APRIL 2017

PHASE 1

PENNDOT EXTREME WEATHER VULNERABILITY STUDY

APPENDIX D

METHODOLOGY FOR FORECASTING FLOODING VULNERABILITIES

Michael Baker INTERNATIONAL

pennsylvania DEPARTMENT OF TRANSPORTATION

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Methodology for Assessing Impacts of Inland Flooding

Background

This study has incorporated a planning level analysis to evaluate flooding inundation of PennDOT's state-owned roadways and bridges based on existing FEMA 1-percent chance floodplain maps and climate model projections for Pennsylvania. The analyses are intended to provide general insights on potential transportation vulnerabilities within the state. The analyses may be supplemented in the future by more detailed hydraulic modeling at specific site locations. Such modeling may focus on stormwater management, drainage and the details of culvert design and capacity at individual sites.

The study analysis has been conducted for three sample counties (Lycoming, Allegheny and Delaware) with a focus on procedures and tools that can be cost-effectively applied in other counties. The results from these analyses are to be evaluated against local stakeholder knowledge and other historic flooding information including PennDOT's Roadway Conditions Reporting System (RCRS). Assessing the reasonableness and planning value of the study analysis will determine whether additional county analyses are conducted.

The analysis methodology is similar to efforts conducted in several other states. Regression equations like that shown in **Figure 1** have been used to estimate future flood discharges based on specific variables that may change in the future including impervious area (due to development) and precipitation (due to climate change). Other hydraulic "power" equations are used to translate discharge increases to stream depth increases for specific locations within the county. The focus of the effort is not to predict future discharges but to scale the discharges and corresponding depths used in developing the FEMA Flood Insurance Rate Maps (FIRM).

A regression equation was developed for predicting the increase in the 1-percent chance flood discharge as a function of climate and land use change. Future climate projections were obtained from the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections (DCHP) web site: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections.

Future land use projections were obtained from the Integrated Climate and Land-Use Scenarios (ICLUS) project developed by the Environmental Protection Agency (EPA, 2009). The increases in the 1-percent chance discharge were used to predict increases in flood depths and the associated increase in floodplain depth and width at locations within each county.

Regression Equation Estimation

A regression equation for estimating the 1-percent chance discharge for Pennsylvania streams was developed using data for 230 gaging stations in Pennsylvania, New Jersey, New York, Maryland and West Virginia. The location and distribution of these gaging stations is illustrated in **Figure 2**.

$$Q_{1\%} = b\, DA^{d}\ CS^{e}\ ST^{f}\ IA^{g}\ P^{h}$$

Drainage area, in square miles	Channel slope, in feet per mile	Surface area of lakes and ponds, in percent	Impervious area, in percent	Precipitation
DA	CS	ST	IA	P

Figure 1: Statistical regression analysis of stream gauge data

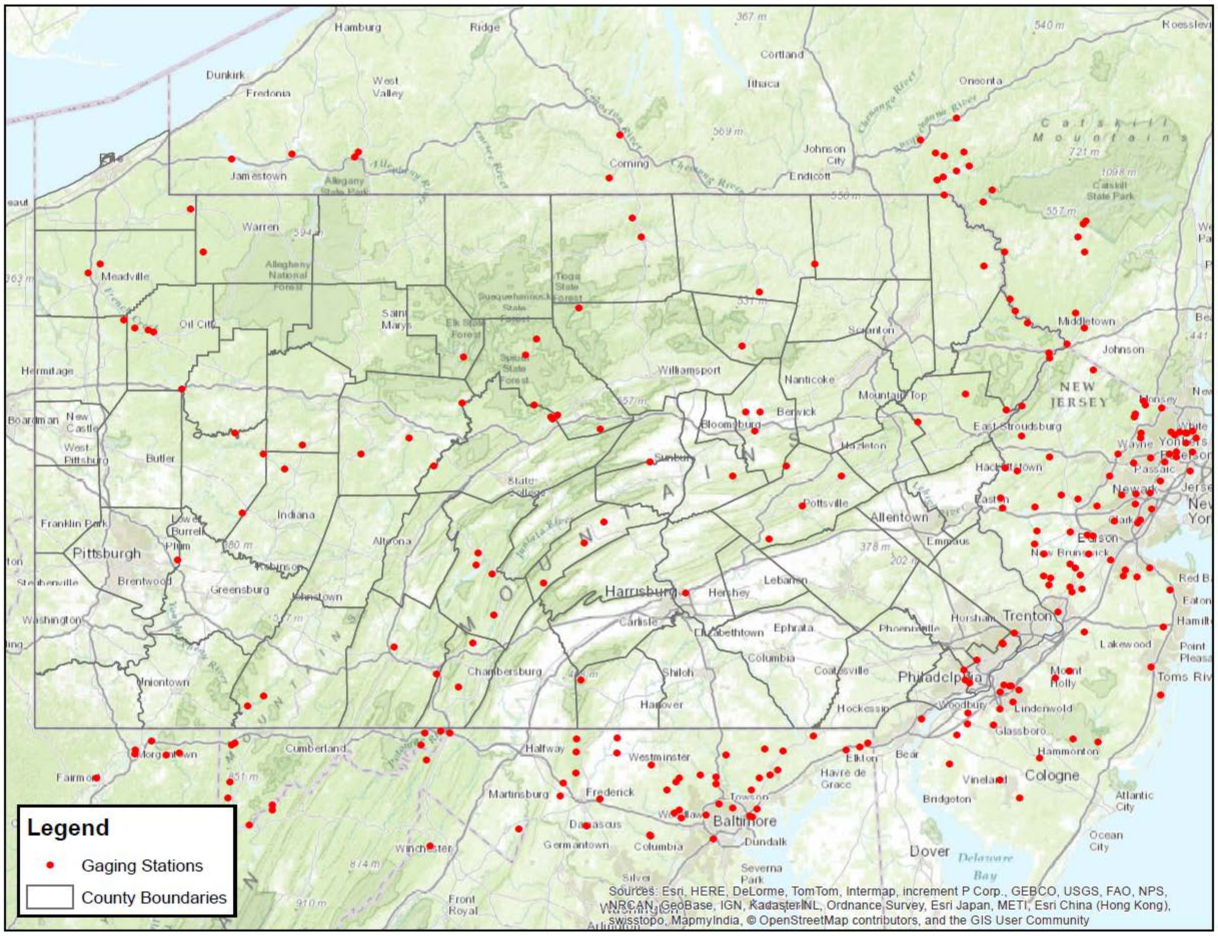

Figure 2: Locations of gaging stations used in the regression analysis

For each gaging station, the characteristics of the watershed and streamflow were obtained from a 2013 climate change study for FEMA (AECOM et al., 2013). The characteristics obtained from the FEMA study included the drainage area, channel slope, percent of the watershed in lakes and ponds, and percent of impervious area in the watershed. The precipitation characteristics for developing the regression equation were obtained from the DCHP web site for the period 1950-99.

