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Opportunities for Leveraging Existing Hydrologic and Hydraulic Models Developed for Water Quantity Management to Mitigate Flooding Due to Extreme Precipitation

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ABSTRACT

With a focus on a specific flood-prone community in Camden, NJ, this research utilizes a detailed hydraulic and hydrologic (H&H) model to assess the impacts of climate change on Combined Sewer Overflows (CSOs) and localized flooding under two different infrastructure scenarios. In the US, the Clean Water Act compels regulated utilities to develop Long-Term Control Plans to reduce combined sewer overflows (CSOs), but there is no parallel mandate to simultaneously reduce flooding within the associated service areas. With different control measures in place, H&H models are frequently used to evaluate CSO volumes and frequencies under historical climate conditions. However, precipitation intensification and sea level rise (SLR) will also modify CSO volumes. This study uses a calibrated and validated 1D and 2D Personal Computer Stormwater Management Model (PCSWMM) simulation to predict both CSO discharges and flooding under different climate and infrastructure scenarios. A total of ten climate change scenarios comprising a range of plausible climate futures are considered. The infrastructure scenario that is tested would divert stormwater generated in an upstream municipality (Pennsauken, NJ) away from Camden's combined sewer system. Without the disconnection, increases in precipitation will increase CSOs, whereas SLR primarily increases flooding. The proposed mitigation strategy can immediately reduce both CSOs and flooding, but with diminishing effectiveness over time, as climate change demonstrates the need for supplemental measures. Areas for further analysis regarding alternative mitigation methods and future research are outlined.

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1. INTRODUCTION

Aging drainage systems are often unable to convey flows at their designed conveyance capacity (USEPA 2004), leading to sewer backups and surface flooding, which are bound to get worse with climate change. Increases in the amount or intensity of precipitation can worsen pluvial flooding, while sea level rise (SLR) can worsen coastal and compound flooding (Wright et al. 2019). In older municipalities served by combined sewer systems (CSSs) (Lund et al. 2020) floodwaters can include both stormwater runoff and municipal sewage. Combined sewer overflows (CSOs) create public and environmental health risks (De Sousa et al. 2012) and are some of the leading causes of pollution to surface water bodies (Montalto et al. 2007). In the U.S., as mandated by the Clean Water Act (CWA), the Environmental Protection Agency (EPA) developed a CSO Control Policy requiring permitted entities to characterize, monitor, and model CSSs, ultimately supporting development of Long-Term Control Plans (LTCPs) that limit the frequency and/or volume of CSOs (USEPA 1994). Compliance with federal CSO control policy can involve upgrading or expanding grey infrastructure to capture and treat overflows (Zimmer et al. 2018) or applying a decentralized, source control approach that uses grey or green stormwater infrastructure (GSI) to reduce the volume of stormwater runoff from entering CSSs (Zhang et al. 2021).

The CWA compels regulated entities to develop LTCPs to reduce CSOs, but there is no parallel mandate to simultaneously reduce flooding within the associated service areas. There is also currently no requirement that the precipitation and outfall tailwater time series used in hydrologic and hydraulic (H&H) models be adjusted to consider climate change. Though major investments to reduce CSOs are underway nationwide (Bierbaum et al. 2012), climate change could reduce the effectiveness of these projects (Huong and Pathirana 2013). Ideally, utilities seeking to comply with EPA CSO Control Policy would stress test CSO mitigation strategies under both historical and future climate conditions (Lai et al. 2022) to ensure long-term infrastructure performance (Olsen et al. 2017). H&H models can be crucial in such evaluations.

One obstacle to representation of climate change in H&H models is persistent uncertainty regarding the extent, severity, and magnitude of the climatic changes associated with specific places (Underwood et al. 2020; Hallegatte 2009; Lopez-Cantu et al. 2020). It is unequivocal that humans have changed the climate (IPCC 2021), but global projections of climate change are subject to uncertainty due to incomplete understanding of the climate system and future emissions, insufficient representation of climate system in global climate models, and limited computer resources (Wu et al 2022). Though climate change is modifying precipitation, causing SLR, and triggering complex compounding effects (Douglas et al. 2011; Han et al. 2010), the forecasted changes are non-uniform and can be highly variable (Zhang and Fueglistaler 2019; Richter et al. 2012). The outputs from multiple Global Climate Models (GCMs), completed using a range of future greenhouse gas emissions, must be considered to fully characterize uncertainty. Shepherd (2014) points out that climate projections from GCMs are subject to greater uncertainty when applied on regional scales, discouraging their direct usage in engineering decision making (Lai et al. 2022).

Precipitation is among the most uncertain GCM outputs and statistical and dynamic approaches have been developed to downscale GCM outputs to finer spatial scales that are more suitable for use in H&H modeling. Dynamic strategies involve forcing higher resolution regional climate models (RCMs) with the outputs from coarser resolution GCMs to generate more spatially precise climate forecasts that can resolve differences due to topography, land use, and other local factors. Statistical approaches are, however, more common. Delta change factors (DCFs) computed as ratios of future GCM or RCM- forecasted annual or monthly precipitation amounts to historical baseline amounts are used to modify finer temporal resolution historical precipitation observations (Maimone et al. 2019), often in specific quantiles (or frequencies).

If urban drainage systems discharge into receiving water bodies connected to oceans, sea level rise must also be incorporated into the tailwater conditions assumed for H&H model outfalls. One way to generate future, climate-changed outfall tailwater conditions is to add forecasted changes in localized mean sea level to historical water level observations at the point of interest in modeling (Nauels et al. 2017).

Even under historical climate conditions, efforts to reduce CSOs and mitigate flooding are challenging to implement and difficult to finance (Mobley et al. 2020, Lund et al. 2020). Climate change will make compliance with local and national clean water regulations (Pasquier et al. 2019) even more challenging, especially for coastal, low-income, communities that are generally more susceptible to flood damages, displacement (Lee and Jung 2014) and other socioeconomic challenges (Bick et al. 2021). Stormwater management strategies designed to historical climate conditions (De Sousa et al. 2012), may not perform well under future conditions (Wang et al. 2021). To avoid stranding these valuable assets, decision makers must factor climate change into infrastructure planning and design (Martinich and Crimmins 2019). A “climate stress test” or “vulnerability analysis” (Brown and Wilby 2012) in which low, medium, and high values of climate variables are sampled from the statistical range of model outputs (Albano et al. 2021; de Klerk et al. 2021) can be part of robust risk and vulnerability analysis (Tate et al. 2021), that balances current and future costs in infrastructure planning (IPCC 2007). This approach can be especially valuable to low-income communities that have historically been less likely to obtain state or federal aid to prepare for natural disasters (Godschalk et al. 1999).

This study aims to explore how climate change will impact CSOs and flooding in Camden, a New Jersey coastal environmental justice community. A climate stress test is performed on a Personal Computer Stormwater Management Model (PCSWMM) (CHI 2022) model representing a portion of the city’s CSS. The study predicts both CSO discharges and flooding under different climate and infrastructure scenarios. A total of ten climate change scenarios comprising a range of plausible climate futures are considered. The infrastructure scenario that is tested would divert stormwater generated in an upstream municipality (Pennsauken, NJ) away from Camden’s combined sewer system.

2. METHODS

2.1 Study area

The study area (Figure 1) is in Camden, New Jersey, a coastal community bordering the Delaware River, east of Philadelphia, Pennsylvania. The City of Camden and Camden County are served by CSSs, operated by the Camden County Municipal Utilities Authority (CCMUA) that collect stormwater and municipal sewage from 29 sewersheds, with 23 CSOs that discharge into local tributaries during high flows (CCMUA 2018). The specific area of study is Cramer Hill, a largely residential community located upstream of CSO-32, the largest CSO in CCMUA's system. Cramer Hill routinely experiences pluvial flooding, and large portions of it are located within the New Jersey Department of Environmental Protection (NJDEP) coastal flood hazard zone, with coastal flooding bound to worsen as the sea level rises. The CSS that serves Cramer Hill also collects stormwater from an adjacent Camden County municipality, Pennsauken, located north-east of Cramer Hill.

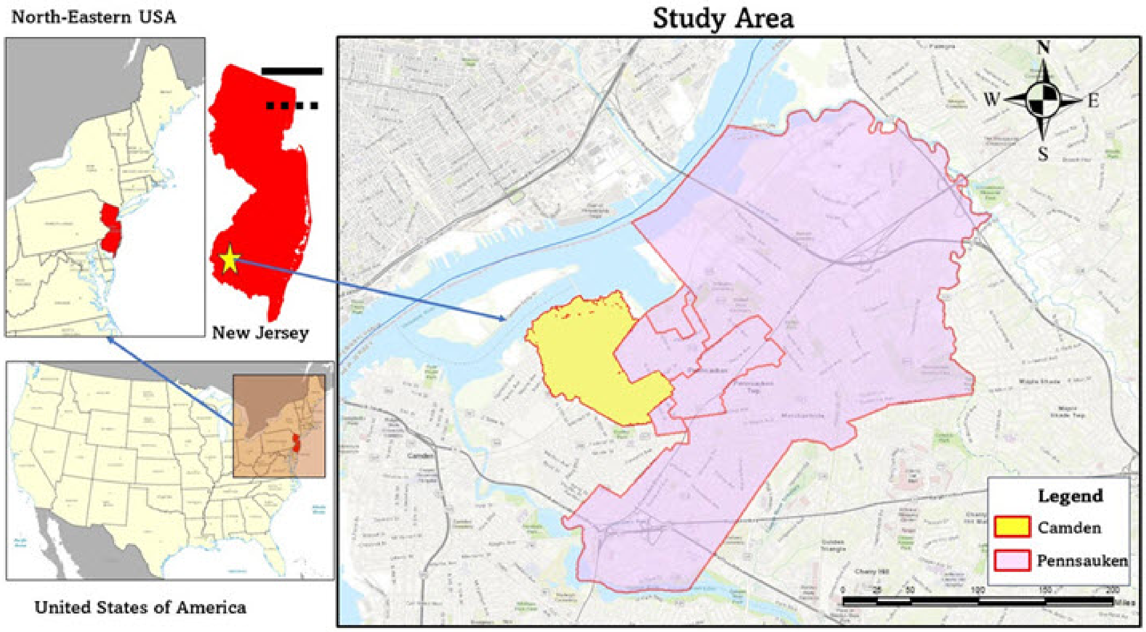

Figure 1 Camden and Pennsauken, NJ study area borders.

