

**IDENTIFYING SURFACE TRANSPORTATION VULNERABILITIES AND
RISK ASSESSMENT OPPORTUNITIES UNDER CLIMATE CHANGE: A PORTLAND,
OREGON CASE STUDY**

Lindsay Walker
Portland State University
Lnwalker8@gmail.com

Miguel A. Figliozi (*)
Portland State University
figliozi@pdx.edu

Ashley R. Haire
Portland State University
haire@pdx.edu

John MacArthur
Oregon Transportation Research and Education Consortium
macarthur@pdx.edu

(*) Corresponding Author

Mailing address:
CEE Portland State University, PO Box 751
Portland, Oregon 97207

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ABSTRACT

Transportation departments are beginning to recognize that adaptation for climate change must become an integral part of their planning efforts. However, staff members frequently lack adequate local data, training, or guidance to begin adaptation planning assessments. As a result, climate change adaptation planning has remained generally abstract and lacks specificity needed to identify potential system vulnerabilities, assess risk and prioritize responses. In this report, we outline a geographic information system-based method for transportation departments to assess climate change vulnerabilities in their multi-modal surface transportation systems. The City of Portland, Oregon, is used as an illustrative case study. The proposed method allows for preliminary vulnerability identification, prioritization, and impact assessment and can also be used as a basis for more advanced analysis and scenario testing. This research also identifies and describes data gaps and other barriers to climate change adaptation planning for surface transportation.

KEYWORDS: Climate Change, Flooding, Landslide, Adaptation, Vulnerability, GIS

INTRODUCTION

Our changing climate and response to its impacts will affect public life across a variety of sectors. Examples include agricultural changes to where and when crops can be grown, an extended range for mosquito-borne diseases affecting public health, and shifting wildlife habitat patterns impacting wildlife management practices. The transportation sector is no exception to changes brought on by a shifting climate. While organizations that own and operate transportation facilities have traditionally focused on efforts to mitigate climate change through reductions in greenhouse gas emissions, many organizations, both public and private, are beginning to recognize that climate change adaptation responses must also become integral parts of their transportation planning efforts. Increasingly, these organizations are working to develop their understanding of what potential impacts climate change will have on local transportation infrastructure and operations, and preparing plans to adapt to changing conditions so that system disruptions and damage are minimized.

Climate change research in coastal communities has focused on the anticipated transportation impacts of sea-level rise and the prospect for more frequent and intense hurricanes; however, a significant threat of climate change in the Pacific Northwest is the effect that changes in seasonal precipitation may have on surface transportation. In the Pacific Northwest region of the U.S., scientists forecast that average annual regional temperatures will increase approximately 2-3°C over the course of the next century as a result of climate change (1). In addition to warmer temperatures, average annual precipitation is expected to increase up to ten percent along with changing seasonal variations in rainfall, including, most notably, a decrease in summer precipitation and an increase in fall and winter precipitation (2). Furthermore, much of the precipitation is anticipated to fall as rain rather than snow, reducing the overall amount of winter snowpack stored in the mountain ranges (3). What snowpack remains can be swiftly melted by warmer rains, raising river flows throughout regional waterways and increasing flood risk during the winter and spring months, leaving little snow to replenish these same waterways during dry summer months. Extreme precipitation events, some previously anticipated to occur only once every 100 years, are projected to occur with greater frequency. Winter and spring seasonal flooding and inundation as well as increased erosion and risk of landslides are likely to damage transportation infrastructure and will undoubtedly impose delay on goods movement and the traveling public.

Operating and maintaining transportation systems under these increasingly unpredictable conditions presents new challenges to transportation organizations as additional impacts associated with climate change continue to be revealed. For example, although increased precipitation and resulting higher river flows have long been anticipated, few in the City of Portland expected that this might affect bridge clearance for traffic navigating the Willamette River through downtown Portland. In fall 2009, a Willamette River cruise boat operator raised concerns about the proposed height of a new bridge currently under design to cross the river. Already limited from passing under an existing nearby bridge during high winter river flows, he insisted that potential higher river levels resulting from climate change would only exacerbate these limitations and requested that the new bridge be designed with increased clearance to ensure that the legal obligation to preserve a navigable waterway is met (4). In order to address concerns regarding vertical bridge clearance, bridge clearances were modeled under a variety of river elevations and the project consultant team incorporated current climate change research in their evaluations (5).

Although general interest in and awareness of climate change and adaptation responses

is increasing among transportation organizations, there remain significant barriers to development of actionable adaptation plans. Perhaps most significantly, staff members frequently lack adequate data and guidance required to develop adaptation plans that go beyond broad generalizations of climate change impacts to transportation infrastructure and operations. In order to make real progress in this area they must answer questions such as: Where are impacts most likely to occur? How can we estimate the levels of risk associated with the impacts? A lack of answers to these fundamental questions limits transportation professionals' understanding of climate change impacts at the local level and stymies real progress towards identifying vulnerabilities in the transportation system, assessing impacts and taking action.

In this report, we outline a transferable method for transportation departments to begin assessing climate change vulnerability on their multi-modal surface transportation systems using a geographic information system (GIS). The City of Portland, Oregon is used as an illustrative case. The resulting framework allows for preliminary vulnerability identification, impact assessment and prioritization, and can be used as a basis for more advanced analysis. This research also identifies data gaps and other barriers to adaptation planning for surface transportation.

