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ASSESSING THE NEED FOR ACCURATE FLOOD DAMAGE PREDICTION BASED ON FUTURE CHANGES IN PEAK FLOW OF RIVERINE SYSTEMS: IS THERE MORE UNCERTAINTY IN THE HYDROLOGY OR THE DEGREE OF DAMAGE?

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by

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Abstract

Goz K. Assessing the need for accurate flood damage prediction based on future changes in peak flow of riverine systems: Is there more uncertainty in the hydrology or the degree of damage? [thesis]. [Syracuse (NY)]: State University of New York College of Environmental Science and Forestry, 2019. CSE style guide used.

In most riverine systems, the impact of future climate change on flooding remains uncertain. However, the majority of studies that evaluate future flood risk focus on discharge alone, with little assessment of the degree to which damages (the actual impact due to floods) relates to discharge. This study assesses flood-frequency, stage-discharge, and stage-damage relationships to evaluate how uncertainty in future hydroclimatological drivers of flooding may translate into uncertainty in future damages within a flood plain. The areas of interest for this study were the Onondaga Creek, Syracuse, NY and Susquehanna River, Binghamton, NY watersheds. The results of this study were that flood damages were found to be highly sensitive to the uncertainty in the hydrology of both study areas. In the Onondaga Creek watershed, damage sensitivity was amplified 3.0 times, while in the Susquehanna River basin the amplification was 3.1 to 3.6 times the uncertainty in the hydrology. The uncertainty findings indicated that hydrology plays a large role in flood damage estimations for both watersheds. Each watershed displayed the same response to different future climate change scenarios whereby future flood risk increased as a result of an increase in the magnitude of precipitation events and either remained the same or declined minimally for decreased snowmelt events. The methodology and findings of this study can aid policy and decision makers, flood risk managers, and research scientists in more accurately predicting flood risk areas and potential damages from different flood events by emphasizing a focus on more accurate hydrologic prediction and the incorporation of uncertainty analysis to better predict flood risk and allocate resources for communities in flood prone areas.

Keywords: Onondaga Creek, Susquehanna River, geographic information systems, flood risk assessment, uncertainty, hydrology, flood damage, flood.

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CHAPTER 1: INTRODUCTION

OVERVIEW

On a global scale, there is strong evidence that the global water cycle and water resources are being impacted by climate change. There is a global scientific consensus that our climate is warming and as a consequence, global air and ocean temperatures are rising, earlier and increased snow and ice melts are occurring, subtropical rainy seasons have shortened, sea levels are rising, and there are larger variations in regional temperature and precipitation (Solomon et al. 2007). According to the U.S. Global Change Research Program, the warming of global temperatures is predicted to lead to more intense rainfall events, such as convective systems and tropical cyclones, greater variations in weather related events, and significant disparities in precipitation patterns across North America (Karl et al. 2009).

There is a large degree of uncertainty around predicted flood risk due to the fact that floods are a result of complex hydrologic processes. For example, riverine flooding has increased in the northeastern United States due to significant changes in annual precipitation and soil moisture and it is expected that flood magnitude and frequency will increase due to climate change. However, since riverine flooding is highly dependent on basin specific features, such as pre-existing soil moisture content, topography, anthropogenic changes, etc., future flood risk projections for riverine flooding currently have low to medium confidence (Melillo et al. 2014).

For the areas of interest in this study, flooding generally occurs in the winter and early spring season as existing snow and ice, melting snow, and rainfall combine to produce increased river flows. Along Onondaga Creek in Syracuse, NY, the most significant flood event occurred in July 1974 due to high intensity severe storms which precipitated over three inches of rain within a 24-hour period causing the creek to crest at its highest recorded flood stage at nearly six and a half feet (FEMA 1991). Figure 1a depicts the annual peak streamflow for Onondaga Creek from 1952 to 2017. In analyzing flood frequency based on peak discharges, there is an appreciable increase in flows during the 1970s. For the Susquehanna River, the flood of record occurred in June of 2006 when extra-tropical storm Ernesto struck the region causing widespread damage throughout the basin and nearly breaching the levees along the river (FEMA 2010). Figure 1b depicts the annual peak streamflow for the Susquehanna River from 1913 to 2017. Based on the figure, there are two periods of noticeably higher flows occurring around the 1940s and 2010s.

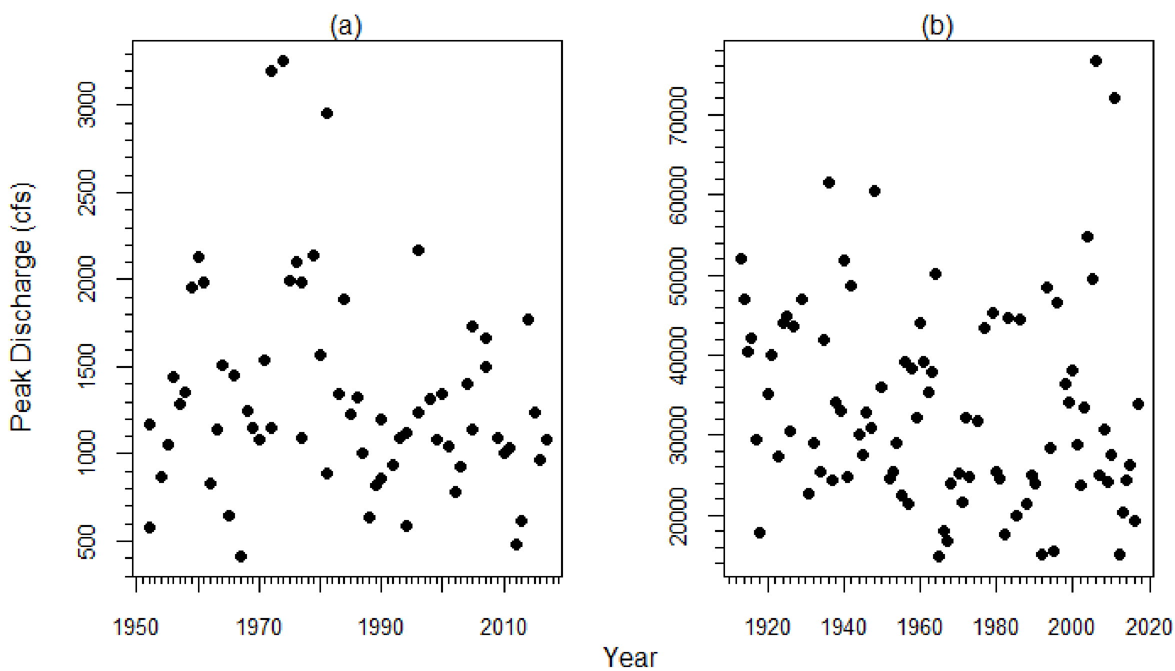

Figure 1. Annual peak streamflow for (a) Onondaga Creek using data from USGS 04239000 gaging station at Dorwin Avenue and (b) the Susquehanna River using from the USGS 01510300 gaging station at Conklin, NY.

Flood risk assessments (FLRs) have evolved in recent decades from protection standards and management strategies to a more risk-based approach. These risk-based approaches are generally specific to a county, region, and/or flood type, but follow the same basic concept with four general components: hydrological characteristics mostly representing flood depth; risk elements often estimated using land use and/or property data; the full and/or depreciated value of said risk elements; and vulnerability of risk elements to hydrological characteristics, usually represented by depth-damage curves. Flood risk managers acknowledge that each component of an FLR introduces varying degrees of uncertainty, however, most FLR studies have generally addressed the uncertainty in one of the components during their assessments and in most cases, it has been the hydrological component (Moel and Aerts 2011).

Uncertainty analysis is vital in FLRs due to the fact that accurately quantified and communicated uncertainty in FLR results can lead to informed decisions by policymakers and increased stakeholder engagement and participation, which in turn enhances the legitimacy and acceptance of decision-making processes (Ascough et al. 2008; Inam et al. 2017a, b). Despite the active research surrounding FLRs, accurate flood damage modelling at high spatial and temporal resolutions remain difficult and error-prone due to the complex nature of flooding and uncertainty in flood models (Freer et al. 2011; Merz and Thieken 2005). This study proposes a unique approach to address uncertainty in FLRs by analyzing two components: hydrological characteristics and the vulnerability of risk elements. This approach differs from the more established FLR methodology in the United States, which relies on the flood damage estimation tool HAZUS, by incorporating two vital components that HAZUS lacks: high spatial resolution topographic data and an uncertainty analysis. High spatial resolution light detection and ranging (LiDAR) data will be used in conjunction with a geographic information system (GIS) to develop a unique methodology for the estimation of flood damages. Uncertainty in the hydrological characteristics and vulnerability of risk elements will be analyzed and the flood damage estimates determined by this new methodology will be compared to more established HAZUS methods to assess the model output and results.

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CHAPTER 2: ASSESSING UNCERTAINTY IN HYDROLOGY VERSUS SENSITIVITY IN FLOOD DAMAGES

INTRODUCTION

As humankind has progressed over the last century, so too has our awareness of risk from environmental hazards. Globally, floods are the most common and destructive reoccurring natural hazard affecting both people and property (Shalikovskiy and Kurganovich 2017). Floods are typically divided into three categories: riverine flooding; urban flooding caused by heavy precipitation events that overwhelm drainage systems; and coastal flooding.

The certainty of changes in future flood risk due to climate change depends on the flood type. There have been statistically significant trends in the number of localized, heavy precipitation events and rising sea levels, indicating direct climate-change related controls on increases in flooding in urban and coastal areas (Galloway et al 2018; Nicholls et al 1999). However, at the riverine scale there continues to be a lack of evidence regarding the sign of trend in the magnitude and/or frequency of floods (Stocker et al. 2013). This uncertainty in future changes in riverine flooding originates from the fact that unlike urban and coastal flooding, a large number of interacting processes control riverine flooding, including land use characteristics, precipitation events, snowmelt rates, ice jams, erosion and sedimentation, and dam failures (Wang et al. 1996).

This lack of certainty in riverine flood risk is often only characterized in terms of hydrology as scientists aim to predict the frequency of flows of a given magnitude (Hirabayashi et al. 2013; Stocker et al. 2013; Ivancic and Shaw 2015). However, a comprehensive evaluation of flood risk would also consider actual changes in damages. Throughout the world, large numbers of buildings have been built within the boundaries of floodplains, exposing these properties and assets to damages and major losses should a flood event occur. In assessing future flood risk, there is the possibility that damages in some places may be relatively insensitive to variations in river flow, making uncertainty behind future riverine flood hydrology moot. This degree of connection between hydrology and damage can only be assessed by having a clear knowledge of potential for damages.

A number of flood damage models have been developed to support policymakers and insurance companies in analyzing the potential loss of life and property. These models use various stage-damage curves, or loss functions, which relate a specific class of building or land use type and depth of flood water to estimate flood damages (Smith 1994). The unit loss method, which is based on actual or potential property by property flood damages, is the most commonly used for assessing flood damages with numerous examples in the literature as well as directly applied in practice (Romali et al. 2015; Wagenaar et al. 2016). These include the HIS-SSM for the Netherlands (Kok et al. 2005), the Multi-Coloured Manual in the United Kingdom (Penning-Rowsell et al. 2005), the HAZUS in the United States (Scawthorn et al. 2006), and the FLEMO in Germany (Thieken et al. 2008; Kreibich et al. 2010).

When flood damage models are considered collectively, there is often an acknowledgment that the damage models introduce a large amount of uncertainty. For instance, Jongman et al. (2012) compared the damages of seven different flood damage models with recorded flood damages from events in the United Kingdom and Germany. The differences between the smallest and largest damage estimates was a factor of 5 for the German event and a factor of 10 for the United Kingdom event. Chatterton et al. (2014) compared two different damage assessments for the United Kingdom and found the estimates differed by around a factor of 5 to 6 for both residential and commercial damages. The inherent limitations of the different flood damage models are based on their lack of spatially specific data for properties and/or structures found within a floodplain.

RESEARCH OBJECTIVE

The aim of this study is to develop discharge-frequency, stage-discharge, and stage-damage curves to establish a linkage between discharge, stage, and flood damage; characterize uncertainty in discharge-frequency relationships under non-stationary climatic conditions; assess how uncertainty in future hydrologic processes translates into uncertainty in future flood damages; and provide a framework to help engineers and floodplain managers better evaluate what level of uncertainty in hydrometeorological processes is acceptable when making practical decisions on floodplain management.

It is within this context that this study focuses on using a unique FLR methodology that targets individual parcels while using established damage functions to estimate flood damages. Flood damage estimates are performed using a combination of LiDAR and tax parcel data. This new High Spatial Resolution (HSR) based method will be compared to the HAZUS Flood Model due to the fact that the study areas are located in the United States. The major distinction between the HSR-based method and HAZUS is the spatial resolution of the properties and assets that lie within the floodplain. The HAZUS model will be executed using the Level 1 parameters established in the HAZUS technical manual. Level 1 analysis is based primarily on data provided with the software and some user-supplied inputs including defining the study region, specifying the hazard (probabilistic or deterministic), and deciding the extent and format of the output (FEMA 2018). The HAZUS model uses national population and property data, which is overlaid on areas of flooding to determine damage and losses. To estimate direct physical damage, the HAZUS flood model uses data for general building stock (Scawthorn et al. 2006a). For the analysis of direct physical damage, the HAZUS flood model assumes that the general building stock inventory is evenly distributed throughout a census block and then utilizes area-weighted estimates of damage to reflect the variation in inundation throughout the census block (FEMA 2018).