Over the last two decades, CCMUA has leveraged its investments in state and federal clean water regulatory compliance to advance environmental justice (CCMUA 2016) and to identify and remedy ecosystem service gaps in its service area (Zidar et al. 2017), while minimizing the financial burden on rate payers. This effort has included attempts to simultaneously reduce CSOs and flooding (CCMUA 2016, USEPA 2004). In 2012, CCMUA helped to create Camden's Stormwater Management and Resource Training (SMART) initiative to foster public participation in its efforts to upgrade its stormwater infrastructure. CCMUA published its CSO Long Term Control Plan (LTCP) in June of 2018 and set a goal of capturing 85% of the combined sewage generated during precipitation events occurring over the typical year (CCMUA 2020). CCMUA's LTCP will consider different strategies, including green stormwater infrastructure (GSI). However, in Cramer Hill a key question has been whether overflows at C32 and flooding can be reduced by using the High Street Pump Station to divert stormwater generated in Pennsauken away from Cramer Hill's CSS. To begin to evaluate the potential benefits of this so-called "Pennsauken disconnection" CCMUA partnered with the authors to develop a high resolution, all pipes H&H model with which to evaluate both CSOs and flooding, with and without the Pennsauken disconnection system in place. The study would consider both historical and future climate scenarios.

2.2 Model platform

Pluvial flooding can be triggered at any manhole or catchbasin in which surface runoff is not captured. Runoff that is not intercepted by the drainage system flows overland in the direction of the topographic gradient. Because it was used to simulate flows over all CCMUA's service area, the SWMM-based H&H model used to develop the LTCP was 1D only, and of relatively coarse spatial resolution and thus unable to simulate localized pluvial flooding in Cramer Hill. An all-pipes 1D-2D PCSWMM model was developed that would receive upstream flows from the system-wide LTCP model yet be calibrated – under existing conditions – to produce downstream flows that also matched the LTCP model. In this way, the model would add the resolution required to answer the specific management questions relevant to Cramer Hill, while also benefiting from the work that went into building and calibrating the system-wide model.

PCSWMM was the ideal modeling platform to use in this study because it allows users to perform both continuous and event-based simulations to quantify runoff, flooding, sewer surcharging, and other relevant physical phenomena (CHI 2022). Figure 2 illustrates the all-pipes PCSWMM model that was developed, highlighting some of its main 1D features such as CSO-32, Von Neida Park, junctions including sanitary flow (inflow junctions) boundary conditions, and the High Street pump station (PS) to be referenced throughout this paper.

Figure 2 PCSWMM detailed sewer network of Camden, NJ with key features.

2.3 1D and 2D modeling

PCSWMM adopts a systematic and fully integrated approach to 1D and 2D modeling, streamlining the process of integration. In the development of the 1D model, the process begins with the creation of the 1D urban sewer network and defining the sub-catchments. In the 2D model development, the initial phase entails the establishment of the bounding layer, serving as the foundational framework for the 2D model. Within this layer, the spatial extent of the model is defined, with subareas designated for the application of diverse mesh types. This flexibility allows for the customization of mesh types and styles to align with specific modeling requirements. In this model, a hexagonal mesh is employed, but PCSWMM allows for different mesh geometries and resolutions to be specified based on modeling needs. In the Cramer Hill model, open spaces and lots are allocated a coarser resolution of 50 ft, while streets receive a finer resolution of 30 ft. This deliberate differentiation in mesh resolution minimizes the number of mesh elements across the entire model area, preventing instability and excessive computational demands.

Following the establishment of the bounding layer, the subsequent step involves the creation of the 2D nodes layer. This layer plays a crucial role in defining the key junction points within the 2D network. To accurately characterize the 2D cells, the 2D nodes layer utilizes elevation data sourced from a Digital Elevation Model (DEM) layer.

Once the 2D cells and nodes are in place, the 2D mesh is generated (Figure 3), providing a comprehensive spatial representation of the 2D network, and enabling the simulation of water flow across the model. To achieve a complete representation of hydraulic and hydrological dynamics, the final step integrates the 1D model with the 2D overland mesh using the "connect 1D directly" approach. This seamless integration ensures that both surface and subsurface flow processes are accurately considered, enabling comprehensive and accurate simulations.

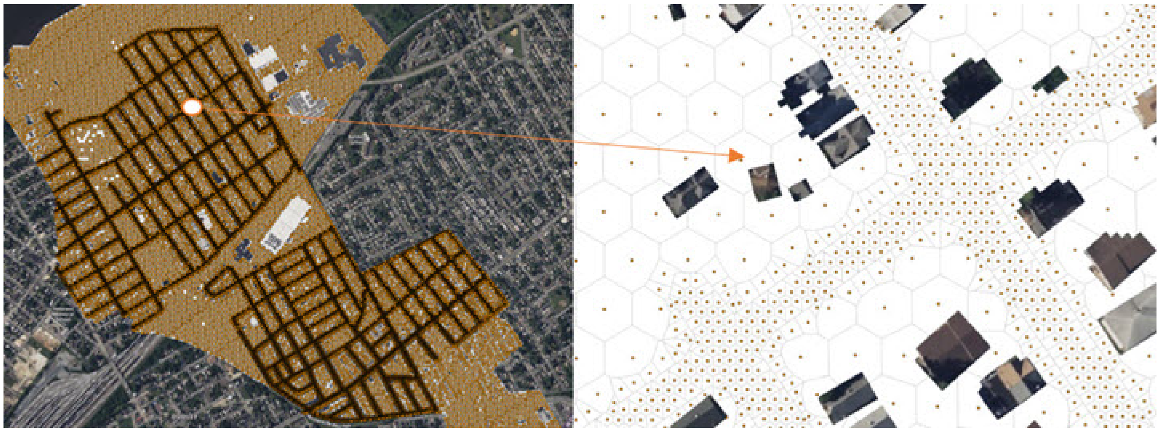

Figure 3 PCSWMM generated 2D mesh of the study area.

2.4 Parameterization of physical model elements

Geospatial data sets used in model development include a digital elevation model (DEM) to represent local topography, a building footprint file to be used to represent surface obstructions to flow, an impervious surface file to be used in subcatchment parameterization, and other map layers to represent other relevant local features like parks in the model. In this application, all geospatial data was obtained from the New Jersey Department of Environmental Protection (NJDEP) Bureau of GIS (BGIS). The DEM is referenced vertically to the North American Vertical Datum of 1988 (NAVD88), and horizontally to the North American Datum of 1983 (NAD83). The resolution of the DEM is approximately 3 meters, and all NJDEP BGIS elements were clipped to match the extents of the model. Parameterization of the model’s other subcatchment, conduit, junction, and outfall properties were based on attribute data obtained from CCMUA, the NJDEP BGIS data repository, the LTCP model (CCMUA 2018), and best engineering judgment from industry standard sources, like the PCSWMM User’s Manual (CHI 2022). CCMUA also provided official engineering design plans of the sewer network (1975 Weston map and 1989 Utilities map), which are not easily accessible to the public. While detailed soil information for this area was not available, the local Soil Conservation Service (SCS) categorized this land as local urban land, followed by the assumption that local soils had similar properties to sandy loam. With the stated assumptions, a Horton infiltration model was used.

2.5 Simulation options

Because pipe surcharging processes were of interest, dynamic wave routing was used for hydraulic routing with the Hazen-Williams force main equation with a normal flow criterion and Slope & Froude equation. Overall, most simulation editor options were identical in the 1D and 2D models, but extensive 2D simulation run times required slight adjustments to certain simulation editor options. Table A1 in Appendix I summarizes all simulation editor parameters incorporated in the 1D and 2D models.

2.6 Time-series inputs to event-based and continuous simulations

The model was used to run both event-based and continuous simulations. The event-based simulations were mainly used in the 2D model calibration and validation processes and included events on July 13, 2021, August 21, 2021, and September 1, 2021, for which 15-minute precipitation data collected locally by CCMUA was provided. A continuous simulation was used in the 1D model calibration process and utilized the modified 2014 hourly precipitation time series used in the LTCP model. This was considered a “typical year”, but included modifications to two large storms on April 29, 2014, and June 10, 2014, to modify the storm intensities to less than or equal to a 1-year average recurrence interval (ARI). The LTCP stipulates that this modified 2014 typical year hourly precipitation time series data be used in infrastructure planning. Monthly evaporation data was also used based on LTCP model values (CCMUA 2018).

Each of the event-based and continuous simulations required tidal boundary conditions on the various model outfalls to accompany the precipitation. These were downloaded from the NOAA tide gauge located on the Delaware River, just downstream of Cramer Hill (gauge #8545240). Data from this gauge was downloaded for the entire 2014 year, as well as for the July 13, 2021, August 21, 2021, and September 1, 2021 precipitation events. This data can be found on the *National Oceanic and* Atmospheric *Administration (NOAA) Tides & Current Data* website (NOAA 2022a). Local tide data is vertically referenced in NAVD88 and horizontally referenced in NAD83.

Dry weather node inflow included both base flow and dry weather sanitary flow (DWF), applied throughout the model, as shown in Figure 2. Average DWF flow was initially determined from CCMUA treatment plant inflow data, with peaking factors and baseflow per the LTCP. Baseflow followed monthly patterns, while DWF followed hourly and weekend patterns for both Camden and Pennsauken. During model calibration, the simulated time series of CSO-32 overflows from the all-pipes model was compared to the LTCP CSO time series, and these values were found to be too low. Inflow and DWF were adjusted as part of the calibration process to best fit the LTCP CSO time series. Baseflow and DWF patterns included in this model can be found in Appendix II in the supplemental material section.

2.7 Model calibration and validation

Calibrating and validating an H&H model is a meticulous process that draws from various methods. Traditionally, observations of wet and dry weather flow are available to the modeling team and are divided into two sets. Set#1 is used to tune the model's uncertain parameters to obtain the best fit, after which the model's ability to replicate Set #2 observations (without further tuning) is used to quantify model error.

The traditional model calibration and validation process could not be undertaken for two reasons. First, no dry weather flow data, nor any quantitative flood data was available to the modeling team at the time this project was initiated. Second, the 2D model would have required an unacceptable amount of time to run a continuous simulation of all of 2014.

Instead, an ad-hoc, integrated, four-step calibration and validation process was developed with two versions of the model. The first step involved calibrating the cumulative annual volume of CSO discharge at CSO-32 (during 2014) using a 1D-only version of the model against the previously calibrated LTCP model. As stated before, the initial sanitary flow values underestimated the flow from CSO-32, thus, multipliers were applied to the baseflow and DWF pattern values to mimic annual discharge at CSO-32 observed by the calibrated LTCP model.

The second step, also performed using the 1D version of the model, involved creating scatter plots in which the model's peak CSO flow rates and total volume of CSOs for each CSO event in 2014 were compared to the values simulated at CSO-32 by the system-wide LTCP model. Events incorporated in this calibration process were defined with a 4-hour inter-event period and a threshold of 0.00028 cubic meters per second (cms). This configuration was chosen to align with the number and characteristics of events utilized in CCMUA's LTCP model, ensuring consistency and comparability in the calibration outcomes. During this process, PCSWMM's built-in SRTC tool was used to tune uncertain parameters, such as the subcatchment imperviousness and width to maximize the number of events that fall within +25% to -15% of the LTCP values for peak flow rate, and +20% to -10% of the LTCP values for total volume based on industry standards from Wastewater Planning Users Group (WaPUG) (WaPUG 2002).