USING TRANSPORTATION ASSET MANAGEMENT TO PLAN FOR CLIMATECHANGE ADAPTATION

In the 2010 paper *Transportation Asset Management Systems and Climate Change: An Adaptive Systems Management Approach*, Michael Meyer *et al.* outline how transportation asset management systems can be used to incorporate climate change adaptation into transportation planning (6). The Federal Highway Administration (FHWA) defines Transportation Asset Management systems (TAMs) as:

“a systematic process of maintaining, upgrading, and operating physical assets cost-effectively...Thus, asset management provides a framework for handling both short- and long-range planning.” (7)

A TAM generally includes goals and policies for system performance, an inventory of all assets, condition assessment and performance monitoring for these assets, system improvement and optimization alternatives, short- and long-range plans, and implementation and monitoring. Meyer's approach incorporates climate change considerations into each element of the TAM. For example, he notes that identification of system vulnerabilities to climatic events may be included in asset inventory, risk to assets associated with climatic events may be included in the condition assessment and performance modeling, and so on.

Meyer proposes that by, “incorporating the consideration of anticipated effects of climate change into an agency's infrastructure preservation and asset management process... transportation officials could end up with the most cost effective approach toward system adaptation to changing environmental conditions.” This approach is advocated as a good use of resources since most transportation agencies already have some type of asset management system in place upon which to build. The City of Portland, for example, employs a TAM in the form of a computerized pavement management system to monitor current pavement conditions, project future conditions, evaluate alternatives for improvement including reconstruction, rehabilitation and maintenance, and to prioritize repairs on the city's 1700 miles of roadway based on cost effectiveness (8). Although this tool is primarily used to manage pavement quality,

such a system could potentially be adapted to assist in climate change adaptation planning decisions. Given that much of climate change adaptation planning takes place at the local level where staff and funding resources are constrained, the effective re-use of existing tools as suggested by Meyer is particularly appealing (9). In this study, the process outlined by Meyer is followed using several data resources commonly available to local transportation organizations, in order to identify opportunities or constraints presented by this approach, with a focus on asset inventory.

In addition to a lack of local climate change data, uncertainty regarding the location and magnitude of potential climate change impacts is also noted as a major barrier to agency action with respect to climate change adaptation (10). The primary objective of this study is to develop a method for identifying potential vulnerabilities of a local surface transportation system to anticipated climate change impacts. Locations with potential vulnerability to flooding and landslide are identified for the surface transportation system in the City of Portland, Oregon using a GIS. Recommendations for other TAM elements such as impact analysis (which may be used in risk management) and prioritization after potential vulnerabilities have been identified are also explored.

RISK MANAGEMENT UNDER CLIMATE CHANGE

Risk management is a decision-making process that has traditionally been associated with insurance and financial institutions but its use has extended beyond these fields. According to Noble *et al.*, “the risk management process offers a framework for identifying, assessing and prioritizing climate related risks, and developing appropriate adaptation responses” (11). It is particularly appropriate in the context of climate change because it allows for decisions under uncertainty.

Risk management approaches generally include the following elements, described below in the context of climate adaptation:

- Preliminary Evaluation: Define the scope of the analysis including the hazards that will be examined and the study limits. Both the geographic field of study and the transportation modes should be defined.
- Risk Identification: Identify potential risks, based upon a record of historical vulnerabilities as well as projected future scenarios.
- Risk Estimation: Determine the costs associated with a particular risk should it occur (magnitude) and assess the likelihood of the event occurring over a specified time span (probability).
- Risk Control: Develop strategies for addressing identified risk(s) – protection, accommodation, or retreat – based within the context of other competing risks on the system and prioritize.
- Action and Monitoring: Develop an implementation plan and evaluate effectiveness.

In the City of Portland, researchers at Portland State University have analyzed the potential impacts of climate change on transportation in terms of travel delay associated with flooding in the Fanno and Johnson Creek watersheds and the resulting closure of two major roads (12). This study employed a variety of climate change scenarios, hydrologic modeling, roadway and stream channel surveys, and travel forecast models to estimate potential impacts in locations known to be susceptible to periodic flooding. Although vehicle miles traveled were

not significantly affected in this particular model, vehicle delay was impacted. This conclusion suggests the need for detour and congestion response plans in areas at risk for disruption due to climate change in the short-term, as well as long-term physical improvements, such as locating signal control electronics above flood level. Although a study as detailed as this is not feasible throughout the entire city, such an approach can be used to estimate impacts and weigh response in other vulnerable areas as they are identified, particularly in locations where impacts and the associated adaptation improvements are likely to be costly.

Other organizations have also begun to identify potential locations of transportation system vulnerabilities and assess risk utilizing a variety of approaches. Examples are provided below in Table 1.

PORTLAND, OREGON ILLUSTRATIVE CASE

In the next three sections we applied a geographic information system (GIS)-based transferable method for transportation departments to assess climate change vulnerabilities in their multimodal surface transportation systems. The City of Portland, Oregon was selected as an illustrative case for this study for a number of reasons including:

- Access to GIS data;
- Access to City staff;
- Familiarity with the transportation system; and
- The small size of the study area (134 sq. mi.) (17).

Portland's transportation network is truly multi-modal, offering driving, bicycling, walking, bus, light rail and streetcar options for passenger trips, as well as truck, rail and maritime options for freight trips. With approximately 7% of residents using a bicycle as their primary means of traveling to and from work, Portland has a relatively high rate of cycling compared to other U.S. cities (averaging less than 0.7% bicycle mode split nationwide), (18) and an established goal to increase bicycle use to 25% mode share by 2030 (19). Transit use is also relatively high with 10% using bus, streetcar or light rail as the primary means of transportation to and from work compared with 5% nationwide. 75% of residents report driving alone or with others as their primary mode of commute transportation compared with 86% nationwide (20). Considering these statistics, it was important not to limit of transportation vulnerability analysis to personal automobile routes. Thus, transportation facilities used in the model include major arterials, rail lines (passenger and freight), bicycle facilities (bicycle routes and multiple-use paths), bus routes, and streetcar/light rail (including planned improvements).