The DCHP web site includes daily precipitation data from the Coupled Model Intercomparison Project Phase 5 (CMIP5) for an observed period of time 1950-99 and projected values of the daily precipitation from 21 Global Climate Models (GCMs) for the period 1950-2099. The 21 GCMs are identified in **Table 1** with an indication if projections are available for the Representative Concentration Pathways (RCP) 2.6 and RCP 8.5. The gas emission scenario for RCP 2.6 actually has concentrations at 2100 that are lower than present-day concentrations.

The projections for RCP 8.5 were used in the analysis and are consistent with the projections used for the Pennsylvania Climate Impacts Assessments Update (Pennsylvania State University, 2015). That report adopts RCP8.5 and provides a summary of the climate impacts within the state, which includes a statement that annual precipitation and extreme precipitation events are projected to increase.

Table 1: Climate model projections on the DCHP web site for RCP 2.6 and RCP 8.5

Climate Model	RCP 2.6	RCP 8.5
access1-0	No	Yes
bcc-csm1-1	Yes	Yes
bnu-esm	No	No
canesm2	Yes	Yes
ccsm4	Yes	Yes
cesm1-bgc	No	Yes
cnrm-cm5	No	Yes
csiro-mk3-6-0	Yes	Yes
gfdl-cm3	Yes	Yes
gfdl-esm2g	Yes	Yes
gfdl-esm2m	Yes	Yes
inmcm4	No	Yes
ipsl-cm5a-lr	Yes	Yes
ipsl-cm5a-mr	Yes	Yes
miroc-esm	Yes	Yes
miroc-esm-chem	Yes	Yes
miroc5	Yes	Yes
mpi-esm-lr	Yes	Yes
mpi-esm-mr	Yes	Yes
mri-cgcm3	Yes	Yes
noresm1-m	Yes	Yes

The precipitation data are available for 12 km by 12 km grids covering the gaging stations within the study area (Pennsylvania and neighboring states). The observed data on the DCHP web site was used as the basis for defining a climatic variable for development of the regression equation. The daily precipitation data for the observed period 1950-99 was analyzed as follows:

1. Estimate the maximum daily precipitation for each year for each grid,
2. Estimate precipitation statistics for each grid using the 50 years of annual maximum daily precipitation: minimum, median, mean, 90th percentile, 99th percentile, and maximum.
3. Average the statistics from step #2 over the watershed drainage area using the percentage of the grids in the drainage area of a given gaging station.

The six precipitation statistics given in step #2 above were investigated for statistical significance in a regression analysis. The minimum and median values were not statistically significant because they had the least variability. The other four statistics were significant with the significance increasing from the mean value to the maximum value. The **mean of the annual maximum daily precipitation** was chosen for use in the regression equation for the following reasons:

- The maximum and 99th percentile are about the same for a sample of 50 years, and
- The mean is considered more stable and robust than using the maximum value or 90th/99th percentiles.

The following regression equation was developed for estimating the 1-percent chance discharge ($Q_{1\%}$) using the mean of the annual maximum daily precipitation (Pmeanrain) for the observed period 1950-99:

Equation (1)

$Q_{1\%}$=4.442 $DA^{0.898}$ $SL^{0.307}$ $(Stor+1)^{-0.580}$ $(IA+1)^{0.217}$ $Pmeanrain^{0.809}$

where DA = drainage area, in square miles; SL = channel slope, in feet per mile, Stor = surface area of lakes and ponds, in percent of the watershed area, IA = impervious area, in percent of the watershed area, and Pmeanrain = the mean of the annual maximum daily precipitation for the period 1950-99.

The standard error of Equation 1 is 45.9 percent and the R^2 value is 0.903 implying the five independent variables are explaining 90.3 percent of the variability in the dependent variable $Q_{1\%}$.

All variables were converted to logarithms and a multiple linear regression analysis was performed. The analysis of variance table for Equation 1 is shown in **Figure 3** for the logarithms of the data.

The column "Parameter Estimate" in **Figure 3** provides the regression coefficients given in Equation 1 (intercept value is in log units). All independent variables are statistically significant at the 5-percent level of significance as indicated by the Pr>|t| column values being less than 0.05 (5-percent level normally used in regression analysis). The t value is a measure of statistical significance and must exceed 1.96 for that independent variable to be statistically significant at the 5-percent level of significance. The Variance Inflation Factor is a measure of correlation between the independent variables and should be less than 5 to avoid multicollinearity issues in the equation.

Equation 1 can be used to estimate the increase in the 1-percent chance discharge by comparing the discharge for future climate and land use to existing conditions. The purpose of Equation 1 is just to estimate the increase in the 1-percent chance discharge, not the absolute value.

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|	Variance Inflation
Intercept	1	0.64758	0.46689	1.39	0.1668	0
lda	1	0.89794	0.02928	30.66	<.0001	3.53618
lsl	1	0.30665	0.04934	6.22	<.0001	3.31323
lstor	1	-0.57967	0.04292	-13.51	<.0001	1.44985
lia	1	0.21689	0.04730	4.59	<.0001	3.65503
lmeanrain	1	0.80851	0.29034	2.78	0.0058	3.10501

Figure 3: Analysis of variance table for Equation 1

Estimation of Flood Depths

There is a relation between depth and discharge as shown in **Figure 4.** For out of banks flows, like the 1-percent chance discharge, the slope of the depth-discharge relation is relatively constant across many natural stream channels.

The following relation between depth and discharge was developed in the 2013 nationwide climate change study for FEMA (f = 0.408) and can be used for this project:

Equation (2)

$$d = 0.2158\ Q^{0.408}$$

where d is maximum depth in feet in the main channel and Q is the discharge in cubic feet per second.

Equation 2 is analogous to a stage-discharge relation for the channel where the depth is used in place of stage (elevation). The discharge in the channel is function of the maximum depth in the main channel. Equation 2 can be used to estimate the increase in depth of the 1-percent chance flood given the increase in the discharge. If you substitute Equation 1 in Equation 2 and form the ratio for future and existing conditions, you get the following equation:

Equation (3)

$$d_{future}/d_{existing} = [Q_{future}/Q_{existing}]^{0.408}$$

The ratio on the right of Equation 3 comes from application of Equation 1 for future and existing climate and land use. The right side the Equation 3 is defined further to be:

Equation (4)

$$[Q_{future}/Q_{existing}]^{0.408} = \{[(IA+1)^{0.217} * Pmeanrain^{0.809}]_{future} \ / \ [(IA+1)^{0.217} * Pmeanrain^{0.809}]_{existing}\}^{0.408}$$

The watershed characteristics (drainage area, channel slope and storage) cancel out in the ratio since they do not change, that is, their ratio is 1.0 for future and existing conditions. The ratio from Equation 4 can be multiplied by $d_{existing}$ from the effective depth grids to get the future 1-percent chance depth d_{future}. The existing depth must be determined at the "thalweg" or centerline of the main channel and represent the maximum depth for a given cross section. The increase in depth is added to the existing 1-percent chance elevation at the given cross section to obtain a new elevation for the revised floodplain mapping.

