Appendix C
Sources and Recommended Framework for Hydrologic and Hydraulic (H&H) Modeling

Memorandum

To: Jennifer Fogliano, Jeff Perlman | North Jersey Transportation Planning Authority (NJTPA)

From: Derek Etkin PE, Melissa Harclerode PhD, BCES (CDM Smith)

Date: March 5, 2018

Re: Tasks 1 and 2 Technical Memo for NJTPA Passaic River Basin Climate Resilience Plan: Sources and Recommended Framework for Hydrologic and Hydraulic (H&H) Modeling

Purpose

This memorandum describes the limited existing hydrologic and hydraulic (H&H) information that is available within the Passaic River Watershed study area, which can be used to both: (1) evaluate the existing flood risks, and (2) be modified to approximate flood risks associated with future precipitation and storm surge scenarios developed under Task 2 of this project. In addition, this memorandum presents a recommended methodology framework for evaluating the potential flood risk of transportation assets from selected storm events based on each asset's proximity to the best available H&H data set within the study area.

As an overview, there are no State-wide detailed H&H model coverages available and the project team is making best use of the limited available data and models.

Hydrologic and Hydraulic (H&H) Modeling Basics

Computer modeling of hypothetical storm events allows engineers to provide planners and stakeholders with estimates of flooding depths and their associated probability for assets in a study area. What follows are some important terms used to describe modeling the hydrology and hydraulics (H&H) of a watershed.

- A "Storm Hyetograph" is a time series of rainfall intensity distributed over the duration of an observed or hypothetical storm event. The hyetograph describes the total amount of rain that falls during the storm, as well as how that rainfall is distributed within the event. Hyetographs can be generated from observed rainfall data for a storm that occurred, or generated from long-term statistical analysis to represent a particular recurrence interval (e.g. 25-year storm, 100-year storm). The units of a hyetograph are depth (inches), or intensity (inches/hour).

- “Riverine Discharge” refers to flow in a river which rises during and immediately following a storm event. Because it changes with time, riverine discharge can be represented by a time series known as a “hydrograph” with the commonly used units of cubic feet per second (cfs).
- The “peak discharge” is the highest discharge in a time series and nearly always corresponds to the highest flooding condition.
- “Hydrologic Runoff Analysis” refers to an estimate of the riverine discharge associated with a particular storm hyetograph. The “Runoff Model” represents the area of the contributing watershed and simulates the amount of rainfall that either (a) infiltrates into the soil or (b) “runs off” and accumulates in the rivers. The model is based on the physical characteristics of the watershed and is often calibrated based on observed data. The output of the model is a set of riverine discharge hydrographs. Often only the discharge from the hydrologic runoff analysis is reported.
- “Hydraulic Profile Model” refers to the detailed simulation of a stretch of river represented by cross sections. Detailed hydraulic models include bridges, culverts and dams which cross the river and reduce the conveyance of flow during floods. A hydraulic model takes discharges and calculates the associated flood profiles. These profiles can be used to make inundation maps
- “Reach Routing” refers to calculations within a large hydrologic model that represent the degree to which flood waters are stored in the floodplain of a river reach and retard the passage of the flood wave downstream. A variety of techniques for estimating routing may be used by a model.

Figure 1 shows a basic schematic of the H&H process for reference.

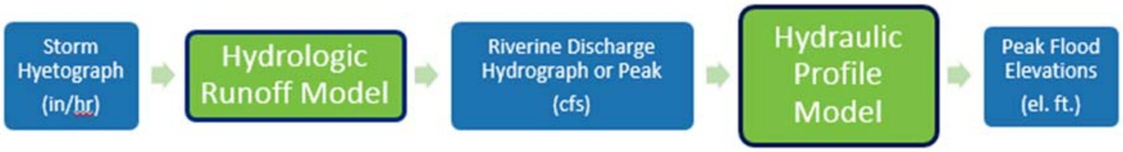

Figure 1. Schematic of H&H Modeling Process

2012 Passaic River Watershed Detailed Study

In December 2012, Risk Assessment Mapping and Planning Partners (RAMPP) presented the U.S. Federal Emergency Management Agency (FEMA) Region 2 with a *Hydrologic and Hydraulic Study* *of the Passaic River Watershed* [1]. The study supported the detailed flood hazard mapping of a 41.2-mile reach of the Passaic River, which replaced prior detailed study of the Passaic River from 1978. The peak flood profiles, comprised of 10-, 50-, 100-, and 500-year return period design storms, used to re-map the Passaic River were generated from a detailed hydraulic profile model built in HEC-RAS [2]. This is a small fraction of the total amount of stream reaches in the watershed study area (41 of 1,976 miles of streams in the National Hydrologic Database). Hydrologic runoff modeling of the contributing watershed built in HEC-HMS [3] was used to generate the peak discharge conditions input to the HEC-RAS hydraulic model.

Hydrologic Runoff Modeling

The 2012 study included hydrologic runoff modeling of the 937-square-mile Passaic River Watershed. A set of HEC-HMS runoff models were developed to simulate the discharges in major reaches of the Passaic River during a series of design storms (10-, 50-, 100-, and 500- year return periods).

HMS Runoff Subbasins

There are seven HEC-HMS models within the Passaic River Watershed, each representing a different basin (Upper Passaic, Whippany, Rockaway, Pompton, Central Passaic, Lower Passaic, and Saddle). **Figure 2** shows the subbasin boundaries that comprise the seven HMS models from the 2012 RAMPP study. Each subbasin simulates the runoff for a given rainfall hyetograph (i.e., a graphical representation of the distribution of precipitation over time) based on the physical characteristics of the basin which were calibrated from available gage data within the study area. The HMS models generate a runoff hydrograph (i.e., a graph showing the rate of discharge versus time past a specific point in a river) representing the storm event runoff at the outlet of each subbasin based on the runoff characteristics of the subbasin.