Sensitivity of flood damages to streamflow is evaluated to determine if uncertainty in future riverine hydrology is transferred to the sensitivity in flood damages. This concept is illustrated in Figure 1, which is a representative diagram of potential sensitivity relationships between river flow and flood damages. The figure depicts three possible sensitivity relationships: (a) very sensitive, (b) sensitivity to a point, and (c) low sensitivity. In a very sensitive scenario, as river flow increases so too do damages at a nearly constant rate that is close to 1:1. In a sensitivity to a point scenario, flow and damages increase at a near constant rate to a specific point, then damages remain constant even as flow increases. In a low sensitivity scenario, flow and damages may increase at a constant rate, but at a rate that is much lower than 1:1.

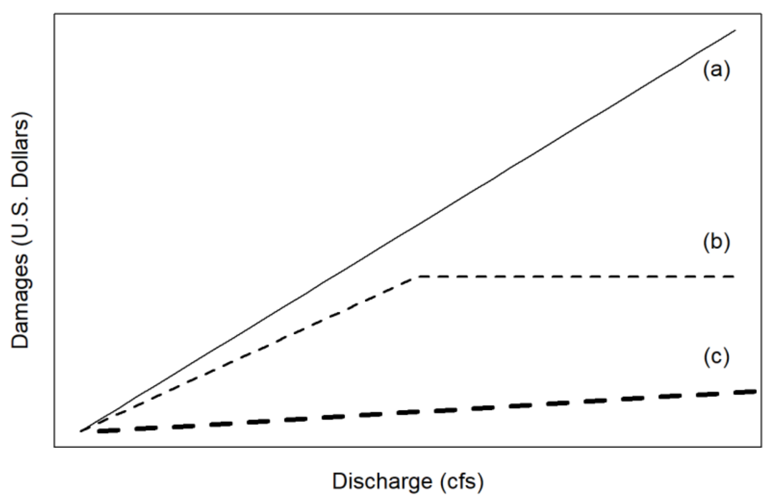

Figure 1. Representative diagram of potential sensitivity relationships between discharge and flood damages. (a) Flood damages are very sensitive to river flow; (b) flood damages are sensitive to a specific value, then there is no sensitivity to flow; and (c) flood damages are not considerably sensitive to river flow.

Uncertainty in hydrology surrounding flood damages can be used by policymakers, hydrologists, insurance companies, and risk assessors to better allocate resources when performing FLRs for communities in flood prone areas. In communities with high sensitivity relationships, research and funding should focus on the hydrologic processes that cause flooding in their respective communities to identify the magnitude of future flows in order to develop flood mitigation plans that can effectively reduce future flood risk. For those communities with low sensitivity relationships, flood mitigation practices can vary from maintaining and enforcing current practices to employing floodplain management practices, such as reducing development in the floodplain, ensuring any new development in the floodplain is built to local flood codes, increasing riparian zones to mitigate the extent and intensity of future floods, etc., as long as the assumption that current hydrologic measures are sufficient predictors of flood risk remains true.

METHODS

Study Area

Two separate hydrologic systems were chosen in order to evaluate how uncertainty in flood magnitude translates into uncertainty in damages (Figure 2). The first system is the Onondaga Creek floodplain due to the historical flood record and the vulnerability of the area to flood exposure and loss. Onondaga Creek is located in Onondaga County and runs through the city of Syracuse, NY. Major flooding occurred on Onondaga Creek in the early 1900's (1902 and 1915), which prompted the city to implement extensive channelization and damming of the creek (Syracuse . . . 2010). However, the dam and channelization of Onondaga Creek has not been able to prevent all subsequent flood events; between 1953 and 2008, there have been at least three reported flooding events with associated damages along Onondaga Creek (Tetra Tech EM, Inc. 2010).

The second hydrologic system is the branch of the Susquehanna River that extends from the New York – Pennsylvania border near Great Bend, Pennsylvania through the city of Binghamton to the border of Broome and Tioga counties in New York (Figure 2). This branch is referred to as the Susquehanna River Reach #1 in FEMA studies (FEMA 2010); however, for the purposes of this analysis, this branch will be referred to as the Susquehanna River. This reach of the Susquehanna River has overflowed its banks numerous times since 1913 causing extensive damage to commercial, industrial, and residential buildings, infrastructure, and agriculture. In response to large losses by floods in the early twentieth century, levees and reservoirs were built around the Susquehanna River and its tributaries during the 1940's and 1950's, which have reduced losses by flooding since their completions (FIA 1976). More recently, floods from a stalled frontal system in June of 2006 brought up to 13 inches of rainfall causing widespread flooding and damages totaling $227 million, while the remnants of Tropical Storm Lee in 2011 brought upwards of twelve inches of rain leading to the Susquehanna River cresting at 23.94 feet and catastrophic flooding in the City of Binghamton and to the Towns of Vestal, Owego, and Waverly. Overall, Broome county had approximately $502.8 million in property damages from this single event (Masters 2011; Tetra Tech Inc. 2019).

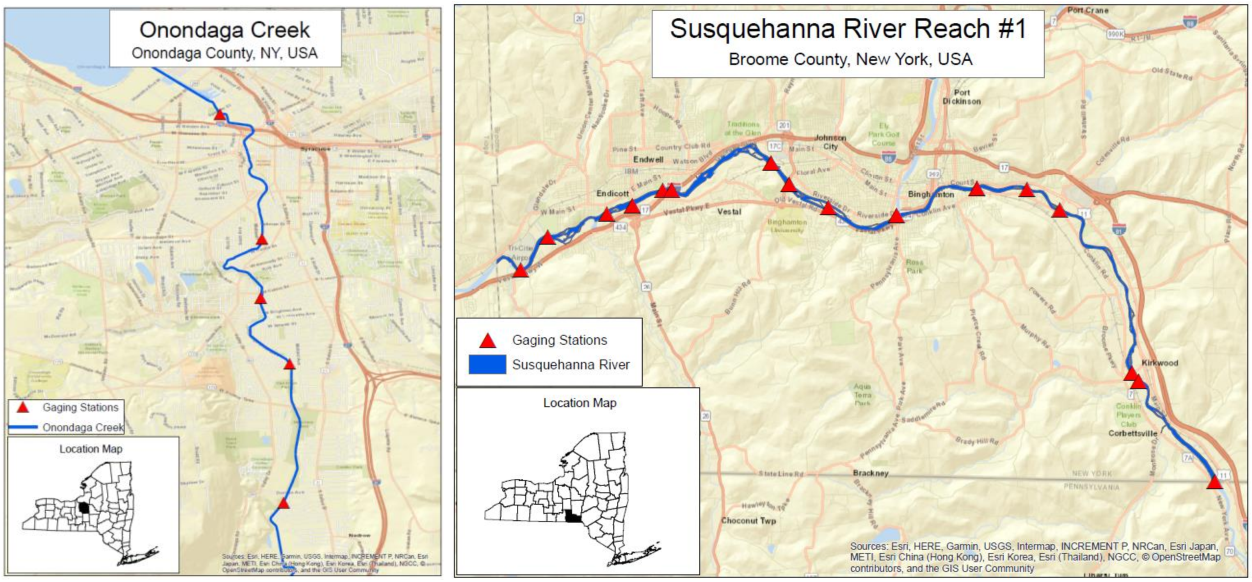

Figure 2. Location maps for Onondaga Creek [Left] and the Susquehanna River [Right] including FEMA Flood Insurance Study and U.S. Geologic Survey measurement station locations.

Data

The data used in this study was available through various state and federal agencies. Data to develop the HSR-based method for flood damage estimation included FEMA Flood Insurance Study (FIS) flood profile data, floodplain maps, county tax parcel data, and LiDAR digital elevation models (DEMs). The floodplain data and FIS reports were downloaded from FEMA's Flood Map Service Center. The county tax parcel data was downloaded from each counties respective Office of Real Property and Tax Services (ORPTS) departments through the New York State GIS Clearinghouse. LiDAR DEM data for the City of Syracuse is maintained by the State University of New York College of Environmental Science and Forestry. LiDAR data for Broome County was obtained through the NY GIS Clearinghouse and processed into a bare earth DEM using ESRI's ArcGIS software suite. Data used to develop hydrologic processes and relationships including peak discharge and drainage area was obtained through the FIS reports and U.S. Geologic Survey (USGS) surface water data for gages along river reaches for the study areas.

Hydrologic Relationship Calculations

For both hydrologic systems, three main relationships were developed: a discharge-frequency curve, a stage-discharge curve, and a discharge-damage curve. The annual maximum peak discharges are reported as area normalized flow instead of volumetric flow to simplify comparisons made at different points along the river reach. Area normalized flow is calculated by dividing volumetric flow by the basin drainage area for the reporting station.

To develop discharge-frequency relationships, the traditional method of using a standard distribution relationship was used. Hydrologic analyses for Onondaga Creek were performed using peak streamflow data from the USGS 04239000 gaging station at Dorwin Avenue and for the Susquehanna River from the USGS 01510300 gaging station at Conklin, NY. In this study, the Generalized Extreme Value (GEV) distribution was paired with a non-traditional method to test uncertainty and account for non-stationarity. The GEV distribution was tested along with the Pearson type 3 and log-Pearson Type 3 distributions using the R programming software under the “lmom” package to determine the best fitting distribution to the data. The Pearson Type III distribution with a log transformation of the data (log-Pearson Type III distribution) is recommended by the USGS and the Advisory Committee on Water Information (ACWI) due to the fact that the distribution performs well in studies and is appropriate for applications with historical and paleo-flood data. However, the procedure does not cover watersheds where flows are hydrologically nonstationary (England et al., 2018). Based on the results of the distribution test, the GEV distribution was determined to be the best fit for the data (Appendix I). Variability in the flow data was calculated using the confidence interval function (ci.fevd) in the R programming software under the “extRemes” package. This function calculates the mean of the sample data and the 95% confidence intervals by taking the $\alpha/2$ and $1 - \alpha/2$ quantiles of the sample, also known as the percentile method (Gilleland 2019).

In addition to calculating the flood frequency statistics on the full record of peak flows, the data was re-sampled using a non-traditional approach to evaluate the non-stationarity of the data. Assuming that historic long-term persistence in streamflow data is partially reflective of possible future shifts in streamflow, flood frequency statistics for an ensemble of twenty re-sampled 30-year periods was calculated with their 95% confidence intervals and used to develop a range of flows at each return period. The range in confidence intervals at each return period for the discharge-frequency relationships were then evaluated to determine the bounds for the uncertainty in hydrology, which was used to assess the sensitivity of flood damages.

As discussed earlier, floods in the northeastern U.S. are caused by a range of hydrologic and topographic processes and future climate change may impact the predominant processes in this region differently thereby influencing future flood risk. Future uncertainty in river discharge and flooding was assessed using a qualitative flood causation process where the annual maximum discharge reported by USGS gaging stations for each waterbody were analyzed. For each reported annual maximum discharge, the meteorological processes underlying the discharge was evaluated. Snowmelt events were determined to be the primary driver of peak annual discharges in both study areas. To assess future uncertainty in flows due to changes in precipitation and climate, three climate scenarios were developed and analyzed for each watershed. Snowmelt events were assessed by analyzing meteorological and snow pack data from the nearest meteorological weather station to determine if there was a significant change to snowpack in the seven days prior to the annual peak streamflow measurement without any significant rainfall events in the same period. If there was found to be a significant change in snowpack without a corresponding rainfall event then the next highest, independent, non-snowmelt related event for that year was found and replaced the annual peak streamflow value in the analysis for that given year. The replacement streamflow data used is the maximum daily mean discharge for the given year, which was then normalized for flow. The three different future climate scenarios outlined in Table 1 represent possible future climates that were chosen due to their realistic outcomes based on current climate projections. This methodology was adapted from Shaw and Riha (2011).

Table 1. Climate scenario descriptions and procedures for causative processes analysis.

Scenario	Climate	Procedure
1	10% less snowmelt with no change in other processes	Replace 10% of snowmelt related discharges with next highest, independent, non-snowmelt related event for that year
2	20% less snowmelt with no change in other processes	Replace 20% of snowmelt related discharges with next highest, independent, non-snowmelt related event for that year
3	2ºC rise in global temperatures, which would increase the magnitude of all precipitation events by 14% (according to the Clausius-Clapeyron Equation)	Multiply all annual peak streamflow values by 14%

After the discharge-frequency analysis, a stage-discharge curve was developed using hydrologic and hydraulic data from each study areas respective FIS report. The stage-discharge curve was created by extracting water elevation above the stream bed from FIS flood profiles for various flood events. Flood profiles are cross-sectional drawings that show contiguous cross sections along a stream or river with streambed and potential flood elevations plotted following the centerline of a stream or river. Plotted data typically includes elevations for the stream bed and the 0.2%, 1%, 2% and 10% annual chance flood water elevation above the vertical datum NAVD88 based on specific hydrologic and hydraulic analyses, locations of streets and other structures crossing the waterbody, and hydraulic structures along the waterbody (FEMA 2003). The flood water elevations in this study were interpolated from the flood profiles and each flood events elevation was subtracted from the corresponding stream bed elevation to determine the depth of water for individual parcels at each specific flood event. The depth of water data is then used in conjunction with the HAZUS depth-damage curve for RES1 occupancy type buildings by the R programming software to calculate estimated flood damages per parcel for each flood event.

