January 30, 2024

To be sent via Email: PDPA-NAP@usace.army.mil

Re: Comments on U.S. Army Corps of Engineers Eastwick Flood Risk Management Study's Draft Integrated Feasibility Report and Environmental Assessment

To Whom It May Concern:

Our research project team is writing to provide research results and comments on the Draft Integrated Feasibility Report and Environmental Assessment. These are based upon our NOAA-funded research project *Compound Fluvial-Coastal Flood and Climate Adaptation: Engagement, Modeling and Adaptation Assessment*. Our research began in 2019 and has just concluded in last 2023, and while we have interacted frequently with members of the USACE Eastwick study team, results of our adaptation assessments are hot-off-the-press. Furthermore, we wish to provide a list of all our project's key results and a set of appendices laying out the details of our research.

In our project, we developed two hydrologic-coastal flood models (PCSWMM and HEC-RAS) and spent several years interacting with the Eastwick community to learn of their interests and ideas for flood risk reduction ("adaptation"). Adaptation scenarios including the USACE Tentatively Selected Plan (TSP) were investigated using a coupled version of the two flood models and evaluated under severe and extreme fluvial, coastal and compound flood events and present-day and pessimistic (~90^{th} percentile) mid- and late-century climate change scenarios.

Key points of our project are listed below with specific pages in our appendices of detailed results.

- Flooding from fluvial, coastal, and compound climate conditions will get worse over time. Base simulations (without protective action, and assuming 2020 mean sea level) show high present-day vulnerability of Eastwick to fluvial and extreme compound events, and high future vulnerability to all types of flooding. (See Appendix A Figure 7/p.11; Appendix B13-14 "base" scenario).

- TSP provides partial fluvial and zero coastal flood protection: Using our models, we find that a levee with the same alignment and elevation of the USACE TSP would provide protection of Eastwick from fluvial flooding overtopping at the Planet Streets, but would leave the community exposed to other riverine flood pathways as well as coastal flooding, which is projected to worsen in the future due to climate change. (See B7/B8/B9/B10 center panels).

- The TSP has reduced effectiveness under future sea level rise (SLR): The USACE assumed 0.95 ft of SLR relative to 2025 in its analysis. After reviewing multiple sources and climate scenarios, our team determined that 4 feet of SLR between 2020 and the 2080s (~95th percentile from SSP5-8.5, IPCC AR6) was a more appropriate figure to use in adaptation planning. With this higher estimate of SLR, the TSP will be less effective in reducing future fluvial, coastal, and compound flood events than reported by USACE. (See B11 and B12 center panels; B13, B14).

- TSP provides no protection from future high-tide flooding: Eastwick may experience SLR-induced monthly high tide flooding as soon as the 2060s, and the flood extent could become as large as present-day extreme event fluvial flooding as soon as the 2080s, based on 95th percentile SLR projections (Appendix A). As configured, the TSP will not protect Eastwick residents from future high-tide flooding.

- TSP may provide more fluvial flood protection than reported by USACE: The USACE developed flow exceedance probability distributions for the Darby and Cobbs Creeks from regression equations and applied the 100-year return period peak flow with the TS Isaias observed hydrograph shape for their simulation. Our analyses utilize a 100-year design rainstorm from Atlas 14 precipitation quantities and apply them uniformly across the Darby-Cobbs watershed (using areal reduction factors). Our simulated flows are similar to the USACE flows for Cobbs Creek, but 27.6% lower for Darby Creek, suggesting the potential for residual capacity in the TSP, as proposed, above the 100-year fluvial event.

- Need to accompany the TSP with supplemental measures to improve risk reduction: Though it can reduce the frequency with which Cobbs Creek overflows into the Planet streets, the TSP does not prevent Eastwick from flooding from its southern border with Heinz Preserve, or its Eastern border with the SEPTA tracks. The TSP also induces new areas of flooding in Delaware County (evident in USACE modeling and our own). If the TSP is to be part of a holistic solution to the historic flooding problem faced by the Eastwick community, it must include supplemental measures that will reduce other flood risks. Our modeling shows that a significant investment in upstream stormwater management could reduce flooding in Delaware County induced by the levee. Strategic regrading of the 124.5 acre, city-owned vacant land located east of Lindbergh Blvd, and elevation of a section of Lindbergh Blvd in the vicinity of the entrance to Heinz, could both help to reduce floodwaters entering the community from the Refuge. The 58.6 acre city-owned vacant land located north of S. 84th street could be used to detain flood waters entering Eastwick from the south. Without remediation, the Refuge's plan to re-introduce tidal flow to its impoundment could further exacerbate coastal flood risks to Eastwick. (See Appendix C)

We hope to meet to present these final research results to the USACE project team and are always happy to give more information if needed.

Thank you for considering these comments,

PI Philip Orton — Co-PI Franco Montalto — Co-PI Marc Cammarata

Philip M Orton — Franco Montalto — Marc Cammarata

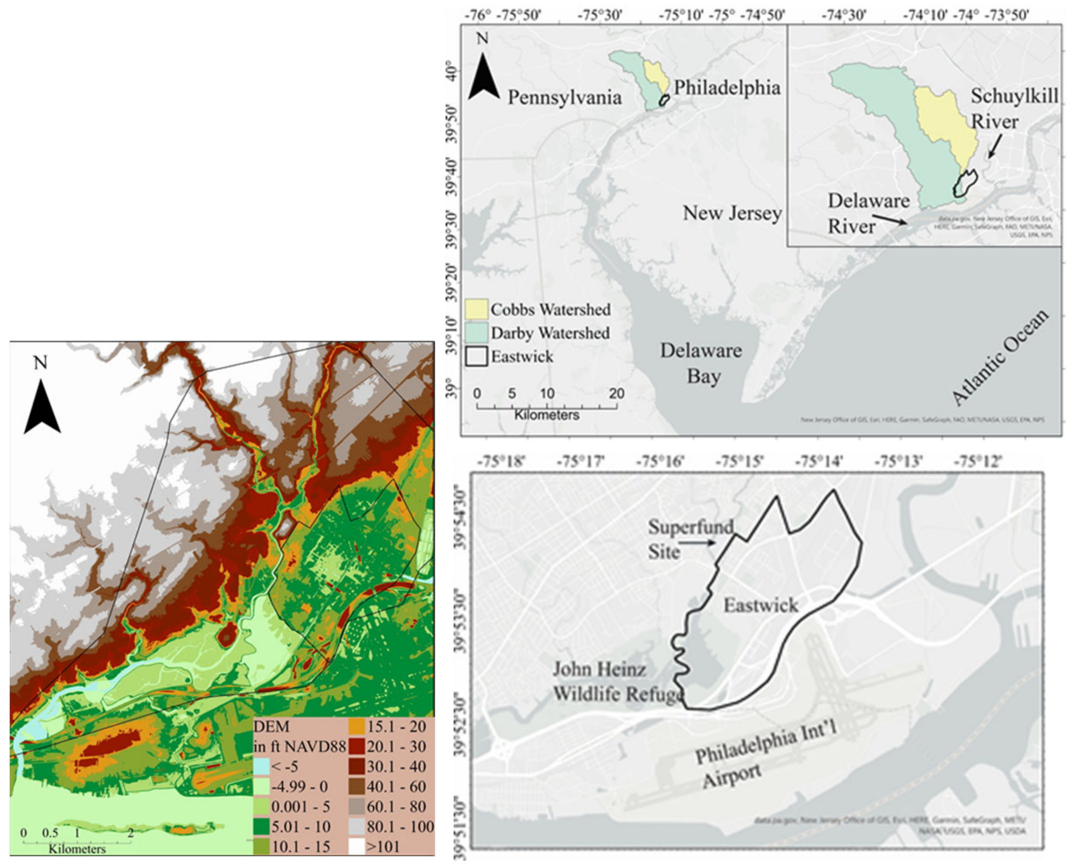
Compound Fluvial-Coastal Flood and Climate Adaptation: Engagement, Modeling and Adaptation Assessment

Team – Philip Orton (PI) and Kazi Mita, Stevens Institute of Technology, Franco Montalto (Co-PI) and Fatemeh Nasrollahi, Drexel University, Marc Cammarata (Co-PI) and Julia Rockwell, Philadelphia Water Department

Funding – NOAA Climate Program Office, Coastal Ocean and Climate Applications (COCA) and Science Applications Research Program (SARP)
+ NOAA Climate Adaptation Partnerships Program (CAP, formerly RISA)

Motivation and Goals (NOAA-COCA)

- Develop modeling tools that can accurately predict flooding in Eastwick due to extreme precipitation, storms and surges, and their combined occurrence
- Work with the Eastwick community to develop viable adaptation scenarios
- Use the modeling tools to simulate the effectiveness of these strategies to reduce flood risks now and in the future



Key aspects of the NOAA-COCA modeling effort

1. Conducting extensive stakeholder engagement
2. Coupled hydrologic model (PC-SWMM) to hydraulic model (2D HEC-RAS)
3. Modeling the entire Darby-Cobbs watershed (from headwaters to Delaware River), enabling investigation of land use and stormwater management on flooding
4. Accurately representing spatial variability in precipitation in the hydrology model
5. Capturing interactions between tides, surges, sea level rise, and precipitation and impact on Eastwick flooding
6. Investigating climate change scenarios of changing rain and sea level
7. Will perform side-by-side comparison of effectiveness of different adaptation strategies, including new strategies of interest to the local community

Coupled PC-SWMM/HEC-RAS Modeling

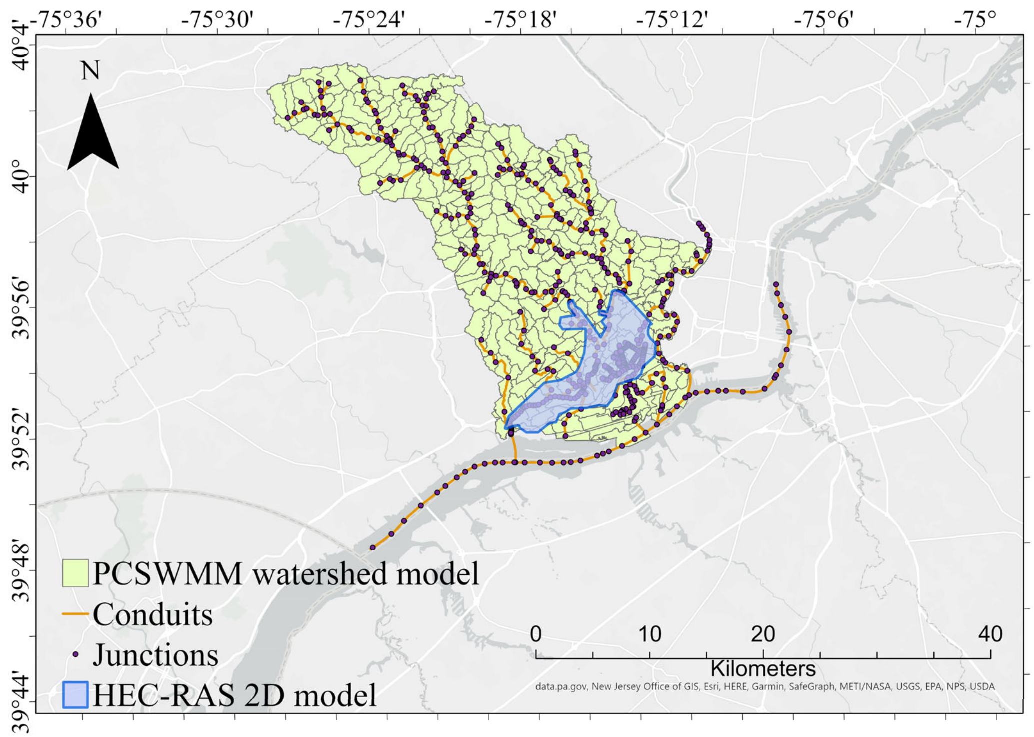
Software: HEC-RAS 6.0
State of the art model widely used in understanding rainfall, river and coastal flooding – used for 2D modeling of flooding in Eastwick.

Grid cell size: 25' by 25' on average

Upstream boundaries: From PC-SWMM hydrologic model

Downstream boundary:
NOAA 8545240 Philadelphia, PA (Upstream from model D/S boundary)
NOAA 8540433 Marcus Hook, PA (Downstream from model D/S boundary)

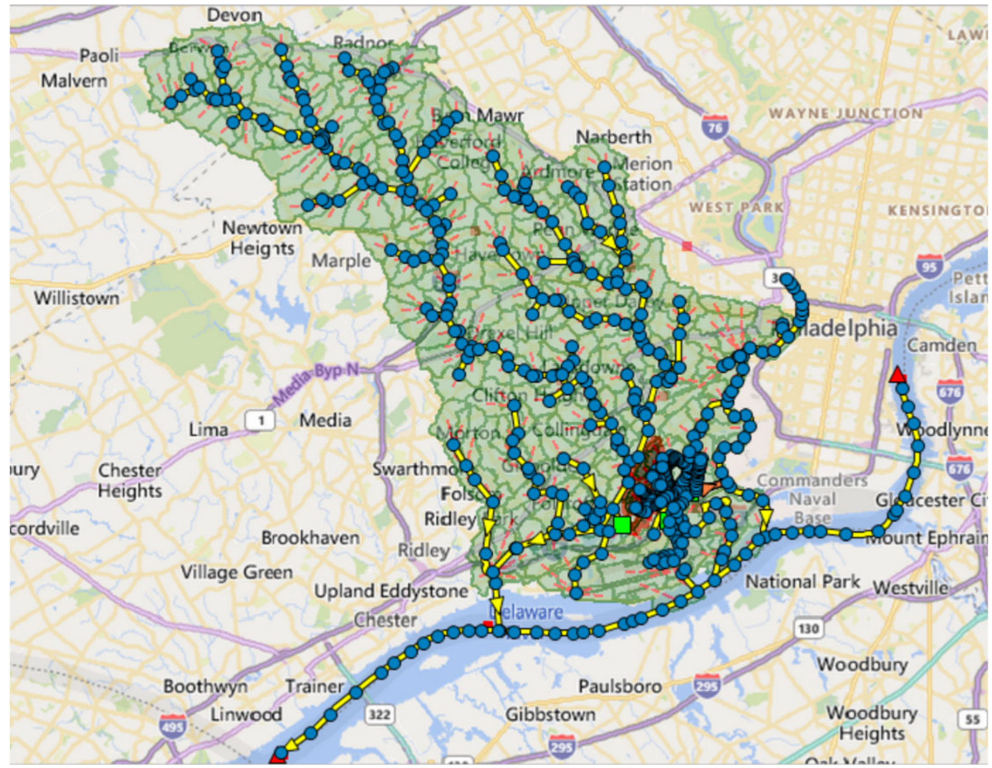
Model Calibration and Validation:
USGS 01475553 Darby Creek at 84th St. Bridge at Eastwick, PA
Isaias High Water Marks



Coupled model domain

PC-SWMM Hydrologic and Flood Modeling

- Watershed rainfall-runoff response: PC-SWMM
- 2D flood modeling in Eastwick
  - Full representation of infrastructure: Quasi-2D PCSWMM



PC-SWMM Model

Appendix A:
Sea Level Rise-Induced Transition from Rare Fluvial Extremes to Chronic and Compound Floods

water

MDPI

Article

Sea Level Rise-Induced Transition from Rare Fluvial Extremes to Chronic and Compound Floods

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Abstract: Flooding is becoming more frequent along U.S. coastlines due to the rising impacts of fluvial and coastal flood sources, as well as their compound effects. However, we have a limited understanding of mechanisms whereby sea level rise (SLR) changes flood drivers and contributes to flood compounding. Additionally, flood mitigation studies for fluvial floodplains near tidal water bodies often overlook the potential future contribution of coastal water levels. This study investigates the role of SLR in inducing high-tide flooding (HTF) and compound flooding in a neighborhood that lies on a fluvial floodplain. Eastwick, Philadelphia, is a flood-prone neighborhood that lies on the confluence of two flashy, small tributaries of the tidal Delaware River. We develop a combined 1D-2D HEC-RAS fluvial-coastal flood model and demonstrate the model's accuracy for low-discharge tidal conditions and the extreme discharge conditions of tropical Cyclone (TC) Isaias (2020) (e.g., Root Mean Square Error 0.08 and 0.13 m, respectively). Simulations show that Eastwick may experience SLR-induced HTF as soon as the 2060s, and the flood extent (34.4%) could become as bad as present-day extreme event flooding (30.7% during TC Isaias) as soon as the 2080s (based on 95th percentile SLR projections). Simulations of Isaias flooding with SLR also indicate a trend toward compounding of extreme fluvial flooding. In both cases the coastal flood water enters Eastwick through a different pathway, over a land area not presently included in some fluvial flood models. Our results show that SLR will become an important contributor to future flooding even in fluvial floodplains near tidal water bodies and may require development of compound flood models that can capture new flood pathways.

Keywords: high-tide flooding; fluvial flooding; climate change; sea level rise; compound flooding

check for updates

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1. Introduction

Flooding is one of the costliest and deadliest natural hazards [1–3] affecting many regions around the world [4–6]. Coastal regions are particularly vulnerable to flooding impacts due to dense and rapidly growing population centers [7,8] and intensely developed urban land areas. Along with these factors, increases in sea level and rainfall intensity are also driving increased flooding. The Global Mean Sea Level (GMSL) has been rising and will continue to rise in this century under all the Shared Socioeconomic Pathways (SSPs) considered by Intergovernmental Panel on Climate Change (IPCC). Along much of the U.S. East Coast, the Relative Mean Sea Level (RMSL) rise is projected to be greater than GMSL [9]. The increase in RMSL increases the frequency of high-tide flooding [10,11] and the risk of compounding extreme flood events [6,8,12].

Traditionally, studies of flood impacts have mainly focused on extreme fluvial and coastal flood events separately [13–16]. For example, the standard flood hazard assessment framework of the U.S. Federal Emergency Management Agency (FEMA) is univariate [6,15,17,18]. FEMA fluvial flood hazard studies neglect the contribution of dynamic coastal water levels [6,19]. Even in univariate studies of large-scale fluvial floods, the local flood risk is underestimated by neglecting flow from smaller streams, using coarse resolution terrain data, and assuming simplistic physics of flood spreading [20]. According to Wing et al. [20], FEMA flood hazard area delineation studies thoroughly mapped the coastal flood hazard, but fluvial and pluvial flood hazard zones are incomplete nationwide.

Compounding of flooding from multiple sources (typically storm surge and streamflow) has gained significant recent attention [6,12,21,22]. There have been studies focusing on local [23–25], continental [26], and global scales [12] examining the correlation between rain and surge. Wahl et al. [26] found a significant increase in the number of compound flood events over the past century for some coastal locations. US studies suggest that the risk of compounding flood drivers is higher on the US East Coast [6,26]. In addition, future SLR projections [4,27,28] and rainfall intensity increases [27,29,30] imply the trend in increasing flood risk will likely continue [8].

SLR is also increasingly inducing flooding outside of extreme conditions. High-tide-flooding (HTF) (alternatively known as nuisance, sunny day, and recurrent tidal flooding) is of much lesser magnitude than major flooding [10,31]. However, small, frequent HTF events can cause significant property damage cumulatively [32]. Several studies suggested that HTF flood frequency has increased exponentially in the last 70 years [10,11,33], and it will continue to rise due to SLR [11,34,35] under various SSPs. According to Dahl et al. [33], in the next 15 to 30 years, many communities will face chronic HTF due to sea level rise which will later cause permanent inundation. Thompson et al. [24] reported the onset of rapid increase in HTF frequency from the mid-2030s onwards in the US. In some coastal regions, today's HTF and minor surge flooding have similar impacts compared to major surge or hurricane impacts in the past [28].

Local scale modeling and process studies of SLR impacts on compounding of extreme flood events and HTF have been understudied. Moreover, these studies have typically focused only on extreme flooding induced by tropical cyclones (TCs)/extreme coastal water level [4,21,36–39]. Numerical modeling of HTF, on the other hand, is still under-explored in flood research. A holistic focus on both extremes and chronic floods can better help reveal the full range of processes and effects of SLR on changing drivers and compounding floods. Monthly tidal flooding with SLR is a valuable metric representing the future onset of chronic flooding [40]. With the increase in frequency, depth, and extent of HTF in coastal urban neighborhoods, the importance of addressing HTF in flood management measures is also becoming imperative.

In this study, a model capable of simulating HTF, coastal, fluvial, and compound flooding is developed for a neighborhood historically impacted by fluvial flooding but increasingly at risk of coastal flooding. The model is validated using monthly high tide and an extreme rainfall event. The effects of SLR on tidal floods and the conversion of fluvial floods to compound floods are explored. This submission constitutes the first in a series focused on flood modeling, changing flood hazards, and potential flood risk mitigation solutions for the neighborhood of Eastwick, Philadelphia.

2. Study Area

Eastwick is a community of about 42,000 people in Southwest Philadelphia adjacent to Philadelphia International Airport (referred to as Airport in Figure 1b). Hydrologically, Eastwick is located at the confluence of the Darby and Cobbs Creeks which have watershed drainage areas of approximately 104 km^2 and 60 km^2, respectively. The hydrologic complexity in Eastwick arises from several features, including the elevated Clearview Landfill Superfund site located near the confluence ("landfill" in Figure 1b), the impounded John Heinz Wildlife Refuge (JHR in Figure 1b) further downstream, and the largest remaining freshwater tidal marsh in Pennsylvania (in the LDC area in the Figure 1b). In addition to minor flooding events, heavy precipitation during tropical storms Floyd (1999), Irene (2011), Sandy (2012), and recent TC Isaias (2020) have caused extensive and severe flooding in this area. Based on U.S. Army Corps of Engineers (USACE) high water mark data and interactions between the research team and long-term residents, TC Floyd and TC Isaias were the first and second worst flooding events in Eastwick during the post-urban renewal period (~1960s to present). Eastwick's high susceptibility to flooding arises from its proximity to the Darby–Cobbs, the tidal Delaware River, and the Schuylkill River.

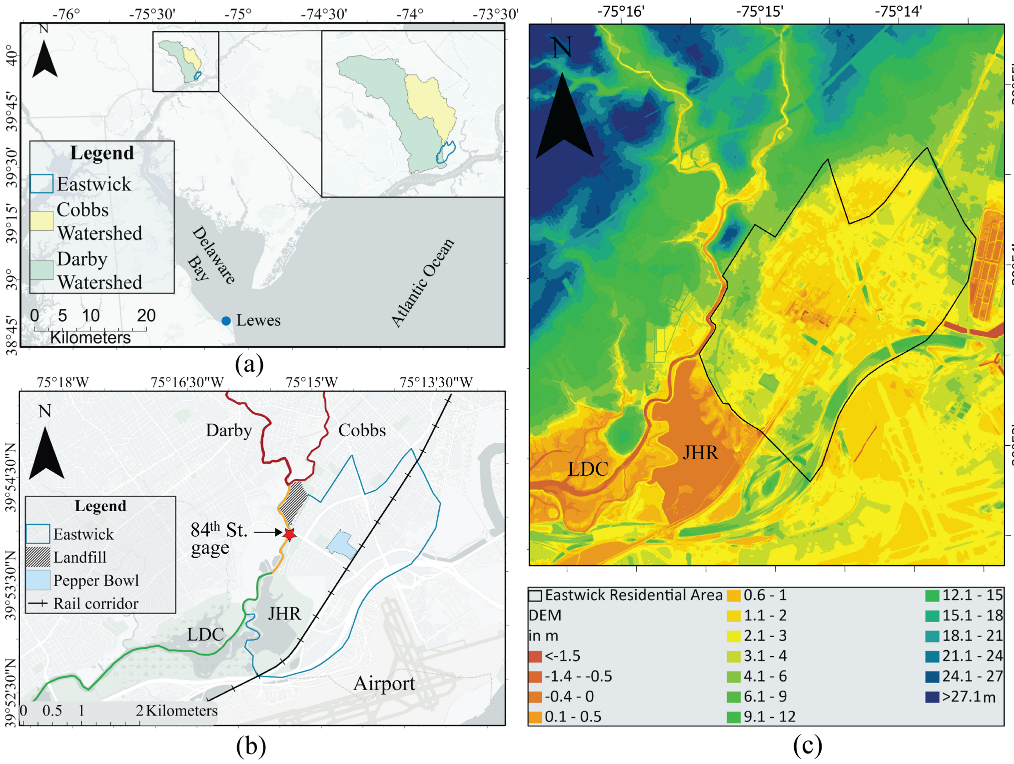

Figure 1. Map of the study area. (**a**) shows the location of Eastwick from the Atlantic Ocean including Delaware Bay and Rivers, and (**b**) shows Eastwick and some other local key features (JHR and LDC are acronym for John Heinz Wildlife Refuge and Lower Darby Creek respectively); red, yellow, and green lines show different Manning's roughness region along the creeks (discussed more in Section 3.1.5). (**c**) Digital Elevation Model (DEM) of the study area.

Flooding has been a longstanding and growing concern of the Eastwick community, and there have been multiple studies assessing flood risk and effectiveness of various adaptation measures [41–43]. USACE [41] conducted a hydraulic analysis of existing conditions and the impacts of a proposed levee (embankment). The USACE study represented the study area by cross-sections (1D model) and modeled steady flow during extreme hurricanes Floyd, Irene, and Lee. To improve the initial modeling effort and accurately represent multidimensional flows in the neighborhood, a Princeton Hydro [43] study represented the neighborhood (Figure 1b) as a 2D model domain keeping the channels 1D. Like this study, AKRF [42] modeled the neighborhood for redevelopment purposes as a 2D flow area but extended river reaches using a 1D model in both upstream and downstream directions. While modeling the river reach in 1D is computationally less expensive and adequate for regular flow conditions, the wetlands in the Darby–Cobbs system make the flow dynamics more complex, especially during extreme events [44,45]. So, to understand current and future flood pathways into Eastwick, in this study, we improve upon previous attempts and incorporate the Darby–Cobbs creeks as a 2D flow area extending the downstream boundaries to the Delaware river (Figure 2).

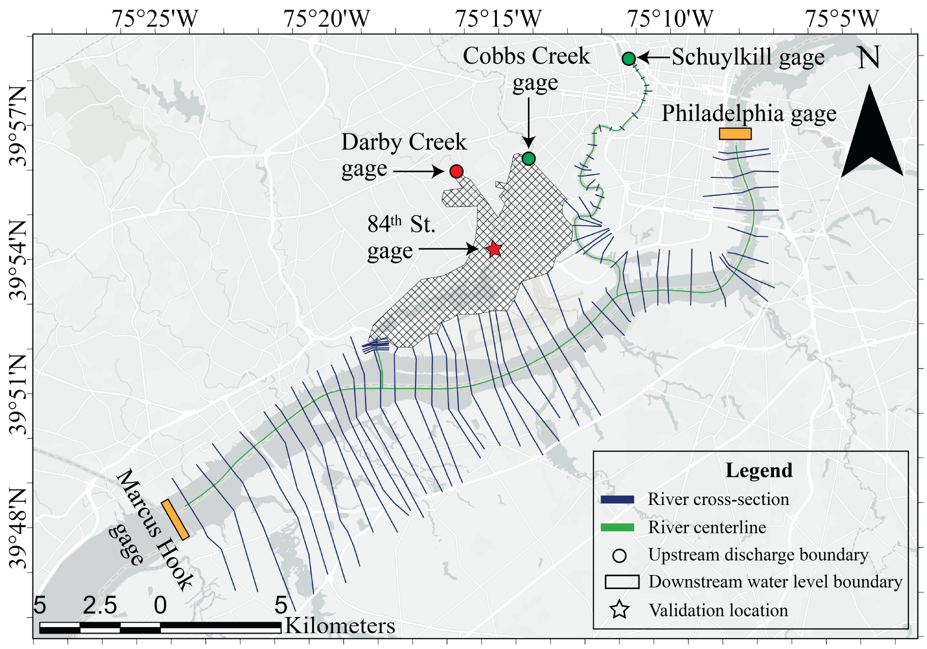

Figure 2. Model Domain. Cross-hatched polygon represents 2D model domain, and river cross-sections and centerline indicate 1D model domain. The circle represents discharge boundaries, and rectangles represent water level boundaries. Fill color red indicates limited data record (~5 years).

There have also been limited attempts to simulate coastal flooding in Eastwick. While the USACE [41] study did not address coastal events, Princeton Hydro [43] simulated a NOAA 1% storm and NOAA SLOSH category one storm with a 1D-2D HEC-RAS model. This analysis used a 1D model in the Lower Darby Creek and only allowed for Eastwick flooding from the 1D Darby river channel and not across the John Heinz Refuge (JHR) floodplain. Thus, the Princeton Hydro study does not capture the possible overflow location at the south end of Eastwick near the rail corridor (Figure 1b). AKRF [42] incorporated a few coastal events like TC Sandy, 1950 storm (in present and future SLR conditions), and two synthetic compound events. But their study, too, was limited by the unavailability of observed data during extreme events (described in Section 3.2.2). To deal with these limitations, the AKRF study made simplistic assumptions that involved scaling up/down the Isaias hydrograph to simulate these storms. While their model is the most detailed among all these published studies, the model is not validated. Our research is a continuation of previous efforts to study flood mitigation strategies in Eastwick. Through our research, we plan to address the shortcomings of prior studies and develop a model of Eastwick capable of simulating coastal, fluvial, and compound flooding efficiently. The project is a collaboration with Drexel University, Philadelphia Water Department (PWD), and the model has been shared [46] through workshops with PWD, Philadelphia Office of Sustainability, the US Army Corps of Engineers, local community organizations, and other partners.

3. Methodology

In this study, a widely used publicly available modeling tool HEC-RAS (v6.0) developed by the USACE is used. Many previous studies applied HEC-RAS to study compound flooding in different places around the world [5,29,37,47,48]. HEC-RAS has these unique capabilities of performing combined 1D-2D modeling within the same flow model which gives modelers the scope of using 1D in large river systems and 2D in areas requiring more accuracy in hydraulics, making the model computationally less expensive. The model was applied with full momentum balance mode in its 2D regions. The following sub-section describes the model set-up parameters; validation for regular and extreme flow conditions;

and analyses of the impacts of SLR on HTF and compounding of fluvial extreme flooding in Eastwick.

3.1. Model Set Up

3.1.1. Topo-Bathymetry Data of the Model

LIDAR-based topography data are merged with boat survey bathymetry data to form the model's digital elevation model (DEM) data in the Eastwick and Darby–Cobbs area. The topography comes from the Pennsylvania Spatial Data Archive [49] in the form of LIDAR (light detection and ranging) generated DEM of 1 m (3.28 ft) resolution. The bathymetry of the Delaware River, Schuylkill River, Darby Creek, and Cobbs Creek are collected from various sources. The channel bathymetries of Darby and Cobbs Creeks are incorporated from the 2014 USACE study. The channel bathymetry used in this study is developed by merging the PWD survey data from above the Darby–Cobbs confluence with Environmental Protection Agency (EPA) Bathymetry Survey data south of the confluence of Darby and Cobbs Creeks [41]. Bathymetries of the Delaware and Schuylkill River reaches are collected from National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information's (NCEI) combined topographic and bathymetric DEM data [50] and NOAA Nautical Charts [51]. Data are combined from these two sources using the Nautical Charts data as the base information and supplementing them with the NCEI data [42].

3.1.2. Upstream and Downstream Boundary Conditions

Model boundaries are placed in locations where existing discharge and/or water level gage stations exist. The upstream boundaries of the model are USGS gage stations [52]. For Darby Creek upstream boundary, USGS gage Darby Creek near Darby, PA (Gage ID: 01475510); for Cobbs Creek, Cobbs Creek at Mt. Moriah Cemetery, PA (Gage ID: 01475548); and for Schuylkill River, Schuylkill River at Philadelphia, PA (Gage ID: 01474500) have been used. The USGS gage at 84th Street (Gage ID: 01475553) is used as the model validation location. This station is the only operational gage station located within the model domain and adjacent to the area of interest. One constraining factor in modeling historic flooding in Eastwick is limited records. One of the contributing tributaries, the Darby Creek gage, has a time series of discharge data going back to only Nov 2018. The validation location, USGS 84th St. gage, has water level data records from 2017. These data constraints limit the number of events that can be simulated using observed data.

One of the challenges setting up the model was capturing the tide timing at Darby–Cobbs inlet (from the Delaware River) correctly. Initially the model was set up using only a 2D model domain (Figure 2). To set up the downstream boundary at the inlet, a simplistic assumption of progressive wave was used to offset tide gage data from Marcus Hook based on travel time to the NOAA tide gage station at Philadelphia. But the resulting tide phasing was delayed compared to observations at 84th St. To capture the tide phasing and propagation correctly, the 1D model of the Delaware and Schuylkill River is connected to the 2D model domain. The downstream boundaries in the Delaware River are tidal water level boundaries. The NOAA Philadelphia gage station and NOAA Marcus Hook gage stations are used as downstream boundary conditions in this study [53].

3.1.3. Grid Size

In the 2D model domain, 7.62 m $\times$ 7.62 m (25′ $\times$ 25′) model grid has been used. Levees require higher resolution and are defined by break lines aligned along their axis. For example, in the John Heinz National Wildlife Refuge (JHR in Figure 1b) where strong tidal flow occurs, grid cells near the break lines can have significantly smaller resolution 1.52 m $\times$ 1.52 m (5′ $\times$ 5′). Cells in HEC-RAS can have up to eight sides. Each cell is a detailed elevation volume/area relationship that represents the details of underlying terrain. Because of these high-resolution sub-grid features, wetted flood area will be based on underlying detailed terrain, not computational grid size. This feature of HEC-RAS enables us to use comparatively coarser grid without compromising the accuracy of output. The 2D flow area comprises of nearly 467,562 cells.

3.1.4. Computational Time Step

Computational time step is another important parameter to attain a numerically stable model and good results. A too large time step causes numerical diffusion and may cause model instability. If the time step is too small, the computation time can be very long which is not desired in most cases. In this study, the time step of simulation 30 s has been chosen based on convergence test of numerical solutions for various time steps.

3.1.5. Land Cover and Land and Bed Roughness

In this study, land use data from National Land Cover Database (NLCD) collected in 2016 at a 30 m resolution are used [54]. Then, appropriate roughness values have been associated with various land use types (see Supplementary Materials Table S1a) [55]. For example, medium intensity developed region and Estuarine emergent wetland are assigned Manning's roughness of 0.1 and 0.05, respectively.

A physics-based approach was used to set reasonable Manning's roughness in river channels. In the 2D model domain, four regimes (shown in red, yellow, and green lines (Figure 1b)) are defined based coarsely on river slope, and Manning's numbers are roughly estimated for each based on prior studies, images of the creek bed, and the bed slope. The channel bed from upstream boundaries (both Darby and Cobbs) to confluence of Darby–Cobbs is relatively steeper (0.002) and has boulders and vegetation obstruction along the way. Bed material downstream of the confluence becomes finer gradually, and the bed slope declines to 0.001. To account for these differing substrates and their hydraulic effects, we applied Manning's roughness from range of possible values based on bed characteristics [56]. The Manning's n values used within the river channels are shown in Table S1b in Supplementary Materials.