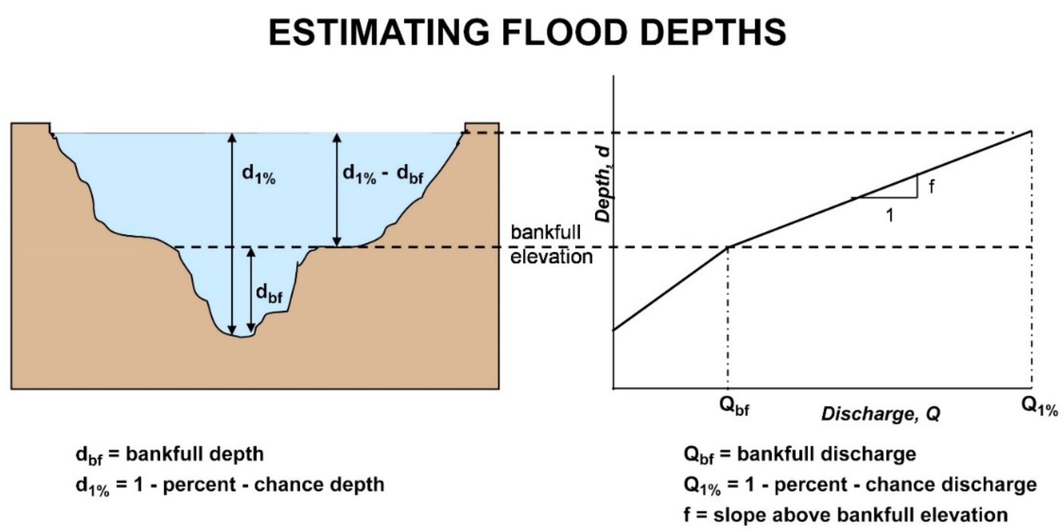

Figure 4: Schematic of the relation between channel shape, depth and discharge

Application Method

As discussed earlier, several GCMs are available and have estimates of daily precipitation for the period 1950 to 2099 on the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections (DCHP) web site available at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections. Climate projections for RCP 8.5 were used in the analysis. The Infrastructure and Climate Network (ICNET) website provides information on choosing and applying climate models. Many of the models listed above are related to each other and therefore may produce similar results. For pilot studies and research projects, it is recommended to choose models that are not closely related to each other. Based on guidance provided at The ICNet web site (http://theicnet.org/?page_id=50), three GCMs were chosen for getting estimates of future precipitation (Pmeanrain):

- CCSM4 – developed by the National Center for Atmospheric Research, USA,
- CSIRO-Mk3.6.0 – developed by Commonwealth Scientific and Industrial Research Organization in collaboration with the Queensland Climate Change Centre of Excellence, Australia, and
- MIROC5 – developed by Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan.

Three pilot studies were completed in Delaware, Lycoming and Allegheny Counties. **Figure 5** shows the extent of the grids that were downloaded to cover the watersheds which contribute to the streams in the three pilot counties.

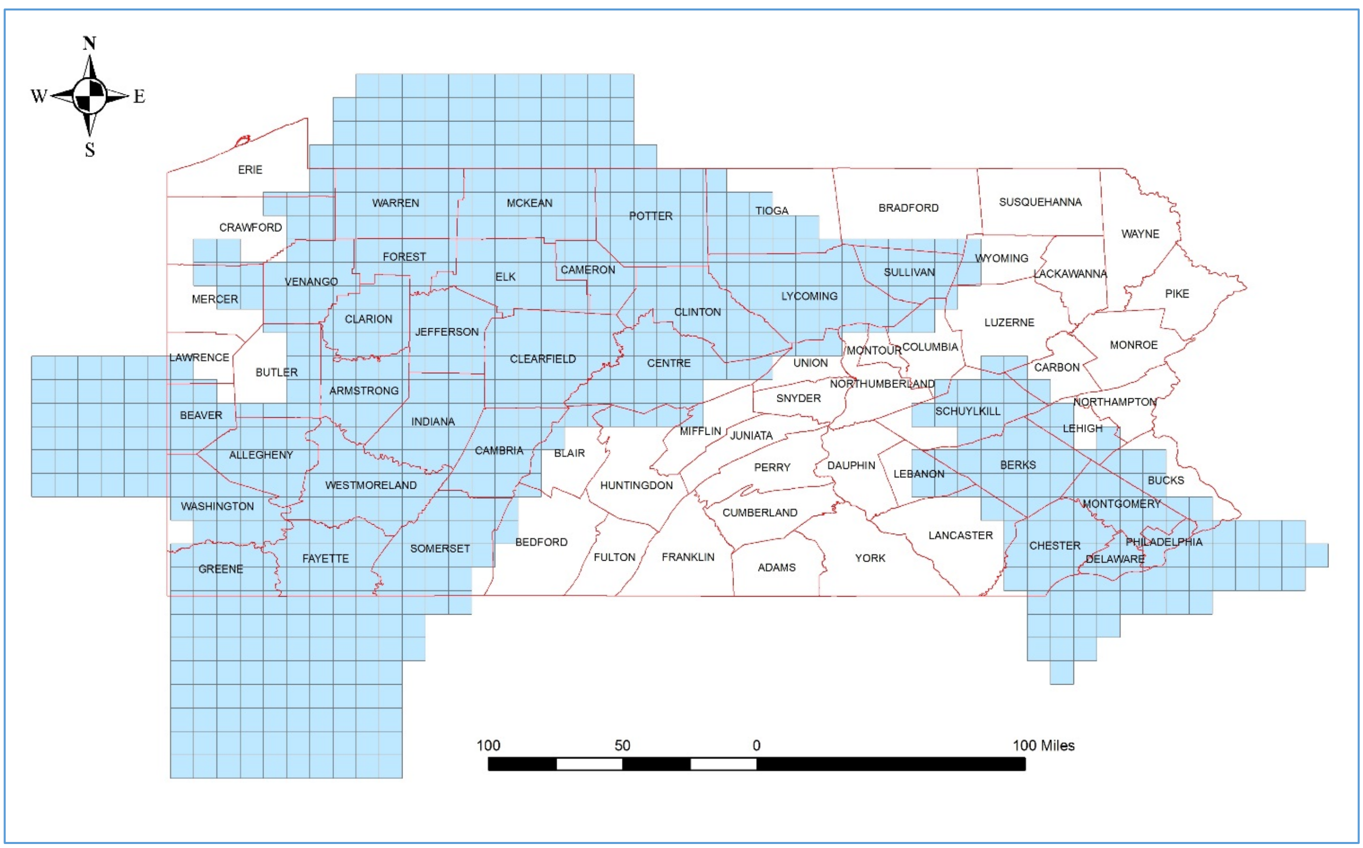

Figure 5: Precipitation data grids for the three pilot counties in Pennsylvania

The three GCMs listed above were evaluated on the ICNet web site as being reliable and tested and have daily precipitation projections for RCP 8.5. The downloaded data was processed using ArcGIS to convert the NetCDF files to ASCII format for further processing.

