Identifying Sea Level Rise Vulnerability using GIS: Development of a Transit Inundation Modeling Method

Oswald, M. R.[1] and Treat, C.[2]
Department of Civil and Environmental Engineering, Bucknell University, 701 Moore Ave., Lewisburg PA, 17837, USA, E-mail: michelle.oswald@bucknell.edu[1] and cat022@bucknell.edu[2]

Abstract
Sea level rise inundation poses risk to critical transportation infrastructure as the threat of climate change continues. Although mitigation efforts are being implemented, these practices are not timely enough to avoid all potential impact. Therefore, adaptation practices are essential to building resilience and protecting transportation facilities, specifically public transit (rail and bus) networks. This research establishes a method, Transit Inundation Modeling Method (TIMM), used to identify transit infrastructure systems that are vulnerable to sea level rise using Geographic Information Systems (GIS). TIMM allows transit agencies to begin adapting by identifying at-risk links and nodes based on various sea level rise inundation levels. This method is applied to a case study application on the Philadelphia County transit system (railway and bus routes). This case study is used to determine the method's applicability and relevance to a real world transit network. By using this method to identify vulnerabilities, transit agencies throughout the nation can begin to implement adaptation practices (elevate, relocate or reinforce) in order to protect existing facilities as well as plan for future transit projects.

1. Introduction

Climate change has the potential to cause detrimental impacts to the natural as well as the man-made environment (Pew Center on Global Climate Change, 2008). More specifically, the impact of sea level rise causes coastal, low-lying areas to be vulnerable to inundation (Thomas et al., 2012). Scientific studies predict that the rate of sea level rise will accelerate which poses a threat to transportation infrastructure along the coast (IPCC, 2007). Increasing demands on transportation systems suggest the need for evaluating the potential risk and impacts associated with coastal transportation facilities (Trilling, 2002). Transportation and climate change discussion and efforts are primarily focused on mitigation, which aim to reduce the greenhouse gas emissions and other contributions to global warming (Valsson and Ulfarsson, 2009). Mitigation efforts for transportation, including advances in fuel technology, vehicle efficiency, and revised land use planning strategies, are being implemented across the U.S. (ICF International, 2011). However, these mitigation efforts are not timely enough to remove all potential impacts associated with global warming (Pew Center on Global Climate Change, 2008). In particular, public transit networks are critical transportation infrastructure as they are vital to maintaining mobility and accessibility (Murray et al., 1998). As a result, miles of rail and bus networks are at-risk to sea level rise inundation which can lead to inaccessibility and immobility. Therefore, adaptation practices that support changes in infrastructure must be implemented to reduce vulnerabilities and avoid potential detrimental impacts (Oswald et al., 2012). The primary objective of this research is to establish a vulnerability modeling method, *Transit Inundation Modeling Method* (TIMM), developed to identify transit infrastructure systems that are vulnerable to sea level rise using Geographic Information Systems (GIS). Based on a review of existing modeling strategies and a needs assessment, TIMM is developed with the goal of assisting transit agencies to begin adapting by identifying at-risk links and nodes based on various sea level rise inundation levels. The step-by-step method is described in detail with the goal of being applicable, repeatable, and relevant to evaluating transportation infrastructure throughout the country. With this goal in mind, TIMM is applied to a case study application on the Philadelphia County transit system (railway and bus routes), which lies adjacent to the Delaware River. This case study is used to determine the method's applicability and relevance to a real world transit network. By using this method to identify vulnerabilities, transit agencies throughout the nation can begin to implement adaptation practices (elevate, relocate or protect) to existing facilities as well as plan for future transit projects.

2. Climate Change Impacts

Climate change is defined as the long term alteration in average weather patterns (WMO, 1984). These changes occur at a global scale and cause region-wide issues, including an increase in heat waves, hot days, and intense precipitation events as well as more frequent extreme weather events and sea level rise (CIER, 2007). Observational evidence of the effects of climate change includes changes in Arctic ecosystems, pole-ward shifts of species of animals and plants, and rising marine and freshwater temperatures (IPCC, 2007). Although these impacts will vary by region, climate change will affect major economic sectors throughout the U.S. (CIER, 2007).