Flood Damage Modeling

Damage curves were developed using two different approaches. The first approach used the Level 1 Parameters in the FEMA HAZUS model. Level 1 parameters are readily available and include a DEM or equivalent topographic information, stream discharge, and national data for property and population distribution. Level 1 parameters are the standard approach due to the fact it is the simplest type of analysis requiring minimum effort by the user (FEMA 2018). The built-in flood model in HAZUS derives a flood surface elevation relative to the DEM data to provide areas and depth of flooding and then incorporates the property data to determine damages and losses (Scawthorn 2006a). Most notable about using the Level 1 parameters in HAZUS is that property and population are summarized at the scale of a census block and not individual homes.

The second approach used tax maps and LiDAR data to analyze damages to individual properties. The HSR-based method determined flood damages by using GIS to calculate property inundation by subtracting property base elevation from flood stage level for residential tax parcels in the areas of study (Appendix II). By incorporating site specific building types taken from the tax parcel building type classification as described in the NYS ORPTS Assessor's Manual, damage estimates were applied to each tax parcel based on the specific building type

(NYSORPTS 2002). Flood damages were then calculated using the HAZUS depth-damage functions for each specific parcel building type within the floodplain.

Flow was then incorporated with damage relationships to assess their sensitivity. This concept is illustrated in Figure 3, which is a representative diagram of potential flood damage sensitivity. When analyzing a specified range of uncertainty in flow values, there is an associated range of damages due to the sensitivity of flood damages to hydrologic processes. If the uncertainty in flow and range of damages are small then it can be understood that the hydrologic processes do not have a considerable effect on the degree of damage caused by flooding. However, if the uncertainty in flow is small and the range in damages is large then hydrologic processes are assumed to have a significant effect on flood damages. In other words, if the uncertainty in flow and the range of damages is small then future research should focus on flood damage assessments since the hydrologic processes do not drive flood damage estimation. Sensitivity between flow and damages were assessed based on the conditions outlined in Table 2.

Table 2. Sensitivity categories for discharge-damage relationships.

Degree of Sensitivity	
Weakly Sensitive	< 0.7
Moderately Sensitive	0.8 – 1.3
Strongly Sensitive	1.3 – 2.0
Very Strongly Sensitive	> 2.0

The degree of sensitivity values were calculated using the following formula:

$$\frac{maximum\ damages - minimum\ damages}{maximum\ flow - minimum\ flow} * \frac{1}{normalization\ factor}$$

This formula was used to determine the absolute degree of sensitivity by using the maximum and minimum damages and flow for the study area and for the relative degree of sensitivity between each of the annual chance flood events. Since the damage values are several orders of magnitude greater than the flow values, a normalization factor of 10^6 and 10^7 was used for Onondaga Creek and the Susquehanna River, respectively.

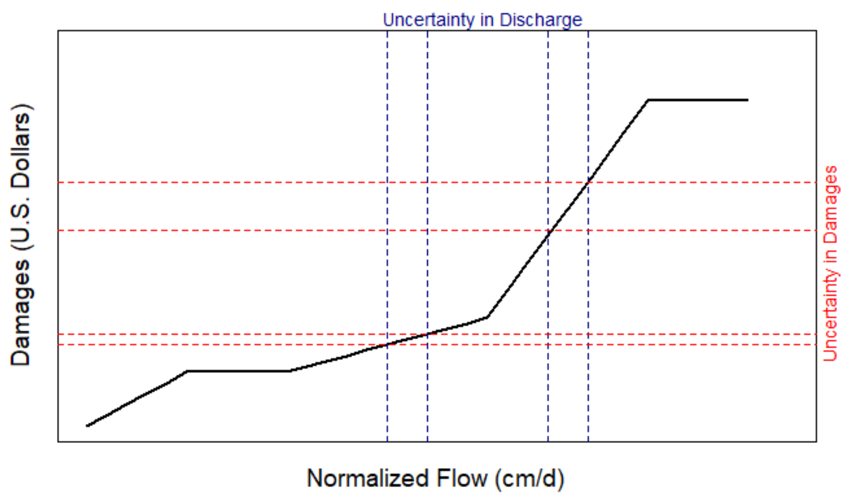

Figure 3. Representative graph of the sensitivity of flood damages to normalized flow with error bars. When the uncertainty in damages and flow is small, then it can be understood that the hydrologic processes do not have a considerable effect on the degree of damage caused by flooding. However, if the uncertainty in flow is small and the uncertainty in damages is large then hydrologic processes are assumed to have significant effects on flood damages.

An additional set of discharge-damage curvers were developed to analyze the influence of levees along the Susquehanna River. Levees were accounted for by manually creating two sets of flood profiles along the banks of the river where levees were constructed. Levee bank flood profiles were manually adjusted so that any water depth below the levee height was set to a value below the minimum LiDAR elevation. This would ensure that during inundation calculations the parcels closest to the levees would be assigned negative inundation values indicating no flood damage. Non-levee bank flood profiles were assigned interpolated values from flood profiles surrounding the levee so parcels closest to the banks without levees would be assigned flood profile values for water elevations.

Based on the sensitivity and uncertainty analysis, the importance of hydrologic processes in estimating the degree of damages from floods was examined in an effort to better guide future research in FLRs of riverine systems.

Results

Discharge-Frequency Relationships

The re-sampling of the ensemble data was performed to estimate possible future climate in the watersheds when compared to the annual data. Due to the uncertainty in future hydrologic predictions, twenty randomly selected re-sampled ensemble datasets were developed to represent "wetter" or "drier" climate conditions based on the historical climatic variability of each watershed. As discussed earlier, both datasets display appreciable increases in peak discharges at different times in the record, which suggests a degree of variability and the potential for non-stationarity. By re-sampling the data, this variability is addressed and possible future flows for different return periods can be analyzed.

Figures 4a and 4b illustrate the discharge-frequency relationship for Onondaga Creek in normalized flow from 1952 to 2017 and the Susquehanna River from 1913 to 2017 and twenty ensemble 30-year period re-sampled data with their associated 95% confidence intervals. Based on the resulting figure, the Susquehanna River ensemble 30-year resampled data had the highest range in confidence intervals and lower annual flow values for each return period when compared to Onondaga Creek. The high degree of variability in both datasets can be attributed to the large shift in discharges for both study areas as evidenced in Figure 1.

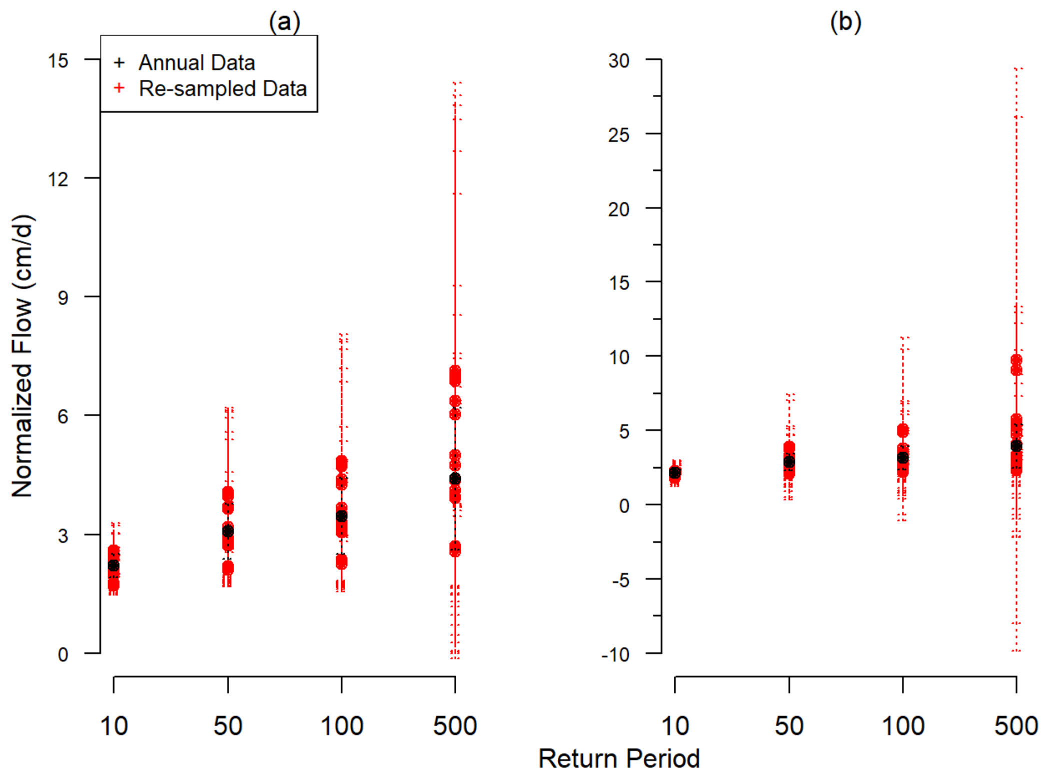

Figure 4. (a) Discharge-frequency relationship for Onondaga Creek using peak streamflow data from USGS 04239000 gage station at Dorwin Ave from 1952 to 2017 and ensemble randomly selected 30-year period re-sampled data with 95% confidence intervals. (b) Discharge-frequency relationship for the Susquehanna River using peak streamflow data from the USGS 01510300 gage station at Conklin, NY from 1913 to 2017 and randomly selected 30-year period re-sampled data with 95% confidence intervals.

Causative Flood Analysis

The climate scenario analysis was performed using the R programming software. For both study areas, annual peak streamflow data was used to develop each climate scenarios predicted future flows. Appendix III displays the data used for each climate scenario for both study areas. Due to the GEV distributions tendency to model the smallest or largest values in a given series and the variability in streamflow data for both study areas, the predicted future flows for climate scenario 2 for both study areas fell outside the expected range of values for flood events greater than the 100-year return period. For consistency throughout the study, the GEV distribution was still used to predict future flows for the climate scenario analysis.

Figure 5a and 5b depict the discharge-frequency relationship for Onondaga Creek and the Susquehanna River, respectively, displaying the predicted future flows for three climate scenarios and annual maximum flows. Based on the figures, the discharge-frequency relationship for different climate scenarios for both Onondaga Creek and the Susquehanna River display similar patterns, which indicate that the hydrologic processes that dominate each basin is comparable between the two study areas. For both study areas, there is very little variation in the reduced snowmelt climate scenarios from the annual mean, but there is a distinct increase in flows when the magnitude of the precipitation events is increased indicated by climate scenario 3. The variation in flows at each return period for Onondaga Creek is much higher, which is an indicator that the hydrologic future of the watershed has a greater degree of uncertainty than the Susquehanna River, which has a much narrower range in flow values.

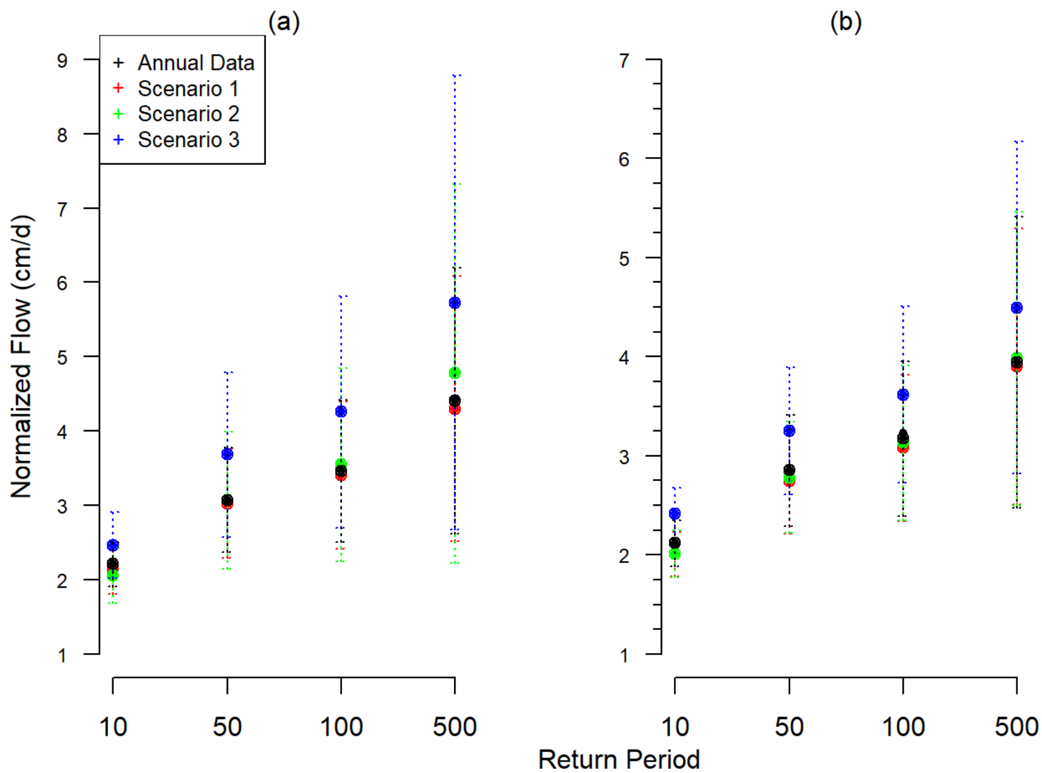

Figure 5. (a) Discharge-frequency relationship for Onondaga Creek using peak streamflow data from USGS 04239000 gage station at Dorwin Ave for annual data from 1952 to 2017 and (b) Discharge-frequency relationship for the Susquehanna River using peak streamflow data from USGS 01510300 gage station at Conklin, NY for annual data from 1913 to 2017 and projected future data based on three climate scenarios: (1) 10% less snowmelt with no change in other processes; (2) 20% less snowmelts with no change in other processes; and (3) increase of 14% magnitude of in all precipitation events.

