Flooding outside the floodplains: Evaluating pluvial flooding in the Ellerbe Creek Watershed

by

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Executive Summary

Historically, flood-related policies and programs have focused on riverine and coastal flooding. In recent decades, rapid urban growth and increased frequency and intensity of storms due to climate change have heightened the prevalence and severity of a different type of flooding—pluvial flooding. Pluvial flooding occurs when the rainfall rate exceeds the capacity of the ground to absorb water and/or storm water drains to uptake water (Houston et al., 2011). This process is exacerbated in urban landscapes where impervious surfaces preclude the drainage of rainfall and the drainage infrastructure lacks the capacity to convey the excess water.

The damages incurred from pluvial flooding are significant. In 2007, England experienced pluvial flooding events that cost the economy £3.2bn (“England Floods,” 2007). For these reasons, federal and local governments must begin to address the knowledge gap and lack of planning tools related to pluvial flooding, and ultimately incorporate pluvial flooding into their larger flood management policies and programs.

This project aims to highlight the value of evaluating pluvial flooding by providing the first pluvial flood model for the Ellerbe Creek Watershed. Our client for this project is the Ellerbe Creek Watershed Association (ECWA). ECWA is a Durham-based nonprofit organization whose mission is to protect and restore Ellerbe Creek to safeguard its valuable ecological services and social benefits to the surrounding community. This project was developed to complement ECWA’s ongoing watershed protection projects that safeguard green space in areas that can reduce flooding and property damage and that implement green infrastructure to treat stormwater runoff. Specifically, this project has two main objectives:
**Objective 1:** *Evaluate and run models for pluvial flooding in the Ellerbe Creek Watershed.*

We researched existing pluvial flooding models to evaluate the capacity of and tradeoffs between current software. We found that several models existed, but they were developed by private engineering firms and not yet integrated into city management. Many of these models came from Europe, where pluvial flooding has been more greatly studied over the past decade. We used the Stormwater Management Model (SWMM) by US EPA to identify flood prone subcatchments in the Ellerbe Creek Watershed because it was freely available. A map of flooding complaints from Durham’s GIS & Stormwater Services was used to generally validate the model.

**Objective 2:** *Build a Strategic Planning Tool to integrate pluvial flooding into existing ECWA watershed protection strategies.*

While pluvial flooding is an important factor to consider in watershed protection, it is not yet widely-recognized and most of ECWA’s plans and funding sources are based on other strategies. In order to integrate our pluvial flood map with existing ECWA plans, we created a GIS-based web app that overlays multiple strategies and allows the user to adjust their weightings to prioritize parcels for acquisition or stormwater best management practices (BMPs). The parameters were selected through conversations with ECWA, and include the pluvial flood map, Upper Neuse Clean Water Initiative (UNCWI) Conservation Strategy, Small Scale Residential Stormwater Control Retrofits from the City of Durham, ECWA’s green infrastructure map, and ECWA’s Restoration Strategy. As a subcomponent of this tool, the weights for the four parameters underlying UNCWI scores can be adjusted and the breakdown of scores explored for each parcel.

In conclusion, this project is an exploration of existing possibilities for pluvial flood modeling and the use of pluvial flooding as a parameter in watershed protection planning. As with all types of flooding, pluvial flooding should be studied and planned for in relation to its interaction with other types of flooding. This project will hopefully serve as a stepping stone for future work on understanding and incorporating pluvial flooding into larger flood management policies and programs.
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Introduction

Pluvial Flooding

The important distinction between pluvial flooding and commonly held notions of flooding is that floodwater does not come from an overflowing watercourse. Instead, it occurs when heavy rainfall overwhelms an urban area’s drainage infrastructure and the excess water is not absorbed by the system (Stott, 2011). Pluvial flooding is usually associated with short duration and high intensity rainfall, but can occur under less intense conditions depending on the area’s topography, water infrastructure capacity, ground permeability, and antecedent soil conditions (Falconer, n.d.). This process can occur naturally, but is common in cities because of the high percentage of land covered by impervious surfaces, which inhibit rainfall from infiltrating into the ground.