2.1 Sea Level Rise

One of the most anticipated effects of climate change is sea level rise (Savonis et al., 2008). In the past century, oceans have been rising at a rate much faster than in the past thousand years (Titus et al., 2009). Though change in sea level has been a long term process, it has been exacerbated by thermal expansion of warming ocean waters and deglaciation (Titus et al., 2009). The Intergovernmental Panel on Climate Change (IPCC, 2007) predicts that these levels will increase between 0.18 to 0.59 meters over the next 100 years. In the United States, this will be most pronounced along the Gulf and the Atlantic Coasts (IPCC, 2007). Other sea level rise projections report a range from 0.2 meter to 2.0 meters (Pfeffer et al., 2008 and Rahmstorf, 2010). Furthermore, current IPCC data compared to predicted values show that these predictions may be underestimated (Rahmstorf et al., 2007). Worst case scenario values include a 5.0 meter increase of world sea levels due to catastrophic collapse of the Antarctic ice sheets (Vaughan, 2006).

2.2 Transportation Impacts

Transportation infrastructure is extremely susceptible to even minimal increments of sea level rise. Based on a study in New York City, a one meter rise of inundation increases the probability of flooding from storm surges by an average factor of three (Jacob et al., 2007). Hodges (2011) discusses the impacts of structural damage as a "vicious cycle" for transportation. Increased maintenance has its own fixed costs, but also creates service interruptions, a greater need for last-minute manpower, and a strain on limited supplies of alternate transportation modes. In addition to the concern of structural damage due to floodwaters, inundation of specific links causes a significant impact on the transportation system due to network effects (Gorman, 2005; Centre for Transport and Navigation, 2006). In particular, since railways are often located in low-lying areas, they are specifically at-risk to flooding of underground tunnel and rail tracks, erosion of the rail base, and reduced clearance under bridges (TRB, 2008).

3. Transportation Adaptation

In order to prepare and protect societies, economies, and the environment, climate change adaptation practices are required (Oswald et al., 2012). The IPCC (2007) defines climate change adaptation "as the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects which moderates harm or exploits beneficial opportunities." The IPCC Coastal Zone Management (1992) defined three types of response strategies for adapting to sea level rise: retreat, accommodation, and protection. Together, these response strategies are part of an iterative risk management approach that encourages cost-effective decision-making (NRC, 2010).

3.1 Existing Adaptation Efforts

Studies that target sea level rise impacts on coastal transportation infrastructure are an emerging topic. The Gulf Coast Study (U.S. DOT, 2011) is a regional analysis that focuses on the process of identifying regional climate change impacts and developing risk assessment tools for use by transportation planners in the Gulf Coast region. The Florida DOT applied a similar methodology focused on sea level rise inundation of the roadway network to identify vulnerabilities (Berry, 2012). At the national level, the Federal Transit Administration (FTA, 2011) and the Federal Highway Administration (FHWA, 2011) are conducting pilot programs for agencies to begin implementing inundation modeling and adaptation practices. Additional efforts such as Meyer and Weigel (2011) have promoted the use of an adaptive systems framework to manage transportation assets and Oswald et al., (2012) have developed a Climate Change Adaptation Tool for Transportation (CCATT) to assist transportation agencies in integrating adaptation practices into long range transportation plans.