Stage-Discharge Relationships

Figures 6a and 6b depict the stage of flood waters above the stream bed based on the vertical datum of the NAVD88 for the four representative flood events, 0.2%, 1%, 2%, and 10% annual chance, and their associated peak discharges normalized by drainage area for the reporting USGS gage stations along Onondaga Creek and the Susquehanna River, respectively. The difference in the stage-discharge values at the gaging stations along Onondaga Creek can be attributed to the different hydrologic and stream channel properties at these points. Stream channelization and downstream flow accumulation explain why the gaging stations between Oxford Street and Hovey Street and USGS gage 04240010 on Spencer Street have the highest recorded stage-discharge values since these two stations are the most downstream stations prior to reaching the Onondaga Lake outlet. For the Susquehanna River, the difference in stage-discharge values between the upstream and downstream reporting stations can be explained by the river management practices and natural tributaries that flow into the river. The confluence of the Chenango River with the Susquehanna River causes a sharp increase in stage and peak discharge as water from the Chenango River flows into the Susquehanna River. Downstream gage stations and measurement locations have significantly higher stage-discharge values than their upstream counterparts as a result.

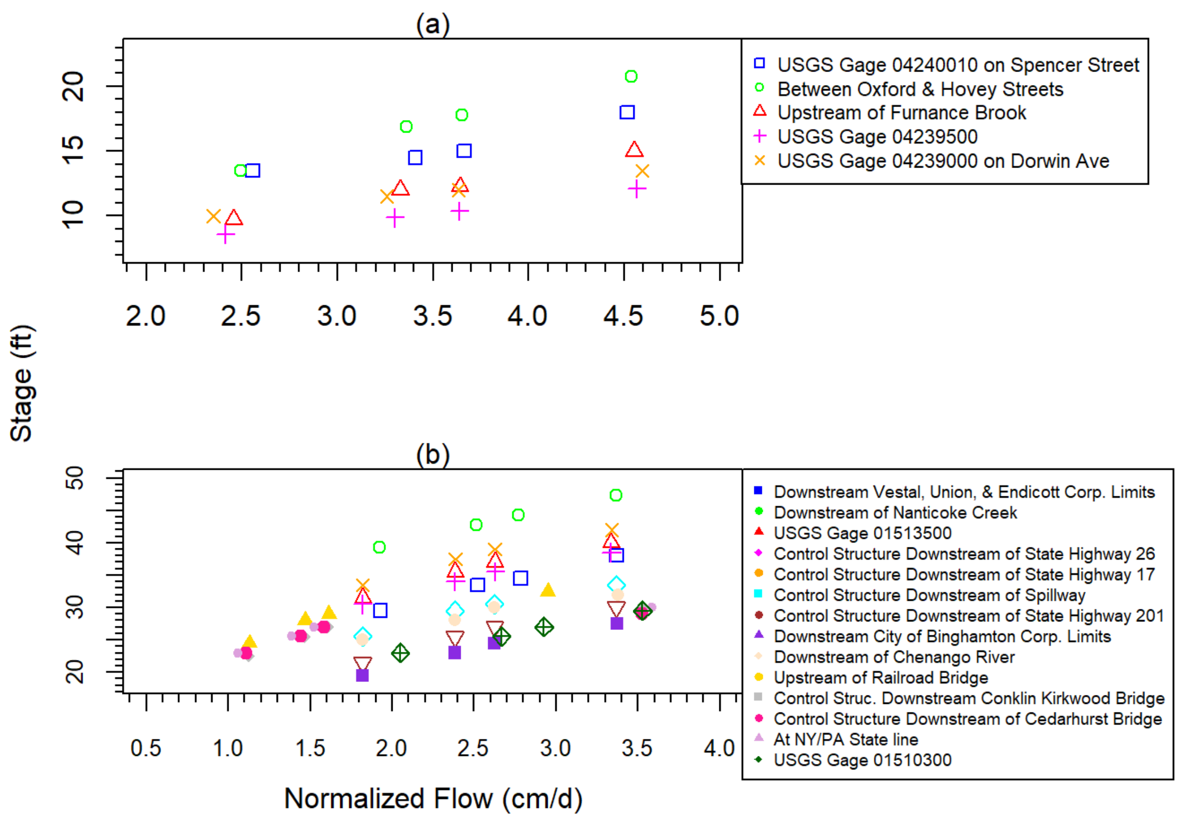

Figure 6. (a) Stage-discharge relationship based on water elevation (stage) in feet from the NYS DEC and FEMA FIS flood profiles for Onondaga Creek and peak discharge in cubic feet per second (cfs) divided by the watershed area for each gage station for the 0.2%, 1%, 2%, and 10% annual chance flood events for the five reporting gage stations along Onondaga Creek. (b) Stage-discharge relationship for the Susquehanna River for the thirteen measurement locations along the Susquehanna River.

HSR Model Flood Damage Estimates

After performing the HSR-based method, total flood damages for each residential occupancy type were calculated and summarized based on annual chance flood event. Table 3 is calculated flood damages for each occupancy type based on the four representative flood events for parcels within the Onondaga Creek flood risk area. As would be expected, the estimated flood damages are highest for a 0.2% annual chance flood event and decrease as the magnitude of the flood event decreases. In addition, the occupancy type with the highest estimated flood damages are properties that have two or more floors and a basement, while properties that have two or more floors with no basement are estimated to have the lowest damage totals.

Table 3. Summary table of estimated flood damage by occupancy type using the HSR-based method for Onondaga Creek for the four representative flood events.

HSR-based Method Estimated Flood Damages: Onondaga Creek Floodplain				
Occupancy Type	**0.2-Percent**	**1-Percent**	**2-Percent**	**10-Percent**
1 Story, Basement	$353,173	$128,781	$116,587	$63,048
1 Story, No Basement	$403,228	$88,580	$53,352	$13,471
2+ Story, Basement	$6,273,551	$3,222,416	$2,688,806	$1,273,327
2+ Story, No Basement	$62,679	$16,641	$11,013	$0
Split Level, Basement	$265,923	$164,234	$135,238	$51,286
Split Level, No Basement	$337,609	$118,153	$84,374	$19,277
Total Damages	$7,696,164	$3,738,805	$3,089,370	$1,420,409

Table 4 is calculated damages for each occupancy type based on the four representative flood events for parcels within the Susquehanna River flood risk area. A similar pattern to the Onondaga Creek damages can be seen where the 0.2% annual chance flood has the highest estimated damages; however, there is a sharp decline in damages between the 0.2% and 1% annual chance flood events. In addition, the occupancy type with the highest estimated flood damages are properties that have two or more floors and a basement, while properties that have two or more floors with no basement are estimated to have the lowest damage totals.

Table 4. Summary table of estimated flood damage by occupancy type using the HSR-based method for the Susquehanna River for the four representative flood events.

HSR-based Method Estimated Flood Damages: Susquehanna River Floodplain				
Occupancy Type	**0.2-Percent**	**1-Percent**	**2-Percent**	**10-Percent**
1 Story, Basement	$3,074,026	$2,365,807	$1,902,423	$912,520
1 Story, No Basement	$12,305,763	$7,933,830	$6,213,033	$3,160,483
2+ Story, Basement	$45,672,263	$30,580,279	$24,409,487	$12,119,459
2+ Story, No Basement	$434,380	$273,514	$212,368	$88,658
Split Level, Basement	$813,709	$610,660	$488,800	$303,265
Split Level, No Basement	$1,573,815	$990,922	$711,449	$354,384
Total Damages	$63,873,956	$42,755,012	$33,937,561	$16,938,769

Discharge-Damage Curves

Based on the estimated total flood damages from the HSR-based method and the normalized flow of each study area, discharge-damage relationships were developed and plotted. Figure 7a and 7b are the discharge-damage relationship for Onondaga Creek and Susquehanna River, respectively, developed using the HSR-based flood estimation method. Based on the figure, the discharge-damage relationship varies depending on the level of flow. In the Onondaga Creek watershed, flows below 3.41 cm/d cause an increase in damages at a rate of $1,963,484 per cm/d of water flow. This relationship increases for flows between 3.41 and 3.66 cm/d to $2,597,740 per cm/d of water flow. Estimated damages for flows above 3.66 cm/d increase sharply to a near 1:1 relationship and at a rate of $4,601,580 per cm/d of water flow. Overall there is a strong sensitivity relationship between normalized flow and damages for Onondaga Creek with sensitivity ratio values of 1.9, 2.0, and 4.4 for the flows below the 2%, 1%, and 0.2 % annual chance flood events, respectively. The discharge-damages relationship of the Susquehanna River was found to be very similar to that of Onondaga Creek; however, the sensitivity of the Susquehanna River flood damages to flow is much higher than that of Onondaga Creek. For flows below 1.53 cm/d, damages increase at a rate of $47,218,867 per cm/d of water flow. This relationship increases for flows between 1.53 and 1.68 cm/d to $58,793,007 per cm/d of water flow. Estimated damages for flows above 2.02 cm/d increase slightly to a rate of $62,114,541 per cm/d of water flow. Overall there is a very strong sensitivity relationship between normalized flow and damages for the Susquehanna River with sensitivity ratio values of 2.4, 4.4, and 3.5 for the flows below the 2%, 1%, and 0.2 % annual chance flood events, respectively.

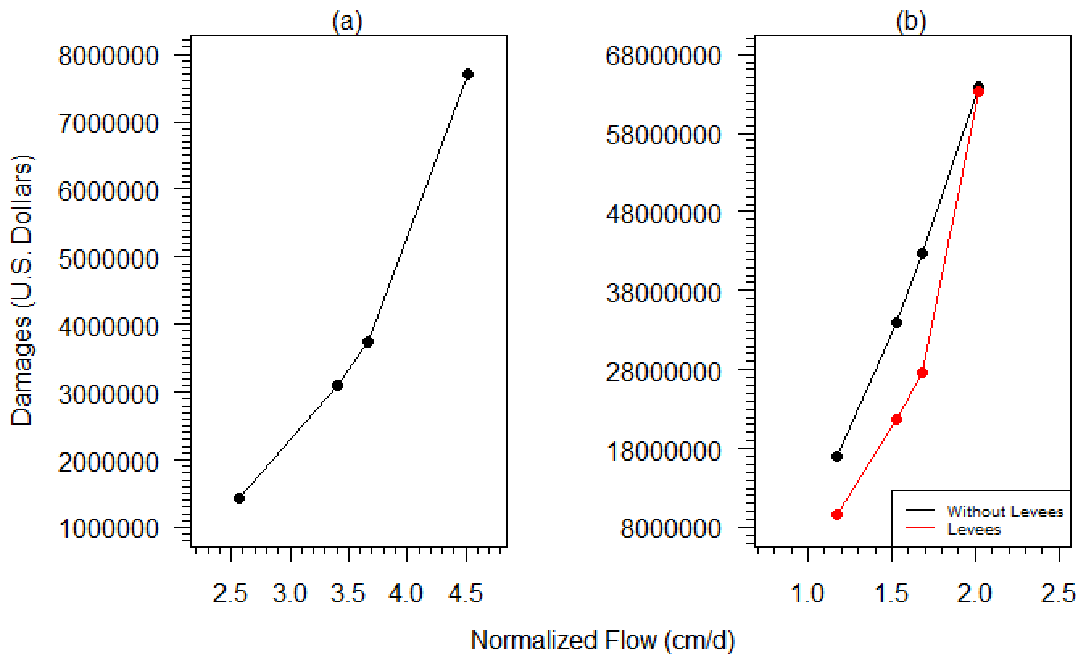

Figure 7. (a) The normalized discharge-damage relationship developed using the HSR-based flood estimation method and the USGS gage 04240010 on Spencer Street as a hydrologic representative based on the ratio of peak discharge and drainage area for the Spencer Street gage at the 0.2%, 1%, 2%, and 10% annual chance flood event levels calculated in the FEMA FIS. (b) The normalized discharge-damage relationship for the Susquehanna River using the USGS 01510300 gage station at Conklin, NY as a hydrologic representative for the standard (black) and levee (red) methodologies.

