

A Framework for Planning and Evaluating the Role of Urban Stream Restoration for Improving Transportation Resilience to Extreme Rainfall Events

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Received: 30 March 2020; Accepted: 3 June 2020; Published: 6 June 2020



Abstract: Recent extreme rainfall events produced severe flooding across North Carolina's Coastal Plain, revealing deep vulnerabilities in many communities. Climate change is expected to exacerbate these problems by further increasing rainfall intensity and the frequency of extreme rainfall events. Due to the risks posed by these changing rainfall patterns, a shift in the approach to infrastructure planning and management is needed for many floodprone communities, particularly in regard to managing streams and floodplains in urban areas. This study proposes a framework for systematically evaluating stream restoration in combination with engineered improvements to culvert and bridge crossings to identify and optimize options for mitigating extreme events in urban areas. To illustrate the methodology, extensive hydraulic modeling was conducted to test four different strategies for reducing flooding along a channelized and armored stream, Big Ditch, located in Goldsboro, North Carolina, USA. The results indicate that neither floodplain restoration nor infrastructure modification alone could alleviate flooding along Big Ditch. Rather, a combination approach would be required to mitigate flooding, which could result in substantial benefits for storms in excess of the 100-year event. The results suggest that shifting to a multi-faceted approach to improve resiliency to extreme events could improve public safety and reduce future damages due to flooding.

Keywords: stream restoration; flooding; climate change; extreme events; transportation resilience

1. Introduction

Hurricanes Matthew and Florence revealed deep vulnerabilities to flooding in North Carolina's Coastal Plain communities. Hundreds of roads were closed due to inundation or washouts and many communities were isolated by road closures. These events that overwhelm communities' transportation infrastructure pose serious challenges for emergency service responses and recovery efforts. The flooding of transportation infrastructure is a serious public safety issue as research indicates that more than three quarters of flood-related fatalities occur when people drive into or attempt to walk through floodwaters [1,2]. In addition to the spate of recent extreme rainfall events, the intensity of heavy rainfall is increasing in the southeastern U.S. [3]. This trend towards more intense rainfall and larger storms is expected to continue as a warmer atmosphere will hold more moisture [4]. More intense rainfall events will likely result in more frequent nuisance and flash flooding.

Like most urbanized areas, the infrastructure in small Coastal Plain communities in the southeastern U.S. lacks the capacity to handle more intense rain events. Many of these communities were developed decades or even centuries ago when the prevailing wisdom suggested that streams should be deepened,

straightened and armored [5,6]. In addition to questionable stream management, this approach did not account for or properly value the mitigating effects of riparian buffers or floodplains. As a result, development occurred within the historic floodplain. However, floodplain development is not isolated to small communities; nationwide, nearly one fifth of all urban land is located in the 100-year floodplain [6]. In addition to the loss of floodplain connectivity, stream crossing structures (i.e., culverts and bridges) were often sized based on rules of thumb with minimal engineering analyses [5]. Newer construction or upgrades to municipal roads are often designed for the 10- or 25-year return period event. The rainfall depth and the stream discharge value for these return periods are determined using historical data [7,8]. However, as the frequency of extreme events and more intense rainstorms increase, the historical data do not account for the higher risk to infrastructure moving forward [9], potentially resulting in more frequent flooding. In this changing climate, the assumption of stationary risks (i.e., 100-year event) that underpins the engineering design of infrastructure projects is no longer valid [10]. This translates to an increased probability of occurrence for current 100- or 500-year events in the future due to climate change.

Stream and floodplain restoration are sometimes used to mitigate flooding resulting from historical development practices [11–13]. There are many examples of stream restoration projects reducing localized flooding, both in the United States (e.g., [14,15]) and internationally [13]. However, often, only small sections of stream are targeted for restoration and a thorough upgrade of stream crossings is limited or absent, and a systematic evaluation of stream crossings is rarely conducted. To realize the full flood reduction and ecological benefits of stream restoration, a reachwide analysis that accounts for the stream channel, floodplain and stream crossing structures concurrently is needed. The overall goal of this paper is to propose a planning-level framework for evaluating the potential impacts of stream and floodplain restoration in urbanized catchments with a focus on increasing resilience to extreme events. This evaluation process is illustrated using a hydraulic modeling case study on Big Ditch, a floodprone urban stream in Goldsboro, North Carolina, USA.

2. Methods

2.1. Case Study Site

The Big Ditch drains an area of 8.0 square kilometers of the City of Goldsboro, NC to the Neuse River (Figure 1). The watershed is 93% developed, and 35% of the area is covered by impervious surfaces [16]. Long segments of the stream have been straightened and armored; many sections through the town are rectangular or trapezoidal concrete channels (see Figure 2). There is no functioning floodplain aside from a small section where a restoration project was completed. In addition, there are 20 road or railroad crossings of the stream within the city limits (Figure 1). Local officials have reported flash flooding along the stream, which has resulted in property damage and road closures. During extreme events, flooding along the stream can limit the movement of emergency services and resources, isolating some sections of the town.