The regression analysis was performed using the mean of the annual maximum daily precipitation using the observed period 1950-99, a 50-year period. The future precipitation for 2050 and 2100 are also based on 50-year periods as estimated by the GCM models. For estimating the increase in precipitation, the future precipitation projections based on the GCM models are compared to the model estimates of precipitation for the historical 1950-99 period, not the observed data. Comparison of model estimates for the observed and future periods provides a more reasonable approach for estimating the increase in precipitation.

The application of the methodology included:

- Estimate the existing depth of the 1-percent chance flood in the main channel at selected locations along the channel. Judgment is required in deciding how many locations (see **Figure 6** for sample),
- Determine impervious area (IA per formulas provided in previous section) from the ICLUS data for 2050 and 2100 for scenario A2 for which land use change is assumed to be similar to RCP 8.5,
- Determine Pmeanrain from the DCHP web site for each grid in the watershed area above the point of interest for RCP 8.5 for the three GCMs noted above,
- Apply Equation 4 for estimates of Pmeanrain for 2050 and 2100 for the three GCMs for RCP 8.5 (Pmeanrain estimated from projected values for 2000 to 2049 to get 2050 conditions, Pmeanrain estimated from projected values for 2050 to 2099 to get 2100 conditions),
- Use the average ratio for the three GCMs from Equation 4 for each time period (2050 and 2100) to adjust the existing depth to get the future depth of the 1-percent chance flood,
- Use the future depth to define a revised flood elevation and floodplain boundary, and
- Determine the additional miles of roadway/bridges that are vulnerable to flooding from climate and land use change.

Figure 6: Sample depth calculations in Lycoming County

Methodology for Assessing Impacts of Sea-Level Rise

Background

This section summarizes available sea level rise projections and provides recommendations for the most appropriate projections for use in PennDOT's Extreme Weather Vulnerability Study. The study seeks to identify potential vulnerability of PennDOT infrastructure to both coastal and riverine flooding in the present day and in the future. For the coastal vulnerability analysis, this includes the incorporation of sea level changes along the tidal Delaware River over time. Using the best available climate science on sea level rise is an important component of this assessment.

Sea level rise projections recommended for this study are described in terms of local sea level change. Local sea level is the height of the sea with respect to a specific point on land (Parris et al., 2012). It is caused by the combination of eustatic (i.e., global) and isostatic (i.e., local) sea level effects. Eustatic effects refers to alterations in global sea level due to changes in the volume of water in ocean basins through processes such as thermal expansion, glacial melt, etc., or net changes in the size of ocean basins. Isostatic sea level effects refers to local changes in vertical land movement. **Figure 7** illustrates various processes that contribute to local sea level change.

Most of the observed climate-related rise in global mean sea level over the past century can be attributed to thermal expansion. However, loss of land-based ice has surpassed thermal expansion in recent decades and is expected to be the largest component of global sea level rise during the 21st century (Church et. al., 2011).

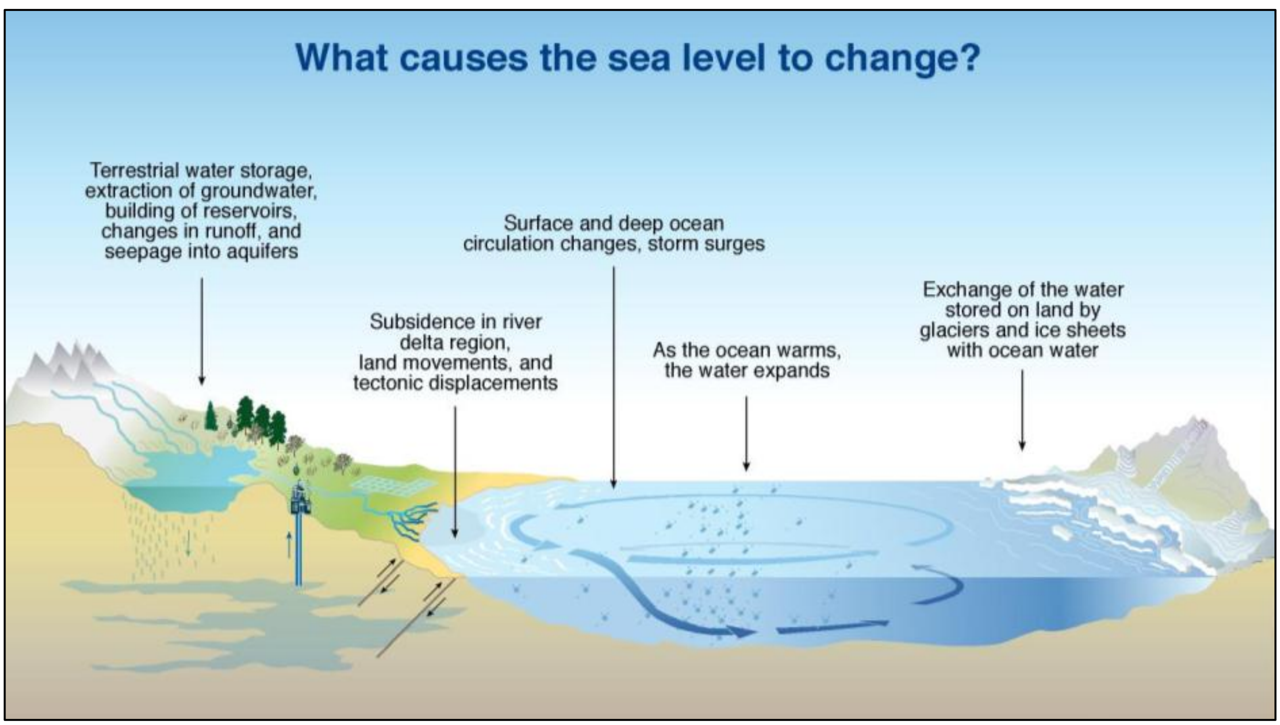

Figure 7: Graphic illustration of contributing factors to eustatic and isostatic sea level change (IPCC, 2001)

Literature Review

Pennsylvania is subject to coastal flooding along the tidally influenced portion of the Delaware River. Since this area experiences coastal flooding, it is also vulnerable to sea level change impacts. At present, Pennsylvania has no existing guidance on sea level rise recommendations for planning or engineering use.

