Effects of Historical Land-use Change on Surface Runoff and Flooding in the Amite River Basin, Louisiana, USA Using Coupled 1D/2D HEC-RAS–HEC-HMS Hydrological Modeling

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A Thesis
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in partial fulfillment of the
requirements for the degree of
Master of Science
in
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by
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B.S., McGill University, 2017
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# Table of Contents

Acknowledgements

List of tables

List of figures

Abstract

Chapter 1. Introduction
   1. Background
   1.2. Study objectives
   1.3. Organization of thesis

Chapter 2. Literature Review
   2.1. Floodplains and ecosystem services
   2.2. Urban flood modeling

Chapter 3. Methodology
   3.1. Amite River Basin Numerical Model overview
   3.2. Green and Ampt soil loss method
   3.3. Modified Clark precipitation transform method
   3.4. Land use/land cover and imperviousness
   3.5. Storms
   3.6. HEC-RAS model

Chapter 4. Results
   4.1. Impervious surface estimation
   4.2. Spatially uniform storm results
   4.3. ARBNM storm results
   4.4. Results from selected subbasins
   4.5. Parks plan results

Chapter 5. Conclusions and Discussion

References

Vita

iv
v
ix
1
13
14
16
16
20
25
25
29
29
31
44
52
54
56
61
74
77
87
92
98
List of tables

Table 1. Population in the counties and parishes of the Amite River Basin, 1900-2019.....8

Table 2. Manning’s n values for 2D flow areas for use with HEC-RAS NLCD land cover import..................................................................................................................................................31

Table 3. Correlations between population change and impervious area change from 1990-2000 in the Chesapeake Bay watershed.........................................................42

Table 4. Sample treatment of Amite County, MS for 1992 land cover scenario..............43

Table 5. Peak flows, return periods, and annual exceedance probabilities measured for the four Dewberry calibration storms at three storm gauges along the Amite and Comite rivers.................................................................47

Table 6. Manning’s n values for 2D flow areas for use with HEC-RAS EROS land cover import, showing corresponding NLCD categories and values............................................................................................................................................53

Table 7. Impervious change from 1938 to 2016 for six selected subbasins in the Amite Basin................................................................................................................................................................59

Table 8. Increase in peak flow from 1938-2016 for six subbasins expressed in % relative to 1938 flow values......................................................................................................................59
List of figures

Figure 1. Amite River Basin showing main channels of the Comite and Amite Rivers and their outlet channels, including the Amite River Diversion Canal.............2

Figure 2. Physical geography of the Amite River Basin showing soil groups, physical features, and floodplain extents.......................................................3

Figure 3. Idealized flood zones of the Lake Maurepas watershed.......................5

Figure 4. The Amite River Basin spans parts of four Mississippi counties and seven Louisiana parishes.................................................................9

Figure 5. 1948 development plan for the Baton Rouge metro area, with planned parks and greenways shown in green.............................................11

Figure 6. Map showing the overlap of developed areas for the year 1938 of the greater Baton Rouge region east of the Mississippi River with the 100-year FEMA flood zone.................................................................12

Figure 7. Map showing the overlap of developed areas for the year 2016 of the greater Baton Rouge region east of the Mississippi River with the 100-year FEMA flood zone.................................................................13

Figure 8. Ecosystem services provided by healthy ecosystems, grouped by category.................................................................17

Figure 9. Conceptual diagram illustrating the effects of hydrology on wetland function and the biotic feedbacks that affect wetland hydrology..............18

Figure 10. The main physical impacts of riparian vegetation on water cycling.........20

Figure 11. Flows along four bayous in the Houston area during Hurricane Harvey, with pre-anthropogenic baseline conditions, addition of climate change effects, addition of developed areas, and present-day conditions...........22

Figure 12. Simulations of precipitation from Hurricane Harvey over a present-day urbanized scenario and “NoUrban” scenario, in which developed areas were replaced with cropland.........................................................24

Figure 13. HEC-HMS model of the Amite River Basin, with flowlines, routing reach lines, individual subbasins and junctions indicated with icons, and subbasins color-coded by sub-watershed...........................................26

Figure 14. Levels of detail applied in creation of the Amite River Basin Numerical Model..................................................................................28
Figure 15. 2016 MRLC NLCD land cover for the Amite River Basin ..................32
Figure 16. 2016 MRLC NLCD imperviousness for the Amite River Basin ..........33
Figure 17. 1938 USGS EROS land cover scenario for the Amite River Basin ....35
Figure 18. 1964 USGS EROS land cover scenario for the Amite River Basin ....36
Figure 19. 1992 USGS EROS land cover scenario for the Amite River Basin ....37
Figure 20. Relationship between 2010 population density and 2011 imperviousness at the parish and county level for the 4 MS counties and 7 LA parishes of the ARB ..................................................39
Figure 21. EROS 1938 land cover raster clipped to parish/county and Amite Basin boundaries for a total of 11 fragments ..........................40
Figure 22. Parks proposed as part of the 1948 Baton Rouge master plan .........45
Figure 23. 1948 Harland Bartholomew plan overlaid with NLCD 2016 imperviousness layer showing addition of parks and greenways ....46
Figure 24. The March 2016 storm event used in the ARBNM .....................48
Figure 25. The August 2016 storm event used in the ARBNM .....................49
Figure 26. The August 2017 storm event used in the ARBNM .....................50
Figure 27. The October 2017 storm event used in the ARBNM ....................51
Figure 28. Simple schematic showing main data integration pathway ..........53
Figure 29. Change in peak flow vs. change in percent impervious in each HEC-HMS subbasin for four spatially uniform storms .....................57
Figure 30. The six subbasins from high-detail 2D regions of the model isolated for further analysis of spatially uniform storm HEC-HMS simulation results ..................................................58
Figure 31. HEC-HMS hydrographs for hypothetical, spatially uniform 1% and 50% annual exceedance probability storms for 1938 and 2016 land use conditions for six selected subbasins ..................................................60
Figure 32. Relationship between change in imperviousness and change in peak flow for all subbasins for the March 2016 storm event ............62
Figure 33. Relationship between change in imperviousness and change in peak flow for all subbasins for the August 2016 storm event

Figure 34. Relationship between change in imperviousness and change in peak flow for all subbasins for the August 2017 storm event

Figure 35. Relationship between change in imperviousness and change in peak flow for all subbasins for the October 2017 storm event

Figure 36. October 2017 storm event with AmiteR_R03 subbasin

Figure 37. Differences in maximum WSE between 2016 and 1938 land cover scenarios for the March 2016 storm event

Figure 38. Differences in maximum WSE between 2016 and 1938 land cover scenarios for the August 2016 storm event

Figure 39. Differences in maximum WSE between 2016 and 1938 land cover scenarios for the August 2017 storm event

Figure 40. Differences in maximum WSE between 2016 and 1938 land cover scenarios for the October 2017 storm event

Figure 41. A profile line drawn in RAS Mapper that intersects the Amite River just south of the Amite-Comite confluence in Denham Springs

Figure 42. Flow hydrograph at Denham Springs for the March 2016 storm event over the 1938 and 2016 land cover scenarios

Figure 43. Flow hydrograph at Denham Springs for the August 2016 storm event over the 1938 and 2016 land cover scenarios

Figure 44. Flow hydrograph at Denham Springs for the August 2017 storm event over the 1938 and 2016 land cover scenarios

Figure 45. Flow hydrograph at Denham Springs for the October 2017 storm event over the 1938 and 2016 land cover scenarios

Figure 46. Three subbasins with different trends in imperviousness from 1938 to 2016

Figure 47. March 2016 storm event hydrograph for all four LULC scenarios for the COMITE_DS_OB subbasin

Figure 48. March 2016 storm event hydrograph for all four LULC scenarios for
the BFount_Nich_US subbasin........................................................................76

Figure 49. March 2016 storm event hydrograph for all four LULC scenarios for
the AmiteDivCnl_01 subbasin........................................................................77

Figure 50. Left: 1948 Bartholomew plan for Baton Rouge showing the locations
of the five subbasins that saw the greatest proportional decrease in
surface impervious cover with the introduction of parks..........................78

Figure 51. HEC-HMS results for the five subbasins that had the largest percent
change in impervious surface cover with the addition of the 1948
Bartholomew parks.......................................................................................79

Figure 52. Relationship between impervious change and peak flow change
when 1948 Bartholomew parks were added to 2016 NLCD for March
2016 and August 2016 storms......................................................................80

Figure 53. March 2016 inundation depths over 1948 Baton Rouge master plan,
showing RAS Mapper profile line downstream of the confluence of
Dawson Creek and Bayou Duplantier in Baton Rouge.................................82

Figure 54. HEC-RAS flow hydrographs for 2016 NLCD land cover scenario,
with and without addition of 1948 parks.....................................................83

Figure 55. Differences in WSE for the March and August 2016 storms between
2016 land cover scenarios with and without the 1948 Bartholomew
parks added..................................................................................................85

Figure 56. Rating curve along the profile line shown in Figure 47...................86
Abstract

The Amite River Basin is a largely rural watershed spanning parts of four counties in southern Mississippi and seven parishes in southeast Louisiana, with basinwide imperviousness increasing from 0.82% in 1938 to 3.85% in 2016. The Basin has been the subject of significant research interest since catastrophic flooding in 2016 caused 13 deaths and widespread damages. Rapid development in recent decades has led to an expansion of impervious surfaces in Baton Rouge and surrounding areas, encroaching on floodplains and wetlands. At the basin scale, differences in flooding due to impervious cover changes were found to be somewhat limited, particularly along the main rivers and streams and for the larger, less frequent events. The Amite Basin is topographically flat with wide floodplains, high precipitation, and clayey soils. To model the effects of these historical changes, simulations were run in a HEC-HMS and coupled 1D/2D HEC-RAS model of the Amite River Basin for a variety of storms and land cover scenarios. The impacts of increasing surface imperviousness were more prominent at smaller spatial scales, where there has been significant development, and differences were more pronounced for smaller storms. Given the low impact of increasing impervious cover on flooding caused by the August 2016 storm and other large storms, flood mitigation efforts in the Amite River Basin and similarly flood-prone areas are likely best suited to large-scale projects like the Comite Diversion Canal and Darlington Dam, as well as smaller-scale interventions to manage the impacts caused by higher frequency, lower intensity storms that are often controlled by backwater conditions.
Chapter 1. Introduction

1.1. Background

1.1.1. Study area

The Amite River Basin (ARB) spans parts of seven parishes in southeastern Louisiana and four counties in southwestern Mississippi. The primary channels are the Amite and Comite Rivers, which drain into Lake Maurepas and ultimately through to the Gulf of Mexico via Lake Pontchartrain (Figure 1). The HUC-8 level delineation of the Amite watershed has an area of approximately 1,880 square miles (U.S. Geological Survey, 2017). This study, however, will use the 2,220-square mile version of the Amite Basin used in Dewberry Engineers’ Amite River Basin Numerical Model (Dewberry Engineers Inc., 2019).

The Basin is relatively flat and low-lying; elevation peaks under 500 ft. above mean sea level (MSL) in the Plio-Pleistocene Terrace of southern Mississippi, but most of the southern third of the Basin consists of bottomland hardwood swamps at 1-5 ft. MSL (Gulf Engineers and Consultants Inc., 2015). Away from the river channels, soils are silty and loess-like, while deposits along the rivers are more heterogeneous mixtures of sands, silts, and clays (U.S. Army Corps of Engineers, 2012). Channels in the northern part of the Basin are more deeply incised, while the alluvial soils and prairie terraces of the southern part of the Basin are characterized by wider floodplains (Figure 2). This typically leads to higher water velocities in the north and lower velocities and sluggish flow in the south.
Figure 1. Amite River Basin showing main channels of the Comite (left) and Amite (right) Rivers and their outlet channels, including the Amite River Diversion Canal (bottom) Source: Dewberry Engineers Inc. (2019).
Figure 2. Physical geography of the Amite River Basin showing soil groups, physical features, and floodplain extents. Source: Gulf Engineers and Consultants Inc. (2015).
Hydrologically, most of the Basin’s soils are classified as Hydrologic Soil Group C or D soils (Soil Survey Staff, 2020). Soils in Group C have low water transmission rates and are characterized by having a layer that impedes downward infiltration (Cronshey et al., 1986). Group D soils consist largely of soils with high clay content and/or high water tables and have the highest runoff potential of any soil group. Precipitation levels are also quite high, regularly exceeding 60 in. per year in the Basin (Gulf Engineers and Consultants Inc., 2015), which, when combined with slow infiltration rates, can lead to high water tables and runoff rates. The flat topography, low elevation, high precipitation, clayey soils, and coastal proximity lend themselves to a naturally high flood hazard in the Basin even before changes in land use are considered.