3.2 GIS Application

Spatial analyses are particularly useful in identifying areas at-risk to inundation. Geographical information systems (GIS) can bring together multiple dimensions of a study area, such as economic data, building footprints, hydrology, and land use, and visually display patterns in the projection. A multidimensional approach through the use of GIS tools is crucial for identifying vulnerable infrastructure and prioritizing for adaptation purposes, especially when this technology is incorporated into other transportation planning projects (FHWA, 2012). Climate change and sea level rise are emphasized at the national and global level, yet these issues arise at a regional level (Lichter and Felenstein, 2012). Opportunities for adaptation can be effectively captured using GIS through spatially displaying and analyzing relationships between land use, hydrology, and infrastructure elevation. Thus, GIS can be used to model different sea level rise scenarios to identify vulnerable structures, and present these findings in a very powerful and visual manner for policymakers and public audiences (Volpe Center, 2011). Existing inundation modeling approaches have been reviewed in order to conduct a needs assessment and develop a formal method for inundation modeling of public transportation infrastructure. Colgan and Merrill (2008) estimated the economic cost of inundation in coastal communities in Maine using the hurricane forecasting model SLOSH (Sea, Lake, Overland Flow Surge from Hurricanes). At a regional level, the Coastal Adaptation to Sea-Level Rise Tool (COAST) combines inundation layers with employment, wages, and number of businesses to determine and visualize overall economic vulnerability in the Gulf Coast region (Merrill et al., 2010). For transportation planning, this scope is narrowed, as planners aim to identify specific links and nodes vulnerable to inundation. For example, Oswald et al., (2012) conducted a transportation vulnerability study on Delaware focusing on the sea level rise impact of the I-95 corridor (rail, road, and bus routes).

3.3 Needs Assessment

According to the literature review on past modeling approaches, there is a need for methodologies that operate at a regional level and can be readily integrated into transportation agencies. Current sea level rise projections used in past models include only a small range of conservative inundation levels. However, climate change inherently contains uncertainty, and methodologies designed for transportation planning need to account for this with a broader range of scenarios. In addition, sea level rise models that consist of multiple parameters such as storm surge, wave action, and coastal erosion are powerful predictors, but their sophistication has limited applicability and use by transit agencies. GIS is already in use by transportation agencies, but inclusion of GIS applications for climate change needs to become more widespread and accessible to agencies that are pressed for time and have limited resources. Thus, transportation agencies need: (1) information that is readily available and accessible, (2) a methodology that has straightforward steps and requires limited technological background, (3) a detailed process on how to develop and analyze inundation maps using GIS, and (4) an example of how to apply the methodology to a study area. The needs assessment serves as the foundation for this study, specifically the development of TIMM and the case study.

4. Transit Inundation Modeling Method (TIMM)

This section describes the proposed method based on a five-step process. Each of the steps are listed and described in detail for application to transit agencies.

4.1 Framework

TIMM is based on a five-step process that can be applied to transit agencies to identify vulnerabilities. The process is repeatable, straightforward, GIS-based, and uses publically available geographic data. The five steps include: (1) Define Study Area, (2) Gather Data, (3) Create Inundation Layers, (4) Analyze Data, and (5) Synthesize Results and Recommendations. Each step is described in detail below in terms of the implementation process.

4.1.1 Define study area

The first step of the method is to define the area under evaluation. The study area is selected based on the transit agency jurisdiction, location to coastal zones and extent of the transportation network and infrastructure in the area. Proximity to coastal regions increases the exposure to climate-related sea level rise hazards, thereby increasing the risk of damage to the network and associated infrastructure. Thus, a region with the greatest number of facilities at-risk is the most in need for planning strategies and implementation of TIMM.

4.1.2 Gather data

The second step is to gather relevant data in order to complete spatial analysis using GIS. The data required for creating the maps is available through DOT agency websites, local university websites, and data clearinghouses such as the U.S. Census Bureau (2012). Depending on the desired extent of the study area, the resolution of the geographic data retrieved should be identified. For example, statewide transportation network data is typically generalized; therefore, rendering this information unsuitable for high resolution analysis at a county level. If the resolution or quality of the data is insufficient for regional analysis, specific agencies/departments may be able to provide higher quality or be able to digitize pertinent infrastructure by referencing existing maps. In terms of gathering the data layers for the basemap, it is recommended to begin with county boundary shapefiles and hydrology in the area. Transportation layers, including point files of bus stops, and polyline files of bus routes and rail networks, are added to the basemap. The basemaps with various transportation layers (bus and rail networks) serve as the foundation for creating inundation maps and region-specific data, based on access and availability, can be added. For example, if available, ridership data can be input as a layer in relation to the bus routes or rail network to display high priority routes. In preparation for the step 3, creation of inundation layers, elevation data for the study area is required. Elevation data can be found in Digital Elevation Models (DEMs) which are available from the U.S. Geological Survey National Elevation Dataset (NED) (Gesch et al., 2002). The highest possible resolution is the 1/9 arcsecond version (3m resolution), up to a 1 arcsecond version (30m resolution) (U.S. Geologic Survey, 2010). Coverage of the 1/9 version is not available in all regions of the U.S., but the best quality available for the study area should be used in data processing.