3.2. Flood Events for Model Validation and Flood Mapping

3.2.1. Model Set Up for Tidal Flooding

The model is validated for a week-long spring tide period with low stream flows and a high coastal sea level anomaly of ~0.3 m at Lewes, Delaware, shown in Figure 1b (NOAA station 8557380). The peak water level of 1.56 m North American Vertical Datum of 1988 (NAVD88) is exceeded 14 times per year on average at 84th St. tide gauge (USGS station 8557380 data from 2017 to 2022), and we hereafter refer to this as monthly HTF [40]. The period of the simulation is from 24 August to 31 August 2019, and the average median daily discharge through Darby, Cobbs Creeks, and Schuylkill River during this period is 0.34 m^3/s, 0.79 m^3/s, and 33.7 m^3/s, respectively. The tidal boundary conditions at Philadelphia and Marcus hook gage are shown in Figure 3.

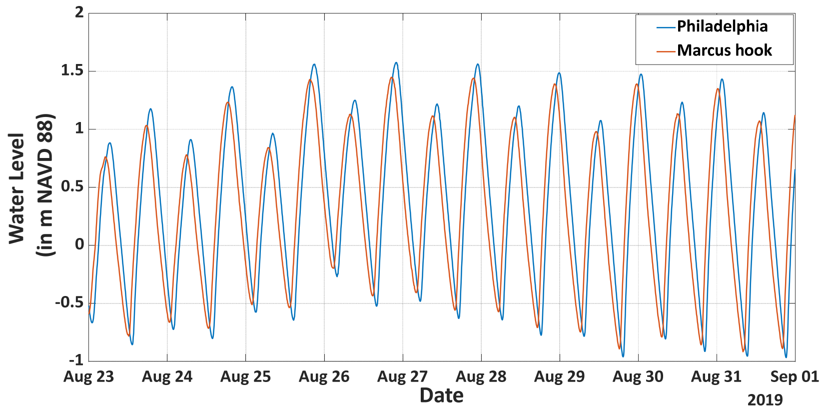

Figure 3. Tidal water level boundary conditions.

3.2.2. Model Set Up for TC Isaias

The model is validated for TC Isaias (2020) due to both the widespread severe flooding in Eastwick and the wider availability of useful data in comparison to earlier floods. TC Isaias was mainly a fluvial flood event with a return period of ~30 years, given that it was the second worst event in about 60 years of historical information (the Weibull unbiased empirical probability assumption; [57]). It was not an extreme event in terms of water level on the Delaware River, with a water level return period of about 2 years at the Philadelphia tide gauge. The Darby Creek upstream gage station has data from 2017, and the 84th St. gage used for model validation has data from late 2018 to present. Therefore, observed data for prior storms are significantly lacking. For Isaias, in addition to water level at 84th St., High Water Marks (HWMs) were collected by the USACE right after Isaias in Eastwick. The uncertainty of the HWMs is reported to be 0.06m (0.2 ft) which is classified as fair in quality assuring process [58].

The Isaias simulation includes scaled up streamflow following the recommendations of previous studies [41,43,59]. During extreme flow events, the accuracy of measured flow data at Mt. Moriah gage at Cobbs Creek and Darby Creek gage is questionable. In USACE [41,59] studies, it is mentioned that the flow measurement method at Mt. Moriah gage is reported to be indirect, indicating that reported discharge is an estimate based on either extrapolation or calculation. There is high suspicion that gage data at high flows may be impacted by the bridge downstream of the gage [41,59]. During high flow events, the water level at the bridge reaches the low steel above the opening, and the relationship used for calculation and extrapolation at the gage is affected. The USACE study [41] did not trust flow values in cases of extreme flow events and used a stage discharge relationship based on 1977 Flood Insurance Study (FIS) as an alternate method to convert measured peak stages to flows. At the time of the USACE study, the Darby Creek station was not operational. But there is similar suspicion about the current measured discharge data at this location too. Though this gage has observed flow data for Isaias, around the time of peak discharge, the gage discontinued logging observed data, and estimated discharge was provided instead. To test the claim, we simulated Isaias using USGS-provided discharge data which showed no flooding at all in Eastwick (see Supplementary Materials Figure S1). This is contrary to many media reports and USACE HWMs data. This analysis supports the claim that both gages are underestimating discharge during extreme flow events. Because of the uncertainties in observed data, we assumed that the recorded data could capture the shape and timing of the hydrographs at both gages but underestimate the flow magnitude in accordance with these prior studies [41,43]. So, the flows at Darby and Cobbs Creek are scaled up using the same methodology as USACE [41] in this study (Table 1).

Table 1. Summary of rating curve comparison at Mt Moriah gage location at Cobbs and Providence Road at Darby for TC Isaias.

Stream	Measured Stage (m)	WSE (in m NAVD 88)	Estimated Discharge from 1977 FIS Study (m^3/s)	Measured Discharge (m^3/s)	Coefficient
Cobbs	5.5	11.30	325.64	211.24	1.54
Darby	3.94	9.71	205.22	171.60	1.2

3.3. SLR Scenarios and Estimated Time of Arrival

To study the onset of tidal flooding in Eastwick, SLR scenarios ranging from 0.3 to 1.8 m with 0.3 m increment (integers between 1 to 6 ft) on top of a baseline in 2019 are considered in this study. Using a range of SLR values enables us to model the onset of tidal flooding in Eastwick and the progression of flooding as sea level rises.

Based on the latest IPCC Sixth Assessment Report (IPCC AR6) 2022 SLR projections for Philadelphia, decades when these SLR scenarios occur at 5th, 50th, and 95th percentiles are estimated. To create this decadal estimate, the available projection data are plotted against the year and regressions equation of 4th order polynomial for 5th percentile (R^2 = 0.998), linear for 50th percentile (R^2 = 0.999), and 2nd order polynomial for 95th percentile (R^2 = 0.999) are formulated. Using these regression equations, projected SLR for each year is calculated. Lastly, the SLR scenarios considered in this study and the corresponding projected decade of occurrence are obtained. The projection timeframe for each SLR scenario is useful for planning, implementation, and mitigation purposes.

3.4. Compounding of Extreme Fluvial Flooding Due to SLR

To study the compounding of extreme fluvial flood due to SLR, we simulated TC Isaias with 0.6 m (2 ft) and 1.2 m (4 ft) SLR. The spatial differences between maximum water level of base scenario and future scenarios are mapped and compared to understand the potential change in flood pathways due to SLR.

4. Results

4.1. Model Validation Results

4.1.1. Tide Validation

The HEC-RAS 1D-2D model has high accuracy for capturing the phase and high waters during the tide simulation (Figure 4). The modeled and observed water level has a root mean square error (RMSE) of 0.08 m, mean average error (MAE), and mean error (ME) of 0.04 m, respectively (Table 2). The Nash–Sutcliffe model efficiency coefficient (NSE) representing the predictive skill of model is calculated to be 0.97 (1.00 being a perfect model). But at times of low water (LW), the simulated water level does not reach the observed data, and there is a consistent bias of −0.1 m. However, we did not tune the model to get better results at LW because our focus is on high waters and floods. This bias in LW can be attributed to the uncertainty of the bathymetry data. There are localized uncertainties associated with the bathymetry of the river channel. The 84th St. gage is located on the bend of Darby Creek, and a point bar forms and erodes below the gage at the center pier periodically [41,43]. Because of the periodic formation and erosion of the point bar, there is a possibility of error in the surveyed bathymetry and overestimation/underestimation of LW levels.

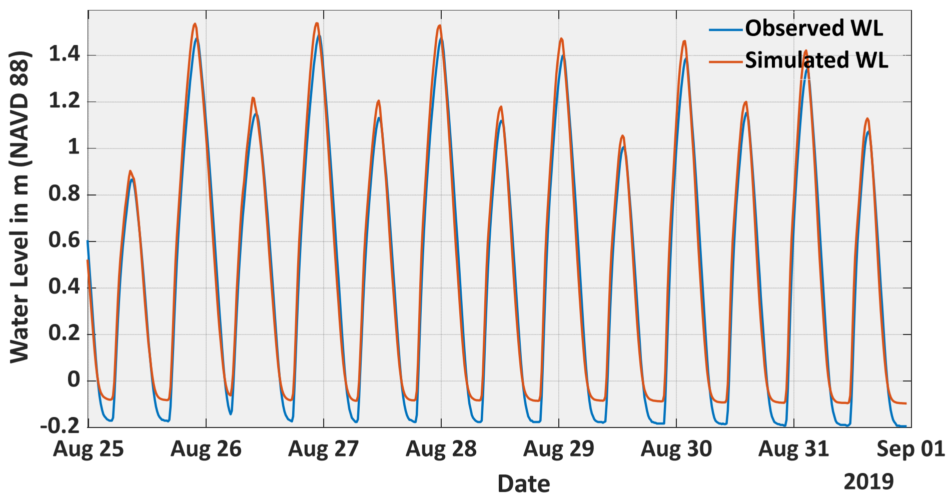

Figure 4. Water level comparison at USGS 84th St. gage.

Table 2. Summary of statistical indicators for different validation approaches.

Indicator \ Event	Monthly Tide	Extreme Flow Event Isaias	
	Tide Time Series	Isaias Time Series	High Water Marks
RMSE (m)	0.08	0.13	0.32
ME (m)	0.04	−0.08	0.28
MAE (m)	0.07	0.14	−0.09
NSE	0.97	0.98	-
R^2	-	-	0.8803

4.1.2. TC Isaias Validation

The model also has good accuracy for capturing the flooding extent in Eastwick based on the comparison with HWMs data (Figure 5). Figure 5a shows the model-simulated maximum inundation extent during TC Isaias. During flooding, the overtopping starts to occur near the confluence of Darby and Cobbs and inundates nearby streets and ultimately reaches the low-lying area in the middle of Eastwick, locally known as Pepper Bowl (Figure 1b,c). In Supplementary Materials Figure S2, the spatial distribution of high-water marks (HWMs) collected after TC Isaias is shown. The comparison between observed and modeled HWMs at every point is presented (Figure 5b). As it is seen from the results, the model simulated HWMs are consistent with surveyed HWMs with RMSE 0.32 m, ME of 0.28 m, MAE of HWM is 0.28 m, and R^2 of 0.88, which is a relatively good fit for a flood model and HWMs [15,60,61].

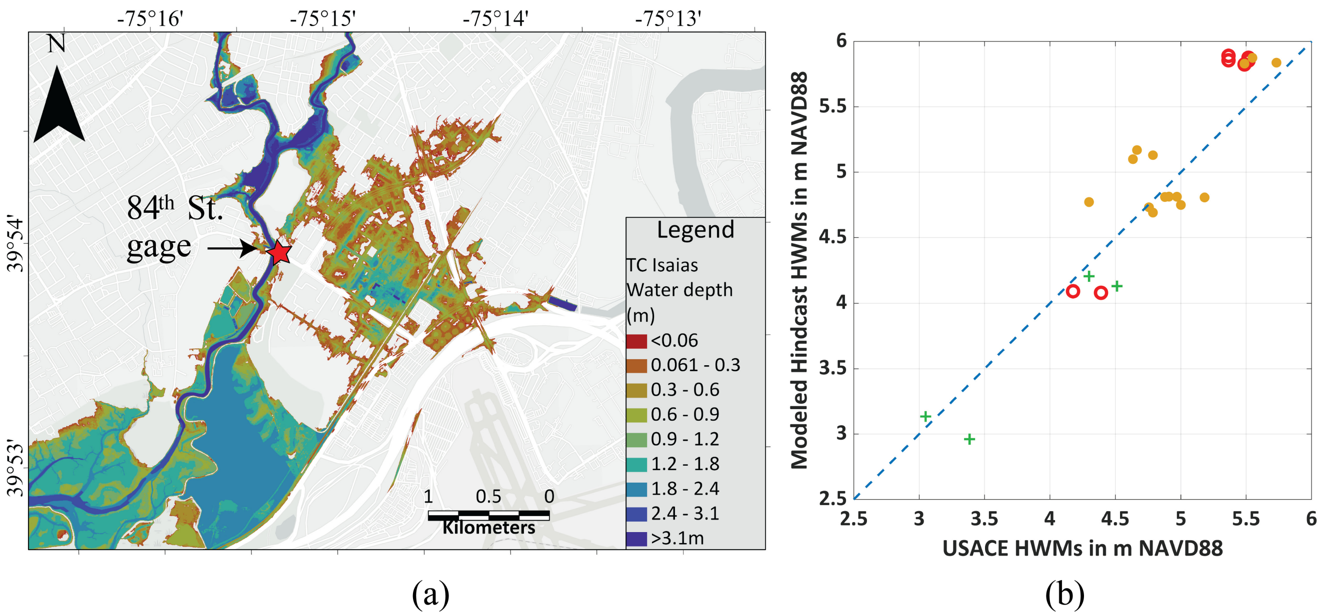

Figure 5. (**a**) Maximum inundation extent during Isaias. (**b**) Comparison of model-simulated HWMs with recorded HWMs. Color indicates closeness of points to the creek (red points are closest to the creek, and green denotes furthest ones; see Supplementary Materials Figure S2).

The water level time series during Isaias at 84th St. generally shows good agreement with observed data, except for a discrepancy at the peak (Figure 6). To quantify the model's performance during extreme flow event, we used a segment of time series around the peak to calculate the statistical indicators (black dashed portion in Figure 6). The RMSE, MAE, ME, and NSE of the model in this extreme flow scenario are 0.13 m, −0.08 m, 0.14 m, and 0.98, respectively (Table 2). Similar to the time series of the tidal water level, the water level during Isaias also has some discrepancy during low tide, which can be attributed to the bathymetry uncertainty as discussed in Section 4.1.1. Another source of uncertainty comes from the estimation of upstream discharge based on the methodology described in Section 3.2.2. The 0.14 m difference in peak water level with observation can be caused by this reason or complexities of the bridge itself that may be obstructing flow. Simulating extreme flows below bridges with potential debris trapping and morphologic changes can be a challenging topic [62,63].

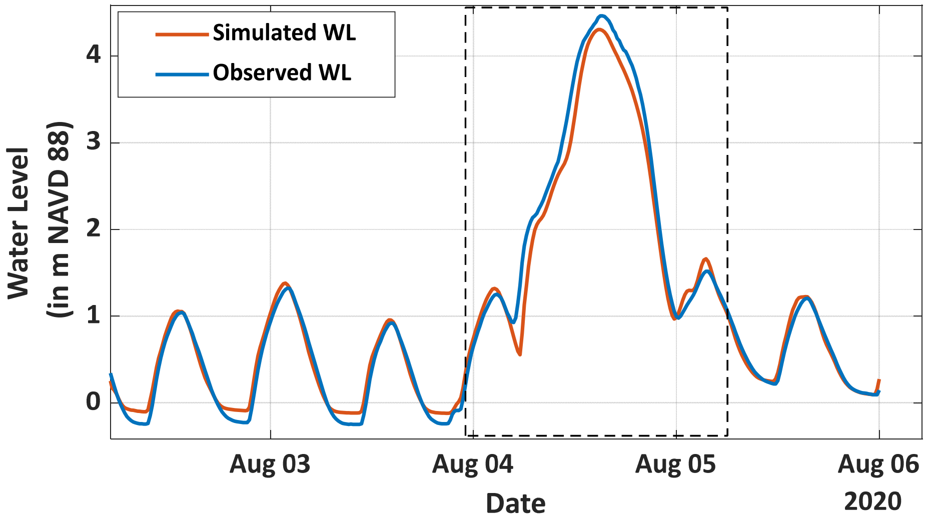

Figure 6. Water level comparison at USGS 84th St. gage during Isaias. Black dashed portion represents data used to calculate the statistical indicators in Table 2.

4.2. Future Impact of SLR on Tidal Flooding

The tide simulation (described in Section 3.2.1) with added SLR demonstrates that monthly HTF will eventually begin to affect Eastwick after an additional 0.6 m of SLR and increasingly with further SLR increments (Figure 7). Analyses of the modeled flood pathway show that water starts to propagate from JHR through the rail corridor (indicated in Figure 1b) and ponds in the 'Pepper Bowl' of Eastwick (indicated in Figure 1b). As the magnitude of SLR grows, the depth of water in and around Pepper Bowl increases, as does the total flooding extent. Table 3 below shows the tidally flooded area for a range of SLR scenarios. For 0.6 m of SLR, about 3% of Eastwick is flooded, whereas for 0.9 m of SLR, the total flooded area increases to more than 18%. With 1.2 m of SLR, the flood extent (34.4% of Eastwick) becomes greater than that for Isaias (30.7% of Eastwick). Additional SLR (1.5 and 1.8 m) causes about half of Eastwick to experience chronic HTF.

Table 3. Various tidal and flow scenarios resulting in inundated area (in %) in Eastwick. Raster cells greater than 3 cm are considered wet for inundated area calculation.

Flow Conditions	Scenario	Inundated Area (%)
SLR scenarios	0.3 m (1 ft)	~0
	0.6 m (2 ft)	3.1
	0.9 m (3 ft)	18.6
	1.2 m (4 ft)	34.4
	1.5 m (5 ft)	46.1
	1.8 m (6 ft)	57.9
Isaias (2020)	Isaias	30.7

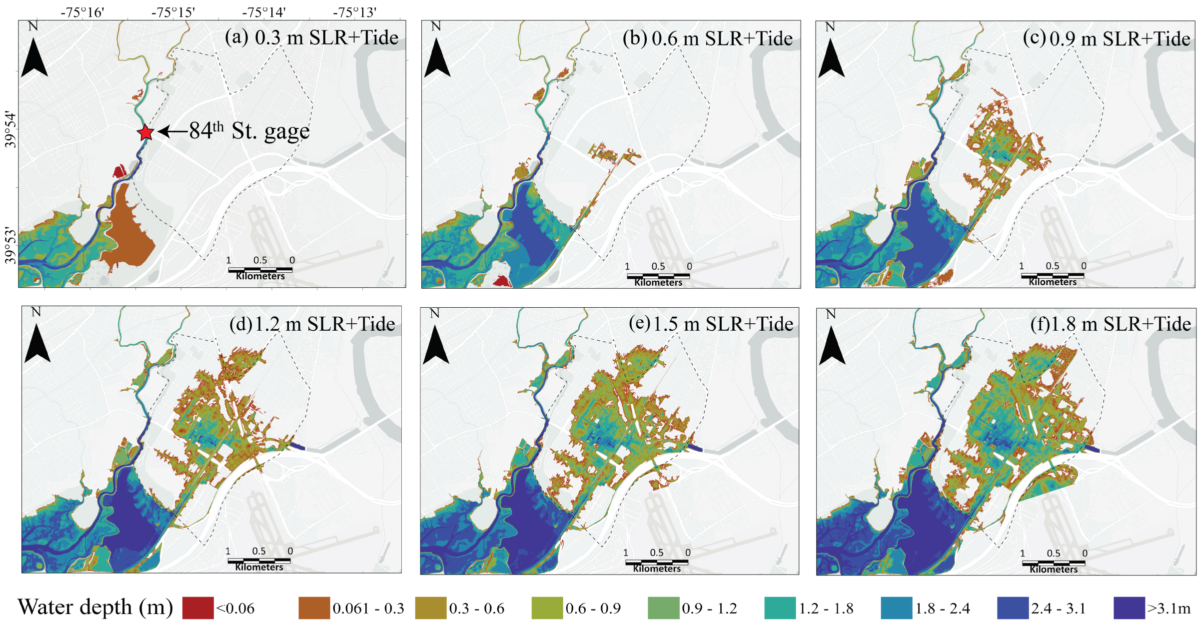

Figure 7. Monthly high-tide flooding with various sea level rise (SLR) scenarios (see caption on top left). Depths shown are temporal maxima of the monthly high-tide simulations. All sub-figures have the same spatial extent.

Estimated Decade for Each SLR Scenario

According to Tables 3 and 4, some areas of Eastwick might start experiencing monthly HTF due to SLR as soon as the 2060s. As the flooding extent expands with increasing SLR, Isaias-like flooding may occur monthly by the 2080s under a high-end SLR scenario. If other anthropogenic factors such as dredging or shoreline hardening cause the tidal high-water levels to rise, similar flooding can occur sooner [64–66].

Table 4. SLR scenarios and approximate decadal timing for the 5th, 50th, and 95th percentile projections. MSL 2019 is 0.28 m NAVD88.

SLR in m (above MSL 2019)	Low End (5 Percentiles)	Median (50 Percentiles)	High End (95 Percentiles)
0.3	2080s	2050s	2040s
0.6	>2150	2090s	2060s
0.9	>2150	2130s	2070s
1.2	>2150	>2150	2080s
1.5	>2150	>2150	2100s
1.8	>2150	>2150	2110s

Note(s): SLR estimate over NAVD 88 datum.

4.3. Compounding of Extreme Fluvial Flooding under SLR Scenarios

For this analysis, we compared flooding during Isaias in base (2020) and future SLR (0.6 m, 1.2 m) scenarios. Figure 8a shows the coastal water contribution to flood water depth during Isaias in the 2D model domain. Overall, the approximately 2-year return period storm tide did not compound the fluvial flooding in Eastwick significantly. Along the creeks, from JHR to upstream of creeks and in the flooded area, the flood water depth remains unchanged due to the presence of storm tide. Storm tide compounds the water depth in LDC, surrounding wetlands, and JHR (Figure 1b) by various degrees: from a few centimeters in Eastwick to up to 1 m near the downstream boundary.

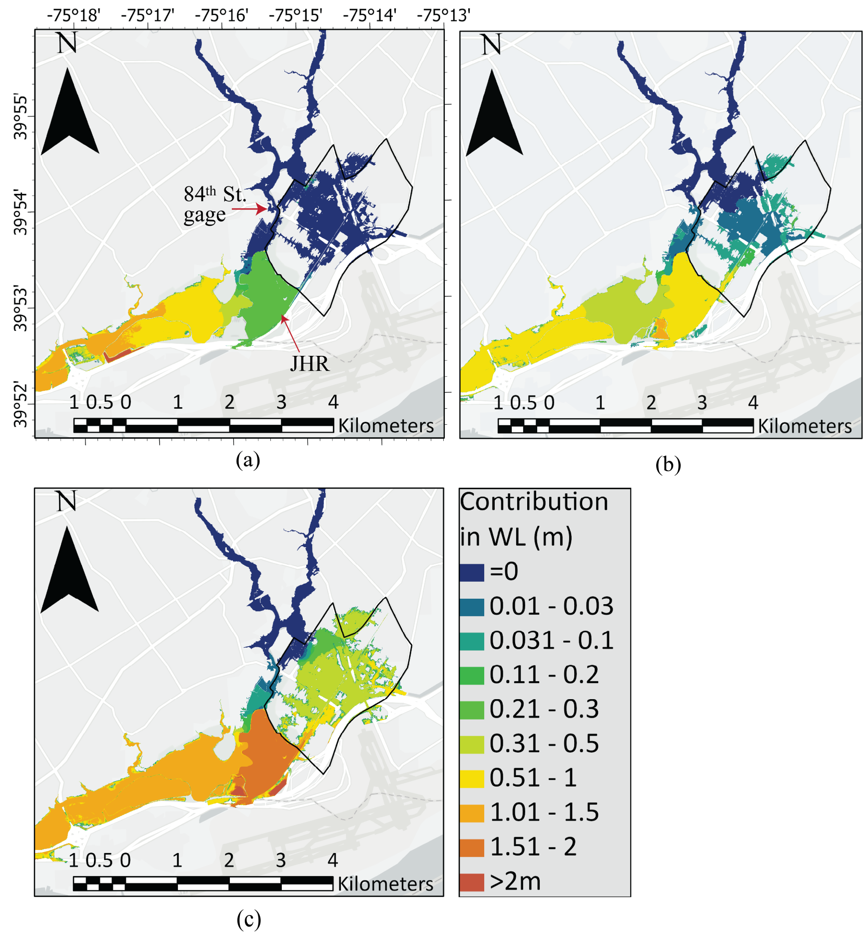

Figure 8. Contribution in rise in water level during Isaias (**a**) due to the coastal contribution in the base scenario, (**b**) due to coastal contribution of 0.6 m SLR, and (**c**) 1.2 m SLR scenario, respectively. All sub-figures have the same spatial extent.

For Isaias occurring with 0.6 m of SLR (Figure 8b), the water depth increases in various degrees along the channel up to 84th St. (water depth ranging from about 0.5 m to few centimeters). In Eastwick, the increased water travels along the rail corridor, and water depth gets increased by <10 cm in most places to up to about 1 m near the rail corridor. From 84th St. to upstream, boundaries and overflow region near the landfill are unaffected by 0.6 m SLR. In this SLR scenario, JHR acts as a water retention basin as the comparison between Figure 8a,b shows a significant increase in water depth. For Isaias with 1.2 m of SLR, the effect of compounding reaches slightly northward near the landfill (comparison along the channel between Figure 8b,c). The water depth increases within the range of 10 s of cm to about 1.5 m inside Eastwick. In the downstream region, water depth increases about 1.5 m or less. A little newly flooded area near the airport accumulates water up to 2 m. This analysis shows that during an extreme event like Isaias, SLR will mainly cause additional flooding from downstream (through JHR along the rail corridor). In the present-day condition, Eastwick gets flooded from Cobbs Creek near the confluence of Darby and Cobbs (Figure 8a). Our analysis shows that SLR does not directly contribute to water level along the current overflow path into Eastwick. However, it will potentially create a new overflow path from downstream and exacerbate the flooding conditions. This illustrates that even a two-year return period storm tide event can exacerbate an extreme fluvial flood in future SLR conditions.

5. Discussion

This study develops a flood model of coastal and fluvial flooding for flood-prone Eastwick and applies it to study how SLR will affect tidal and fluvial flooding. A high-resolution 1D-2D fluvial-coastal flood model is developed to efficiently capture the hydraulics of the study area. We show accurate validations for two separate events: (i) monthly tidal event and (ii) extreme fluvial flood event Isaias. Results show high fidelity in replicating flooding conditions with time series RMSE of 0.08 m for tides (Figure 4) and 0.13 m for Isaias (Figure 6), the latter of which is similar to prior flood modeling studies [5,21,60]. This is a collaborative research project with Drexel University and the Philadelphia Water Department (PWD), and the model has been shared [46] through workshops with PWD, Philadelphia Office of Sustainability, the US Army Corps of Engineers, and others, who are either using our model to directly inform Eastwick planning efforts or have replicated aspects of our model in their own projects.

The results demonstrate a case where SLR can lead to chronic HTF and compounding of fluvial extreme floods in a fluvial floodplain. Prior research has demonstrated how SLR causes increased high-tide flood frequency and area [10,28,33], but little research has investigated the transition from fluvial extremes to high-tide flooding. Below, we discuss this further in Section 5.1. An important finding here is that the pathway by which coastal compounding of fluvial floods occur is outside the river channel, across a complicated floodplain. This water pathway may not be captured by models originally developed to study the purely riverine-driven flooding, such as that used by the USACE [41] in an ongoing flood risk reduction study. This is further discussed in Section 5.2.

Our modeling of the Isaias fluvial flood neglects both pluvial flood water and the stormwater drainage system, which during extreme rain events like Isaias likely leads to relatively small errors that partially counteract each other. A previous study of Isaias by AKRF [67] evaluated the flood water volume budget and showed that the total storm sewer volume is very low compared to extreme runoff volume. Additionally, the combined area of the Darby–Cobbs watershed is about 10 times larger than the area of Eastwick (Figure 1a), so the local pluvial source is also likely a relatively small fraction of all floodwaters. Modeling rain on the model grid requires significant additional computational power on our 2D model domain, and we have chosen to neglect it due to our broader project's goal of simulating hundreds of flood events for risk and adaptation assessment. From our perspective, allowing rain on grid modeling without incorporating the stormwater pipe networks will also show overestimation of flooding. Moreover, our HWM validation is very accurate, so our simulation represents a very good representation of Isaias flooding. In addition, the neglect of rain and stormwater system should have a minimal impact on the specific conclusions of this research.

5.1. Impact of SLR in a Fluvial Flood Prone Coastal Area

This paper demonstrates that SLR can lead to chronic HTF in a fluvial floodplain and compounding of fluvial extreme floods. Previous studies of Eastwick focused on fluvial extreme events and ignored [41] or greatly oversimplified the effect of SLR by only looking at the coastal 100-year flood event [43]. In this analysis, we illustrate the inception and gradual progression of tidal flooding over a range of SLR scenarios in Eastwick (Figure 7). With only 0.6 m of SLR, Eastwick will start experiencing monthly HTF flooding, and this could occur as soon as the 2060s. Eastwick is an example of communities that will be affected by SLR-induced HTF as predicted in Dahl et al. [33] and Thompson et al. [24], although there is no historical case of Eastwick experiencing a coastal flood.

Moreover, consistent with what was demonstrated by Sweet and Park [28], our results illustrate that future, regularly occurring tidal floods in Eastwick can be as extensive as today's extreme fluvial floods. According to SLR projections, as soon as the 2080s, current day Isaias-like flooding can become a frequent phenomenon in Eastwick. Because of the high frequency of occurrence, HTF can cause more cumulative damage than infrequent extreme flood events [17].

In the case of extreme fluvial flood, SLR causes a shift towards flood compounding from the coastal source. In the analysis of impact of SLR in extreme fluvial flood like Isaias, first we study the influence of present-day tide in the water level inside the model domain. The result (Figure 8a) shows that the overtopping region and flooded area in Eastwick is predominantly driven by river flow. But with imposed SLR of 0.6 m and 1.2 m (Figure 8b,c), it is seen that the flood water depth in Eastwick increases significantly compared to the increase in the water level along the creek channel. SLR-driven higher tide exacerbates the flooding from Eastwick, directing additional flooding from the downstream breach location (along railroads in Figure 1b). This indicates that Eastwick will be prone to more flooding during extreme events in the future, and the additional flooding due to SLR will have more compounding characteristics.

5.2. New Pathways: An Additional Compound Flood Modeling Challenge

An additional challenge for modeling future compound flooding is that rising sea levels can lead to new floodwater pathways outside of river channels. Not only is compounding often neglected in flood-risk assessment and mitigation studies, but past models may not be capable of capturing these novel flood pathways. Only one recent study of Eastwick for redevelopment purposes by AKRF [42,67] initially incorporated compounding effects of sea level rise into a fluvial flood model with some simplistic assumptions. Because of less computational expense, 1D and 1D-2D flood modeling is very popular in fluvial flood related studies [5,29,37,48]. However, 1D or 1D-2D models based on existing flood flow pathways may overlook new flood pathways emerging from alterations in flood drivers. For example, because of not placing the lateral connection between 1D-2D flow area, the Princeton Hydro [43] study would not capture the flow pathway along the rail corridor. AKRF [42], on the other hand, captured this pathway because of connecting the 2D area with 1D cross sections.

The design of flood mitigation measures without considering possible HTF and compounding of extreme floods might not provide adequate protection in the future. For example, the current proposed USACE ([41,59]; and current ongoing work) mitigation measure for Eastwick is building a levee along the overtopping region north of the landfill in Eastwick. A levee can be effective in reducing the impact of fluvial flood, but with time, as the impact of SLR becomes more observable, residents of Eastwick will be facing frequent HTF and flooding from coastal sources along novel pathways.

6. Summary and Conclusions

This study investigates the impact of SLR in high-tide flooding and compounding of extreme flooding in a historically fluvially flooded area. An efficient 1D-2D HEC-RAS model is developed based on the best available data and made publicly available. The 1D-2D approach effectively captures the flooding in Eastwick with correct tide phase in the creeks. The model is validated for two events: (i) regular high-tide event and (ii) extreme flow event TC Isaias. To overcome the scarcity of good quality observed data, a scaled-up flow estimation approach used by USACE is used to estimate the flow during extreme event TC Isaias. Model results accurately replicate the water level time series and high water marks with RMSE 0.08 m for tide, 0.13 m for Isaias time series, and 0.32 m for Isaias high water marks inside Eastwick. The ME values are 0.04, −0.08, and 0.28 m, and the MAE values are 0.07, 0.014, and −0.09 m for these respective validation datasets. The error in the low waters can be attributed to the uncertainty in the river bathymetry below the 84th St. gage location.

This paper demonstrates that SLR can lead to chronic monthly HTF and compounding of fluvial extreme floods in what is presently only a fluvial floodplain. In the investigation of the impact of sea level rise in high-tide flooding, we found that Eastwick can start experiencing high-tide flooding as soon as the 2060s based on IPCC 2022 SLR projections. The total flooded area will increase rapidly and, in the 2080s, Eastwick may be experiencing high-tide flooding that is similar in extent (34.4%) to today's extreme fluvial flooding

(30.7%). Fluvial extreme flooding also gets compounded due to SLR. For an Isaias -like extreme event with 0.6 m of SLR, the water level gets increased by <10 cm in most places inside Eastwick except for along a rail corridor where the water level increases up to 1 m compared to the base scenario. With 1.2 m of SLR, the water level increases by 30–50 cm in most places, reaching 1.5 m in the most vulnerable places. In both cases of SLR-driven monthly HTF and extreme flooding, JHR retains flood water, and any excess water enters Eastwick from a new pathway. The 2D representation of the Lower Darby Creek and its neighboring wetlands enables us to identify this new flow pathway. The impact of SLR and alteration in flood pathways has rarely been considered in flood-related studies in Eastwick. All the current adaptation plans address protection from upstream riverine overflow only. However, our analysis suggests that SLR will be an important flood driver in the future, causing HTF and compound flooding, and, hence, needs to be incorporated in future flood protection plans.

A better understanding of the future changes in flood sources and pathways is crucial to identifying effective, long-term, and holistic flood risk mitigation measures. Fragmented approaches towards flood risk reduction need to be replaced by a more integrated approach [68,69]. Several studies have argued for the need for investing in holistic adaptation now to avoid greater costs in the future [70,71]. The application of bi/multivariate flood hazard assessments considering climate change effects can lead to improved design and testing for flood mitigation measures. Places at risk of facing more compounding of flooding in the next few decades, similar to Eastwick, should be studied, and the implementation of effective adaptation measures should be prioritized.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15142671/s1, Table S1: Manning's roughness with (a) various land use types (b) channel sections; Figure S1: Temporal maxima flooding of USGS measured flow-forced model of Isaias; Figure S2: Location of High-Water Marks of Isaias in Eastwick neighborhood collected by USACE.