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1 FEMA Region II, Task Order HSFE02-09-J-0001 for Passaic River Watershed Hydrologic & Hydraulic Study, New Jersey. FEMA Contract No. HSFEHQ-09-D-0369. Prepared by RAMPP, a joint venture of Dewberry, URS, and ESP. December, 2012.

2 HEC-RAS is the commonly-used open channel flow modeling environment maintained by the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers (USACE). It is the mostly widely used hydraulic model for FEMA floodplain mapping.

3 HEC-HMS is the hydrologic runoff modeling environment maintained by the USACE HEC.

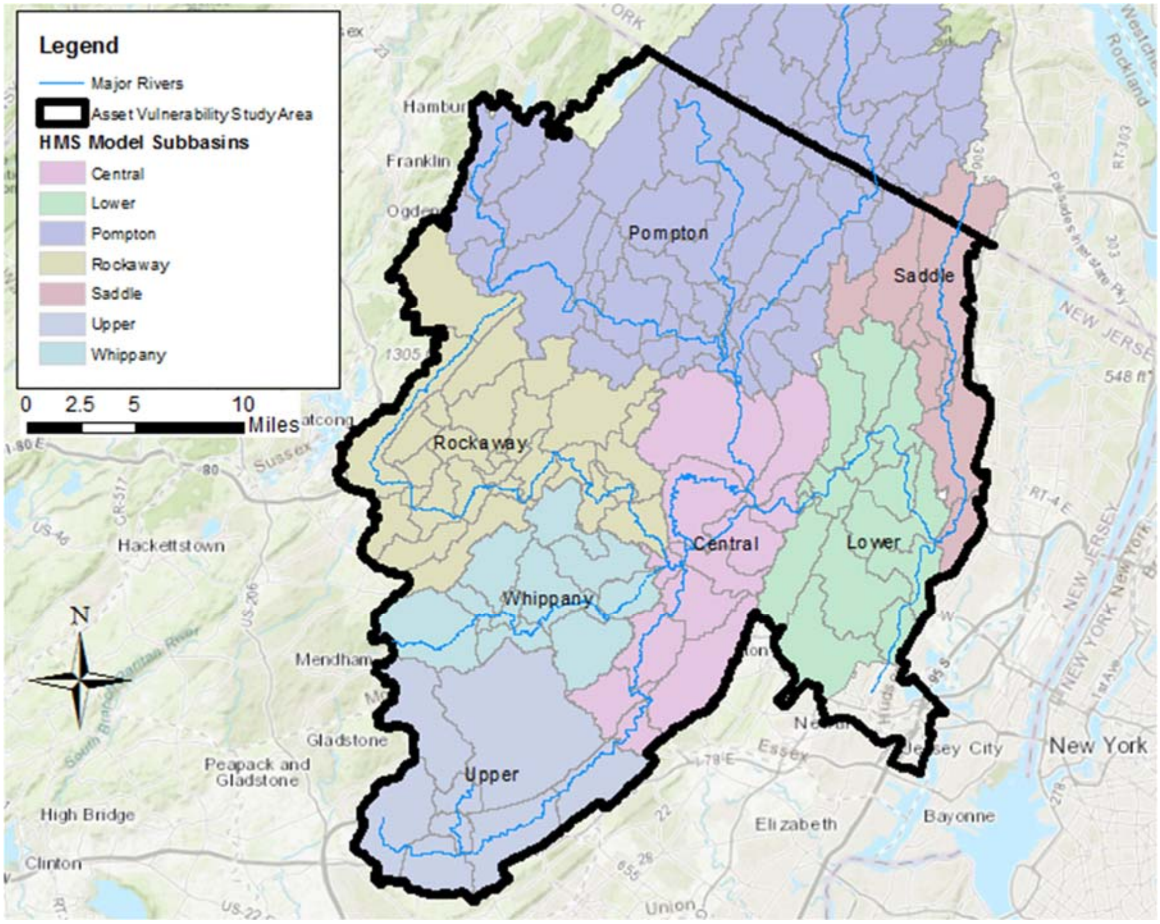

Figure 2. RAMPP 2012 Study HEC-HMS Subbasins

HMS Reach Routing

A network of Passaic River channel reaches in the HEC-HMS model, each representing a collection of large tributaries, combine and route the runoff hydrographs from the subbasins to predict changes in discharge as water moves through the river. Hydrograph routing in each channel reach is represented by one of two methods: (1) Muskingum-Cunge approach with a hydraulically-representative 8-point cross section, and (2) Modified-Puls approach with storage-discharge relationship derived from approximate HEC-RAS models. **Figure 3** shows the location of the 64 channel reaches, with the average length of each reach at just over 3 miles. For each storm simulation, the HMS model generates the discharge hydrograph at the upstream and downstream end of each channel reach, and a single stage hydrograph for the representative 8-point cross section.