The lower ARB is also vulnerable to storm surge effects due to coastal influences (Bilskie & Hagen, 2018; Bilskie et al., 2021), as shown in Figure 3. As relative sea level rise driven by climate change and land subsidence pushes the coastal zone further inland (Twilley et al., 2016), the transition zone between coastal and hydrologic flooding may eventually disappear. Weeks after the August 2016 rainstorm that inundated the Amite River Basin, Hurricane Hermine made landfall in Florida on September 2. The combined damage if the hurricane had made landfall in Louisiana during the unnamed rainstorm would have been catastrophic, and accurate modeling of the Basin’s hydrological dynamics is of great public interest.
Figure 3. Idealized flood zones of the Lake Maurepas watershed. Riverine flooding dominates in the hydrologic zone (green) and coastal processes, including storm surge, are dominant in the coastal zone (blue). The yellow transition zone, which includes much of the lower Amite River Basin, is subject to influence by both. Source: Bilskie and Hagen (2018).

1.1.2. Amite River Basin flooding

The ARB has experienced several major inundation events over the last century, including in 1983 and 2016. From April 4-8, 1983, up to 17 inches of rain fell across much of southern Mississippi and southeastern Louisiana over four days, causing widespread flooding in the Amite River Basin, especially around Denham Springs, LA (Stone & Bingham, 1991). The winter of 1982-83 had already seen high levels of precipitation before the flood, so the saturated soil, swollen creeks, and high water levels in the lakes contributed to the severity of the flooding. Two large-scale proposed engineering
Interventions gained traction in response to the 1983 floods, the Comite River Diversion Canal (CRDC) and the Darlington Dam. The CRDC is a 12-mile canal currently being built to divert flow from the Comite River directly west to the Mississippi River during periods of high flow (U.S. Army Corps of Engineers, 2012). The proposed 3 mile long, 86 foot tall earthen dam across the Amite River near Darlington, LA would be operated to preferentially flood parts of East Feliciana and St. Helena parishes to prevent downstream flooding in the much more heavily populated East Baton Rouge, Livingston, and Ascension parishes (U.S. Army Corps of Engineers, 2019). As of early 2021, the Dam is still being studied for feasibility.

Many of the precipitation and inundation records set in 1983 were subsequently broken with the historic floods of August 2016. From August 10-14, 2016 a slow-moving, low-pressure storm system stalled over the Basin, with 48-hour rainfall peaking at 31.39 inches in Watson, LA, the highest 48-hour rainfall total ever recorded in Louisiana (Brown et al., 2020). Consequences of these floods were significant; in all, there were 13 deaths and $10-15 billion worth of property damages, but although 90,000 homes were damaged, only 11% of those in affected parishes carried flood insurance (Disaster Recovery Unit, 2017). Storm Precipitation Analysis System (SPAS) modeling by Brown et al. (2020) estimated that a 4-day maximum accumulation of 34.65 inches was likely achieved near Watson, exceeding the measured state record by over 3 inches. The extreme nature of the storm was primarily driven by its duration, however. The highest reliable amount of hourly rainfall recorded during the storm was 3.32 inches at New Iberia, LA, which is less than the amount expected for a 25-year return period event according to NOAA Atlas 14 (Perica et al., 2013). Despite no extreme single-hour totals, locations
such as Baton Rouge and New Iberia received 55 consecutive hours of rainfall (Brown et al., 2020). Many locations in the Basin surpassed NOAA Atlas 14 estimates for a 48-hour, 1000-year return period event by 8 inches or more, including Baton Rouge, Denham Springs, and Lafayette.

Return period estimates are based on modeling that includes examination of the historical record. As climate change proceeds, however, the intensity and frequency of extreme storm events is expected to increase, as well as associated flooding (Wang et al., 2013). Trenberth et al. (2003) have estimated that rainfall intensity will likely increase by 7% per degree Celsius of temperature rise. As total atmospheric moisture increases with warming temperatures, Chou et al. (2009) describe a “rich-get-richer” mechanism by which areas with higher precipitation will see an increase in precipitation while areas with lower precipitation will experience a decrease. Such a mechanism could also cause an increase in the intensity of major precipitation events even as mean annual precipitation totals change more gradually. Meanwhile, findings by Jansen et al. (2020) suggest that Arctic sea-ice is melting at rates significantly higher than past climate change studies have predicted. Given the uncertainty of future precipitation patterns and that climate change may be progressing more rapidly than previously recognized, the term “annual exceedance probability,” or AEP, will be used preferentially in subsequent sections of this thesis for better statistical representation of storm frequencies.

1.1.3. Population dynamics

Most of the Amite River Basin is rural except for the greater Baton Rouge region, which has undergone pulses of migration and urbanization following the oil boom of the 1970s and in the aftermath of disasters such as Hurricanes Katrina and Rita. While the Basin's
overall population increased from 275,345 in 1900 to nearly 875,000 in 2019, population growth has not been uniform; in the Basin’s Mississippi counties, total population decreased from 77,857 to 62,793 over the same period (Table 1). Figure 4 shows the locations of the Louisiana parishes and Mississippi counties that make up the Amite Basin. Mississippi's urban population grew from a 19.8% share of the state’s total population in 1900 to 49.3% in 2010, and Louisiana’s population shifted from 41.5% to 73.2% urban (U.S. Census Bureau, 2012). The single largest proportional decadal population loss for the study area during this time frame was -19.1%, when the population of Amite County, MS dropped from 19,261 in 1950 to 15,573 in 1960. This coincides with the Great Migration, in which African Americans fled racist persecution in the rural South in great numbers from approximately 1940-1970 (Jackson et al., 1991). The largest proportional population gain by decade was 79.0%, when the population of East Baton Rouge Parish, LA increased from 88,415 in 1940 to 158,236 in 1950.

Table 1. Population in the counties and parishes of the Amite River Basin, 1900-2019 (modified from GEC 2015 with addition of Mississippi counties and 2019 population estimates (U.S. Census Bureau, 2020a, 2020b)).

<table>
<thead>
<tr>
<th>State</th>
<th>County/Parish</th>
<th>1940</th>
<th>1960</th>
<th>1980</th>
<th>2000</th>
<th>2019 (est.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mississippi</td>
<td>Amite</td>
<td>21,892</td>
<td>15,573</td>
<td>13,369</td>
<td>13,599</td>
<td>12,297</td>
</tr>
<tr>
<td></td>
<td>Franklin</td>
<td>12,504</td>
<td>9,286</td>
<td>8,208</td>
<td>8,448</td>
<td>7,713</td>
</tr>
<tr>
<td></td>
<td>Lincoln</td>
<td>27,506</td>
<td>26,759</td>
<td>30,174</td>
<td>33,166</td>
<td>34,153</td>
</tr>
<tr>
<td></td>
<td>Wilkinson</td>
<td>15,955</td>
<td>13,235</td>
<td>10,021</td>
<td>10,312</td>
<td>8,630</td>
</tr>
<tr>
<td>Total, MS</td>
<td></td>
<td>77,857</td>
<td>64,853</td>
<td>61,772</td>
<td>65,525</td>
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</tr>
<tr>
<td>Louisiana</td>
<td>Ascension</td>
<td>21,215</td>
<td>27,927</td>
<td>50,068</td>
<td>76,627</td>
<td>126,604</td>
</tr>
<tr>
<td></td>
<td>East Baton Rouge</td>
<td>88,415</td>
<td>230,058</td>
<td>366,191</td>
<td>412,852</td>
<td>440,059</td>
</tr>
<tr>
<td></td>
<td>East Feliciana</td>
<td>18,039</td>
<td>20,198</td>
<td>19,015</td>
<td>21,360</td>
<td>19,135</td>
</tr>
<tr>
<td></td>
<td>Iberville</td>
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<td>32,159</td>
<td>33,320</td>
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</tr>
<tr>
<td></td>
<td>Livingston</td>
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<td>58,806</td>
<td>91,814</td>
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</tr>
<tr>
<td></td>
<td>St. Helena</td>
<td>9,542</td>
<td>9,162</td>
<td>9,827</td>
<td>10,525</td>
<td>10,132</td>
</tr>
<tr>
<td></td>
<td>St. John the Baptist</td>
<td>14,766</td>
<td>18,439</td>
<td>31,924</td>
<td>43,044</td>
<td>42,837</td>
</tr>
<tr>
<td>Total, LA</td>
<td></td>
<td>197,488</td>
<td>362,697</td>
<td>567,990</td>
<td>689,542</td>
<td>812,067</td>
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<tr>
<td>Total, all</td>
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<td>275,345</td>
<td>427,550</td>
<td>629,762</td>
<td>755,067</td>
<td>874,860</td>
</tr>
</tbody>
</table>
Figure 4. The Amite River Basin spans parts of four Mississippi counties (Franklin, Lincoln, Wilkinson, and Amite) and seven Louisiana parishes (East Feliciana, St. Helena, East Baton Rouge, Livingston, Iberville, Ascension, and St. John the Baptist).
1.1.4. Changing land use

As with population trends, trends in land use and land cover change have differed between the northern and southern parts of the Amite Basin. Following the Great Depression and World War II, a series of agricultural commodity price support and land conservation programs enacted at the federal level directly incentivized the conversion of agricultural land in the Basin—especially in its rural northern reaches—to forests and wetlands (Bowers et al., 1984). The trend in the southern part of the Basin, however, was toward increasing urbanization and development of lands in and around Baton Rouge. This development includes housing developments, commercial developments, and fossil fuel refineries. These have greatly expanded the footprint of impervious surfaces, which increases volume and velocity of surface runoff during inundation events, as will be discussed further in Section 2.1. As far back as 1948, Baton Rouge’s poor drainage capacity and vulnerability to flooding were explicitly acknowledged and addressed in city planning discussions. Figure 5 shows a proposal commissioned by the City-Parish at the time that included a network of greenways and water channels to address these concerns (Harland Bartholomew & Associates, 1948).

In the 1960s and ‘70s, however, focus was drawn away from these plans as the petrochemical industry underwent rapid economic and spatial expansion, drawing in new workers and their families by the thousands (Allen, 2006). The 1948 plan was not implemented, and sprawling, suburban-style development practices took over. The 1983 flood inundated many of these newly-created housing subdivisions, but the number of homes that experienced flooding during the August 2016 storm increased nearly by a factor of 10 relative to the 1983 storm (Colten, 2017). Over the same time period, the
Figure 5. 1948 development plan for the Baton Rouge metro area, with planned parks and greenways shown in green. Source: Harland Bartholomew & Associates (1948).
number of homes in Livingston and Ascension Parish tripled and the population more than doubled (Table 1). Many of the housing developments built during this time period were located in areas that had flooded in 1983 and would again in 2016; over 50% of the land area of Ascension, East Baton Rouge, Iberville, and Livingston Parishes lie within the 100-year Federal Emergency Management Agency (FEMA) flood zone (Jacobsen, 2017). In 1938, roughly 11.3 square miles of developed land fell within the flood zone, representing about 28.5% of the total developed area (Figure 6). By 2016, this figure had increased to 99.1 square miles, or 32.8% of the developed total (Figure 7). The slab on grade style houses in these developed areas were also being built progressively larger, as average home size in the greater Baton Rouge region increased by 60% from pre-World War II to the 2010s (Mosby & Birch, 2019).

![Figure 6. Map showing the overlap of developed areas (in red) for the year 1938 of the greater Baton Rouge region east of the Mississippi River with the 100-year FEMA flood zone (cyan) in the parishes of East Baton Rouge, Livingston, Ascension, and Iberville (Federal Emergency Management Agency, 2007). 1938 land cover pixel resolution is 250 by 250 m (Sohl et al., 2016).]
Figure 7. Map showing the overlap of developed areas (in red) for the year 2016 of the greater Baton Rouge region east of the Mississippi River with the 100-year FEMA flood zone (cyan) in the parishes of East Baton Rouge, Livingston, Ascension, and Iberville (Federal Emergency Management Agency, 2007). 2016 land cover pixel resolution is 30 by 30 m (Yang et al., 2018).