Author Contributions: Conceptualization, P.O. and K.S.M.; methodology, P.O. and K.S.M.; software, K.S.M. and F.S.; validation, K.S.M.; formal analysis, K.S.M.; investigation, K.S.M. and P.O.; resources, P.O., F.M. and J.R.; writing—original draft preparation, K.S.M.; writing—review and editing, K.S.M., P.O., F.M., F.S. and J.R.; visualization, K.S.M.; supervision, P.O.; project administration, P.O., F.M. and J.R.; funding acquisition, P.O., F.M. and J.R. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: All data used in this study are available through public repositories. The DEM data is downloaded from https://www.pasda.psu.edu (accessed on 12 June 2023). For mentioned USGS gages, data are downloaded from https://waterdata.usgs.gov/nwis (accessed on 12 June 2023). Water level data are collected from NOAA https://tidesandcurrents.noaa.gov (accessed on 12 June 2023). The land use dataset is obtained from https://www.mrlc.gov (accessed on 12 June 2023). The current version of the model is shared in public domain: https://data.mendeley.com/datasets/3wjvmymf68/2 (accessed on 12 June 2023).

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Appendix B:
Climate Impacts and Adaptation Assessment for Fluvial, Coastal and Compound Flooding in Eastwick

Methodology

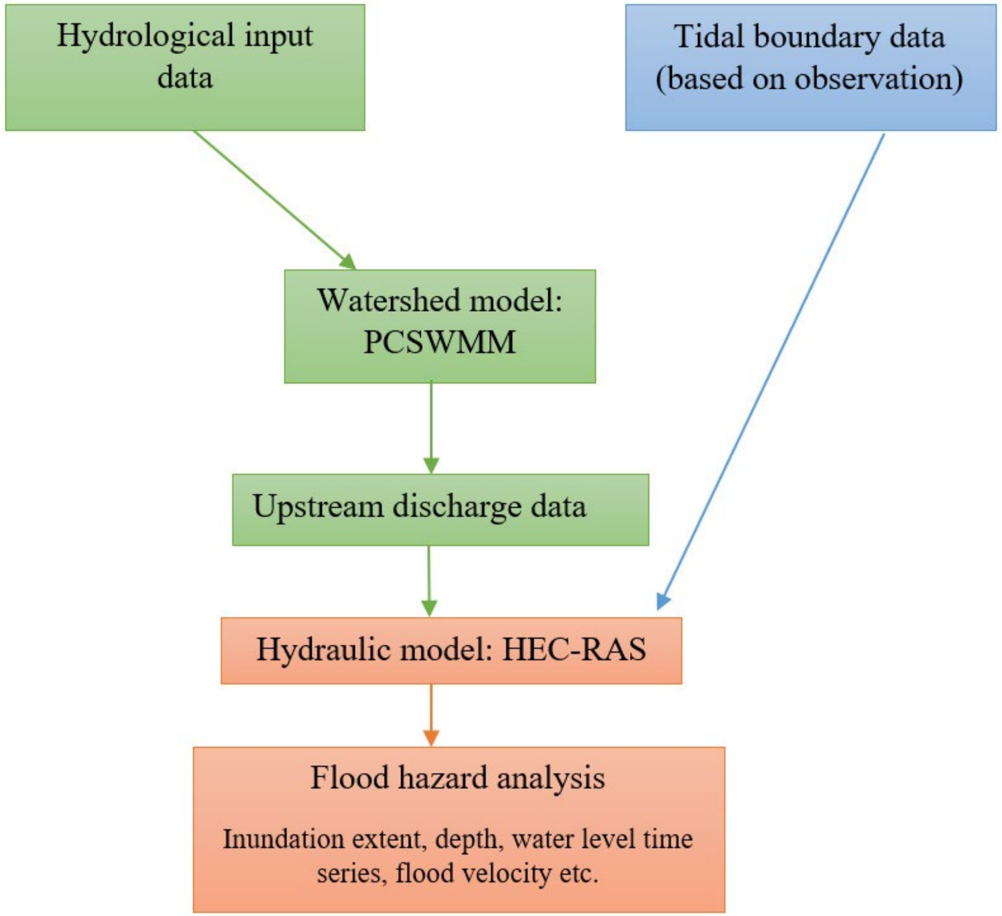


Figure: Flow chart of one-way coupling modeling framework.

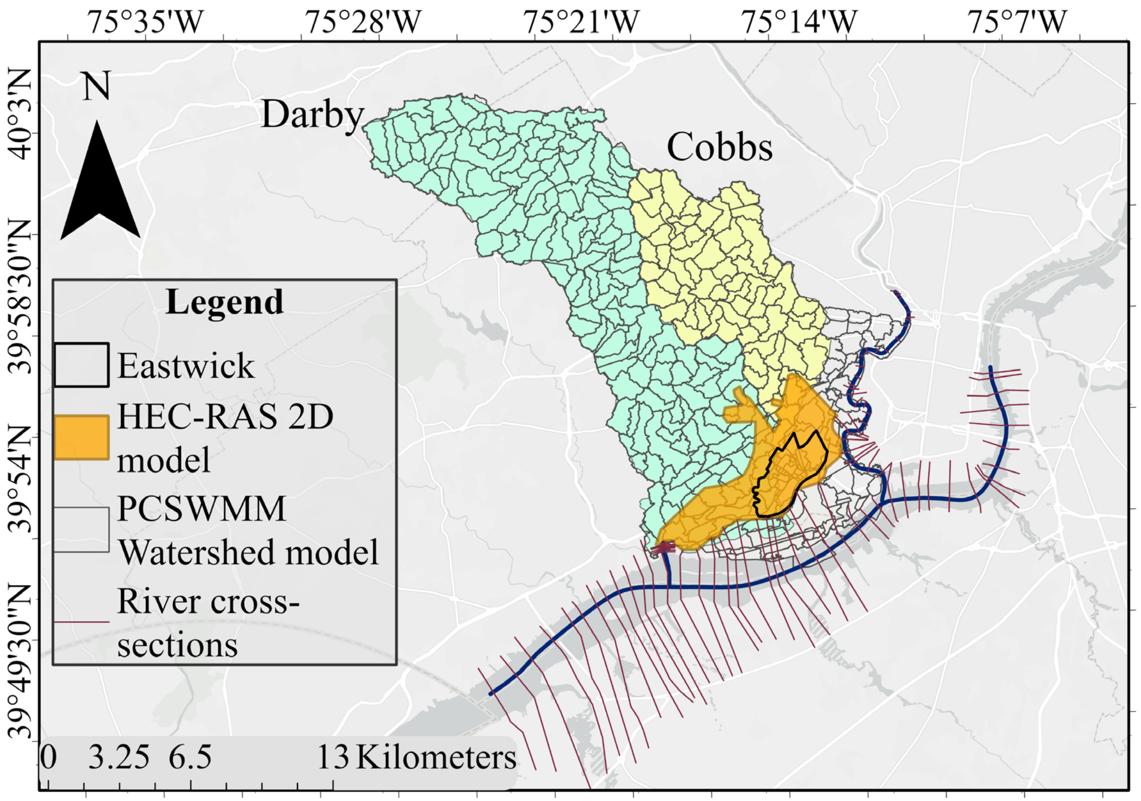


Figure: Combined model domain PCSWMM watershed model and 1D-2D HEC-RAS model domain

Storm set

Storm set

Historical discharge dominated event : **Isaias (~30 year return period)**
Synthetic discharge dominated event : **100-year fluvial event**
Historical water Level dominated event: **1950 storm (~175-year event)**
Historical compound event **: Irene (see below)**
Synthetic compound event : **100-year compounding event**

	Return period (years)	
Event	Rainfall	Water Level
Isaias	~30	0.908
1950	4.42	175
Irene	33.21	6.013

Climate Scenarios

Sea level rise

According to IPCC AR6 2022 SSP58.5 Projections

Mid century - 2 ft SLR

End century- 4 ft SLR

Rain Increase

NOAA mid-Atlantic Regional Integrated Sciences and Assessments (MARISA) study Miro et al., 2021)

Mid century- 25% increase in rainfall

End century- 50% increase in rainfall

TC climatology change

(only for extreme coastal event)

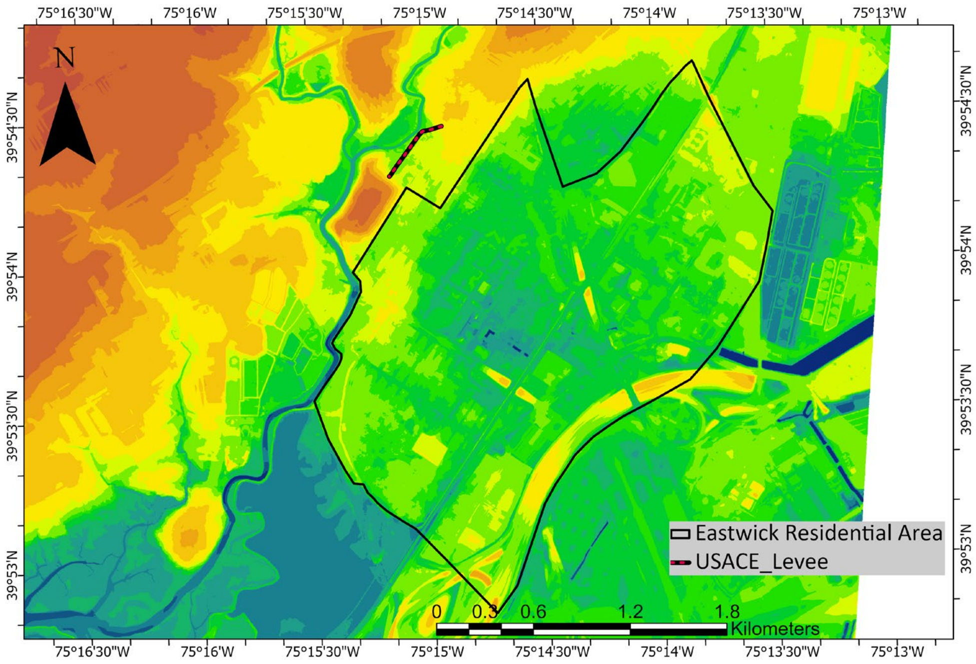
According to Marsooli et al. (2019) Under SSP5 8.5, contribution in coastal water level due to TC climatology is projected to be

Mid century – 0.5 ft

End century- 1 ft

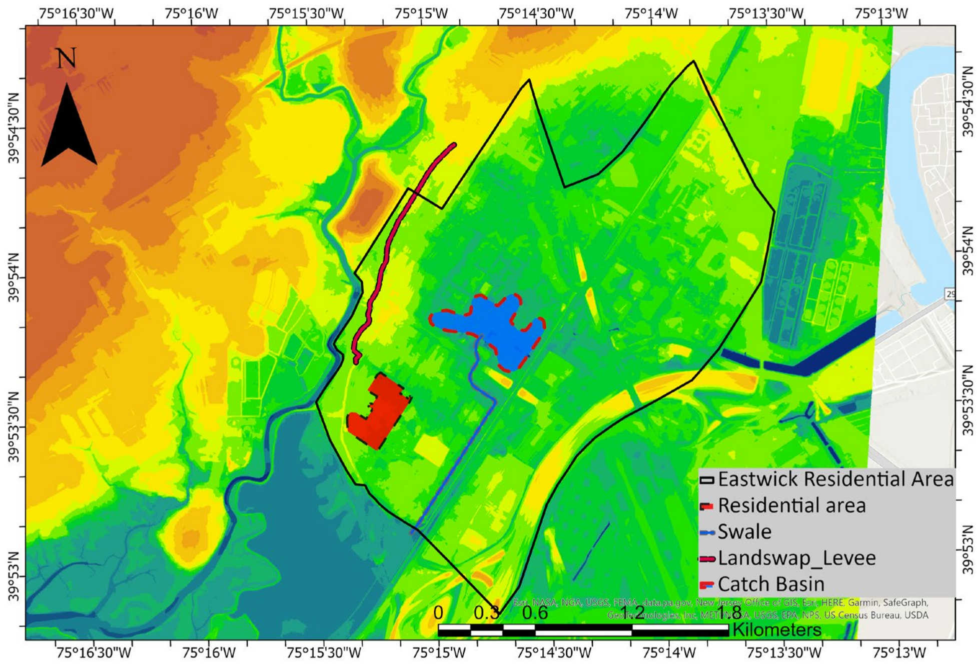
Flood mitigation Strategies

Levee



- Levee alignment based on recommendation of USACE (2023) study
- Top of berm elevation set to 24.7 ft NAVD-88**

Land Swap



- Co-developed with community in our project
- Includes grey, green infrastructure and moving community across neighborhood **

**These adaptation plans are based on latest available information.

Simulation scenarios

Storm Set

1. Isaias
2. Irene
3. 1950 storm
4. 100-year fluvial event
5. 100-year coastal event

Adaptation strategy

1. No Adaptation
2. USACE Proposed levee
3. Land swap

Climate change scenarios

Base scenario (2020 MSL)

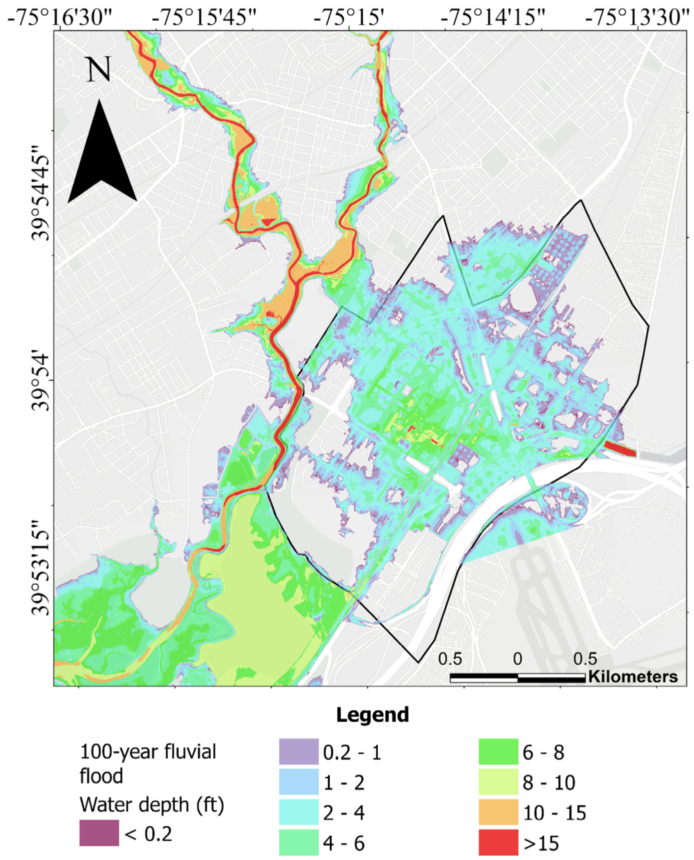
Mid-century Scenarios

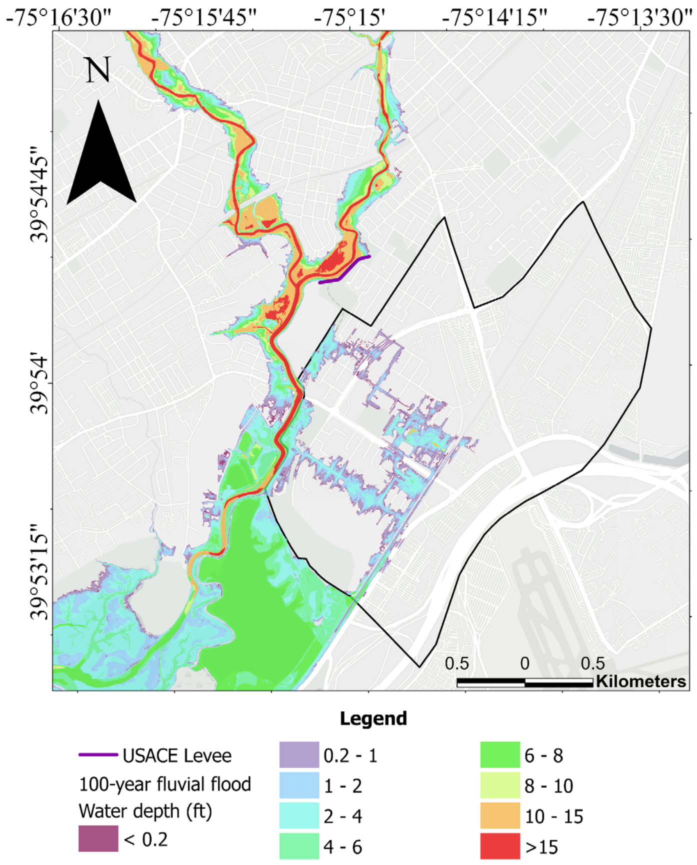
1. SLR 2 ft
2. Rainfall increase 25%
3. Both

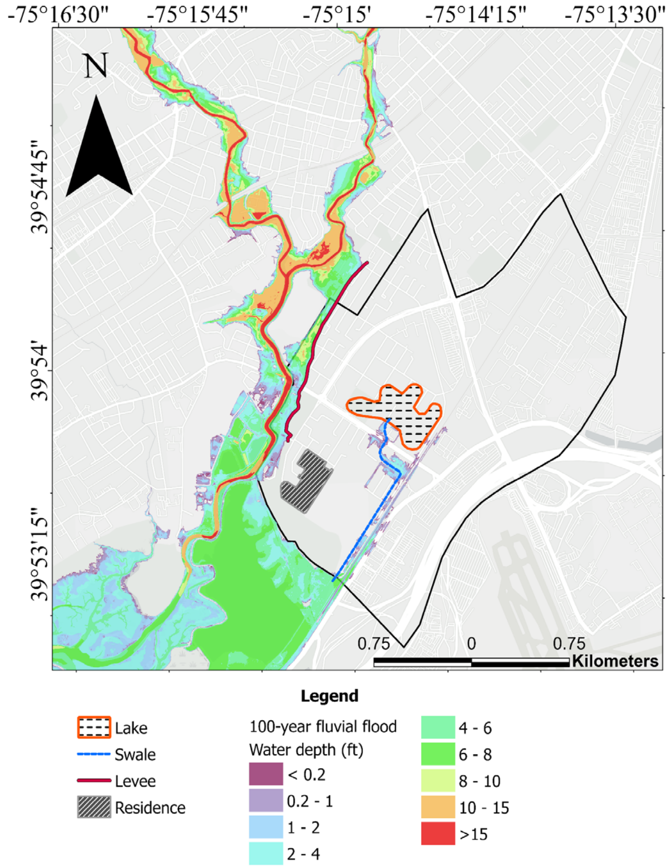
Late-century Scenarios

1. SLR 4 ft
2. Rainfall increase 50%
3. Both

Adaptation Efficacy Comparison: 100-year Fluvial (Present day)

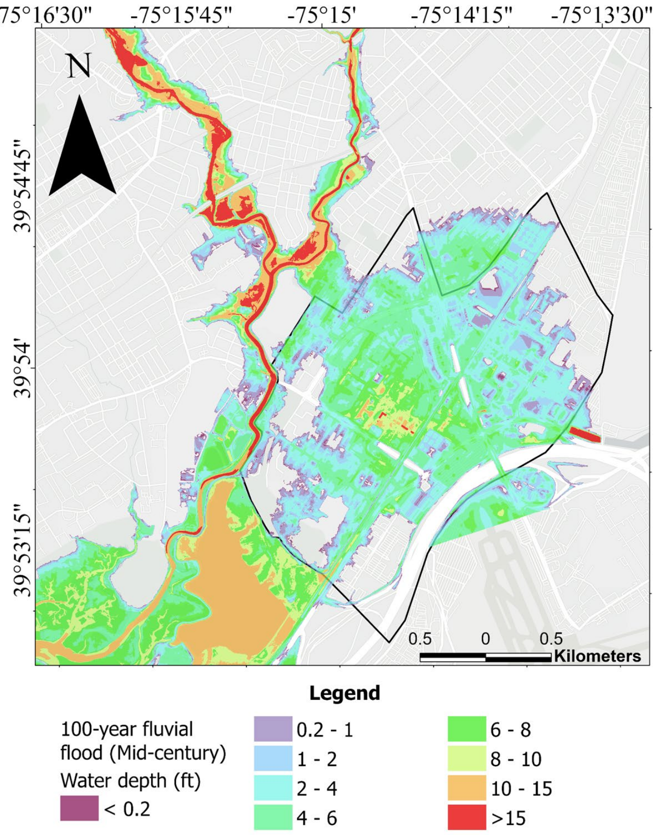


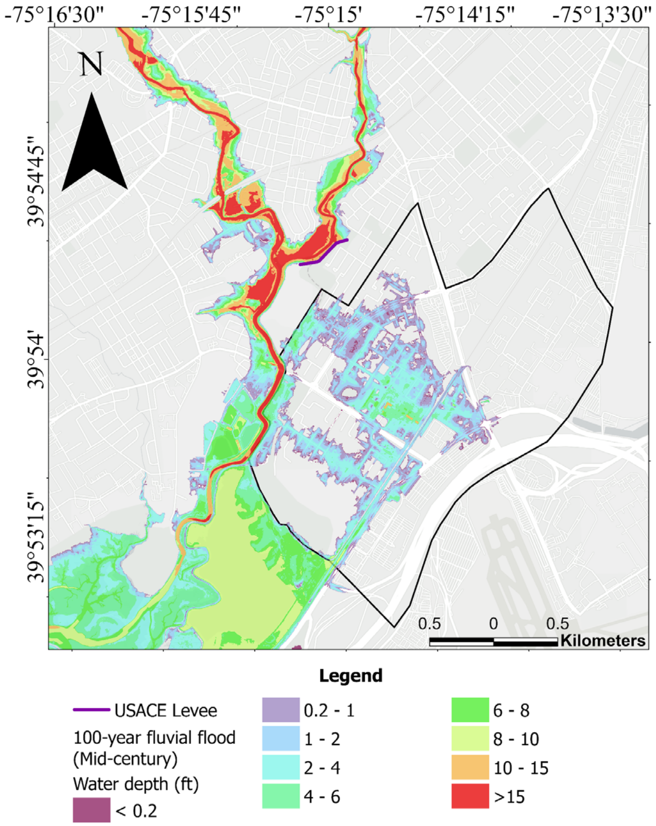


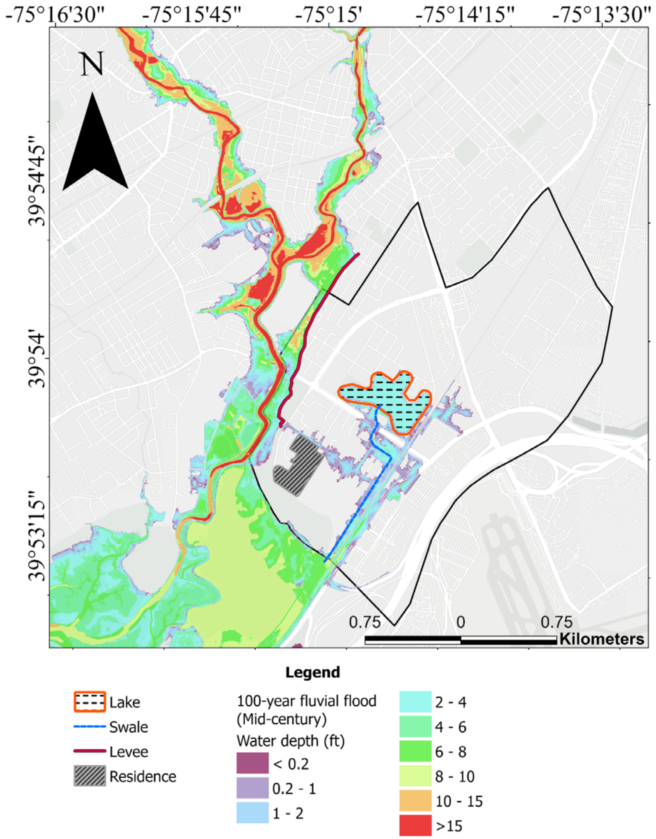


Both levee and landswap reduces flooding significantly in Eastwick.
However, neither provides protection entirely from flooding as there is slight overflow in both cases

Adaptation Efficacy Comparison: 100-year Fluvial (Mid century)



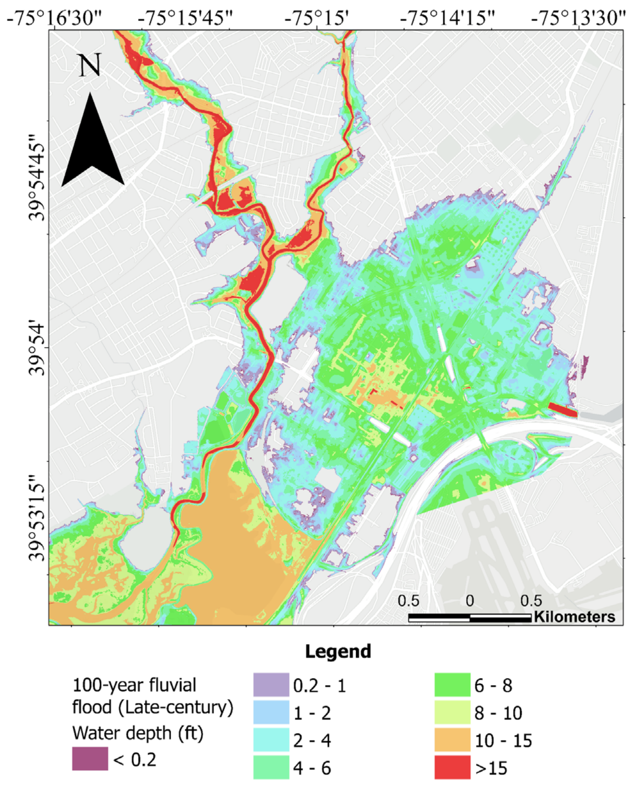


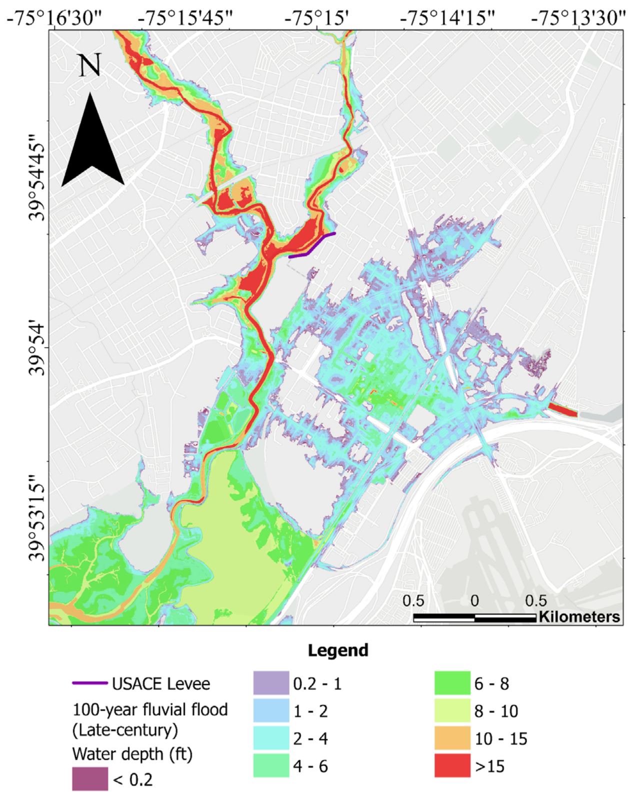


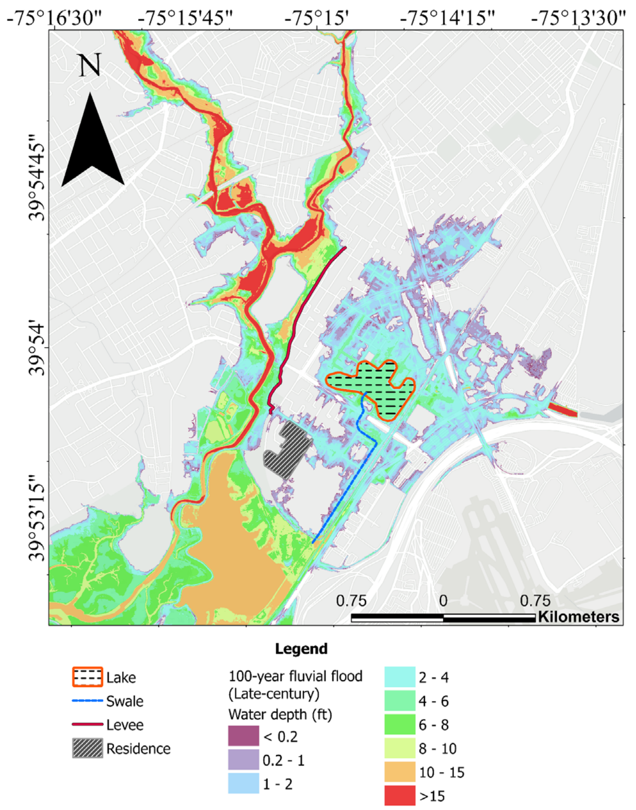
Levee: While still effective in reducing flooding, in mid century climate change scenario, overflow region near 86th st. and SEPTA track causes extensive flooding in Eastwick.

Landswap: Landswap provides partial protection reducing flooding from the 86th st. overflow region but there is still flooding from SEPTA track direction

Adaptation Efficacy Comparison: 100-year Fluvial (Late century)



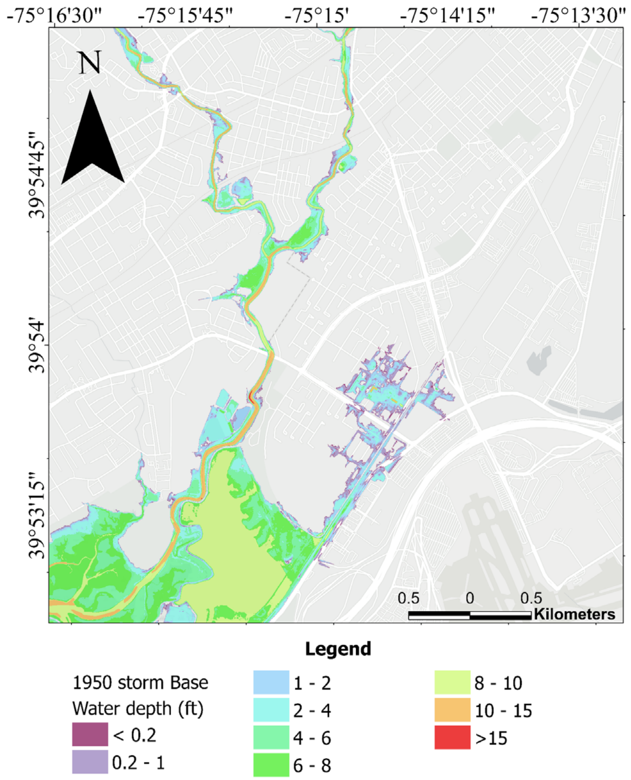


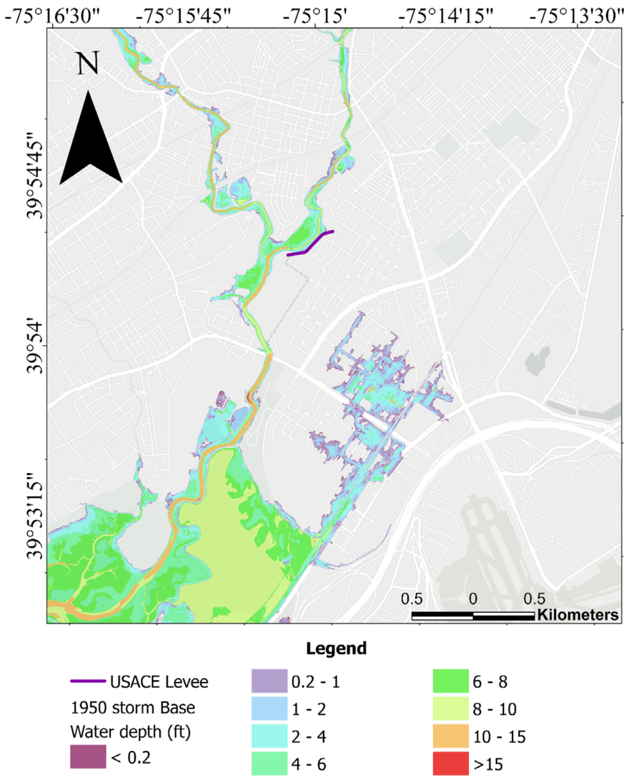


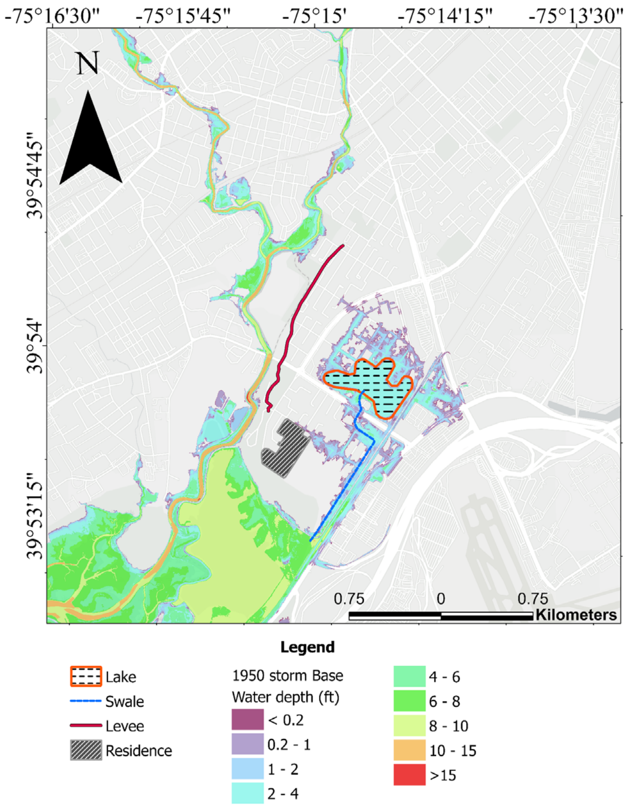
Levee: The levee is partially protective in reducing flooding in Eastwick. It protects against flood pathway, but not others.

Landswap: Flooding occurs from both 86th st. overflow region and SEPTA track direction.