The third calibration step utilized the integrated 1D-2D model (with 1D model parameters as tuned during the first two steps). The modeling team visited Cramer Hill during a series of extreme precipitation events in 2021 and photo documented flooding. Event-based 1D-2D model simulations were completed for July 13, 2021, August 21, 2021, and September 1, 2021, precipitation events that caused real time surface flooding in Camden, NJ. During this step of the calibration, the 2D model parameters were adjusted until the spatial extent and depth of simulated flooding best matched the field observations conducted by the authors.

The final step involved using the 1D-2D model to perform event-based simulations for a few of the events in 2014 for comparison with the LTCP model. In this step, all 1D and 2D model parameters were set at the values as adjusted during the previous three steps. Simulated CSO-32 hydrographs generated from the new model were compared with those generated by the LTCP model, focusing on June 10, 2014, July 13, 2021, August 21, 2021, and September 1, 2021. The process was iterative. Prior steps were repeated until all four calibration/validation activities resulted in satisfactory results.

2.8 Modeling scenarios

The calibrated/validated models were used to evaluate CSOs and flooding under historical and future climate conditions, with and without the Pennsauken disconnect in place. Because of Camden’s geographical proximity to Philadelphia, and the availability of previously downscaled climate change projections for that city, no new climate downscaling was undertaken as part of this study. Rather, the climate stress testing utilized precipitation increases and SLR estimates were selected to represent previously reported low, middle, and high values for the region. These values do not represent probabilistic outcomes (with the highest value being the least likely, for example). Rather, they represent the range of values obtained by different researchers, using different GCMs, under different climate conditions, forcing scenarios in this region.

To sample the variability associated with previously downscaled climate projections, a variety of data sources were reviewed, and the data is compiled in Figure 4. The City of Philadelphia commissioned ICF Incorporated (2014) to publish Useful Climate Information for Philadelphia: Past and Future. The Philadelphia Water Department (PWD) is currently undertaking an internal, multi-year effort to estimate future precipitation increases and SLR to support its own planning. A variety of NOAA-funded research teams have published climate change estimates for the Camden/Philadelphia region: The NOAA-funded Climate & Urban Systems Partnership (CUSP 2016) developed Mean Annual Changes values for the Philadelphia region; The Consortium for Climate Risk in the Urban Northeast (CCRUN) projected SLR (NOAA 2022b); the Mid-Atlantic Regional Integrated Sciences and Assessment (MARISA), Northeast Regional Climate Center (NRCC), and the RAND Corporation (Miro et al. 2021) developed precipitation change estimates for the Chesapeake Bay area, but extended their methods up to Camden. The USEPA developed the SWMM Climate Adjuster Tool (SWMM-CAT) (USEPA 2014) to assist SWMM modelers in developing geographically specific DCFs based on the Coupled Model Intercomparison Project Phase 3 (CMIP3) GCM outputs (it has not been updated to CMIP4, 5, or 6).

Based on the ranges associated with these data sources, multiplicative DCFs that increase historical precipitation by 10% (multiplier = 1.1), 20%, and 30% were selected, along additive sea level change factors that add 0.3 meters, 0.9 meters, and 1.8 meters to historical NOAA gauge values. Per Miro et al. (2021), these values can be considered representative of the ranges associated with both low and high emission scenarios, spanning the periods from 2020 to 2070, and 2050 to 2100.

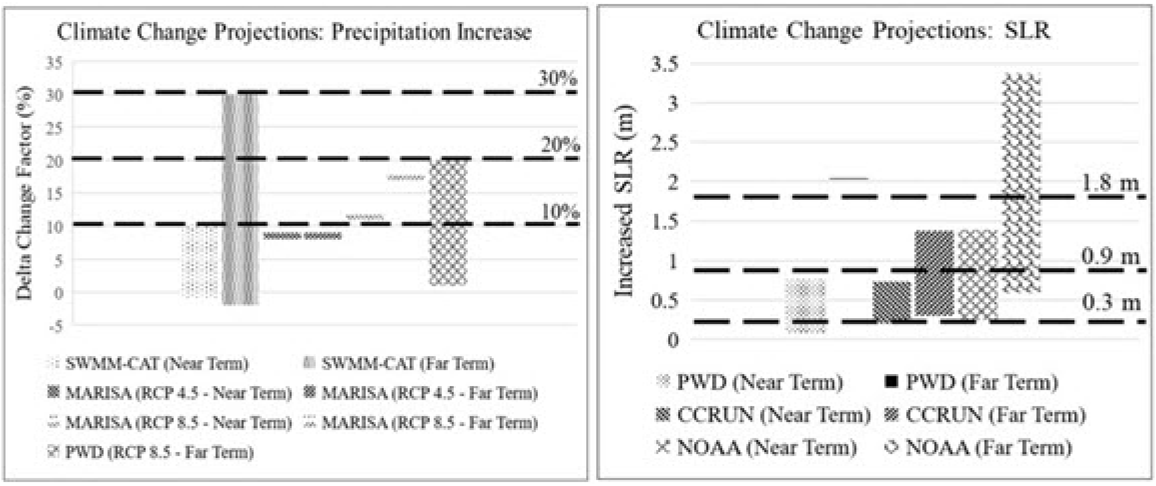

Figure 4 Climate stress test demonstrating future climate change projections.

Per Table 1, baseline scenarios feature existing conditions (e.g., Scenario a, no disconnect) without climate change (Scenario 1.1). Climate change considerations for only precipitation increase will explore DCFs with a 10% increase (Scenario 2.1), 20% increase (Scenario 2.2), and 30% increase (Scenario 2.3). Climate projections for only SLR will apply additives to current tide data of 0.3 meters (Scenario 3.1), 0.9 meters (Scenario 3.2), and 1.8 meters (Scenario 3.3). Compound climate change conditions will also be studied by applying both precipitation increase and SLR projections for low (Scenario 4.1), middle (Scenario 4.2), and high (Scenario 4.3) estimates. The same climate scenarios are repeated with the Pennsauken disconnect in place (e.g., Scenario b). All told, 20 modeling scenarios, including ten climate change scenarios and two infrastructure scenarios, were performed.

Table 1 Climate change modeling scenarios.

Climate Change Considerations		Precipitation Increase (%)			
		None	+10%	+20%	+30%
Sea Level Rise (m)	None	1.1	2.1	2.2	2.3
	+0.3 m	3.1	4.1	-	-
	+0.9 m	3.2	- 4.2 - -		-
	+1.8 m	3.3			4.3

2.9 Modeling metrics

A variety of metrics have been selected to present the differences in the results. Metrics associated with the 1D model include the cumulative annual volume of discharge at CSO-32, the annual number of discharge events at CSO-32 throughout 2014, the annual number of events triggering nodes flooded throughout 2014, the number of nodes flooded at least once in 2014, and cumulative hours of node flooding throughout the model. In contrast to the approach taken in the model calibration/validation process, events are defined using a 24-hour inter-event period with a threshold of 0.00028 cms.

Metrics associated with the 2D model include peak flooding depth, maximum area flooded throughout the model, and number of structures impacted by flooding in June 2014. The flooding metrics quantify the number of nodes flooded based on surcharging nodes, how many events cause node surcharging, the hourly total of surcharged nodes, and finally the maximum flooding based on water depths determined from the 2D mesh. The number of structures impacted by flooding was evaluated by highlighting all flooded 2D cells, and then using PCSWMM's built-in tools to count how many structures were touching flooded cells from the NJDEP BGIS building footprint.

3. RESULTS AND DISCUSSION

The outcome of the PCSWMM calibration and validation process is presented first in Section 3.1, followed by the 1D (Section 3.2) and 2D (Section 3.3) CSO and flooding metrics associated with the 20 different climate and infrastructure scenarios. Section 3.4 provides a more general discussion of the results.

3.1 Calibration and validation results

To best fit the cumulative annual discharge at CSO-32, predicted with the LTCP model, baseflow and DWF patterns in the LTCP model were adjusted using different multipliers. A multiplier value of 2.2 yielded the best-fit curve with <1% difference in CSO-32 annual discharge between the detailed model and LTCP model (Figure 5).

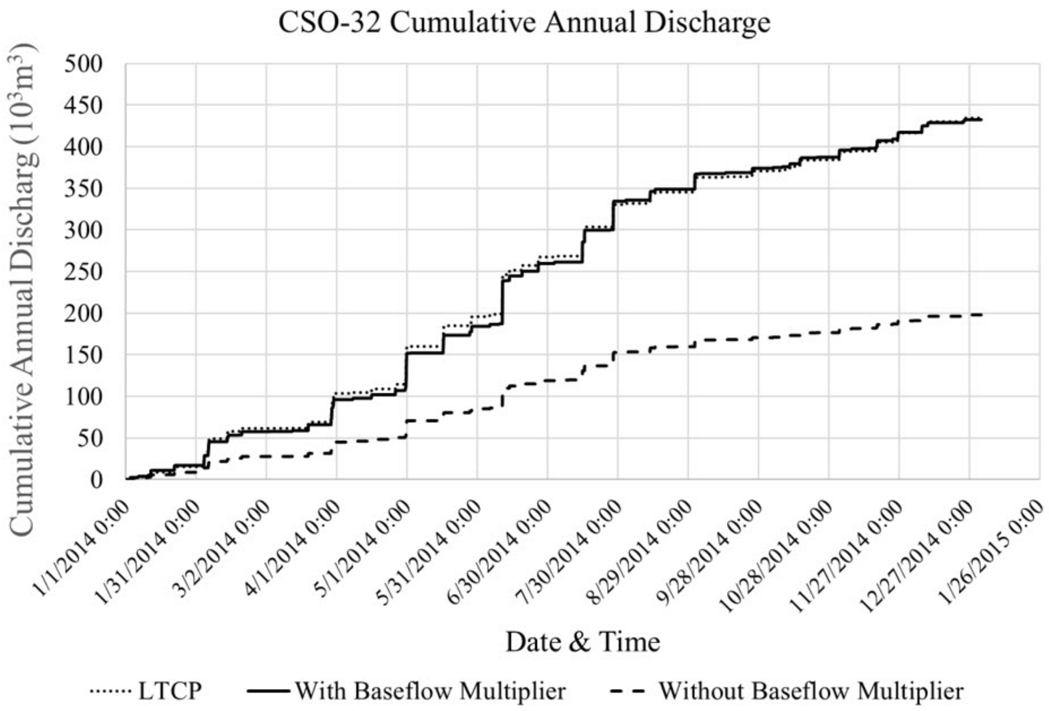

Figure 5 Calibrated cumulative annual discharge at CSO-32.