In an online survey conducted in late fall 2009/winter 2010, transportation planners in the Pacific Northwest were asked about their climate change planning activities, focusing particularly on activities related to climate change adaptation for their transportation systems. Both in the online survey as well as in follow-up interviews, respondents (including City of Portland Transportation Bureau staff) indicated that of the potential climate changes impacts likely to occur in the Pacific Northwest, flooding/inundation was considered the biggest threat to the City's transportation infrastructure and operations due to the tremendous damage standing water has on roadway structures. This response is consistent with a 2007 Intergovernmental Panel on Climate Change (IPCC) report that named urban flooding as the most costly impact of climate change on transportation (21). Erosion and landslides associated with heavy precipitation were also of concern due to the city's topography — chiefly the steep, slide-prone

hills directly west and southwest of the city center. Respondents expressed particular concern regarding how road closures and/or delays could not only impact travel delay but also potentially impede emergency response.

Located at the confluence of the Columbia and Willamette Rivers, Portland is no stranger to flooding. In the winter of 1964, flooding on the Willamette River damaged waterfront property, swept away homes and roadways, and ultimately left twelve people dead (22). Other major, albeit less devastating, floods have occurred more recently, including the winter flood of 1996. During this event, the Willamette River reached a height of 31.8 feet and lapped at the edges of the City's downtown seawall (flood stage for the Willamette is 21.2 feet and the seawall is at 32.5 feet) (23). Significant damage downtown was narrowly avoided thanks to rapid coordination between dam operators upriver to delay the release of additional river water and efforts of City employees and more than 1500 resident volunteers to build a four-foot tall, mile-long temporary seawall along the river. However, other parts of the city and surrounding region experienced substantial flooding, resulting in road closures along local roads and Interstates 5 and 84 (22).

As a result of storms and flooding during the 1996 event, City staff also reported significant landslide activity throughout the metropolitan area. Approximately 750 individual landslides occurred throughout the Portland region, predominately in the West Hills area of Portland. The amount and extent of landslide activity during this time was so great that, in the report *Landslides in the Portland, Oregon Metropolitan Area Resulting from the Storm of February 1996: Inventory Map, Database and Evaluation*, researchers suggest this was a 100-year event for landslide recurrence (24). This report also states that the geological susceptibility to landslide and steep slopes of many sites in Portland naturally contributed to the extreme landslide activity observed in 1996. Landslide vulnerability increases when the geologic and slope characteristics of these sites are combined with abundant, mismanaged storm water that saturates soils. According to Burns *et al.*, in 76% of the landslides studied after the 1996 landslide events, human activity such as the formation of cut slopes and fill failures contributed to the increased landslide risks (24). Furthermore, an estimated 9% of the landslides could have been reduced had there been better storm water control measures (for example, conveying standing water off the property to avoid saturation of soils or better siting of homes on properties).

Both the 1964 and 1996 flood events were attributed to heavy snow precipitation in upper elevations followed by intense, warmer-temperature rain that quickly melted snowpack and saturated soils. These climatic events are often referred to as "rain on snow" (24). Research by Mote and Salathe suggests that while projected increases in annual precipitation in the Pacific Northwest are relatively small, changes in seasonal variations of precipitation are likely, with wetter autumns and winters and drier summers (2). With more precipitation projected to fall as rain rather than snow during winter, potential exists for reduced long-term water storage in the form of winter snowpack, earlier snowmelt and saturated soils, and higher stream flows in waterways— these conditions may not be dissimilar to those observed in previous flood events.

Although they cannot definitively be attributed to climate change, several recent storms have also brought unusual weather patterns to the Portland region for which local transportation agencies were largely unprepared, leading to transportation emergencies. Examples include snowstorms during the winters of 2008 and 2009. Except in higher elevations such as the West Hills area of the city, heavy snow is relatively uncommon in Portland. However, in winter of 2008, 18.9 inches of snow fell on the city in a short time span (25). With little to no equipment

to handle such a large quantity of snow, several roads were closed, buses were brought to a crawl, flights were canceled, and the city generally closed for business. As events like these suggest, agencies cannot rely on historic events alone when planning for climate change adaptation but must also develop localized climate change scenarios, including potential extremes.

STUDY DESCRIPTION

As discussed earlier, one of the earliest steps noted by Meyer in Transportation Asset Management (TAM) and in risk management is the identification of potential system vulnerabilities. In this study, a GIS was used to model two anticipated climate change impacts, flooding and landslide hazard locations, that could leave the City of Portland's surface transportation networks vulnerable to the effects of climate change. Risk assessment and development of adaptation responses are not carried out for this case study. However, recommendations for how the results can be used for these purposes are provided.

GIS has been used in a similar function in several studies including the *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I* (26). GIS offers several advantages for modeling hazards, including the ability to model multiple data sets simultaneously, the relative ease of adapting new or revised data sets to the model, the range of analysis options from simple to highly advanced, the ability to export data for analysis in other programs (such as traffic modeling programs), and the ability to visually present spatial data to stakeholders and other interested parties.