Pluvial flooding can be incredibly hazardous to people’s lives and property. In 2007, the UK experienced pluvial flooding events that damaged 55,000 properties, necessitated the rescue of around 7,000 people, and caused the death of 13 people (Falconer, n.d.). These types of events are likely to become more frequent and extreme. It is estimated that the global population could grow by more than 3 billion in the next 30 years. Based on current trends, most of this growth will occur in urban settings, further exacerbating issues of impervious surfaces and under-capacity drainage systems (O’neill et al., 2010). Additionally, patterns and intensities of precipitation are expected to alter under climate change (McCabe et al. 2001). The EU White Paper on Adapting to Climate Change states that annual precipitation could increase more than 40% in some parts of northern Europe by 2100, which is expected to at least double damages caused by flooding (Falconer, n.d.).
The policies, knowledge, and tools related to pluvial flooding are significantly less than those surrounding riverine and coastal flooding in the United States. This is largely due to a history of development around waterways, which provide a means for irrigation, transportation, water, power, and waste disposal. Since the 1800s, the U.S. has encouraged development in coastal towns and riverine floodplains through federal policies to finance and implement “internal improvements” to the landscape such as roads, canals and levees (Arnold, 1988). Inevitably, these areas would flood and incite new flood regulations and interventions, building the current repertoire of flood management policies and understanding.

Flood management began moving away from purely structural interventions to land use management and zoning in the 1930s (White, 1945). At first, many local governments were reluctant to enact land use management practices without reliable flood maps (Murphy, 1958). Therefore, the various arms of the federal government involved in flood management, such as USGS, SCS, and eventually Federal Emergency Management Agency (FEMA), began to work with communities to produce flood maps and flood risk reports. The 1965 establishment of the Bureau of the Budget Task Force on Federal Control Policy took these developing thoughts and methodologies and formalized them in the federal system. The Task Force also catalyzed the creation of the National Flood Insurance Program (NFIP) in 1968, which provides federally-backed flood insurance to communities who implement flood loss reduction measures (Wright, 2000). In general, the use of riverine floodplain maps to regulate land use and flood insurance discounts to incentivize flood plan implementation has remained the model for flood management in the U.S. Absent from these maps, incentive programs, and city plans are other types of surface water or groundwater flooding, such as pluvial flooding.
Adding to pluvial flooding’s absence from government policies and programs are the many technological challenges associated with modeling pluvial flooding. Models must take into account both surface flow of water and flow into and out of the underground piping network. Additionally, in order for the results of pluvial flood models to provide flood control recommendations at the appropriate street-scale, cities must have fine-scale data to accurately base models on (Ochoa-Rodriguez, 2013). Without this dimensionality and level of detail, models cannot realistically capture the complexity of pluvial flooding—the overland flow of water into and from sewers, the preferential paths of water along streets, and surface ponding across the urban catchment (Boonya-Aroonet et al., 2007). A recent assessment of the technical feasibility of providing some form of warning system for pluvial flooding determined that the resources did exist (Falconer, 2009). However, without federal financial and technical support, the costs of modeling pluvial flood may be too great for cities to cover.

This imbalanced state of riverine and coastal focus over other flooding types does not appropriately reflect today’s built environment, which has elevated the threat of pluvial flooding. In England, an estimated 3.8 million properties, or 10% of all properties, are believed to be at risk from pluvial flooding. This is compared to 2.4 million properties at risk from riverine and coastal flooding (Environment Agency, 2009). In the U.S., 25% of all national flood insurance claims come from people outside of mapped high risk flood zones, which accounts for one-third of Federal Disaster Assistance for flooding (“Low-Risk Flood Zones”, n.d.)

The European Water Association (EWA) has recognized this disparity and the growing risk of pluvial floods. In 2009, the EWA called together participants from seven European Union member states and various research organizations for an Expert Meeting on Pluvial Flooding
(“Understanding Pluvial Flooding,” n.d.). The meeting initiated programs on assessing the extent of pluvial flood risk, approaches to mapping and risk assessment, potential mitigation measures, and areas of future research (Falconer, n.d.). Additionally, the UK Department for Environment, Food, and Rural Affairs (Defra) has brought together government and stakeholder organizations to collaborate on a new flood and coastal erosion strategy for England and Wales called Make Space for Water (MSfW, Derf, 2005 from Falconer, 2009). The strategy highlights the need to expand flood warning to cover sources of flooding other than rivers and seas, and to build technical expertise in these areas (Falconer, 2009). The U.S. has not yet organized similar pluvial flood research and initiatives.