Using the best fit baseflow and dry weather flow, most of the predicted peak rate and total volume of CSOs fell within an acceptable range of the LTCP values, as shown in Figure 6. A very small number of events fell on or just outside of the acceptable range.

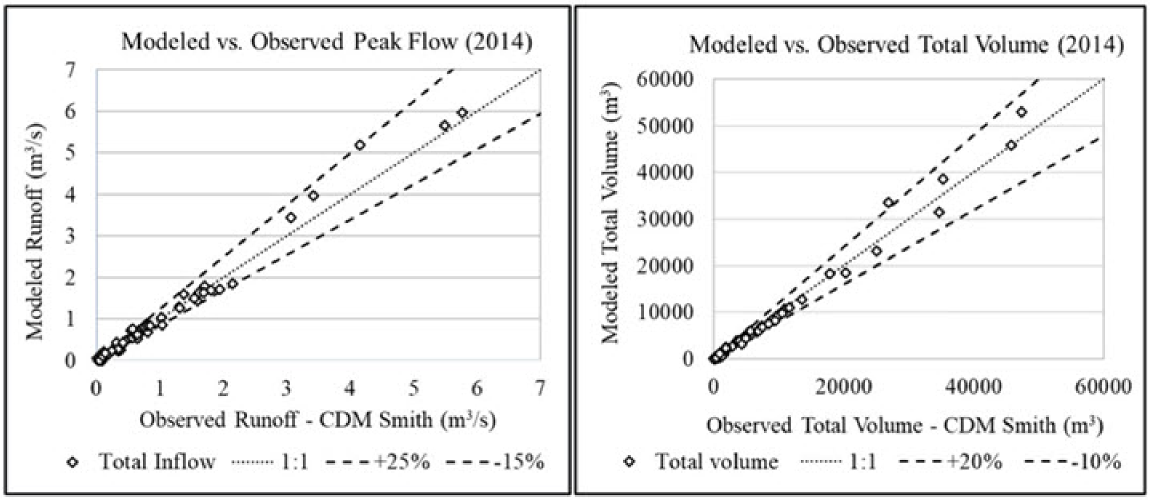

Figure 6 Calibrated scatter plots under modeled and observed conditions.

The simulated surface flooding patterns were close in terms of extent and depth to conditions photo documented in the field. Considering the July 13, 2021 precipitation event, Figure 7 demonstrates accurate modeled versus observed surface flooding conditions with approximate viewer location and direction demonstrated on the modeled image (left) at the time of field data collection. The arrows represented by points A1 (intersection curb), A2 (surcharging manhole), A3 (intersection curb), B1 (trees), and B2 (intersection curb) represent the same point on both the modeled and observed images. Similar results were obtained for the August 21, 2021 and September 1, 2021 precipitation events (not shown).

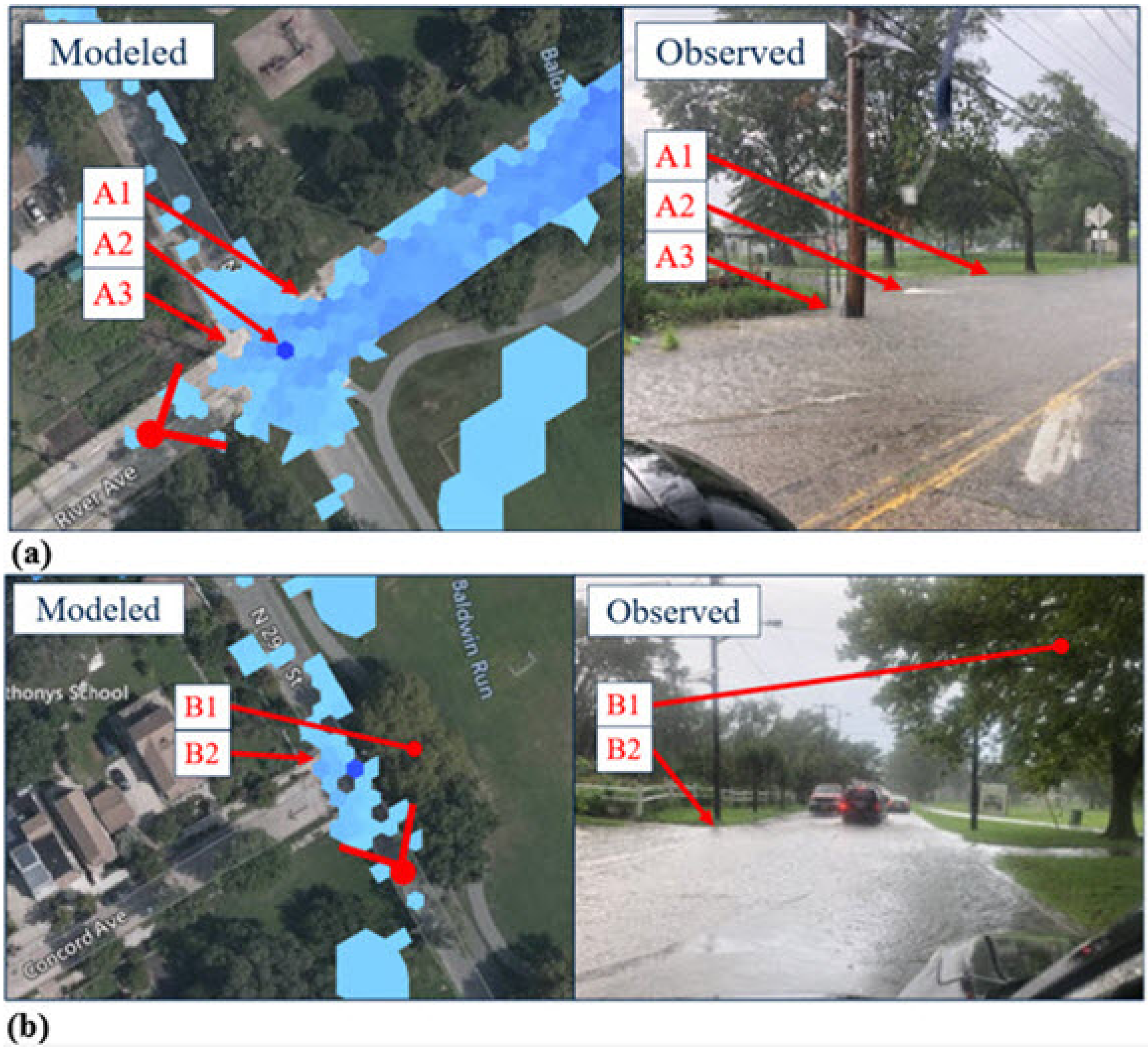

Figure 7 Surface flooding in Camden, NJ during July 13, 2021 precipitation event: (a) River Ave. & North 29th St., Camden, NJ; (b) Concord Ave. & North 29th St., Camden, NJ.

The last step in the four-step calibration and validation process found comparable hydrographs from the 1D model, the integrated 1D-2D model, and the LTCP model. Figure 8 shows this comparison for the June 5, 2014 event. Hydrographs for all three models were studied and compared for other events in 2014 with similar results (not shown).

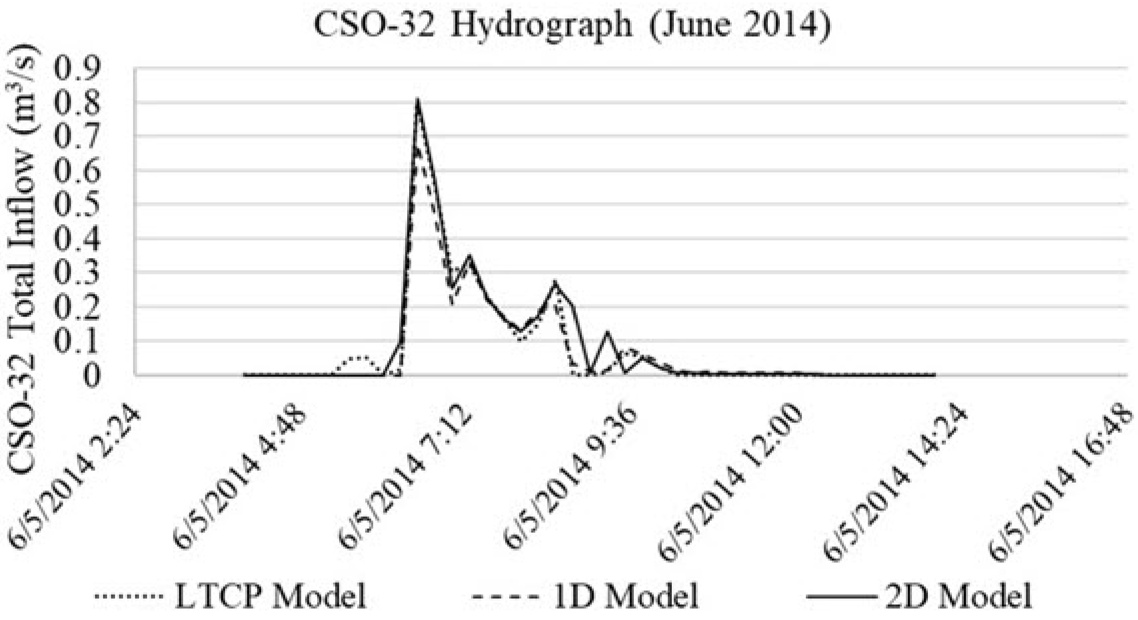

Figure 8 June 5, 2014 precipitation event hydrograph.

3.2 1D model results

Table 2 summarizes the results from the 1D model for the various CSO and flood metrics under the different climate change and infrastructure scenarios. These are discussed separately for Scenario a (existing conditions) and Scenario b (disconnected conditions).

Table 2 1D modeling results of climate change and infrastructure considerations.