Levees

As discussed earlier, the Susquehanna River had numerous levee systems constructed along the banks that run through the cities of Binghamton and Vestal, NY in order to mitigate damages from minor flood events (less than 1% annual chance flood events). These levee systems had considerable influences on the model output for the HSR-based method. Table 5 is calculated damages for each occupancy type based on the four representative flood events for parcels within the Susquehanna River flood risk area including the influence of levees.

Table 5. Summary table of estimated flood damage by occupancy type using the HSR-based method for the Susquehanna River for the four representative flood events including levees.

HSR-based Method Estimated Flood Damages: Susquehanna River Floodplain with Levees				
Occupancy Type	**0.2-Percent**	**1-Percent**	**2-Percent**	**10-Percent**
1 Story, Basement	$3,086,969	$468,266	$356,571	$106,386
1 Story, No Basement	$12,321,497	$4,534,539	$3,366,888	$1,538,737
2+ Story, Basement	$44,912,316	$21,216,888	$16,921,868	$7,271,705
2+ Story, No Basement	$441,007	$172,910	$135,912	$68,560
Split Level, Basement	$815,454	$531,952	$439,105	$266,687
Split Level, No Basement	$1,572,001	$778,525	$555,592	$301,520
Total Damages	$63,149,246	$27,703,080	$21,775,936	$9,553,593

Figure 7b is the normalized discharge-damage relationship for the Susquehanna River depicting both the standard (black) and levee (red) methodologies. Based on the levee methodology data, flows below 1.53 cm/d caused an increase in damages at a rate of $33,950,953 per cm/d of water flow. This relationship increases for flows between 1.53 and 1.68 cm/d to $39,514,293 per cm/d of water flow. Estimated damages for flows above the 1% annual chance flood event normalized flow rate of 2.02 cm/d increase significantly to a rate of $104,253,429 per cm/d of water flow. Overall there is a considerably strong sensitivity relationship between normalized flow and damages for the Susquehanna River with sensitivity ratio values of 1.7, 3.0, and 6.0 for the flows below the 2%, 1%, and 0.2 % annual chance flood events, respectively.

The impacts of the levees on flows below the 1% annual chance flood events for the Susquehanna River were significant in reducing HSR-based method model damage output. For the discharge-damage relationship, flood damage reductions by the levee system were $15-20 million per cm/d of flow for events equal to or below the 1% annual chance. There is a sharp and significant increase in estimated flood damages for flow once the 1% annual chance flood event is exceeded. This is to be expected, however, due to the fact that the parcels which were protected by the levees would be devastated by a 0.2% annual chance flood event and incur significant damages once the levees were breached.

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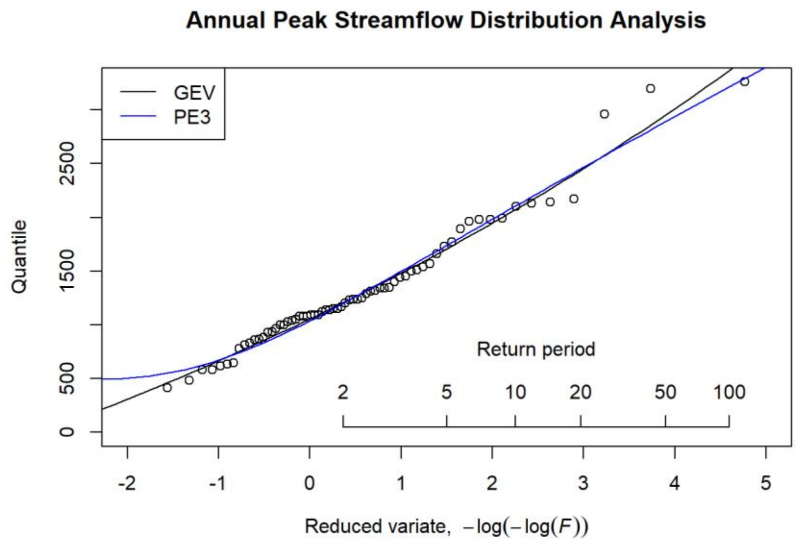
APPENDIX

Appendix I: Discharge-frequency analysis for Onondaga Creek from the USGS 04239000 gage station at Dorwin Avenue.

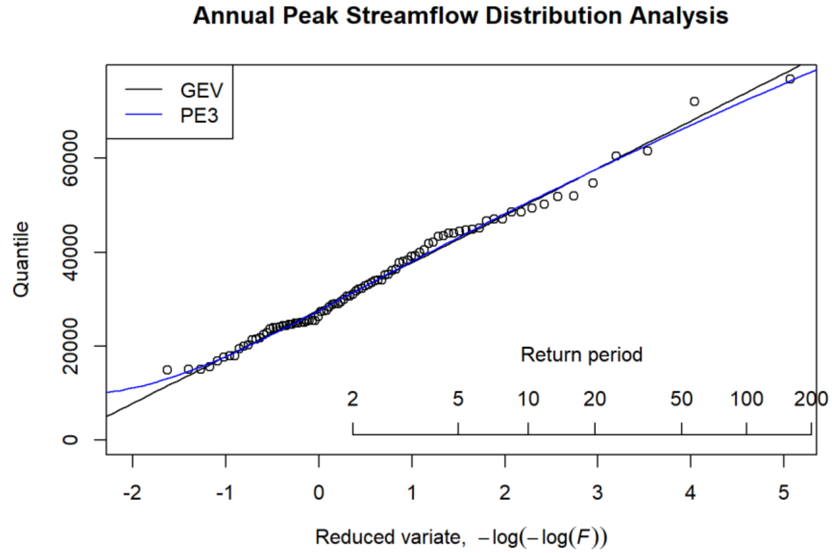


Discharge-frequency analysis for Onondaga Creek from the USGS 04239000 gage station at Dorwin Avenue				
	Discharge (cfs)			
	500 Year	**100 Year**	**50 Year**	**10 Year**
GEV	4430	3369	2955	2070
Pearson 3	3955	3219	2894	2105
log-Pearson 3	4062	3221	2872	2078
FIS, 2016	4300	3400	3050	2200

Non-stationarity test results using “ADF” package in R programming language to perform an Augmented Dickey-Fuller test for stationarity.

Augmented Dickey-Fuller Test	
Data	Annual Peak Streamflow
Dickey-Fuller	-3.407
Lag Order	4
P-value	0.062
Alternative Hypothesis	Stationary

Discharge-frequency analysis for the Susquehanna River from the USGS 01510300 gage station at Conklin, NY.



Discharge-frequency analysis for Susquehanna River from the USGS 01510300 gage station at Conklin, NY				
	Discharge (cfs)			
	500 Year	**100 Year**	**50 Year**	**10 Year**
GEV	90,395	74,050	66,996	50,359
Pearson 3	86,261	72,415	66,187	50,666
log-Pearson 3	93,178	75,374	67,917	50,664
FIS, 2010	83,414	69,186	63,031	48,424

Non-stationarity test results using "ADF" package in R programming language to perform an Augmented Dickey-Fuller test for stationarity.

Augmented Dickey-Fuller Test	
Data	Annual Peak Streamflow
Dickey-Fuller	-4.02
Lag Order	4
P-value	0.012
Alternative Hypothesis	Stationary

Appendix II: The HSR-based methodology:

1. Use GIS software and download the FEMA Flood Map data for areas surrounding the waterbody of interest to isolate the floodplain.
2. Download tax parcel and DEM/topographic information data.
3. Using the DEM data layer, assign elevation values to each tax parcel using the Extract Values to Points tool.
4. Create a new GIS layer using the FEMA FIS flood profile data for each flood event along the water body of interest. Using the GIS software, use the Spatial Join tool to join the flood profile data to each individual parcel throughout the floodplain.
5. Determine inundation levels by subtracting the flood profile elevation for each flood event from the parcel elevation.
6. Delineate a Flood Risk Area that encompasses all tax parcels at risk of flood damage by adding a buffer of 1000 feet to the FEMA Flood Map 0.2% annual chance flood boundary.
7. Use the Select by Location tool to select all the tax parcels in the Flood Risk Area.
8. Using the HAZUS damage functions for specific occupancy types (Appendix IV), categorize each parcel in the Flood Risk Area by building type.
9. Using the inundation levels, calculate total damages for each parcel by multiplying the estimated percent damage for the occupancy type and the building assessed value, which is the total assessed value subtracted by the land assessed value.

Appendix III: Climate scenario datasets for both Onondaga Creek and the Susquehanna River.

USGS 04239000 Onondaga Creek at Dorwin Avenue, Syracuse, NY							
Date	**Year**	**Month**	**Day**	**Annual Flow (cm/d)**	**S1 Flow (cm/d)**	**S2 Flow (cm/d)**	**S3 Flow (cm/d)**
3/11/1952	1952	3	11	1.25	1.25	1.25	1.50
5/4/1954	1954	5	4	0.93	0.93	0.93	1.11
3/1/1955	1955	3	1	1.12	1.12	1.12	1.35
3/8/1956	1956	3	8	1.54	1.54	1.54	1.85
8/4/1957	1957	8	4	1.38	1.38	1.38	1.65
6/2/1958	1958	6	2	1.44	1.44	1.44	1.73
1/22/1959	1959	1	22	2.09	**0.81***	**0.81***	2.51
3/31/1960	1960	3	31	2.28	**0.27***	**0.27***	2.73
2/25/1961	1961	2	25	2.12	**0.49***	**0.49***	2.54
3/12/1962	1962	3	12	0.89	0.89	0.89	1.07
3/26/1963	1963	3	26	1.22	1.22	1.22	1.46
3/5/1964	1964	3	5	1.61	1.61	**0.52***	1.94
3/8/1965	1965	3	8	0.69	0.27	0.27	0.83
3/13/1966	1966	3	13	1.55	1.55	1.55	1.86
3/28/1967	1967	3	28	0.44	0.34	0.34	0.53
6/26/1968	1968	6	26	1.34	1.34	1.34	1.60
5/20/1969	1969	5	20	1.23	1.23	1.23	1.47
4/2/1970	1970	4	2	1.15	1.15	1.15	1.38
3/15/1971	1971	3	15	1.65	1.65	**0.85***	1.97
6/23/1972	1972	6	23	3.42	3.42	3.42	4.10
7/3/1974	1974	7	3	3.48	3.48	3.48	4.18
9/26/1975	1975	9	26	2.13	2.13	2.13	2.55
4/16/1976	1976	4	16	2.24	2.24	2.24	2.69
10/17/1977	1977	10	17	2.12	2.12	2.12	2.54
3/6/1979	1979	3	6	2.29	**0.35***	**0.35***	2.74
3/22/1980	1980	3	22	1.68	1.68	**0.72***	2.01
10/28/1981	1981	10	28	3.16	3.16	3.16	3.80
4/24/1983	1983	4	24	1.43	1.43	**0.9***	1.72
2/15/1984	1984	2	15	2.02	**0.79***	**0.79***	2.42
2/24/1985	1985	2	24	1.31	1.31	**0.73***	1.58
3/15/1986	1986	3	15	1.41	1.41	1.41	1.69
3/8/1987	1987	3	8	1.07	1.07	1.07	1.28
3/26/1988	1988	3	26	0.67	0.67	0.67	0.81
9/20/1989	1989	9	20	0.87	0.87	0.87	1.05
2/16/1990	1990	2	16	1.28	1.28	1.28	1.54
3/27/1992	1992	3	27	1.00	0.49	0.49	1.20
4/2/1993	1993	4	2	1.16	1.16	1.16	1.40
3/24/1994	1994	3	24	1.20	1.20	1.20	1.44