_Ellerbe Creek Watershed_

Ellerbe Creek is a tributary of the Neuse River, flowing for more than twenty miles from northeast Durham to its confluence with Falls Lake Reservoir (see Figure 1). The 37-square mile watershed is predominantly urban, draining nearly half of the city of Durham (Ellerbe Creek Green Infrastructure Partnership, 2014). In 2013, more than 22% of the Ellerbe Creek Watershed was covered with impervious surfaces. This is projected to increase to 27.5% by 2025 (“Watershed Plan - Executive Summary”, n.d.). The removal of space for natural infiltration has been shown to drastically alter the natural hydrologic regime and threaten drinking water quality in Falls Lake (NCDENR, 2013). In 2010, the Ellerbe Creek was classified as “impaired” by the North Carolina Water Quality Division due to measurements of heightened levels of nutrients, suspended sediment, heavy metals, oil, and biochemical oxygen demand. The Division noted that the likely cause of this contamination was urban stormwater (NC Water Quality Division, 2010).
The Ellerbe Creek watershed is part of the upper Neuse River Basin in Durham County. Similar trends in high development and issues with managing water quality and quantity can be found in the Neuse River Basin. The basin contains around one-sixth of the entire state’s population. This population is expected to grow from 1.3 million in 2000 to 3 million people by 2020 (Neuse River Basin, n.d.). This rapid population growth and the land use changes associated with this development can stress these precious freshwater communities and impair ecosystem function. The basin has been designated as a priority watershed by the EPA and one of the most threatened river systems in the country by American Rivers (Baker, 2012).

Figure 1. Ellerbe Creek and its watershed, the extent of this project.
Ellerbe Creek is under the purview of several water management plans because of its state of impairment, connection to a large water supply reservoir, and potential to engage communities in recreational and educational opportunities. These plans include the Neuse River Basinwide Water Quality Plan (1993), Neuse Nutrient Strategy (1997), Upper Neuse River Basin Watershed Management Plan (1998), Neuse River Basin Water Resources Plan (2010), Watershed Improvement Plan for Ellerbe Creek (2010), Falls Lake Nutrient Management Strategy (2011), and the Upper Neuse Clean Water Initiative (2015). While these plans range from statewide to city-level strategies, they all identify the reduction of urban runoff into Ellerbe Creek as a way to address water quality and quantity issues faced by North Carolina. As such, these plans all call for interventions to flooding in the Ellerbe Creek Watershed.

**Ellerbe Creek Watershed Association (ECWA)**

Our client, ECWA, is a land trust based in Durham. ECWA’s main objective is to turn Ellerbe Creek into a healthy, living and functional stream. The organization does this by protecting and restoring the watershed and its natural features and by connecting human and natural communities. Since its founding in 1999, ECWA has built a network of nature preserves and trails that both improve watershed function and are accessible to the public (ECWA, 2016).

ECWA considers stormwater runoff as the greatest threat to the Ellerbe Creek. Increased percentage of impervious surfaces leads to what Walsh et al. term as the “urban stream syndrome,” which includes flashier hydrograph, elevated nutrient concentrations, altered channel geomorphology, and loss of habitat for riparian organisms (2005). Traditional stormwater mitigation approaches known as “grey infrastructure” rely on piping and channelizing to quickly...
move stormwater away from communities; however, these practices are costly and can exacerbate issues leading to urban stream syndrome. It is estimated that the City of Durham would have to spend hundreds of millions of dollars to reach their restoration goals for Ellerbe Creek using strictly a hard infrastructure approach (Ellerbe Creek Green Infrastructure Partnership, 2014).

An alternative to these practices is stormwater Best Management Practices (BMPs) and green infrastructure, such as downspout disconnections, rain water harvesting, rain gardens, bioswales among others. The benefits of these alternatives can be seen in a study conducted in the Neuse River Basin, where green roofs held 64% of the rainfall measured at the site (Hathaway, Hunt, & Jennings, 2008). In addition, land can be acquired to be turned into green space, preventing further development. Land acquisition can be done strategically to create green space in locations that are most beneficial to reducing water quantity and improving water quality.

To help the city achieve its stormwater mitigation goals, ECWA is involved in both individual and joint projects related to green infrastructure installation and land acquisition. ECWA has conducted GIS analyses and field verification of potential sites for green infrastructure retrofits. In 2016, ECWA started an initiative called Creek Smart. Under the program, the city of Durham provides funding to ECWA to install green infrastructure retrofits including rain gardens and cisterns on private properties. ECWA also conducts training and educational programs on installing green infrastructure.

