Lower Fanno, and Lower Johnson Creek under most climate change scenarios. In the Upper Johnson Creek, however, flood frequency is projected to decrease except under the IPSL-B1 climate change scenarios. This suggests that highly urbanized areas are likely to be more vulnerable to climate change than less urbanized areas. The results also suggest that 5 year or 10 year flood events are likely to occur more frequently in the future. However, uncertainty still exists in projecting flood frequency in the future as changes are dependent upon what greenhouse gas emission scenarios are used when developing climate change scenarios.

Watershed Name	GCM & Emission scenario	Changes in flood frequency (%)					
		2 year	5 year	10 year	25 year	50 year	100 year
Upper Fanno	CCSM-A1B	+2.1	+5.9	+7.8	+10.1	+11.3	+12.9
	CCSM-B1	-5.3	+0.4	+2.2	+4.1	+4.9	+5.6
	ECHAM5-B1	+4.9	+3.4	+2.1	-0.4	-2.3	-4.1
	IPSL-B1	+14.7	+12.3	+13.2	+15.2	+17.0	+20.0
Lower Fanno	CCSM-A1B	+4.1	+8.0	+10.1	+12.7	+14.4	+16.0
	CCSM-B1	-3.2	-0.9	+0.3	+0.9	+1.6	+1.6
	ECHAM5-B1	+0.5	-4.5	-5.9	-7.0	-7.2	-7.4
	IPSL-B1	+13.6	+14.3	+17.4	+23.9	+29.8	+36.1
Upper Johnson	CCSM-A1B	+1.1	-2.6	-3.5	-3.4	-2.8	-2.0
	CCSM-B1	-15.0	-10.8	-9.9	-9.2	-9.2	-9.7
	ECHAM5-B1	+4.7	-2.7	-6.0	-9.3	-11.2	-12.7
	IPSL-B1	+9.1	+9.3	+11.1	+14.1	+16.7	+19.3
Lower Johnson	CCSM-A1B	+0.3	+0.2	+1.8	+4.6	+7.2	+9.9
	CCSM-B1	-10.1	-9.4	-9.5	-10.2	-10.7	-11.4
	ECHAM5-B1	-3.5	-8.0	-9.2	-10.0	-10.2	-10.1
	IPSL-B1	+5.6	+7.1	+11.4	+18.8	+25.4	+32.7

Table 1. Changes in flood frequency (%) in the 2040s from the reference period

Changes in the probability of road flooding

The HAC-RAS model output shows that all cross-sections with the exception of Scholls crossing are inundated during a 100-year flood event. However, the basins diverge greatly for smaller events. With Fanno Creek, the Oleson crossing is flooded during a 10-year magnitude event, while the Hall crossing is first flooded during a 25-year flood event. The Schools crossing is never inundated. The Oleson crossing area has an active floodplain upstream of the bridge but is controlled downstream by a wooden wall and riprap; in addition, the top of the bridge is below the 100-year flood plain as mapped by FEMA. This crossing is well known as a problem flood area, and our modeling simply reinforces the frequency with which this bridge can become impassable due to flooding. The Hall crossing has a much more extensive floodplain than the Oleson crossing and the channel is not constricted other than when passing through the bridge. Yet, the bridge opening itself is not large; hence, this road is subject to fairly frequent flooding. This bridge is crowned, as is Schools, and the stream does not cover the bridge during any flood event; however, water does flow across the road in the floodplain during a 25-year event, which leads to closure of this crossing. With a large floodplain and a large bridge opening, the Schools crossing does not flood at any discharge; however, the bike path adjacent to the stream that goes under the bridge is often inundated.

The bridge openings in Johnson Creek are much larger than most bridge openings in Fanno Creek, a legacy of channelization in Johnson Creek. Hence, neither bridge is inundated until a 100 year-event occurs. However, the rock walls at each crossing location are up to two meters lower than the bottom of the bridge but are still slightly higher than the areas adjacent the walls. Hence, water spills over the walls beginning with a 25-year event and floods the adjacent areas. In the case with Bell crossing, water will actually flow north of the stream channel, through a parking lot, and across the road approximately 3 meters north of the bridge itself; hence, this road is closed more frequently than would be expected by our models. The road at Linwood is higher above the walls than at Bell and is only truly flooded during a 100-year flood event.