1.2. Study objectives

This research project was completed as part of the Inland from the Coast (IFC) project, a larger multi-disciplinary effort that seeks to assess, model, and support community resilience and well-being in the face of extreme storm events. As climate change increases the intensity and frequency of severe storm events, a more comprehensive understanding of all variables affecting humans and their environment during extreme flood events is urgently needed, including health and well-being, design practices, and the hydraulics and hydrology of flood dynamics. The hydrological modeling team’s objective is to improve understanding of how changes in river geometry, urbanization and land use, and precipitation patterns have impacted the flood hazards and risk as well as provide insights into community resilience. The purpose of this study is to quantify and
analyze historical land use changes in the Amite River Basin and their impacts on surface runoff and flood dynamics. As part of south Louisiana’s inland-coastal transition zone, the ARB poses unique challenges for human habitation. Continued economic growth in the region and immigration from rural areas impacted by natural disasters will likely continue to increase urbanization trends in the Basin. Guiding questions regarding the effects of land use and land cover change include:

- How does the expansion of impervious surfaces via urban development affect surface runoff and flood dynamics in the Amite River Basin?
- How do changes in flood impact vary spatially, in different parts of the Basin and over different spatial scales?
- How would flooding change under certain restoration or land management scenarios?

1.3. Organization of thesis

This thesis consists of 5 chapters. Chapter 1 introduces the study area, context, and motivation for this study on the hydrological dynamics of the Amite River Basin of southeastern Louisiana and southwestern Mississippi. Chapter 2 provides a literature review of ecosystem services, impacts of land use/land cover change on hydrology, and previous urban flood modeling studies. Chapter 3 presents the methodology used for this study, which used the Amite River Basin Numerical Model’s HEC-HMS (U.S. Army Corps of Engineers Hydrologic Engineering Center Hydrologic Modeling System) and HEC-RAS (HEC River Analysis System) components to model the effects of changing land use and land cover on surface water dynamics in the ARB. ArcGIS was first used to determine imperviousness values for various land use/land cover (LULC) scenarios, including a hypothetical one in which a series of parks and greenways were added in the city of Baton
Rouge. HEC-HMS was then used to model the impacts of changing imperviousness on surface runoff, and, finally, HEC-RAS was used to spatially model inundation in the Amite River Basin due to simulating several storms of varying intensity and spatial distribution over the different LULC scenarios. Next, Chapter 4 presents the results of numerous simulations based on different combinations of storms and LULC scenarios. Finally, Chapter 5 presents some discussion and conclusions based on the findings reported in Chapter 4, as well as highlighting some opportunities for future research.
Chapter 2. Literature Review

2.1. Floodplains and ecosystem services

In addition to their intrinsic environmental value, floodplains and wetlands provide valuable ecosystem services to human communities, ranging from photosynthesis and provision of fresh water to tourism and flood control (Figure 8). The view that natural ecosystems have intrinsic value independent of their relationship to humans has been argued extensively, e.g. by Singer (1977) and Rea and Munns (2017), and forms the basis of modern conservation biology (Piccolo, 2017). Building on this valuation, economic values can also be calculated to represent more tangibly the value of these ecosystems to human communities. A study on the wetlands and floodplains in the Otter Creek watershed of Vermont valued the damages prevented by these natural systems during Hurricane Irene at between $627,000 and $2,000,000 (Watson et al., 2016). The environmental degradation of the ARB due to channelization and encroachment from development not only poses a threat to the Basin’s ecology in its own right, but also results in the loss of critical ecosystem services on which human residents of the Basin depend. Zedler and Kercher (2005) identify four main ecosystem services provided by wetlands: support for biodiversity, water quality control, flood mitigation, and carbon storage. This thesis will focus primarily on the capacity of the Amite River Basin’s floodplains for flood control and mitigation.

Land cover change affects hydrology and flow regimes in several ways, including the expansion of impervious surfaces, urban encroachment onto existing floodplains, and loss of the ability of wetlands to mitigate flooding effects. As the population of the ARB has increased, suburban sprawl has dominated development patterns, even in areas
known to be flood-prone (Colten, 2017). Aside from the consideration that risk of flooding is elevated for residents living in floodplains, increasing impervious cover also affects hydrology directly by changing the basin geomorphology, as shown in Figure 9. The effects of increased imperviousness involve reduced infiltration and interception, changing evapotranspiration dynamics, and loss of surface roughness (Alley & Veenhuis,
Taken together, these effects reduce the amount of water absorbed and increase the volume and velocity of surface runoff.

Changes in vegetation patterns can affect runoff routing and surface flow. Riverine wetlands act as an important check on flooding by increasing interception and infiltration, and their removal, coupled with channelization and straightening, further reduces the natural ability of floodplains to absorb and slow floodwaters, especially for lower AEP
storms (Brinson, 1993). Roughness of channels and overland areas is represented in hydraulic software models by the Manning’s “n” coefficient, which can be valuable for modeling flow along channels and over land surface, but may lose some precision in the latter due to its empirical nature (Kalyanapu et al., 2009).

Figure 10 shows some of the physical effects of plants on streamflow, including the physical impediment of flow and interception of precipitation. During a storm, leaves and stems will intercept a portion of the overall rainfall, which then either descends the plant more slowly or evaporates before reaching the ground altogether. Interception of precipitation can be significant, especially for broadleaf forests. A study by Rowe (1983) of beech forest (Notofagus sp.) in New Zealand found that a maximum of 35% of precipitation was lost to interception during summer when leaf coverage was greatest. Interception losses were measured at 8-18% in a mixed rice, maize, and cassava cropland in Indonesia (van Dijk & Bruijnzeel, 2001b), demonstrating that even moderate vegetative cover can have a significant effect on altering land surface runoff. A recent Soil and Water Assessment Tool (SWAT) model analysis of surface runoff patterns in the Biobío Region of Chile found that the conversion of 28.64% of the study area from scrubland and native forest to exotic tree plantations decreased annual surface water flowrates, largely due to a 4.22% increase in annual evapotranspiration rates (Martínez-Retrete et al., 2020). For a storm such as the Louisiana August 2016 event, the extreme number of consecutive hours of rainfall would likely result in a saturated canopy, which would likely provide diminishing returns regarding interception of precipitation as the storm progressed (van Dijk & Bruijnzeel, 2001a). For this thesis, the introduction of parks and green spaces via incorporation of the 1948 Bartholomew parks plan into the Amite
River Basin Numerical Model (ARBNM) will change impervious cover, time of concentration, and storage coefficients for several Hydrologic Unit Code (HUC)-12 level subbasins in the city of Baton Rouge.

![Diagram](image)

Figure 10. The main physical impacts of riparian vegetation on water cycling: 1, interaction with over-bank flow by stems, branches and leaves (turbulence); 2, flow diversion by log jams; 3, change in the infiltration rate of flood waters and rainfall by litter; 4, increase of turbulence as a consequence of root exposure; 5, increase of substrate macroporosity by roots; 6, increase of the capillary fringe by fine roots; 7, stemflow (the concentration of rainfall by leaves, branches and stems); 8, condensation of atmospheric water and interception of dew by leaves. Source: Tabacchi et al. (2000).

2.2. Urban flood modeling

Relationships between urban LULC change and flood dynamics have been established, as well. The relationship between anthropogenic influence and corresponding rise in surface runoff rates has been supported by studies such as Ward et al. (2008), in which climate and hydrological models were coupled to simulate discharge in the Meuse basin of northwest Europe for baseline (4000-3000 B.C.E.) and anthropogenically-influenced
(1000-2000 C.E.) climate and land cover conditions. Land cover change via deforestation and urban expansion was found to be the greatest driver of increased discharge in the basin for 1000-2000 C.E. relative to the pre-development historical baseline, with mean annual discharge increasing from 244.8 m$^3$/s from 4000-3000 B.C.E. to 270.0 m$^3$/s during the 20$^{th}$ century, a 10.3% increase. As reforestation has replaced significant swaths of agricultural land, however, climate change replaced land use change as the main driver of increased discharge since the 19$^{th}$ century as the AEP of high-flow events increased from 1.3% under natural conditions to 1.5% from 1000-2000 C.E. and, finally, to 2.5% during the 20$^{th}$ century.

A number of models have been used to examine the impact of urbanization on flooding along the Gulf Coast of the United States due to extreme precipitation events (Hovenga et al., 2016; Sebastian et al., 2019; Zhang et al., 2018). SWAT modeling of the combined effects of climate change and LULC change on surface runoff and sediment transport in the Apalachicola River watershed of Florida determined the response to be nonlinear, with LULC contributing more significantly to sediment loading than to surface runoff (Hovenga et al., 2016). An analysis of the relative impacts of urban development and climate change on Hurricane Harvey flooding in Houston using the Vflo® distributed hydrologic model found urbanization effects to be the larger contributor to exacerbated flooding impacts (Sebastian et al., 2019). In their study, the authors compared four scenarios representing a circa-1900 baseline, present-day conditions, development-only, and climate change-only scenarios (Figure 11). To approximate a pre-development condition, the study authors changed imperviousness and channel roughness values based on historical maps and imagery. Bodies of water with significant impacts on
hydraulics, such as reservoirs and detention ponds, were incorporated into the model via stage-storage and stage-discharge curves rather than being modeled physically. For the climate change scenario, present-day conditions were taken to represent a 15% increase in precipitation over 1900. In terms of relative impacts, the maximum observed increase in peak flow for the development-only scenario was 54% (±28%) higher relative to 1900 baseline conditions, while the maximum increase observed in the climate change-only scenario was a 20% (±3%) increase over baseline, and the two scenarios combined produced an increase of 84% (±35%).

Figure 11. Flows along four bayous in the Houston area during Hurricane Harvey, with pre-anthropogenic baseline conditions in grey, addition of climate change effects in blue, addition of developed areas in green, and present-day conditions with both in black. Relative to present-day conditions, the no-development scenarios (grey and blue) show an attenuated peak, peaking at a lower total discharge value AND peaking later than the two developed scenarios (green and black). Source: Sebastian et al. (2019).
One climatological analysis based on the Weather Research and Forecast model (WRF) suggests that urbanization in Houston, TX affected flooding not only hydrologically at ground-level, but also in the amount of precipitation that fell on the city itself (Zhang et al., 2018). The authors concluded that in addition to exacerbating flooding by increasing conductivity and reducing infiltration, urbanization both increased total precipitation by increasing surface drag and urban surface warming and shifted it spatially toward the east when compared to a “NoUrban” scenario where urban land cover was replaced with cropland (Figure 12). Ultimately, they found that the combined effects of urbanization on the frequency, distribution, and intensity of precipitation and inundation increased the likelihood of similarly extreme flooding by 21 times versus the “NoUrban” scenario.

The Corps of Engineers’ HEC suite of programs, especially HEC-HMS and HEC-RAS, are also widely used in simulations of past and future land cover scenarios. Studies employing these programs often derive land cover data directly from Landsat imagery (Olang & Fürst, 2011) or, in the U.S., from various LULC products produced by USGS and partner agencies (Woltemade et al., 2020). Examining land cover changes in Kenya’s Nyando River Basin between 1973 and 2000, Olang and Fürst (2011) used HEC-HMS to show that peak flood discharges increased by 16% for the whole basin while areas deforested to make way for agriculture experienced significantly higher increases in peak discharge of between 30 and 47%. Woltemade et al. (2020) used 1992-2011 National Land Cover Dataset maps (Homer et al., 2015) and 1938-2010 USGS EROS historical backcasting and future projections maps (Sohl et al., 2016) with HEC-HMS in their study to determine the impacts of land cover and climate change on flooding in the Delaware River Basin. Similarly to Sebastian et al. (2019), they found land cover change to have a
Figure 12. Simulations of precipitation from Hurricane Harvey over a present-day urbanized scenario on top and “NoUrban” scenario on the bottom, in which developed areas were replaced with cropland. Accumulated precipitation totals are much greater for the Urban BEM model than for the NoUrban scenario. Source: Zhang et al. (2018).

greater relative impact on flooding than climate change in actively developing urban areas. Climate change was found to have more of an impact outside of urban areas and in urban areas where development and growth rates were either stagnant or relatively low.
Chapter 3. Methodology

3.1. Amite River Basin Numerical Model overview

This study was conducted using Version 1.0 of the Amite River Basin Numerical Model (ARBNM) produced by Dewberry Engineers for the Louisiana Department of Transportation and Development (LADOTD). The model consists of several software components, including a HEC-HMS model and coupled 1D/2D HEC-RAS model. A copy of the model was obtained from LADOTD via public records request for this study.