In terms of land acquisition, ECWA receives much of their funding from the Upper Neuse Clean Water Initiative (UNCWI) Conservation Strategy. Developed by a number of
stakeholders in the Upper Neuse basin, the conservation strategy is a long term (2015-2045) plan that aims at improving the water quality in nine drinking water reservoirs that lie in the Upper Neuse watershed, including the Falls Lake reservoir. Funding for this initiative comes mainly from N.C. Clean Water Management Fund, cities of Raleigh, Durham, and Creedmoor, and counties of Durham and Orange. To prioritize parcels, stakeholders came up with a GIS-based analysis which scored parcels based on several criteria, such as current land use, location in a floodplain, distance from the stream, among others (see Table 4). Organizations receive funding for parcels with a score of 4.2 or higher. In addition to preserving pristine areas for green space, ECWA also priorities land based on its potential to have its ecological function restored. Finally, ECWA also aligns its goals with Durham’s green space and stormwater infrastructure plans.

**Project Objectives**

We worked with ECWA to identify pluvial flooding as a currently unexplored area of interest for the organization. Research on pluvial flooding for the Ellerbe Creek watershed is relevant in a global context, potentially beneficial to the numerous water management plans that relate to Ellerbe Creek watershed, and meaningful to ECWA’s stakeholders who have experienced neighborhood flooding outside of riverine floodplains. In order to incorporate our pluvial flooding findings into ECWA’s existing strategies, we also identified the need for an integrated Strategic Planning Tool that will allow ECWA to evaluate their various conservation programs together with pluvial flooding. This will both link pluvial flooding interventions to existing funding and allow ECWA to prioritize parcels that benefit the most strategies at once. These two project components are summarized below:
Objective 1: Evaluate and run hydrological models for pluvial flooding in the Ellerbe Creek Watershed.

This component provides ECWA with an understanding of the current availability of and tradeoffs between technologies for modeling pluvial flooding. It will also contain a map of flood-prone areas from a selected model. This map will be validated against a map of flooding complaints from Durham Stormwater Services.

Objective 2: Build a Strategic Planning Tool that integrates pluvial flooding into existing ECWA watershed protection strategies.

This component makes the pluvial flooding findings transferrable to existing ECWA watershed protection strategies. The ultimate goal of the GIS tool is to prioritize parcels that can either be acquired by ECWA to turn into green space or retrofitted with stormwater BMPs/green infrastructure. In addition to pluvial flooding, the tool will include other strategies that inform ECWA’s work that will have adjustable weights. Pairing pluvial flooding with other strategies will allow for parcels that are beneficial to multiple strategies to be prioritized and will enhance the feasibility of acquiring the necessary funds and support for pluvial flooding interventions. The tool will be user-friendly and easily updateable so that it can continue to be used as ECWA’s priorities and strategies evolve.

These deliverables will allow ECWA to engage stakeholders in discussions regarding pluvial flooding and promote awareness of both this issue and potential solutions.

Methods

Pluvial Flood Modeling

In order to evaluate models to be considered to create the pluvial flood map, four parameters were considered:
1) **Process-based versus stochastic approaches:** Hydrologic models are broadly classified as process based models and stochastic models. Process based models use mathematical equations to represent the physical world whereas, stochastic models are based on statistical analysis of previously available data. We evaluated only process based models as pluvial flooding does not have a lot of historical data.

2) **Scale of subcatchment delineation:** Pluvial flooding is a street level, local phenomenon; therefore, the delineation of subcatchments would ideally occur at a user-defined, fine scale. This is possible with fully distributed models, where the smallest unit of operation can be defined by the user. In contrast, semi distributed models divide the watershed into several sub-watersheds or subcatchments. While fully distributed models are ideal, due to the limited number of fully distributed models, both semi and fully distributed models were considered.

3) **Dimensionality:** Since pluvial flooding is the result of dynamic processes; it occurs when there is overland flow and/or because the stormwater infrastructure doesn’t have enough capacity to carry away all the water from an area. Therefore, we wanted a model which could represent the 2D overland hydrological processes as well as hydraulic processes or the movement of water in pipes.

4) **Cost:** Due to budgetary constraints, we wanted a model that was free and easily accessible.
Based on these four criteria, we ideally wanted a process-based, fully distributed model with 2D hydrologic-1D hydraulic capabilities that was freely available. We evaluated and tested six models listed in Table 1. While several commercial models met the ideal dimensionality and delineation criteria, their limited free access versions did not provide access to the necessary capabilities. Therefore, we used the free, semi-distributed model, EPA-Stormwater Management Model (SWMM). It is a hydrologic-hydraulic water quality simulation model that is mainly used for planning, analysis and design related to stormwater runoff. The runoff component generates runoff from the precipitation and the routing portion transports the runoff through a system of conduits, channels, storage systems and other devices (US EPA, 2016).