Adaptation Efficacy Comparison: 1950 storm (Present day MSL)

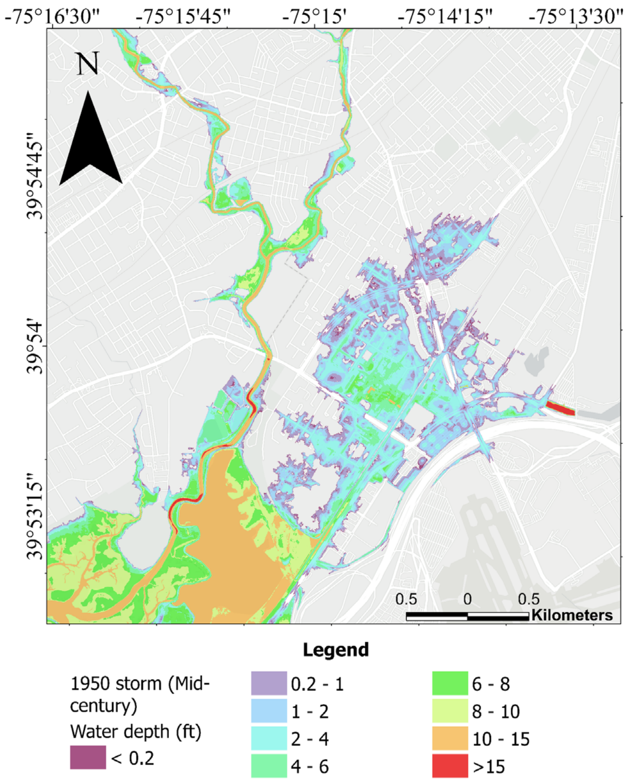


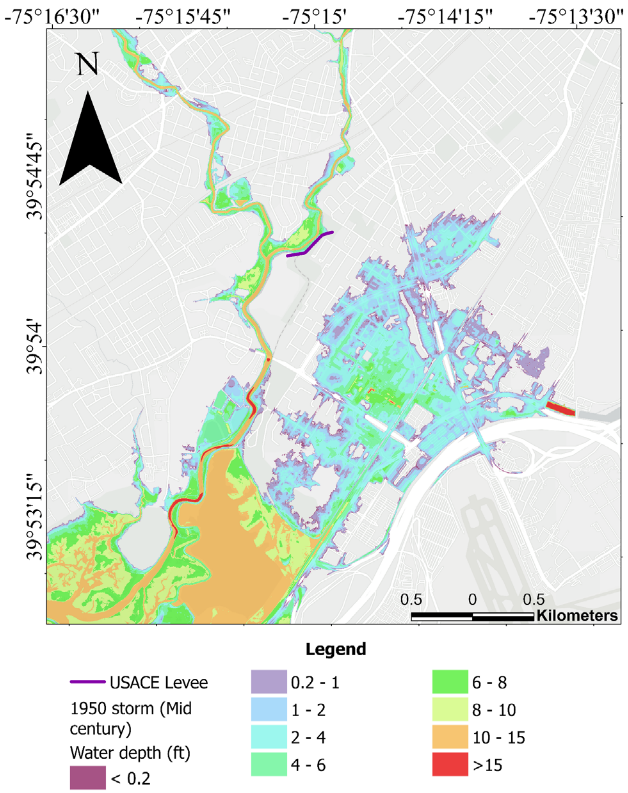


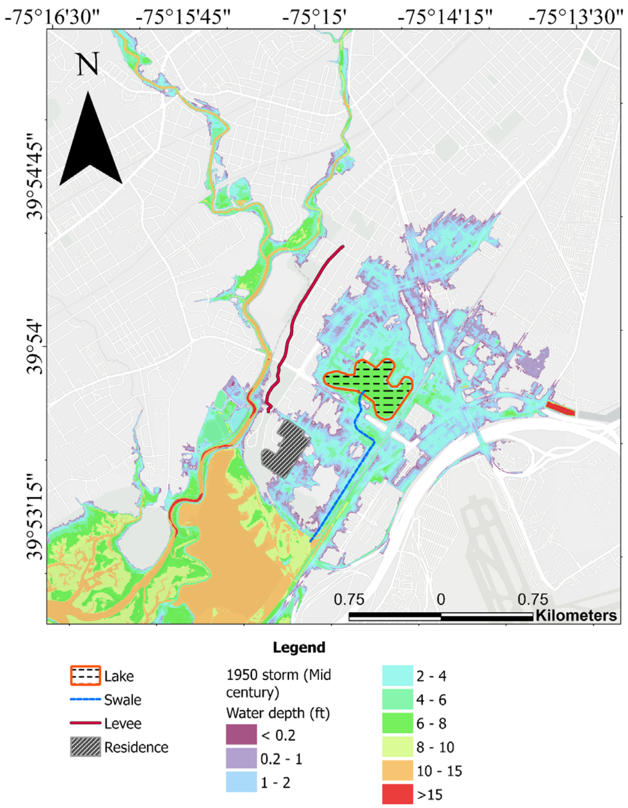


- In present day condition, extreme coastal flood event causes moderate amount of flooding in Eastwick
- The proposed adaptation strategies do not attenuate present day coastal flooding

Adaptation Efficacy Comparison: 1950 storm (Mid century)

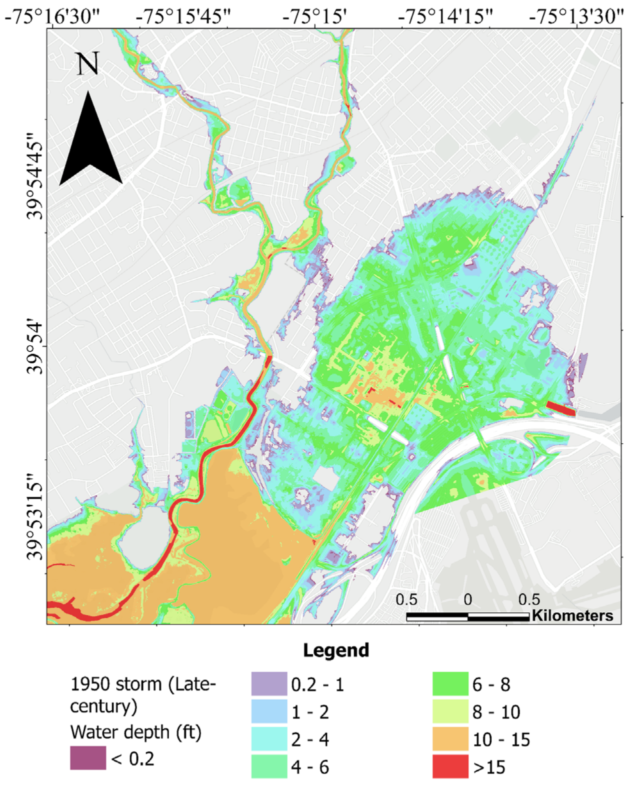


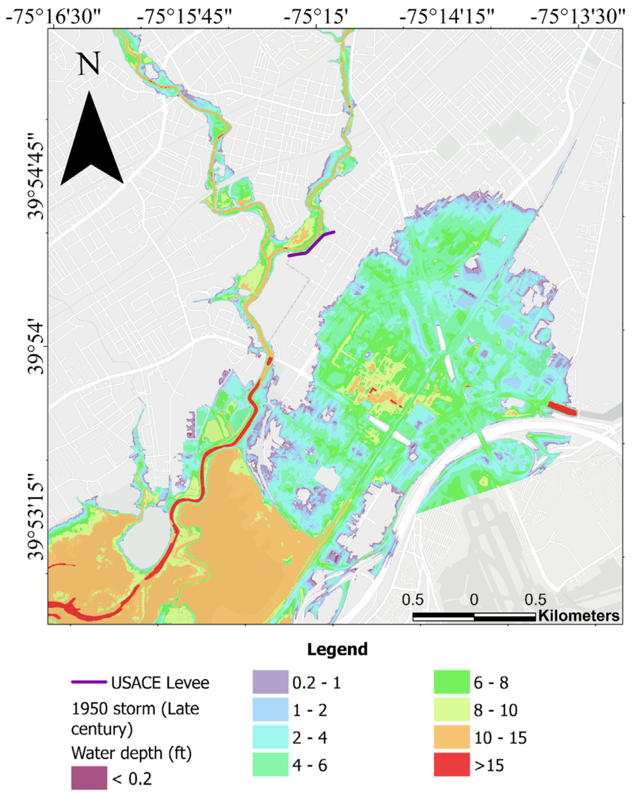


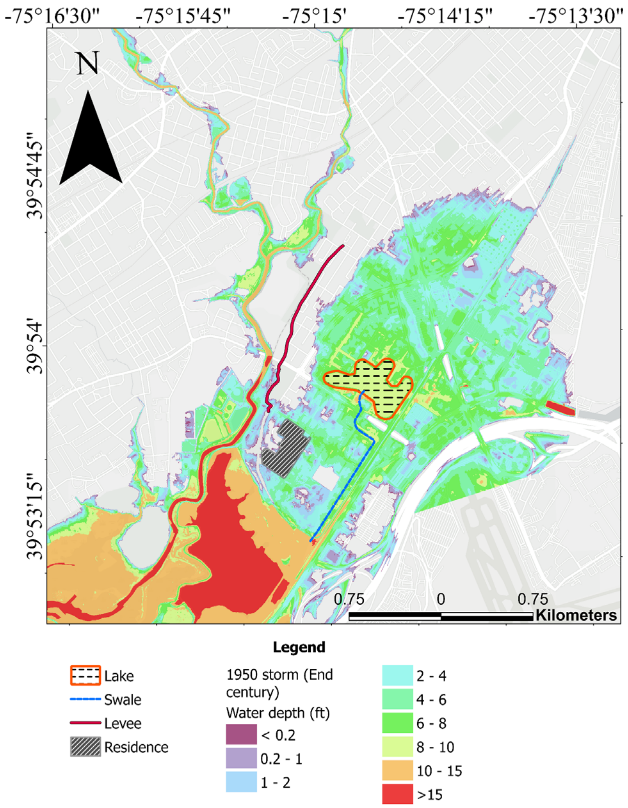


In Mid and Late century scenarios, coastal flooding gets worsened significantly

Adaptation Efficacy Comparison: 1950 storm (Late century)







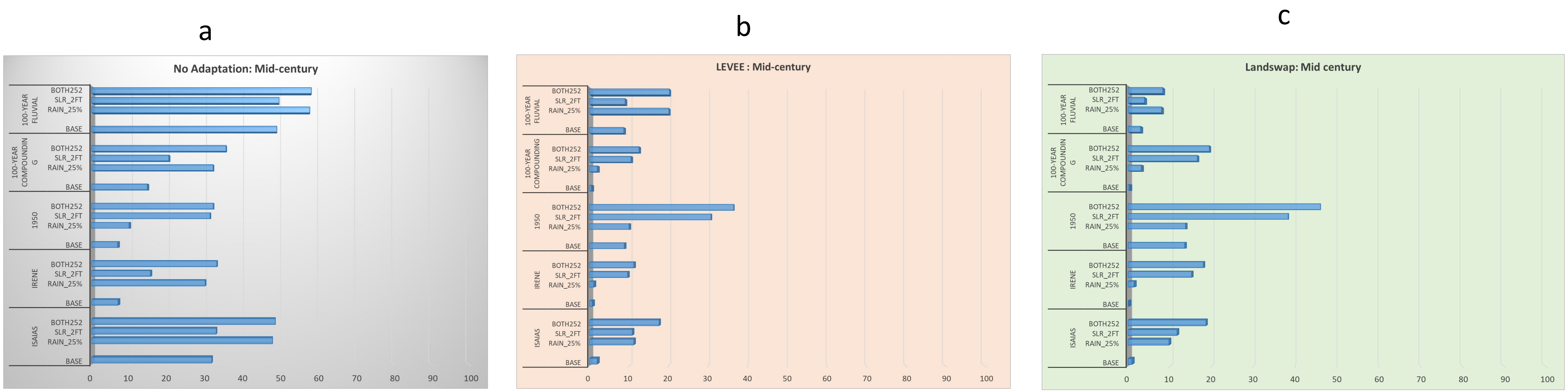


Figure: Total flooded area in base and mid-century scenarios in (a) No adaptation (b) Levee and (c) Landswap adaptation scenario

Total flooded area: Mid century

- Both levee and landswap is effective in reducing fluvial and compound flooding in Eastwick. However, both are not as effective in reducing the flooding in extreme coastal event.
- Landswap worsens the coastal flooding, due to having an intentional pathway (the canal) leading to a retention basin lake at Pepper School

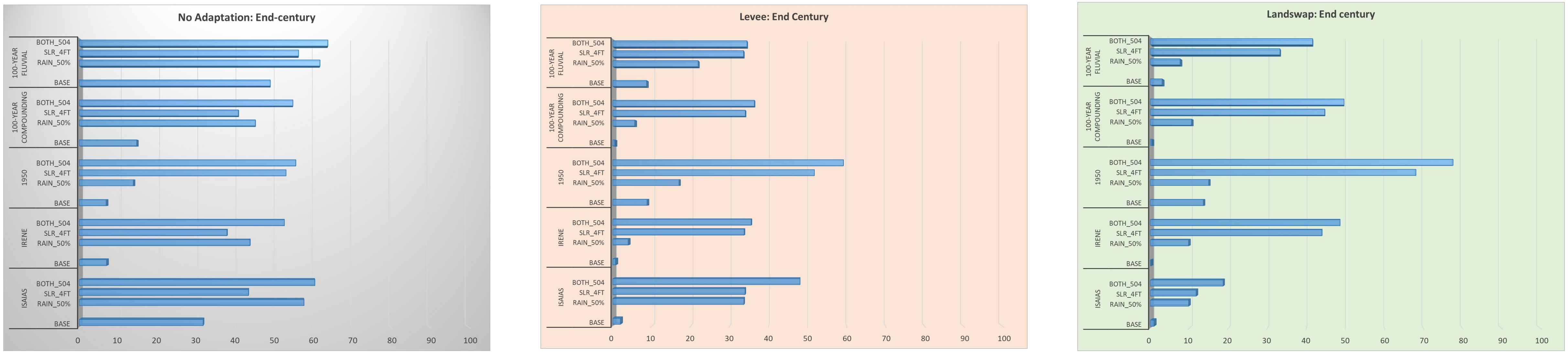


Figure: Total flooded area in base and Late-century scenarios in (a) No adaptation (b) Levee and (c)Landswap adaptation scenario

Total flooded area: End century

- Both levee and landswap is effective in reducing fluvial and compound flooding in Eastwick. However, both are not as effective in reducing the flooding in extreme coastal event.
- Landswap again worsens the coastal flooding

Synthetic 100-year Fluvial Event

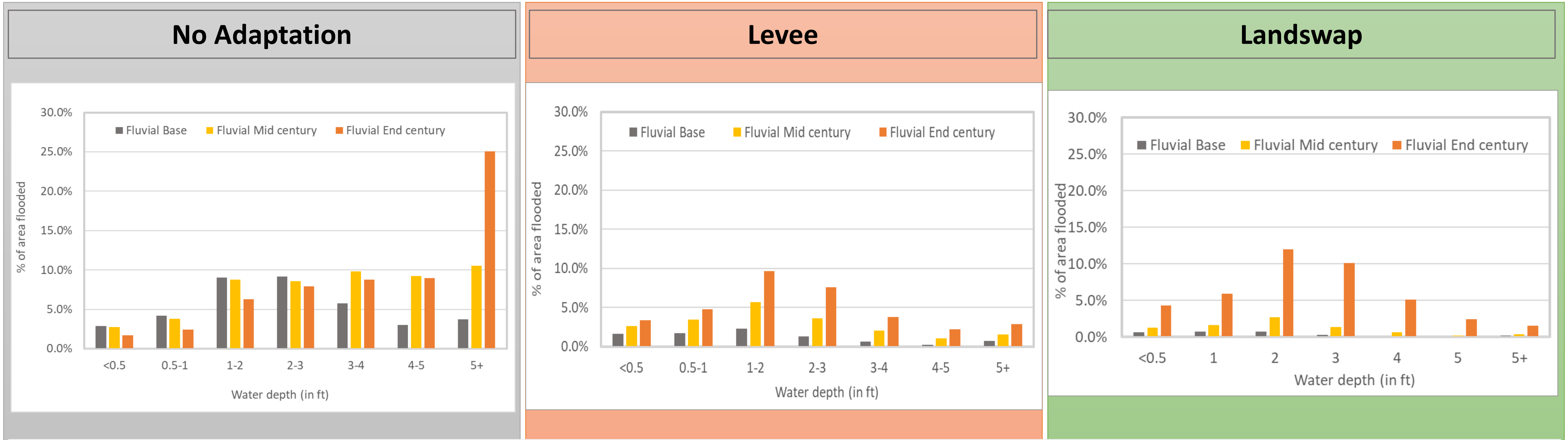


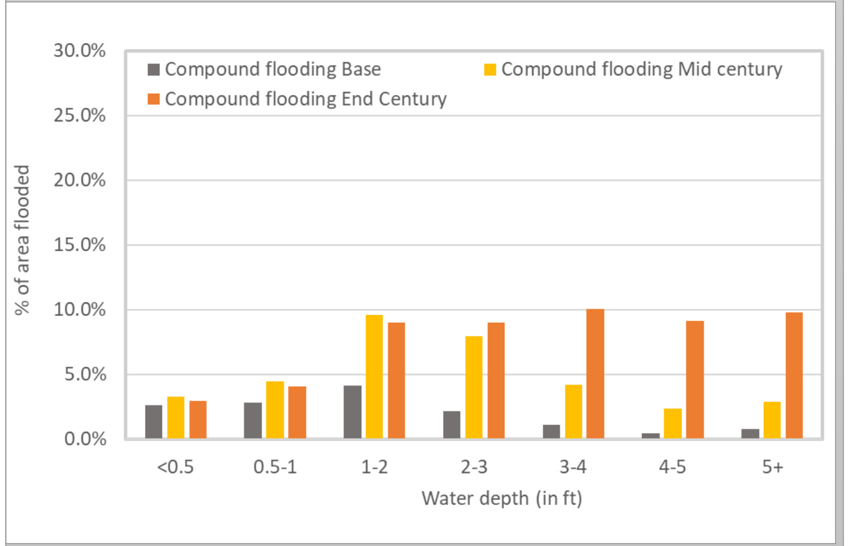
Figure: Temporal variation in flooded area under water depth range for 100-year fluvial event in (a) No Adaptation (b) USACE Levee and (c) Landswap adaptation scenarios

Levee and landswap both provide significantly reduce flood depths in base scenario (comparing grey bars)

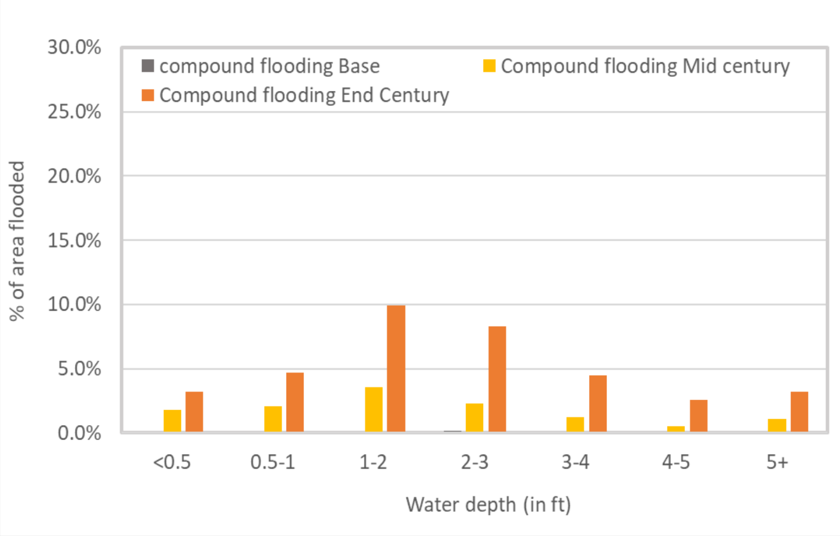
In climate change scenarios both levee and landswap effectively reduce areas under higher flood depth (comparing distribution of yellow and orange bars)

Synthetic 100-year Compound flood Event

No Adaptation



Levee



Landswap

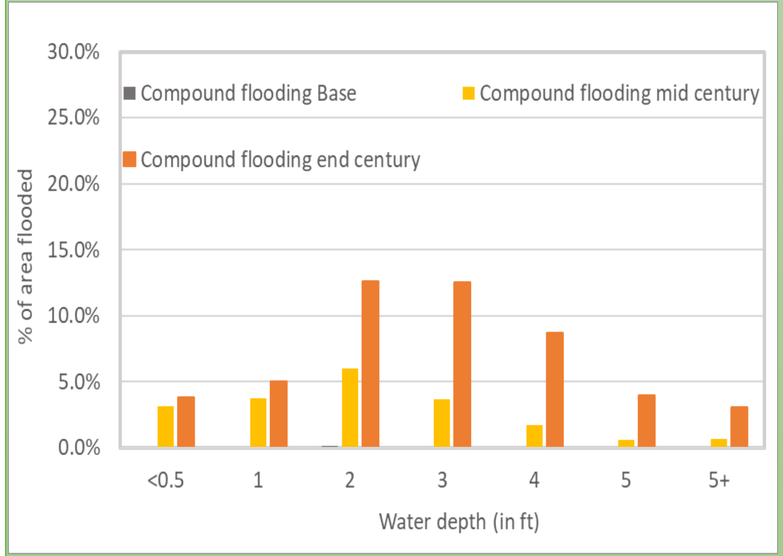


Figure: Temporal variation in flooded area under water depth range for 100-year compound flood event in (a) No Adaptation (b) USACE Levee and (c) Landswap adaptation scenarios

Levee and landswap both provides great protection in reducing flooding in base scenario (comparing grey bars)

In climate change scenarios both levee and landswap effectively reduces areas under higher flood depth (comparing distribution of yellow and orange bars)

1950 Coastal Event

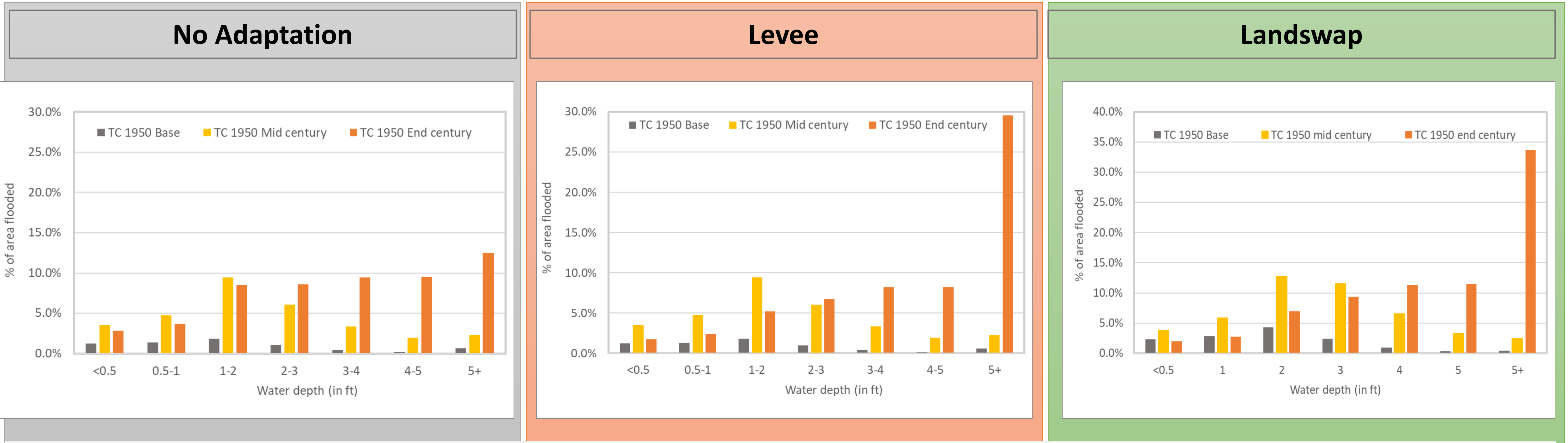


Figure: Temporal variation in flooded area under water depth range for 1950 coastal event in (a) No Adaptation (b) USACE Levee and (c) Landswap adaptation scenarios

Both levee and landswap does not provide protection against extreme coastal storm induced flooding in base, mid and end century scenarios. Both of the adaptation measures worsen the flood condition to various degrees during the time horizon (this chart and total area flooded chart).

Both adaptation measures causes area under deeper flooding to increase.

TC Irene

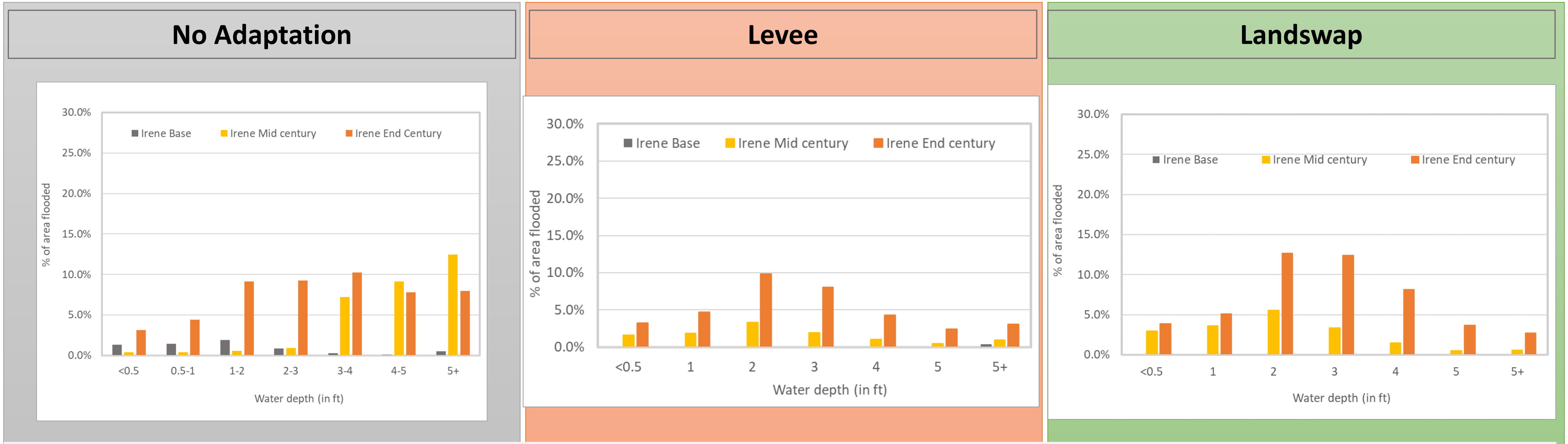


Figure: Temporal variation in flooded area under water depth range for TC Irene in (a) No Adaptation (b) USACE Levee and (c) Landswap adaptation scenarios

For Irene, comparing base scenarios, landswap provides better protection in reducing flooding than levee.

In future climate conditions however, levee performs slightly better than landswap.

In both cases, there is significant reduction in deep flood water

TC Isaias

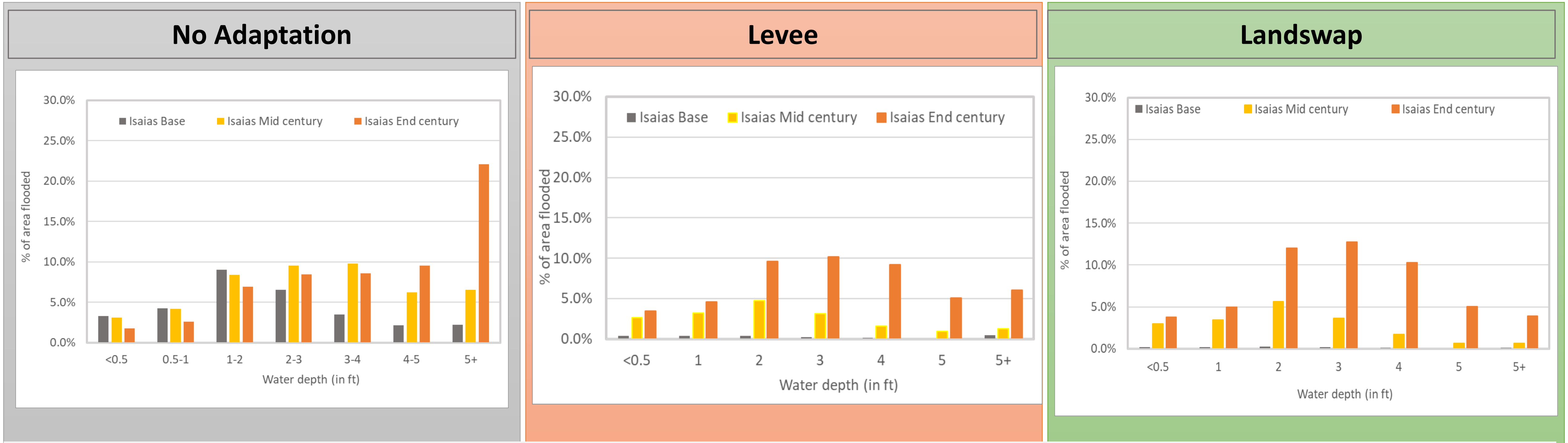


Figure: Temporal variation in flooded area under water depth range for TC Isaias in (a) No Adaptation (b) USACE Levee and (c) Landswap adaptation scenarios

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Appendix C

PCSWMM Simulations of TS Isaias

PCSWMM Modeling of Isaias Flooding in the Downstream Portion of the Darby Cobbs Watershed With and Without Adaptation

Dr. Franco Montalto, P.E.

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DREXEL UNIVERSITY College of Engineering

CCRUN A NOAA RISA Team

STEVENS INSTITUTE of TECHNOLOGY THE INNOVATION UNIVERSITY

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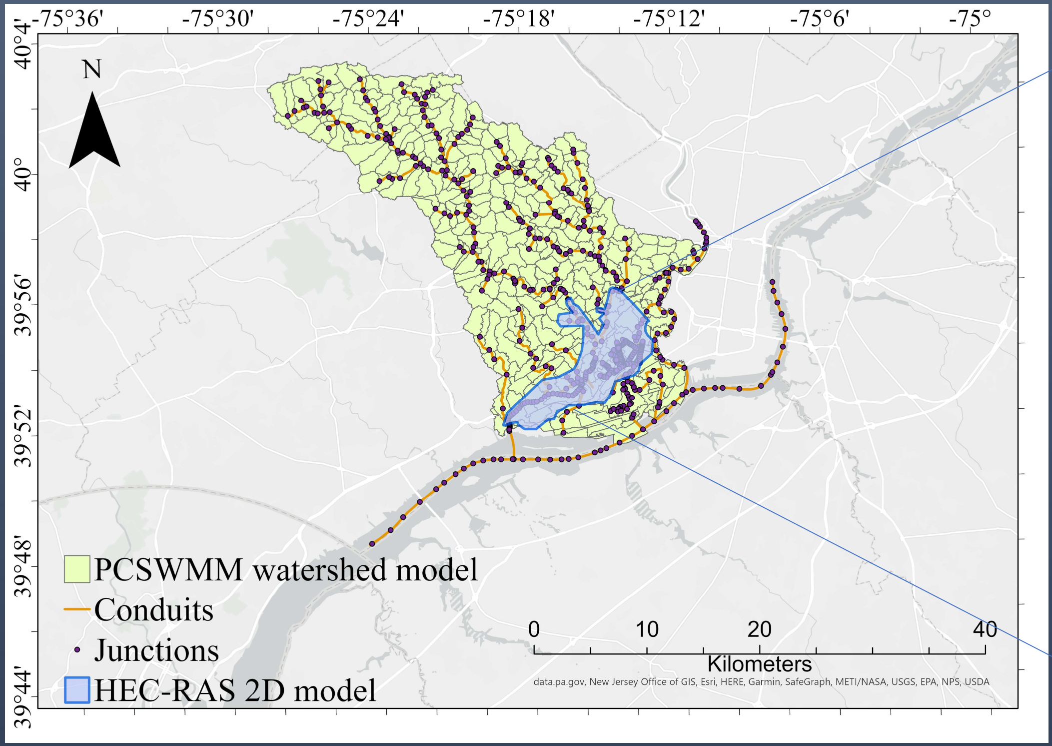
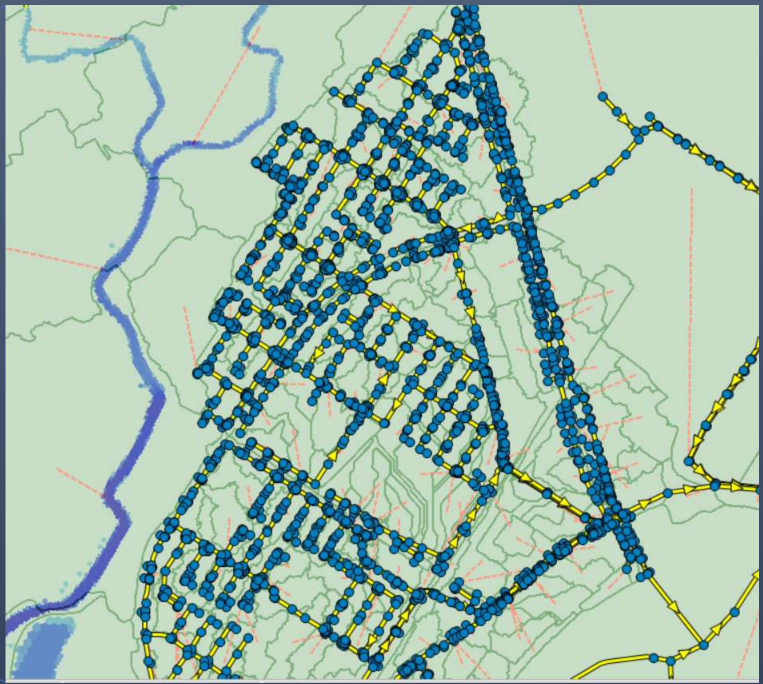
Description of Modeling Tools

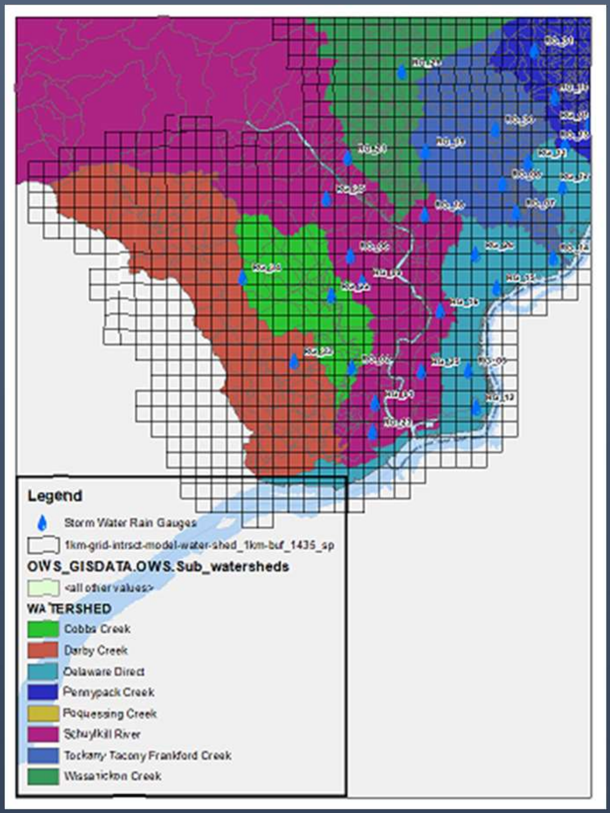
A. PC-SWMM watershed model
B. 1D/2D HEC-RAS-1D/2D coupled with PC-SWMM watershed model
C. PC-SWMM watershed model with quasi-2D representation of Eastwick drainage system