Much of the GIS data used in the study was obtained through the Regional Land Information System (RLIS), a clearinghouse for spatial data managed by Metro, the regional government for the Portland metropolitan region (see Table 2). Many jurisdictions lack the resources to collect and maintain a spatial data resource as comprehensive as RLIS. However, a significant amount of spatial data, including transportation networks, waterways and the Federal Emergency Management Agency (FEMA) 100-year flood map can be readily obtained online at no cost through several reputable data clearinghouses such as Geodata.gov, the United States Geological Survey (USGS) and the Economic and Social Research Institute (ESRI), to name a few. More specialized spatial data used in this study, including landslide hazards and planned transit improvements, were obtained through city and transit agency staff.

GIS Processing

Most shapefiles used in the model include data for the entire Metro region and were first clipped to the Portland city boundary. This clipping action limited analysis to only those areas within the Portland city limits and was done primarily to reduce processing time and keep the analysis at a manageable scale. Shapefiles of both the FEMA 100-year flood maps (last updated in 2004) and a shapefile delineating areas inundated during the 1996 flood were projected. Although the shapefiles are largely identical, some flooding in the 1996 flood occurred outside the 100-year flood boundary. In order to capture all areas of potential and recent flooding, these two shapefiles were combined using the "union" analysis tool to form a single flood polygon.

Next, a shapefile for a specific transportation network, for example, major arterials, was projected. Using the "select by location" analysis tool, segments of the major arterials were selected that intersected the flood polygon. The selected segments were then exported and reprojected as a "flood vulnerable" shapefile, representing the segments of major arterials that may be vulnerable to flooding. Figure 1 provides an example of this type of analysis with major

arterials within the City of Portland that are potentially vulnerable to flooding highlighted in red. These “red segments” of roadway are portions of the roadway that intersect with areas historically known to flood and which are likely vulnerable to more frequent and/or intense flooding as a result of climate change. The map inset provides a larger view of SE Foster Avenue, one of the highlighted roadway segments identified using this process. SE Foster Avenue is a route that carries approximately 9100 vehicles daily (27). An identical process was carried out for each of the transportation system network shapefiles. Following identification of potential flood vulnerabilities, an identical analysis was performed using a landslide hazard polygon. These “hazard” shapefiles were then layered over base shapefiles of the transportation network, along with land use zoning and major waterways for reference.

Each of the transportation shapefiles comprise multiple segments of varying length. When selecting features that intersect the flood or landslide hazard areas, portions of a segment that lie outside of the hazard area may be selected as well. This action provides generalized locations of potential hazards. However, for greater accuracy, a listing of vulnerable segments was compiled by mode based upon a description of the segment including the intersections nearest to the hazard area (for example, “Lombard Street between Ramsey Street and Burgard Street”). A complete listing of segments potentially vulnerable to flooding and/or landslide by facility type can be found at the webpage for this project on the Portland State University Intelligent Transportation Systems Lab website: <http://www.its.pdx.edu/project.php?id=2010-02>.

Results

While all segments of the transportation system network that intersect the flood and landslide polygons were identified as potentially vulnerable to flood or landslide, they will not all be flooded during an extreme event. Although it can be added to the model with more advanced GIS data analysis, this model does not incorporate elevation data and thus requires further analysis to determine if intersecting transportation routes are at an elevation susceptible to flooding. For example, several bridges were selected as vulnerable to flooding although it is known that, due to the height of these bridges, flooding is unlikely. As this model is intended as a preliminary assessment, the focus is on areas that may be subject to flooding rather than specific segments. In this case, although the bridge itself is unlikely to flood, the model highlights potential issues for travelers accessing the bridge (as lower-elevation approaches may be susceptible to flooding), bridge clearance limitations for river traffic, and/or potential scour to bridge abutments as a result of higher water flow.

In addition to identifying the locations of transportation segments vulnerable to flood and landslide, for several modes the GIS shapefile also provides length data, allowing for a tally of affected transportation segments within the Portland city limits:

- Major Roadways: The model identified 40 miles of major arterials (approximately seven percent of major roadways) potentially affected by flooding, primarily located adjacent to major waterways. Roughly 70 miles of major roadways (approximately 13 percent of major roadways) were identified as vulnerable to landslide, primarily in the West Hills area. This mileage could increase substantially if local roads are included in the analysis.
- Roughly 70 miles (or approximately 18 percent) of railways (comprising both passenger and freight lines) within the city limits were identified as vulnerable to flood, primarily near rail yard facilities adjacent to the Willamette River in northeast Portland. The

model identifies roughly 50 miles (approximately 13 percent) of railways as vulnerable to landslide.

Mileage of transit routes vulnerable to flood and landslide were not calculated for transit modes (bus, streetcar and light rail) due to a large portion of identified segments that extended outside of the hazard areas and a lack of data regarding lengths of affected route segments. Bus routes were primarily impacted by flooding in areas outside of the downtown core, particularly in northern parts of the city. Fortunately, bus routes can be easily detoured (or truncated). Similarly, light rail may also be truncated using “crossovers” that allow trains to turn around and “pocket tracks” which allow trains to pass one another, located approximately every 7.5 minutes (in travel time) along the light rail alignments according to a Trimet (the regional transit agency) representative. Further, the light rail vehicles have engines on both ends allowing the train to operate in either direction. Segment length data were also unavailable for bicycle lanes and multi-use paths; however, the model does indicate that routes directly parallel to the river’s edge, including major multi-use pathways, are potentially at risk for flooding. Notably, many bicycle facilities are located along these open space areas vulnerable to flooding. Fortunately, there are typically nearby alternative routes (local streets) available.

The majority of facilities potentially affected by landslide occurred in the hilly, western area of the city where there are fewer major arterials, bicycle facilities, and rail lines. However, because there are fewer alternate routes in the event of a landslide, these routes carry greater risk. It is notable that Barbur Boulevard, identified by the model as landslide-vulnerable, is also recommended by the regional planning agency as a future high capacity transit corridor (28).