First, surface runoff calculations were conducted in HEC-HMS, Version 4.2.1. The HMS model of the Basin, shown in Figure 13, consists of 720 subbasins, over 550 hydrological routing reaches, and over 700 junctions. It is the primary input point for parameters related to urbanization and land use/land cover change. The six primary components of the HEC-HMS model are the Basin Models, Meteorological Models, Control Specifications, Time-Series Data, Paired Data, and Grid Data. Basin Models describe the physical properties of the soil and land surface, Meteorological Models control amount and timing of precipitation, Control Specifications set start and end times for the simulation, Time-Series Data incorporates measurements from precipitation and discharge gauges, Paired Data enables more precise control of specific regions using inputs such as stage-discharge curves and diversion functions, and gridded precipitation models are incorporated in Grid Data. Dewberry included four rain-on-grid calibration storms models for use with the ARBNM based on precipitation events of differing intensities that occurred in March 2016, August 2016, August 2017, and October 2017 that were then employed in this study. Data for each subbasin is translated into a point outflow value for each subbasin at each time step. The HMS model also uses Green and Ampt soil loss and
Figure 13. HEC-HMS model of the Amite River Basin, with flowlines in green, routing reach lines in blue, individual subbasins and junctions indicated with icons, and subbasins color-coded by sub-watershed. Source: Dewberry Engineers Inc. (2019).
ModClark precipitation transform methods, which will be explained in detail in Sections 3.2 and 3.3. Outputs from the HEC-HMS model simulations are stored in HEC-Data Storage System (DSS) files, which are then linked to the HEC-RAS model via unsteady flow boundary conditions.

The HEC-RAS model is a coupled 1D/2D model which is used to simulate 1D channel and 2D overland flow data. Both 1D and 2D domains receive HEC-HMS output data directly via DSS files. Figure 14 shows the distribution of 1D and 2D areas and level of detail applied to channel reaches and 2D areas throughout the RAS model. 1D routing was used for main channels and for nearly all of the model north of the Mississippi border. There, Modified Puls Routing was used to enable correct routing of flows to the confluence of the East and West Forks of the upper Amite River. 1D was used here instead of 2D to conserve computing resources and simplify routing in the less-populated northern part of the Basin, where flooding was more limited than in the 2D areas to the south. 2D modeling was mostly reserved for the greater Baton Rouge region, from East Baton Rouge and Livingston Parishes, south. This area was modeled in 2D to capture greater detail and accuracy in flood dynamics in the urbanized part of the Basin. In both 1D and 2D areas, highest detail was applied to the main channels of the Amite and Comite Rivers, as well as the Amite River Diversion Canal (ARDC), while medium detail was used for major tributaries and low detail for minor tributaries. Within the 2D areas of the HEC-RAS geometry, a new Manning’s n land surface roughness coefficient layer was created for each land cover scenario using the same land cover rasters used in ArcGIS. Profile lines were drawn in RAS Mapper to enable closer examination of flow effects in specific locations of interest.
Figure 14. Levels of detail applied in creation of the Amite River Basin Numerical Model. Source: Dewberry Engineers Inc. (2019).
3.2. Green and Ampt soil loss method

The HEC-HMS portion of the ARBNM was developed by Dewberry using the Green and Ampt soil loss method. Equation 1, the Green and Ampt equation, calculates the rate of infiltration of precipitation into soil:

\[ f_t = K \left[ 1 + \frac{(\phi - \theta_i)S_f}{F_t} \right] \]

Equation 1.

Here, \( f_t \) represents precipitation loss during the time period \( t \), \( K \) is the saturated hydraulic conductivity, \( \phi \) is soil porosity, \( \theta_i \) is initial water content, \( S_f \) is the wetted suction front, and \( F_t \) is the cumulative loss at time \( t \) (U.S. Army Corps of Engineers, 2000). In HEC-HMS, an initial abstraction parameter accounts for any interception process not captured by the primary equation. Additionally, the percent impervious field indicates the portion of the subbasin for which the software will not calculate soil loss values. For this project, the only Green and Ampt variable adjusted was percent impervious. Values were calculated in Microsoft Excel based on land cover rasters and then pasted into the “Impervious (%)” field of the Green and Ampt loss parameters in HEC-HMS. The other Green and Ampt components were not modified for this study, given that they represent more intrinsic properties of the soil and thus generally would not be expected to have significantly changed over the given study period, especially in undeveloped areas.

3.3. Modified Clark precipitation transform method

The Modified Clark (ModClark) method was required for the ARBNM HEC-HMS model due to the use of Next Generation Weather Radar (NEXRAD) gridded precipitation data (Dewberry Engineers Inc., 2019). Its use allows for variations in travel time of surface runoff from different grid cells within a subbasin to the outlet point, which are then adjusted
according to the overall time of concentration, TC. The main parameters for the ModClark method are TC and storage coefficient, R. The below equations were used to calculate ModClark parameters for each of the modeled LULC scenarios in all of the HEC-HMS subbasins (Fort Bend County Drainage District, 2011):

\[
TC + R = 128 \frac{(L)^{0.57}(N)^{0.8}}{(S_0)^{0.11}(10)^{1}}
\]

Equation 2.

\[
TC = (TC + R) \times 0.38(\log S_0)
\]

Equation 3.

\[
R = (TC + R) - TC
\]

Equation 4.

Where L = channel length, S = channel slope, N = weighted Manning’s n roughness coefficient, S_0 = average basin slope, and I = effective impervious ratio. A ponding adjustment factor may be applied to the storage coefficient to account for ponded areas. Ponding factors were calculated by Dewberry for the ARBNM using National Hydrology Dataset Plus (NHD+) data; all land with slopes under 1% was included in the ponding area (E. Zgonina, personal communication, July 8, 2020). Channel length and slope were not modified for this research project, although they have changed throughout the Basin during the time period used for this study (Harris, 2020). Average basin slope was not modified, either, as it was not expected to have changed significantly over the study period. Manning’s n values for ModClark calculations were broadly applied, ranging from 0.03 near Maurepas to 0.05 for some 2D areas. Manning’s n values were applied at finer granularity in HEC-RAS by loading land cover maps and assigning Manning’s n values to
different land cover types as defined in the Multi-Resolution Land Characteristics (MRLC) Consortium’s 2011 National Land Cover Database (NLCD) (Table 2).

Table 2. Manning’s n values for 2D flow areas for use with HEC-RAS NLCD land cover import. Source: adapted from Dewberry Engineers Inc. (2019) with light modifications for clarity.

<table>
<thead>
<tr>
<th>2011 NLCD code</th>
<th>Description</th>
<th>Manning’s n</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Open water</td>
<td>0.035</td>
</tr>
<tr>
<td>21</td>
<td>Developed, open space</td>
<td>0.09</td>
</tr>
<tr>
<td>22</td>
<td>Developed, low intensity</td>
<td>0.10</td>
</tr>
<tr>
<td>23</td>
<td>Developed, medium intensity</td>
<td>0.10</td>
</tr>
<tr>
<td>24</td>
<td>Developed, high intensity</td>
<td>0.15</td>
</tr>
<tr>
<td>31</td>
<td>Barren land</td>
<td>0.10</td>
</tr>
<tr>
<td>41</td>
<td>Deciduous forest</td>
<td>0.12</td>
</tr>
<tr>
<td>42</td>
<td>Evergreen forest</td>
<td>0.12</td>
</tr>
<tr>
<td>43</td>
<td>Mixed forest</td>
<td>0.12</td>
</tr>
<tr>
<td>52</td>
<td>Shrub/scrub</td>
<td>0.12</td>
</tr>
<tr>
<td>71</td>
<td>Herbaceous</td>
<td>0.07</td>
</tr>
<tr>
<td>81</td>
<td>Hay/pasture</td>
<td>0.09</td>
</tr>
<tr>
<td>82</td>
<td>Cultivated crops</td>
<td>0.10</td>
</tr>
<tr>
<td>90</td>
<td>Woody wetlands</td>
<td>0.12</td>
</tr>
<tr>
<td>95</td>
<td>Emergent herbaceous wetlands</td>
<td>0.12</td>
</tr>
</tbody>
</table>

3.4. Land use/land cover and imperviousness

3.4.1. Land cover products used

For this study, several different land use/land cover scenarios were created to model various historical and hypothetical conditions for analysis. Dewberry’s ARBNM was created to represent existing conditions as of 2018 (Dewberry Engineers Inc., 2019). Land cover and imperviousness values for the ARBNM were based on MRLC’s 2011 NLCD, which was the most recently published iteration available at the time (Yang et al., 2018). LULC data and imperviousness values for this thesis research have been updated with NLCD 2016, which was released in early 2019. NLCD 2016 land cover and imperviousness are shown below in Figure 15 and Figure 16, respectively.
Figure 15. 2016 MRLC NLCD land cover for the Amite River Basin. Pixel size is 30 m by 30 m. Source: Yang et al. (2018).
Figure 16. 2016 MRLC NLCD imperviousness for the Amite River Basin. Pixel size is 30 m by 30 m. Source: Yang et al. (2018).
Additional land-use scenarios were created for this thesis project based on land cover data created by the United States Geological Survey’s (USGS) Earth Resources and Observation Science (EROS) Center for the years 1938 (Figure 17), 1964 (Figure 18), and 1992 (Figure 19). USGS EROS backcasting datasets covering 1938-1992 were created not with the intent to perfectly recreate historical land cover conditions, but to provide a useful baseline for secondary comparisons (Sohl et al., 2016). The 1938, 1964, and 1992 land cover conditions used for this thesis will therefore be referred to as land cover “scenarios” and not presented as a realistic representation of actual land cover conditions for those given years.

EROS and NLCD land cover rasters were used to develop Manning’s n layers for 2D overland flow areas in HEC-RAS, while EROS land cover and NLCD imperviousness rasters were used to calculate percent imperviousness for the Green and Ampt and ModClark parameters in HEC-HMS. For both the Green and Ampt and ModClark calculations, imperviousness was the only variable altered with the HEC-HMS subbasins. The NLCD 2016 imperviousness raster was clipped to each subbasin and total percent imperviousness was calculated for each, but a different approach was necessary for the 1938-1992 EROS datasets, in which urban areas are represented by a single “Developed” category representing pixels with impervious values of 20% or greater.

3.4.2. Calculation of imperviousness for EROS land cover rasters

Imperviousness for the 1938, 1964, and 1992 land cover scenarios was calculated using EROS land cover rasters, NLCD 2011 imperviousness, and United States Census Bureau population statistics. First, 2010 U.S. Census population totals by parish or county
Figure 17. 1938 USGS EROS land cover scenario for the Amite River Basin. Pixel size is 250 m by 250 m. Source: Sohl et al. (2016).
Figure 18. 1964 USGS EROS land cover scenario for the Amite River Basin. Pixel size is 250 m by 250 m. Source: Sohl et al. (2016).
Figure 19. 1992 USGS EROS land cover scenario for the Amite River Basin. Pixel size is 250 m by 250 m. Source: Sohl et al. (2016).
were divided by parish or county area (Mississippi Geospatial Data Catalog, 2017) to produce estimates of population density per square mile at the parish and county level for each of the 4 Mississippi counties and 7 Louisiana parishes that comprise the Amite River Basin. Population density and parish/county-level NLCD 2011 impervious fraction were then correlated with each other to produce Equation 5:

\[ I = 0.0114d + 0.1647 \]  

Equation 5.