2.2. Proposed Evaluation Approach

A hydraulic modeling approach was proposed to systematically evaluate the flood-reduction impacts of restoration. Several restoration and infrastructure modification scenarios were identified and modeled to evaluate the relative impact of floodplain restoration and crossing modifications on flooding. The results were evaluated by examining the decrease in water surface elevation (WSE) and spatial extent of flooding for a range of flood return periods. The proposed modeling framework and evaluation scenarios can be broadly applied to restoration planning and infrastructure improvement projects. The scenarios evaluated include:

1. Crossings Modified: All the stream crossing structures in the model were modified to a size that would eliminate any flow obstruction (i.e., culverts were replaced with elevated bridges spanning the channel). No changes were made to the channel geometry or floodplain extent. This scenario was intended to gauge the influence of undersized crossings on flooding.

2. **Floodplain Restoration Only:** Stream and floodplain restoration was applied to the entire reach of stream. No changes were made to the road crossings. This scenario was included to gauge the flood reduction that can be achieved by restoration alone.
3. **Restoration and Crossing Modified:** Floodplain restoration combined with increased hydraulic capacity of all crossings (i.e., the crossings were enlarged to eliminate flow obstructions). This scenario represents the maximum possible reduction in flooding and provides a benchmark to compare other scenarios against.
4. **Restoration for Resilience to Extreme Events:** Stream and floodplain restoration combined with strategic modifications of important, high-use crossings (i.e., culverts replaced with bridges spanning the floodplain) and the complete removal of less-used, higher-risk crossings. This scenario is designed as an approach to maintain transportation access during extreme events, reduce risk to the public, minimize future flood damage and reduce long-term maintenance costs.

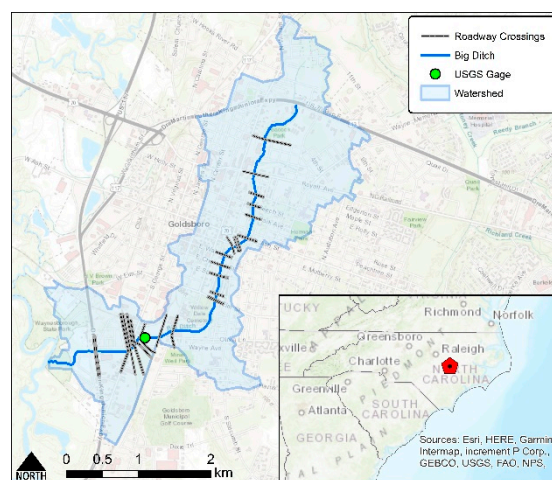


Figure 1. Big Ditch in Goldsboro, NC.



Figure 2. Big Ditch near US 117 (left) and at Walnut Street (right).

2.3. Case Study Hydraulic Model

A Hydrologic Engineering Center–River Analysis System (HEC-RAS) model for Big Ditch was developed by and obtained from the North Carolina Floodplain Mapping Program (NCFMP) [17]. The NCFMP uses these models to develop regulatory floodplain maps for North Carolina. HEC-RAS is a widely used hydraulic model developed by the US Army Corps of Engineers [18]. HEC-RAS has been used to evaluate restoration projects [19], forecast flooding [20], develop floodplain maps [21], design bridges and evaluate dam breaches, and for many other complex hydraulic modeling problems [18]. While HEC-RAS can be used for both one- and two-dimensional hydraulic modeling, a one-dimensional model was used for this analysis because of the availability of the existing model from the NCFMP and because the current version of HEC-RAS 2D (v. 5.0) lacks the ability to simulate bridges.

By contrast, HEC-RAS 1D has routines for simulating the hydraulics of bridges and culverts [22]. For one-dimensional steady-flow models, HEC-RAS simulates the water surface profile by iteratively solving the one-dimensional energy equation (Equation (1)) using the standard step method with a given upstream discharge and downstream water surface boundary condition [22].

$$Z_2 + Y_2 + \alpha_2 V_2^2 / 2g = Z_1 + Y_1 + \alpha_1 V_1^2 / 2g + h_e \quad (1)$$

where Z_1 and Z_2 are the elevation of the channel at adjacent cross sections, Y_1 and Y_2 are the water depths, V_1 and V_2 are the average velocities, α_1 and α_2 are the velocity weighting coefficients, g is the gravitational acceleration constant, and h_e is the energy head loss, which is a function of the friction losses and contraction or expansion losses. Conveyance for each cross section subdivision is calculated using a form of Manning's equation (see Equations (2) and (3)).

$$K = 1/n \times AR^{2/3} \quad (2)$$

$$Q = K \times S_f^{1/2} \quad (3)$$

where K is the conveyance, n is Manning's roughness, A is the flow area, R is the hydraulic radius, Q is the discharge and S_f is the slope of the energy grade line [22].

In the existing HEC-RAS model, the elevations for the overbank areas were based on a 150 cm spatial resolution, 9.25 cm vertical root mean square error (RMSE) DEM (digital elevation model) derived from North Carolina's LiDAR (light detection and ranging) elevation data [23], while the channel cross sections and hydraulic structure elevations were based on detailed survey data. Model cross sections were located upstream of crossings, at slope and channel geometry changes and at other obstructions (i.e., buildings). Flow obstructions were included to represent building structures, and ineffective flow areas were used to represent areas that do not contribute to conveyance [22]. The Manning's n values were based on the land cover and channel material [24]. The parameters for the existing HEC-RAS model are presented in Table 1.

Table 1. Existing Hydrologic Engineering Center-River Analysis System (HEC-RAS) model parameters.