4.1.3 Create inundation layers

Once the basemaps are complete, the inundation layers can be created. DEMs capture elevation information on a cell-by-cell basis and project this information in a raster format. The spatial information used from DEMs is invaluable, but there is inherent vertical uncertainty in the data. This is problematic when mapping sea level rise using DEMs because IPCC projections are on the scale of centimeters and uncertainty can be in the scale of meters (Rahmstorf, 2007). Therefore, it is suggested to model a range of predicted inundation levels, from middle to upper bounds of IPCC projections of one to two meters, as well as the high-risk scenario of five meters using an increment of a one meter rise. This range reflects previous inundation studies (Boateng, 2012; Oswald et al., 2012; Dasgupta et al., 2009; Tol et al., 2006). A commonly used approach for modeling inundation is the "bathtub" approach, where a cell is considered inundated if its elevation value is less than or equal to the projected sea level (NOAA, 2011). However, inland areas that are less than the projected sea level may be inadvertently mapped as inundated because they are not hydrologically connected to a major waterbody. Poulter and Halpin (2008) discuss an alternative approach to modeling sea level rise by accounting for hydrological connectivity to the major waterbody. In this approach, a cell is considered inundated if its elevation value is less than or equal to the projected sea level and at least one neighboring cell is adjacent to another major waterbody or inundated cell. These rules allow for a more accurate model of surface flooding around geologic and man-made features. Hydrologic connectivity can be restricted to cells connected in the four cardinal directions ('four-side' rule) or in the cardinal and diagonal directions (eight-side rule). This method uses the eight-side rule when modeling sea level rise to show maximum potential inundation (Gesch, 2009). The steps taken to create the sea level rise layers are as followed:

a) Based on the desired sea level rise scenario, the DEM is reclassified into an output of land and sea level rise increments. The increments included the possible rise in sea level (0, 1, 2, 3, 4 and 5 meters), and the land value included all other elevations greater than five meters.
b) Hydrological connectivity to the coast is determined by the eight-side rule, as described above. With the connectivity established, the raster was reclassified into land value and sea level inundation extents.
c) In order to use the layers in future data processing with transportation infrastructure, the raster layers are then converted into vector layers.
d) The inundation layers are then overlaid onto the transportation layers/basemaps in order to complete data analysis and identify vulnerabilities.