Validation

In order to validate the results from the model, reports of previous landslide and flooding incidents were compared with the GIS output. City transportation staff members were also consulted for a list of locations known to have flooding and/or landslide problems. Overall, the results from the model were consistent with known experience, with the exception of Willamette bridge flooding. Conveniently, much of the analysis for this study occurred during a series of heavy precipitation events in Portland during which two landslides occurred along segments of a bicycle route and major arterial identified as vulnerable in the model (29, 30).

This model has been shown effective at identifying transportation system vulnerabilities to historical hazards and may be used by local planning staff to begin the process of preparing for climate change. However, while future flooding and landslide activity are likely to occur in the vicinity of known hazard areas, they also have the potential to expand to new areas based on different future climate scenarios. Thus, in order to strengthen the model’s potential to identify new hazards, shapefiles representing a range of flood and landslide hazards under different climate scenarios need to be developed and incorporated into the model. Such shapefiles should be edited as new climate change information becomes available.

POTENTIAL RESPONSE

This model was developed as a proof of concept, in order to evaluate the use of GIS to identify potential transportation vulnerabilities under climate change. Although local planning staffs have expressed interest in continued development of this model, to our knowledge, no new policy or project decisions have been made as result of our findings yet. However, we do recommend several planning responses based on the results of the model.

Once potential transportation system vulnerabilities have been identified, planners must assess the risk presented by these vulnerabilities and develop a prioritized adaptation response. As discussed earlier, the impact of a potential transportation disruption can be estimated in a number of ways, including simple techniques based upon traffic volumes along the affected segments and/or the availability of alternative routes, or through more sophisticated analyses such as traffic modeling to estimate diversion, congestion and associated delay (as well as economic costs of delay). In addition to travel delay, planners must also consider the likely cost of feasible adaptation alternatives.

There are three general adaptation responses:

1. Avoidance – Planning new facilities or rerouting existing facilities outside of hazard areas. An example includes construction of a bypass around a landslide-prone area.
2. Protection – Improvements to existing facilities to increase their resilience to climate change impacts. Examples include increased height of sea walls, landslide fencing and monitoring, or bridge design that exceeds current standards.
3. Abandonment – Disuse of the facility may be the most cost-effective solution if avoidance or protection alternatives are infeasible. Examples include closure of landslide-prone segments.

A fourth adaptation response could include operational responses such as ongoing maintenance and incident response (including temporary or seasonal closure). This alternative would factor in the ongoing cost of repair and incident response based on the projected frequency of events. For vulnerabilities with minimal impact and/or low likelihood of occurrence, or for assets with short lifespan (e.g., pavement) this approach may be an optimal response (15). Examples include a planned detour route in response to periodic flooding of a roadway. The City of Portland has such a plan established (including sandbag locations) for the Johnson Creek area, which is known to flood periodically. Each of these alternatives has an associated cost that must be considered in comparing response options and prioritizing among competing risks located elsewhere within the system. The results of this process may also be incorporated in the agency's overall project selection process for capital improvement and maintenance projects.

RECOMMENDATIONS

Transportation agencies can adopt a GIS model to begin inventorying their transportation facilities for potential vulnerabilities to climate change. After locations have been identified, and ideally validated through expert opinion and/or field assessments, the GIS model can also be used to assess the associated impacts and begin prioritizing an adaptation response for the system as a whole. The results of this analysis can be incorporated into an existing TAM or the TAM may be adapted for this purpose. As new data become available, these should be incorporated into the model, and risks and prioritization reassessed through an iterative process. Additional data may include new events such as flooding and landslides located outside known hazard areas. New data may also arrive as a result of advanced GIS modeling, such as revised flood estimation utilizing digital elevation models (DEM) and/or advanced hydrologic modeling.

Because the GIS model contains geographic location data, it can also be imported into other advanced analysis tools such as VISSIM traffic modeling software and used to model potential traffic delay, detour effects, and to estimate potential economic impacts of these

impacts. Such information would provide an indication of the impact a closure (detour and/or congestion) would have on the system and thus serve in risk estimation and prioritization. Oregon's Department of Land Conservation and Development (DLCD) details additional data sources to quantify the tangible and intangible costs of flooding or climate change required to quantify economic impacts (31). Economic impact analysis would be useful to evaluate a variety of future climate scenarios. However, the estimation of costs associated with climate change impacts may be difficult due to the lack of complete and systematic recordkeeping and uncertainty related to estimation of incremental impacts of climate change on flood event magnitudes, frequencies, and durations (31).

More rudimentary preliminary impact assessment and prioritization can also occur using the functional classification of the transportation system, the availability of emergency evacuation routes near the vulnerable segment, and/or traffic volumes along the segment. For example, the closure of a higher volume roadway would generally have greater impact on the remainder of the system and thus would likely be prioritized for adaptation improvements ahead of lower volume roadways. Larger metropolitan areas are more likely to have the resources (both in terms of resources and expertise) to undertake more complex risk evaluation and response prioritization. However, a simple Delphi approach may also be employed utilizing local expert knowledge.

In addition to preliminary impact assessment and prioritization, the model may also be used to avoid potential impacts in the future. For example, the use of land use zoning data in the model may point to land use planning that can reduce risk to persons and structures in landslide hazard areas by requiring building and landscape designs that reduce risk of soil saturation or instability during intense precipitation. Similarly, the model can be used to avoid and/or minimize private or public investments in potential hazard zones.