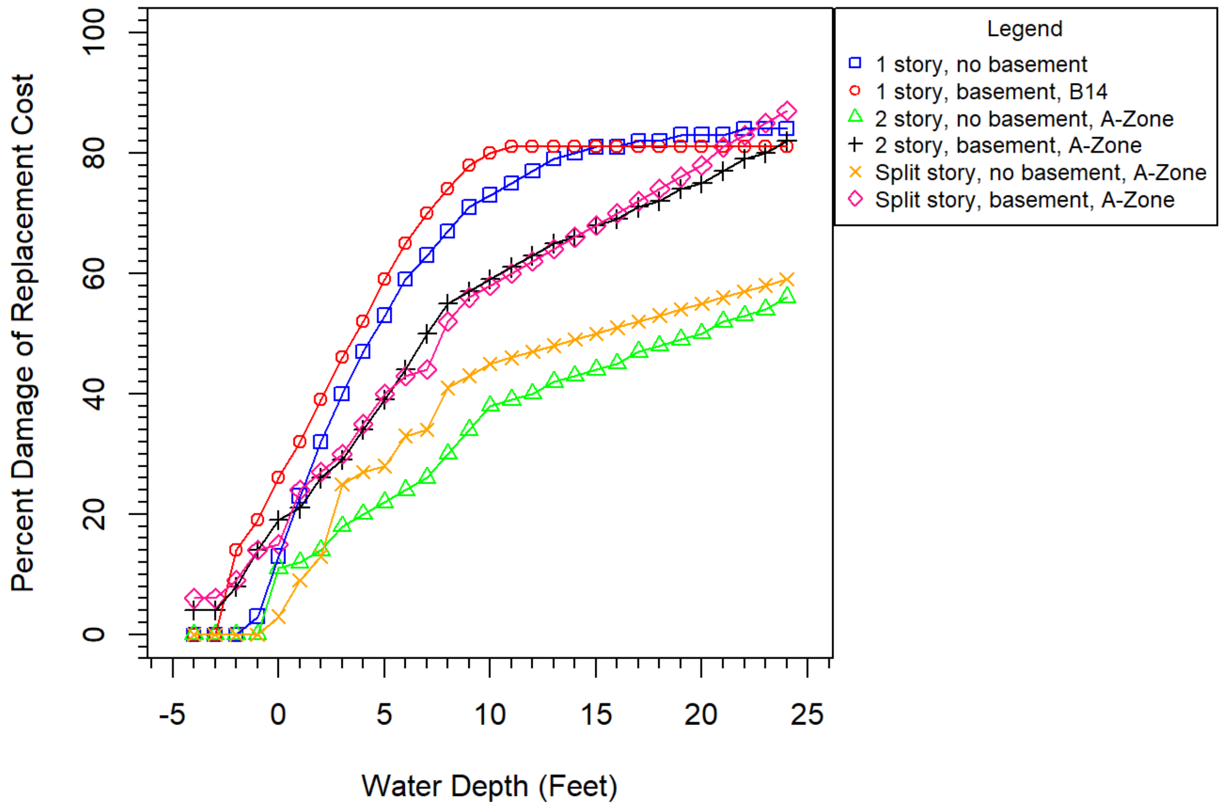
1/19/1996	1996	1	19	2.32	**1.32***	**1.32***	2.78
1/8/1998	1998	1	8	1.40	1.40	1.40	1.68
1/24/1999	1999	1	24	1.15	0.60	0.60	1.38
2/28/2000	2000	2	28	1.43	1.43	1.43	1.72
4/8/2001	2001	4	8	1.11	1.11	1.11	1.33
2/1/2002	2002	2	1	0.83	0.83	0.83	0.99
4/5/2003	2003	4	5	0.99	0.99	0.99	1.19
8/30/2004	2004	8	30	1.50	1.50	1.50	1.79
4/3/2005	2005	4	3	1.85	1.85	1.85	2.22
3/14/2007	2007	3	14	1.77	1.77	**1.60***	2.13
3/9/2009	2009	3	9	1.16	1.16	1.16	1.40
1/25/2010	2010	1	25	1.07	0.51	0.51	1.28
3/11/2011	2011	3	11	1.10	0.90	0.90	1.32
1/27/2012	2012	1	27	0.51	0.51	0.51	0.62
1/31/2013	2013	1	31	0.66	0.66	0.66	0.79
3/30/2014	2014	3	30	1.89	1.89	1.89	2.27
4/4/2015	2015	4	4	1.32	1.32	1.32	1.59
2/25/2016	2016	2	25	1.03	1.03	1.03	1.23
7/1/2017	2017	7	1	1.15	1.15	1.15	1.38
					***Replaced**	***Replaced**	

USGS 01503000 Susquehanna River at Conklin, NY							
Date	**Year**	**Month**	**Day**	**Annual Flow (cm/d)**	**S1 Flow (cm/d)**	**S2 Flow (cm/d)**	**S3 Flow (cm/d)**
3/28/1913	1913	3	28	2.20	2.20	2.20	2.51
3/30/1914	1914	3	30	1.99	1.99	1.99	2.27
7/8/1915	1915	7	8	1.71	1.71	1.71	1.95
4/2/1916	1916	4	2	1.78	1.78	1.78	2.03
10/30/1917	1917	10	30	1.24	1.24	1.24	1.42
10/31/1918	1918	10	31	0.76	0.76	0.76	0.86
3/29/1920	1920	3	29	1.49	1.49	1.49	1.70
11/29/1921	1921	11	29	1.69	1.69	1.69	1.92
3/24/1923	1923	3	24	1.15	1.15	1.15	1.32
9/30/1924	1924	9	30	1.86	1.86	1.86	2.12
2/12/1925	1925	2	12	1.90	**0.82***	**0.82***	2.16
4/10/1926	1926	4	10	1.29	1.29	1.29	1.48
10/19/1927	1927	10	19	1.84	1.84	1.84	2.10
3/17/1929	1929	3	17	1.99	1.99	1.99	2.27
3/30/1931	1931	3	30	0.96	0.96	0.96	1.10
4/1/1932	1932	4	1	1.23	1.23	1.23	1.40
3/5/1934	1934	3	5	1.07	1.07	**0.65***	1.22
7/9/1935	1935	7	9	1.77	1.77	1.77	2.02

3/18/1936	1936	3	18	2.61	2.61	2.61	2.97
1/26/1937	1937	1	26	1.03	1.03	1.03	1.17
9/23/1938	1938	9	23	1.44	1.44	1.44	1.64
2/21/1939	1939	2	21	1.40	1.40	**0.85***	1.60
4/1/1940	1940	4	1	2.19	**1.47***	**1.47***	2.50
4/6/1941	1941	4	6	1.05	1.05	1.05	1.20
12/31/1942	1942	12	31	2.06	**1.13***	**1.13***	2.34
3/18/1944	1944	3	18	1.27	1.27	1.27	1.45
3/18/1945	1945	3	18	1.16	1.16	1.16	1.33
3/9/1946	1946	3	9	1.39	1.39	1.39	1.59
4/6/1947	1947	4	6	1.31	1.31	1.31	1.49
3/22/1948	1948	3	22	2.56	2.56	2.56	2.92
12/4/1950	1950	12	4	1.53	**1.24***	**1.24***	1.74
3/12/1952	1952	3	12	1.04	1.04	**0.85***	1.19
1/25/1953	1953	1	25	1.07	1.07	1.07	1.22
2/18/1954	1954	2	18	1.23	1.23	1.23	1.40
3/13/1955	1955	3	13	0.95	0.95	0.95	1.08
4/7/1956	1956	4	7	1.66	1.66	1.66	1.89
1/23/1957	1957	1	23	0.91	0.91	0.91	1.03
4/7/1958	1958	4	7	1.62	1.62	1.62	1.85
1/22/1959	1959	1	22	1.37	1.37	**1.20**	1.56
4/6/1960	1960	4	6	1.86	1.86	1.86	2.12
2/26/1961	1961	2	26	1.65	**1.21***	**1.21***	1.89
4/1/1962	1962	4	1	1.49	1.49	1.49	1.70
3/28/1963	1963	3	28	1.60	1.60	1.60	1.82
3/10/1964	1964	3	10	2.12	2.12	2.12	2.42
2/10/1965	1965	2	10	0.63	0.63	0.63	0.72
3/6/1966	1966	3	6	0.76	0.76	0.76	0.87
3/30/1967	1967	3	30	0.71	0.71	0.71	0.81
3/23/1968	1968	3	23	1.02	1.02	1.02	1.16
4/3/1970	1970	4	3	1.07	1.07	1.07	1.22
3/16/1971	1971	3	16	0.92	0.92	0.92	1.05
11/9/1972	1972	11	9	1.36	1.36	1.36	1.55
12/28/1973	1973	12	28	1.05	1.05	**0.93***	1.20
10/19/1975	1975	10	19	1.34	1.34	1.34	1.53
3/16/1977	1977	3	16	1.84	1.84	1.84	2.09
3/7/1979	1979	3	7	1.91	1.91	1.91	2.18
3/22/1980	1980	3	22	1.07	1.07	**0.82***	1.22
2/21/1981	1981	2	21	1.04	1.04	1.04	1.19
3/27/1982	1982	3	27	0.75	0.75	0.75	0.85
12/14/1983	1983	12	14	1.89	1.89	1.89	2.16

9/28/1985	1985	9	28	0.85	0.85	0.85	0.96
3/15/1986	1986	3	15	1.88	**0.52***	**0.52***	2.14
5/20/1988	1988	5	20	0.91	0.91	0.91	1.04
5/7/1989	1989	5	7	1.06	1.06	1.06	1.21
10/24/1990	1990	10	24	1.02	1.02	1.02	1.16
3/12/1992	1992	3	12	0.64	0.64	0.64	0.73
4/1/1993	1993	4	1	2.05	**1.48***	**1.48***	2.34
4/7/1994	1994	4	7	1.20	1.20	1.20	1.36
3/9/1995	1995	3	9	0.66	0.66	0.66	0.75
1/19/1996	1996	1	19	1.97	**1.25***	**1.25***	2.25
1/10/1998	1998	1	10	1.54	1.54	1.54	1.76
1/24/1999	1999	1	24	1.44	1.44	**0.39***	1.64
2/28/2000	2000	2	28	1.61	**1.16***	**1.16***	1.83
4/11/2001	2001	4	11	1.22	1.22	1.22	1.39
3/27/2002	2002	3	27	1.00	1.00	1.00	1.14
3/23/2003	2003	3	23	1.42	1.42	1.42	1.62
9/18/2004	2004	9	18	2.31	2.31	2.31	2.64
4/3/2005	2005	4	3	2.09	2.09	2.09	2.38
6/28/2006	2006	6	28	3.25	3.25	3.25	3.70
3/28/2007	2007	3	28	1.06	1.06	**0.70***	1.21
3/9/2008	2008	3	9	1.30	1.30	1.30	1.48
3/11/2009	2009	3	11	1.02	1.02	1.02	1.16
1/25/2010	2010	1	25	1.17	1.17	**0.84***	1.33
9/8/2011	2011	9	8	3.05	3.05	3.05	3.48
1/28/2012	2012	1	28	0.63	0.63	0.63	0.72
6/29/2013	2013	6	29	0.86	0.86	0.86	0.98
5/17/2014	2014	5	17	1.03	1.03	1.03	1.17
4/10/2015	2015	4	10	1.11	1.11	1.11	1.27
2/26/2016	2016	2	26	0.82	0.82	0.82	0.94
4/7/2017	2017	4	7	1.43	1.43	1.43	1.63
					***Replaced**	***Replaced**	

Appendix IV: HAZUS damage functions for RES1 building types.



CHAPTER 3: DISCUSSION

SUMMARY

This study introduced a new method for the determination of first floor elevations and flood risk parcels to more accurately predict flood damage estimates from various annual chance flood events. In addition, uncertainty in future hydrology estimates was analyzed and quantified to determine the range and confidence in flood damage estimates of this new methodology. The study areas used were good illustrations of the methodology and its use, but the calculated uncertainty and flood damage estimations may not be representative of all situations due to the fact that only residential tax parcels were assessed in this study. Another simplification is that only the riverine flood scenario was employed in the analysis. A more inclusive and representative methodology could have included other building types, i.e. commercial, essential, state/federal, etc., a wider range of depth-damage curves, or additional hydrologic data from different gaging stations along each waterbody.

The results of the flood damage estimates using the HSR method was that the total damages and damage per change in flow was higher for the Susquehanna River than for Onondaga Creek. The results of the analysis show strong to very strong sensitivity of damage to flow for Onondaga Creek since the sensitivity ratios ranged from 1.9 to 4.4 for flows below the 2%, 1%, and 0.2 % annual chance flood events. For the Susquehanna River, the discharge-damage relationship was calculated to be very strong for both the standard and levee approaches. The standard approach for the Susquehanna River had calculated sensitivity ratios between 2.4 and 4.4, while the levee approaches ratios ranged from 1.7 to 6.0 for flows below the 2%, 1%, and 0.2 % annual chance flood events. The lower initial, higher final, and wider range of values for the levee approach can be explained by the effect that the levees would have on the different flood events. Since the levees were built to the 1% annual flood chance water elevation, flood water heights in the Susquehanna River basin that did not exceed this elevation would only cause damage to areas without levees, which are generally less densely populated areas of the river banks. This in turn reduces estimated flood damages for flood events below the 1% annual chance; however, once a flood elevation exceeds the 1% annual chance, there is a sharp and drastic increase in estimated damages. This occurs due to the fact that the properties once protected by the levees are now inundated in addition to the parcels that are within the 0.2% annual chance floodplain. The levees perform as intended and protect a large number of properties from being damaged by flood events below the 1% annual chance and save over an estimated $15 million in damages.

Another method that can be used to assess the sensitivity of the discharge-damage relationships is to calculate the elasticity for each waterbody. Elasticity is the ratio of percent change for two variables. If elasticity is less than 1, then the variables are said to be inelastic; equal to 1, then the variables are considered unit elastic; and greater than 1, then the variables are said to be elastic (Dean et al. 2016). For Onondaga Creek, the elasticity ratio is 5.6 so damages increase as flow increases. For the Susquehanna River, the standard approaches elasticity is 3.7, while the levee approaches elasticity is 7.6. These results are in line with the sensitivity ratios of the two waterbodies (Table 1).