Table 1. A summary of the models tested to create the pluvial flooding map.

<table>
<thead>
<tr>
<th>Model</th>
<th>Dimensionality</th>
<th>Delineation</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPA - SWMM</td>
<td>2D overland, 1D sewer model</td>
<td>Semi-distributed</td>
<td>Free</td>
</tr>
<tr>
<td>Info-SWMM</td>
<td>2D overland, 1D sewer model, GIS based</td>
<td>Semi-distributed</td>
<td>Proprietary, limited free access</td>
</tr>
<tr>
<td>Flood modeler suite (Ch2M Hill)</td>
<td>Has both 1D and 2D solvers</td>
<td>Fully distributed</td>
<td>Proprietary, limited free access</td>
</tr>
<tr>
<td>Multi-hydro</td>
<td>Has 4 modules, GIS based</td>
<td>Fully distributed</td>
<td>Free, access unavailable</td>
</tr>
</tbody>
</table>
The SWMM model requires four main inputs: 1) subcatchments, 2) pipe infrastructure, 3) stormwater nodes, and 4) rainfall. Table 2 summarizes each input and its source. The processing of each input and the additional details required for each input will be described further below.

| Table 2. A summary of the four inputs for the pluvial flood model. |
|---|---|
| Data               | Description                                                                                                                                 |
| Subcatchments      | Derived from burning the stormwater pipes shapefile on the 20ft DEM of the Ellerbe Creek watershed obtained from Durham county GIS through our client. |
| Stormwater pipes   | Shapefile depicting all the stormwater pipes in the watershed. Obtained from Durham county GIS through our client. |
| Stormwater nodes   | Shapefile depicting all the stormwater nodes in the watershed. Obtained from Durham county GIS through our client. |
| Precipitation data | Time series data on rainfall. Obtained from USGS. |
1) **Subcatchments:** The first step in our analysis was to delineate subcatchments. To do this, we used the watershed delineation tool in ArcGIS. The watershed delineation tool takes a Digital Elevation Model (DEM) and pour points (point where all the water from a watershed drains to) as inputs. We burnt the stormwater pipes shapefile on the 20-foot DEM of the Ellerbe Creek Watershed to represent water movement through pipes as artificial channels. Stormwater infrastructure nodes were used as pour points. In total, the tool delineated 8,426 subcatchments. Since SWMM only takes inputs as text files or as physically drawn shapes in its interface, we used QGIS to acquire the coordinates of all the vertices of all the subcatchments. These were then transferred to a text file in a format compatible with SWMM. Along with the shape and location of the subcatchments, SWMM also needed information about the subcatchments including percent imperviousness, average slope, and average catchment width. We derived the percent imperviousness using high resolution land use data obtained from the City of Durham’s GIS Services. See Figure 2 for a map of the watershed DEM and Figure 3 for a zoomed in view of the resulting subcatchments. Appendix A provides an overview of the delineated subcatchments for the entire watershed.
Figure 2. The Digital Elevation Model (DEM) with pipe infrastructure 'burnt' into it as channels used to delineate subcatchments.

Figure 3. An inset of the stormwater catchment result from the watershed delineation in ArcGIS.
2) **Stormwater pipes:** In addition to using stormwater pipes in burning the DEM, the pipe data was also required as an input to the model. Pipe properties including length, elevation, depth, diameter, and shape were obtained from the attribute table of the stormwater pipes shapefile. In addition, a roughness coefficient was required, and was determined based on coefficients that correspond with the known pipe materials. All the input data was converted into text file format. See Figure 4 for a map of the location of stormwater pipes in the watershed.

![Stormwater Pipes](image)

*Figure 4. A map of the stormwater pipes used as an input in the pluvial flood model.*
3) **Stormwater nodes**: Stormwater nodes are inlet points to the pipes, junctions where two or more pipes meet, pipe outlets, or stormwater manholes. Inputs including node depth, node elevation, inlet type, and inlet dimensions were required. See Figure 5 for a map of stormwater nodes.

![Stormwater Nodes](image)

*Figure 5. A map of the stormwater inlet locations used as nodes in the pluvial flood model.*
4) **Rainfall data:** We obtained our rainfall data from the one National Weather Service rain gage in the watershed. We used rainfall data from December 23, 2015 to run the model. This date was chosen because model validation was done using the flooding complaints database obtained from Durham City GIS services, and a majority of complaints occurred on December 23, 2015. See Figure 6 for a map of the location of the rainfall gage.