The proposed GIS modeling approach offers a number of advantages described above, however there remain gaps in data that may limit full utilization of this tool. While data sets of existing hazards are frequently available, the currency of the data may vary and the process of updating hazards can be controversial due to the increased liability incurred by property owners. For example, the Oregon DLCD indicates that of the 257 national flood insurance communities, over 70 percent have flood maps that are outdated (32). While GIS datasets can frequently be modified for use as in this study, at times the data may have been collected for a specific purpose and in such a way that limits its use in other analyses. Furthermore, spatial data for future climate scenario impacts have yet to be developed, and when developed, must then be digitized and spatially referenced for use in a GIS model. In addition to uncertainty regarding the location of future impacts, there is also uncertainty regarding the magnitude and probability of these events occurring.

Not only must these data sets be developed, their development should also be coordinated and shared among partner organizations, preferably in a central repository, such as a shared GIS database. Frequently organizations are reluctant to share available data, and/or a lack of communication amongst agencies prevents valuable information from being collected in a useful form. For example, as part of a related climate change project, data regarding thermal expansion of railroad tracks (a heat-related impact of climate change) was sought from private and public railroad operators. Private rail operators, under no obligation to share data, refused to participate in the study, referring to a federal rail authority source of this information. However, the federal source collected only data on incidents that posed a safety hazard. There are likely several reasons behind such reluctance on the part of private operators to share data, among

them a concern that admission of potential risk to their operations may stifle investment. This is likely to be a concern shared among all private transportation operators, including railroads and ports.

While these factors may present obstacles in the use of GIS in identifying climate change impacts to transportation facilities, they do not necessarily prevent analysis. Instead they are issues that practitioners should be aware of during their analysis and that they should work to address through increased coordination in the collection and sharing of GIS data.

CONCLUSIONS

Planning for climate change in the transportation sector is no longer limited to strategies to reduce greenhouse gas emissions. Recognition is increasing among transportation professionals that adaptation strategies to respond to the unavoidable impacts of a changing climate must also be an integral component of climate change planning. Several organizations at the national and local government levels and within the business sector have begun to work towards identifying vulnerabilities and categorizing risk. However, professionals are frequently limited in their ability to plan for climate change adaptation on local transportation networks due to both insufficient local data resources and a lack of guidance on how to identify locations vulnerable to climate change and assess the risk, in terms of both infrastructure loss and operational delay.

The model presented in this report outlines a transferable method to preliminarily assess potential impacts to local transportation systems due to climate change utilizing a GIS. This method, widely accessible to a range of transportation departments due to the simple nature of the GIS analysis, can also be used as a basis for more advanced analysis, such as traffic modeling, and comparative scenario testing. The results of these preliminary analyses can later be incorporated into a TAM to assist with long-range transportation planning decisions. While this method presents a promising first step towards vulnerability and impact assessment, it can only fulfill its promise with continued, coordinated data collection, development, and updates as climate impacts at the local level continue to be revealed.

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REFERENCES

1. Solman, et al., Regional Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge, United Kingdom and New York, NY: Cambridge University Press, 2007.), <http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter11.pdf>.
2. Mote P. and Salathé E., Future climate in the Pacific Northwest, Chapter 1 in The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate (Seattle, Washington: University of Washington Climate Impacts Group, 2009), <http://ces.washington.edu/db/pdf/wacciaexecsummary638.pdf>.
3. United States Global Change Research Program, *Global Climate Change Impacts in the United States*. Cambridge University Press: Cambridge, Massachusetts, 2009. <http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf>
4. Rivera, D., "Rising water worries prompt cruise boat to seek higher bridge clearance," The Oregonian, November 18, 2009, http://www.oregonlive.com/news/index.ssf/2009/11/portland_spirit_sees_a_trimet.html.
5. TriMet, Questions from November 19, 2009 CAC Meeting Willamette River Bridge Vertical Clearance and Bike Connections. January 21, 2010. http://trimet.org/pdfs/pm/CAC/2010/January_21_2010/QA_VerticalClearance_1-21-10.pdf
6. Meyer, M. Amekudzi, A. and O'Har, J., Transportation Asset Management Systems and Climate Change: An Adaptive Systems Management Approach. Presented at the 89th Annual Meeting of the Transportation Research Board. CD-ROM. Washington, D.C., 2010.
7. United States Department of Transportation, Asset Management Primer, Washington, D.C., 1999, [http://assetmanagement.transportation.org/tam/aashto.nsf/All+Documents/3F885001659BB65185256B180058688C/\\$FILE/amprimer.pdf](http://assetmanagement.transportation.org/tam/aashto.nsf/All+Documents/3F885001659BB65185256B180058688C/$FILE/amprimer.pdf)
8. City of Portland, *Street Paving and Repair*, City of Portland Office of Transportation, 2010. <http://www.portlandonline.com/transportation/index.cfm?c=47261>
9. Wheeler, S., State and Municipal Climate Change Plans: The First Generation. *Journal of the American Planning Association*. Vol 74, No. 4 (2008): 481-496.
10. Gallivan, F., Integrating Climate Change into State and Regional Transportation Plans. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2119. Transportation Research Board of the National Academies, Washington, D.C., 2009.
11. Noble, D., *An Overview of the Risk Management Approach to Adaptation to Climate Change in Canada*. Natural Resources Canada Climate Change Impacts and Adaptation Directorate, March 2005.
12. Chang, H., LaFrenz, M., Jung, I., Figliozzi, M., Platman, D. & Pederson, C. (2010) Potential Impacts of Climate Change on Flood-Induced Travel Disruptions: A Case Study of Portland, Oregon, USA. *Annals of the Association of American Geographers*, 100(4), 1-14.
13. Puget Sound Regional Council. Final Draft Transportation 2040: Appendix L Climate Change Background. April 2010.