A literature review of the best available climate science on sea level rise was conducted in order to determine the sea level values to use in the PennDOT Extreme Weather Vulnerability Study. This comprehensive review looked at global sea level rise guidance from the Intergovernmental Panel on Climate Change (IPCC), the National Oceanic and Atmospheric Administration (NOAA), the Federal Highway Administration (FHWA), and the Unites States Army Corps of Engineers (USACE).

In addition to these global sea level rise references, local sea level rise guidance from neighboring Mid-Atlantic states Maryland and Delaware and historical tide gage records from Philadelphia, Pennsylvania were also investigated as part of this literature review. A summary of sea level rise guidance from each source is included below.

Global Sea Level Rise Guidance

IPCC: Guidance from the IPCC 4th Assessment predicts global sea level rise will be between 0.2 m and 1.5 m by the year 2100 (IPCC, 2007). In the most recent IPCC publication, the 5th Assessment, this range was narrowed to between 0.3 m and 1.0 m by the year 2100 (IPCC, 2013). These estimates are based on general circulation model (GCM) ensemble outputs for the 21st century.

NOAA: In 2012, NOAA released the *Global Sea Level Rise Scenarios for the United States National Climate Assessment* report (Parris et al., 2012). Based on the IPCC 4th Assessment GCMs, this report recommends four distinct global sea level rise scenarios for decisions makers such as planners and engineers to choose from. These four scenarios and their recommended applications are presented in **Table *22*** below.

Table 2: Summary of NOAA global sea level rise scenarios

Scenario	Sea Leve Rise at 2100 (m)	Application
Highest	2.0	Little tolerance for risk such as new infrastructure with a long life cycle.
Intermediate-High	1.2	Assess risk from limited ice sheet loss.
Intermediate-Low	0.5	Assess risk from primarily ocean warming.
Lowest	0.2	Great tolerance for risk (scenario is based on historical rates of global sea level rise).

FHWA: The FHWA published a study in 2013 addressing the impacts of climate change on transportation systems and infrastructure along the Gulf Coast, including the impacts of global sea level rise (FHWA, 2013). This study chose three global sea level rise scenarios to assess vulnerability of federal highways: 0.3 m, 0.75 m, and 2.0 m by the year 2100. These scenarios were chosen based on an extensive literature review, including review of the other sources addressed in this memo.

USACE: The USACE developed sea level rise recommendations in 2013 in the report *Sea-Level Procedures to Evaluate Sea Level Change: Impacts,* *Responses, and Adaptation* (USACE, 2014). In the report, global sea level rise estimates are based on recent research and literature review. The range of values the USACE recommends are 0.2 m to 1.5 m by the year 2100. Specific recommended scenarios are not included in the USACE report.

Local Sea Level Rise Guidance

Local sea level rise values incorporate the effects of both global and local sea level rise forcings. Therefore the values for local sea level rise published in the following sources of sea level rise guidance are a combination of both global and local effects.

Maryland: The State of Maryland report, *Updating Maryland's Sea-Level Rise Projections*, gives global and local sea level rise estimates out to the year 2100 (Boesch et al., 2013). For 2100, the Maryland guidance predicts local sea level rise will be between 0.7 m (low scenario) and 1.7 m (high scenario). The Maryland guidance also gives a best estimate scenario of 1.1 m by 2100.

Delaware: Local sea level rise guidance for the State of Delaware is available through the report *Preparing for Tomorrow's High Tide: Sea Level Rise Vulnerability Assessment for the State of Delaware* (DNREC, 2012). This report gives local sea level rise recommendations for four local sea level rise scenarios. The estimates of local sea level rise for each scenario by the year 2100 are stable (0.3 m), low (0.5 m), intermediate (1.0 m), and high (1.5 m).

Philadelphia Tide Gage: The historical linear local sea level trend for the Philadelphia, Pennsylvania tide gage (NOAA Station #8545240) is available through the NOAA Sea Level Trends website (NOAA, 2016). The historical rate of sea level rise at the Philadelphia tide gage is 2.9 millimeters per year (mm/yr). This historical rate of local sea level rise can be used as a minimum estimate when predicting future local sea level because the historical rate assumes that there will be no acceleration in sea level rise in the future. The historical local sea level rise rate can also be used to determine local vertical land movement, which can be combined with global sea level rise projections to predict local sea level rise values that include acceleration in sea level rise rates.

Sea-Level Rise Analysis Scenarios

Based on the available climate science and recommended global and local sea level rise projections guidance, two scenarios were used for evaluating sea level rise impacts in the PennDOT Extreme Weather Vulnerability Study. The two recommended local sea level rise scenarios are based on global sea level rise projections that are adjusted to incorporate local isostatic sea level effects due to vertical land movement. The following sections describe the each of these components, with the final local sea level rise estimates presented in **Table 55**.

Global Sea Level Rise

Global sea level rise scenarios recommended for the PennDOT study come from two of the sources mentioned in the Sea Level Rise Literature Review section. One scenario is the NOAA Highest scenario (Parris et al., 2012) and the other scenario is the IPCC 2013 upper sea level rise estimate (IPCC, 2013). Both sea level rise scenarios will be evaluated for the years 2050 and 2100. **Table *3*:3** below outlines the recommended global sea level rise values:

Table 3: Global Sea Level Rise Values

Scenario	Sea Level Rise by 2050 (m)*	Sea level rise by 2100 (m)	Reference Year
NOAA Highest	0.6	2.0	1992
IPCC 2013 Upper Estimate	0.3	1.0	1986-2005 Mean

**2050 sea level rise values were interpolated based on graph data from each source*

The NOAA Highest scenario was chosen for the PennDOT project for the following reasons:

1. The NOAA study focuses on global sea level rise impacts specific to coastlines of the United States.
2. The NOAA "Highest" scenario sea level rise values fall within the range of values encompassed by all other studies mentioned in the literature review and are a conservative estimate within that range.
3. The NOAA Highest scenario is in line with the most conservative global sea level rise estimate from the FHWA. The FHWA study, a risk assessment for federal highways, is an example of climate change planning for another transportation organization with similar concerns and needs as PennDOT.
4. The NOAA study was written for engineers and planners and includes sea level rise scenarios that are relevant to planning projects. The Highest scenario was intended for use in planning for little tolerance for risk, such as infrastructure with a long lifetime. Roads and bridges are considered to fall within this category.

The IPCC 2013 Upper Estimate was chosen as a second global sea level rise scenario for the PennDOT project for the following reasons:

1. The IPCC 2013 Upper Estimate falls between the NOAA study's Intermediate-High and Intermediate-Low scenarios so it is a reasonable mid-range estimate based on the NOAA study recommendations when only choosing two scenarios.
2. The IPCC 2013 Upper Estimate is the most conservative sea level rise projection within the IPCC study and is therefore applicable to critical infrastructure such as roads and bridges.
3. The IPCC 2013 Upper Estimate value is also within the range of the USACE 2013 guidance on global sea level rise by 2100.