Where \( I \) = effective impervious ratio for the parish or county and \( d \) = the population density. The full relationship is shown below in Figure 20. NLCD 2011 was used instead of NLCD 2016 for this step in order to maintain the fidelity of the relationship relative to the 2010 Census. Application of Equation 5 to other land cover years assumes year-to-year similarity between population density and impervious cover fraction. While this is a reasonable assumption given that most of the parishes and counties in the study area remain largely rural today, it does not account for potential differences in patterns of development between different time periods. Once obtained, Equation 5 was used to translate population density data for the 1940, 1960, and 1990 Census years into impervious cover percentages for each parish and county for the 1938, 1964, and 1992 land cover scenarios, respectively.

Next, population density was calculated for the portions of each parish and county that lie within the Amite Basin watershed. Historical EROS land cover rasters were clipped first to each county/parish unit in ArcGIS. These parish/county-level raster clips were then
clipped a second time to the boundaries of the Amite River Basin (Figure 21), for a total of 11 doubly clipped land cover raster fragments for each land cover year.

![Graph showing relationship between population density and imperviousness.](image)

**Figure 20.** Relationship between 2010 population density (U.S. Census Bureau, 2012) and 2011 imperviousness (Homer et al., 2015) at the parish and county level for the 4 MS counties and 7 LA parishes of the ARB. Population density values for past years were substituted into this equation to produce whole-parish/county percent impervious figures for 1938, 1964, and 1992 scenarios.

To estimate population density for each raster fragment, a second correlation was derived by relating percent developed area cover for EROS land cover year to population density:

\[
D = ad + b
\]

**Equation 6.**

Where \( D \) = developed area as a percent of total area and coefficients \( a \) and \( b \) vary by year. As with Equation 5,

Equation 6 was then applied to each raster fragment in order to estimate the total population contained within each parish/county fragment lying within the boundaries of the Amite Basin. Now having both \( I \) and \( D \) at the parish/county level from Equation 7, it was possible to calculate a parish/county-scale value for \( C \). Population densities estimated by using
Equation 6 were then input into Equation 5 in order to obtain Equation 7, which is required for ModClark calculations when using land cover datasets.
Figure 21. EROS 1938 land cover raster clipped to parish/county and Amite Basin boundaries for a total of 11 fragments.

that use developed area instead of percent impervious (Fort Bend County Drainage District, 2011):

\[ I = CD \times 10^{-4} \]

Equation 7.

Where C = the average impervious percentage of each EROS “Developed” pixel for a given parish or county. Values for C and D specific to each parish/county were then used to calculate the impervious percentage of all 720 subbasins in the ARBNM for the EROS land cover scenarios. Values for C were the same for all subbasins within a given parish or county, while D values were unique to each subbasin. This approach resulted in slightly lower granularity than possible when using NLCD impervious rasters, although some was preserved by using unique values of D for each subbasin based on each one’s count of “Developed” pixels. By averaging pixel values across the entire subbasin, this methodology also avoids problems arising from differing pixel resolutions between the NLCD and EROS datasets.

3.4.3. Accounting for population decrease

Procedural adjustments were made to address population loss in some parishes and counties in the study area. Three of the four Mississippi counties in the Amite Basin—Amite, Franklin, and Wilkinson—experienced population loss over all three time intervals in this study: 1938-64, 1964-92, and 1992-2016, represented by U.S. Census years 1940-60, 1960-90, and 1990-2019 (estimate), respectively. Lincoln County and St. Helena Parish experienced population drops from 1940-60 and East Feliciana Parish lost population from 1960-90. Table 3 shows some changes in population and impervious
surface extent from 1990-2000 in the Chesapeake Bay watershed (Brophy-Price & Rolband, 2010). In both cases where a given locality experienced a net decrease in population, impervious coverage increased regardless.

Table 3. Correlations between population change and impervious area change from 1990-2000 in the Chesapeake Bay watershed. Source: Brophy-Price and Rolband (2010).

<table>
<thead>
<tr>
<th>Jurisdiction (portion within the Chesapeake Bay watershed)</th>
<th>Population Increase (1990-2000) (%)</th>
<th>Impervious Area Increase (1990-2000) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chesapeake Bay Watershed</td>
<td>10.3%</td>
<td>14.2%</td>
</tr>
<tr>
<td>Delaware</td>
<td>23.2%</td>
<td>28.4%</td>
</tr>
<tr>
<td>District of Columbia</td>
<td>-5.7%</td>
<td>1.9%</td>
</tr>
<tr>
<td>Maryland</td>
<td>10.7%</td>
<td>15.2%</td>
</tr>
<tr>
<td>New York</td>
<td>-2.2%</td>
<td>3.7%</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>5.4%</td>
<td>10.6%</td>
</tr>
<tr>
<td>Virginia</td>
<td>16.8%</td>
<td>18.0%</td>
</tr>
<tr>
<td>West Virginia</td>
<td>18.0%</td>
<td>21.0%</td>
</tr>
</tbody>
</table>

The Amite Basin parishes and counties, however, generally have smaller population totals, a more rural setting, proportionally greater and mostly earlier population declines relative to the jurisdictions in the Chesapeake Bay study. Given this, it is assumed here in this thesis that these differences may be sufficient to suggest that population declines observed in the Amite Basin would not necessarily be accompanied by an increase in impervious surface cover. Therefore, the population density-based methodology described above for calculating the imperviousness of the Amite watershed’s subbasins was adjusted by halving reductions in population that would otherwise occur in given time intervals (see Table 4).

By using a lower population value for Amite County in the 1992 scenario, for example, than that measured by the 1990 Census, the effective impervious ratio, I, would be slightly lower than if the full population value were used instead. As shown in Table 3, and further
Table 4. Sample treatment of Amite County, MS for 1992 land cover scenario using methodology described above.

<table>
<thead>
<tr>
<th>1990 population (est.)</th>
<th>2019 pop. (est.)</th>
<th>Change</th>
<th>Adjusted change (50% of observed change)</th>
<th>1990 pop. (adj.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13,328</td>
<td>12,297</td>
<td>-1,031</td>
<td>-515.5</td>
<td>12,812.5</td>
</tr>
</tbody>
</table>

Supported by the 1-pixel increase in Developed cover for Amite County between the 1938 and 1964 scenarios despite a 19.1% decrease in population from 1940 to 1960, this adjustment acknowledges that population decline does not necessarily imply a reduction in impervious or developed surface. The impervious ratio of developed areas, C, increased for the Amite Basin from 26.6% in NLCD 2001 to 29.7% in NLCD 2016, indicating that developed areas became more impervious in parallel with the overall increase in developed area from 3.11% to 3.85% over the same time period.

Reducing population loss by half in these calculations avoids having historical impervious values that are too high. Eliminating population loss altogether from impervious surface calculations, such as by assigning the 2019 estimated population total to the 1990 population-based scenario for Amite County in Table 4 above, would result in higher impervious values for historical scenarios in those parishes and counties that experienced population losses. This would then be expected to lower ModClark time of concentration, TC, and storage coefficient, R, parameter values, indicating shorter time to outlet for runoff in the subbasin and lessened storage capacity. Conversion of cropland to forest and wetland in many of these same parishes and counties occurred at the same time as these population losses, but this change in vegetative composition does not affect surface imperviousness and thus would not figure in the ModClark calculations as addressed in this thesis. Vegetation can have significant effects on surface runoff, however (Martínez-Retureta et al., 2020; Rowe, 1983; van Dijk & Bruijnzeel, 2001b; Zhao et al., 2016).
Reducing population loss by only half in these calculations potentially avoids having historical TC and R values that are too low, as might be the case if population loss effects were totally negated in impervious cover calculations.

### 3.4.4. 1948 Baton Rouge parks plan

An additional land use scenario was created for this study by using the 1948 parks plan (Figure 22) to model the effects of restoring vegetative cover to parts of Baton Rouge. The parks plan, showing only the parks and greenways proposed as part of the plan, is a subset of the master plan shown in Figure 5.

To incorporate the plan into the ARBNM, proposed and existing parks were traced in ArcGIS and saved as a shapefile. The NLCD 2016 imperviousness raster was then clipped around the parks shapefile, excising the park areas from the raster’s coverage extent (Figure 23). Imperviousness was calculated as with the original 2016 land cover conditions for affected subbasins, with the new impervious percentage results being divided by the total area of each subbasin. In this way, impervious surface values were effectively rendered to zero within all areas covered by the proposed parks. Green and Ampt and ModClark calculations were then performed as before, using the newly calculated impervious values for subbasins within the plan’s area of coverage.

### 3.5. Storms

#### 3.5.1. ARBNM storms

The ARBNM has four meteorological models based on storms that occurred in the Amite River Basin in March 2016, August 2016, August 2017, and October 2017; their peak flow values and estimated frequencies are shown in Table 5. These storm models were developed for model calibration with the goal of recreating the storms of 2016 and 2017.
Figure 22. Parks (shown in green) proposed as part of the 1948 Baton Rouge master plan. Park boundaries were traced in ArcGIS and then added to NLCD and USGS LULC rasters to analyze the effects of additional pervious green space on runoff and inundation. Source: Harland Bartholomew & Associates (1948).
Figure 23. 1948 Harland Bartholomew plan overlaid with NLCD 2016 imperviousness layer showing addition of parks and greenways (in green). Amite River Basin boundary shown in black.
as accurately as possible and are thus variable both spatially and temporally (Figures 24-27). The geographical center of each storm differs between events, as well as the amount and intensity of precipitation outside this focal region. This complicates efforts to compare results across subbasins directly.

Table 5. Peak flows (in cubic feet per second [cfs]), return periods, and annual exceedance probabilities measured for the four Dewberry calibration storms at three storm gauges along the Amite and Comite rivers. Source: Harris (2020).

<table>
<thead>
<tr>
<th>Event</th>
<th>Peak flow (cfs)</th>
<th>Return period (years)</th>
<th>AEP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amite at Darlington</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>August 2017</td>
<td>4,200</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>October 2017</td>
<td>12,700</td>
<td>1.4</td>
<td>71.4</td>
</tr>
<tr>
<td>March 2016</td>
<td>24,900</td>
<td>3</td>
<td>33.3</td>
</tr>
<tr>
<td>August 2016</td>
<td>116,000</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>Amite at Denham Springs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>August 2017</td>
<td>7,740</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>October 2017</td>
<td>25,100</td>
<td>1.6</td>
<td>62.5</td>
</tr>
<tr>
<td>March 2016</td>
<td>64,900</td>
<td>6</td>
<td>16.7</td>
</tr>
<tr>
<td>August 2016</td>
<td>266,000</td>
<td>&gt; 500</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>Comite at Olive Branch</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>August 2017</td>
<td>2,565</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>October 2017</td>
<td>9,096</td>
<td>2.4</td>
<td>41.7</td>
</tr>
<tr>
<td>March 2016</td>
<td>10,101</td>
<td>2.8</td>
<td>35.7</td>
</tr>
<tr>
<td>August 2016</td>
<td>72,642</td>
<td>500</td>
<td>0.2</td>
</tr>
</tbody>
</table>

3.5.2. Spatially uniform storms

To remove the effects of spatial and temporal variability on simulation results and validate methodology, four hypothetical, spatially uniform storms of varying return periods were created for use with the HEC-HMS portion of the ARBNM. Four meteorological models representing annual exceedance probabilities of 1, 4, 10 and 50%, which correspond to expected return periods of 100, 25, 10, and 2 years, respectively, were created. Data for development of the meteorological models was taken from the NOAA Atlas partial duration-based precipitation frequency estimates for NOAA’s Denham Springs station.
Figure 24. The March 2016 storm event used in the ARBNM, showing spatial variation of rainfall depths. Source: Dewberry Engineers Inc. (2019).
Figure 25. The August 2016 storm event used in the ARBNM, showing spatial variation of rainfall depths. Source: Dewberry Engineers Inc. (2019).
Figure 26. The August 2017 storm event used in the ARBNM, showing spatial variation of rainfall depths. Source: Dewberry Engineers Inc. (2019).
Figure 27. The October 2017 storm event used in the ARBNM, showing spatial variation of rainfall depths. Source: Dewberry Engineers Inc. (2019).
(Perica et al., 2013). The four storms were designed according to the same method, with a 15-minute period of peak intensity reached at 50% of the storm duration, which was set at 48 hours. All subbasins received the same rainfall depth and timing of precipitation.