UNCERTAINTY IN HYDROLOGY AND SENSITIVITY IN FLOOD DAMAGES

Based on the findings of this study, there is a high degree of sensitivity of damages to flow in the Onondaga Creek and Susquehanna River basins. These findings strengthen the need to more accurately and reliably measure, model, and predict future hydrological processes in an effort to better understand and assess future flood risk. Figure 1 depicts the discharge-damage relationship with uncertainty bounds at the 2% annual chance flood event for Onondaga Creek and the Susquehanna River using both the standard and levee methodologies. Based on the figure, there is a large degree of uncertainty in damages for both study areas and all methodologies when compared to the uncertainty in flow. The results of this study build upon the work of research surrounding uncertainty in FLRs. Wagenaar et al. (2016) determined there was large uncertainty in flood damage estimates depending on the choice of damage model; while Moel and Aerts (2011) concluded that when the uncertainty in the four components of a flood risk model are analyzed together that the total uncertainty in flood damages estimates can amount to a factor of 5 to 6. This study establishes a connection between the sensitivity of flood damages to the uncertainty in hydrology by determining that uncertainty in hydrology can amplify the absolute sensitivity of flood damages estimates by a factor of 3.0 to 3.6 (Table 1).

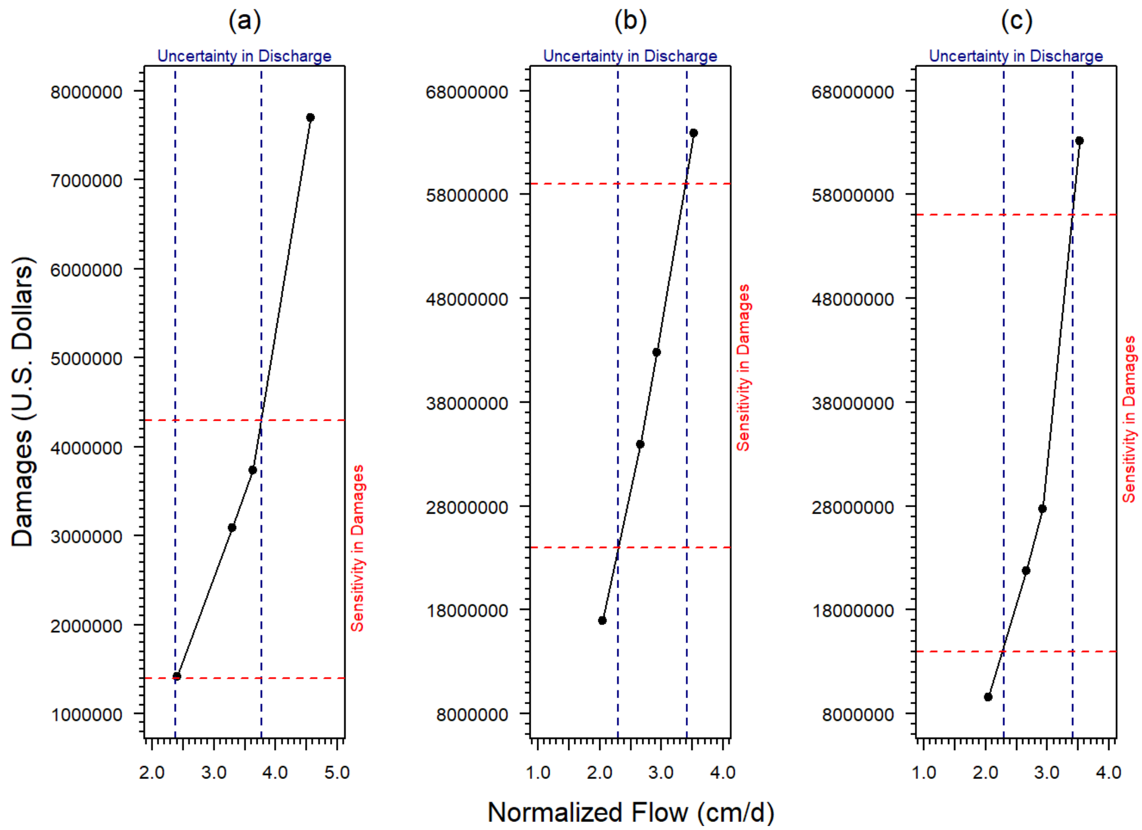


Figure 1. Discharge-damage relationships for (a) Onondaga Creek and the Susquehanna River using the (b) standard and (c) levee methodologies based on the HSR method for FLR including uncertainty bounds in flow plotted at the 2% annual chance flood event.

This sensitivity of damages to flow is not uniform, however, and differs at different ranges of flows and methodology employed. Table 1 is a summary of the sensitivity analysis for Onondaga Creek and the Susquehanna River with the standard and levee approaches based on the degree of sensitivity and elasticity analysis. For Onondaga Creek, the sensitivity of damages to flow is lowest for flows below 3.5 cm/d and increases with increasing flow, while the absolute sensitivity is very strongly sensitive at 3.0. Damages to flow in the Susquehanna River basin vary depending on the methodology. For the standard approach, damages to flow sensitivity are actually highest at flows between 2.7 and 2.9 cm/d and lowest for flows below 2.7 cm/d, while absolute sensitivity is very strongly sensitive at 3.1. Using the levee methodology, sensitivity is highest for flows above 3.5 cm/d and lowest for flows below 2.7 cm/d with an absolute sensitivity of very strongly sensitive at 3.6.

Table 1. Summary table of sensitivity analysis based on percent change performed using the results from the HSR method and hydrologic data from the USGS gaging stations for Onondaga Creek and the Susquehanna River with both the standard and levee methodologies.

Sensitivity Analysis: Onondaga Creek						
Return Period	**Flow (cm/d)**	**Damage (in $U.S. Millions)**	**Sensitivity (D/F)**	**% Change Flow**	**% Change Damages**	**Elasticity**
10	2.6	1.4				
50	3.5	3.1	1.9	34.6	121.4	3.5
100	3.8	3.7	2.0	8.6	19.4	2.3
500	4.7	7.7	4.4	23.7	108.1	4.6
Absolute			3.0	80.8	450.0	5.6
Sensitivity Analysis: Susquehanna River with Standard Methodology						
Return Period	**Flow (cm/d)**	**Damage (in $U.S. Millions)**	**Sensitivity (D/F)**	**% Change Flow**	**% Change Damages**	**Elasticity**
10	2.0	16.9				
50	2.7	33.9	2.4	35.0	100.6	2.9
100	2.9	42.7	4.4	7.4	26.0	3.5
500	3.5	63.8	3.5	20.7	49.4	2.4
Absolute			3.1	75.0	277.5	3.7
Sensitivity Analysis: Susquehanna River with Levee Methodology						
Return Period	**Flow (cm/d)**	**Damage (in $U.S. Millions)**	**Sensitivity (D/F)**	**% Change Flow**	**% Change Damages**	**Elasticity**
10	2.0	9.5				
50	2.7	21.7	1.7	35.0	128.4	3.7
100	2.9	27.7	3.0	7.4	27.6	3.7
500	3.5	63.8	6.0	20.7	130.3	6.3
Absolute			3.6	75.0	571.6	7.6

The climate change scenarios were another method to illustrate the interactions between uncertainty in future discharge and uncertainty in future damages by establishing hydrologic uncertainty bounds and directly relating these flow bounds to the discharge-damage relationship curve to estimate the sensitivity of future flood damages. Based on the findings that damages are highly sensitive to flows, changes in future hydrologic processes will significantly influence future flood processes. For flow regions with low sensitivity to future hydrological changes, the influence on the discharge-damage relationship would be expected to be minimal. However, flow regions with high sensitivity to changes in future flood processes would be expected to have significant influences on the discharge-damage relationship. For Onondaga Creek, climate change scenarios 1 and 2 had the greatest deviations from the normal annual data (Figure 5a). These two scenarios would most likely exert significant influence on future flood processes, especially for flood events with larger return periods. The Susquehanna River, in contrast, had high sensitivity to climate change scenario 3 so this scenario would exert significant influence on future flood processes for events at all return periods (Figure 5b).

MODEL COMPARISONS

The HAZUS Flood model was performed using Level 1 parameters for both the Onondaga Creek and Susquehanna River basins for the 0.2%, 1%, 2%, and 10% annual chance flood events to determine if the results of the HSR method for FLR could be a reasonable alternative approach. The damage estimates from both models are displayed in Table 2. For the HAZUS model, the RES1 occupancy types at their full replacement cost estimates for building losses were determined and summed to calculate the total flood damages for each flood event. In total damages, the HAZUS model calculated there to be significantly higher damages at every flood event as compared to the HSR based method for both the Susquehanna River and Onondaga Creek floodplains.

Table 2. Summary table of flood damage estimates from the HAZUS and HSR method models.

	HAZUS: RES1 Full Replacement Cost – Building Loss		**HSR Methodology**		
Return Period	**Susquehanna River**	**Onondaga Creek**	**Susquehanna River (Standard)**	**Susquehanna River (Levee)**	**Onondaga Creek**
500	$96,117,000	$45,715,000	$63,873,956	$63,149,246	$7,696,164
100	$59,670,000	$38,044,000	$42,755,012	$27,703,080	$3,738,805
50	$46,416,000	$35,724,000	$33,937,561	$21,775,936	$3,089,370
10	$16,275,000	$27,625,000	$16,938,769	$9,553,593	$1,420,409

Table 3 is a summary table of the total number of parcels damaged by flood waters from the HAZUS and HSR methods. For the HAZUS model, the RES1 occupancy type for parcel counts were determined to be much lower for the Susquehanna River and higher for Onondaga Creek at all return periods.

Table 3. Summary table of total number of damaged parcels from HAZUS and HSR method models.

	HAZUS: RES1 By Count		**HSR Methodology**		
Return Period	**Susquehanna River**	**Onondaga Creek**	**Susquehanna River (Standard)**	**Susquehanna River (Levee)**	**Onondaga Creek**
500	1,108	1,091	5,916	5,925	997
100	788	926	4,437	3,013	583
50	658	900	3,839	2,643	532
10	242	763	2,417	1,410	367
Total	2,796	3,680	16,609	12,991	2,479

The differences in flood damage estimates are due to many different factors, but the primary factors are the method of damage calculation, uncertainty in the first-floor elevation, and the aggregation of data. The HAZUS Flood model uses Full Replacement Value, which is how much to replace an asset at the present time according to its current worth, to calculate flood damages. The Full Replacement Value for different occupancy types per block are calculated from socio-economic data from the census combined with an associated replacement cost model. These replacement cost models are from the industry standard cost estimation published in Means Square Foot Costs (Balboni 2006). With the census data combined with a replacement cost model, the HAZUS model is able to have estimated replacement values for each specific occupancy (RES1, RES3A, COM1, etc.) by cost per square foot. These values are then average over a census block and summarized to determine the total flood damages. HAZUS uses a square footage factor of 1,800 in its cost per square foot analysis. Using this information, we can estimate the HAZUS damage per square foot by using the building counts, square footage factor, and estimate flood damages using the following formula:

$$\frac{Total\ Estimated\ Flood\ Damages}{Total\ Number\ of\ Damaged\ Parcels} * \frac{1}{Average\ Square\ Feet}$$

For Onondaga Creek at the 1% annual chance flood event (100-year return period), the estimated damage per square foot was $22.82, while for the Susquehanna River it was $42.07 per square foot. The same analysis can be performed on the HSR methodology using 1,800 square feet as an average for each parcel. For the HSR methodology, the estimated damages per square foot for Onondaga Creek was $3.56, while for the Susquehanna River the estimated damages for the standard and levee methodologies were $5.35 and $5.11 per square foot, respectively.

Table 4 is a summary table comparing the residential parcel values and counts for damaged parcels in the flood risk areas of both Onondaga Creek and the Susquehanna River as determined by the HSR methodology and HAZUS flood model for the 1% annual chance flood event. The HSR methodology calculated significantly lower total and average values for damaged parcels and average flood damages per parcel when compared to the HAZUS flood model. There are two main reasons for differences. First, the HSR methodology used building assessed values for damaged parcels, while HAZUS used building replacement values in its calculations. Most of these properties are in low-income areas with low housing values. Thus, the assessed value is often far below the replacement cost were a new home to be built. Second, the HAZUS model aggregated over census blocks, leading to a presumably less accurate count of the number of impacted properties, with the number overestimated on Onondaga Creek and underestimated on the Susquehanna River.

Table 4. Summary table of damaged residential parcel values and counts in the flood risk areas for both Onondaga Creek and the Susquehanna River using both the HSR methodology and the HAZUS flood model for the 1% annual chance flood event.

	HSR Methodology			HAZUS RES1 Building Replacement Value	
	Onondaga Creek	**Susquehanna River (Standard)**	**Susquehanna River (Levee)**	**Onondaga Creek**	**Susquehanna River**
Total Value of Damaged Parcels	$22,246,680	$138,827,811	$99,492,412	$463,081,000	$823,146,000
Number of Damaged Parcels	583	4437	3013	926	788
Average Value of Damaged Parcels	$38,159	$31,289	$33,021	$500,087	$1,044,602
Estimated Flood Damages	$3,738,805	$42,755,012	$27,703,080	$38,044,000	$59,670,000
Average Flood Damages per Parcel	$6,413	$9,636	$9,195	$41,084	$75,723

The largest disadvantage of the HAZUS Flood model is the lack of accounting for uncertainty in the model results. As stated in the Hazus Flood Model User Guidance, the default input values into the model have a great deal of uncertainty so model results for losses should be interpreted with caution. Furthermore, the report states that HAZUS does not compute uncertainties in the loss estimates or provide ranges for possible losses or confidence intervals (FEMA 2018). The HSR method, on the other hand, gives the user a viable platform in which to calculate uncertainty in the hydrology and flood damage values to develop a range of possible flood loss estimations.