Local Sea Level Rise

To quantify local sea level rise in the region associated with vertical land movement, use of local tide gage historical sea level trend data is recommended. The Philadelphia tide gage sea level trend is a record of historical local sea level rise along the tidal Delaware River and is therefore a more accurate prediction of sea level rise for this project than a regional recommendation from Maryland or Delaware guidance.

The historic mean rate of sea level rise at the Philadelphia tide station is 2.9 mm/yr, as discussed in the Sea Level Rise Literature Review section. This compares with a global historical sea level rise rate of 1.7 mm/yr (IPCC, 2007).

Local sea level rise through the year 2100 is not expected to increase linearly, but rather as a rate that may accelerate through time. To determine local sea level rise at a given year in the future, Equation 1, originally developed by the National Research Council (NRC) Marine Board (1987), can be used:

Equation (1)

$$E(t) = \left(0.0017 + \left(\frac{M}{1000}\right)\right) t + bt^2$$

Where,

E = total local sea level rise (in meters).
0.0017 is the historical rate of sea level rise in m/yr (IPCC, 2007).
t = time (in years) since reference year.
M = vertical land movement (in mm/yr), where positive values of *M* are for decreasing land elevation.
b = coefficient whose value is chosen to satisfy the requirement that *E* equals the correct global sea level rise value at some time (*t*).

For the purposes of this study, using the Philadelphia tide gage sea level trends *M* = historic local sea level rise (2.9 mm/yr) minus historic global sea level rise (1.7 mm/yr).

Values for *t* depend on the reference year, which is 1992 for the NOAA scenario and 1995.5 for the IPCC scenario (midpoint between 1986 and 2005 range).

A sample calculation for coefficient *b* for the NOAA scenario is shown in Error! Reference source not found.**4**.

Once *b* is determined, the local sea level rise rate can be found for each scenario at each time horizon. **Table 5** gives the local sea level rise values, *E*(*t*), for coastal Pennsylvania on the tidal Delaware River for the years 2050 and 2100.

The sea level rise values shown in **Table 5** incorporate the effects of both global and local sea level rise forcings. These are the recommended sea level rise values for use in the coastal analysis and mapping for the PennDOT Extreme Weather Vulnerability Study.

Table 4: Example of calculation to determine coefficient b

$E(t) = (0.0017 + (M/1000))t + bt^2$
ASSUMPTIONS: • 2100 global sea level rise = +2.0 m above 1992 sea level, t = 108 years • 0.0017 m/yr = historical rate of global sea level rise at 1992 • Vertical land movement (M) = 0 mm/yr, therefore E(t) = 2.0 meters
$E(t) = (0.0017\ m/yr)t + bt^2$
$2.0\ m = [(0.0017\ m/yr)*108\ yrs] + (b*(108\ yrs^2))$
$2.0\ m = 0.1836\ m + (11664\ yrs^2*b)$
$1.8164\ m = 11664\ yrs^2*b$
$b = 0.000156\ m/yrs^2$

Table 5. Local Sea Level Rise Values

Scenario	Sea Level Rise by 2050 (m)	Sea level rise by 2100 (m)
NOAA Highest	**0.7**	**2.1**
IPCC 2013 Upper Estimate	**0.4**	**1.1**

Sea-Level Summary

The content of this section is intended to provide an overview of the sea level rise assumptions used for the the PennDOT Extreme Weather Vulnerability Study.

The recommendations described above are consistent with the best available climate science sea level rise projections; however, modifications to the proposed approach can be made. Michael Baker looks forward to assisting PennDOT in incorporating sea level rise into the project and ultimately providing valuable information regarding the proper level of future coastal flood protection.

GIS Process to Estimate Transportation Vulnerabilities

Based on the estimated flood depths described in the previous sections, state roadway and bridge vulnerabilities were identified in the three pilot counties: Allegheny, Delaware, and Lycoming. Vulnerabilities are defined as any roadway or bridge that is projected to be inundated by water due to inland flooding or sea-level rise. The flooding vulnerabilities were determined for three different scenarios as shown in **Table 6**.

Table 6. Flooding Vulnerability Scenarios

Scenario	Description
Existing 1% Floodplain	Utilizing existing FEMA 1% (e.g. 100-year) flood insurance rate maps
Forecast Scenario 1 Floodplain	FEMA 1% floodplain increased based on projected climate change impacts on precipitation through 2050
Forecast Scenario 2 Floodplain	FEMA 1% floodplain increased based on projected climate change impacts on precipitation through 2100

Although separate forecast analyses were conducted for precipitation increases to 2050 and 2100, the forecast mapping has primarily relied on the second scenario through 2100 as it represents the most conservative estimate. **Table 7** provides the key data sources used for the vulnerability analyses.

Table 7. Data Sources

Data	Source
3.2 ft Digital Elevation Model (DEM)	PASDA* open data website: http://www.pasda.psu.edu/uci/SearchResults.aspx?Keyword=lidar+dem (Allegheny, Delaware, Lycoming [2006-2008])
Flood Hazard Areas (*including Base Flood Elevations and Cross Sections*)	National Flood Hazard Layer http://www.pasda.psu.edu/uci/SearchResults.aspx?Keyword=DFIRM
Roadway Data	2016 Roadway Management System (RMS) http://data.pennshare.opendata.arcgis.com/datasets?q=Roadway
Bridge Data	2016 Bridge Management System (BMS) http://data.pennshare.opendata.arcgis.com/datasets?q=bridge

Existing Conditions Methodology

WSEL and Depth Grid Creation

Water Surface Elevation (WSEL) Grids and Depth Grids were created for each county using the latest available FEMA Flood Insurance Rate Map GIS data. For Allegheny and Lycoming Counties the National Flood Hazard Layer (Effective) was used. For Delaware County, the National Flood Hazard Layer (Effective) was used in combination with Preliminary riverine analysis data for the Brandywine-Christina watershed, Preliminary riverine analysis data for the Chester Creek Levee de-accreditation, and Preliminary coastal analysis for the Delaware River. A custom ArcGIS tool was developed to produce the WSEL and Depth grids. For the riverine areas, the WSEL grids were developed using Inverse Distance Weighting (IDW) interpolation of the latest water surface elevation data in the cross section (S_XS) and base flood elevation (S_BFE) layers for detailed flood zone areas (i.e. Zone AE, see **Table 8**), and IDW interpolation of the floodplain boundary elevations for the approximate flood zone areas (i.e. Zone A, see **Table 8**). For the coastal areas, the static Base Flood Elevation (BFE) was translated directly into the WSEL. The Depth grids were developed from the WSEL grids and the ground surface digital elevation model (DEM) grids. Only 1% annual chance outputs were produced.