Impacts on Transportation Network

The Fanno Creek and Johnson Creek flood area of influence generate an estimated 973,000 and 541,000 vehicle miles traveled (VMT), respectively, in the two-hour pm peak travel period. Together, these areas account for 24% of the total VMT generate in the 4:00 – 6:00 p.m. travel period. Both study areas are located in suburban locations where the arterial street network is fairly complete but local street network is often discontinuous. By 2035, as shown in Figure 3, many street networks will have more traffic volumes in the future.

An evaluation of the travel model output for the Fanno Creek and Johnson Creek flooding area of influence forecasted negligible increases (less than 1%) in vehicle miles travel in both travel periods for 2005 and 2035 when flooded links were removed from the street network. The modeled network assumes good alternative arterial routes to the flooded links and that travelers would choose these routes. In reality, travelers may not have perfect knowledge of the road conditions or alternatives in time to make an informed decision about travel, and therefore the model may have underestimated the level of out of direction travel that would contribute to an increase in vehicle miles traveled.

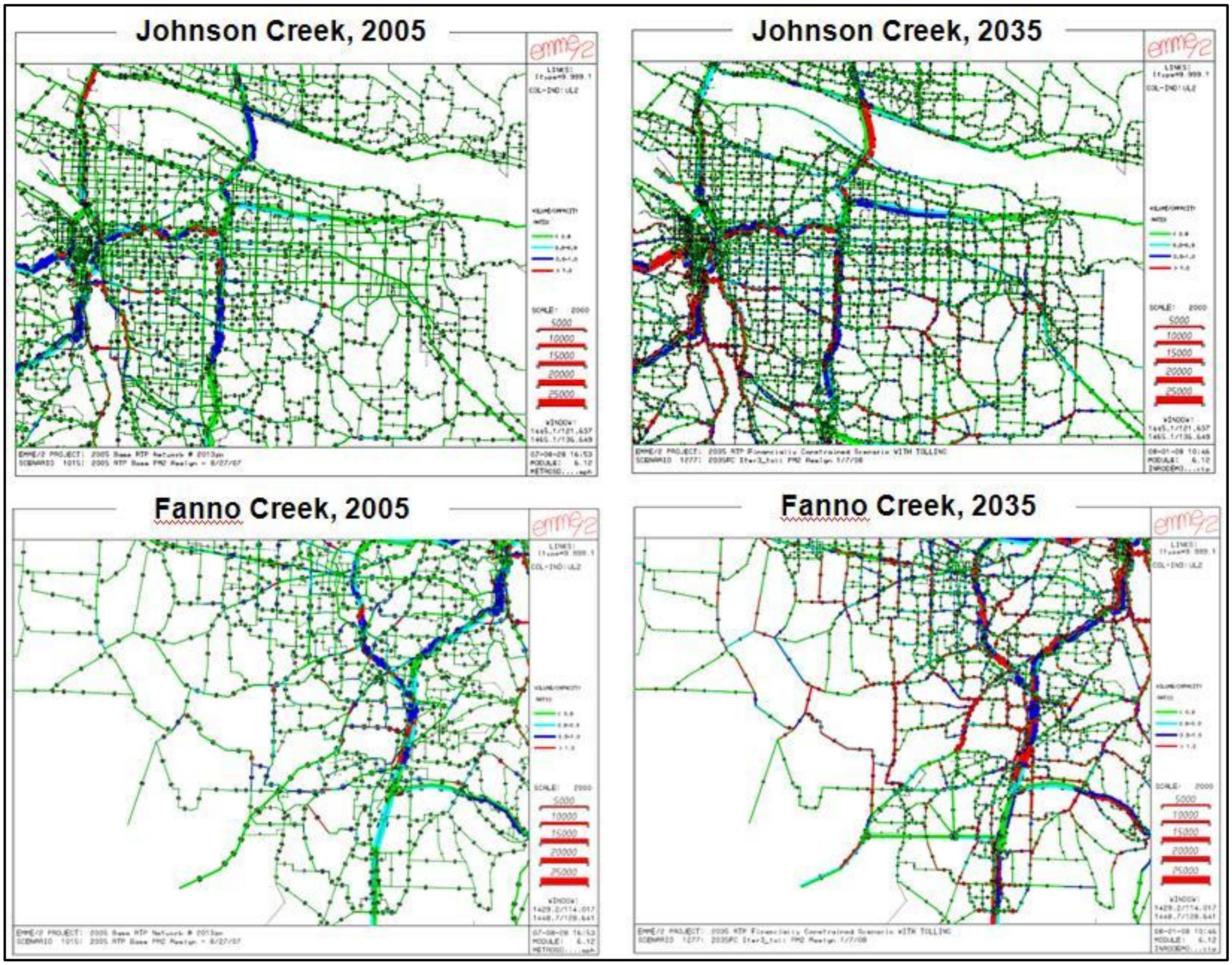

Figure 3. Changes in auto traffic volumes in the study area for 2005 and 2035.

An assessment of vehicle hours delay (VHD) demonstrated a greater impact from flooding. Regionwide delay in the 2005 two-hour pm peak is estimated at 8,900 hours. The base VHD for the Fanno Creek and Johnson Creek flood area of influence is 2000 hours and 800 hours respectively; and accounts for 32% of the region's total delay. In flooded conditions, VHD jumps by 10% in the Fanno Creek area and 4% in the Johnson Creek area. Not surprisingly, when capacity is removed from the network congestion grows as travelers are displaced to alternate routes.

Conclusions

Global climate change will have significant impacts particularly in urban areas where many socioeconomic activities are concentrated. Many growing urban areas such as the Pacific Northwest of America will experience higher amounts and intensity of winter precipitation. As projected in this simulation study, flood frequency is likely to increase in most study sites with more winter precipitation. Although there is uncertainty in projecting future flood frequency solely based on hydroclimate modeling, a 5-year, 10-year small events are generally likely to increase in one of the study site that has a history of chronic flooding. Stream channels will likely lag in adjusting to the new, slowly increasing discharge regimes, which is likely to act to exacerbate roadway flooding. While vehicle miles traveled in both periods show negligible increases, vehicle hours delay demonstrated a greater impact from flooding.