In order to validate the results of both model outputs, data from FEMA's Individual and Household Program was obtained and analyzed. According to the FEMA records, the total verified loan amounts paid by FEMA for individual assistance for the 2011 flooding in Broome

County, NY caused by the remnants of Tropical Storm Lee was approximately $53,144,535 (FEMA 2016). The FEMA records are in line with the Susquehanna River model outputs of both the HAZUS and HSR methods.

DEPTH-DAMAGE SENSITIVTY ANALYSIS

As stated earlier, FLRs generally tend to address only one of the four components that introduce uncertainty into any FLR. This study focuses on two components, the hydrological characteristics mostly representing flood depth and the risk elements, which are often estimated using land use and/or property data, but we do include a brief analysis of a third component: the vulnerability of risk elements to hydrological characteristics, usually represented by depth-damage curves. The HAZUS depth-damage curve for RES1 occupancy type buildings was modified to assess the sensitivity of flood damages from the HSR method in three scenarios: amplified damages resulting in a convex depth-damage curve; reduced damages resulting in a convex depth-damage curve; and only inundation levels above 0 feet under the assumption most flood prone basements have sump pumps or back-flow valves on water and sewer lines to prevent water infiltrating into basements. The modifications were arbitrary and subjective in nature to test the influence that depth-damage curves have over flood damage estimates in modeling. Figure 2 is a summary plot of the six occupancy types and their respective HAZUS RES1 depth-damage curves with modifications.

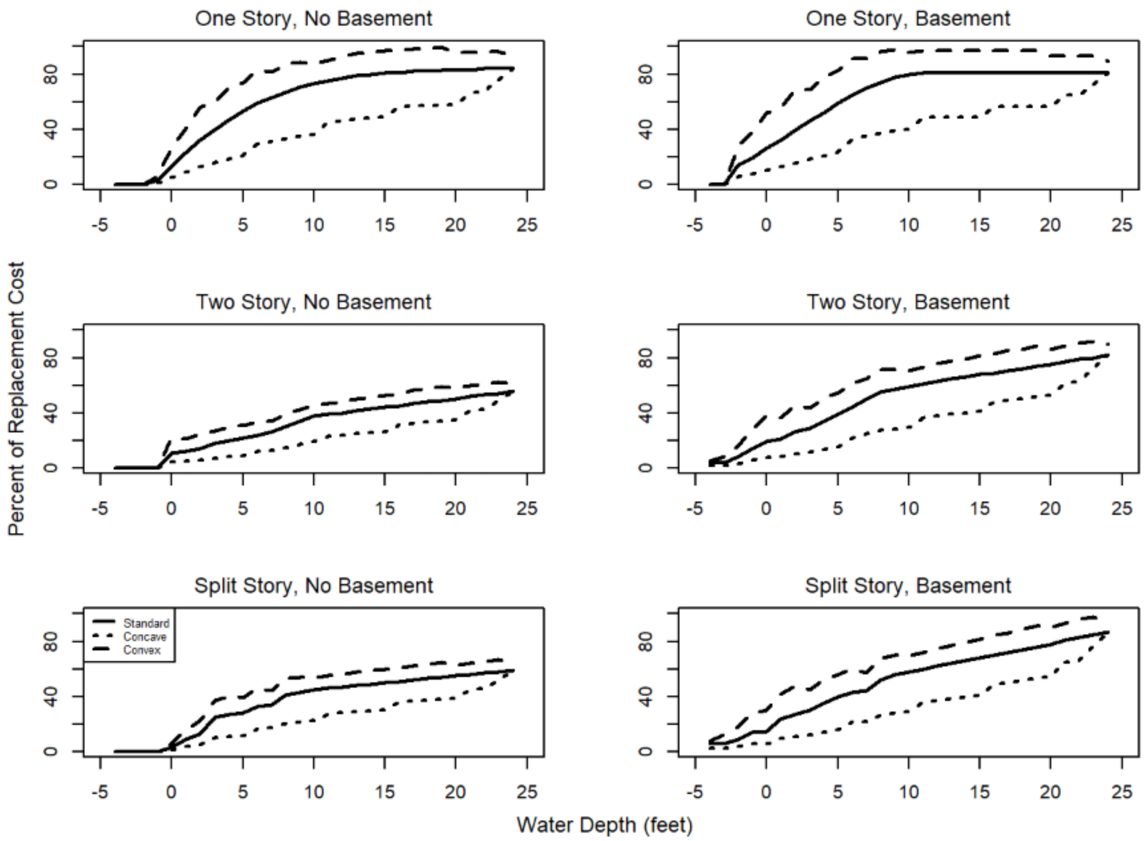


Figure 2. Plots of depth-damage sensitivity curves for each occupancy type based on the HAZUS depth-damage function.

Since the two story with basement occupancy type homes had the greatest impact on model outputs, the depth-damage curve analysis focused on this category. Table 4 is a summary table of flood damages for Onondaga Creek and the Susquehanna River using the standard and levee methodologies based on the three depth-damage curve sensitivity scenarios for 2 plus story with basement occupancy type homes at the 1% annual chance flood event. Based on the results of the table, it is clear the depth-damage curve has a significant influence on flood damage estimations from a flood model. The flood damage estimates for the concave curve had a percent change between -55 and -59%, while the convex curves percent change was between 49 and 74% for both study areas. The flood inundations above 0 feet was less significant with a percent change between -11 and -27%.

Table 5. Summary table for depth-damage sensitivity analysis for Onondaga Creek and the Susquehanna River using the standard and levee methodologies for 2 plus story with basement occupancy type homes at the 1% annual chance flood event.

	Onondaga Creek	**Susquehanna River (Standard)**	**Susquehanna River (Levee)**
HSR model output	$3,222,416	$30,850,279	$21,216,888
Concave Curve	$1,305,440	$13,753,776	$9,449,902
Percent Change from HSR model	-59%	-55%	-55%
Convex Curve	$5,594,268	$45,911,373	$32,269,911
Percent Change from HSR model	74%	49%	52%
Above Zero Inundation	$2,351,099	$27,423,038	$18,530,703
Percent Change from HSR model	-27%	-11%	-13%

FURTHER RESEARCH

Further research should focus on improving the repeatability of this project by developing a streamlined GIS methodology and model, which could include the damage calculations in GIS instead of an external programming software. This would allow future research to expand the scope and hydrologic systems being studied in order to grow the knowledge base of the subject matter. In addition, expanding the type of hydrologic systems, including systems in different climate zones or more natural versus anthropogenically altered systems, and type of flood events, coastal, urban, etc., would aid in the understanding surrounding uncertainty of flow and damages for different hydrologic systems.

Developing a standardized approach to assessing uncertainty in FLRs should be a priority for flood risk managers and policymakers since informed decision-making processes should include accurate uncertainty analyses. Understanding the sensitivity of flood damages to the hydrologic processes in a watershed is the crucial step in any FLR.

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CHAPTER 4: CONCLUSION

From this study, we derived the following main conclusions:

1. Flood damages are highly sensitive to streamflow, which strengthens our need to better understand future streamflow in order to more accurately predict future flood damages.
2. Onondaga Creek displayed strong sensitivity in the discharge-damage relationship.
3. The Susquehanna River displayed a very strong sensitivity in the discharge-damage relationship, which was amplified when levees were included in the analysis.
4. The uncertainty in future flows for Onondaga Creek correlate to uncertainty in future flood risk based on the climate change scenario analysis.
5. For the Susquehanna River, uncertainty in future flows still indicate an increase in future flood risk for the basin, but there is uncertainty in the severity based on the different climate change scenarios.

The disproportionate sensitivity of flood damages to uncertainty in hydrologic processes is an area of research that needs to be addressed due to future climate predictions of increased precipitation magnitudes and potential for floods. The amplification of flood damage sensitivity by hydrologic uncertainty was determined to be a factor of 3.0 to 3.6 in this study. Hydrologists and floodplain managers are aware of the large degree of uncertainty in hydrologic processes using current modeling techniques so future research should be focused on improving hydrologic predictions. This will, in turn, lead to better FLRs and damage estimates from future floods.

This study was performed with a view towards encouraging the inclusion of uncertainty analyses in flood modeling, but also promoting the use of LiDAR and GIS in FLRs and damage calculations to more accurately determine inundation levels. The highlighted pilot methodology for using LiDAR and GIS to determine first floor elevations used in flood damage estimates introduced a more spatially robust approach that is expected to become the new standard in flood risk management for all three types of floods: riverine, coastal, and urban. By using higher spatial resolution data and regionally downscaled atmospheric-hydrologic coupled climate models, FLRs and future flood risk can be more assessed with greater confidence than in the recent past.

Another area of concern surrounding floodplain management highlighted by this study is the spatial relationship of properties to the floodplain. The arrangement and structure of residential and commercial developments in a floodplain directly impact their associated flood risk. As flood inundation levels increase, the amount of assets at risk of damage within the floodplain generally increases. This relationship is highly dependent on topography. In this study, as inundation increased so too did the number of parcels that were damaged by flood waters.

Addressing uncertainty in models that predict flood risk can lead to a more efficient use of models and a more accurate interpretation of the results. As Moel and Aerts (2011) concluded in their research study on uncertainty in flood damage estimates, the flood model is the primary contributor to uncertainty and the quality of the depth-damage curve and values of elements at risk are of critical important in FLRs.

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SUMMARY OF QUALIFICATIONS

- Strong quantitative & analytical skills with interdisciplinary background in history, meteorology, hydrology, and environmental science.
- Extensive knowledge of hydraulic analysis techniques as well as interpretation of atmospheric and hydrologic data.
- Proficient in R programming language, Geographic Information Systems (GIS) software, HAZUS Flood software, and Microsoft Office Suite.
- Ability to identify problem complexities and review related information to develop and evaluate options and implement solutions.

RELATED EXPERIENCE

Teaching Assistant/Research Assistant **August 2017 – Present**
SUNY College of Environmental Science and Forestry, Syracuse, NY

- Performed academic tutoring of ESF 300 Introduction to GIS through laboratory exercises, recitations, and office hours and assist faculty member with exams and grading. Course topics include spatial and non-spatial queries, image processing, spatial analysis, cartographic modeling and site selection, and data acquisition and accuracy assessment.
- Partnered with Faculty Advisor Dr. Stephen Shaw to develop methodology to analyze uncertainty in flood frequency and damage.
- Attended the 2018 New York State Floodplain and Stormwater Managers Association (NYSFSMA) Annual Meeting in Rochester, NY.

Watercraft Inspection Steward Program Application (WISPA) Technical and GIS Support **May – August 2018**
New York State Department of Environmental Conservation/New York Natural Heritage Program, Albany, NY

- Managed and supported existing GIS applications and databases for WISPA 2.0 data collected used by over 100 colleagues from 16 different partner organizations using ESRI ArcGIS Online, ArcDesktop (ArcMap 10.5.1), and ArcCatalog 10.5.1.
- Represented the NYS DEC and NYNHP while implementing and leading WISPA trainings both in-person and online.
- Developed GIS products using ArcGIS Online and Model Builder in ArcDesktop while self-managing and working remotely.
- Created summary reports to be distributed to partner organizations using R programming language and computer scripts.
- Made recommendations for prospective intern skillsets, potential future research, and improvements for WISPA 3.0 data collection and products.

Independent Study Researcher **June – September 2015**
SUNY Brockport, Brockport, NY

- Collaborated with Dr. Mark Noll, researched stratospheric temperature trends using radiosonde data in response to climate change and tropospheric warming trends for various locations in the Northern Hemisphere.

Storm Forecasting and Observation Program - Project Staff Assistant **May – June 2015**
SUNY Oswego, Oswego, NY

- Assisted program director and students in weather briefings and forecast discussions for current and future weather outlooks.
- Launched radiosondes and deployed tornado pods to gather atmospheric data.

RECENT EMPLOYMENT HISTORY

Scientist I **May 2019 – Present**
O'Brien & Gere, Albany, NY

- Applied scientific techniques for data collection and data interpretation and operated and maintained field or lab data collection equipment.
- Developed and executed hydrologic and hydraulic models including researching appropriate modeling parameters for water quality and flood studies.
- Performed field work to assess hydrologic and hydraulic watershed characteristics.
- Assisted the design of Best Management Practices, Green Infrastructure, flood reduction projects, remediation programs, and water quality plans.
- Participated in public and agency meetings and wrote technical memorandum and reports.

EDUCATION

Master of Science, Environmental Science **Expected Spring 2019**
SUNY College of Environmental Science and Forestry, Syracuse, NY

Bachelor of Science, Meteorology **December 2015**
Bachelor of Science, Water Resources Management
SUNY Brockport, Brockport, NY

Bachelor of Arts, History **May 2009**
SUNY Geneseo, Geneseo, NY