Table 8. FEMA Flood Zone Definitions

Flood Zone	Description
Zone AE	An area inundated by 1% annual chance flooding, for which BFEs have been determined.
Zone A	An area inundated by 1% annual chance flooding, for which no BFEs have been determined.

Bridge Vulnerability Analysis

A custom ArcGIS tool was developed to produce bridge and floodplain elevation data for all state bridges in each county that were within or near the exiting conditions 1% Special Flood Hazard Area (SFHA) data. Bridge point data for state bridges were based on available PennDOT data (BMS), and bridge centerlines were developed for all applicable bridge points that were within or near the 1% SFHA. Using the bridge centerlines, WSEL grids, depth grids, ground surface DEM, and the latest SFHA data, the custom ArcGIS tool calculates the average bridge elevation using the ground surface DEM elevations at the end points of the bridge centerlines. This approach accounted for the variability in the existence of the bridge surface being removed or not removed in the ground surface DEM. The tool also calculates the average WSEL for the bridge centerline using Zonal Statistics on the WSEL grid, extracts the maximum depth along the bridge centerline using the depth grid (In cases where the bridge is removed from the DEM, this value will actually be the water underneath the bridge, instead of on top), and calculates average water depth on the bridge by subtracting the average elevation from the average WSEL.

The tool produces a bridge point shapefile as an output. The following fields and attributes are included. All numeric fields are rounded to the nearest tenth of a foot (existing SFHA depths may be less than 0.05 feet in some areas and the result in the bridge point shapefile field may show 0.)

- Bridge ID – PennDOT Bridge ID that allows the bridge to be linked back to the original dataset
- AveBrElev – average bridge elevation along the bridge centerline in feet, NAVD88
- AveBrWSEL – average water surface elevation for the 1% annual chance flood along the bridge centerline in feet, NAVD88
- MaxBrDepth – maximum 1% annual chance flood depth as extracted from the depth grid, along the bridge centerline, in feet
- AveDthOnBr – average 1% annual chance flood depth along the bridge centerline, 0 indicates no flooding is estimated to occur on the bridge
- Notes – any applicable comments or notes, such as bridges in Zone As (see Limitations Section for more information on Zone As)
- AdjDthOnBr – (not populated) available for adjusting automated tool output data values.

Roadway Vulnerability Analysis

A custom ArcGIS tool was developed to produce floodplain elevation data for all state roadways in each county that were within the exiting conditions 1% Special Flood Hazard Area (SFHA) data. Data for state-owned roadways was assembled from PennDOT resources (RMS). The tool first removes sections of roadway that correspond to bridge centerlines using a 40 foot buffer around the bridge centerlines (these sections were already analyzed in bridge vulnerability analysis), then extracts the minimum, maximum, and average water depths along the remaining roadway segments using zonal statistics on the WSEL and depth grids. Individual roadway segments are defined using a combination of the PennDOT RMS roadway feature attributes (including county code, state route number, and segment number). This segment ID (ROAD_ID) can be used to link the output layer back to the original PennDOT dataset.

The tool produces a roadway segment shapefile as an output. The features in this shapefile are roadway segments within the SFHA that are inundated by water. Roadway segments within the SFHA that are not flooded are not included. The following fields and attributes are included. Note that some fields are rounded to the nearest tenth.

- Side_ind – Side of roadway indicator, 1 or 2. Extracted from the original roadway dataset. Divided highways will have 1 and 2 representing the N/S and E/W directions, undivided roadways are coded with a value of 1.
- ROAD_ID - PennDOT roadway ID that allows the road to be linked back to the original RMS dataset. ID is based on the [cty_code], [st_rt_no], and [seg_no] fields in the original RMS roadway dataset.
- ZoneField – For roadway sections that intersect two or more separate flooding areas. For each ZoneField layer ID, there is an analysis performed. One ROAD_ID can have multiple ZoneField IDs. This ID is unique and auto generated. It does not link back to S_FLD_HAZ_AR.
- MinDepth – minimum 1% annual chance flood depth as extracted from the depth grid, along the roadway segment, in feet
- MaxDepth - maximum 1% annual chance flood depth as extracted from the depth grid, along the roadway segment, in feet
- AveDepth - average 1% annual chance flood depth along the roadway segment in feet, NAVD88
- DthRange – range of 1% annual chance flood depths along the roadway segment in feet, this is the difference between MaxDepth and MinDepth
- Notes – any applicable comments or notes, such as bridges in Zone As (see Limitations Section for more information on Zone As)

Future Conditions Methodology

Three future condition hydrology models were run for the detailed riverine studies in each county. The average WSEL increase from the three models was applied to the existing conditions cross section layers to develop a future conditions cross sections layer that included water surface elevations for year 2050 and year 2100. The WSEL increase values in the cross sections were then applied to the existing condition BFE layer using a spatial join operation in ArcGIS based upon the "closest" cross section. This output was then modified to account for instances where the "closest" cross section was pulled from adjacent reaches rather than the closest cross section within its reach. This occurred mainly where cross sections were sparsely available along a reach and at confluences and backwater areas. The future BFE layer is also modified to capture static Zone AE areas (such as lakes and backwater ponding areas) and their future elevations. A custom ArcGIS tool was developed to produce future floodplain boundary polygons for years 2050 and 2100 using the future cross section layer and future base flood elevation layer, and temporary WSEL and depth grids. The temporary WSEL grids were produced through IDW interpolation of the future conditions WSEL data. The temporary depth grids were produced from the WSEL grids and ground surface DEM. The future 2050 and 2100 floodplain boundary layers were produced from the output temporary depth grids. The floodplain boundary layers were then modified manually to account for adjustments at confluences, floodplain limits, and hydraulically disconnected areas. Other than these edits, the floodplain boundary layers are raw output. No smoothing operators or filling techniques were used.

Allegheny County and Lycoming County contain riverine flooding. Delaware County contains riverine and coastal flooding. All three counties have riverine vulnerability analyses for the three scenarios provided in **Table 6**. The coastal analysis for Delaware County also included two sea level rise scenarios for each future scenario.

To create the coastal future condition WSELs, the sea level rise values for each scenario were added directly to the present day 1% annual chance Stillwater Elevation (SWEL) surface, from the 9/2/2015 Effective FEMA coastal study, using raster math. Since the SWEL surface was used for the coastal future conditions analysis, the effects of waves on the WSELs were not included in the future conditions mapping (see the limitations section below for details). This created temporary WSELs for each scenario that were used to create a coastal floodplain boundary by subtracting the topographic data from each WSEL using the Surface Difference tool in ArcGIS. Outputs from this tool are vector polygons that show areas above and below the flood elevation. The polygon below the flooding elevation that exhibits hydraulic connectivity with the Delaware River was isolated and smoothed to be used as the floodplain boundary. This was repeated for each of the four future year coastal scenarios.