Parameter	Description
Stream length in study area	4.5 km
Model cross sections in study area	67
Bridges and culverts in study area	19
Channel area	7.5–26 m ²
Manning roughness	0.013–0.05 (channel) 0.058–0.12 (overbanks)
Average channel slope	0.0017 m/m
Downstream boundary condition	Constant water surface elevation (20.1 m)—threshold for major flooding on the downstream Neuse River
Overbank elevation source	LiDAR DEM—150 cm spatial resolution, 9.25 cm vertical RMSE
Channel cross section elevation source	Detailed bathymetric cross section survey

Discharges for a range of return periods were calculated using US Geological Survey (USGS) streamflow data. The USGS operated a gaging station (USGS #02088682) on the Big Ditch at Retha St. from 1951 to 1984. Annual peak discharges from this 34-year period were used to develop discharge values at the gage for a range of return periods using methods outlined in USGS Bulletin #17B [25]. For other stations along the stream, discharge values were computed by multiplying the discharge calculated using USGS regional regression equations (based on drainage area) by the ratio of the

discharge calculated using USGS Bulletin #17B to the USGS regression flow at the gaging station location. Final discharge values were then increased by 16.5% to account for the increased frequency of extreme events since 1980 [26]. The modeled discharges at flow change locations along the stream are presented in Table 2.

Table 2. Calculated discharge values for return period and flow change location.

Return Period	River Station (m) Drainage Area (km ²)	Model Discharge (cms)				
		4500 2.8	4200 3.3	3600 4.0	2560 5.2	1200 * 6.5
10-year	_____	17.6	20.5	22.4	26.9	30.1
100-year	_____	30.9	34.9	38.8	46.1	51.8
500-year	_____	41.7	46.4	52.1	61.6	69.3

* US Geological Survey (USGS) stream gage location.

2.4. Model Calibration

The HEC-RAS model was calibrated by adjusting the Manning's roughness coefficients for the main channel to minimize the difference between the simulated rating curve and the most recent observed rating curve at the USGS gage location. The roughness was adjusted uniformly along the channel based on the adjustments at the USGS gage. The goodness of fit was evaluated using the Nash–Sutcliffe efficiency and percent bias between the simulated and observed rating curves. Only minor adjustment of the Manning's roughness (increased by 5%) was required to achieve excellent goodness of fit (see Figure 3). However, there is considerable uncertainty associated with the calibration. First, there is only one calibration station (at the USGS gage). In addition, the rating curve was developed over a short period (1982–1984) several decades ago. As a result, the rating curve is limited to the lower range of observed discharge values. The gage datum elevation was not available; however, because the channel is concrete-lined at the measurement location, the channel bottom was used as a common datum for comparing the modeled discharges to the observational rating curve.

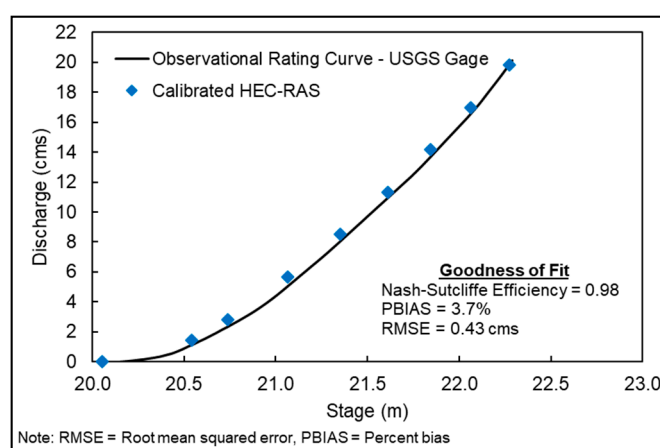


Figure 3. Observed rating curve and calibrated HEC-RAS model results at stream gage location.

2.5. Stream and Floodplain Restoration

A Priority 2 restoration approach was assumed for the modeling evaluation [27]. The channel cross section was sized according to the watershed size by using the bankfull area regional curve for the Coastal Plain [28]. The channel bankfull cross sectional area ranged from 1.9 to 2.6 m². An entrenchment ratio (width of the floodplain to the width of the channel) of 6 was used to size the floodplain for all reaches. An entrenchment ratio of 6 allows for adequate meandering based on reference streams and is considered moderate for low gradient streams in the Southeast [29,30]. An entrenchment ratio

of 6 also maximized the use of properties directly adjacent to the channel and limited impacts on existing utilities. The entrenchment ratio is generally a project-specific parameter that depends on the available land parcels and target stream type. The resulting floodplain width ranged from 22 to 34 m along the stream. The channel bed of the proposed restoration followed the elevation of the existing stream bed. In the HEC-RAS model, a Manning's roughness value of 0.1 was used for the floodplain, and a value of 0.04 was used for the restored channel [24]. While Manning's roughness will vary along the floodplain as the vegetation matures, 0.1, which corresponds to "medium to dense brush, in summer", was used as a conservative value [24]. Figure 4 shows a typical cross section of the proposed floodplain restoration. The floodplain restoration width was assumed to be uniform along the length of the stream and was not modified to accommodate existing infrastructure for the analysis. AutoCAD Civil 3D [31] was used to develop a surface for the restored channel and floodplain, which was imported to HEC-RAS, and the cross sections were updated accordingly.