3.6. HEC-RAS model

After calculating Green and Ampt and ModClark parameters and completing HEC-HMS runoff simulations, HMS results were integrated into the HEC-RAS model via DSS files. DSS files provided the source information for all unsteady flow boundary conditions except for five locations along the Amite River and diversion canals that used stage hydrographs instead. In addition to modifications of the HEC-HMS parameters, a new Manning’s n layer was created for each land cover scenario in the HEC-RAS model. The primary data integration pathway for this project is shown in Figure 28; impervious cover values determined from LULC maps were used in parameter calculations for HEC-HMS, and outputs from HEC-HMS simulations were then integrated into the HEC-RAS model to produce flood maps for analysis. Manning’s n layers were also created in HEC-RAS from the land use/land cover layers used in ArcGIS. Manning’s n values were applied to EROS land cover rasters following the values assigned for NLCD as a guide with only minor deviations when necessary to consolidate or split categories (Table 6). The ARBNM’s default 2018 Existing Conditions geometry was copied for each land cover scenario created and then associated with the correct Manning’s n layer. Unsteady flow simulations were then run for each of the calibration and spatially uniform storms over each of the land cover scenarios. Finally, profile lines were drawn in RAS Mapper to enable closer examination of flow effects in specific locations of interest.
Figure 28. Simple schematic showing main data integration pathway.

Table 6. Manning’s n values for 2D flow areas for use with HEC-RAS EROS land cover import, showing corresponding NLCD categories and values. Source: adapted from Dewberry Engineers Inc. (2019) with additional data from Sohl et al. (2016).

<table>
<thead>
<tr>
<th>NLCD code</th>
<th>NLCD description</th>
<th>Manning’s n</th>
<th>EROS code</th>
<th>EROS description</th>
<th>Manning’s n</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Open water</td>
<td>0.035</td>
<td>1</td>
<td>Water</td>
<td>0.035</td>
</tr>
<tr>
<td>21</td>
<td>Developed, open space</td>
<td>0.09</td>
<td>2</td>
<td>Developed</td>
<td>0.12</td>
</tr>
<tr>
<td>22</td>
<td>Dev., low intensity</td>
<td>0.10</td>
<td>3-5</td>
<td>Clear-cut</td>
<td>0.11</td>
</tr>
<tr>
<td>23</td>
<td>Dev., medium intensity</td>
<td>0.10</td>
<td>6</td>
<td>Mining</td>
<td>0.10</td>
</tr>
<tr>
<td>24</td>
<td>Dev., high intensity</td>
<td>0.15</td>
<td>7</td>
<td>Barren</td>
<td>0.10</td>
</tr>
<tr>
<td>31</td>
<td>Barren land</td>
<td>0.10</td>
<td>8</td>
<td>Deciduous forest</td>
<td>0.12</td>
</tr>
<tr>
<td>41</td>
<td>Deciduous forest</td>
<td>0.12</td>
<td>9</td>
<td>Evergreen forest</td>
<td>0.12</td>
</tr>
<tr>
<td>42</td>
<td>Evergreen forest</td>
<td>0.12</td>
<td>10</td>
<td>Mixed forest</td>
<td>0.12</td>
</tr>
<tr>
<td>43</td>
<td>Mixed forest</td>
<td>0.12</td>
<td>11</td>
<td>Grassland</td>
<td>0.07</td>
</tr>
<tr>
<td>52</td>
<td>Shrub/scrub</td>
<td>0.12</td>
<td>13</td>
<td>Cultivated crops</td>
<td>0.10</td>
</tr>
<tr>
<td>71</td>
<td>Herbaceous</td>
<td>0.07</td>
<td>14</td>
<td>Hay/pasture land</td>
<td>0.09</td>
</tr>
<tr>
<td>81</td>
<td>Hay/pasture</td>
<td>0.09</td>
<td>15</td>
<td>Herbaceous wetlands</td>
<td>0.12</td>
</tr>
<tr>
<td>82</td>
<td>Cultivated crops</td>
<td>0.10</td>
<td>16</td>
<td>Woody wetlands</td>
<td>0.12</td>
</tr>
<tr>
<td>90</td>
<td>Woody wetlands</td>
<td>0.12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>95</td>
<td>Herbaceous wetlands</td>
<td>0.12</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 4. Results

4.1. Impervious surface estimation

The Amite River Basin, as a whole, is largely rural, contributing to the mostly smaller differences observed between land cover scenarios in HEC-RAS results for the Amite and Comite River main stems. Only 3.85% of the ARB was impervious in 2016, an increase from 0.82% calculated using the 1938 EROS land cover raster. Impervious surface cover percentages were likely slightly overestimated for the 1938, 1964, and 1992 EROS land cover maps, which provide developed area data but not imperviousness values. Because of this, differences in runoff and inundation were likely underestimated between the EROS land cover scenarios and 2016 conditions. C coefficients, the percent impervious of developed pixels for the EROS land cover maps, were calculated at the county/parish level. This reduced granularity of the results relative to using the NLCD impervious maps, which allow for a more direct calculation of imperviousness at the subbasin level. This likely led to an overestimate of impervious area for more rural subbasins and an underestimate for more highly developed subbasins in the 1938, 1964, and 1992 scenarios.

Imperviousness was probably also overestimated within Developed pixels in the EROS maps. The EROS Developed category is defined as being at least 20% impervious. Pixels in the EROS maps with less than 20% impervious cover were not captured by the methods used in this study, and population densities were thus slightly underestimated in non-Developed pixels and overestimated in Developed pixels. This effect was strongest in the Basin’s Mississippi counties, where the number of Developed pixels was low. C
coefficients ultimately had to be capped at 100% in a handful of subbasins for the EROS scenarios (given that an area cannot be more than 100% impervious). The SUB_COMITE_01 subbasin straddling the Comite River near Centreville, MS is an illustrative example of impervious overestimation. The subbasin was 0.87% impervious in 2016 according to NLCD impervious cover, but calculations using EROS data returned a value of 2.02% impervious in 1938. Although most of the subbasin is within Amite County, all of its developed pixels for the 1938 EROS scenario are in Wilkinson County, accounting for 37.5% of Wilkinson’s total developed area. Population in Wilkinson County fell from 15,955 in 1940 to an estimated 8,630 in 2019 (Table 1). Although the population of Wilkinson County dropped by 45.9% during this time, the impervious calculations resulted in a 56.9% decrease in impervious area for SUB_COMITE_01. It is unlikely that a decrease in population since 1938 would have been accompanied by an even greater decrease in impervious surface area in this part of rural Mississippi, given that residential and commercial development patterns in 1938 likely included smaller buildings and lower overall imperviousness. Imperviousness was also underestimated in many subbasins, such as BFount_Nich_US which had no Developed pixels in the 1938 EROS map despite including much of Louisiana State University’s Baton Rouge campus and the athletic stadium. Given that overestimations of imperviousness affected mostly rural subbasins, underestimations affected urban ones, and that the Amite River Basin was between 0.82% and 3.85% impervious during the study period, the ultimate effect on the whole Basin was most likely an overestimation of imperviousness for the EROS land cover scenarios and an underestimation of the effects of changing imperviousness on runoff and flooding.
4.2. Spatially uniform storm results

The charts in Figure 29 show the change in peak flow for all the subbasins for each of the four spatially uniform storms plotted against the change in imperviousness of each subbasin from 1938 to 2016. The changes in peak flow decrease slightly as storm size increases; the greatest observed change in flow is 169% for the 50% AEP storm, but 142% for the 1% AEP storm. The greatest absolute change in peak flow, however, was +2,247.90 cfs for the 1% AEP storm and +1,021.70 cfs for the 50% AEP storm. Eliminating spatial variability from storm models highlights the effects on flow peak and timing due to surface imperviousness—higher imperviousness results in higher flow amounts and earlier flow peaks. Larger storms with lower annual exceedance probabilities see greater absolute differences, but lesser proportional differences in flow rates than smaller storms with higher probabilities of annual exceedance. Differences in ground conditions lose importance as the soil approaches saturation and less of the water column is subject to friction effects from the land surface.

Six subbasins representing a range of impervious surface trends from high to little or no change between 1938 and 2016 land cover scenarios were chosen from higher-detail model regions (high-detail 1D and medium-detail 2D) for further analysis of the effects of the spatially uniform storms on runoff. From north to south, the selected subbasins and their associated waterways were SUB_DOYLEBAYOU_08 along Redwood Creek near Plank Road in East Baton Rouge Parish (EBRP), ColtonCrk_HWY16 along Colton Creek near Louisiana Highway 16 in Livingston Parish, Clyell_JoelWatts along Colyell Creek near Joel Watts Lane in Livingston Parish, Un2_NBrWards_US along the Normandy Lateral drainage canal west of North Branch Ward Creek in EBRP, GraysCrk_Hwy1033
along Gray’s Creek south of Denham Springs, and WardsCr_Highland along Ward Creek near Highland Road in Baton Rouge (Figure 30).

The impervious values for each subbasin were calculated as shown in Table 7, and flow results for these six subbasins from the 1% and 50% annual exceedance probability storms are plotted in Figure 31. Three of the subbasins, SUB_DOYLEBAYOU_08, GraysCrk_Hwy1033, and Clyell_JoelWatts, had low impervious values for both land use scenarios and showed relatively little difference in flood peak or timing between 1938 and
Figure 30. The six subbasins from high-detail 2D regions of the model isolated for further analysis of spatially uniform storm HEC-HMS simulation results. From north to south: SUB_DOYLEBAYOU_08 (black), ColtonCrk_HWY16 (green), Clyell_JoelWatts (magenta), Un2_NBrWards_US (blue), GraysCrk_Hwy1033 (yellow), and WardsCr_Highland (red). Subbasins are relatively small at this map scale, so stars were used instead of subbasin polygon outlines to enhance clarity and visibility.
2016. Un2_NBrWards_US, ColtonCrk_HWY16, and WardsCr_Highland, meanwhile, showed significant increases in and earlier onset of peak flow in 2016 relative to 1938.

Table 7. Impervious change from 1938 to 2016 for six selected subbasins in the Amite Basin.

<table>
<thead>
<tr>
<th>Subbasin name</th>
<th>% impervious, 1938</th>
<th>% impervious, 2016</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUB_DOYLEBAYOU_08</td>
<td>0.53</td>
<td>0.71</td>
<td>0.18</td>
</tr>
<tr>
<td>ColtonCrk_HWY16</td>
<td>0</td>
<td>20.95</td>
<td>20.95</td>
</tr>
<tr>
<td>Clyell_JoelWatts</td>
<td>0</td>
<td>0.68</td>
<td>0.68</td>
</tr>
<tr>
<td>Un2_NBrWards_US</td>
<td>18.79</td>
<td>35.42</td>
<td>16.63</td>
</tr>
<tr>
<td>GraysCrk_Hwy1033</td>
<td>1.04</td>
<td>2.58</td>
<td>1.54</td>
</tr>
<tr>
<td>WardsCr_Highland</td>
<td>0</td>
<td>11.88</td>
<td>11.88</td>
</tr>
</tbody>
</table>

Results from the above subbasins confirm that smaller magnitude, higher-AEP storms show a change in peak flow proportionally greater than the change observed for larger magnitude, smaller-AEP storms, which have greater absolute change in peak flow values (Table 8). Regarding the timing of flows, peak flow was reached sooner in 2016 than in 1938 for subbasins with higher increases in imperviousness, and slightly earlier for the 1% AEP storm than for the 50% AEP storm. Together, these results indicate that flow values peak earlier and at higher magnitudes when impervious surface cover increases in a given subbasin.

Table 8. Increase in peak flow from 1938-2016 for six subbasins expressed in % relative to 1938 flow values.