In areas where riverine flooding meets coastal flooding, the coastal floodplain boundary extents were manually clipped at the inland location in which the coastal BFE matched the riverine BFE. This clipping location varied depending on the coastal scenario. Once the floodplain polygons were manually edited, they were used to clip the temporary WSELs. The clipped coastal WSELs were then merged in with the riverine WSELs to create combined riverine and coastal WSELs that included interpolations in the elevations between the riverine and coastal areas as needed to provide a seamless transition. The depth grids were created using raster math to subtract the topographic data from the WSELs.

To create the final WSELs and depth grids, the floodplain boundaries for both the coastal and riverine scenarios were then used to clip the WSELs and depth grids. The result was four WSELs and four depth grids, two for 2050 and two for 2100, in which the coastal differs for all four (due to the different sea level rise scenarios used) but the riverine is the same for both 2050 scenarios and both 2100 scenarios.

These grids were then used as input to the bridge analysis and roadway analysis tools (discussed in the Existing Conditions Methodology section) to create future conditions vulnerability outputs for the bridges and roadways. (Note that only detailed SFHA areas are included in the future conditions output).

Analysis Limitations

This section highlights limitations of the vulnerability analysis and supporting data.

LiDAR Data

LiDAR data that has been processed and converted to a “bare earth” DEM was readily available and used for this project. Part of what makes a DEM “bare earth” is the removal of trees, buildings, bridges and other infrastructure not part of the ground. This was the case with the DEMs used for Allegheny, Delaware, and Lycoming counties. Large bridges were removed from the DEM preventing extraction of an exact elevation value for the bridge and leading to the development of an automated estimated elevation calculation which is detailed in the methodology section above. When LiDAR is collected the “Last Returns” of the dataset can be also be processed into its own raster grid. The Last Returns are tops of buildings, bridges, and trees. Last Returns were not readily available for this project, but for a more accurate analysis, they can be added as an input dataset to the analysis.

Accuracy of Data

In some instances the bridge points based on available PennDOT data were not spatially located on the bridge. While digitizing the bridge centerlines, in areas of multiple bridges, it was unclear what point corresponded to what bridge. Best assumptions were made in preparing this data for the analysis, however, it is possible inaccuracies may exist within the Bridge IDs.

Anomalies were also found within the roadway dataset. Small, isolated, roadway segments that corresponded to bridge locations were found, however, some of these locations did not have a bridge point in the bridge dataset. This was observed in Delaware County and may be present in Allegheny and Lycoming as well. At this time these segments were left as is. As a result, they may be present in the output roadway dataset and appear as inundated even though they may not be.

Local inaccuracies may exist in the WSEL and depth grids. Their creation is automated using best available FEMA FIRM GIS data inputs. This is a higher level analysis so local inaccuracies in the overall results may be present.

The future conditions WSEL grid datasets are developed from the detailed future conditions cross section and base flood elevation data. The existing conditions WSEL grid datasets are developed from the detailed cross section and base flood elevation data as well as approximate floodplain elevation data extracted from the ground surface DEM along the boundaries of the approximate floodplains. This additional elevation data being used as water surface elevation data in the development of the WSEL grids results in a differences between the Existing Conditions WSEL grids and the Future Conditions WSEL grids around confluences where the Zone A areas meet the detailed reaches. These differences will also result in differences between Existing Conditions and Future Conditions vulnerability results in the bridge and roadway data. Anomalies in the vulnerability results in these areas should be expected.

Stream Profiles

Bridges can be included on detailed stream profiles located in the Flood Insurance Study (FIS) report. In instances where bridges are shown on the profile, one can ascertain whether each flood event shown on the profile overtops the bridge or not. Due to the manual nature of such a review, bridge profile determinations are not included in the analysis and output for this project. In most cases, the automated results will match the profile determination, however in certain instances where the WSEL is very close to the bridge deck, the automated results may not match the profile due to the way the automated tool averages values. For a more refined analysis, this can be a recommended task.

Zone A

The results for bridges and roadways in Zone A areas should be interpreted cautiously. Zone A areas are approximate 1% annual chance flood zones without any published elevation information. Newer Zone A areas are required to have model-backed cross section elevations available, however many of the Zone As in the pilot counties did not have this information. These Zone As are older, sometimes delineated decades ago on topography that was much coarser than the LiDAR-based topography available today. The GIS tools developed for this project were able to estimate water surface elevations and water depths for Zone A areas, but these are ***only*** estimates. In order to easily identify bridges and roadways in Zone A areas, a "Notes" field has been added to the GIS deliverables and "Zone A" included in that field where applicable.

Future Conditions WSEL and Depth Grids in Zone A Areas

Future conditions hydrology models were only run for the detailed riverine and coastal studies in each county. Zone As are not included due to lack of available model information.

Future Conditions WSEL and Depth Grids in Accredited Levee Areas

Lycoming County has several levee systems that are currently shown as accredited in the NFHL. Levee freeboard analysis was not performed using the future conditions estimates as part of this project. As such, bridges and roadways within the current levee "protected areas" continue to be shown as free of flooding in the 2050 and 2100 results, even though they may actually be at risk due to future conditions flooding.

Future Conditions Roadway Vulnerability Results

Vulnerable roadway segments produced in the 2050 and 2100 analyses may not match extents of the existing conditions roadway results and as such should not be compared in a 1:1 fashion. The roadway analysis is based upon a clip of the roadway segment within the floodplain. The 2050 and 2100 floodplains will be larger in most areas. There will also be small areas within the floodplains that may have been smoothed or filled in for the existing FEMA 1% floodplain, but have not for the 2050 and 2100 floodplains. As a result vulnerable roadway segments may be a larger or smaller geographical extent for 2050 and 2100 compared to the existing conditions results. The minimum, maximum, and average flood depth along these segments of roadway may be different and in some cases lower than the existing conditions results.

Coastal Wave Action

The present day coastal analysis for Delaware County used FEMA 9/2/2015 Effective mapping and associated BFEs for the bridge and roadway vulnerability analysis. The BFEs in the mapping include the impacts of waves on the WSEL. The future conditions coastal approach however, did not address wave impacts.

The future conditions mapping incorporated sea level rise on top of the present day 1% SWEL surface and did not include additional wave modeling to incorporate the effects of future conditions waves. Wave action along the Delaware River in Delaware County is minimal and predominantly concentrated as “runup” along the developed shoreline. Because of this, waves generally do not impact bridges or roadways in the county as much as elevated waters due to storm surge, which is included in the 1% SWEL.

Since waves are not included in the future conditions analysis, WSELs in some areas may be higher in the present day mapping than in the future conditions mapping, even though the future conditions mapping includes sea level rise.

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