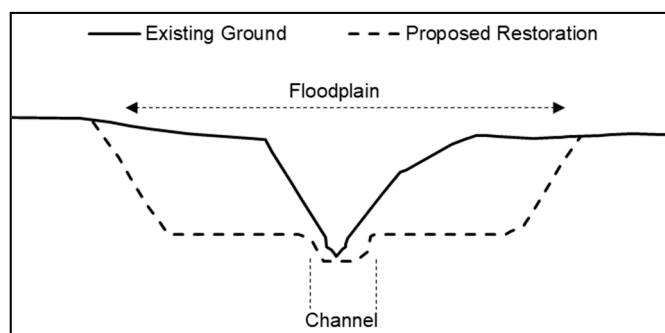


Figure 4. Typical cross section modification for floodplain restoration.

3. Results

3.1. Crossings Modified

The first step of the analyses evaluates the extent to which the road crossings contribute to flooding. This scenario represents a traditional civil engineering approach of addressing the hydraulic capacity of the stream crossing to reduce flooding. The water surface profile for the 100-year event resulting from increasing the hydraulic capacity of all 19 road crossings is shown in Figure 5. The stream crossing structures at the most upstream and downstream extents of the model appear to cause backwater effects (i.e., the water surface was substantially lower when the crossings were removed from the model). By contrast, there was very little impact from the road crossing structures throughout the most developed area of the city (i.e., the water surface did not drop substantially when the crossings were removed from the model from river stations 1000 to 4000 m). However, for the 100-year event, the overtopping of five road crossings could potentially be prevented with these modifications.

For the 10-year event (see Figure 6), the crossings appear to have some effect throughout the most developed area of the city; removing the crossings results in a 0.3 to 0.6 m decrease in WSE compared to the existing condition. The overtopping of ten roads could be prevented for the 10-year event if all the crossings were altered. This indicates that modifying the crossings to eliminate any flow obstructions could result in some benefit for low return period events; however, the limited benefits would likely not justify the costs.

The minimal change in peak WSE for the 100-year event along most of the stream indicated that the road crossing structures are not the only cause of flooding along the stream. For much of the stream length, the channel does not have the hydraulic capacity to convey the flow of the smallest modeled discharge, the 10-year event (i.e., water level above the banks even with the crossings removed). These results indicate that the flooding problems along the Big Ditch cannot be resolved by modification of the road crossings alone.

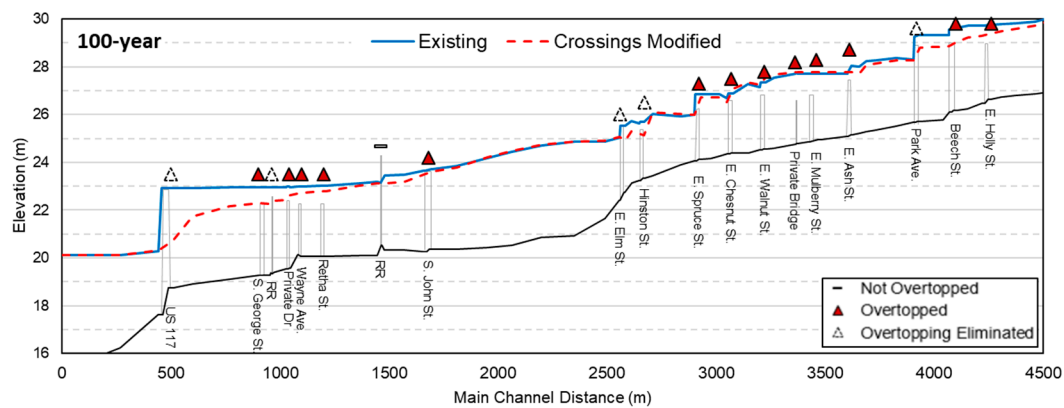


Figure 5. Water surface profiles for the Existing Condition and the Crossings Modified scenario for the 100-year event.

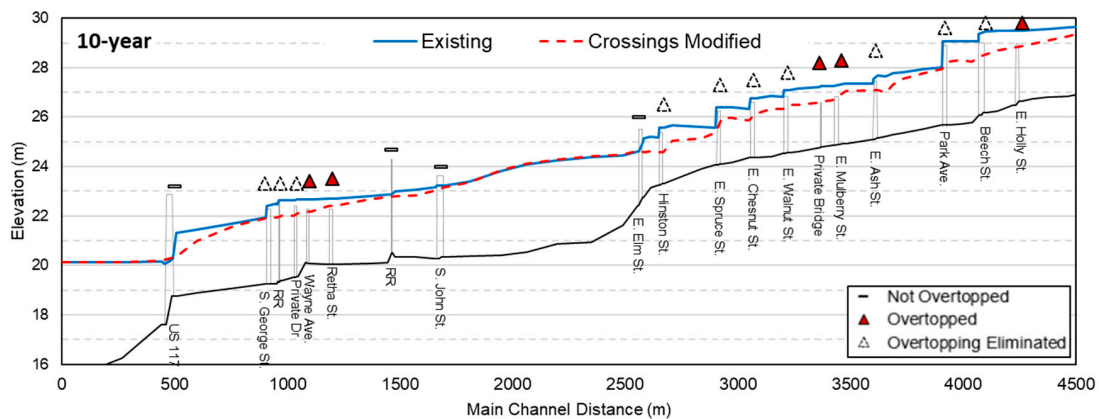


Figure 6. Water surface profiles for the Existing Condition and the Crossings Modified scenario for the 10-year event.