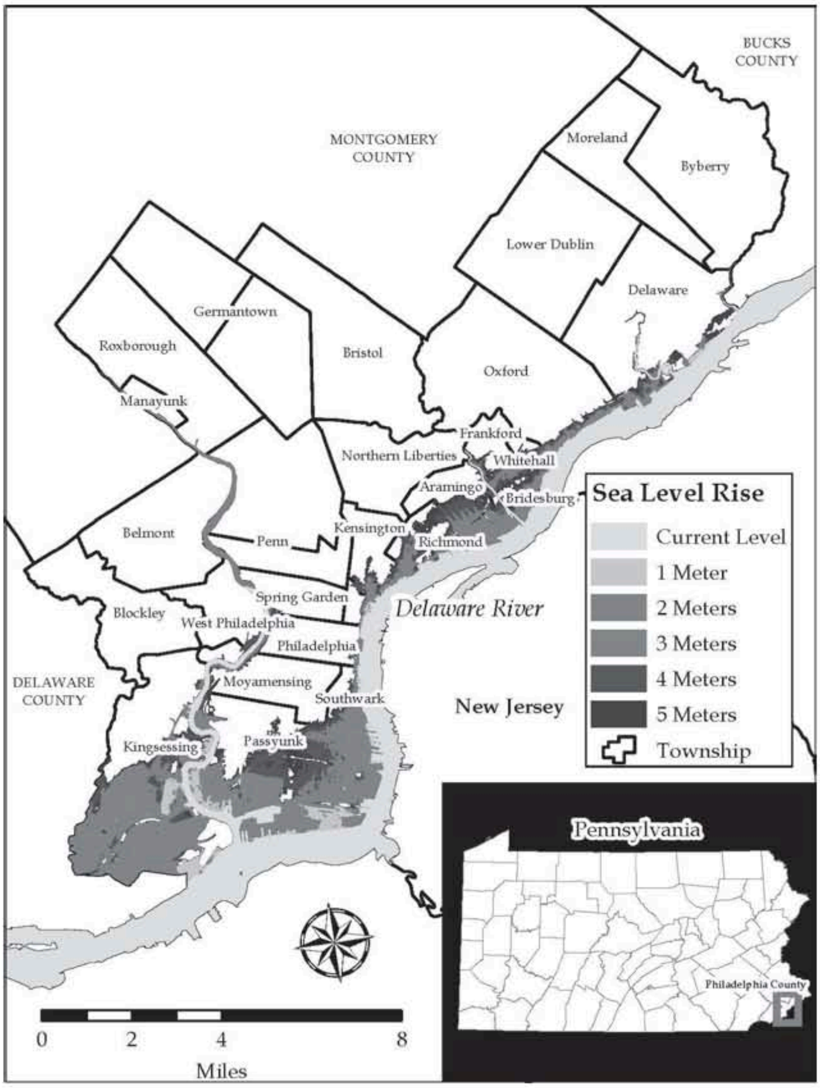

Figure 1: Sample Map Showing Sea Level Rise Inundation in Philadelphia County, PA

Figure 1 shows a sample map displaying inundation layers for a coastal region in Philadelphia County, Pennsylvania.

4.1.4 Analyze data

To visualize the impact of different inundation scenarios on the transportation layer, the infrastructure is symbolized by color corresponding to the vulnerability of flooding. Infrastructure in an area prone to one meter inundation, for example, is more vulnerable than infrastructure in an area of five meters of inundation based on low to severe impact sea level rise scenarios. To qualitatively define each region based on this severity index, the infrastructure inundated at each level is "clipped," or extracted, from the layer.

The inundated infrastructure layers are added to their respective (rail or bus network) map. Depending on the source and level of detail, transportation geographic data includes ridership information based on routes or by link. This information is useful for prioritization of at-risk infrastructure and can be included in the data analysis process. In order to quantify the impact of each inundation scenario on the transportation network, summary statistics are calculated. Using the sea level rise inundation layers created in step 4, the mileage or count of infrastructure (for example, number of bus stops) within each inundation level is calculated. Both the mileage/count is identified for each individual level as well as the cumulative amount inundated. Acreage of land inundated is also included in the analysis. The inundation layers created in step 3 include the original hydrology features; therefore, in order to accurately calculate the actual inundation, existing hydrology features for this layer are eliminated. Using the attribute table, the acreage for each scenario is computed, and then the total acreage of inundation for each one meter sea level rise scenario is calculated.

4.1.5 Synthesize results and recommendations
The results of mileage of inundated facilities, acreage of land inundated, and number of stops that are vulnerable to inundation are valuable for transit planning. Identifying vulnerabilities allows for proactive decision-making with regards to existing and future projects. The process for identifying vulnerabilities should be iterative as infrastructure as well as scenario projections change. Repeating the process on a yearly basis can aid in determining changes as well as updating proposed projects that maybe at-risk to inundation. Knowing the proposed severity of inundation as well as the facility demand can aid in prioritizing projects and allow for cost-effective decision making.

5. Case Study Application
In order to determine the applicability and relevance of TIMM to a real world transit network, the methodology is applied to a case study. The case study is based on the transit infrastructure located within the coastal region of Philadelphia County, PA. This application serves as an example of how to implement TIMM at the transit agency level.