Climate Change (CC) Scenarios & Descriptions				Scenario	1D Model Metrics				
CC Scenario	Precipitation Increase	Sea Level Rise (SLR)	Existing vs. Disconnected Conditions		Cumulative Annual Discharge	Discharge Events	Node Flooding Events	Nodes Flooded in 2014	Node Flooding (Cumulative hrs)
					$10^3 m^3$	#	#	#	h
No CC	N.A.	N.A.	Existing	1.1 (a)	432.1	61	11	85	778.7
			Disconnected	1.1 (b)	272.5	63	11	82	787.8
Precipitation Increase	+10%	N.A.	Existing	2.1 (a)	523.4	62	14	93	1,001.0
			Disconnected	2.1 (b)	420.8	62	14	86	1,004.9
	+20%	N.A.	Existing	2.2 (a)	615.8	62	15	105	1,244.8
			Disconnected	2.2 (b)	495.1	62	15	92	1,241.5
	+30%	N.A.	Existing	2.3 (a)	715.1	66	15	112	1,532.8
			Disconnected	2.3 (b)	574.3	65	15	103	1,526.3
SLR	N.A.	+0.3m	Existing	3.1 (a)	411.3	58	16	86	3,079.2
			Disconnected	3.1 (b)	325.7	55	16	86	3,083.7
	N.A.	+0.9m	Existing	3.2 (a)	369.4	47	19	85	32,997.0
			Disconnected	3.2 (b)	287.2	47	16	87	32,995.0
	N.A.	+1.8m	Existing	3.3 (a)	263.4	31	17	87	190,960.8
			Disconnected	3.3 (b)	187.9	26	15	86	190,776.3
Compound	+10%	+0.3m	Existing	4.1 (a)	498.9	60	20	94	3,331.2
			Disconnected	4.1 (b)	434.3	60	18	87	3,331.7
	+20%	+0.9m	Existing	4.2 (a)	538.9	54	24	102	33,691.9
			Disconnected	4.2 (b)	421.1	53	20	95	33,656.0
	+30%	+1.8m	Existing	4.3 (a)	495.5	39	28	111	192,309.2
			Disconnected	4.3 (b)	372.8	35	23	107	192.071.0

1D model results – Existing infrastructure conditions

Cumulative annual discharge at CSO-32 (Table 2 and Figure 9) varied under all three climate change considerations. Increased precipitation resulted in increases in discharges above baseline climate conditions, showing a 21%, 43%, and 66% increase in cumulative annual discharge for low (Scenario 2.1(a)), middle (Scenario 2.2(a)), and high (Scenario 2.3(a)) precipitation increases, respectively (Table 2). Conversely, increased SLR scenarios resulted in discharges that were reduced below baseline climate conditions, showing a 5%, 14%, and 39% reduction in cumulative annual discharge for low (Scenario 3.1(a)), middle (Scenario 3.2(a)), and high (Scenario 3.3(a)) SLR estimates, respectively (Table 2). Under compound conditions, CSO discharge volumes increased above baseline climate conditions, but without a consistent trend. Discharges increased by 15%, 25%, and 15%, low (Scenario 4.1(a)), middle (Scenario 4.2(a)), and high (Scenario 4.3(a)) compound conditions, respectively (Table 2).

Like annual CSO volume, the number of CSO discharge events appear to be positively correlated with an increase in precipitation, and negatively correlated with SLR. However, the number of events decreases with increasingly severe compound conditions (Figure 9).

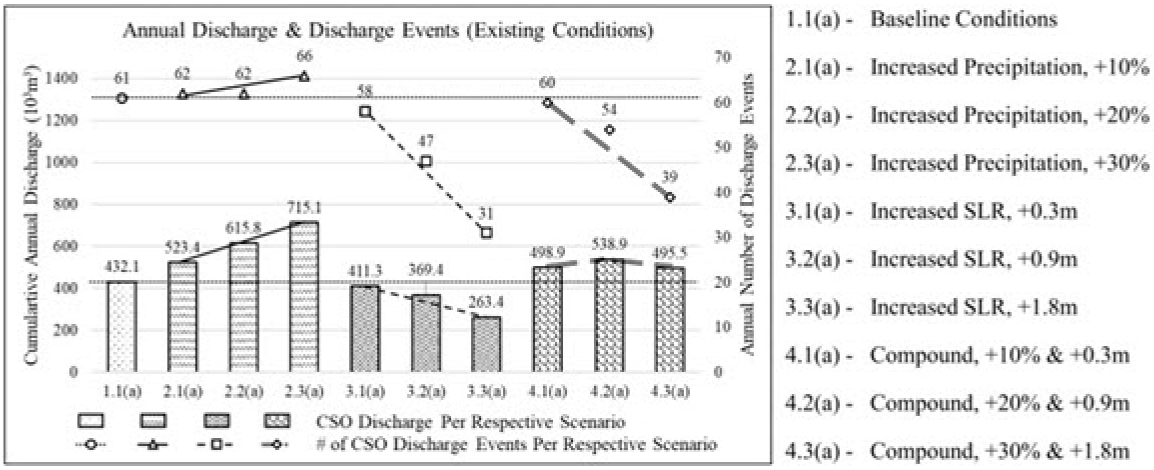

Figure 9 CSO metrics under existing infrastructure conditions.

Depending on how it plays out, climate change under Scenario a could result in greater or lesser annual CSO volumes for the number of CSO events that occur in a typical year. However, pluvial flooding appears to worsen under all climate scenarios (Figure 10). Both the number of nodes flooded, and the number of flooding events increase with all forms of climate change. SLR will have the smallest impact on the number of nodes flooded and the number of flooding events (though both increase with SLR). Increased precipitation and compound climate change conditions show more significant increases over baseline conditions (Figure 10). However, cumulative hours of flooding are drastically increased under SLR and compound conditions, while cumulative hourly flooding values are similar to baseline conditions under increased precipitation scenarios (Figure 10). The results suggest that an increase in precipitation will cause flooding to occur in more places in the model and slightly more regularly, but SLR will make it much more difficult for flood waters to drain out of Cramer Hill, greatly increasing the duration of flooding.

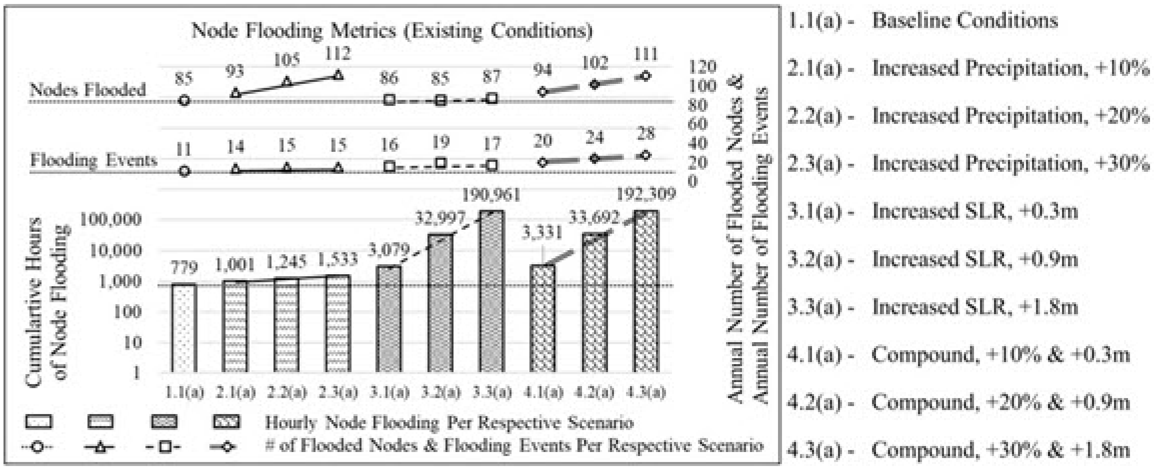

Figure 10 Node flooding metrics for existing infrastructure conditions.

1D model results – Disconnected infrastructure conditions

Compared to existing (Scenario a – no disconnection) conditions, Scenario b will result in sizeable reductions in cumulative annual CSO discharge under all climate scenarios (Figure 11). Without any climate change, the disconnection showed a maximum reduction in annual CSO discharge volumes of 37%. Some of the improvement due to the disconnection is lost if precipitation increases. Under all precipitation increase scenarios, the reduction in CSO discharges is reduced to 20% below the baseline conditions, with a reduction of at most one of the baseline CSO events. SLR will also reduce the effectiveness of the disconnection, but not as much as precipitation intensification. The reduction in CSO discharge volume will be between 21–29% below baseline conditions, with at most a reduction of 5 CSO events. Compound climate conditions yield intermediate results. The disconnection reduced annual CSO volumes by 13–25% relative to baseline conditions, reducing the number of CSO events by up to 4.

Interestingly, the Pennsauken disconnection showed an increase by two in the annual number of discharge events under baseline climate conditions, likely due to the increased hydraulic capacity of the drainage system that will be able to accept storm flows generated in Cramer Hill that previously ponded faster on the surface once the Pennsauken flows were eliminated.

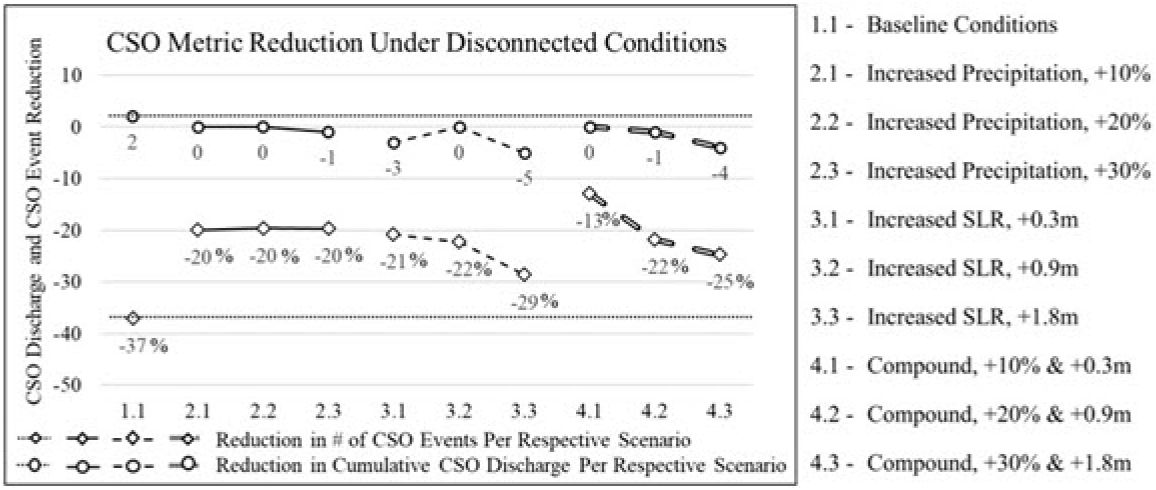

Figure 11 CSO metric reduction under disconnected infrastructure conditions.

The impacts of climate change on the *disconnected* baseline results are similar (in terms of trends in annual CSO volumes and events) to the impact of climate change on the existing (no disconnection) baseline conditions. However, the magnitudes of the impacts differ significantly (Figure 12).

Increases in precipitation will increase annual CSO discharges above baseline climate conditions, but at greater ratios; the results suggest 54%, 82%, and 111% increases for low (Scenario 2.1(b)), middle (Scenario 2.2(b)), and high (Scenario 2.3(b)) estimates, respectively (Figure 12). Increases in SLR result in 20% and 5% increases in annual CSO discharges for the low (Scenario 3.1(b)) and middle (Scenario 3.2(b)) scenarios. However, the high SLR estimate (Scenario 3.3(b)) shows a 31%reduction of CSO discharge. Under compound conditions, annual CSO discharges are greater than under baseline conditions, but with lesser values at more severe compound conditions. CSO conditions are 45%, 35%, and 27% above baseline disconnected climate conditions for low (Scenario 4.1(b)), middle (Scenario 4.2(b)), and high (Scenario 4.3(b)) estimates.