3.2. Floodplain Restoration Only

The next step of the evaluation process was to determine if stream and floodplain restoration alone could alleviate flooding. The resulting HEC-RAS water surface profile for the 100-year event is shown in Figure 7. With the exception of the reach between station 1700 and 2500 m, where there were no structures and a relatively steep channel slope, there was very little change in WSE along a majority of the stream. These results illustrate floodplain restoration alone would have minimal impact on reducing flooding along the Big Ditch for the 100-year event (18/19 crossings overtopped for Existing Condition and 17/19 crossings with Floodplain Restoration). Even for the 10-year event, there would be minimal change in WSE (15/19 crossings overtopped for Existing Condition and 14 crossings overtopped if floodplain restoration was implemented) (see Figure 8). These results suggest that the road crossing structures are a major contributor to flooding, even for low return period events. As a result, flooding problems along the Big Ditch cannot be resolved by modifying road crossings or floodplain restoration alone. Rather, a combination of floodplain restoration and roadway crossing improvements is needed to alleviate flooding.

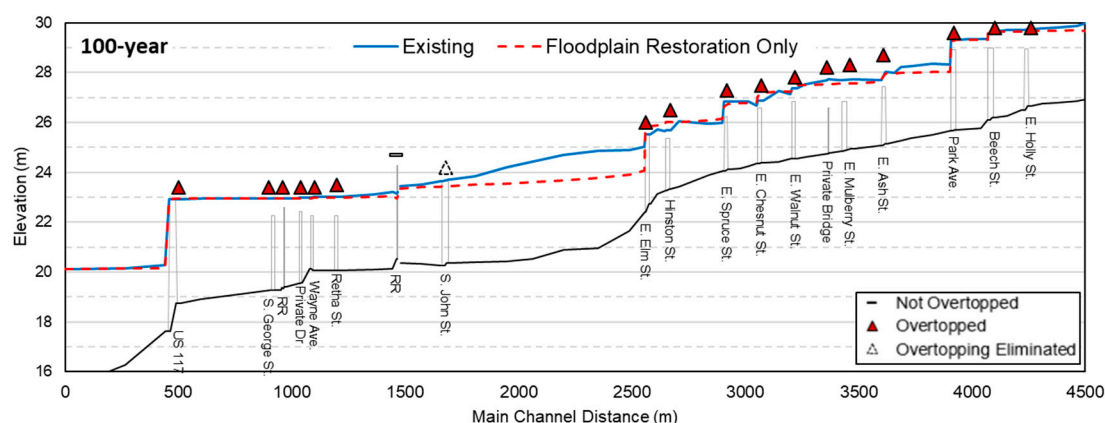


Figure 7. Water surface profiles for the Existing Condition and the Restoration Only scenario for the 100-year event.

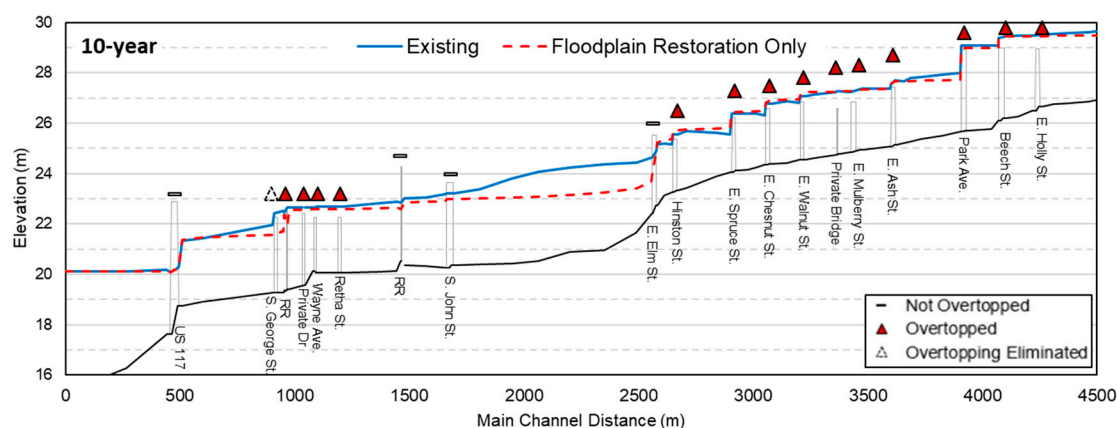


Figure 8. Water surface profiles for the Existing Condition and the Restoration Only scenario for the 10-year event.

3.3. Restoration and Crossings Modified

The next step of the proposed evaluation process was to assess the maximum potential reduction in flooding that could be achieved through restoration and infrastructure modifications. This step helps determine if the target stream is a good candidate for restoration to reduce flooding and establishes a benchmark for comparing other scenarios. This scenario combines stream and floodplain restoration with the increased hydraulic capacity of all the crossings along the stream. The HEC-RAS simulated water surface profiles are shown in Figure 9. For the 100-year event, the maximum potential reduction in peak WSE ranged from 1 to 1.5 m compared to the existing condition along Big Ditch. For the 100-year event, the WSE could be decreased to a level that would only overtop 2/19 stream crossings. For events in excess of the 100-year, overtopping could not be prevented for some of the crossings, even under the most intensive restoration/modification scenario. The results of these analyses indicate that there is potential for flood reduction benefits, and further analysis is warranted.