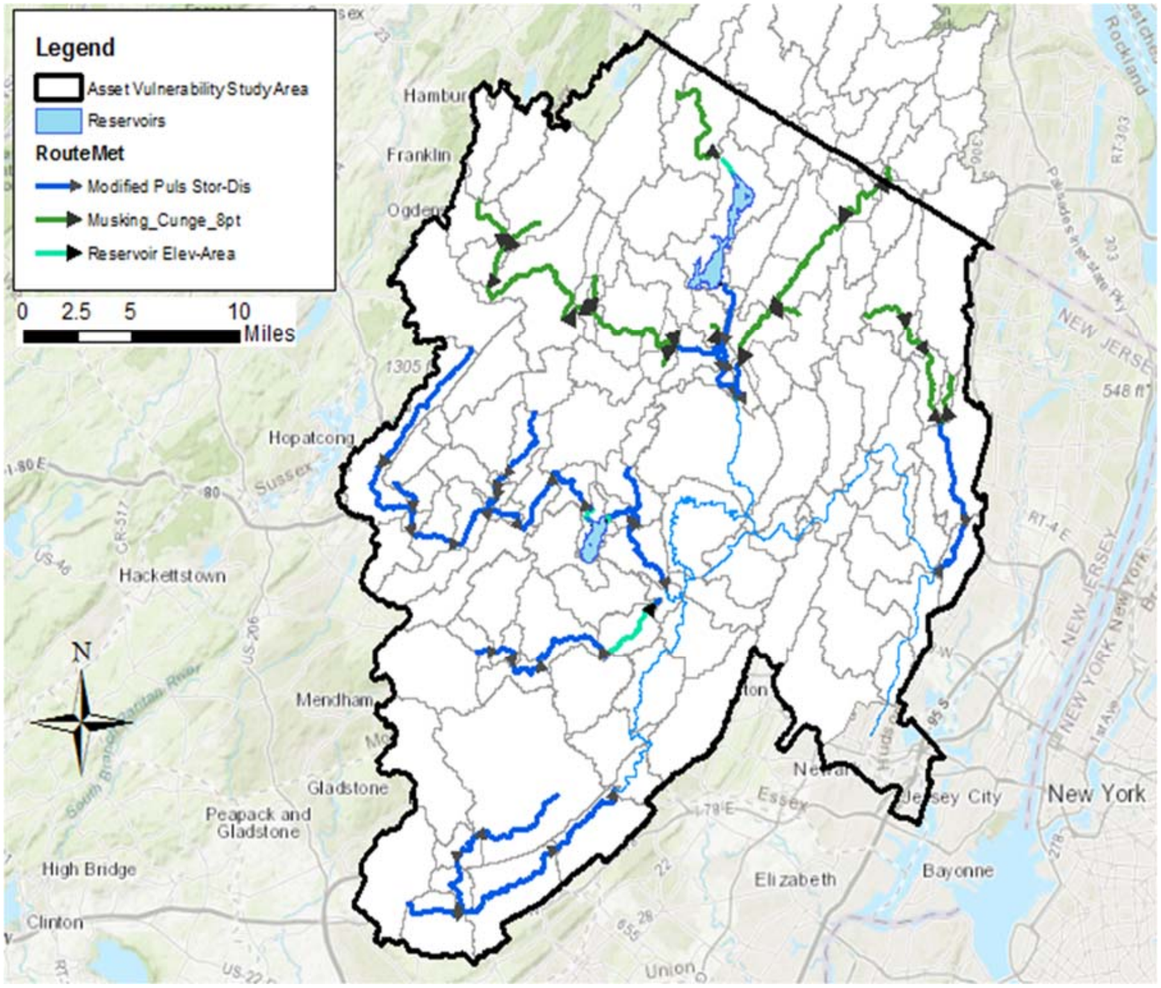

Figure 3. RAMPP 2012 Study – HEC-HMS Reaches

HMS Reservoirs

Additionally, the HMS models include three reservoirs (Boonton Reservoir, Wanaque Reservoir, and a flat reach of the Whippany River), where a stage-storage-discharge curve is used to represent routing within the watershed. These locations are also shown on **Figure 3**. For each storm simulation, the HMS model generates a stage hydrograph of the reservoir.

Storm Hyetographs

All the 10-, 50-, 100-, and 500-year average return period storm simulations are based on 4-day hyetographs. It is necessary to run a 4-day rainfall time series to allow for the time it takes for the runoff to be routed through the 937-square mile watershed and accumulate at the outlet. This process is also known as the “time of concentration” for a watershed, which RAMPP determined was approximately 4-days in their 2012 study. **Table 1** shows the partial duration depths for the associated 4-day hyetographs.

Table 1. Passaic River Watershed Detailed Study Partial-Duration Depths

Top Level	10-yr	50-yr	100-yr	500-yr
15 Minutes	1.1 in	1.3 in	1.4 in	1.5 in
1 Hour	2.0 in	2.5 in	2.8 in	3.4 in
2 Hours	2.5 in	3.3 in	3.7 in	4.7 in
3 Hours	2.8 in	3.7 in	4.2 in	5.3 in
6 Hours	3.6 in	5.0 in	5.6 in	7.3 in
12 Hours	4.6 in	6.4 in	7.4 in	9.9 in
1 Day	5.2 in	7.3 in	8.4 in	11.4 in
2 Day	6.0 in	8.4 in	9.6 in	12.8 in
4 Day	6.6 in	9.0 in	10.2 in	13.4 in

Acronyms: in = inches, yr = year

Alternative hyetographs, or adjusted versions of the effective hyetographs, could be used as input to the HMS models to generate associated discharges and elevations in the subbasin outlets, channel reach outlets, and reservoirs. To generate the discharges associated with a 25-year event, the partial-duration depths could be interpolated from the values in **Table 1** directly or based on the effective Atlas 14 depths from National Oceanic and Atmospheric Administration (NOAA), which include the 25-year recurrence interval[4].

To generate the discharges associated with a future climate scenario event, these partial-duration depths could be adjusted based on analysis of Global Climate Models which also analyzed 4-day precipitation magnitude values (inches) corresponding to a specific set of recurrence intervals and reflective of future (2045 and 2080) climate conditions (to be submitted under a separate cover).

Hydraulic Profile Modeling

The 2012 RAMPP study was performed to generate updated detailed hydraulic profiles for a 41.2-mile stretch of the Passaic River, which was represented by a detailed open channel flow model. The analysis was performed with two detailed HEC-RAS models: (1) a 23-mile long steady-state model of the Lower Passaic River, and (2) an 18-mile long unsteady-state model of the Central Passaic River. Inflows to the unsteady-state (Central Passaic River) model were based on the outlet hydrographs from the HEC-HMS models representing the contributing drainage areas. The flows in the steady state (Lower Passaic River) model represent the peak flow condition under the 10-, 50-, 100-, and 500-year floods, and were taken from the upstream

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4 Bonnin G. M. et al. (2006) "Precipitation-Frequency Atlas of the United States Volume 2 Version 3.0: Delaware, District of Columbia, Illinois, Indiana, Kentucky, Maryland, New Jersey, North Carolina, Ohio, Pennsylvania, South Carolina, Tennessee, Virginia, West Virginia." National Weather Service, National Oceanic and Atmospheric Administration. Silver Spring Maryland, revised 2006.

unsteady HEC-RAS model and the discharge hydrographs from the HEC-HMS models representing the directly contributing areas.