The same trends in the number of discharge events exist are evident under the disconnected conditions as were evident under existing infrastructure conditions. However, two of the three precipitation increase scenarios suggest the number of CSOs will drop by one below baseline disconnected conditions. All three scenarios were reduced relative to baseline conditions in the existing conditions model. Under SLR and compound conditions, the number of CSO events drop sharply.

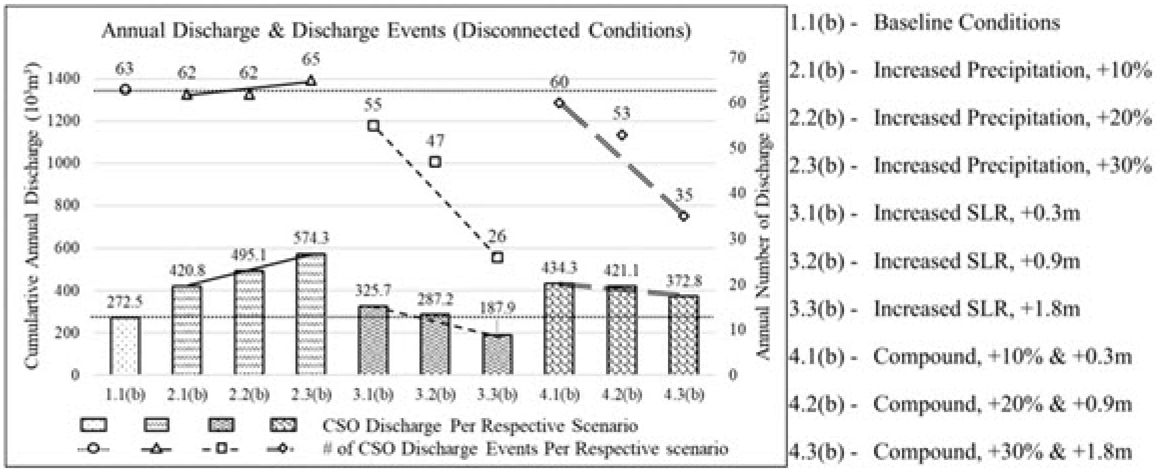

Figure 12 CSO metrics under disconnected infrastructure conditions.

The impacts of climate change on the *disconnected* baseline results are similar (in terms of trends in flooding) to the impact of climate change on the existing (no disconnection) baseline conditions, and in this case with no significant difference in magnitudes (Figure 13). All flooding metrics increase above baseline conditions with climate change, and nearly all metrics show some positive correlation between flooding and severity of climate change. Increasing precipitation causes increases in the number of nodes flooded, minor changes in the number of flooding events, and modest changes in the cumulative hours of node flooding. SLR demonstrates no significant trends in the number of nodes flooded, nor the number of flooding events, but significant increases in the duration of flooding with increasing SLR. Under compound conditions, there are modest increases in the number of nodes flooded and the number of flooding events, and significant changes in the duration of flooding (greater than the changes predicted from SLR alone).

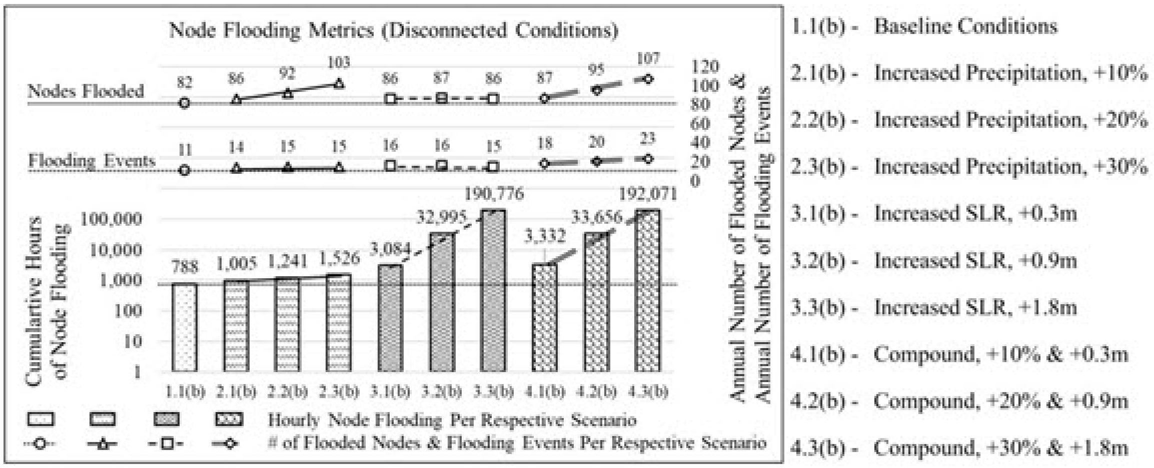

Figure 13 Node flooding metrics under disconnected infrastructure conditions.

3.3 2D model results

The 2D model was used to simulate baseline and mid-range climate change conditions (Scenarios 1.1, 2.2, 3.2, and 4.2) under existing and disconnected infrastructure conditions to evaluate additional metrics of flooding with any changes due to the disconnection or climate change (Table 3). These results are discussed separately for Scenario a (existing conditions), and Scenario b (disconnected conditions).

Table 3 2D modeling results of climate change and infrastructure considerations.

Climate Change (CC) Scenarios & Descriptions				Scenario	2D Model Metrics		
CC Scenario	Precipitation Increase (P.I.)	Sea Level Rise (SLR)	Existing vs. Disconnected Conditions		Peak Flooding Depth (m)	Maximum Area Flooded (ha)	Structures Impacted by Flooding (June 2014) #
No CC	N.A.	N.A.	Existing	1.1 (a)	0.45	3.0	10
			Disconnected	1.1 (b)	0.44	2.2	4
P.I.	+20%	N.A.	Existing	2.2 (a)	0.53	6.5	22
			Disconnected	2.2 (b)	0.50	4.3	15
SLR	N.A.	+0.9m	Existing	3.2 (a)	1.21	9.9	42
			Disconnected	3.2 (b)	1.15	7.1	22
Compound	+20%	+0.9m	Existing	4.2 (a)	1.22	11.9	46
			Disconnected	4.2 (b)	1.16	8.2	28

2D model results – Existing infrastructure conditions

The 2D modeling suggests that under Scenario a (existing infrastructure) climate change worsens flooding (Figure 14). Increased precipitation shows a small (e.g., 8 cm) increase in peak flooding depth over baseline conditions (Scenario 2.2(a)). SLR and compound conditions, however, show much larger increases (e.g., 76-77 cm) in peak flood depth (Scenarios 3.2(a) and 4.2 (a)) (Figure 14). The area flooded roughly doubles with the increase in precipitation, more than triples due to SLR, and almost quadruples due to compound conditions. The number of structures impacted mirrors this trend and scale of impact.

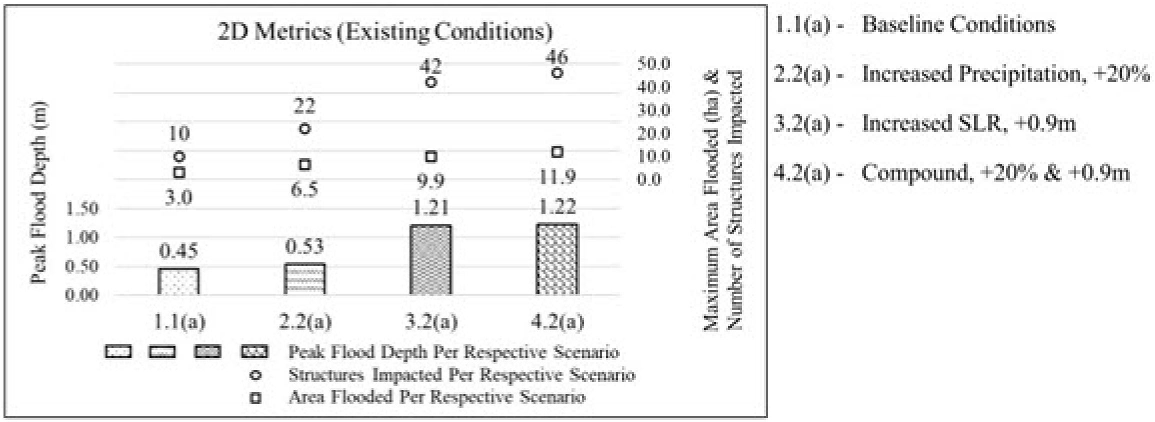

Figure 14 2D modeling metrics for existing infrastructure conditions.

2D model results – Disconnected infrastructure conditions

Compared to the respective climate condition in Scenario a, the disconnected conditions show minor differences in reduction in peak flood depth compared to the existing conditions (Figure 15). Under the disconnected conditions, climate related increases in the maximum area flooded were reduced by up to 3.7 ha (for the compound scenario). The disconnection also reduces the number of structures impacted by flooding by 60% for the baseline condition, and between 32 and 48% for the climate changed conditions.

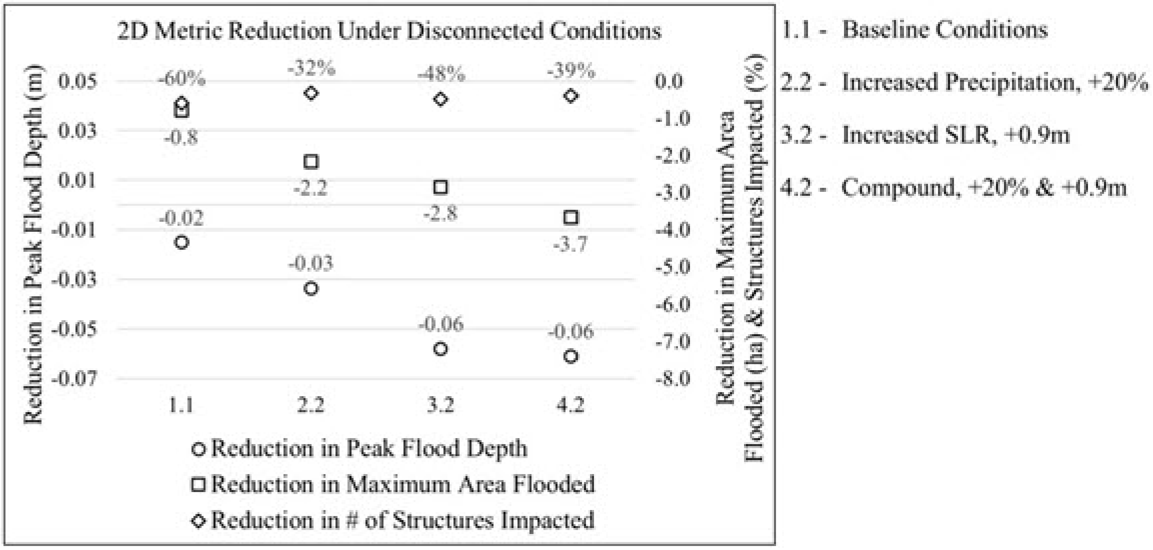

Figure 15 Metric reduction under disconnected infrastructure conditions.