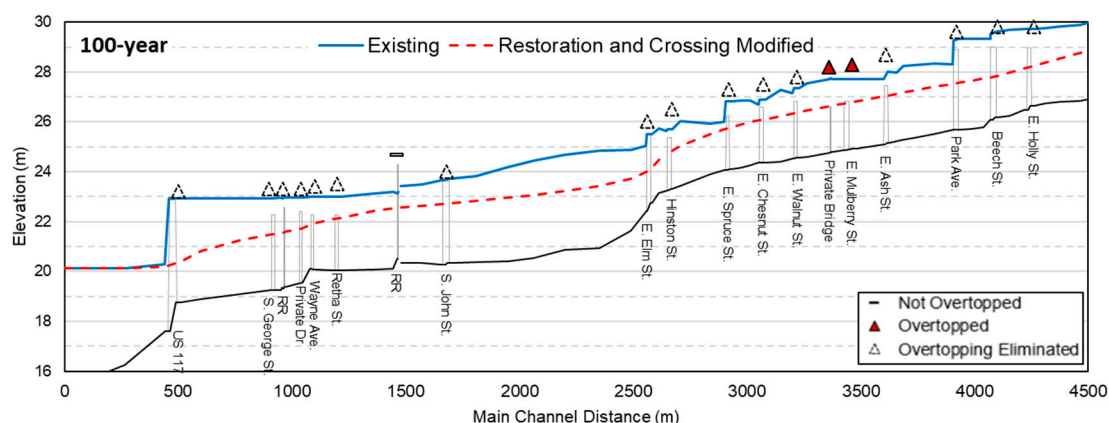


Figure 9. Water surface profiles for the Existing Condition and the Restoration and Crossing Modified scenario for the 100-year event.

3.4. Restoration for Resilience to Extreme Events

To have a meaningful impact on flooding along Big Ditch, most of the crossings would need to be modified in combination with stream and floodplain restoration. However, upgrading all the crossings would be prohibitively expensive in terms of initial capital investment and ongoing maintenance. However, retaining the existing condition does not seem viable given that repeated flooding presents a public safety hazard, restricts and slows emergency response efforts, and results in recurring damage to buildings and other infrastructure. With increasing rainfall intensity and the frequency of extreme events, a shift to a more comprehensive and strategic approach to infrastructure planning and management is needed; simply increasing capacity is an inadequate solution.

The Restoration for Resilience to Extreme Events scenario proposes an alternative approach to redeveloping these areas with a focus on adapting to climate change. The objectives of this scenario were to alleviate flooding as much as possible, provide continuous transportation access during extreme events and limit long-term infrastructure maintenance and damage costs. To achieve this, floodplain restoration was combined with modification of selected high-use road crossings by spanning the floodplain with a bridge to increase hydraulic capacity. All less-used, redundant road crossings were eliminated. To select and optimize which culverts and bridges to enlarge or completely remove, several criteria should be considered, including the road level of service, estimated replacement cost, structural condition, modeled road crossing overtopping frequency (e.g., 10-year, 25-year, etc.), proximity to alternate routes and critical transportation importance (proximity to and use for emergency service response). For this project, the eliminated crossings are all located on secondary roads that primarily provide access to medium-density residential neighborhoods. The transportation system is a grid network, and the removed crossings are located at a maximum of 500 m from an adjacent crossing alternative. This scenario might increase travel time in some areas but also would provide critical access during extreme events and prevent flooding caused by backwater conditions upstream of the road crossings.

The resulting WSE profile for this scenario is shown in Figure 10. The peak WSE was decreased by about 1 to 1.5 m compared to the existing condition along most of the stream, and flooding was substantially reduced, with none of the remaining crossings overtopped for the 100-year event. In fact, this scenario resulted in a similar reduction in WSE as removing all the crossings from the model. This scenario also prevents overtopping for six of the seven remaining crossings for the 500-year event (see Figure 11).

The reduction in WSE resulting from the floodplain restoration and modification of the road crossings would substantially reduce the areal extent of flooding and generally confine the overbank flow to the restored floodplain area for the 100-year event (see Figure 12).

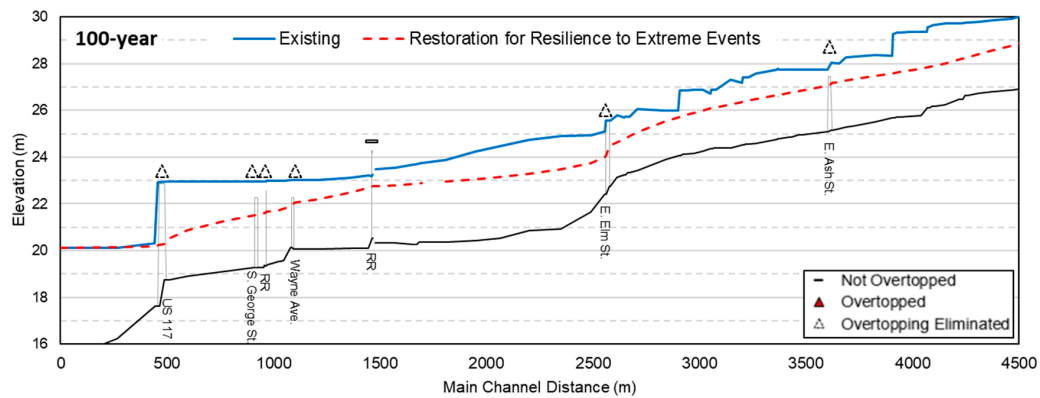


Figure 10. Water surface profiles for the Existing Condition and the Restoration for Resilience to Extreme Events scenario for the 100-year event.