Figure 4 shows the linear extent of the detailed steady-state hydraulic modeling along the Lower Passaic River, the detailed unsteady hydraulic modeling along the Central Passaic River, and the four approximate unsteady models used for routing upstream contributions. These approximate unsteady routing models are not sufficiently detailed enough to generate flood elevation profiles.

All of the HEC-RAS models offer an opportunity to run alternative storm conditions to generate profiles for conditions such as a 25-year event or future climate scenarios. The alternative hyetograph would be serve as inputs to the HEC-HMS models to generate discharge hydrographs, which in turn would be serve as inputs into the HEC-RAS models to generate profiles along the rivers with HEC-RAS modeling shown in **Figure 4**.

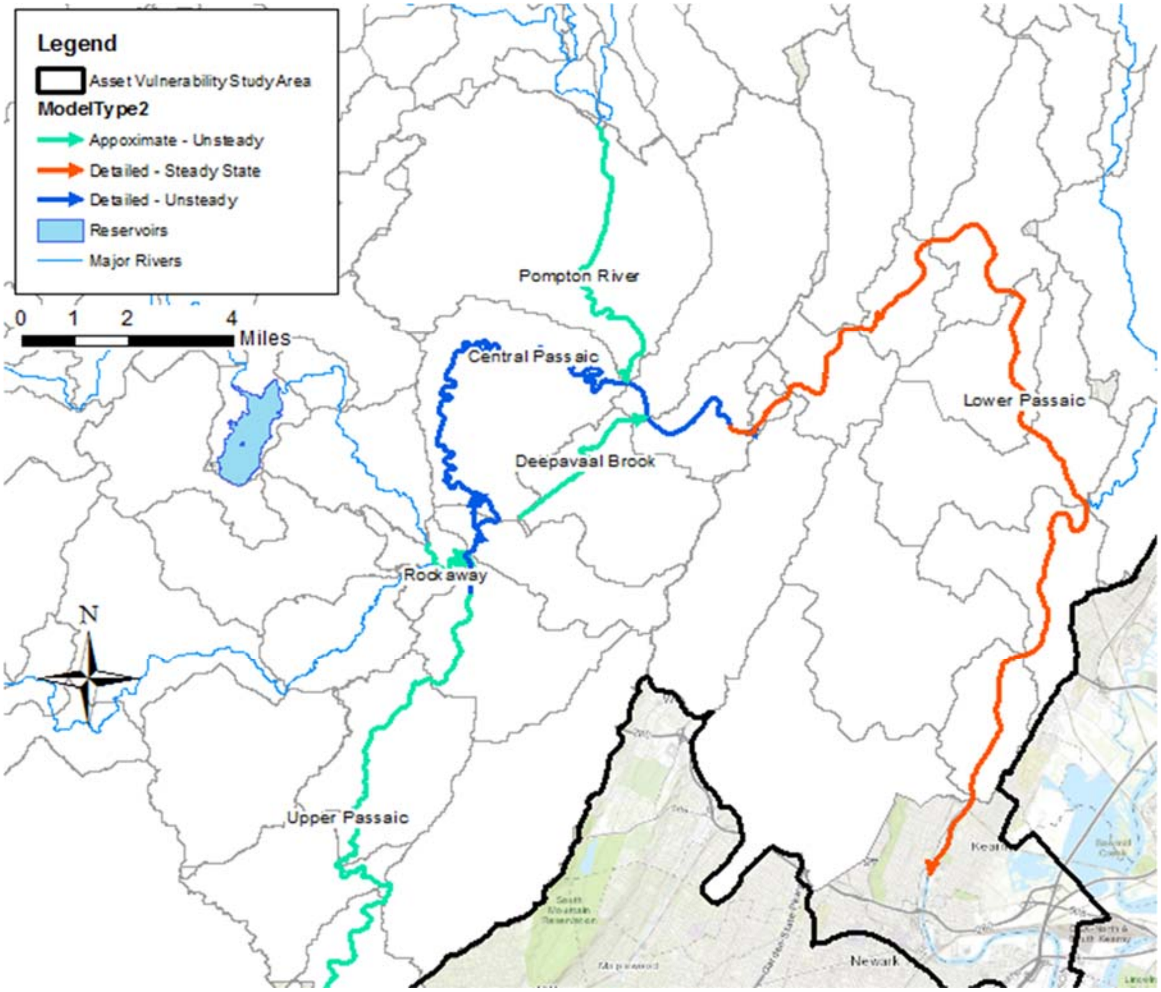

Figure 4. RAMPP 2012 Study – HEC-RAS Hydraulic Modeling Extents

Tidal Boundary Conditions

The boundary conditions for the Lower Passaic River are based on the effective FEMA stillwater elevations. Sea Level Rise (SLR) estimates may provide alternative boundary conditions to represent future climate scenarios. Running the steady-state Lower Passaic River model with alternative boundary conditions would provide an evaluation of the degree to which assets along the Lower Passaic River and nearby tributaries may be impacted.

Using 2012 Study for Flood Risk Analysis

The 2012 RAMPP study provides several options for evaluating the flood hazards facing transportation infrastructure in the NJTPA Passaic River Basin study area, by evaluating the detailed model results (discharges from HEC-HMS and peak flood profiles from HEC-RAS) from runs using (1) the effective storm hyetographs, and (2) new hyetographs representing new storms of interest.

Because the extents of the hydraulic modeling are limited to the roughly 41.2 miles of open channel HEC-RAS modeling, approximate methods must be used to extrapolate results from alternative runs of the 2012 HEC-RAS and HEC-HMS models to evaluate the hazards at sites outside of the floodplain of the detailed reaches.