<table>
<thead>
<tr>
<th>Subbasin name</th>
<th>Increase in peak flow (1938-2016, in %)</th>
<th>Increase in peak flow (1938-2016, in cfs)</th>
<th>Change in timing of peak flow (1938-2016, in h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1% AEP storm</td>
<td>50% AEP storm</td>
<td>1% AEP storm</td>
</tr>
<tr>
<td></td>
<td>50% AEP storm</td>
<td>1% AEP storm</td>
<td>50% AEP storm</td>
</tr>
<tr>
<td>SUB_DOYLEBAYOU_08</td>
<td>0.36</td>
<td>4.7</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1.9</td>
<td>0</td>
</tr>
<tr>
<td>ColtonCrk_HWY16</td>
<td>39.64</td>
<td>505.9</td>
<td>-1.0</td>
</tr>
<tr>
<td></td>
<td>47.66</td>
<td>216.4</td>
<td>-0.75</td>
</tr>
<tr>
<td>Clyell_JoelWatts</td>
<td>1.21</td>
<td>32.7</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1.55</td>
<td>14.5</td>
<td>0</td>
</tr>
<tr>
<td>Un2_NBrWards_US</td>
<td>29.17</td>
<td>282.9</td>
<td>-0.5</td>
</tr>
<tr>
<td></td>
<td>34.30</td>
<td>129.3</td>
<td>-0.5</td>
</tr>
<tr>
<td>GraysCrk_Hwy1033</td>
<td>2.96</td>
<td>55.3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3.59</td>
<td>22.5</td>
<td>0</td>
</tr>
<tr>
<td>WardsCr_Highland</td>
<td>22.92</td>
<td>1253.6</td>
<td>-1.0</td>
</tr>
<tr>
<td></td>
<td>27.80</td>
<td>562.1</td>
<td>-0.75</td>
</tr>
</tbody>
</table>
Figure 31. HEC-HMS hydrographs for hypothetical, spatially uniform 1% and 50% annual exceedance probability storms for 1938 and 2016 land use conditions for six selected subbasins: (a) SUB_DOYLEBAYOU_08, (b) Un2_NBrWards_US, (c) ColtonCrk_HWY16, (d) WardsCr_Highland, (e) GraysCrk_Hwy1033, and (f) Clyell_JoelWatts. Note different y-axis scales.
4.3. ARBNM storm results

4.3.1. Basin-wide HEC-HMS results

All four of the storms used for model calibration by Dewberry in their ARBNM report were run over all four historical and present-day land cover scenarios. Results from HEC-HMS simulations indicate a generally positive correlation between change in imperviousness and change in peak flows observed for each subbasin (Figures 32-35). In general, subbasins that had an increase in impervious surface saw an increase in peak flow, and vice-versa. Overall, the greatest impact on flows due to impervious expansion happened during the 1964-1992 time interval. For the March 2016 event, 13.3% of all subbasins saw an increase in peak flows of 10% or greater during this time interval, versus 8.3% for the 1938-1964 interval and 11.0% for 1992-2016. These numbers were comparable to the same intervals for the August 2016 and 2017 storms. 1960-1990 was also the time interval that saw the greatest population increase in the Amite Basin during the study period, both percentage-wise and in absolute numbers: total Amite Basin population increased by 152,205 from 1940-1960 (55.3%), by 202,212 from 1960-1990 (61.9%), and by 182,305 from 1990-2019 (17.3%; Table 1).

Relationships between peak flow and impervious change are less tightly correlated between the 1992 EROS and 2016 NLCD scenarios for all storms and for the October 2017 storm for all land cover scenarios. For the 1992-2016 interval, this is largely attributable to the differences between EROS and NLCD land cover products. MRLC advise end users that NLCD products are not directly comparable to older land cover datasets, including the 1938, 1964, and 1992 EROS land cover rasters, due to differing methodologies used to create each dataset, respectively. Despite a 30.4% population
Figure 32. Relationship between change in imperviousness and change in peak flow for all subbasins for the March 2016 storm event, including plots for each consecutive time interval and a plot of cumulative results for 1938-2016.

Figure 33. Relationship between change in imperviousness and change in peak flow for all subbasins for the August 2016 storm event, including plots for each consecutive time interval and a plot of cumulative results for 1938-2016.
Figure 34. Relationship between change in imperviousness and change in peak flow for all subbasins for the August 2017 storm event, including plots for each consecutive time interval and a plot of cumulative results for 1938-2016.

Figure 35. Relationship between change in imperviousness and change in peak flow for all subbasins for the October 2017 storm event, including plots for each consecutive time interval and a plot of cumulative results for 1938-2016.
increase from 1990 to 2019 among the counties and parishes of the ARB, 545 subbasins experienced less than 5% absolute change in impervious cover, whether positive or negative. On average, impervious cover for these subbasins increased by 0.19% from 1938 to 2016. 57 subbasins had a greater than 5% decrease in impervious cover, for an average decrease of -12.2%. At the other end, 118 subbasins experienced over 5% increase in impervious surface area, for an average increase of 15.3%. Combined, there was a 6.34% average increase in impervious surface area for the 175 subbasins that saw a change in impervious surface cover in excess of 5%.

October 2017 simulation results showed a much greater range of proportional changes in peak flow than the other 3 ARBNM storms. Unlike the other three storms modeled by Dewberry, rain from the October 2017 storm fell primarily across the rural northern part of the ARB (Figure 27). Although the range of changes to individual subbasins’ peak flow values is greater than for the other storms, this is primarily driven by a number of subbasins that had little to no impervious cover in the 1938 LULC scenario. Peak flow in the AmiteR_R03 subbasin (Figure 36) at Baton Rouge’s present-day eastern limit, for example, increased 526.7% from 0.3 cfs in the 1938 scenario to 15.8 cfs in 2016. The AmiteR_R03 subbasin’s overall imperviousness increased from 0% to 25.7%, and the October 2017 calibration storm delivers less than an inch of precipitation to the subbasin in HEC-HMS simulations. This indicates that the large proportional increase in peak flow was influenced by low initial flow values, low initial percent imperviousness, and low precipitation totals during the modeled storm.
Figure 36. October 2017 storm event with AmiteR_R03 subbasin shown in red. Numbers in map show rainfall in inches. Full figure shown in Figure 27. Source: (Dewberry Engineers Inc., 2019).

4.3.2. Basin-wide HEC-RAS results

Results from HEC-RAS flow simulations are largely similar at the Basin level between land cover scenarios, with more pronounced differences evident in certain areas at smaller scales. Figures 37-40 show differences in water surface elevation (WSE) between the 1938 and 2016 land cover scenarios, with 1938 WSE values subtracted from 2016 WSEs. Across scenarios, there was fairly little change in most of the Basin, with most
differences in WSE between 1938 and 2016 ranging from -0.1 to 0.1 ft and few values outside of the -0.2 to 2 ft range.

Although differences in flooding between land cover scenarios were slight overall, the greatest differences were found for smaller storms in the Baton Rouge area, where the greatest differences in WSE were observed. WSE differences were small for the August 2016 storm, indicating that differences in impervious cover between land cover scenarios had a lesser effect on extreme flooding caused by that storm. The March 2016 and August 2017 storm events showed the greatest differences in WSE between years overall. Flows measured across a RAS Mapper profile line south of the Amite-Comite confluence (Figure 41) are shown in Figures 42-45. Flows through the Amite and Comite Rivers were quite high for the larger events, exceeding 250,000 cfs for the August 2016 storm over 2016 land cover. For all storms, a significant portion of the Comite River saw slight decreases in WSE over the study period, mostly between -0.1 and 0 ft. While relatively small and probably within the model accuracy, this could be at least partially due to the conversion of croplands to forests in the northern part of the Basin. Within the inset in Figure 38, which shows much of south Baton Rouge, the lowest differences were around -0.25 ft and the highest were just over 1.8 ft. The greatest increases in WSE differences across scenarios were observed in Baton Rouge and its surrounding areas where impervious surface cover increased the most from 1938 to 2016, especially along Bayou Fountain, Ward Creek, and Jones Creek. For the March 2016 storm, WSEs were up to 1.3 ft higher in 2016 than 1938 in Ward Creek and nearly 2 ft higher in parts of Jones Creek.
Figure 37. Differences in maximum WSE between 2016 and 1938 land cover scenarios for the March 2016 storm. Inset: The Ward Creek—Jones Creek area had some of the highest measured WSE differences between scenarios for this storm. Areas in black were inundated in 2016 but not 1938. The pink line is a profile line drawn in HEC-RAS and shown in greater detail in Figure 41. A flow hydrograph across this profile line is shown in Figure 42.
Figure 38. Differences in maximum WSE between 2016 and 1938 land cover scenarios for the August 2016 storm. Overall, differences in WSE were muted between scenarios relative to the other, higher AEP storms. Inset: closer look at the Bayou Manchac—Jones Creek area; differences between 0-1 ft predominate. Values in the northwest corner of the inset reach as low as -0.25. Areas in black were inundated in 2016 but not 1938. The pink line is a profile line drawn in HEC-RAS and shown in greater detail in Figure 41. A flow hydrograph across this profile line is shown in Figure 43.
Figure 39. Differences in maximum WSE between 2016 and 1938 land cover scenarios for the August 2017 storm. Inset: The Bayou Manchac—Jones Creek area had some of the highest measured WSE differences between scenarios for this storm. The deep blue in this figure covers the wetlands between Bayou Fountain to the north and Bayou Manchac to the south. Areas in black were inundated in 2016 but not 1938. The pink line is a profile line drawn in HEC-RAS and shown in greater detail in Figure 41. A flow hydrograph across this profile line is shown in Figure 44.
Figure 40. Differences in maximum WSE between 2016 and 1938 land cover scenarios for the October 2017 storm. Inset: October 2017 produced comparatively little flooding in and around Baton Rouge relative to the other ARBNM storms, with White Bayou being a notable exception. Areas in black were inundated in 2016 but not 1938. The pink line is a profile line drawn in HEC-RAS and shown in greater detail in Figure 41. A flow hydrograph across this profile line is shown in Figure 44.
Figure 41. A profile line drawn in pink in RAS Mapper that intersects the Amite River just south of the Amite-Comite confluence in Denham Springs. Flow hydrographs in Figures 42-45 represent total flow across this line.

Figure 42. Flow hydrograph at Denham Springs for the March 2016 storm event over the 1938 and 2016 land cover scenarios.
Figure 43. Flow hydrograph at Denham Springs for the August 2016 storm event over the 1938 and 2016 land cover scenarios.

Figure 44. Flow hydrograph at Denham Springs for the August 2017 storm event over the 1938 and 2016 land cover scenarios.
While the vast majority of the Amite Basin is rural, the greatest impacts of imperviousness on flooding are concentrated in urban areas in and around Baton Rouge. The August 2017 storm, the smallest of the four ARBNM storms by intensity and with the highest AEP (Table 5), had some of the largest relative differences in flow (Figure 44) and WSE (Figure 39) between land cover scenarios, although the August 2016 event produced the highest absolute flow rates (Figure 43) and WSEs (Figure 38) of the four storms by far. Spatial distribution of precipitation also affects extent and intensity of inundation, as seen along White Bayou for the October 2017 storm in Figure 40’s inset and in Livingston Parish for the March 2016 event in Figure 37. These were the areas that received the most rainfall from their respective storms, as can be seen in Figures 27 and 25, respectively. The next section of this chapter takes a more detailed look at the relationships between imperviousness and surface runoff.
4.4. Results from selected subbasins

The following three subbasins were selected to demonstrate some of the spatial differences in flow response to the March 2016 storm event: COMITE_DS_OB, BFount_Nich_US, and AmiteDivCnl_C01 (Figure 46).

Figure 46. Three subbasins with different trends in imperviousness from 1938 to 2016: COMITE_DS_OB (red), BFount_Nich_US (green), and AmiteDivCnl_C01 (blue).

COMITE_DS_OB is located in the northern part of the ARB near Olive Branch, LA along the Comite River. Between 1938 and 2016, impervious surface cover for this subbasin decreased from 12.07 to 3.57%. Flow rates for 2016 were lower and peaked slightly later
than in the 1938 scenario (Figure 47), which was as expected; reductions in impervious cover should result in lower and delayed flow peaks.

![COMITE_DS_OB](image)

Figure 47. March 2016 storm event hydrograph for all four LULC scenarios for the COMITE_DS_OB subbasin.

BFount_Nich_US contains much of the western portion of LSU's Baton Rouge campus, including the athletic stadium. In this subbasin, the surface imperviousness increased from 0% in 1938 land cover scenario to 62.6% in 2016. There were no Developed pixels in the subbasin in the 1938 EROS land cover map, but the stadium has stood at its present location since 1924, and seating capacity in 1936 was already at 46,000 (Richardson & Richardson, 1983). Pixels in the EROS dataset under 20% impervious do not get classified as Developed, although given the age and number of buildings in this part of LSU's main campus, the lack of Developed pixels seems to be an underestimate of the extent of development in this subbasin during that time period. The 2016 peak flow of 194.7 cfs was 79.0% higher than the estimated flow peak of 108.8 cfs in 1938 (Figure 48). Peak flow was also reached 15 hours earlier in 2016 than in the 1938 scenario.
Figure 48. March 2016 storm event hydrograph for all four LULC scenarios for the BFount_Nich_US subbasin.