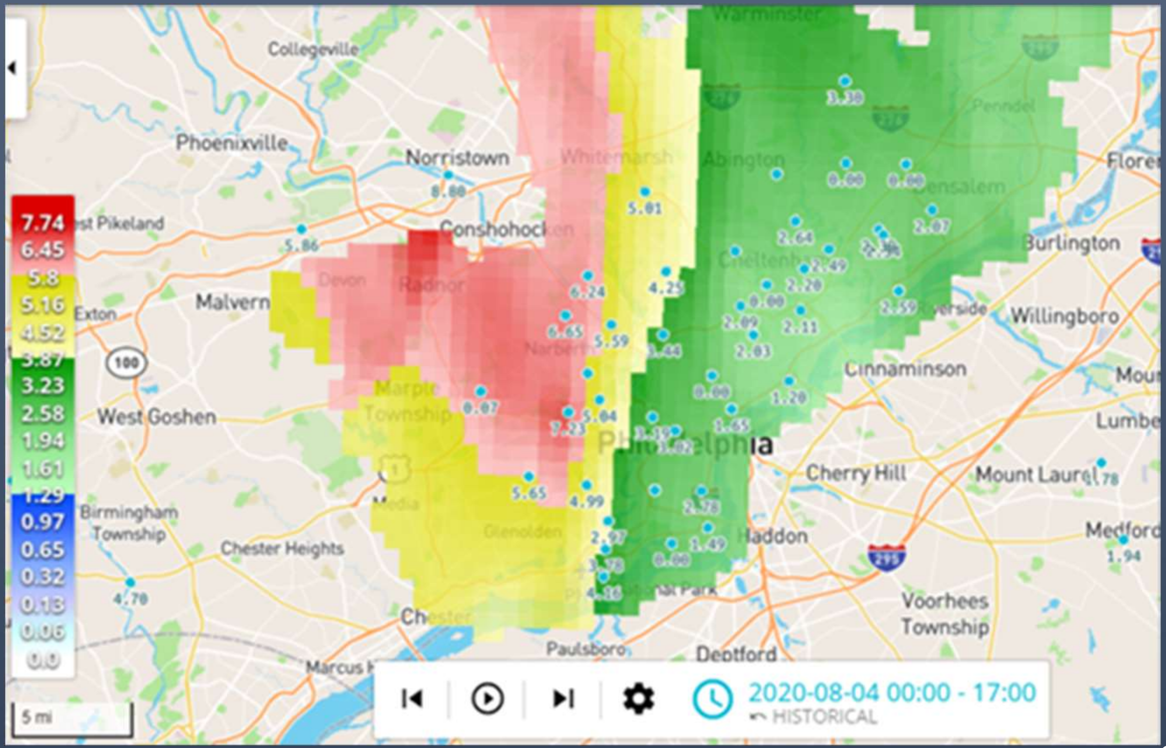


PC-SWMM Model Design

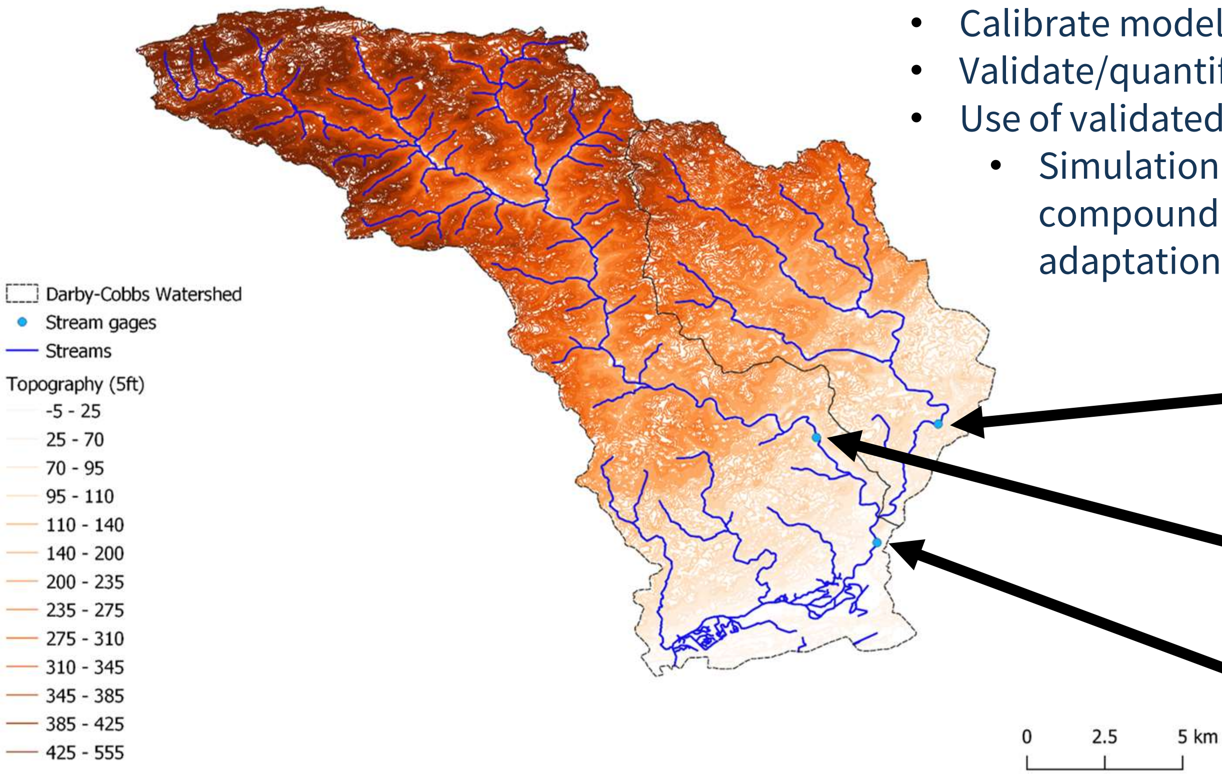
PWD Gage Adjusted Radar Rainfall (GARR)



Rainfall distribution, Isaias 8/4/20



PC-SWMM Calibration and Validation Procedures



Overview of Approach

- Calibrate model to Isaias and other 2020 events
- Validate/quantify model accuracy using Hurricanes Irene and Lee
- Use of validated model:
  - Simulation of Darby/Cobbs flows under different future compound climate conditions, with different forms of adaptation strategies in place

Cobbs Creek flow data:

- USGS Gage 01475548 at Mt. Moriah Cemetery, Philadelphia

Darby Creek flow data:

- USGS 01475510 near Darby, PA

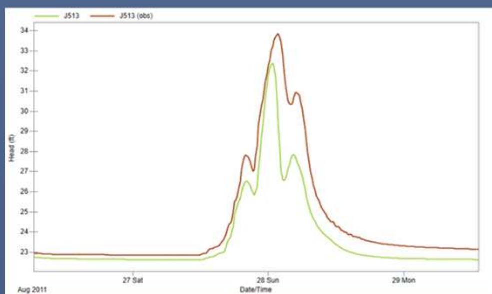
Combined flow

- USGS 01475553 at 84th Street

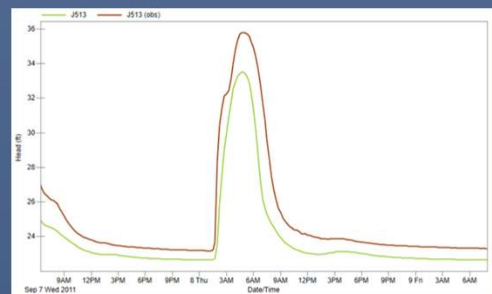
PC-SWMM Calibration and Validation Procedures

Simulated and Observed Cobbs Creek Stage (USGS Gage 01475548 at Mt. Moriah Cemetery, Philadelphia)

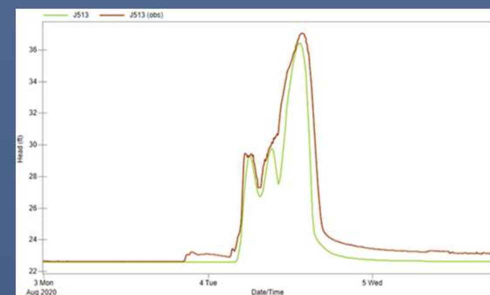
Hurricane Irene (2011)



Hurricane Lee (2011)

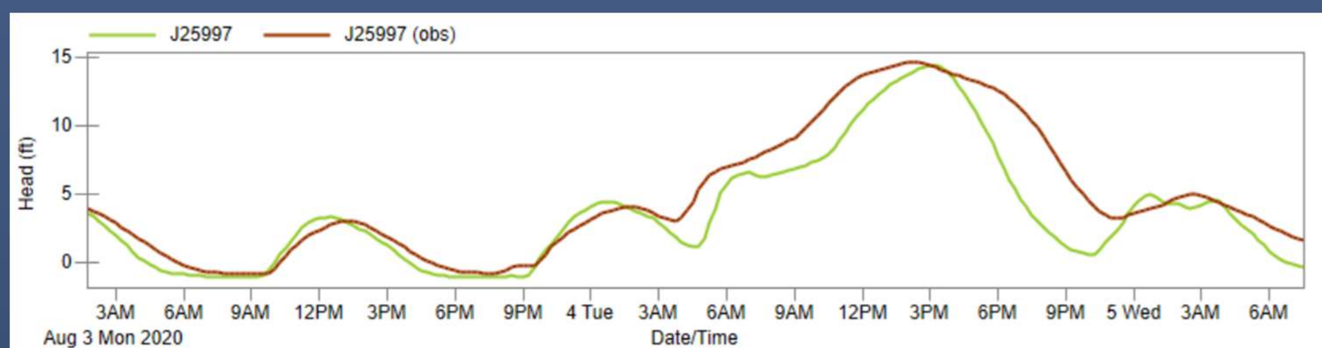


Tropical Storm Isaias (2020)

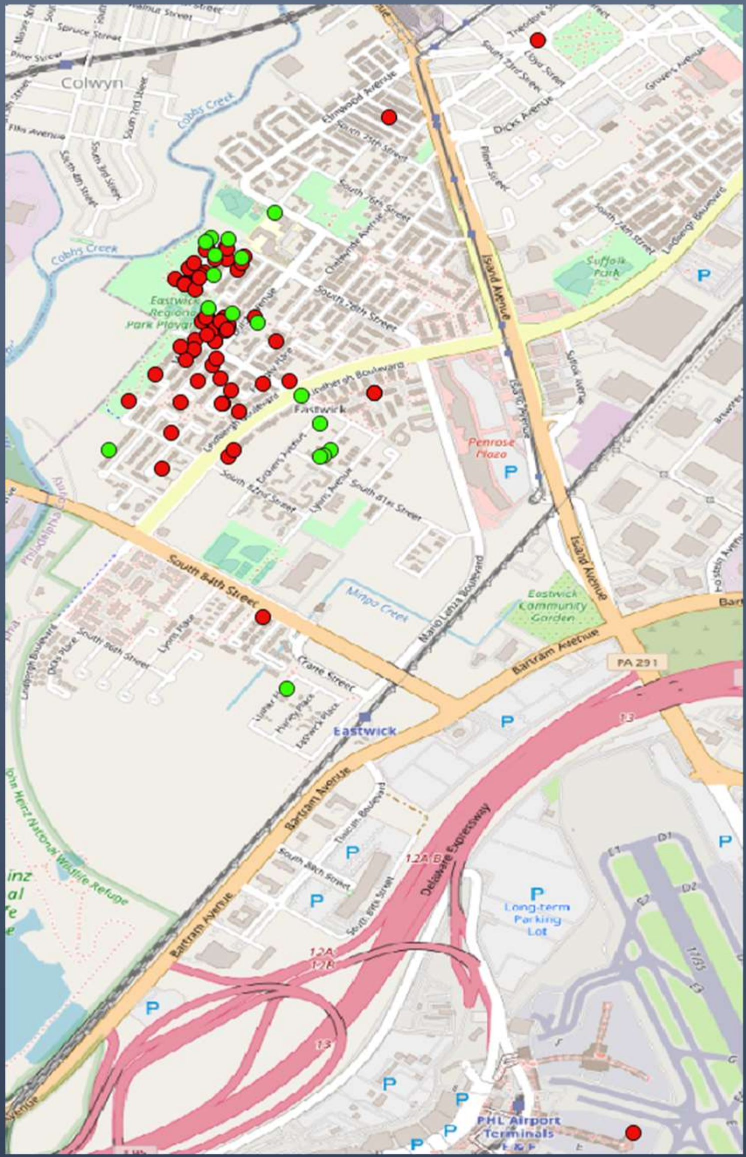


Simulated and Observed Darby Creek Stage (USGS 01475553 at 84th Street Philadelphia)

Tropical Storm Isaias (2020)



High water marks (Isaias)



PC-SWMM predicted flooding matched observations gleaned from resident surveys conducted by the research team, as well as ACOE HWMs.

Benefits of having two H&H models

- PC-SWMM model
  - Can be used to simulate hydrology of entire watershed, including 1D and 2D elements
  - Avoids uncertainty introduced by streamflow frequency analysis
  - Enables simulation of impact of upstream stormwater controls on downstream flooding
  - Efficiently simulates rain on mesh, enabling infiltration, storm drainage system hydraulics, and flow around obstructions
- HEC-RAS model
  - Fully 2D representation of surface flows.
  - Smaller model that can be driven by PC-SWMM to focus on flows through the lower watershed
  - Can simulate surface flood patterns with less computational resources than PC-SWMM

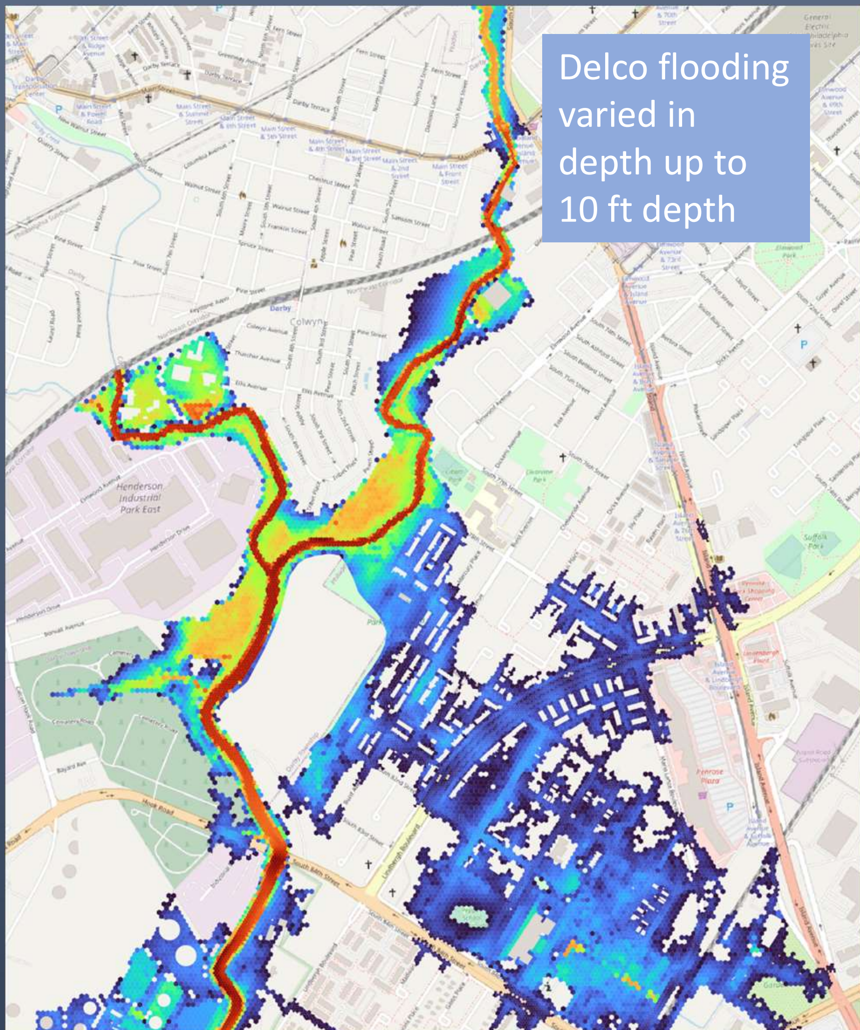
Outline of PCSWMM Scenarios

- Simulation of historical flooding due to TS Isaias
  1. Existing watershed configuration

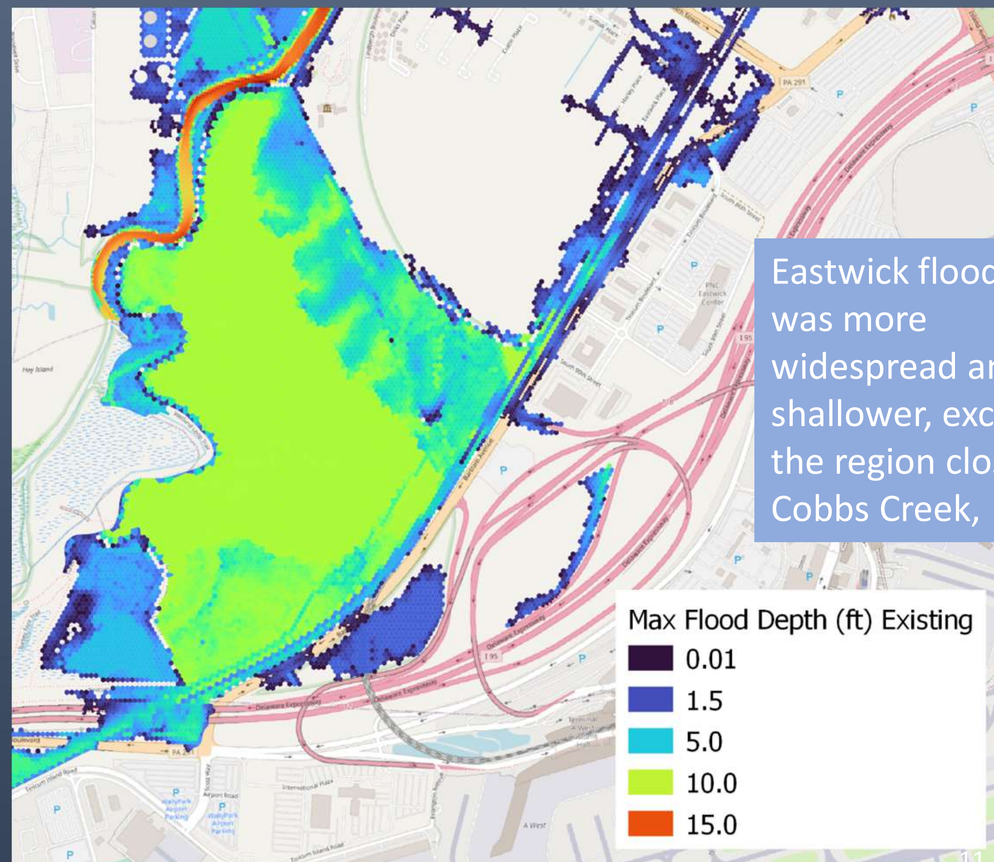
- Simulation of differences in TS Isaias flooding due to adaptations
  2. With ACOE proposed levee
  3. With GSI analysis and simulation assuming GSI treatment of 65% of impervious surfaces (25% of watershed) at HLR=5
  4. With Landswap
  5. With ACOE levee and GSI (Scenario #3)

1) Historical flooding due to TS Isaias (no adaptation)

Historical peak flooding due to TS Isaias (PC-SWMM)

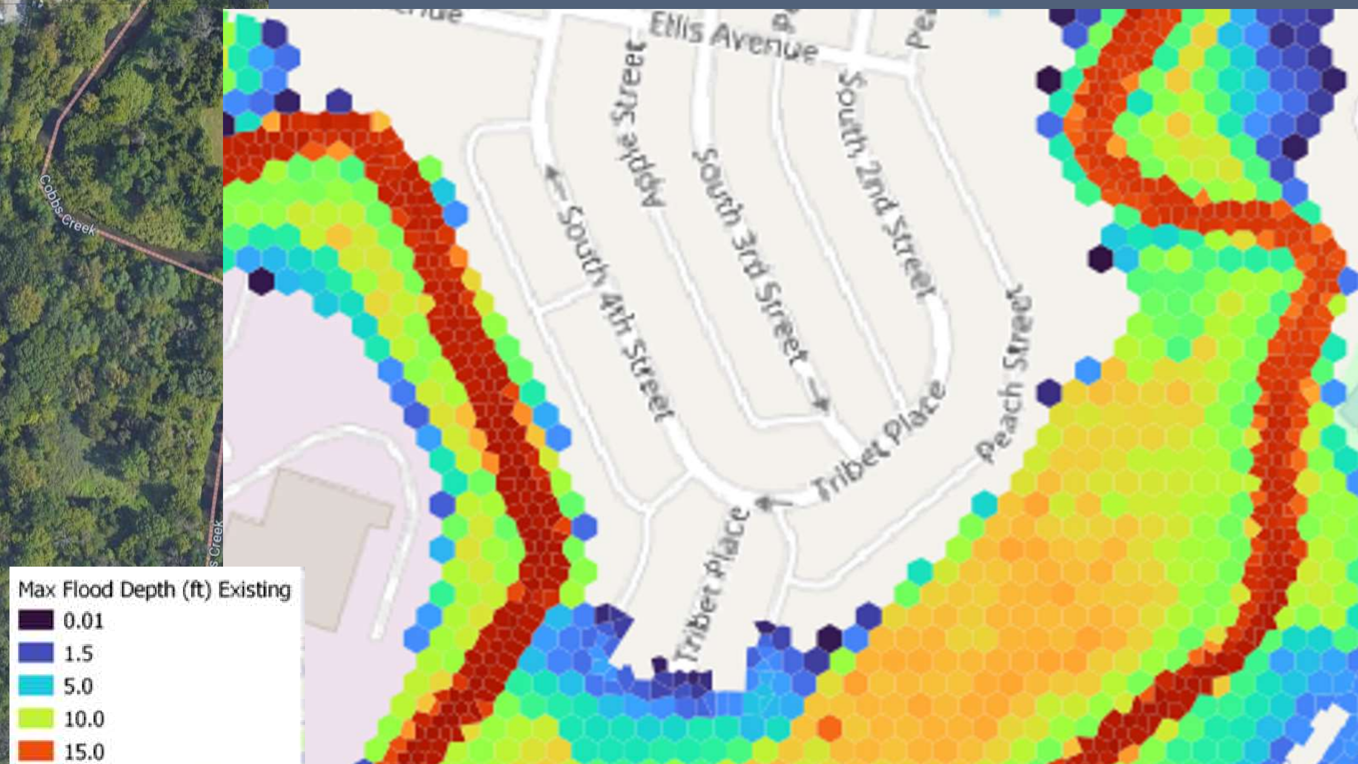


Delco flooding varied in depth up to 10 ft depth



Eastwick flooding was more widespread and shallower, except the region close to Cobbs Creek,

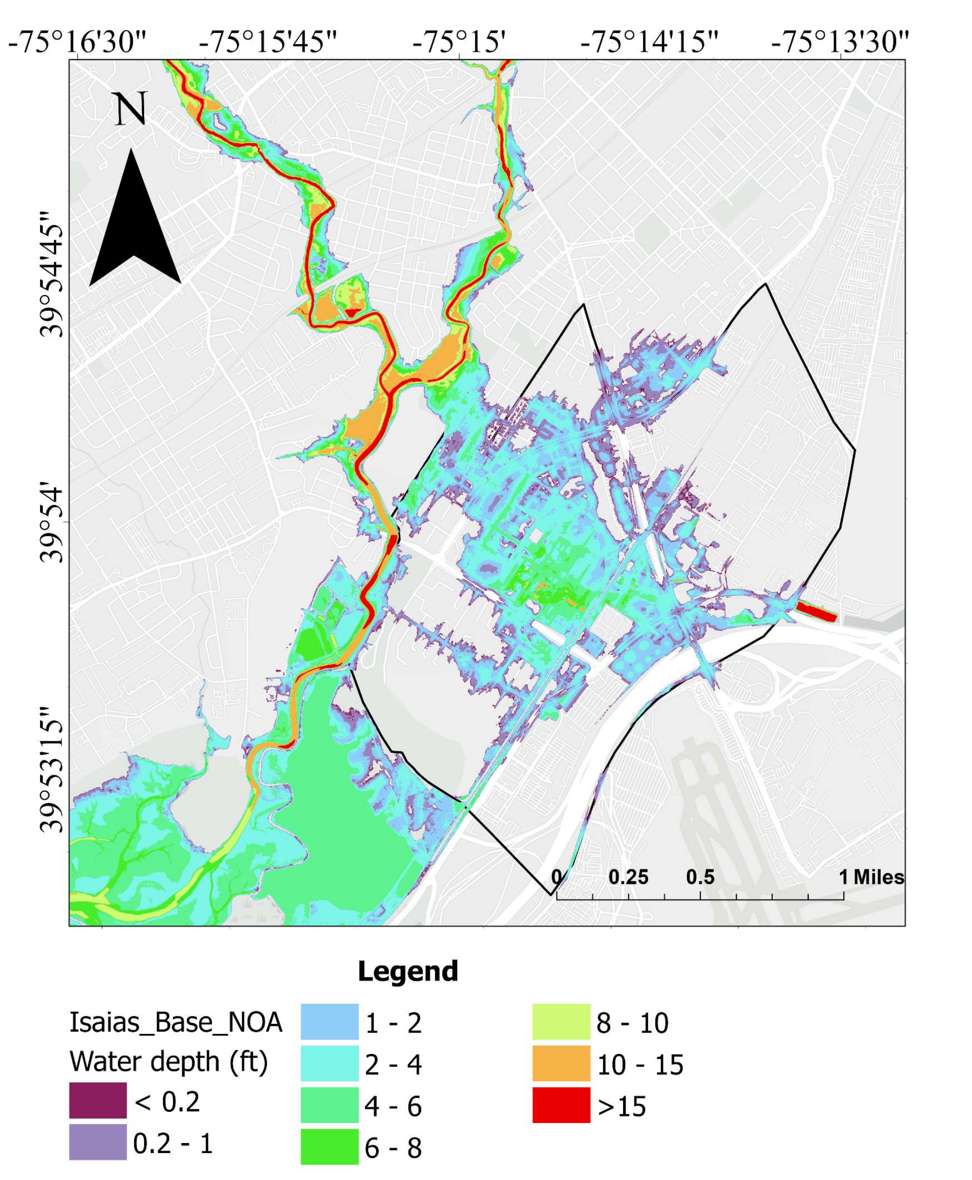
Close up sample of peak flooding due to TS Isaias, existing conditions (PC-SWMM)



TS Isaias historical flooding (HEC-RAS)

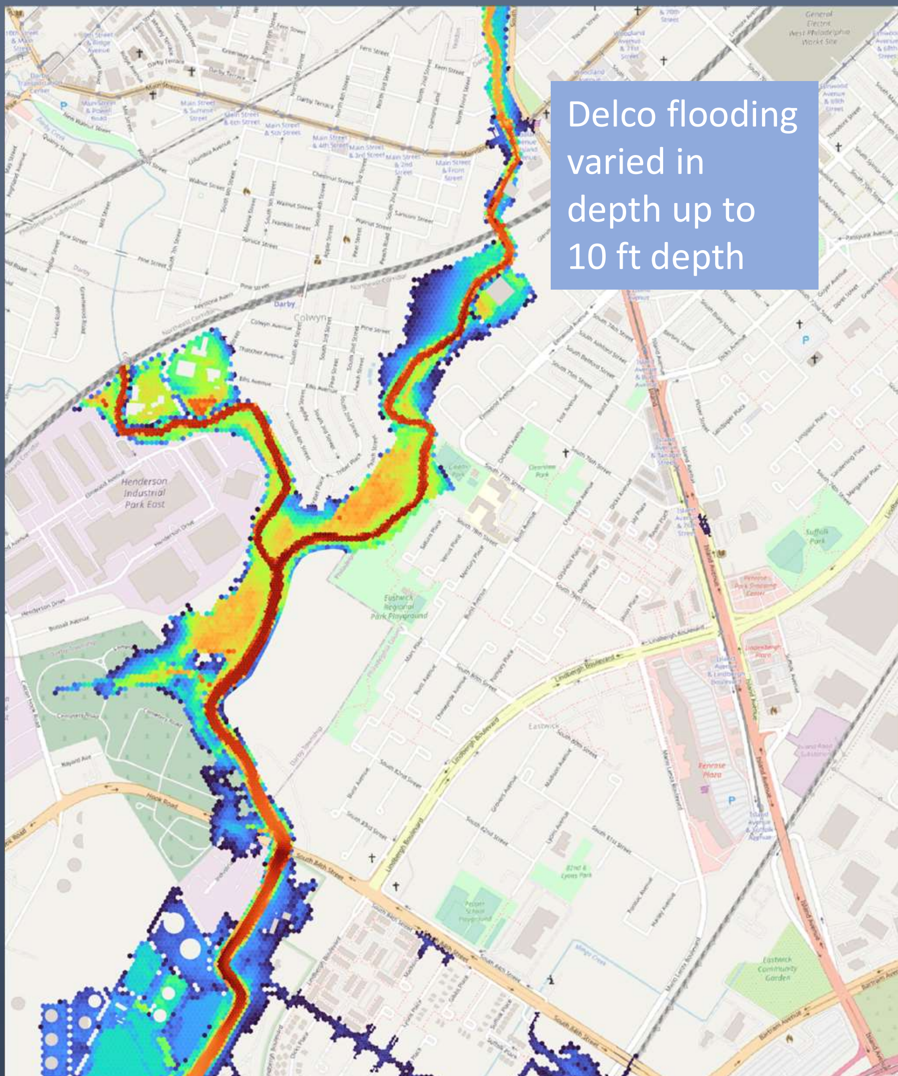
Delco flooding varied in depth up to 10 ft depth

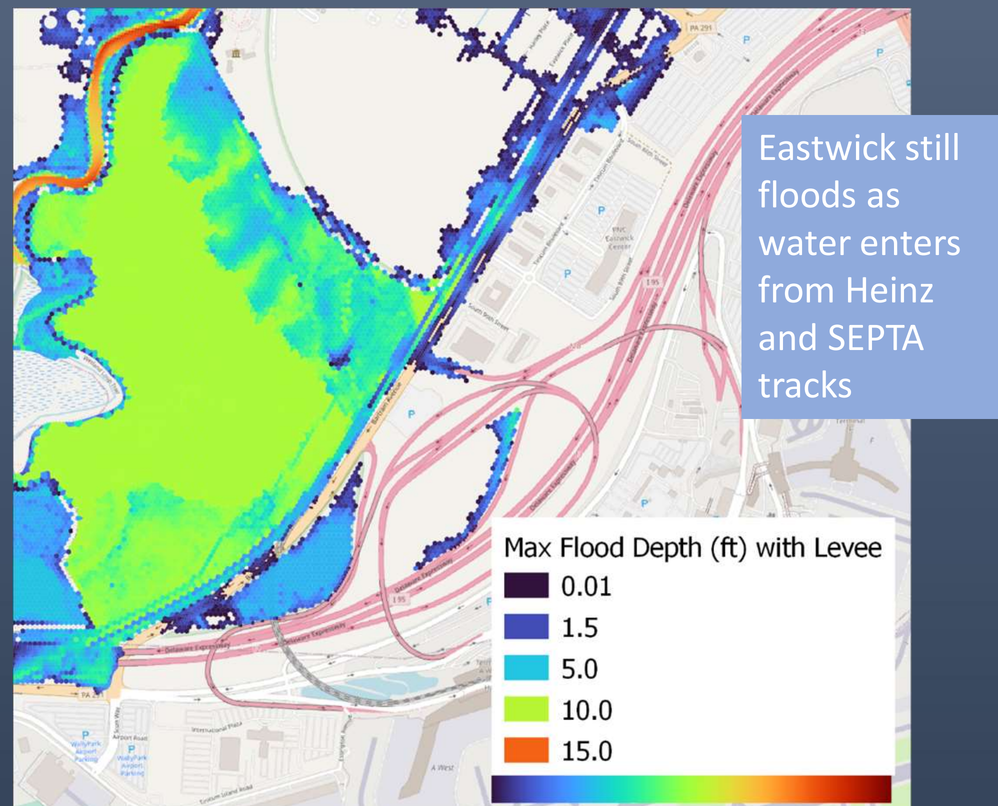
Both modeling platforms predict similar flood depths



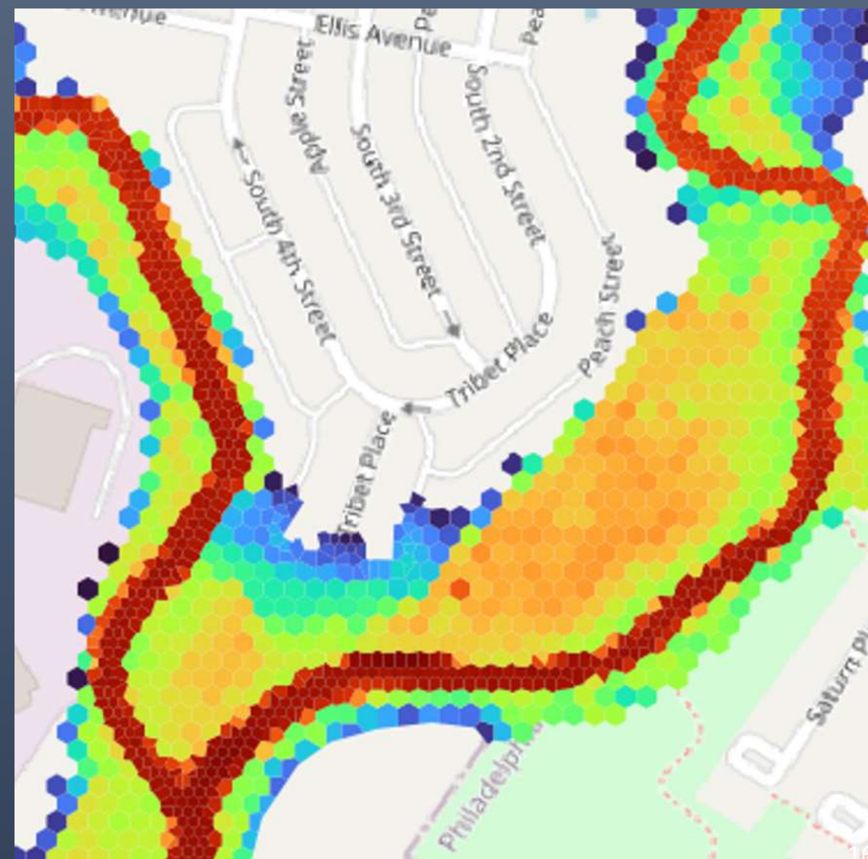
2) Modified flooding due to TS Isaias (with ACOE levee)