14. Annals of the New York Academy of Sciences. Climate Change Adaptation in New York City: Building a Risk Management Response: New York City Panel on Climate Change 2010 Report. May 2010.
15. Kinsella, Y. and McGuire, F., Climate Change Uncertainty and the State Highway Network: A Moving Target. Transit New Zealand. Auckland, New Zealand, 2005.
16. Sussman, F. and Freed, J., Adapting to Climate Change: A Business Approach. Pew Center on Global Climate Change. April 2008.
17. United States Bureau of the Census, State and County Quickfacts: Portland, Oregon, 2000, Washington, D.C., <http://quickfacts.census.gov/qfd/states/41/4159000.html>
18. Office of the City Auditor, City of Portland 2009 Resident Survey Results, Portland, Oregon, 2009, <http://www.portlandonline.com/auditor/index.cfm?c=49566&a=270760>
19. City of Portland Bureau of Transportation, Portland Bicycle Master Plan for 2030, Portland, Oregon, 2010, <http://www.portlandonline.com/transportation/index.cfm?c=44597&a=289122>
20. Bureau of Transportation Statistics, National Transportation Statistics Table 1-38: Principal Means of Transportation to Work, Washington, D.C., http://www.bts.gov/publications/national_transportation_statistics/html/table_01_38.html
21. Intergovernmental Panel on Climate Change, Climate Change 2007: The Physical Science Basis. Contribution of the Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2007.
22. Oregon Department of Transportation, *History Center: 1964 Flood*. Oregon Department of Transportation Business Services Webpage, February 4, 2007. http://www.oregon.gov/ODOT/CS/BSS/history_center_flood.shtml
23. City of Portland, *Floods*. City of Portland Bureau of Transportation, n.d. <http://www.portlandonline.com/transportation/index.cfm?a=301326&c=35704>
24. Burns, S. et al, Landslides in the Portland, Oregon Metropolitan Area Resulting from the Storm of February 1996: Inventory Map, Database and Evaluation, Portland State University Department of Geology, Portland, Oregon, 1998.
25. Tomlinson, S., The Weather of 2008: Snow, Fire and Fury, *The Oregonian*. January 16, 2009. http://blog.oregonlive.com/weather/2009/01/the_weather_of_2008_snow_fire.html
26. Savonis, M. et al., Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I. *U.S. Climate Change Science Program Synthesis and Assessment Product 4.7*. March 2008.
27. City of Portland Office of Transportation, Traffic counts, Updated July 1, 2010. <http://www.trans.ci.portland.or.us/trafficcounts/SearchTrafficCounts.htm>
28. Collette, C., Barbur corridor recommended as next high capacity transit corridor. Carlotta Collette: *Metro Council District 2 News*. December 17, 2009. <http://news.oregonmetro.gov/3/post.cfm/barbur-corridor-recommended-as-next-high-capacity-transit-corridor>
29. Krough, D., Landslide Closes Portion of Forest Park Trail. *KGW.com*. June 16, 2010. <http://www.kgw.com/news/local/Landslide-closes-section-of-Forest-Park-trail-96498264.html>

30. Fox 12 Oregon, Slide Shuts Down Highway 26 On-ramp. *KPTV.com Traffic*. June 9, 2010. <http://www.kptv.com/traffic/23818808/detail.html>
31. Oregon Department of Land Conservation and Development, DLCD Natural Hazards Floods: Local Government. June 16, 2008. <http://www.oregon.gov/LCD/HAZ/localgov.shtml>
32. Solman, et al., Regional Climate Projections. In: *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge, United Kingdom and New York, NY: Cambridge University Press, 2007.), <http://www.ipcc.ch/pdf/assessmentreport/ar4/wg1/ar4-wg1-chapter11.pdf>.

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TABLE 1 Approaches for Identifying Transportation Vulnerabilities and Assessing Risk