Depending on the location of the assets of interest, there are a variety of ways in which the 2012 HEC-RAS and HEC-HMS models could be used to approximate flood hazards for existing and future climate conditions:

1. Assets located directly on the reaches with approximate and detailed HEC-RAS models from the 2012 study (including the Passaic River, Deepavaal Brook, portion of Pompton River, and portion of Rockaway River) containing existing and climate-adjusted profiles associated with their location; it would be necessary to generate flood elevation rasters (i.e., polygons) in RAS Mapper to get the specific elevations/depths at each location. Such a raster would require intersection with available LiDAR.
2. Assets located near the downstream tidal boundary condition of the Lower Passaic River model could have alternative profiles available representing future climate scenarios and associated sea level rise.
3. Assets located directly on either of the three HEC-HMS reservoirs (Wanaque Reservoir, Booton Reservoir, and lower reach of Whippany River) will have peak flood elevations associated with the existing and future climate scenario condition. This would not require running the hydraulic HEC-RAS models.
4. Assets located directly on modeled HEC-HMS reaches will have discharge hydrographs associated with existing and future climate scenario storm events. These can be used to conceptually approximate the flood depth and inundated area for potential impacts to transportation assets.

5. For assets located within subbasins (which includes all features in the study area), the HEC HMS could be used to estimate the relative increase in peak discharge for the nearest waterway. This approach assumes uniform runoff and routing characteristics within each subbasin, and that a linear drainage area ratio is sufficient for transposing discharge from the outlet to locations within the subbasin.

The recommended flood risk analysis approach is presented in the Methodology Framework: Relating Assets to Available H&H Data Section of this Memorandum.

Other Effective FEMA Study

FEMA also conducted an extensive, effective study within the study area in addition to the RAMPP study that was performed in 2012 for the Central and Lower Passaic River. The Region 2 2017 Coordinated Needs Management Strategy (CNMS) database documents 690 miles of detailed riverine study and 217 miles of approximate study. These analyses are documented in Flood Insurance Studies (FIS) spread across Sussex County, Passaic County, Morris County, Essex County, Somerset County, Union County, and Bergen County. **Figure 5** shows the detailed and approximate studies by channel reach location.

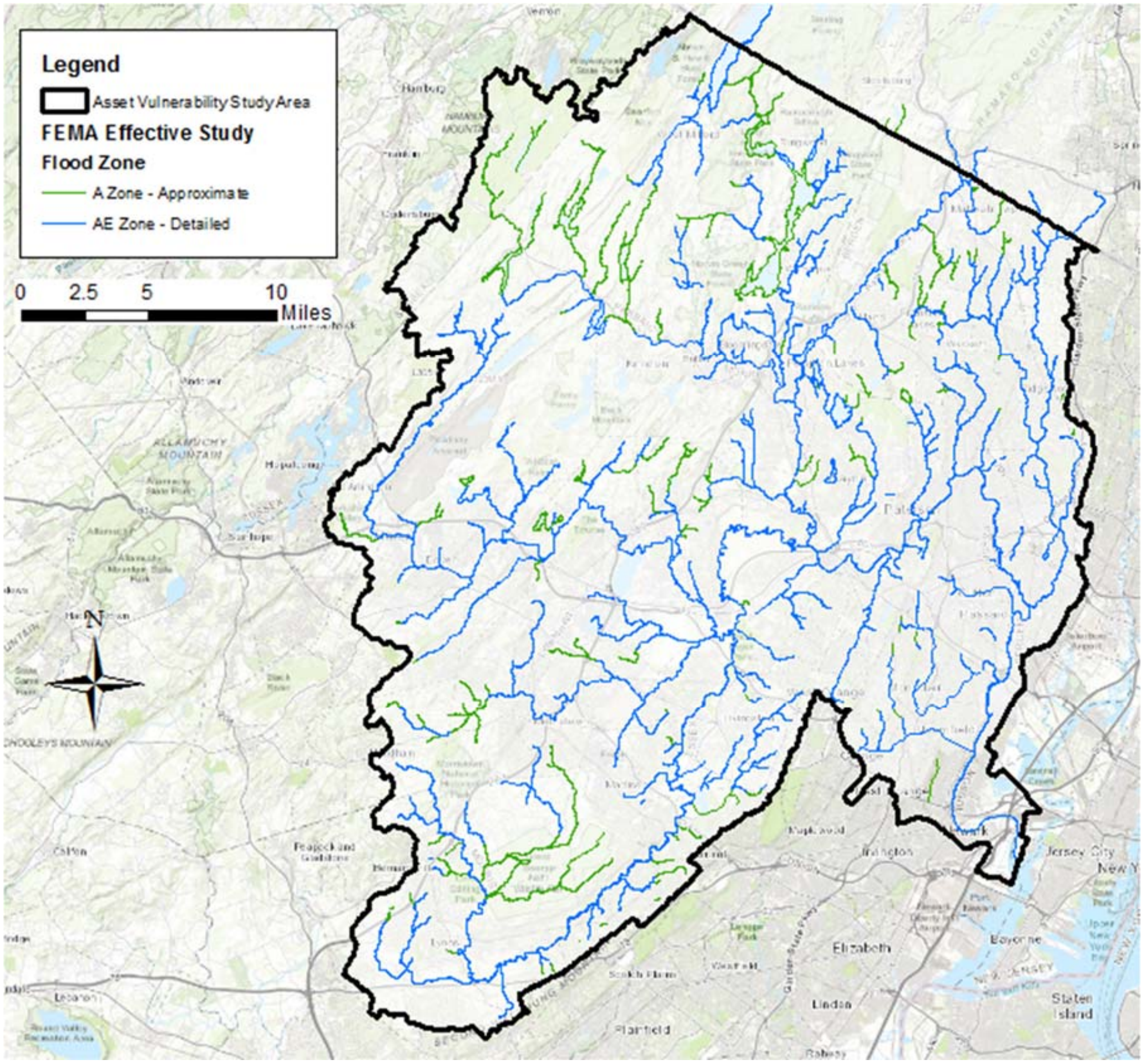

Figure 5. Effective Detailed and Approximate FEMA Studies

NFHL Geodatabase

The National Flood Hazard Layer (NFHL) geodatabase includes flood hazard areas depicting the 100-year flood extents for detailed ("AE Zone") and approximate ("A Zone") studies. The NFHL coverage also includes the location of "lettered" cross sections, which is subset of the cross-sections from the open channel analysis (HEC-RAS or HEC-2) used in detailed hydraulic study. Each cross-section feature in the geodatabase is associated with a 100-year base flood elevation (BFE). There is no information for the 25-year average return period recurrence interval in the NFHL spatial dataset.