Within the 2D model domain, the trends in the impact of climate change are the same under disconnected conditions as they were under existing conditions (Figure 16). Peak flooding depth increases the most under compound conditions (Scenario 4.2(b)), followed closely by SLR conditions (Scenario 3.2(b)). Trends in maximum area flooded are identical, as are the number of structures impacted. Like existing infrastructure conditions, disconnected conditions show all modeling metrics affected by climate change above baseline climate conditions.

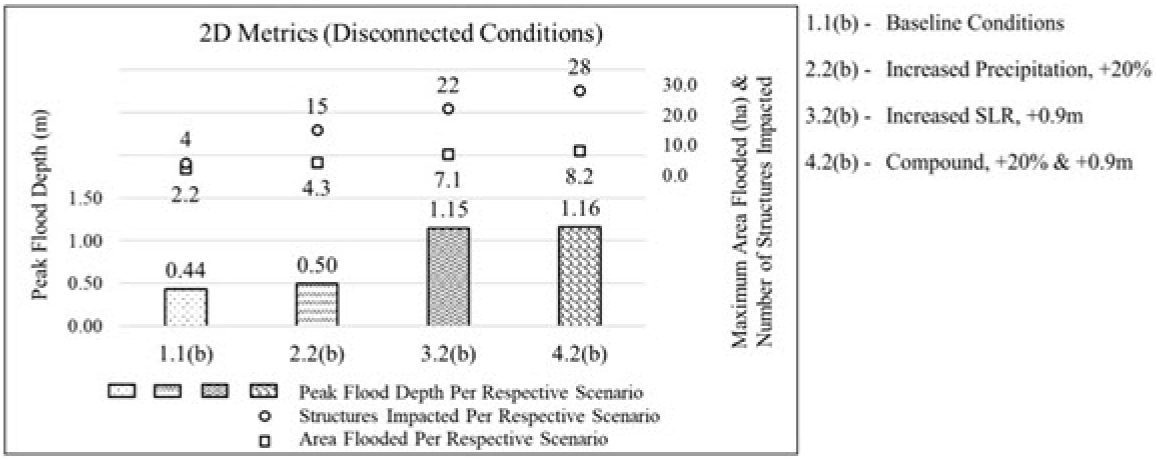

Figure 16 2D modeling metrics for disconnected infrastructure conditions.

3.4 Overall discussion

Without climate change, the disconnection (Scenario b) will reduce annual CSOs from 432.1 x 10^3 to 272.5 x 10^3 cubic meters per year, and slightly increase (by ~9 hours) the cumulative hours of flooding in Cramer Hill compared to existing conditions (Scenario a). The latter could be due to an observed increase in flooding at the High Street pump station under Scenario b. After subtracting the hourly flooding measured at the High Street PS, all cumulative hourly flooding for disconnected infrastructure conditions was shown to be less than for the respective existing infrastructure conditions, suggesting increased pumping capacity at the High Street PS may be necessary. Overall, these no-climate change results suggest immediate and significant water quality benefits could accrue as a result of the disconnection.

However, as time passes, the results suggest that climate change will worsen CSOs and flooding under both existing (Scenario a) and disconnected (Scenario b) conditions. The disconnection will help to lessen, though not eliminate, the negative impacts of climate change in the study area.

Specifically, under both scenarios, increases in the intensity of precipitation will significantly increase the annual volume of overflows, and slightly increase the number of annual CSO events. Increases in the intensity of precipitation will increase the duration of flooding by nearly 65 days/y under existing conditions, and 31 days/y under disconnected conditions.

By contrast, SLR will significantly reduce the annual number and volume of CSOs but will result in a much more pronounced worsening of flooding which, under both scenarios, will increase to levels much greater (e.g., up to 2 orders of magnitude) than those associated with increases in precipitation intensity. Under disconnected conditions (Scenario b), SLR reduces CSOs to much lower volumes (up to 187.9 x 10^3 cubic meters per year) than they would be under existing conditions (263.4 x 10^3cubic meters per year) for the highest SLR scenario. The impact of the disconnection on SLR-induced increases in flooding are less pronounced under the two scenarios.

Viewed together, these results suggest that increases in precipitation will force more water through the CSS, increasing CSOs, while SLR will make it harder for discharges to the Delaware River to occur due to increases in the tailwater depth on CSO-32. SLR alone is thus associated with an increase in flooding due to the restriction in pluvial flows. Disconnection softens these trends but does not change them.

The compound climate change scenarios show intermediate sets of results under both scenarios. Both scenarios show significant increases in flooding, of similar orders of magnitude, to those shown in the SLR only scenarios. Under compound conditions, both scenarios depict increases in CSO volume and reductions in the number of CSOs over the respective baselines. The increases in CSO volumes lessen – under both scenarios – with increasing severity of compound conditions. Viewed together, it appears that the SLR scenarios largely exacerbate flooding, while precipitation intensification largely exacerbates CSOs, except if a higher tailwater condition makes it harder for the overflows to occur. Again, the disconnection lessens these consequences slightly but cannot eliminate them. The results suggest that if the disconnection is implemented, other green or grey approaches will be required to minimize the negative impacts of climate change on CSOs and flooding.

4. CONCLUSIONS

With substantial local and national CSO requirements, utilities like CCMUA must seriously consider CSO mitigation methods for current and future conditions. Climate change will be a looming threat coastal cities will face throughout this century; however, appropriate infrastructure upgrades can help provide relief from flooding and CSO concerns. While this H&H modeling exercise quantified the effectiveness of the Pennsauken Disconnection under current and future climate conditions, this approach also showed an increase in flooding surrounding the High Street pump station. Should the disconnection be implemented, the CCMUA should consider increased capacity at this pump station and surrounding conduits. Increasing climate metrics will only continue to exacerbate flooding in this region, causing present day grey infrastructure investments to lose a portion of their value. Studies like this one can help inform future planning, to determine present and future economic infrastructure upgrades.

Future research will involve the collection of inline flow and surface flooding data to better calibrate and validate the model. The Pennsauken disconnection will be compared to other grey and green solutions to ascertain which of these methods is the most cost-effective now and in the future.

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APPENDIX I SIMULATION EDITOR PROPERTIES

Table A1 PCSWMM 1D and 2D simulation editor properties.

General	1D	2D
Process Models	Rainfall/Runoff	Rainfall/Runoff
	Rainfall Dependent I/I	Rainfall Dependent I/I
	Flow Routing	Flow Routing
Infiltration Model	Horton	Horton
Routing Method	Dynamic	Dynamic
Allow Ponding	YES	YES
Min. Conduit Slope (%)	0	0
Flow units	CFS	CFS
Dates	1D	2D
Start Analysis	01/01/2014	05/31/2014
Start Reporting	01/01/2014	05/31/2014
End Analysis	12/31/2014	06/30/2014
Antecedent Dry Days	0	0
Dynamic Wave	1D	2D
Inertial Terms	Dampen	Ignore
Normal Flow Criterion	Slope & Froude	Slope & Froude
Force Main Equation	Hazen-Williams	Hazen-Williams
Surcharge Method	Extran	Extran
Variable Time Step Adjustments	0.75	0.75
Min. Variable Time Step	0.5 seconds	0.5 seconds
Time Step for Conduit Lengthening	10 seconds	0 seconds
Min. Nodal Surface Area	1.167 m^2	0.009 m^2
Max. Trials per Time Step	8	8
Head Convergence Tolerance	0.0015 m	0.0015 m
Number of Threads	4	4
Time Steps	1D	2D
Reporting	15 minutes	15 minutes
Runoff: Dry Weather	1 hour	30 minutes
Runoff: Wet Weather	5 minutes	30 minutes
Control Rule	0	0
Routing	15 seconds	1 second
Skip Steady Flow Periods?	NO	NO

APPENDIX II SANITARY FLOW PATTERNS

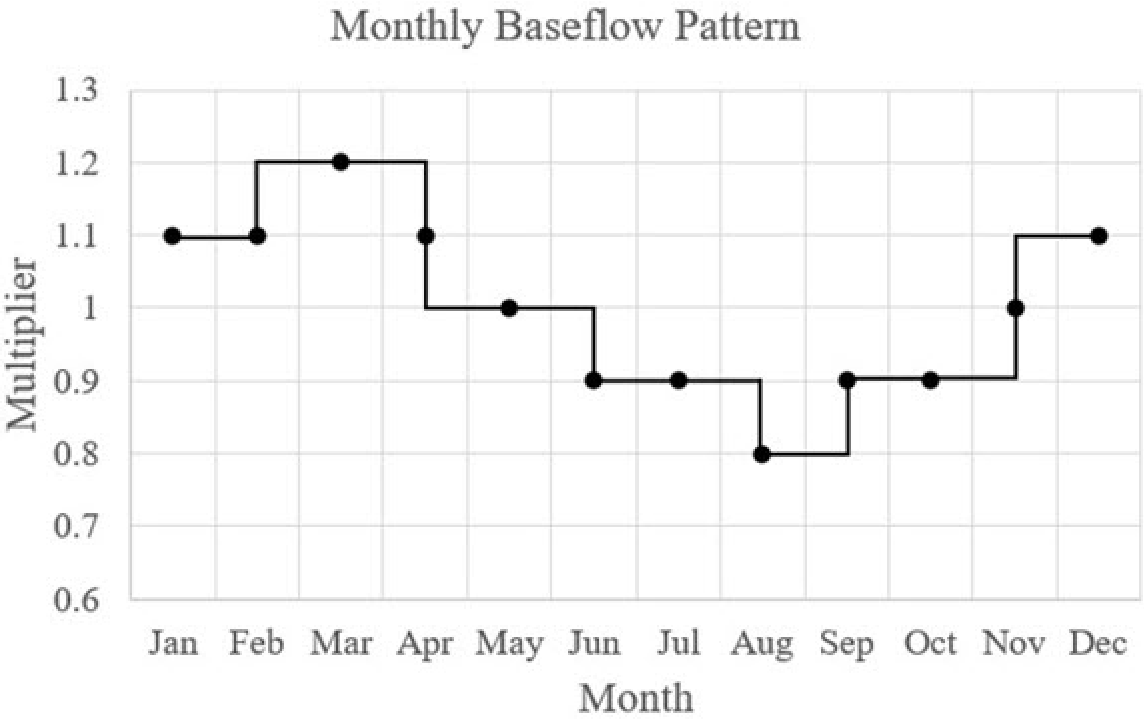

Figure A1 Monthly baseflow pattern.