![Ellerbe Creek Watershed](Image)

Figure 6. A map of the location of the rainfall gage used as an input in the pluvial flood model.
**Geospatial Analysis: Strategic Planning Tool**

The Strategic Planning Tool takes strategies that are important to ECWA, weights them, and combines them to generate a Total Score. ECWA identified five key strategies to be included in the Strategic Planning Tool: 1) Pluvial flood zones, 2) UNCWI scores, 3) Small Scale Residential Stormwater Control Retrofits in Durham, 4) Restoration scores, and 5) Green infrastructure opportunities. These parameters are explained in greater detail in Table 3. To see maps of these parameters in the order listed, see Appendices B – F.

**Table 3. A summary of the parameters used in the Strategic Planning Tool.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Pluvial flood zones</em></td>
<td>The polygon shapefile of pluvial flood-prone areas created for this Master’s Project.</td>
</tr>
<tr>
<td><em>UNCWI scores</em></td>
<td>A raster provided by the Upper Neuse Clean Water Initiative.</td>
</tr>
<tr>
<td><em>Stormwater Control Retrofits</em></td>
<td>A polygon shapefile of census-block level scores for green infrastructure opportunities identified by the City of Durham in a 2017 report.</td>
</tr>
<tr>
<td><em>Restoration scores</em></td>
<td>A raster created by an ECWA analysis of degraded land with potential for restoration.</td>
</tr>
<tr>
<td><em>Green Infrastructure sites</em></td>
<td>A point shapefile created by an ECWA analysis of potential green infrastructure sites.</td>
</tr>
</tbody>
</table>

The GIS tool was built using R version 3.3.2 (R Core Team, 2016). This software was used because it is compatible with visualization packages that will allow the tool to be interactive and engaging to users. The analysis used the R packages arcgisbinding, shiny, leaflet, rgdal, raster, sp, rstudioapi, RColorBrewer, DT, plotly, and ggplot2 (Esri, 2016; Cheng et al., 2017; Cheng et al., 2016; Bivand et al., 2016; Hijmans, 2016; Pebesma et al., 2005, Bivand et al., 2013;
The general workflow for building the tool is summarized in Figure 7. First, parameters were standardized into polygon files with a projection of CRS ‘4326’, cell size of 30mx30m, and score range from 0 - 10. This is assuming linear utility for each strategy based on the linear utility approaches that were used originally to build each strategy. For the point shapefile, the total number of points in a parcel was used to translate the points into polygons. The individual polygon shapefiles were then intersected with the 2016 parcel data provided by the City of Durham for the Ellerbe Creek Watershed in order to give each parameter the necessary parcel information. Additionally, this step calculated an average score of each parameter for each parcel. The polygons were then merged together by Parcel ID so that every unique parcel contained a score for each parameter. Parcels without a score for a particular parameter were given a score of 0. Finally, the code for the web app was built to allow the user to input weights for each parameter. The inputs allow the final polygon shapefile to be generated. This shapefile contains the parcels with the original parcel information, each parameter’s score, each
parameter’s weighted score, and a Total Score for the sum of the weighted scores.

Of the previously listed R packages, shiny, leaflet, DT, and plotly were most involved in creating the visual components of the tool. Shiny allows the user to interact with a web-app interface that channels user inputs to the code, initiating the code to be re-run with the new user inputs to create an updated product. For this tool, the user-defined inputs are the weights for each parameter. The resulting shapefile is then displayed and made interactive using a summary table built by DT, a pie chart built by plotly, and a map of the parcels built by leaflet. For the table, particular columns can be shown, parcels can be searched for using keywords, and columns can be sorted by ascending or descending value. Selecting a particular row in the table will also generate a pie chart displaying the breakdown of the Total Score by parameter. For the map, the user has the option to search for parcels only within a certain score range and zoom to a particular parcel based on its Parcel ID, which can be obtained from the table. Additionally, for the map the user must select a subset of parcels to view due to the large number of polygons and lengthy render time. The subsets are defined as neighborhoods based loosely on Durham’s development tiers of Urban, Suburban, and Rural, and further separated into areas of roughly 2,000 – 3,000 polygons. The user can continue to change weights and update the table and map until satisfied with the results. When finished, the user can click on the ‘Export Shapefile’ button to save the final product to their working directory.