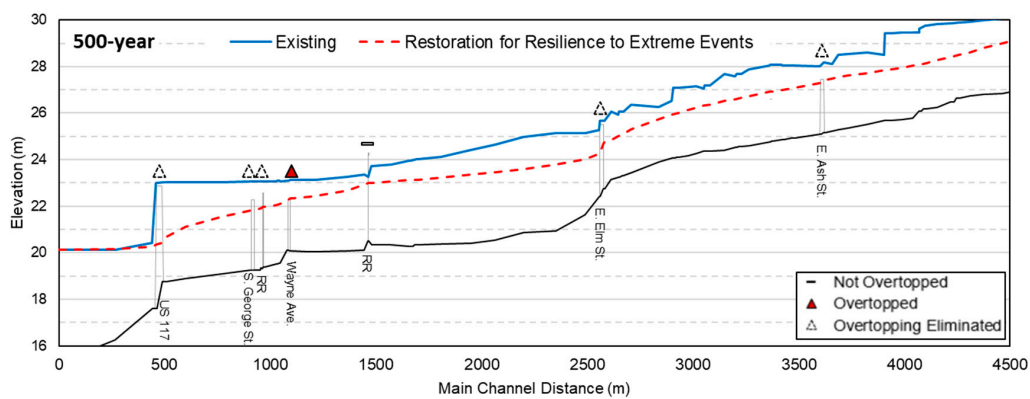


Figure 11. Water surface profiles for the Existing Condition and the Restoration for Resilience to Extreme Events scenario for the 500-year event.

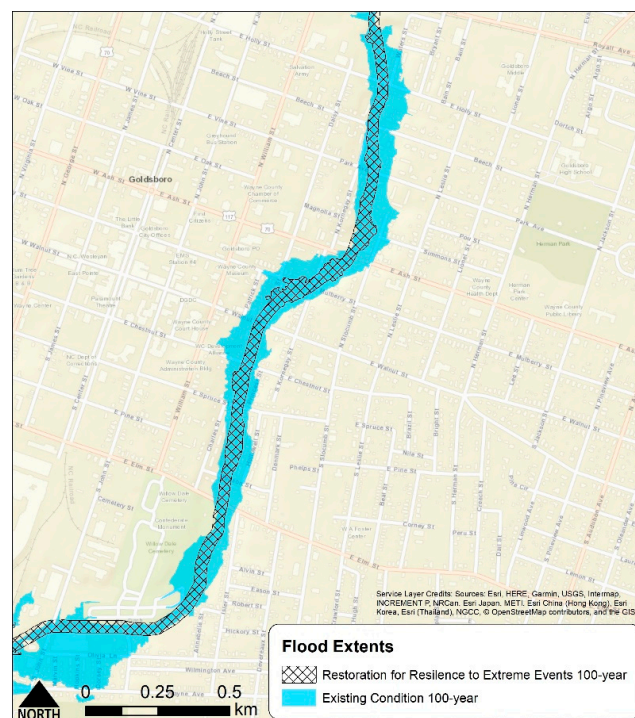


Figure 12. Flood inundation extents for the Existing Condition and the Restoration for Resilience to Extreme Events scenario for the 100-year event in downtown Goldsboro, NC.

4. Discussion

Wilby and Keenan [32] identify three broad measures for managing flood risk: (1) defending against floods with traditional infrastructure, (2) accommodating and living with floods and (3) withdrawing from floodprone areas. The methodology detailed herein combines the three approaches by modifying critical infrastructure, adapting to flooding by recognizing some reduction in transportation efficiency and identifying areas for floodplain recovery. However, the approach described herein has the potential to go beyond simply withdrawing from the floodplain. Rather, this study evaluates a more comprehensive stream restoration approach of converting a highly engineered and armored stream channel into a well-vegetated and properly sized channel with an adjacent floodplain that could provide ecological benefits such as enhanced habitats, potential water quality improvement and sediment capture [13,33] in addition to flood mitigation. Furthermore, the addition of stream restoration to the flood mitigation strategy can facilitate opportunities for incorporating community greenspace and trails [34]. This planning-level analysis and modeling effort were conducted to estimate the relative drivers of flooding and to determine the maximum possible flood reduction during extreme events that can be achieved through stream restoration. Additional detailed design analyses to optimize the size of each crossing and floodplain width are necessary in order to reveal the lowest-risk, most cost-effective design. Figure 13 summarizes the proposed planning-level framework for evaluating the potential for stream restoration projects to provide flood reduction benefits during extreme events.