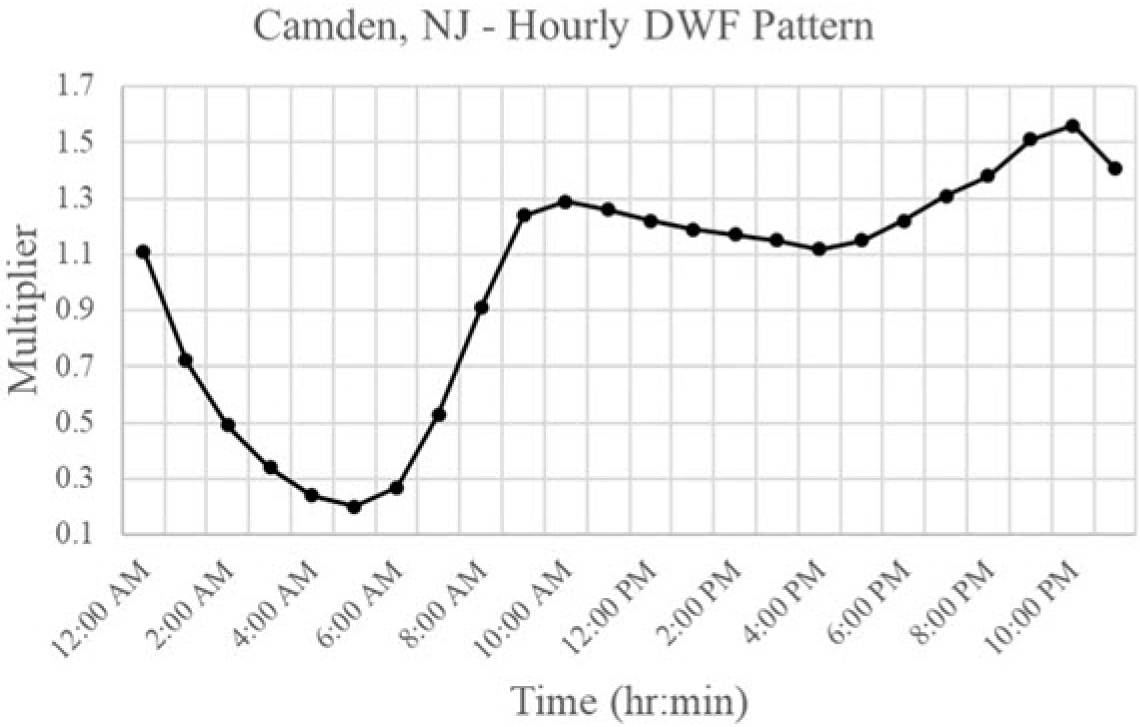

Figure A2 Camden, NJ hourly DWF pattern.

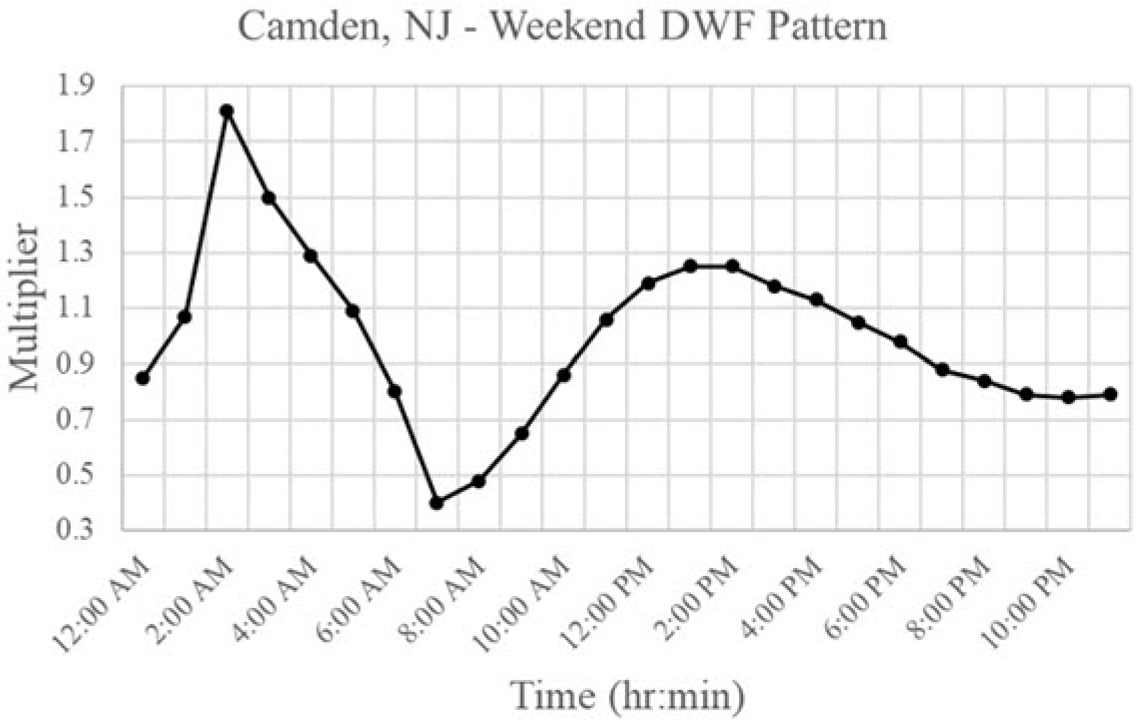

Figure A3 Camden, NJ weekend DWF pattern.

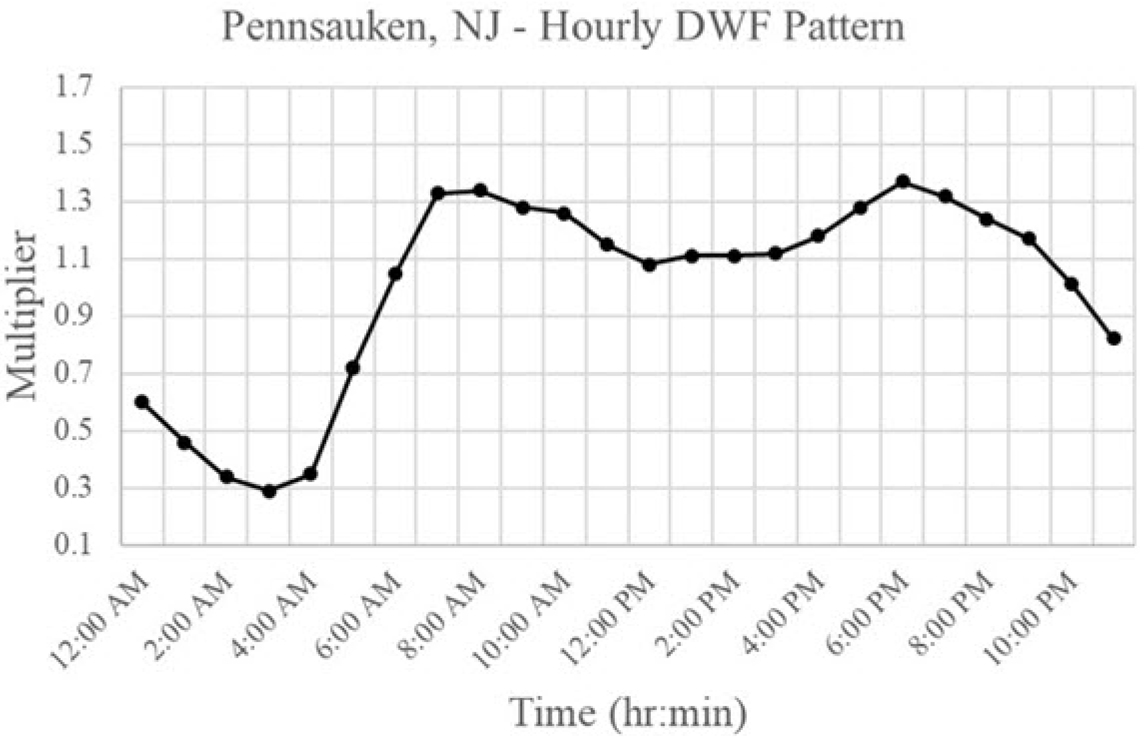

Figure A4 Pennsauken, NJ hourly DWF pattern.

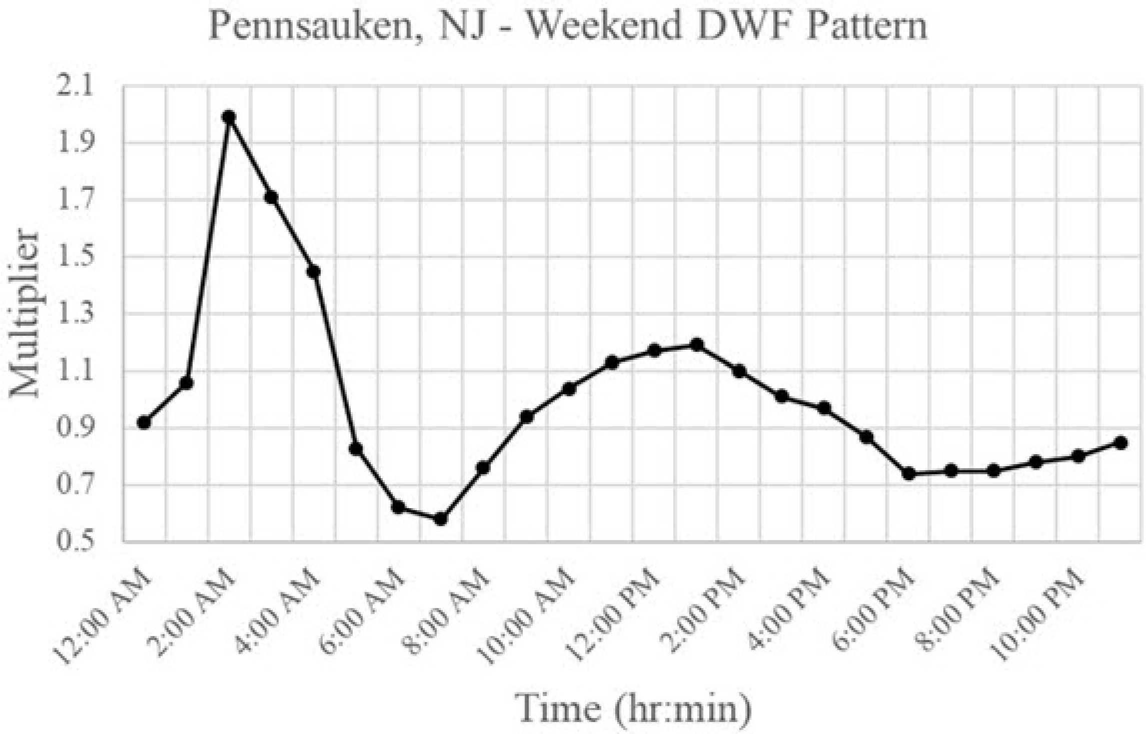

Figure A5 Pennsauken, NJ weekend DWF pattern.