The final deliverables are a web app hosted on a free Duke University server and the original R Script and Environment, which can be run on ECWA’s local devices. The interface of this tool can be seen in Figure 8. Additionally, a video demo of the tool is available at https://youtu.be/IFyboZZyhsA.
Figure 8. The interface of the Strategic Planning Tool web app created to allow ECWA to explore parcel and score details before finalizing their integrated strategy.
In addition, the code was applied to the UNCWI strategy itself, allowing the parameters that generate the UNCWI score to have adjustable weights. This feature will enable ECWA to explore alternative priorities, and to provide a visual explanation to stakeholders when discussing why parcels under the 4.2 threshold may still be suitable for funding when weighted differently.

The UNCWI scores are based on four parameters: 1) Water Sources and Conveyances, 2) Uplands, 3) Infiltration and Retention, and 4) Vulnerable Areas (see Table 4). These four parameters were provided by ECWA as raster files with pixel scores between 0 - 10 based on UNCWI’s previous work. The methodology for the UNCWI tool is the same as described above. As such, the tool’s interface is also similar to the interface seen in Figure 8.

Table 4. Description of the four parameters used in the UNCWI Conservation Strategy.

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Sources and Conveyances</td>
<td>Protect headwater streams, support connected high quality water features, and protect riparian areas</td>
</tr>
<tr>
<td>Uplands</td>
<td>Protect uplands and previous areas, protect areas with minimal impervious surface, protect uplands with forest cover</td>
</tr>
<tr>
<td>Infiltration and Retention</td>
<td>Promote infiltration and retention through wetland protection, promote filtration through floodplain protection, protect underground recharge areas</td>
</tr>
<tr>
<td>Vulnerable Areas</td>
<td>Protect wet and hydric areas, protect steep sloping areas, protect uplands with forest cover</td>
</tr>
</tbody>
</table>

Results

Pluvial Flood Modeling

Modeling results showed that out of 8,426 subcatchments, 4,982 are prone to flooding. In terms of acreage, 4,766 acres are prone to flooding out of 10,496 acres. This amounts to 48% of
the provided subcatchments, or 20% of the Ellerbe Creek Watershed. It is worth noting that the entire watershed covers 23,680 acres. As some of the areas are uninhabited, or lie outside the Durham city limits, stormwater infrastructure data was not available for those areas. Thus, those areas were excluded from the subcatchment delineation process (see Appendix A).

Validation of model results was done using the flooding complaints database obtained from the City of Durham GIS Services office. Out of 27 flooding complaints, 20 were outside the 100-year riverine floodplain (see Figure 9). Overlaying the flooding complaints on our results showed that 11 of the 20 non-riverine flooding points matched with our results. The pluvial flood-prone catchments and complaint locations outside the 100-year riverine floodplain can be seen in Figure 10.

![Flooding complaints overlay on 100 year floodplain](image)

*Figure 9. Flooding complaints overlaid on the 100-year riverine floodplain, demonstrating that most of the complaints fall outside the floodplain.*
Figure 10. Non-riverine flooding complaints overlaid on the subcatchments prone to pluvial flooding.

**Geospatial Analysis: Strategic Planning Tool**

The GIS tool was made for ECWA to adjust as needed in the future. As such, the results of the tool will change to match ECWA’s future criteria. In order to demonstrate the validity of the tool, the tool was run with even weights for each parameter (0.20). The top-scoring parcels were then identified and the original parameters were overlaid using ArcGIS. The top scoring parcels were Parcel ID 114464 and 114465 with a score of 6. As can be seen in Figure 11, the parcels score high in every parameter except Green Infrastructure, which verifies their high score.
Figure 11. Validation of the Strategic Planning Tool by overlaying the original parameters on the top scoring parcels to see that they receive high scores in 4 of 5 parameters.

Discussion

*Pluvial Flood Modeling*

In our pluvial flood modelling, we make several assumptions. The overland flow component of the model considers only subcatchment imperviousness to model the runoff, with no consideration given to the land use. It was assumed that water could freely enter all the nodes. For example, there is no way to account for cases where the pipe inlet could be blocked with leaf litter, trash and other debris. Delineating subcatchments was a tedious task and it was difficult to account for all the nodes and conduits in the subcatchment. The biggest conduit in a
subcatchment was assumed to convey all the runoff, discounting inter-subcatchment conveyance, and discharge in smaller ephemeral streams before the pipe exited the subcatchment.

Although accurate forecasting of pluvial flooding is not possible using SWMM, given the dearth of open source urban flooding models and our constraints, SWMM fit our requirements. Also, due to the lack of data, model validation was done using the flooding complaints database that the city has maintained for the past two years. However, this database is not a comprehensive and a targeted database of complaints. It is a list of complaints voluntarily made by concerned citizens. Our client has expressed interest in engaging local stakeholders, namely, residents, or homeowners’ associations to create a targeted database of flooding complaints in the watershed. This is recommended as future work for our client and interested students.