Peak flooding due to TS Isaias with levee (PC-SWMM)





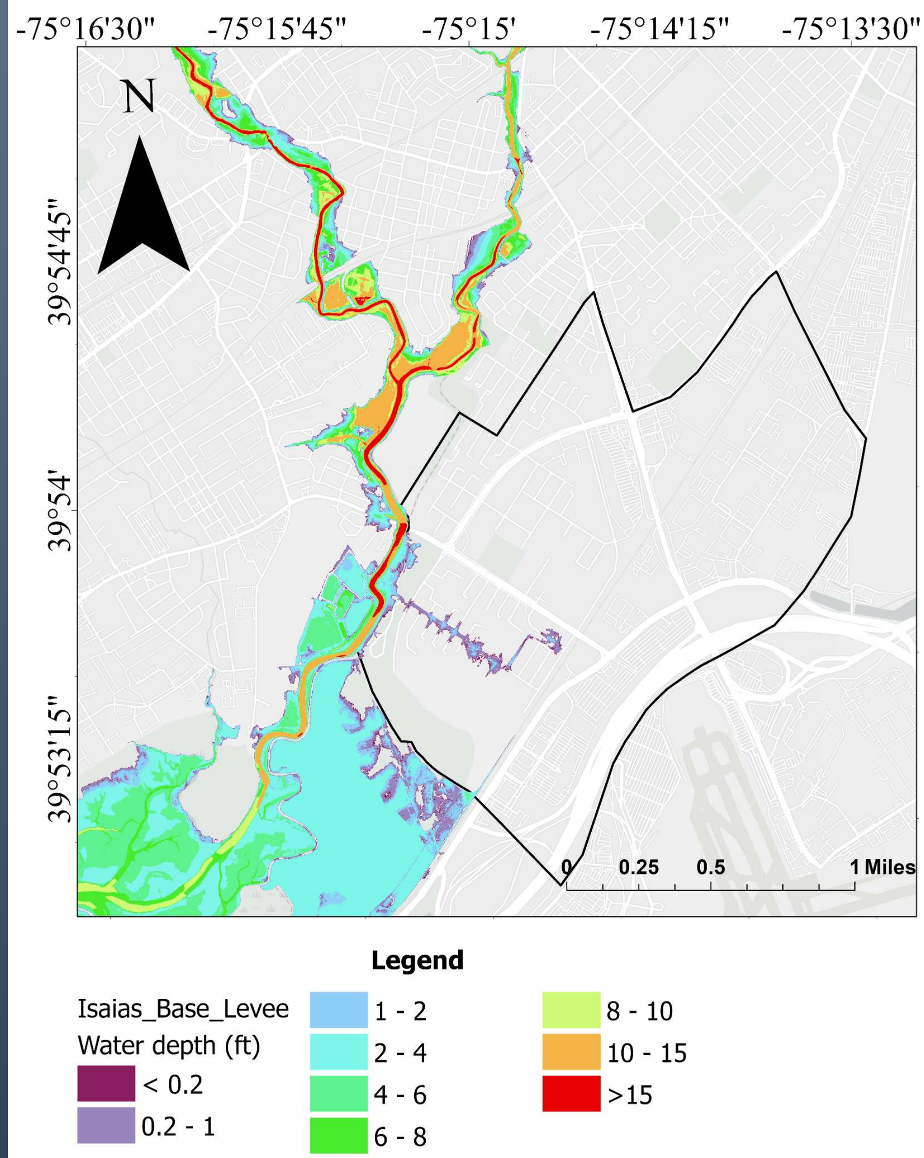
Close up sampling of peak flooding due to TS Isaias, levee conditions (PC-SWMM)



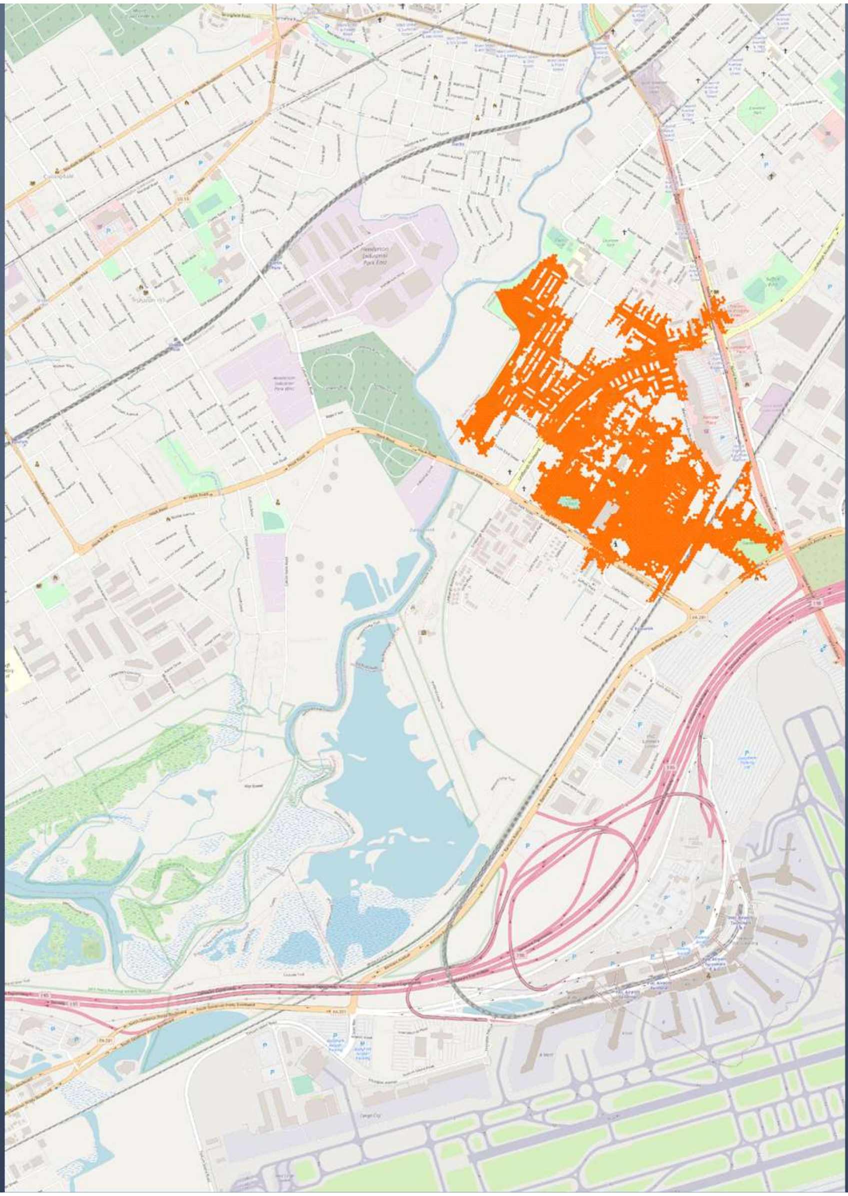
TS Isaias historical flooding with levee (HEC-RAS)

Delco flooding varied in depth up to 10 ft depth

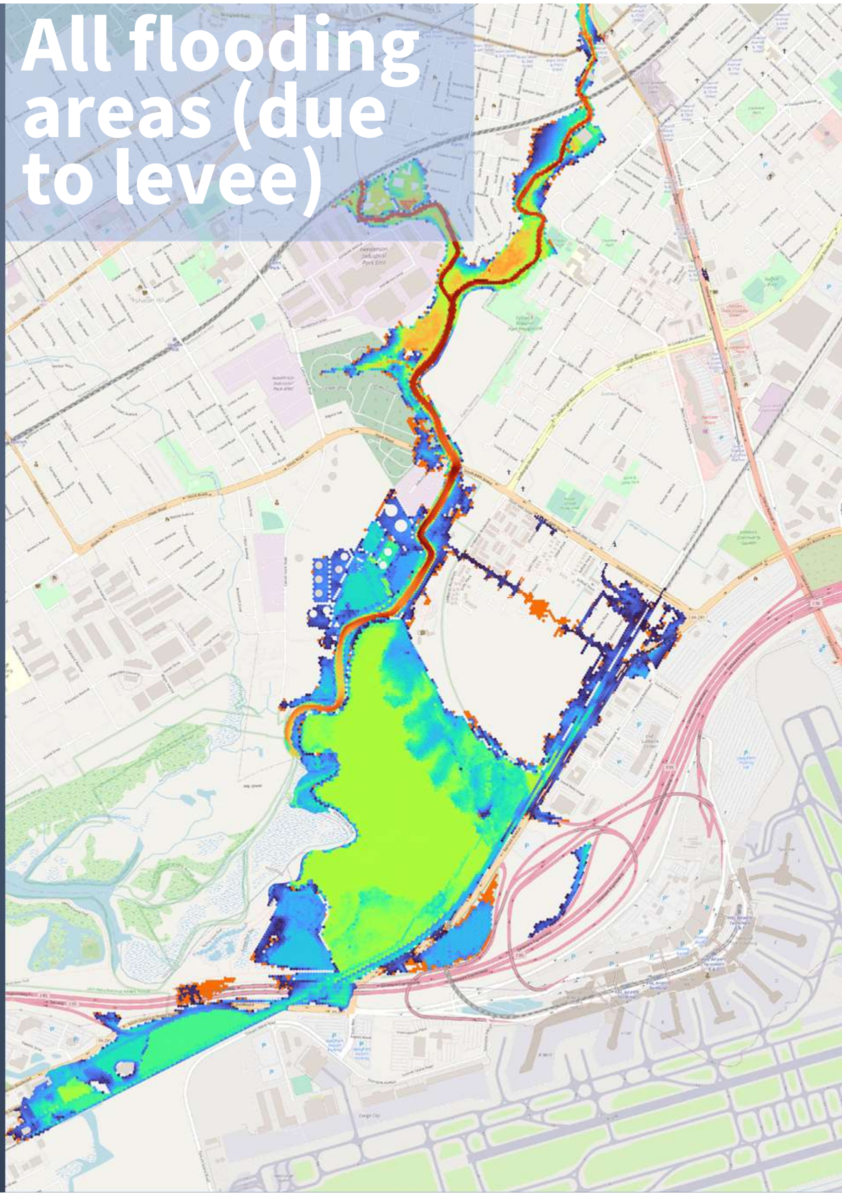
Both modeling platforms predict similar flood depths



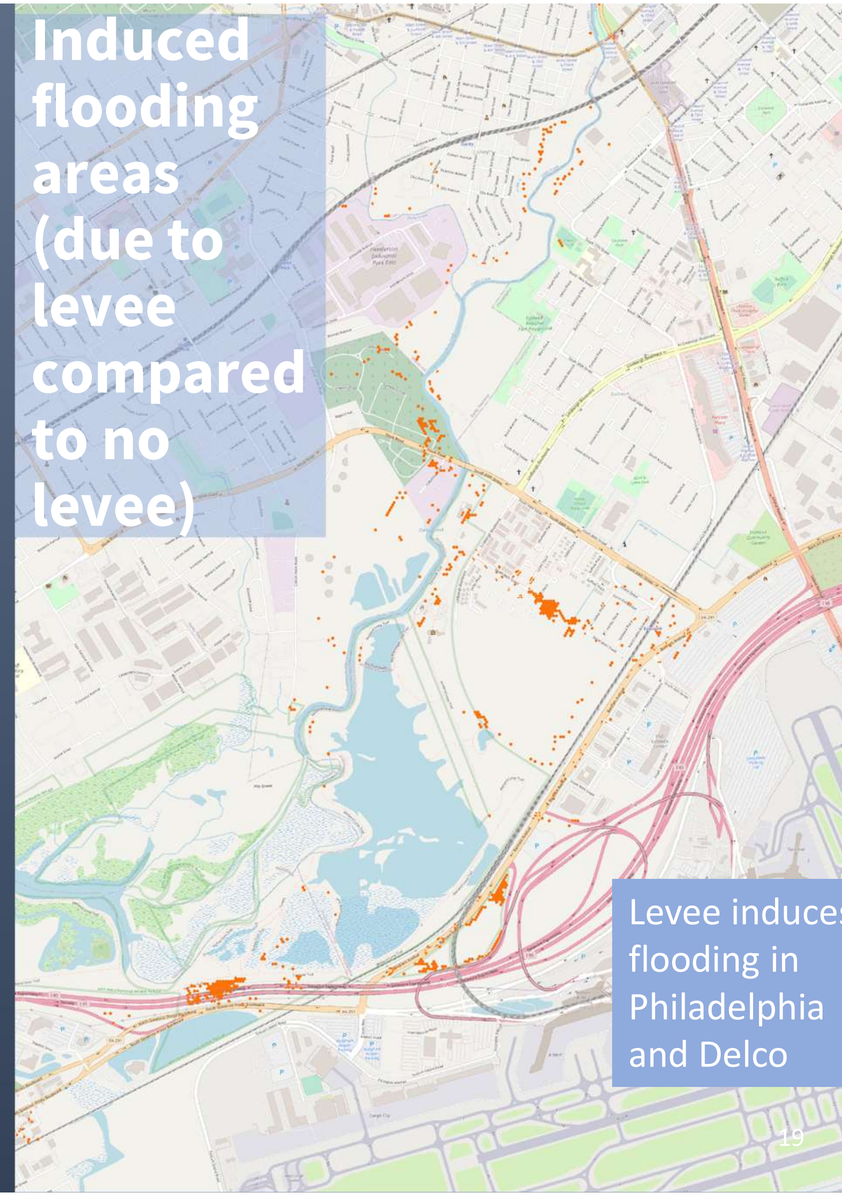
Flooding eliminated by levee



All flooding areas (due to levee)

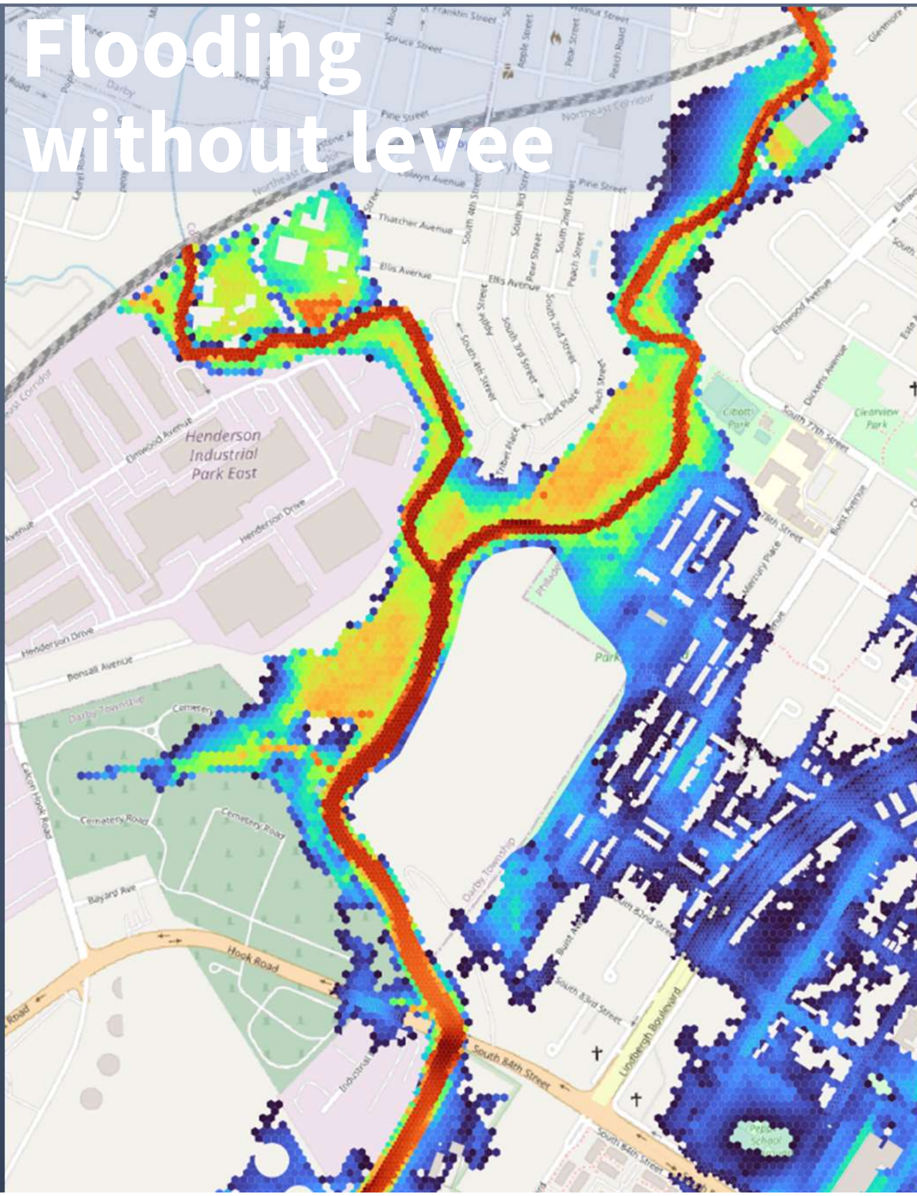


Induced flooding areas (due to levee compared to no levee)

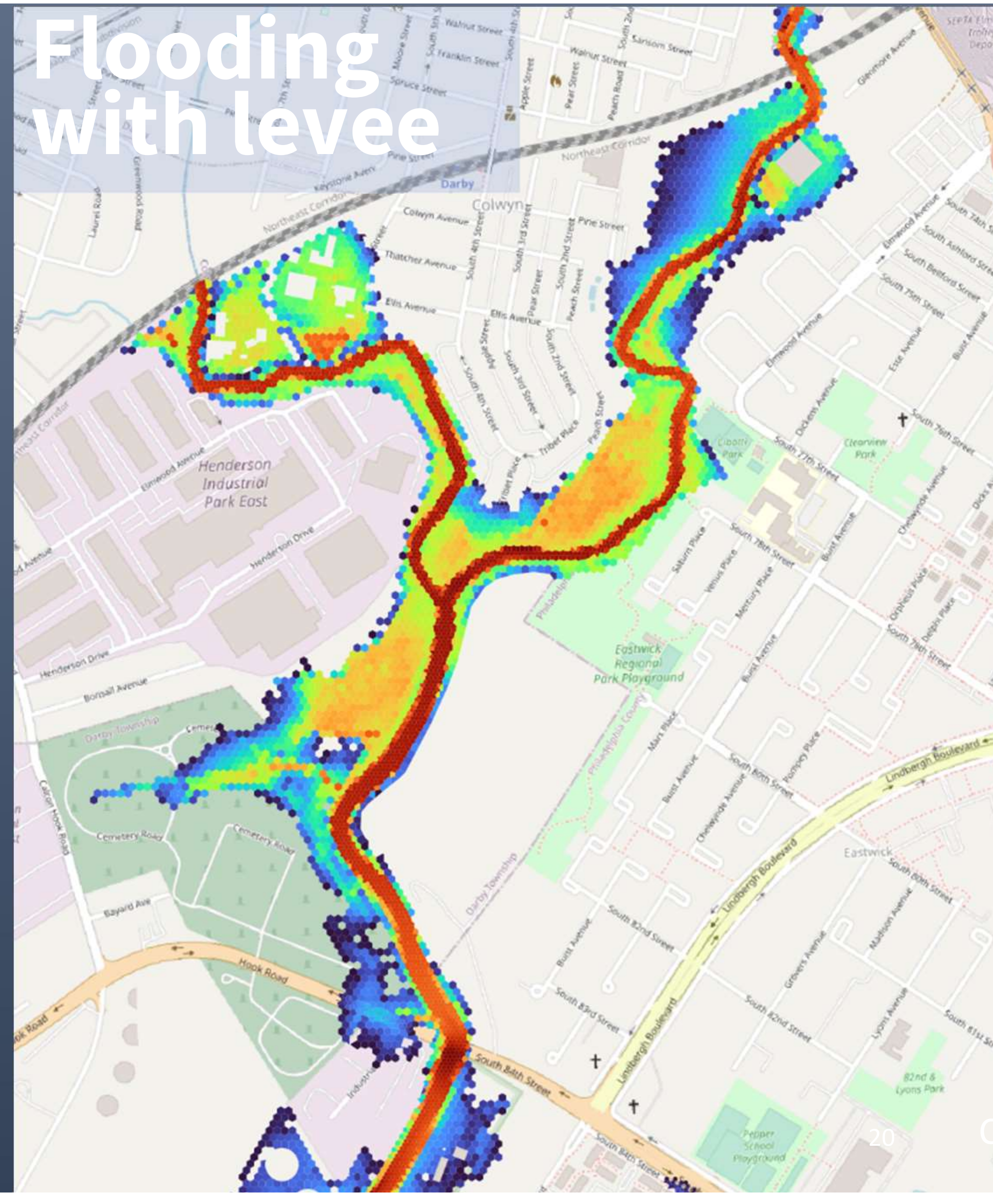


Levee induces flooding in Philadelphia and Delco

Flooding without levee



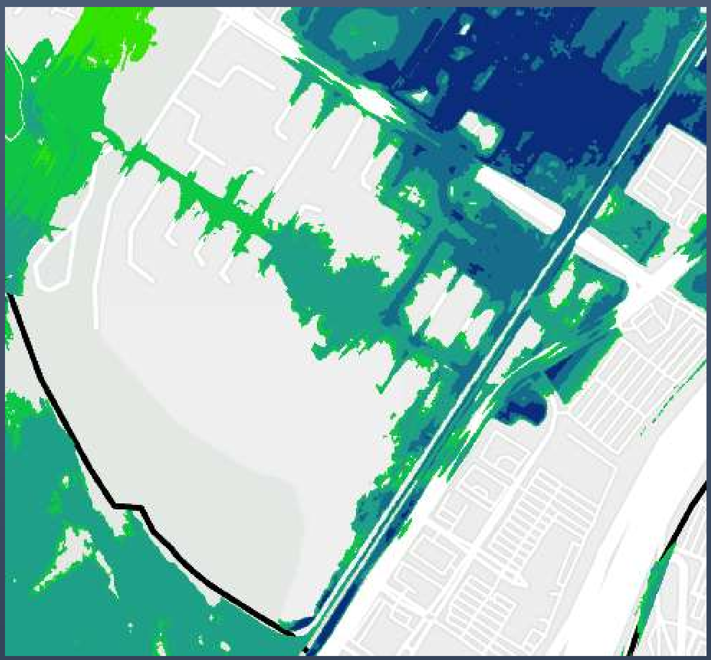
Flooding with levee



Difference in flooding (w/levee – w/o levee)

Negative (-) values → levee reduces flooding
Positive (+) values → levee increases flooding

Levee induces flooding of up to about 1 foot in Delco and 0.5 ft along 86th street, while reducing flooding by up to and above 4 ft in the rest of Eastwick



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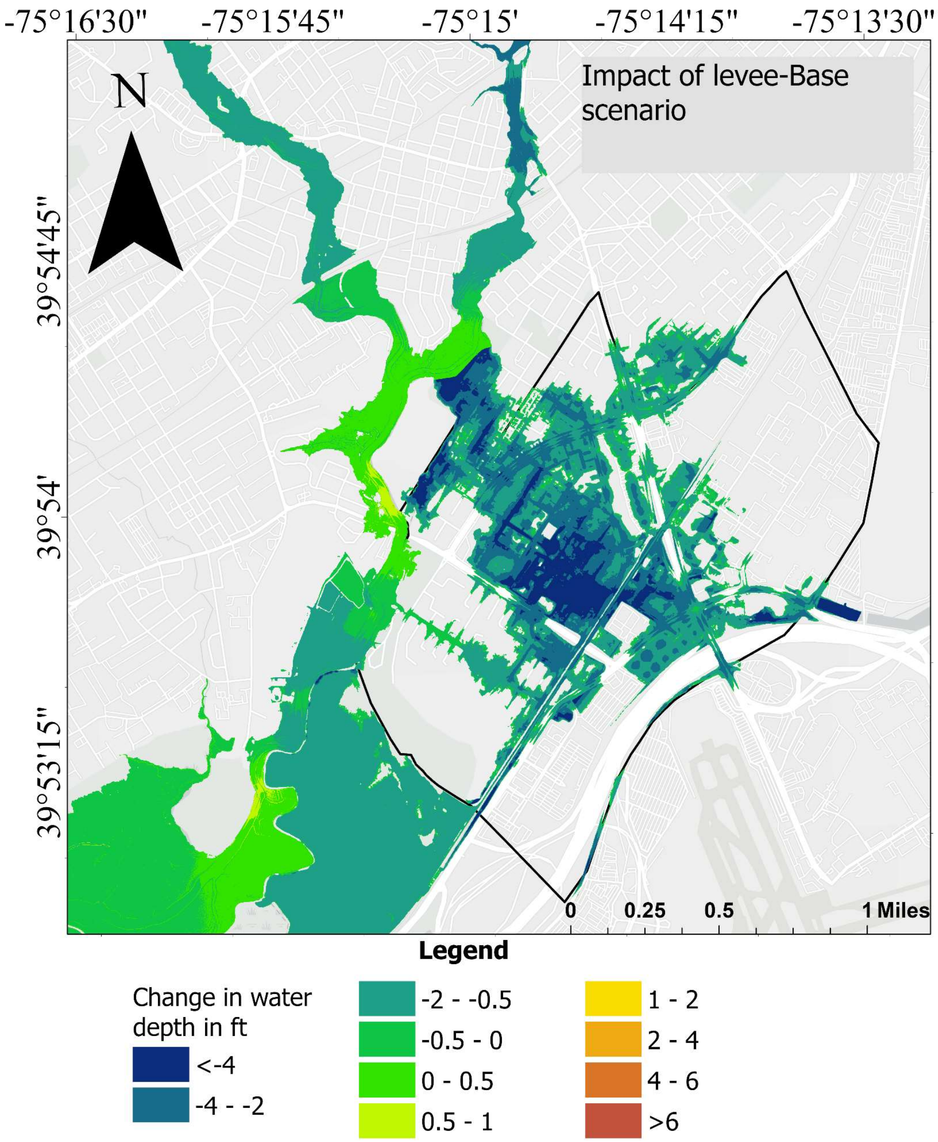
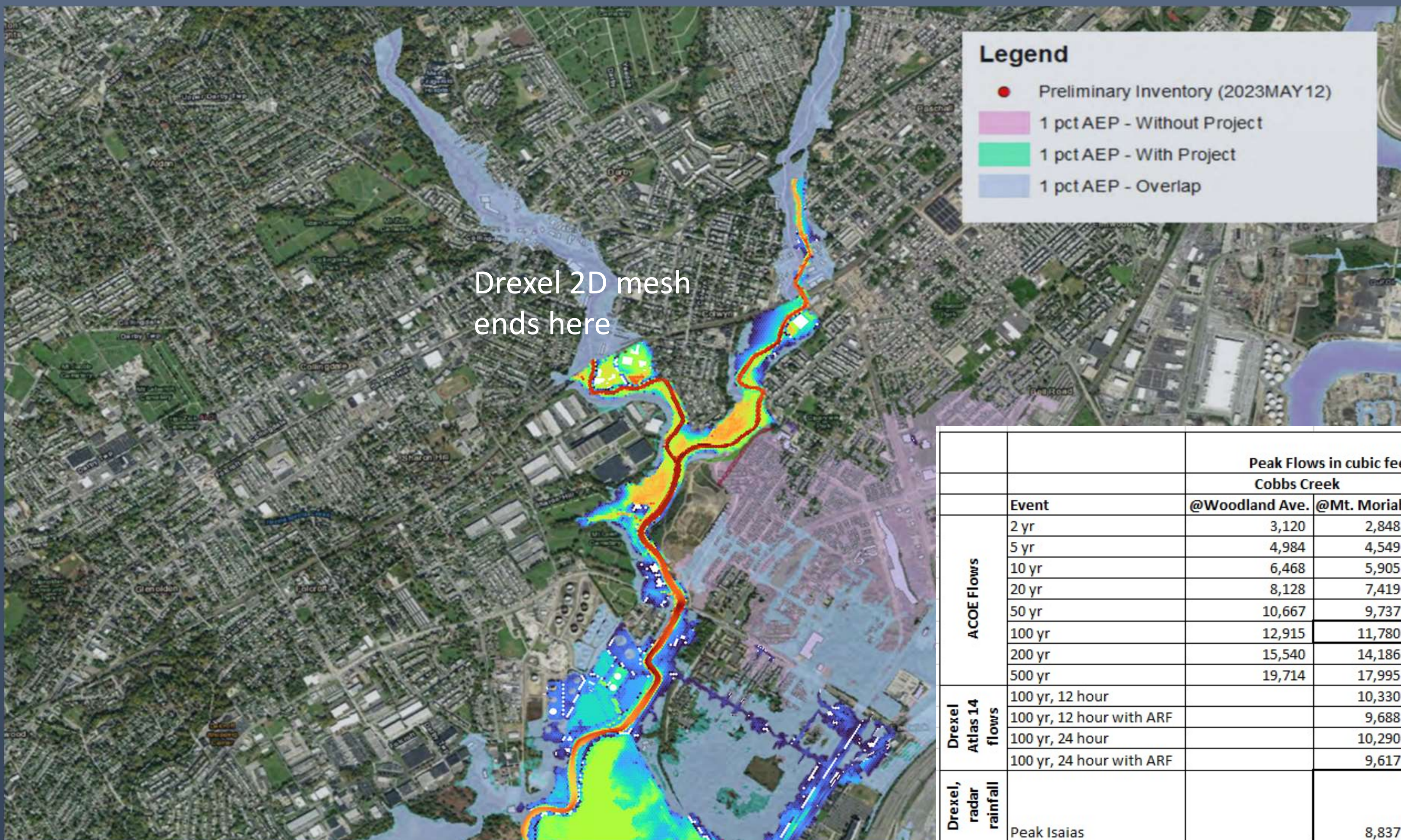


Overlap of Isaias simulation onto ACOE 100 yr map

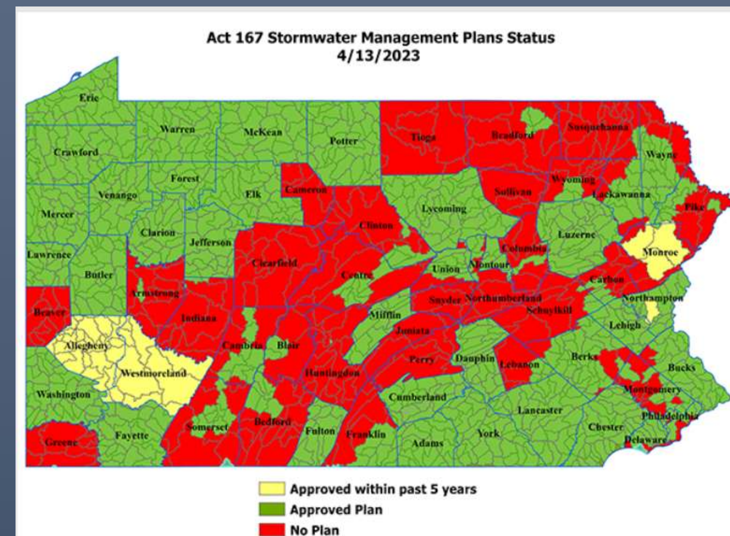


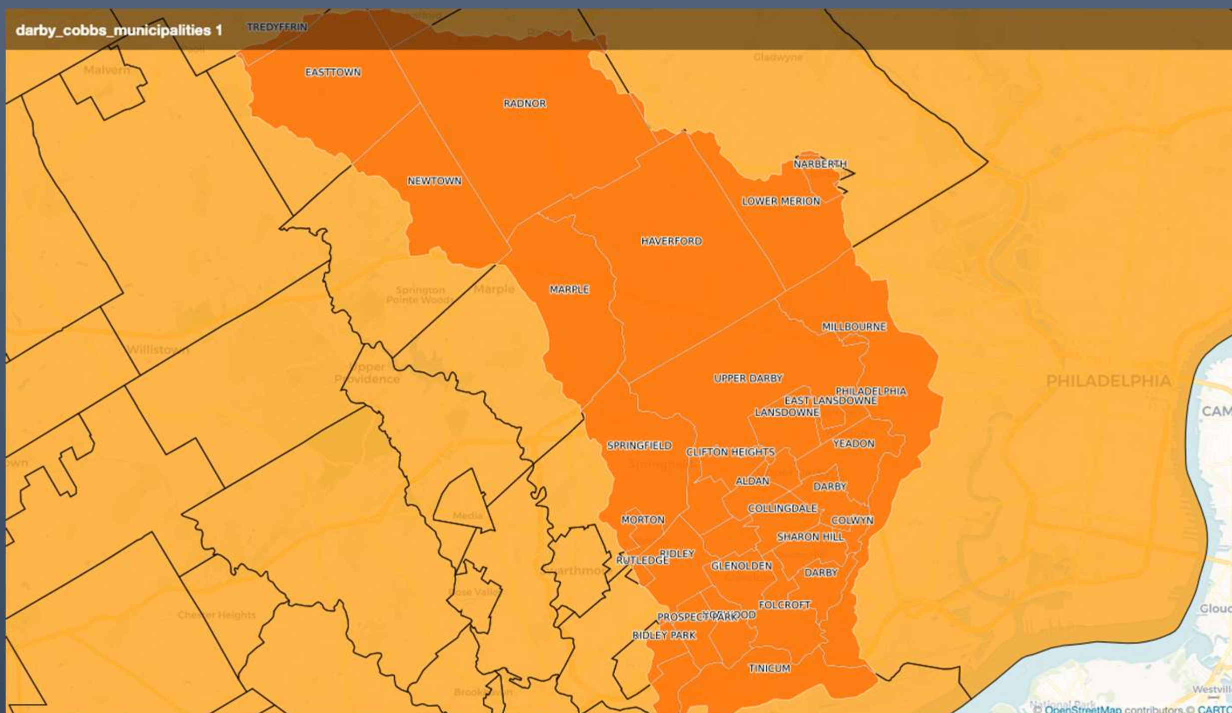
Simulated Isaias flows were less than ACOE 100 yr flows and consequently result in a slightly smaller area of inundation

		Peak Flows in cubic feet/second			% difference from ACOE 100 yr	
		Cobbs Creek		Darby Creek	Cobbs	Darby
	Event	@Woodland Ave.	@Mt. Moriah	@Providence Rd	@Mt. Moriah	@Providence Rd
ACOE Flows	2 yr	3,120	2,848	4,271		
	5 yr	4,984	4,549	6,867		
	10 yr	6,468	5,905	8,952		
	20 yr	8,128	7,419	11,281		
	50 yr	10,667	9,737	14,880		
	100 yr	12,915	11,780	18,003		
	200 yr	15,540	14,186	21,741		
	500 yr	19,714	17,995	27,717		
Drexel Atlas 14 flows	100 yr, 12 hour		10,330	15,660	6.1%	5.2%
	100 yr, 12 hour with ARF		9,688	11,270	-0.5%	-24.3%
	100 yr, 24 hour		10,290	15,020	5.7%	0.9%
	100 yr, 24 hour with ARF		9,617	10,780	-1.2%	-27.6%
Drexel, radar rainfall	Peak Isaias		8,837	7,433	-9.2%	-50.0%

3) Modified flooding due to TS Isaias with GSI

PA Stormwater Management Act of 1978 (Act 167)





Required that each county prepare and adopt a watershed stormwater management plan ("Act 167 Plan") for each watershed in consultation with the municipalities and must periodically review and revise such plans at least every five years.