Transportation assets near to these effective studies with spatial information could be evaluated directly with regard to the 100-year event. Evaluation could include whether or not the asset is within the 100-year flood extent. The hazard evaluation may make further use of the BFE information in the cross sections to establish an existing 100-year flood water surface elevation in the vicinity of the asset.

To understand the hydraulic conditions of storm events other than the 100-year recurrence interval, it would be necessary to use an additional source of information other than the NFHL cover. Furthermore, evaluating the flood hazards associated with future climate scenarios would require additional information, such as Flood Insurance Studies. It should be noted that the NFHL database for Morris County, New Jersey is preliminary at this time.

Flood Insurance Studies

Every detailed NFHL AE Zone study has a profile panel in the Flood Insurance Study (FIS) associated with the county or town in which the detailed study is documented. Profile panels typically include all four recurrence intervals required by FEMA (10-, 50-, 100-, and 500-year) with lettered cross-sections, corporate limits, bridge structures, and other features identified for reference.

At any location along the profile, an implicit rating curve can be interpolated from the four profile elevations and the associated discharges. This rating curve could be used to estimate a 25-year peak flood elevation given a 25-year peak discharge, derived from either an alternative run of the HEC-HMS runoff modeling using a 25-year hyetograph or an interpolated 25-year peak discharge. Similarly, it would be possibly to interpolate a flood elevation between the 100-year elevation and the 500-year elevation given a larger discharge associated with a future climate scenario HEC-HMS simulation.

While it is not feasible to extract rating curves for every asset of interest within the study area (there are 1560 bridges alone), selecting a representative sample from the available detailed studies in the area could inform hazard evaluation more broadly.

National Hydrologic Database

The National Hydrologic Database (NHD) includes spatial coverage of waterbodies and flowlines in the study area that are outside of the extents of detailed AE Zone and A Zone approximate FEMA studies. This spatial coverage can be used to identify assets which may be impacted by riverine flooding but would require some sort of extrapolation from the available modeling data. **Figure 6** shows the NHD coverage in the study area.