5.1 Methodology Applied
The five step process of TIMM, as defined previously, is applied to the case study region. Each step is defined in detail as well as the results of the process. Data was processed and layers were created using ArcGIS 10 and the Spatial Analyst Extension (ESRI, 2011).

5.1.1 Define study area
The study area used for the application of TIMM is Philadelphia County, Pennsylvania. According to the U.S. Census Bureau (2012), Philadelphia County has a population of 1.5 million, an area of 134.1 square miles, and is located along twenty miles of the Delaware River. The primary transit provider in this county is the Southeastern Pennsylvania Transportation Authority (SEPTA); therefore, this case study focuses on rail and bus networks within SEPTA's jurisdiction.

5.1.2 Gather data
The base layers of the maps consisted of county-level state maps and local hydrology of the Delaware River, which were accessed via the Pennsylvania Geospatial Data Clearinghouse (PASDA, 2012). Townships were digitized based on a geo-referenced historic map provided by the City of Philadelphia (City of Philadelphia, 1959). Data layers for transportation infrastructure, including the rail network, bus route network, and bus stops, were provided by SEPTA. Elevation information for the DEM was obtained from NED at the 1/9 arcsecond resolution.

5.1.3 Create inundation layers
The DEM derived from National Elevation Dataset served as the basis for creating the inundation layers. After ensuring the DEM was corrected for hydrological connectivity using the eight-side rule, sea level rise scenarios were extracted at one meter intervals from up to five meters and overlaid onto the SEPTA network.

5.1.4 Analyze data
Using the inundation layers, three inundation maps for Philadelphia County were created for affected rail network, bus routes, and bus stops. In addition, extent maps were created to highlight notably large inundated areas. Figures 2 and 3 illustrate examples of these inundation maps, specifically for the rail network and bus routes. The amount of at-risk infrastructure for each sea level rise scenario was calculated by extracting the transportation features from each corresponding map. The total acreage of inundation at each one meter increment was also calculated. At the worst-case scenario of a 5 meter rise, 177 miles of bus routes, 713 bus stops, 33.2 miles of rail, and 13,586 acres of land are susceptible to inundation. Therefore, the need for applying TIMM and identifying at-risk facilities is useful from a planning perspective for Philadelphia County, PA.

5.1.5 Synthesize results and recommendations
Based on the projected inundation levels, southern Philadelphia County is at-risk for sea level rise inundation. Accordingly, infrastructure in this area is the most vulnerable, and therefore, transit planning should prioritize projects centered in this region. Ridership data was provided by SEPTA for the bus network layer by route and this is included in the map for further adaptation planning analysis.

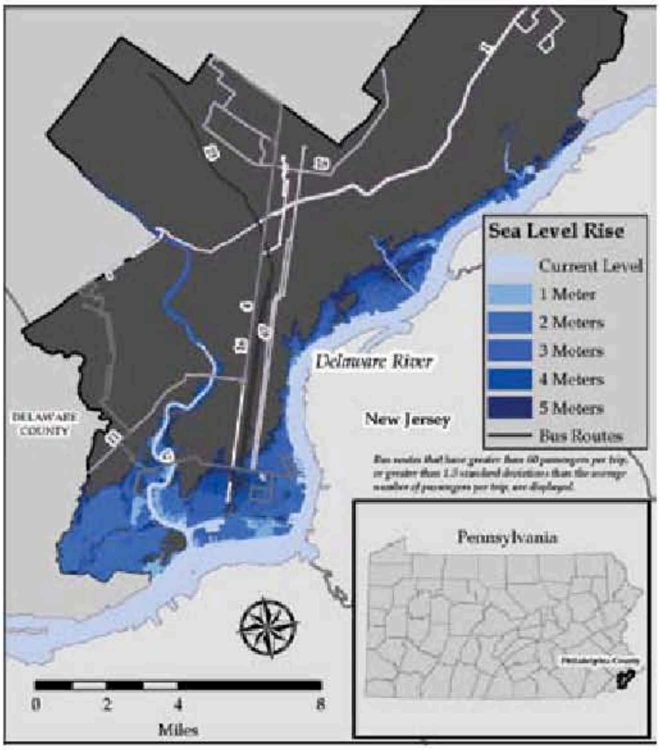

Figure 2: Philadelphia County High Density Bus Routes Inundation (source data layers from SEPTA, 2012)