GSI commitments in current round of PRPs

Darby Cobbs Watershed: Proposed Best Management Practice (BMP) Summary

** Unable to identify PRPs for towns with no proposed PRPs

Municipality	Total Area (sq. miles)	Area Contributing to Darby Cobbs Watershed (sq. miles)	PRP Report Year Written	Stream Restoration (lf)	Trees (#)	curb bump out drainage area (ac)	raingarden/bioretention drainage area (ac)	meadow drainage area (ac)	bioswale (lf)	riparian buffer (lf)	infiltration drainage area (ac)	wetland (ac)	porous paving drainage area(ac)	basin retrofit drainage area (ac)	street sweeping (ac)
Tredyffrin	19.5	0.5	2020	205	56								3.3		
Easttown	6.3	5													
Radnor	13.79	10.6	2017	2704			33.06	37.7			132.31		49.91	200.08	
Newtown	10.09	4.09	2020	2925	500		20								
Marple	10.52	4.77	2017	4667			50							5.5	
Haverford	9.946	9.946	2019	3917											
Lower Merion	23.83	5	2017	3970								898			
Narberth	0.5	0.37	2020			80	70.3				14.1		0.3		
Springfield	6.34	4	2019	4100										43	
Upper Darby*	7.826	7.826	2018	3620			0.01		6795	2900		2.03			
Millbourne	0.07	0.07	2017												
East Lansdowne*	0.2	0.2	2018				0.06		1560		1.8				
Lansdowne	1.181	1.181	2022	80			1.659								78.433
Clifton Heights	0.63	0.63													
Yeadon*	1.59	1.59	2018	1588			0.14		1500						
Aldan	0.6	0.6	2017	410			3				5.6				
Morton*	0.36	0.36	2018						180	320					
Rutledge	0.14	0.14	2018								9				
Ridley	5.2	2	2021	1400							28.31				29.87
Darby Township*	1.421	1.421	2018	4020			4	20	500	2050					
Collingdale*	0.87	0.87	2018	500					440	200					
Colwyn	0.26	0.26	2020											27	
Sharon Hill*	0.77	0.77	2018			0.21	0.08		550		0.5				
Darby Borough*	0.84	0.84	2018	900					825	800	10				
Glenoldon*	0.97	0.97	2018	650					250	400					
Folcroft	1.421	1.421													
Prospect Park	0.74	0.74	2017	350			22								
Norwood	0.82	0.82	2019	100			2	5.78		35	0.027			0.22	
Ridley Park	1.1	0.6	2020	450											
Tinicum	8.78	3													
Philadelphia	143	6.5													
Totals all towns	**280**	**77.1**		**36556.0**	**556.0**	**80.2**	**206.3**	**63.5**	**12600.0**	**6705.0**	**201.6**	**900.0**	**53.5**	**275.8**	**108.3**
Totals, towns with PRPs		65.5		36556.0	556.0	80.2	206.3	63.5	12600.0	6705.0	201.6	900.0	53.5	275.8	108.3
Totals, towns with PRPs (all values in acres)		65.5		83.9	0.2	80.2	206.3	63.5	1.4	15.4	201.6	900.0	53.5	275.8	108.3

PRP research undertaken by the Watershed Adaptation Corps (WAC) members and Drexel

Summary			
	WS area	65	square miles
	WS imp area	25	square miles
	GSI area	1990	acres
	GSI area	3	square miles
	% WS area treated	5%	
	% imp area treated	12%	

At best, current round of PRPs suggests GSI could treat 12% of impervious areas and 5% of watershed

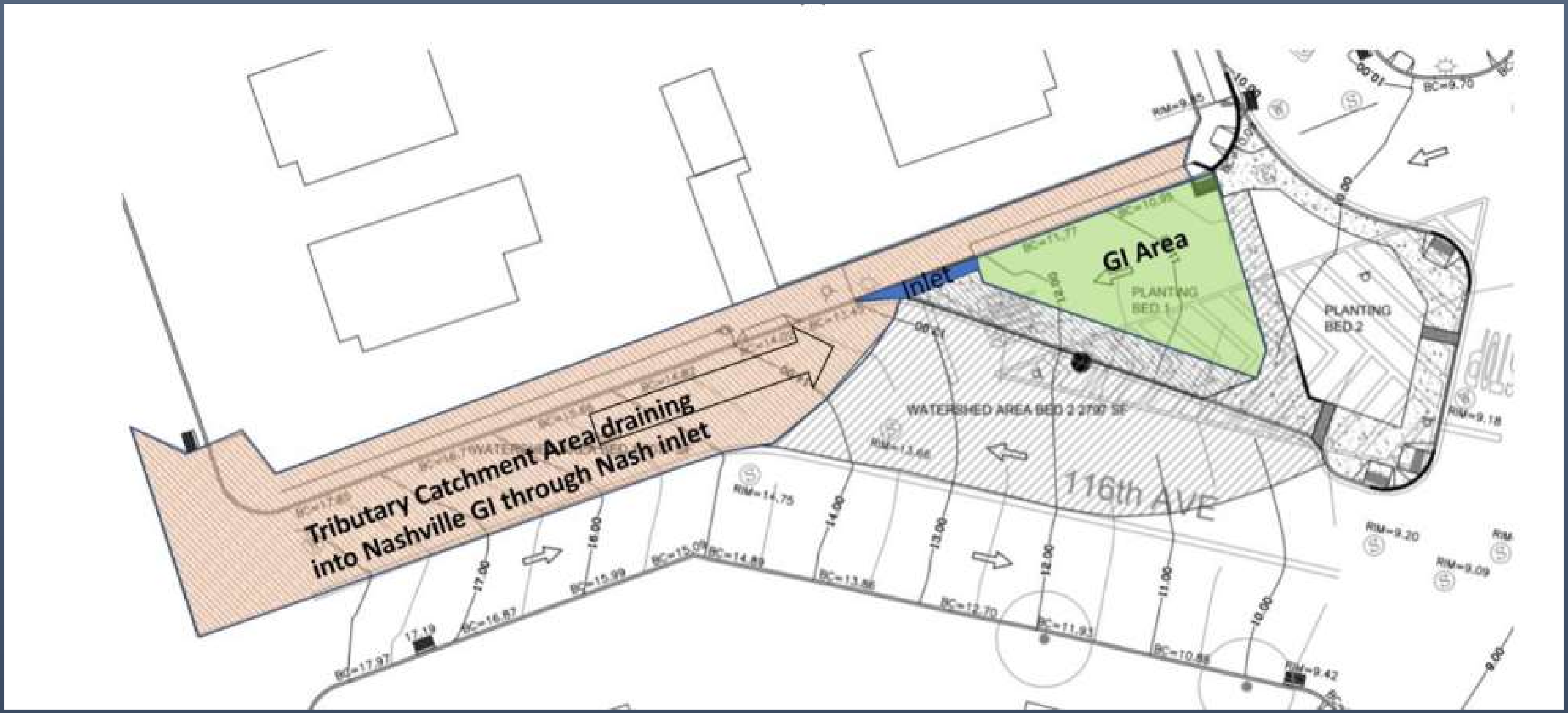
Key Question:

Will the proposed level of watershed GSI (treating 5% of watershed area and 12% of its impervious surfaces) reduce flooding in Eastwick (under TS Isaias conditions)?

Modeling details:

Hydraulic Loading Ratio (HLR) = $\frac{GSI\ Tributary\ Area}{GSI\ Practice\ Area}$

Simulated GSI could have different HLR values



Example:
HLR = 3
Nashville green street (Queens, NY)

The higher the HLR, the more heavily loaded the GSI practice is with runoff

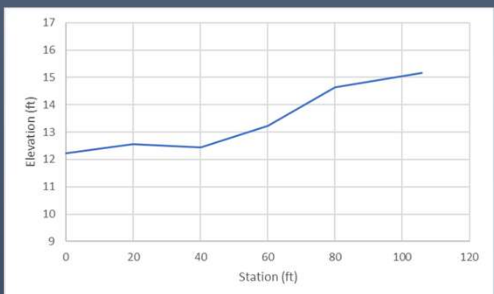
Shevade and Montalto (2021)

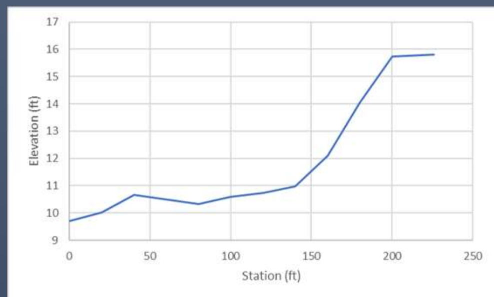
Modeling details:

Cobbs Creek Peak Stage

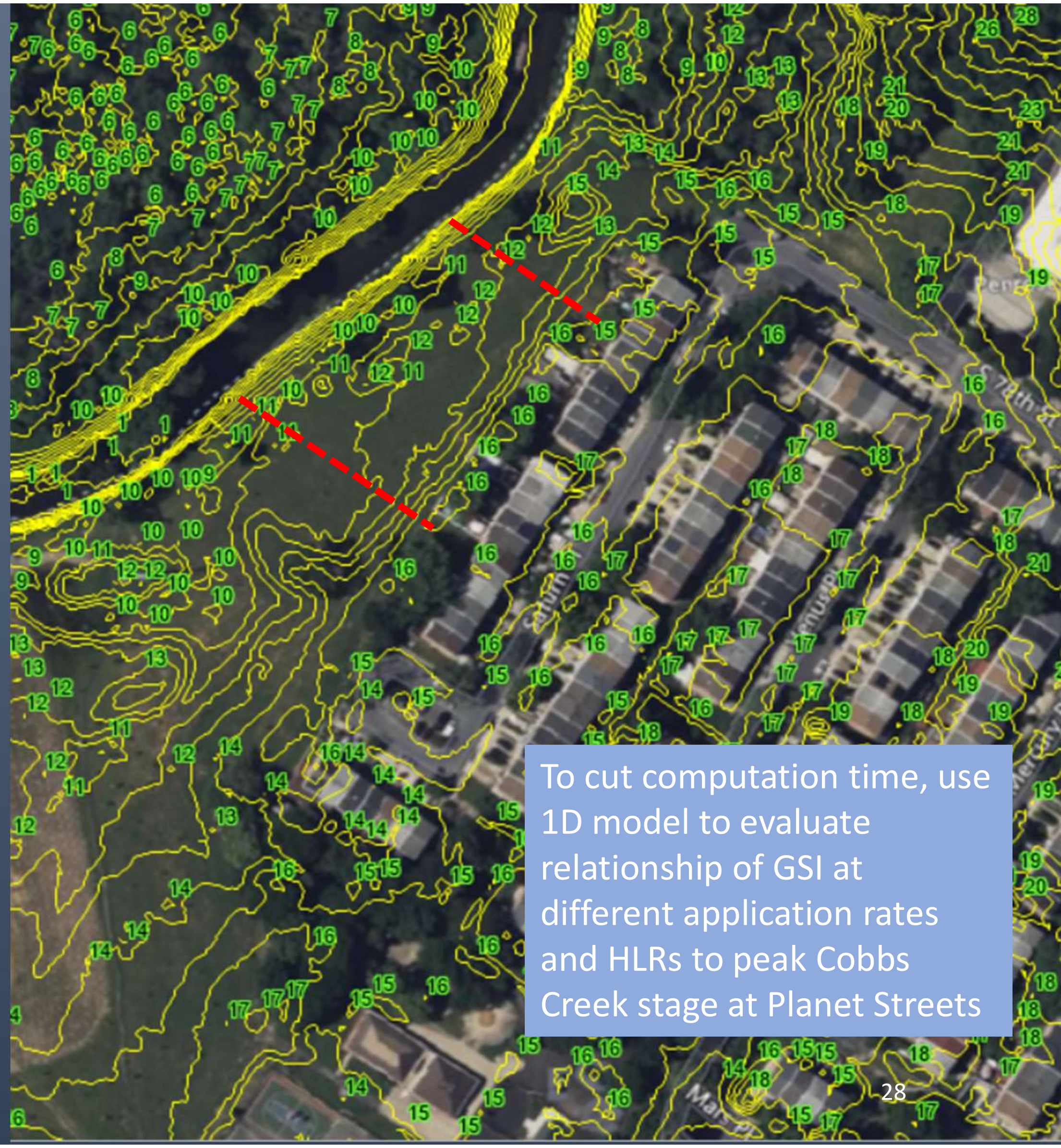
vs.

Land Surface Elevation at Planet Streets





Creek starts to overflow when stage = 15 ft
Water reaches first building when stage = 15.6 ft



To cut computation time, use 1D model to evaluate relationship of GSI at different application rates and HLRs to peak Cobbs Creek stage at Planet Streets

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Modeling scenarios initially considered

Example bioretention area
(Furmanville Greenstreet Queens, NY)

Prototypical GSI type:
Bioretention

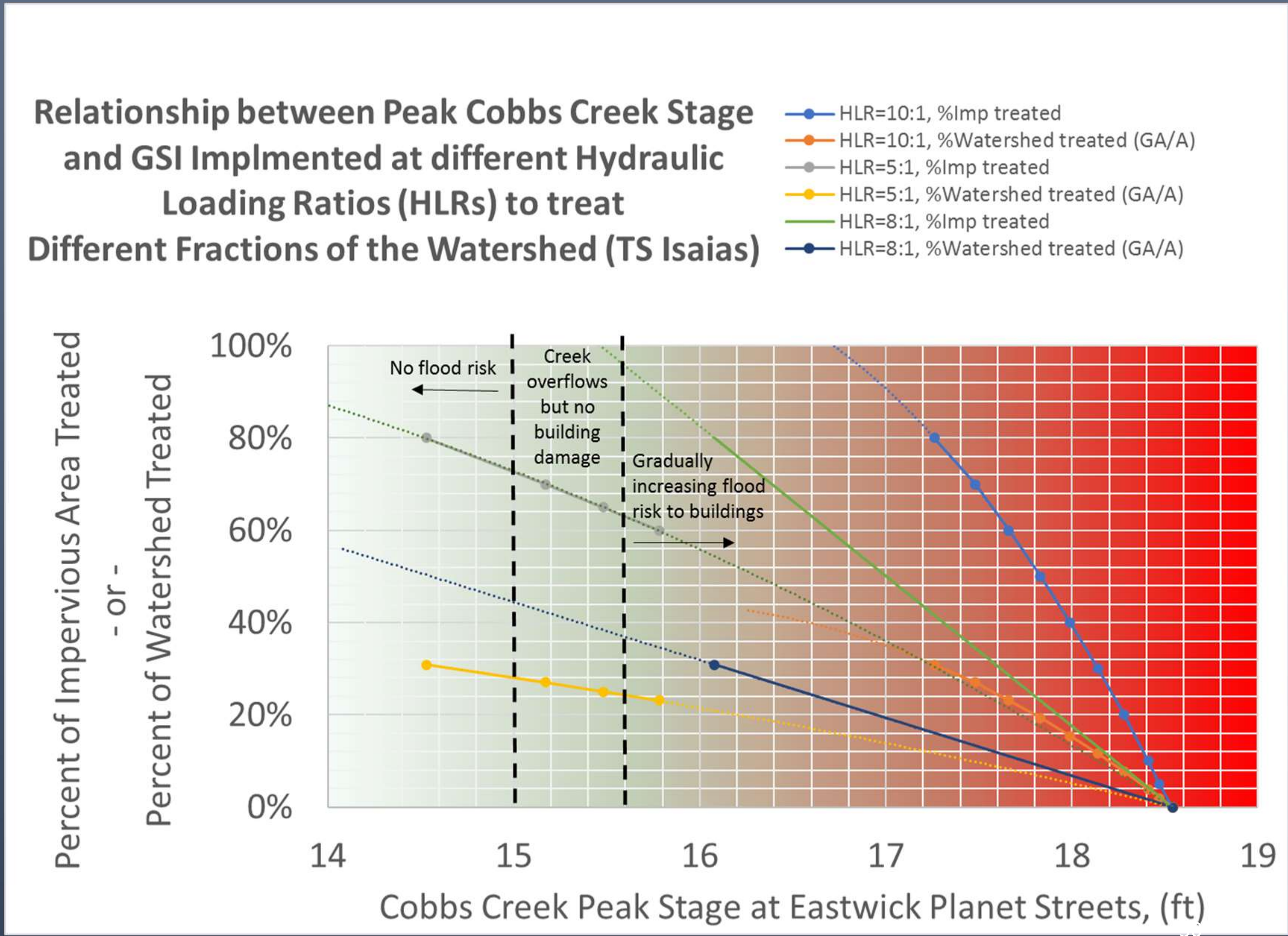
Prototypical GSI area:
300 sf

HLR range:
5-10

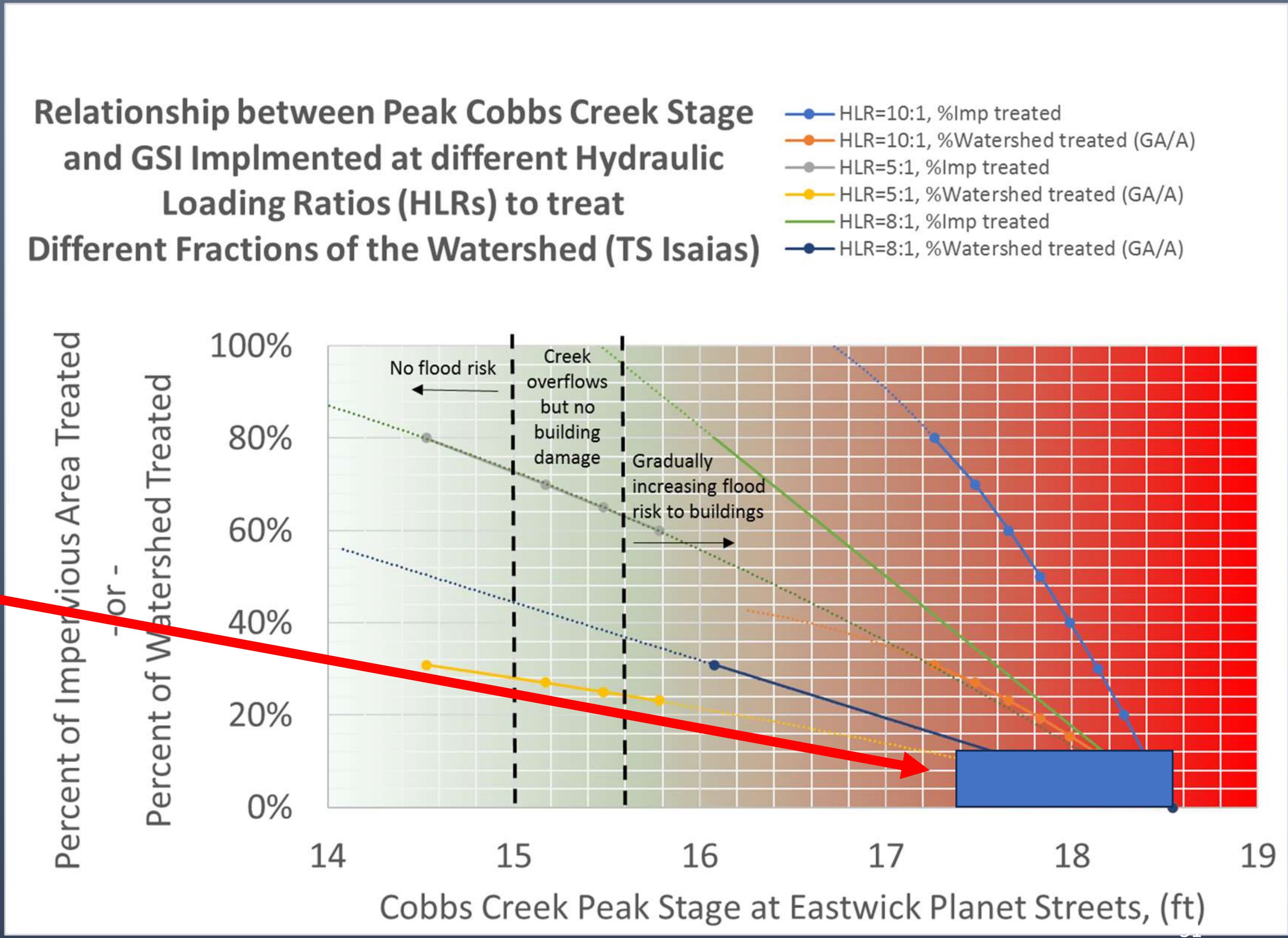
% Watershed treated
0-40%

% Impervious area treated
0-80%

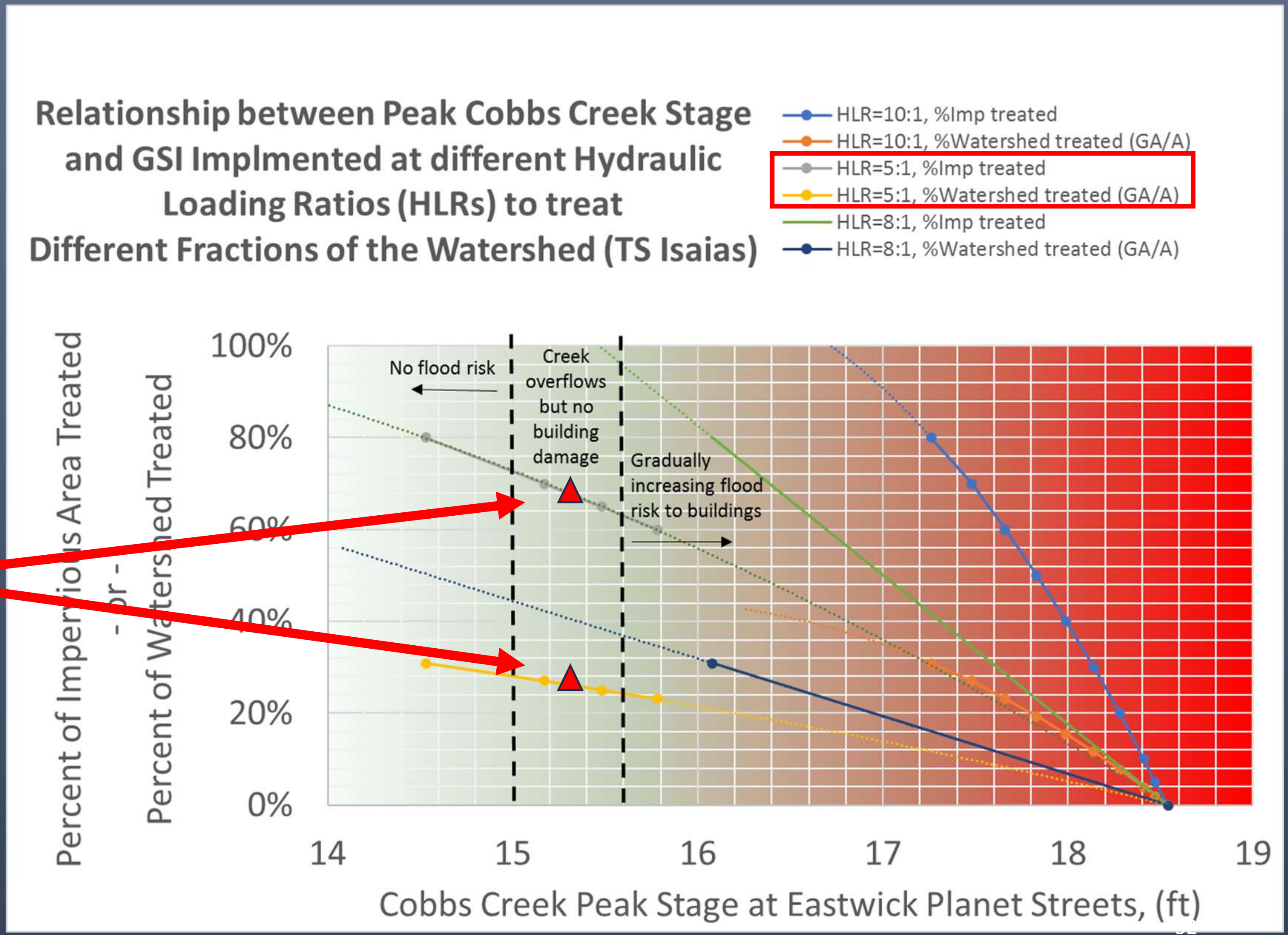
Potential benefit of additional upstream GSI in reducing downstream flood risk with different HLR and area treated



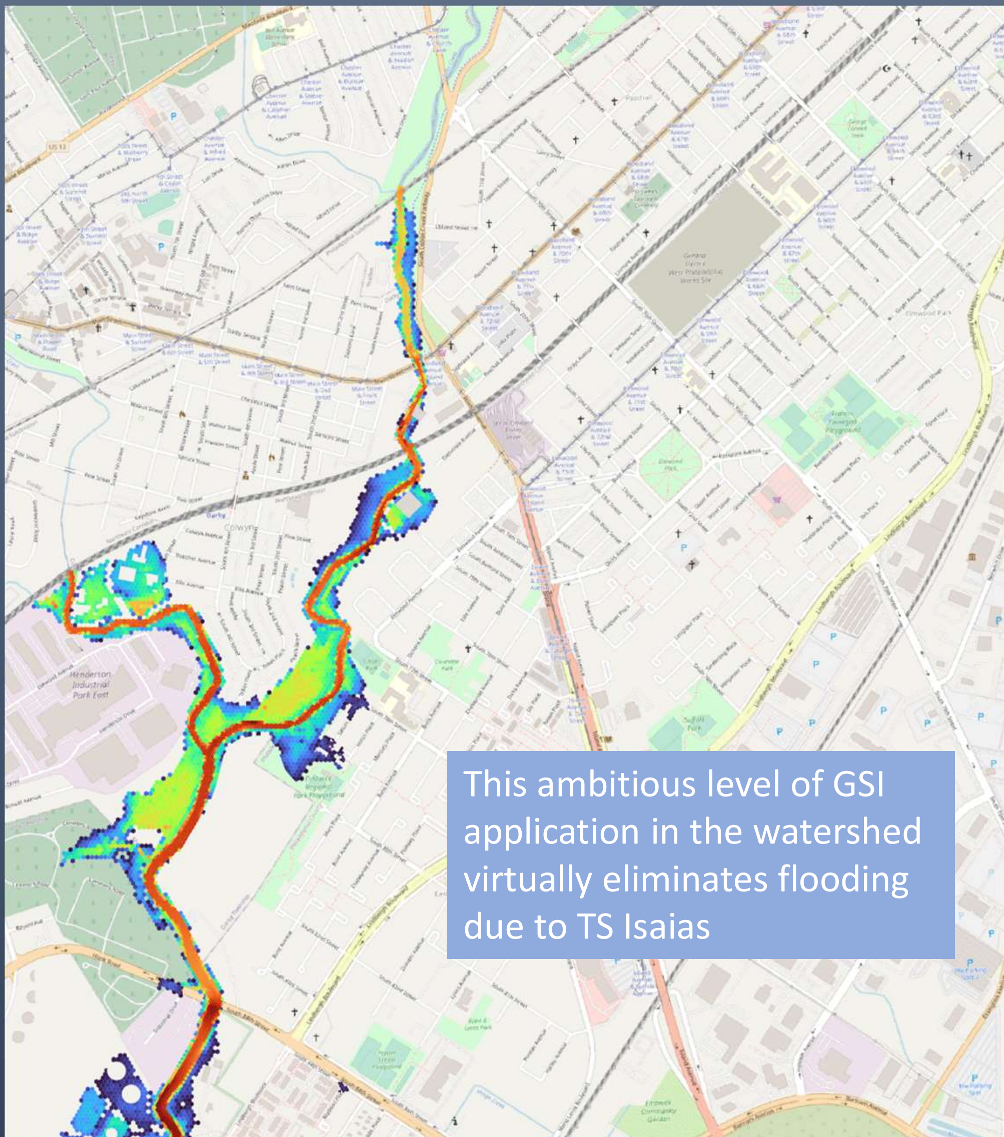
Existing pledged GSI (treating 12% of impervious area) will be unable to reduce downstream flooding significantly regardless of HLR



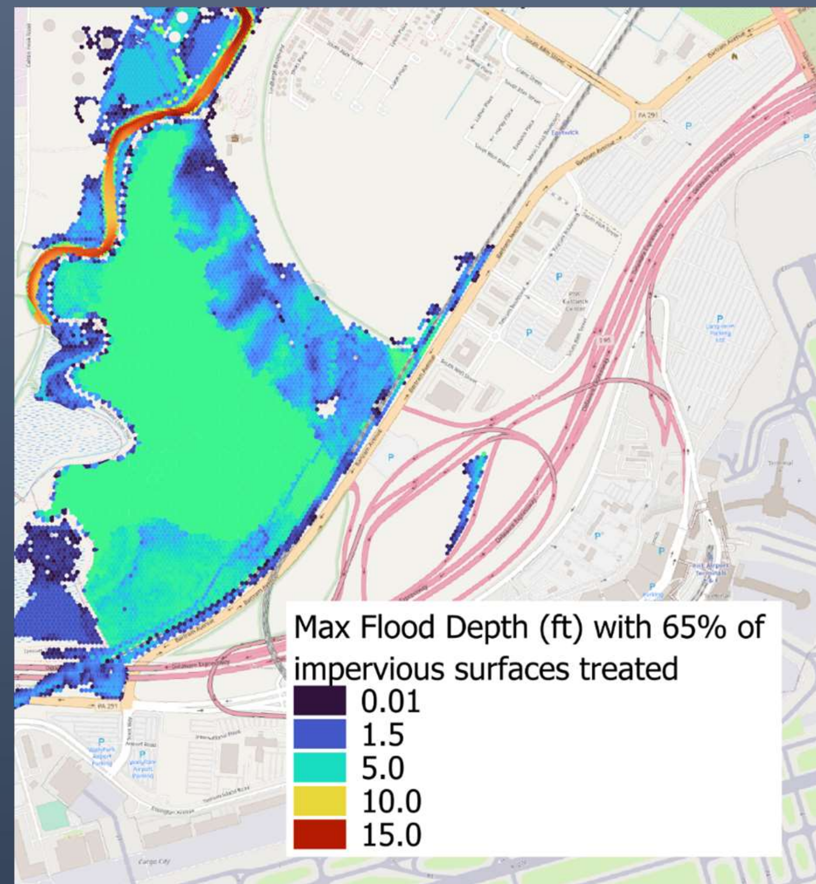
Evaluate GSI co-benefits at a more ambitious level of GSI application
(HLR 5, 65% imp area treated, 25% of watershed treated)



Peak flooding due to TS Isaias with ambitious GSI scenario

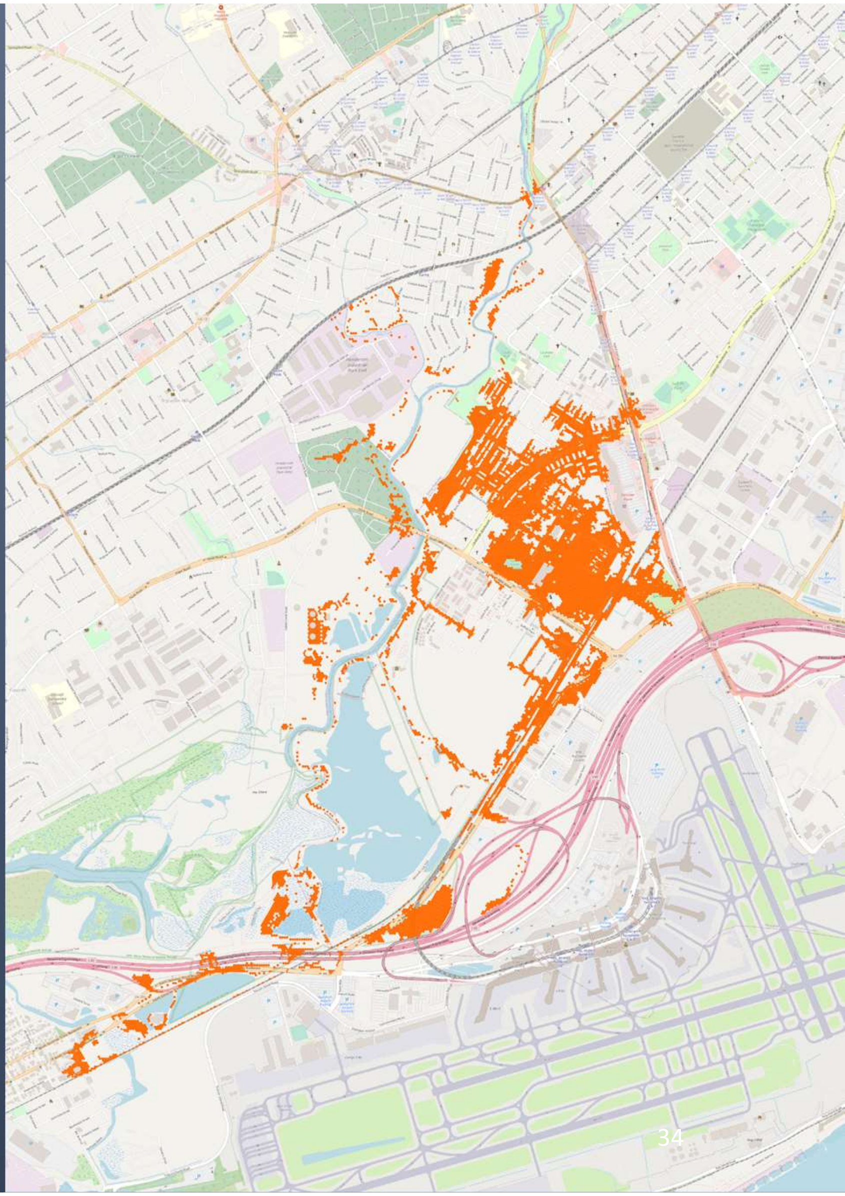


This ambitious level of GSI application in the watershed virtually eliminates flooding due to TS Isaias

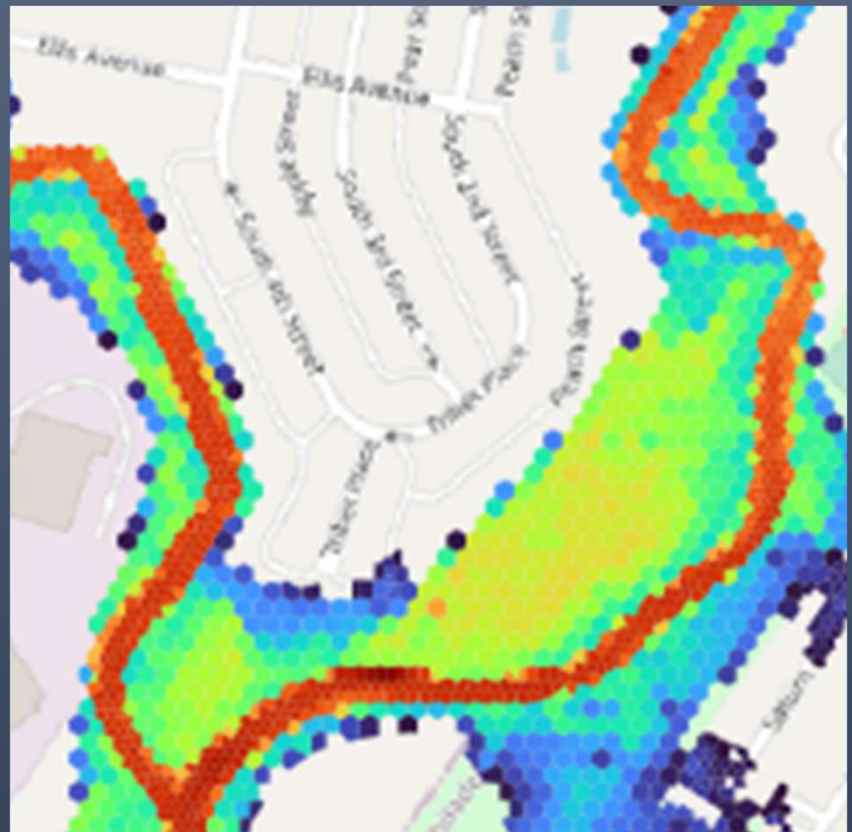


Flooding eliminated by ambitious GSI scenario

Eliminated flooding is in Eastwick as well as DelCo.