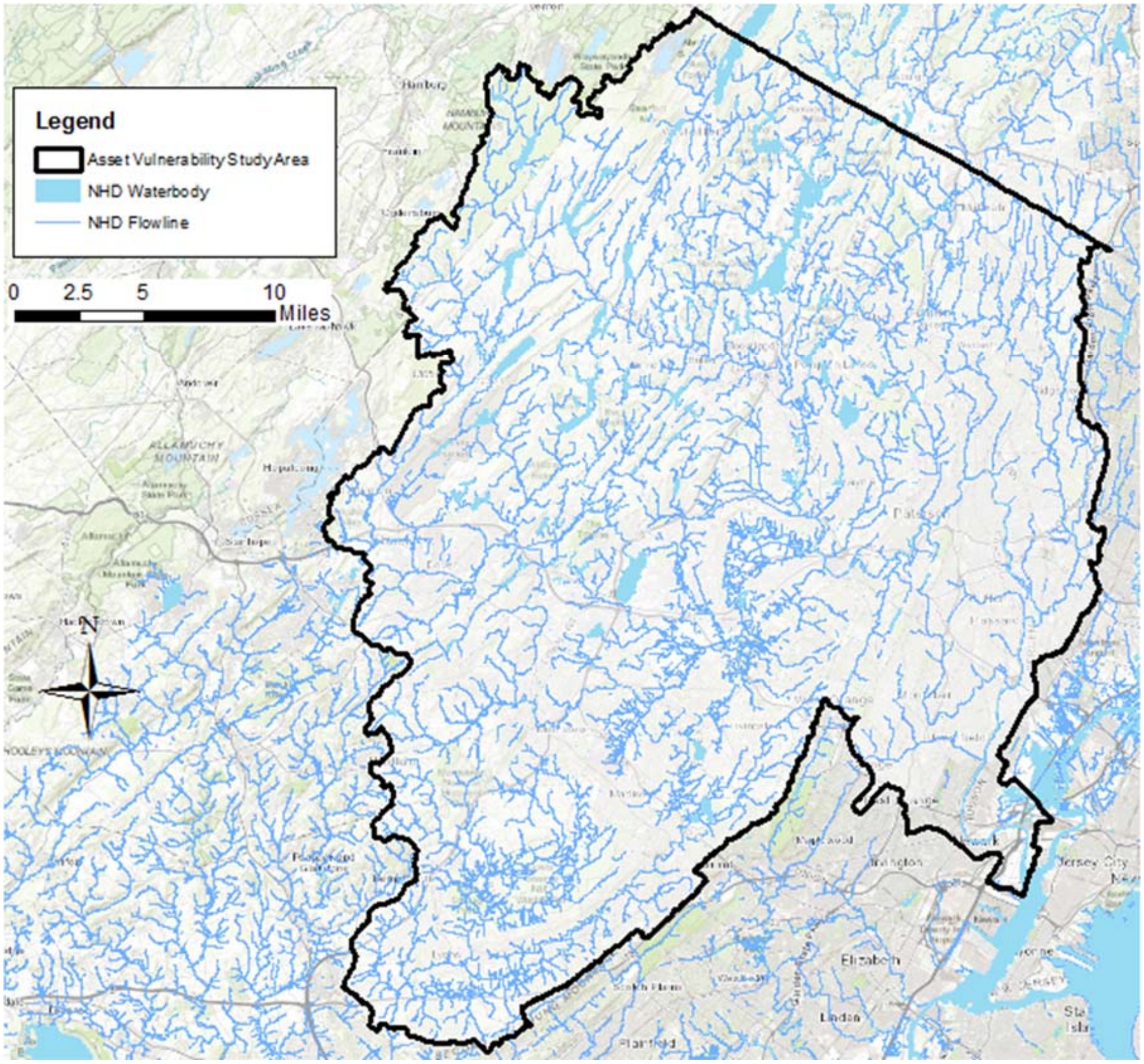

Figure 6. National Hydrologic Database (NHD) Coverage

Methodology Framework: Relating Assets to Available H&H Data

Because there is no single flood hazard model coverage that both (1) covers the entire 937-square-mile watershed study area and (2) can be easily updated with a future climate scenario, evaluating the potential flood risk will require associating each asset of interest to the closest available H&H modeling data set.

This section proposes four tiers in which any asset can be categorized in based on its proximity to H&H information described in the preceding sections. In turn, each tier is associated with a methodology for evaluating the impact of the existing and future climate change adjusted scenarios will have on the assets. **Table 2** describes the approach. The benefits of this approach are to maximize the number of assets that may be evaluated for flood risk based on the available information in the watershed, they may be summarized as:

- Tier 1 is composed of assets along the detailed hydraulic study of the Central and Lower Passaic River developed by RAMPP in 2012 will have the most detailed and comprehensive analysis. Each asset will be associated with a specific flood elevation for the existing and climate-adjusted scenarios.
- Tier 2 is a representative sample of assets for which there is a detailed effective FEMA study (over the past 40 years), but no readily accessible hydraulic model available that can be adjusted with future climate conditions. The hydraulic analysis will produce a set of estimate hydraulic impacts (increases in flood elevation) to generate a picture of flood hazards across the watershed in general. This approach links these focused areas to the detailed hydrologic runoff modeling from the 2012 RAMPP study that can be updated with future climate scenarios.
- Tier 3 are not near existing models and therefore cannot be evaluated.
- Tier 4 uses GIS methods (ArcHydro) to confirm that there is not a significant flooding hazard because there is only a very small contributing watershed.

Table 2. Tiered Approach to Characterizing Potential Flood Risk

	Asset Categories	Existing Flood Risk	Climate Change Adjusted Flood Risk
Tier 1	Assets within proximity of the effective detailed hydraulic study of the Central and Lower Passaic River (RAMPP, 2012) **Identification Method:** • Assets within buffer distance of stream centerline and/or effective AE Zone • Associate each asset with a river station	100 Year Existing • Generate a depth grid from the effective peak profile and LiDAR, and compare to asset elevations 25 Year Existing • Re-run HEC-HMS with 25-year hyetograph to generate peak discharges • Run HEC-RAS with 25-year discharges to generate depth grid	Climate Adjustment • Re-run HEC-HMS with climate-adjusted hyetographs to generate peak discharges for both 25- and 100-year events • Run HEC-RAS with updated year discharges to generate depth grid for future climate adjustment, and compare to asset elevations
Tier 2	Assets within proximity of the other 690 miles of effective detailed FEMA Study in the watershed study area **Identification Method:** • Assets within buffer distance of stream	Depth grids and detailed, spatial flood profile data is not available in the NHFL. An alternative approach is necessary to characterize the existing flood hazard • The AE Zone provides a horizontal extent for 100-year flooding	Running the set of HEC-HMS models with future climate-adjusted hyetographs provides a relative increase in the peak discharge at every HMS reach and subbasin • Associate the relative increase in the peak

	Asset Categories	Existing Flood Risk	Climate Change Adjusted Flood Risk
Tier 2 (con't)	centerline and/or effective AE Zone - Associate each asset with river station and studied reach - Associate each river station with a complete set of effective peak discharge (10-, 50-, 100-, and 500-yr) from the FIS. - Associate each river station with either an HMS reach or subbasin	- In some areas it may be possible to interpolate the water surface elevation or depth from the intersection of AE-Zone with LiDAR, cross-sections or Base Flood Elevation lines	flooding discharge for every Tier 2 asset - For a representative sample of river stations (~25-60) generate a rating curve from the effective discharge (10-, 50-, 100-, and 500-yr) and the associated flood elevation in the FIS profile panel - Estimate climate-adjustment increase in peak flood depth using rating curve and associated HMS discharge
Tier 3	Assets located on a stream not studied by FEMA. **Identification Method:** - Buffer from NHD flowline layer and outside of effective detailed study (Tier 2) - Alternatively, assets not falling under Tier 1, Tier 2, or Tier 4.	N/A	N/A
Tier 4	Assets not vulnerable to riverine flooding hazards **Identification Method:** - Assets with a contributing drainage area smaller than a determined minimum (calculated by ArcHydro for GIS) - Assets outside of a buffer distance from NHD Flowline coverage.	Not vulnerable.	Not vulnerable.

Criteria to Determine the Representative Sample Locations to Implement the Tier 2 Approach to Characterizing Potential Flood Risk

The approach for evaluating potential flood risk for assets assigned to Tiers 1, 3, and 4 is relatively straightforward and can be largely automated using tools developed by GIS-specialists on the project team. The methodology can be quickly applied to assets assigned to any of these three Tiers (1, 3, and 4).

However, evaluating the flood risk associated with assets that fall into the Tier 2 makes use of historical FEMA studies (shown in **Figure 5**) which are not digitized and requires someone from the modeling team to extract rating curve information from the effective profile in the FEMA FIS at each asset of interest. In the absence of digital information of these reaches from FEMA, this process can be time consuming and likely cannot be performed for all of the hundreds of NJTPA bridges and other assets in the study area.