Our results show that there is a nonlinear relation between precipitation change and urban flooding and that impacts on travel disruption are subject to local hydroclimate and watershed land use conditions. This study is one of few interdisciplinary attempts to assess potential impacts of climate change on the transportation sector. Such integrated knowledge and spatially-explicit modeling is essential for establishing proactive flood and transportation management planning and policies under increasing climate uncertainty.

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Biographical Sketches

Heejun Chang is an associate professor of Geography at Portland State University, Portland, OR, USA, where he teaches courses in hydrology, climate and water resources, global water issues and sustainability, GIS for water resources, and spatial quantitative analysis. His research focuses on impacts of climate change and land cover change on runoff and water quality. He has published extensively on this topic in numerous scientific journals, including International Journal of Climatology, Climate Research, Hydrological Processes, Water Research, and Natural Hazards.

Martin Lafrenz is an assistant professor of geography at Portland State and a fluvial geomorphologist who focuses on the impacts of land use and land cover change on stream channel habitat. He has conducted and published several research projects using GIS and field data to classify watershed types as a function of the relationship between watershed attributes and stream channel function.

Il-Won Jung is a post-doctoral fellow at Center for Sustainable Processes and Practices and Department of Geography at Portland State University. His research interest intersects in the areas of hydrology and meteorology. He has been involved in climate change impact assessments for Korea and US river basins, conducting research on downscaling GCMs and hydrologic uncertainty assessment.

Miguel Figliozzi is a transportation engineering scientist and an Assistant Professor of Civil & Environmental Engineering at PSU with over 10 years of experience in the transportation and freight areas. He combines industry experience, consulting and a solid academic career. Figliozzi has published over 15 refereed research articles in transportation journals and has worked in research projects for NSF, FHWA, TxDOT, and the Port of Portland.

Deena Platman is a principal transportation planner at METRO, a regional government in the Portland metropolitan area. She has been instrumental in updating a regional travel model to measure the potential disruption and costs of flooding on the transportation system. She also serves as a board member of a regional transportation group in the Portland metro area.

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