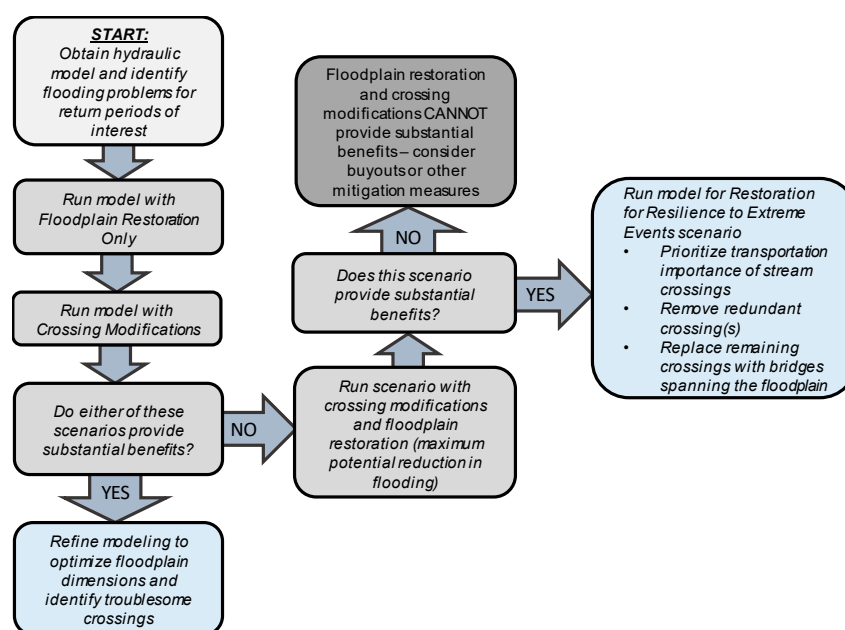


Figure 13. Flow diagram illustrating the proposed planning framework for evaluating stream restoration projects for the potential to provide resilience to extreme events.

The results of this study indicate that a multifaceted mitigation approach is necessary to address the complex problem of flooding facing Coastal Plain communities. In many locations, mitigation approaches that incorporate stream restoration with modifications to traditional infrastructure will be required to effectively mitigate flooding impacts. In Goldsboro, this combined approach could alleviate flooding along most of the Big Ditch, even for the 100-year and greater events. This modeling effort addressed tributary flooding only; flooding along the lower third of Big Ditch cannot be avoided when there is backwater from the Neuse River. Therefore, removing structures and people from floodprone areas in this section of the stream is the most feasible solution. Previous research also indicated that using a system-scale approach can provide substantial benefits, even for the 100-year storm [35].

In areas with extensive development in the floodplain, stream and floodplain restoration of any magnitude would require land acquisition and/or the securing of easements, the relocation or demolition of some structures, and the relocation of underground and overhead utilities. Constraints imposed by property boundaries, infrastructure and high construction costs are major factors that tend to limit the impact of urban stream restoration projects [6]. While this proposed approach may appear excessive and costly, significant future infrastructure improvements and associated investments will be necessary to adapt to more intense rainfall and more frequent extreme events [36], and the opportunity costs associated with this type of project will become less prohibitive as climate change progresses.

Despite the increasingly grave implications of climate change's impacts on transportation infrastructure, recent research indicates that most transportation planning agencies have not undertaken substantial efforts to implement adaptation actions to increase network resilience [37,38]. There are some efforts focused on upgrading infrastructure during routine maintenance activities, adjusting design standards, and developing factors of safety for current design levels [9]. However, many areas are falling short considering the scale of adaptation that will be required. In the most vulnerable areas, shifting the focus from efficient transportation routes to resilient transportation routes that are designed for extreme events will be essential to facilitate critical emergency responses and ensure public safety.

5. Conclusions

The results from this case study showed that floodplain restoration in combination with modifications to stream crossings and adjacent infrastructure can provide substantial flood reduction benefits. In addition to mitigating flooding, a comprehensive approach that includes stream restoration could offset costs by also improving ecological functional benefits and increasing opportunities for developing community assets such as trails and greenspace. The benefits of stream restoration efforts for flood mitigation are likely highly variable across stream reaches and landscapes. For example, benefits may be limited in lower gradient areas or where flooding is compounded by backwater from downstream rivers. For some locations, reducing flood risk and improving resilience might be best addressed by moving structures out of floodprone areas through buyouts and raising the elevation of select road crossings to provide access during extreme events. However, floodplain restoration in these areas may still provide benefits such as decreased nuisance flooding, water quality improvement, habitat enhancement and opportunities for community green space [33,34]. While engineering and policy actions can reduce the flood hazard, the elimination of risks is not achievable for many Coastal Plain communities. Living in low-lying areas will increasingly mean learning to accept some level of damage associated with flooding [32].

Author Contributions: For conceptualization, B.A.D., J.J.K.-F. and D.E.L.; methodology, B.A.D. and J.J.K.-F.; formal analysis, J.J.K.-F.; visualization, J.J.K.-F.; writing—original draft preparation, J.J.K.-F. and B.A.D.; writing—review and editing, B.A.D., J.J.K.-F. and D.E.L.; supervision, project administration and funding acquisition, B.A.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Environmental Defense Fund. Any opinions, findings and conclusions or recommendations expressed in this document are those of the author(s) and do not necessarily reflect the views of the Environmental Defense Fund.

Acknowledgments: The authors acknowledge the North Carolina Floodplain Mapping Program for the use of their HEC-RAS model and the USGS South Atlantic Water Science Center for providing historical rating curves for the study site.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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