In order to focus the effort and maximize value, CDM Smith proposes the following criteria to prioritize a representative sample of asset locations in the watershed:

1. Assets are *not* within the proximity of the effective detailed hydraulic study of the Central and Lower Passaic River, which would be considered under the Tier 1 approach.
2. The location must be identified impacted by the riverine flooding of one of the effective detailed studies shown Figure 5.
3. Strive for a sample that is geographically representative of the political boundaries of the stakeholders (counties, townships, population density).
4. Strive for a sample that geographically representative of the hydrologic boundaries (watersheds and subbasins) shown in Figure 2.
5. A range of transportation assets should fall within the sample areas, to ensure that the study is able to evaluate the flood risk across asset type. This will allow for a more comprehensive study of transportation asset vulnerability (and resilience) throughout the project.
6. Include areas that have been qualitatively identified by the TAC or county Hazard Mitigation Plans as areas of concern or at risk from flooding.

Some example locations that meet these criteria are:

- Crossings over the Pompton River that provide access between Morris and Passaic counties.
- Low points at Route 10 such as in Dover, Parsippany, Denville, and/or Randolph.
- Points of major highways or evacuation routes, such as Route 80.
- Rail stations or lines, such as the Ho-Ho-Kus station.
- NJTRANSIT bus garages such as the location in Wayne.

Figure 7 shows a draft set of potential Tier 1 and Tier 2 sites to evaluate identified from the feature class of NJTPA bridges.

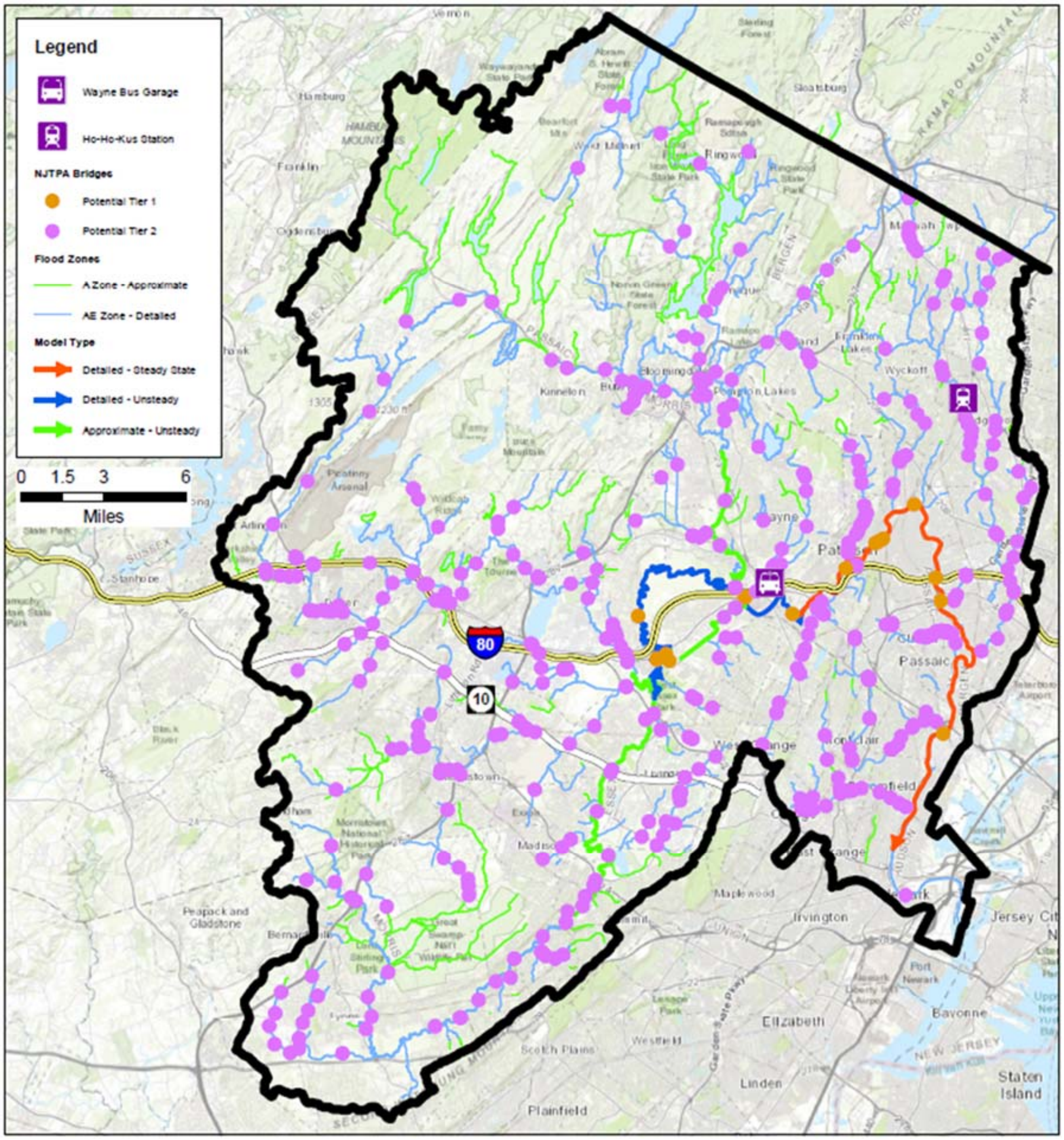

Figure 7. Example of Potential Tier 1 and Tier 2 Asset Locations

Sea Level Rise and Storm Surge Flood Risk

Assets categorized under Tier 1 will be evaluated for increased risk of riverine flooding from the Passaic River due to increased downstream tailwater associated with future climate sea level rise and storm surge. A new hydraulic profile associated with sea level rise will be generated using the HEC-RAS model, and a new depth grid will be generated for the Tier 1 assets.

Summary and Recommendations

The available H&H models and data are limited in their coverage and hydraulic representations for the purposes of this study: to determine the potential risks and vulnerabilities to transportation assets by rainfall design storms and tidal surge. Therefore, the project team has proposed a tiered method to use the limited models and data to approximate these impacts, and the project team will make recommendations for future modeling as needed to refine these estimates as may be required in the future.