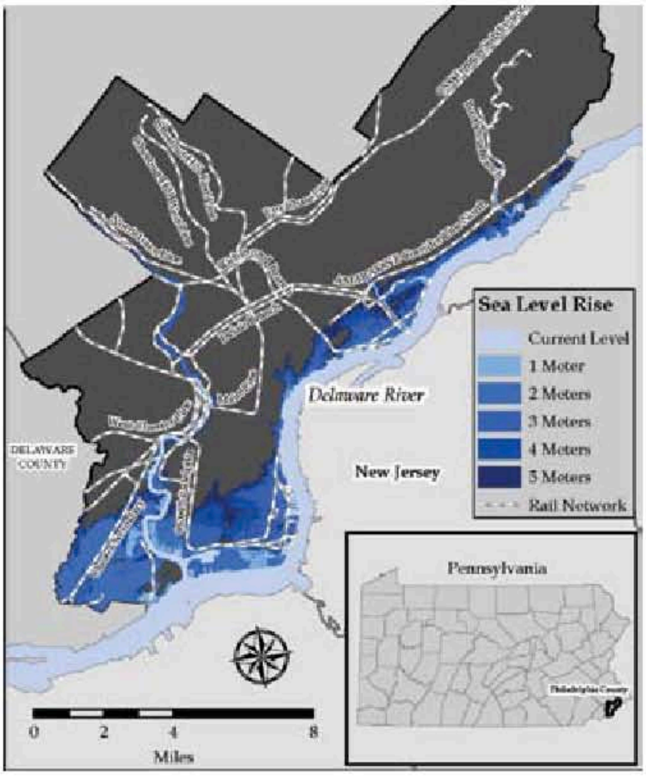

Figure 3: Philadelphia County Rail Line Inundation (source data layers from SEPTA, 2012)

5.2 Reflection

TIMM is an applicable process that is useful for transportation agencies. This case study application based on SEPTA's bus and rail network in Philadelphia County serves as an example for how agencies can begin to apply TIMM to their transit network. Using spatial analysis to determine potential inundation along coastal regions, TIMM identifies at-risk facilities to allow for improved planning of current and future transit projects. The case study includes limitations associated with accessing the geographic data. Although SEPTA's rail and bus data is publically available, more detailed data such as individual track alignment, rail ridership data, and rail stop locations are desired. The bus stop data was more detailed allowing for high density ridership analysis which can assist in prioritizing current and future projects based on demand. Overall, this case study is useful for the transit agency as well as other agencies overseeing infrastructure along coastal low-lying regions.

6. Conclusions

Due to the criticality of public transportation infrastructure as well as the pending threat of climate change impacts, adaptation planning methods such as TIMM are essential. Current mitigation efforts are not timely enough to remove all potential impacts associated with global warming (Pew Center on Global Climate Change, 2008). As a result, identifying potential vulnerabilities through spatial analysis is valuable for improving decision-making at the planning level. TIMM is a five-step process that is repeatable, straightforward, GIS-based, and uses publically available geographic data. Although there are limitations associated with accessing regional specific data, determining the influence of local hydrological impacts, and using newly developed inundation projections, TIMM addresses the primary needs identified with existing methods. As scientific research continues and projections are revised over time, TIMM can be improved. Future research includes streamlining the data collection process, enhancing the method of creating inundation layers to include local effects, and incorporating innovative sea level rise projection models such as COAST. In addition, once TIMM is applied, the next step is to prioritize projects to make cost-effective and sustainable decisions at the planning level. A prioritization index or framework is needed to guide planners in this process. TIMM as well as the case study application serve as a foundation for agencies to start developing adaptation strategies in response to sea level rise impacts. Ideally, the method and results can be applicable to transit agencies along coastal regions throughout the nation to reduce vulnerabilities and protect transportation infrastructure at-risk to sea level rise.

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