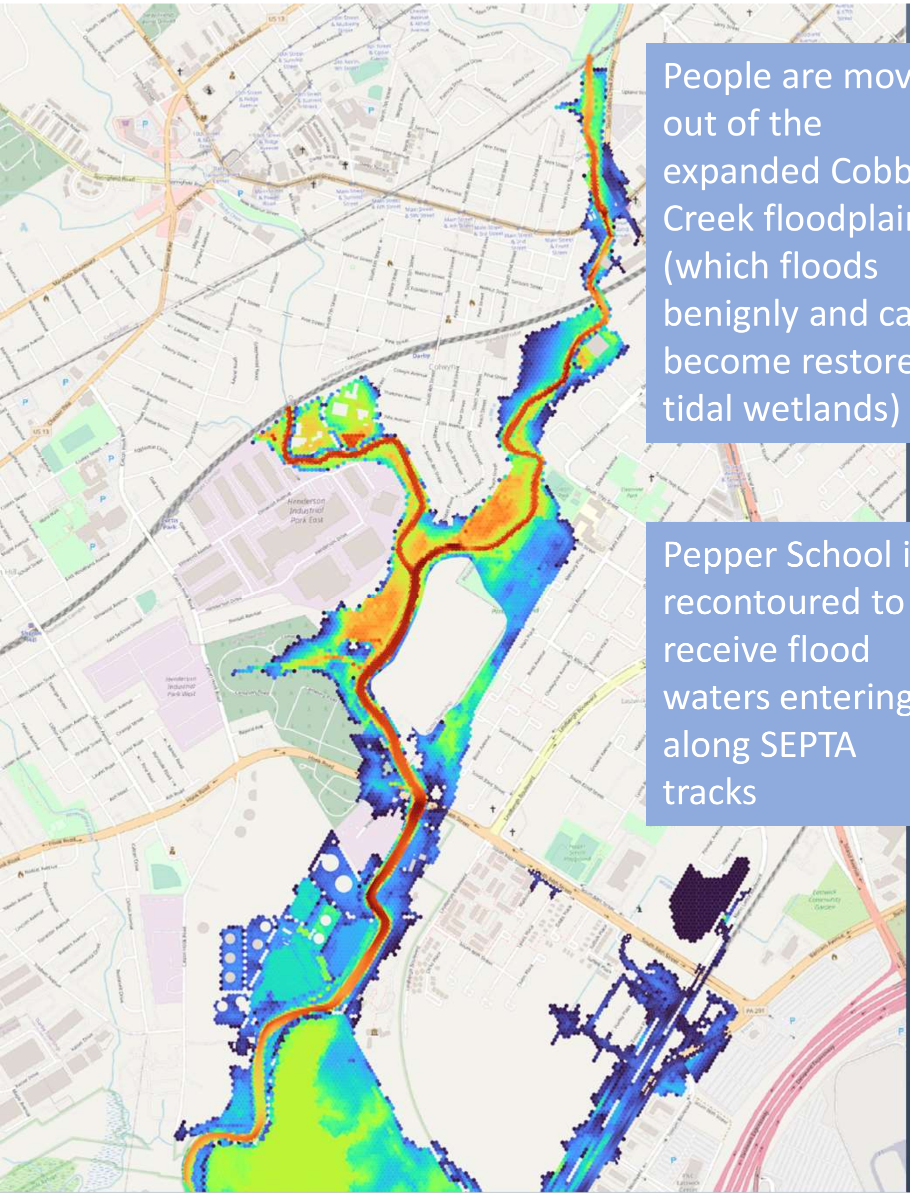


Close up sampling of peak flooding due to TS Isaias, ambitious GSI scenario



4) Modified flooding due to TS Isaias with landswap

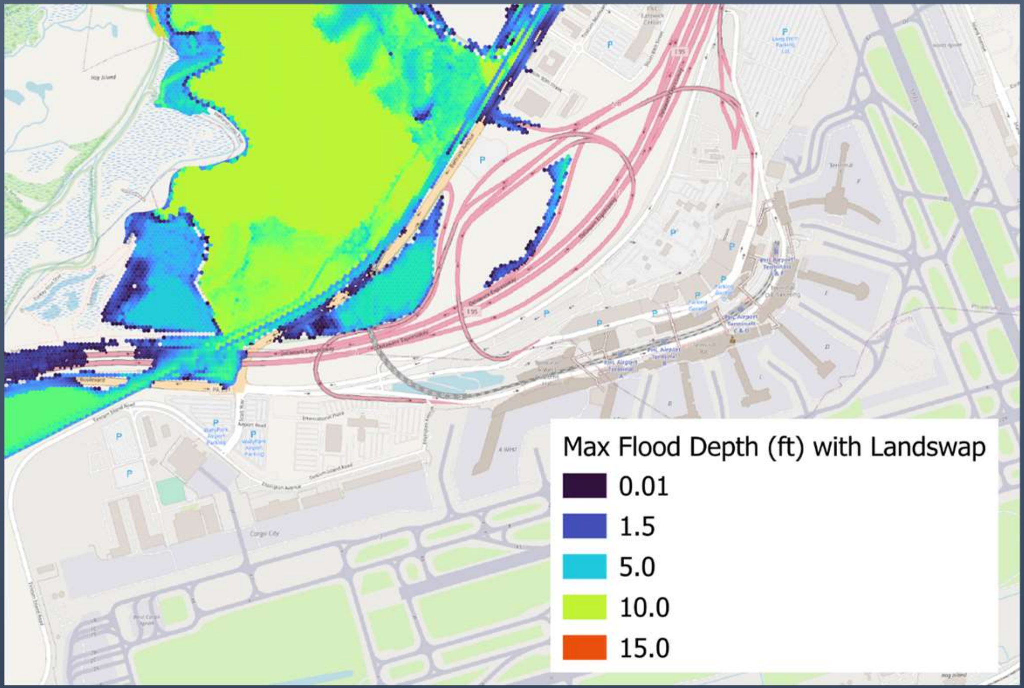
Landswap draft concept



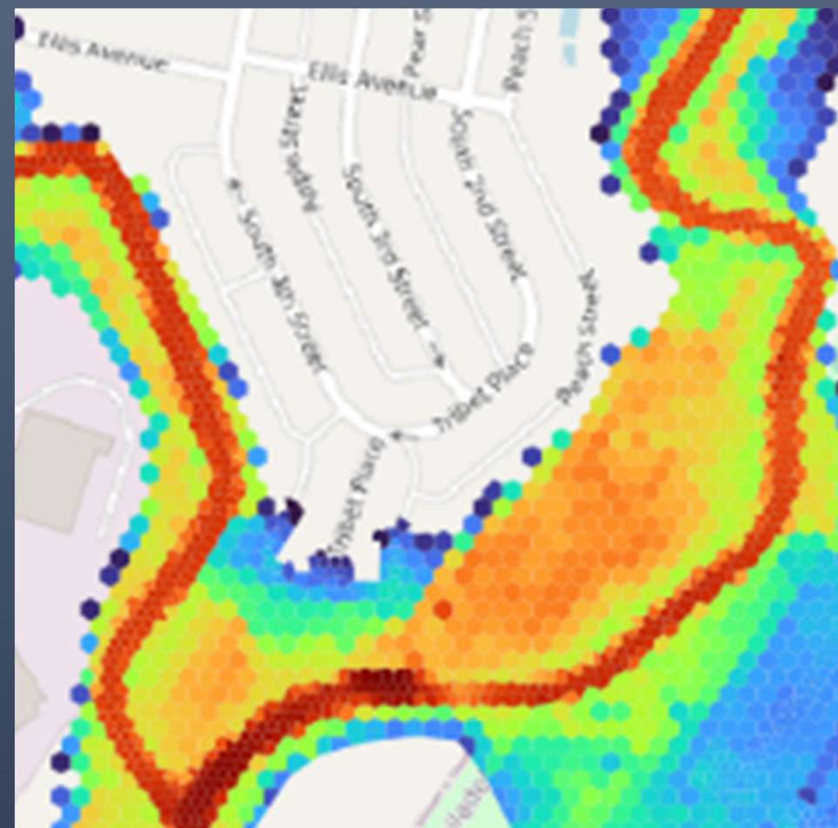
People are moved out of the expanded Cobbs Creek floodplain (which floods benignly and can become restored tidal wetlands)

Pepper School is recontoured to receive flood waters entering along SEPTA tracks

Peak flooding due to TS Isaias with Landswap

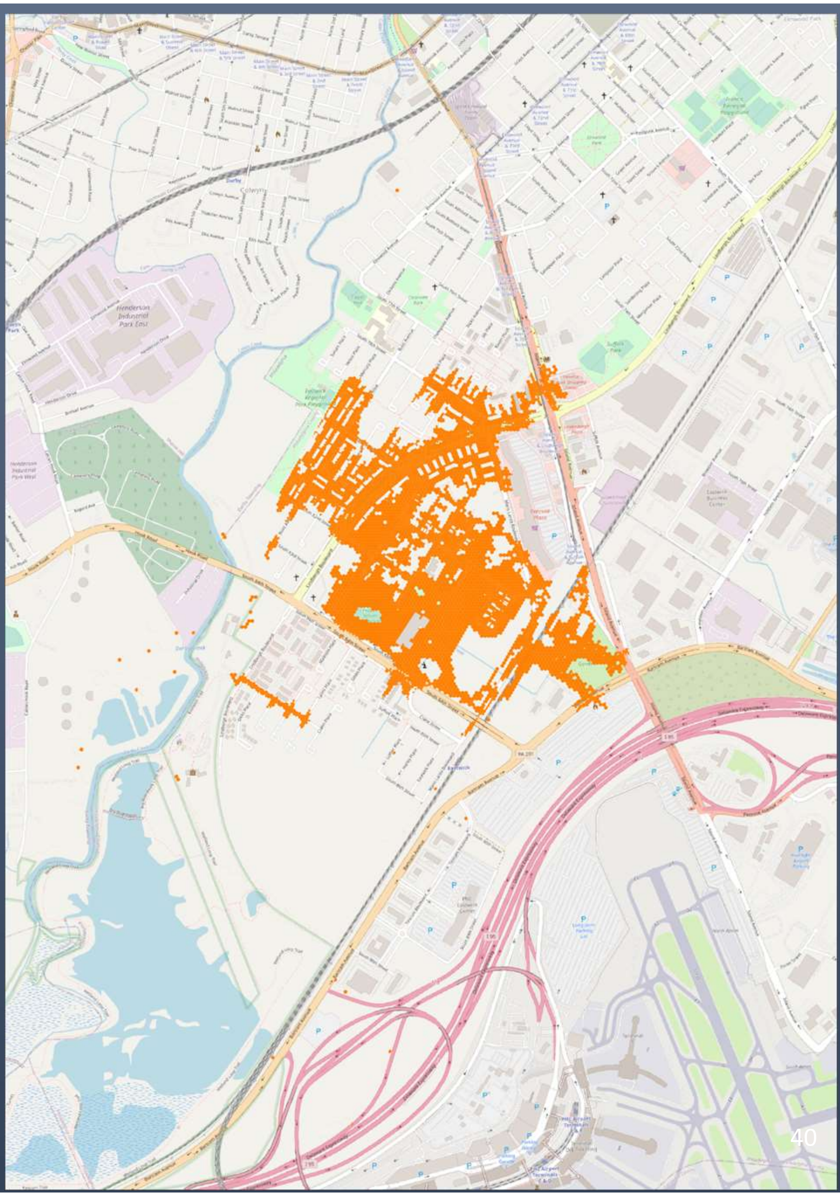


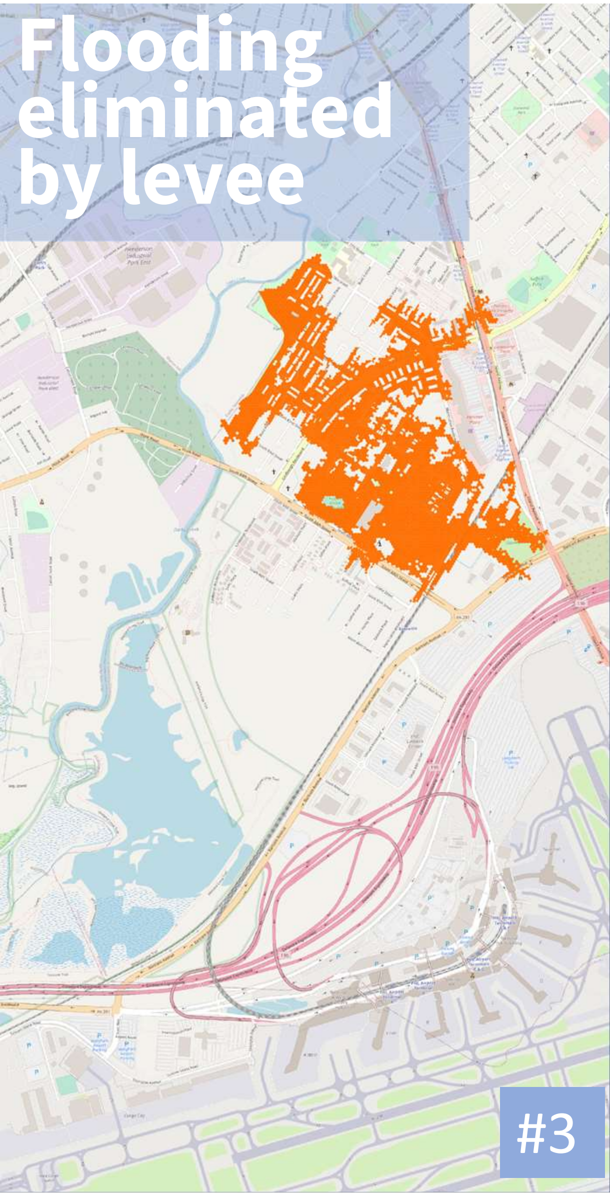
Close up of peak flooding due to TS Isaias with Landswap

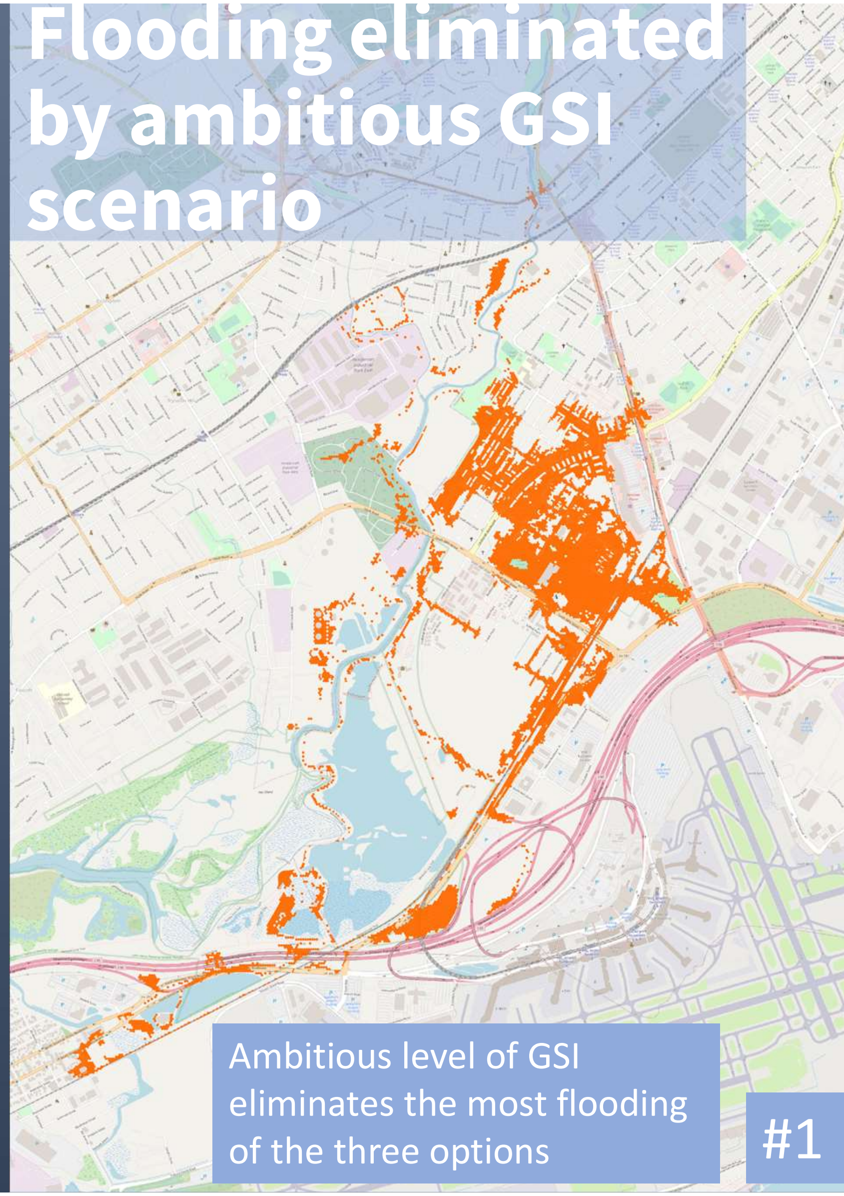


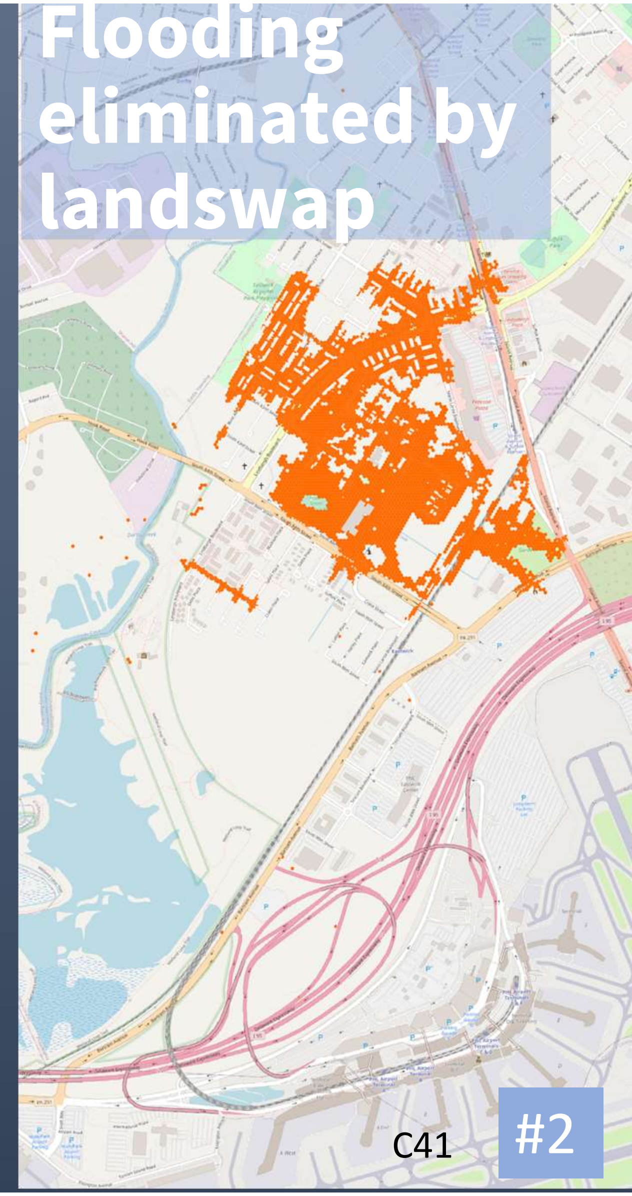
Flooding eliminated by Landswap

Landswap eliminates slightly more flooding in Eastwick than the levee

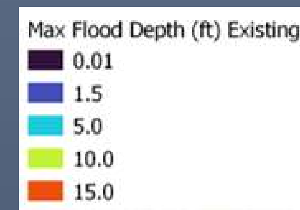



Flooding eliminated by levee
#3

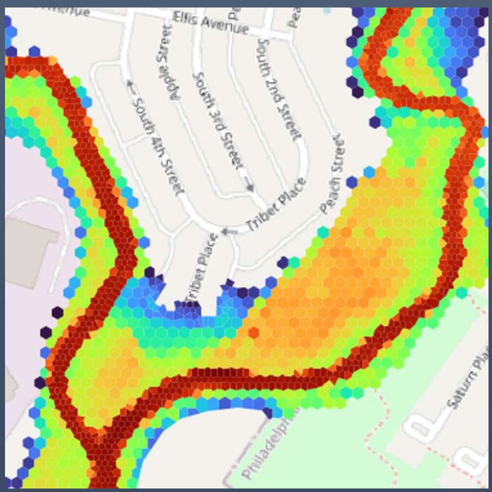

Flooding eliminated by ambitious GSI scenario
Ambitious level of GSI eliminates the most flooding of the three options
#1


Flooding eliminated by landswap
C41
#2

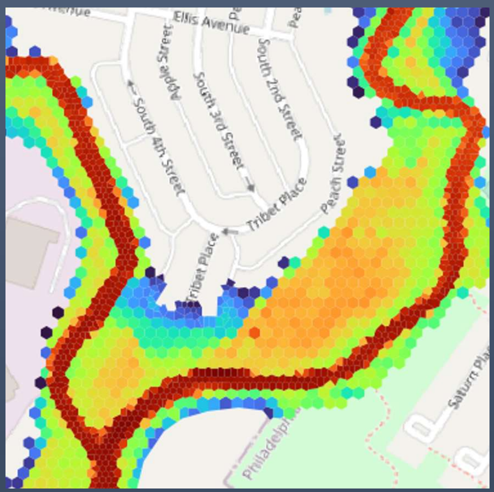
Sample comparison of adaptations, TS Isaias



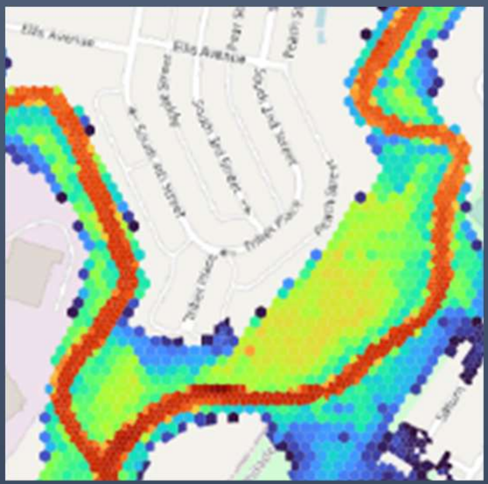
No Adaptation



Levee

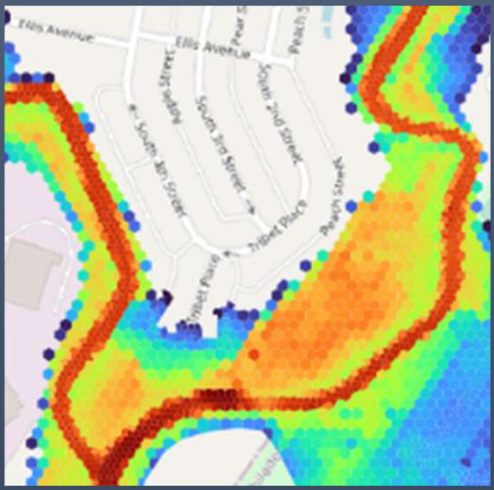


GSI



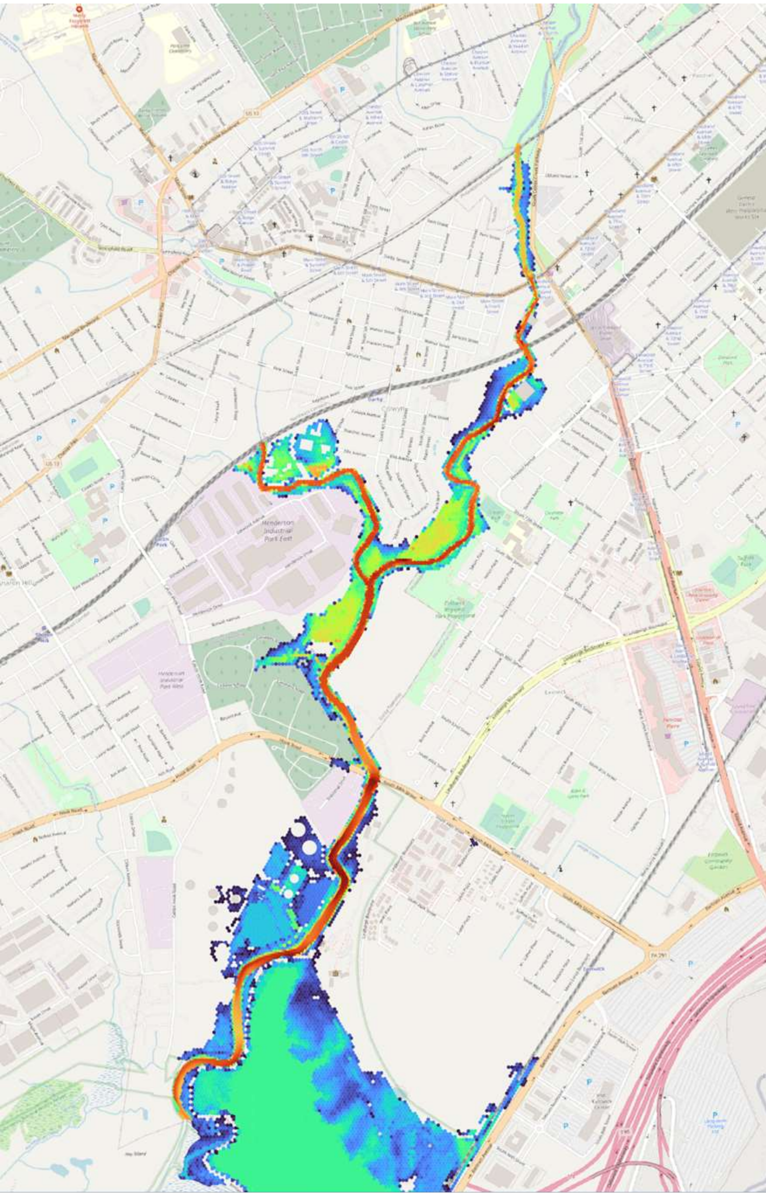
Ambitious level of GSI reduces peak flood depths at this Delco location the most

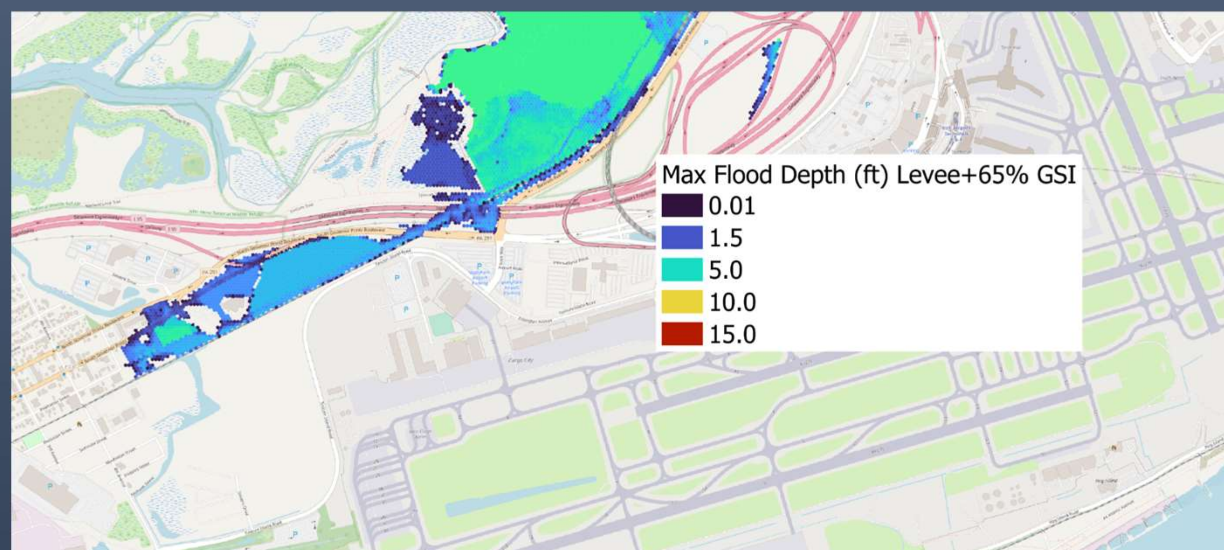
Landswap



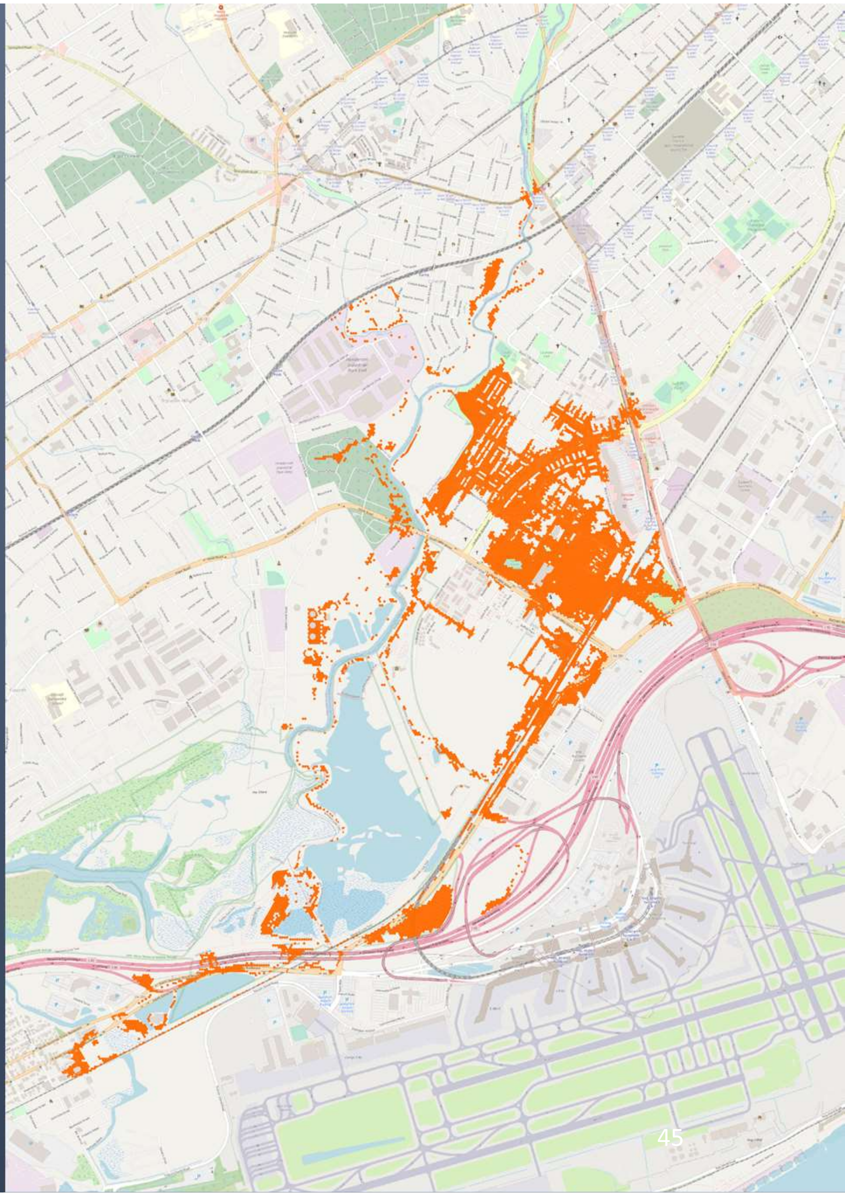
5) Modified flooding due to TS Isaias with levee + ambitious GSI

Peak flooding due to TS Isaias with Levee + ambitious GSI scenario





Flooding eliminated by Levee + ambitious GSI scenario



Conclusions

- Considering TS Isaias, levee would have induced flooding of up to ~1 ft in lower Darby Cobbs watershed
- Levee causes new regions to flood, mostly on the landward extent of the floodplain, and in some portions of Eastwick
- Landswap reduces flooded area slightly more than the levee
- Current levels of committed GSI are inadequate to reduce Isaias flooding
- At HLR=5, treating 25% of watershed area with GSI can significantly reduce flooding in Eastwick and DelCo
- In combination with the levee, induced flooding is significantly reduced (may make sense to examine less ambitious GSI scenario with the levee)
- GSI has the added benefit of reducing upstream flooding
- GSI approach seems to have greater support than the levee
- These modeling tools can be used to simulate other scenarios of interest to local stakeholders

Ongoing work

- Watershed impervious surface inventory and GSI feasibility study (parking lots, roofs, roads, etc)
- Evaluation of less ambitious GSI scenario with levee
- Climate change scenarios
- HAZUS runs with latest simulations
- Benefit cost analyses for GSI, levee, and land swap
- Dissemination of Vensim model within Darby Cobbs watershed

Follow up discussion

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