Organization	Approach
Puget Sound Regional Council (PSRC) - Transportation 2040	The impacts of sea level rise to transportation and other infrastructure are of great concern to the PSRC. As such, one of their efforts towards adaptation planning has involved mapping existing and projected sea level in the region using GIS and consulting with local agency and academic experts for reasonableness and consistency. Projections for future sea level incorporated data from both global climate models as well as locally observed vertical land movement (subsiding and rising) and local atmospheric circulation. LIDAR elevation data were used to map existing sea level and there is some concern regarding the accuracy and consistency of these data. As a result, only medium and high-level sea rise scenarios were mapped. A GIS was then used to identify land below a defined threshold and connected by waterways to Puget Sound in order to indicate general locations within the region likely to be inundated. The resulting maps are not intended to identify specific sites vulnerable to climate change but rather to identify general areas and infrastructure that may be impacted and considered in future long-term planning efforts. (13)
New York City – New York City Panel on Climate Change (NPCC)	As part of the city's long-range sustainability plan, PLANYC, Mayor Bloomberg convened the New York City Panel on Climate Change (NPCC) to advise on issues related to climate change, both in terms of mitigation and adaptation. The panel's climate change adaptation planning efforts employ a combination of local climate scenarios, generally following the process used by the Intergovernmental Panel on Climate Change. Scenarios and their projected impacts to critical infrastructure were then evaluated using a risk-based approach. Over 40 diverse stakeholders were involved in the process, including the insurance industry. The study looks at both historically observed events and potential future impacts and assesses the likelihood of their occurrence. It also recommends an iterative or “Flexible Adaptation Pathways” approach that allows for monitoring and mid-course corrections to projected impacts and associated adaptation responses as needed. The NPCC has also developed a Climate Change Adaptation Guidebook to inventory “at-risk” infrastructure and develop adaptation responses. This guidebook includes risk assessment questionnaires, a risk matrix and a prioritization framework. (14)
Transit New Zealand	Transit New Zealand uses a two-stage process to evaluate the potential impacts of climate change to their facilities on state highways and determine responses. The first stage assesses the necessity of acting immediately to adapt the facility based upon the certainty the impact will occur along with the projected magnitude of the impact, the design life of the infrastructure in question, and the ability of the agency to manage the anticipated climate impact with existing procedures. The second phase employs an economic analysis to assess the feasibility of immediate action based upon three adaptation approaches: no action, retrofitting potentially affected existing infrastructure against climate impacts, and designing future improvements to accommodate future climate changes. The results of Transit New Zealand's study suggest that for facilities with a design life less than 25 years the impacts of climate change can be managed with the agency's current asset management system without major changes to standard agency procedures. For longer-term facilities, such as major new bridges, the potential for climate change impacts, such as larger flood flows, should be considered in the design. However the analysis stated that it would not be economical to incorporate these potential impacts in the design based upon the “uncertainty surrounding the if, where, and by how much flooding will increase, the risk of infrastructure obsolescence and the current discount rate” used in the analysis. The approach used in the Transit New Zealand study does not consider the potential social or economic costs of travel delay associated with climate change impacts. (15)
Business Sector - Entergy	Private sector organizations recognize climate change as a threat to business operations. In <i>Adapting to Climate Change: A Business Approach</i> , Sussman and Freed note how the energy company Entergy is using a three-stage process to insulate its business from climate impacts following Hurricane Katrina. First, likely climatic changes and physical impacts are identified and, based on historic trends, scenarios for different climate impacts were mapped using GIS. In the second phase, climate risks were considered in relation to potentially affected assets and/or operations. In the third phase (currently underway), alternative adaptation responses are being developed. (16)

TABLE 2 Spatial Data Used in the Portland, Oregon Model

Shapefile Data	Source	Purpose
Surface transportation network – Major arterials, bus routes, light rail system, planned transit rail improvements (streetcar and light rail), bike routes, passenger and freight rail lines.	RLIS	Model vulnerabilities
Major waterways	RLIS	Reference
Flood – Federal Emergency Management (FEMA) 100-year flood, 1996 flood.	RLIS	Model vulnerabilities
Landslide Hazard Areas	City of Portland	Model vulnerabilities
City Boundary	RLIS	Reference
Land Use	RLIS	Model vulnerabilities
Shapefile data: The GIS data used in the model are shapefile, a spatial data format that contains both geometri and attribute data and can be displayed as points, lines or areas.		

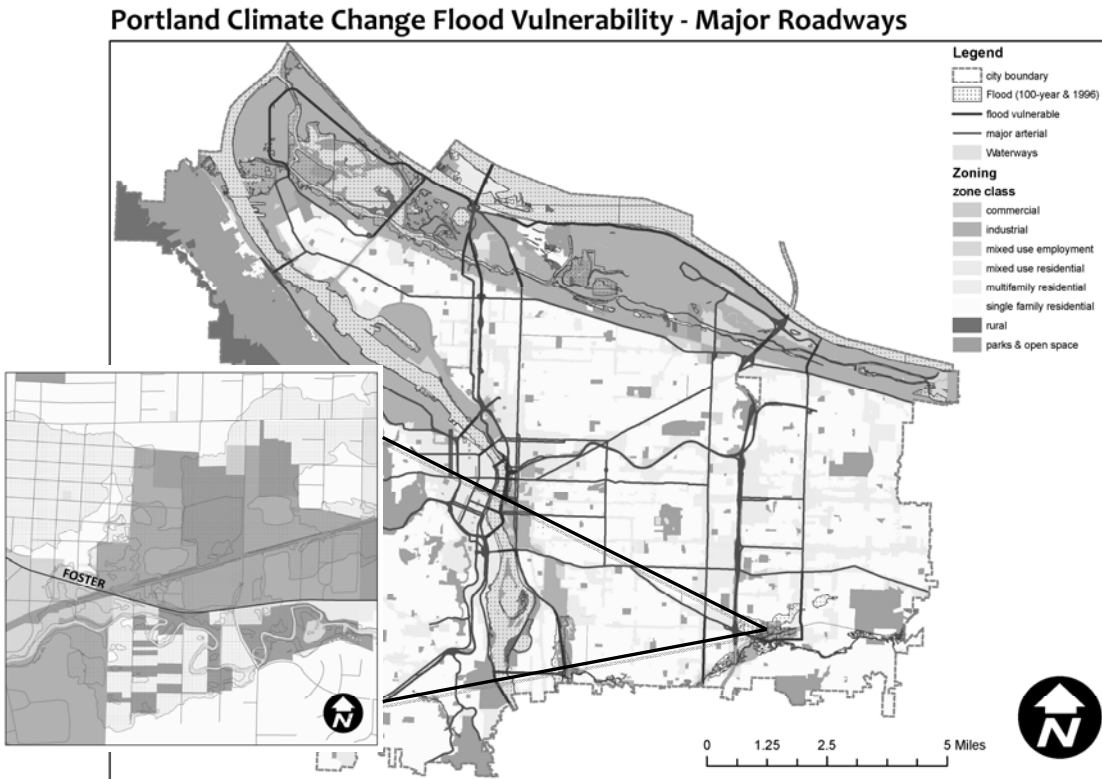


FIGURE 1 Segments of major arterials potentially vulnerable to flooding.