**Geospatial Analysis: Strategic Planning Tool**

We built the Strategic Planning Tool as an example of what small non-profits like ECWA can create using the latest open-source technologies in geospatial analysis. These up-and-coming technologies are widening the tools available to small organizations with limited financial means to conduct in-house analyses. In particular, we wanted to showcase leveraging web functionality to produce dynamic, interactive data visualizations. Our emphasis on creating visual displays is based on the understanding that organizations like ECWA depend on successful stakeholder engagement to gain approval and support for their projects. Accordingly, ECWA requested a tool that could update parameter weightings in real-time with stakeholders and provide a visual result.

The software R was specifically chosen over other geospatial software. This is because it is open source and therefore free for small organizations. Additionally, it interfaces easily with
both ArcGIS software and html, making it possible to move between GIS analysis and web app building. Furthermore, R code used to build the web app is more intuitive than html, and could be written so that organizations without coding expertise could still easily make adjustments, such as changing input files. Finally, R has an extensive user community. This means that there are vast resources available for organizations to learn R online, and that R is continually expanding its functionality.

A challenge faced in the creation of the tool was balancing the extent of user input with the simplicity of the tool. Originally, the tool was designed to allow the user to conduct an analysis on each parameter as well as choose the parameter weightings. For example, the type of landcover and the percentage of it contained in a parcel could be selected and then weighted. However, this level of detail made the tool too bulky, and attempts to streamline it by selecting re-usable inputs limited the type of tools that could be used. Ultimately, feedback from our client confirmed that this component of the tool was not as important as making the tool user-friendly and interactive. Therefore, with the exception of the UNCWI parameter, each parameter’s analysis was completed before being put in our tool. Users can still alter these layers outside of the tool and enter a new input file into the tool.

Our client’s preference for a flexible tool over a specific analysis reflects a need for many organizations. This is because organizations can often be inundated with multiple analyses that have been conducted for a particular partnership, grant, or other funding source. These analyses then remain stagnant—they are not easily updateable and are not made to be compatible with other existing or future strategies. Discussions with ECWA confirmed that the organization already had a number of GIS analyses and prioritization maps for different strategies. Instead of
further complicating their work with our pluvial flood model, we decided to create a tool that would give them the option to include pluvial flooding among other parameters.

**Conclusion**

The city of Durham is a rapidly developing area. This continued increase in impervious surfaces will result in the generation of higher amounts of runoff, which could overwhelm the city’s stormwater conveyance system. While expanding infrastructure systems through grey infrastructure is an option, it is expensive and detrimental to the environment. Green space and green infrastructure offer a cheaper alternative that also helps in treating stormwater, thereby improving the quality of water conveyed to streams.

In our analyses, we identified subcatchments prone to pluvial flooding. This information was included in a GIS-based web tool to prioritize land parcels for green space and green infrastructure. We believe that our Strategic Planning Tool will aid our client in their mission to move Durham to be an example of proactive urban stormwater management. In the future, with better models, we hope pluvial flooding can be predicted with more accuracy and precision. Our work indicates that there is much room for improvement in terms of incorporating pluvial flooding into flood management. However, there are also a number of tools available for city governments and local organizations to use to begin the important conversation of integrating pluvial flooding into current flood management practices.
Acknowledgements

We would like to thank our advisor Mukesh Kumar for his expertise, guidance and support throughout this process. We ran into a number of dead ends and challenges when searching for a hydrological-hydraulic model, and his advice and suggestions were critical to the creation of our final product. Additionally, we would like to thank our client Ellerbe Creek Watershed Association, specifically Chris Dreps, for taking the time to collaborate with us on this project and for being so flexible and encouraging throughout the process. We would also like to thank Durham GIS & Stormwater Services for sharing their data and Matthew Ross for his help with R. To our professors at the Nicholas School of the Environment at Duke University, thank you for providing us with the skills and knowledge needed to complete this project. Finally, we would like to thank our friends and family for their continued support.
References


**R References**


Appendix

Appendix A. Subcatchment result from ArcGIS delineation

Appendix B. Subcatchments prone to pluvial flooding
Appendix C. Upper Neuse Clean Water Initiative Parameter

Appendix D. Small Scale Residential Stormwater Control Retrofits Parameter
Appendix E. ECWA’s Restoration Strategy Parameter

Appendix F. ECWA’s Green Infrastructure Strategy Parameter