AmiteDivCnl_C01 contains the downstream portion of the ARDC and was selected to emphasize that while hydrologic parameters were changed for these subbasins for this study, hydraulic modeling in HEC-RAS retains current physical conditions and geometries across land cover scenarios. The subbasin’s percent impervious was 0 for both years, so the lack of change in flows (Figure 49) is as expected. The ARDC itself was not built by the US Army Corps of Engineers until the 1950s, so its presence in the hydraulic model illustrates a limitation of this study’s methodology. Given the high flow volumes (Figure 49) and near-total inundation of the subbasin’s location (Figures 37-40), the hydraulic structure of the canal may not have had a significant effect on 1938 simulation outcomes. Because only different land use raster files have been used in this study to estimate changes to hydrology due to urbanization, the underlying channel geometries and DEM files remain the same for each scenario, which may obscure changes brought about by changing channel properties.
Figure 49. March 2016 storm event hydrograph for all four LULC scenarios for the AmiteDivCnl_01 subbasin.

4.5. Parks plan results

The 1948 Bartholomew parks plan, shown in Figure 22, included parks within 22 of the subbasins of the Amite River Basin, all located in Baton Rouge’s urban core. For both the March and August 2016 storm events, current conditions (i.e., NLCD 2016 with no parks) were compared directly to NLCD 2016 with parks added. Reducing impervious area in these subbasins by adding these parks led to lower surface runoff values in HEC-HMS simulations and some reduced flows in HEC-RAS, although the effects in RAS were somewhat obscured by backwater effects from downstream of the proposed park areas. The five subbasins for which impervious surface cover decreased the most are shown in Figure 50. HEC-HMS flow hydrographs for the five subbasins are shown in Figure 51 for both storms.
Figure 50. Left: 1948 Bartholomew plan for Baton Rouge showing the locations of the five subbasins that saw the greatest proportional decrease in impervious surface cover with the introduction of parks. NLCD 2016 imperviousness layer is overlaid for each, with parks shown in green. Right: map of the Amite Basin showing the full extent of the master plan. Sources: Harland Bartholomew & Associates (1948) and Yang et al. (2018).

For both the March and August 2016 storms, change in peak flow was roughly proportional to change in imperviousness (Figure 52). In the DawsonCr_QuailDr subbasin, which saw the greatest decrease in imperviousness (-9.65%) of any subbasin when the 1948 parks were added, peak flow values dropped by 11.06% for the March 2016 storm and by 10.91% for the August 2016 event.
Figure 51. HEC-HMS results for the five subbasins that had the largest percent change in impervious surface cover with the addition of the 1948 Bartholomew parks, run for the March 2016 and August 2016 storm events. Note different y-axis ranges.
Figure 52. Relationship between impervious change and peak flow change when 1948 Bartholomew parks were added to 2016 NLCD for March 2016 (top) and August 2016 (bottom) storms. Note that axes represent a decrease in values.
Next, a profile line was created in HEC-RAS just downstream of the junction between Dawson Creek and Bayou Duplantier, two streams whose sub-watersheds were the most influenced by addition of the 1948 parks (Figure 53). Average decrease in percent impervious for the two subbasins along Bayou Duplantier between its source at University Lake and the junction with Dawson Creek was 2.52%, while the average decrease in percent impervious for the three subbasins along Dawson Creek from its source below Government Street to the junction with Bayou Duplantier was 6.42%. Accounting for subbasin area, the total decrease in impervious cover for these five subbasins was 6.45%.

Flows calculated at the confluence of Dawson Creek and Bayou Duplantier are shown in Figure 54. There was a 3.12% decrease in peak flow rate at this location for the March 2016 storm event. While flow across this profile line reached a low of -380.9 cfs at 0700 CST on March 11, 2016 for the non-park scenario, flow down Ward Creek at the same point in time was a far higher 4,052 cfs.

Ward Creek joins Dawson Creek downstream of Dawson Creek’s junction with Bayou Duplantier, and the negative flow values in Dawson Creek between the point where Bayou Duplantier enters Dawson and the point where Dawson enters Ward Creek are likely due to backwater effects, and not a net reverse flow of water in the opposite direction of usual downstream flow. As Ward Creek was experiencing high flows at 0700 CST on March 11, WSEs reached 20.3 ft at the confluence of Ward and Dawson Creeks, while WSE upstream at the confluence of Dawson Creek and Bayou Duplantier was lower, at 19.9 ft. This could have caused water flowing down Dawson Creek to back up, resulting in negative flow values in HEC-RAS. The rating curve shown in Figure 56 indicates that
Figure 53. March 2016 inundation depths over 1948 Baton Rouge master plan, showing RAS Mapper profile line downstream of the confluence of Dawson Creek and Bayou Duplantier in Baton Rouge.
Figure 54. HEC-RAS flow hydrographs for 2016 NLCD land cover scenario, with and without addition of 1948 parks.
a stage of roughly 21 feet was reached around a point that corresponds to 1200 CST on March 11, 2016 (Figure 54) and lasted until peak flow of 761.9 cfs was reached at about 1200 CST on March 12. As maximum stage was reached and WSEs stabilized along the length of Dawson Creek, the flows down Dawson would have overcome these backwater effects, and Figure 54 does indeed show flows reaching positive range and increasing after this point. Similarly for the August 2016 storm, a low of -526.4 cfs at 1600 CST on August 12, 2016 along Dawson Creek coincided with a 4971 cfs down Ward Creek. A 0.71% decrease in peak flow was observed for August 2016 storm for the parks scenario relative to 2016 conditions without added parks. The reductions in peak flow rates obtained in HEC-HMS calculations were likely limited by the backwater and other hydraulic effects seen in HEC-RAS simulations, as water backs up smaller tributaries when flows down the main channels are high.

The relationship between AEP and changes in flow rates suggested by the results of the spatially uniform storm simulations described in Section 4.1 can thus be determined to have held in this scenario. The decrease in peak flow for the higher intensity, lower AEP August 2016 storm was proportionally smaller than the change observed for the lower intensity, higher AEP March 2016 storm, but the absolute magnitude of the decrease was larger. Differences in WSE between scenarios for the March and August 2016 storms are shown in Figure 55. WSEs decreased very slightly overall, with most of the inundated area experiencing WSEs that were 0-0.1 ft lower (cyan) with parks than without, though such small differences likely fall within the model uncertainty. The greatest differences were observed in the Bayou Duplantier—Dawson Creek area for the March 2016 storm, where much of the new green space was added.
Figure 55. Differences in WSE for the March (top) and August (bottom) 2016 storms between 2016 land cover scenarios with and without the 1948 Bartholomew parks added. Though small (~0.12 ft), the greatest differences in WSE with the addition of parks occurred with the March 2016 storm event along Bayou Duplantier and parts of Dawson Creek (medium blue), downstream of where the largest parks were introduced (visible in green). While WSE differences were smaller here for the August 2016 storm, the total area of inundation and absolute WSE values were both greater. Areas in black flooded when parks were not added.
Figure 56. Rating curve along the profile line shown in Figure 53. Flow in cfs is plotted along the x-axis and stage in feet along the y-axis.
Chapter 5. Conclusions and Discussion

The August 2016 rainstorm was devastating for the communities of the Amite River Basin, especially around Baton Rouge and nearby areas which have grown and developed at a rapid pace in recent years. Although the August 2016 flood became the flood of record for Louisiana, it was not the first major flood in recent memory for the Amite Basin. The Basin had flooded in 1983, as well, prompting calls for large-scale mitigation measures such as the Comite Diversion Canal and Darlington Dam. Despite this, many communities were unprepared for the floods of 2016, with only 11% of flooded households carrying flood insurance at the time (Mosby & Birch, 2019). The goals of this thesis research were threefold: to determine the effects of impervious expansion on runoff and flooding in the Amite River Basin, to analyze the variability in flooding across spatial scales, and to model the effects on flooding of a moderate floodplain restoration scenario.

The Amite River Basin is largely rural; only 3.85% of the Amite River Basin’s land surface was impervious according to 2016 NLCD data, and 93.9% of that impervious area was concentrated in the greater Baton Rouge region (the portions of East Baton Rouge, Livingston, Ascension, and Iberville parishes that lie within the Basin’s boundaries). This represents an increase from a calculated 0.82% overall Basin imperviousness in the 1938 EROS land cover scenario, with greater Baton Rouge accounting for 67.6% of the ARB’s total impervious cover in 1938. For the years studied, the interval between 1964 and 1992 saw the most population growth, in terms of both raw numbers and percentage. This coincided with an employment and development boom in the lower Amite Basin, especially in Baton Rouge and nearby communities. Population in the upper Basin, however, decreased significantly during the study period. The combined population of the
counties of Amite, Franklin, and Wilkinson dropped by 43.1% between 1938 and 2016 and coincided with a large-scale conversion of agricultural cropland to forests. The greatest population losses for these counties occurred over the 1938-1964 interval, coinciding with the mass exodus of African Americans from the rural South during the Great Migration.

The methodology used in this study likely led to an overall overestimation of imperviousness for the 1938, 1964, and 1992 EROS land cover scenarios. Percent impervious was overestimated for many rural subbasins and underestimated for some urban ones for these years. During the study period, the Amite Basin remained far more pervious than impervious overall, which ultimately would have led to an overestimate of historic imperviousness for most of the Basin. This, in turn, would have led to an underestimation of the difference in runoff and flooding results between the 2016 NLCD scenarios and historical EROS scenarios.

Effects of impervious surfaces on hydrology were relatively lesser at the full-Basin scale. As part of the Mississippi River Delta region, the Amite Basin and surrounding areas have been shaped by flooding for millennia. Given the Amite River Basin’s flat topography, high precipitation, and clayey soils with low infiltration rates, and the relatively minimal impacts at the Basin scale of urbanization and development, flood hazard is likely already high in the Basin before impervious surfaces are considered. From this perspective, increasing impervious surfaces may not have had a transformative effect on the flooding dynamics of the Basin as a whole, so far. Many of the differences in WSE between 1938 and 2016 land cover scenarios fall in the range of -0.1 ft to 0.1 ft, although it is possible that more
accurate estimations of historical impervious data could show more significant differences between years.

Taken together, the findings from this study suggest that land use and land cover change via urbanization, expansion of impervious surfaces, and loss of ecosystem services can have an impact on local surface runoff and flooding. It is clear from analysis of change in impervious cover versus change in peak flow rates (Figure 29), differences in WSE (Figures 37-40), and individual subbasin cases (such as BFount_Nich_US) that there is an overall positive correlation between increasing surface imperviousness and increasing peak flow values, runoff rates, and WSEs. This relationship held across scenarios.

Another key point supported in this study is the proportionally greater impact of impervious surface changes on flow rates for lower-intensity, higher-AEP storm events. Ground cover and surface friction have less effect on larger water volumes as soils become saturated and increasing water depth enables more water to flow unencumbered by bottom friction and ground-level obstacles. Smaller storms are where human actions can have the greatest potential for impact. Land cover composition loses some importance for larger storms, especially in flat, low-lying watersheds such as the Amite Basin which also receive high annual levels of precipitation. There have also been significant effects on magnitude and timing of peak runoff and flow values at the local level in subbasins and sub-watersheds that have experienced proportionally greater changes in percentage of impervious cover.

Incorporation of the 1948 Bartholomew parks plan led to some reduction in flows, although backwater effects from larger channels conveying significant amounts of water
likely limited the overall impact on flood mitigation. A 9.65% decrease in imperviousness for the DawsonCr_QuailDr subbasin due to addition of parks saw peak HEC-HMS flow values decrease by 11.06% for the March 2016 storm and by 10.91% for the August 2016 storm. As was the case with other subbasins and scenarios, backwater effects obscured some of these differences, which might otherwise be expected to have a more significant effect on inundation, following HEC-RAS simulations. For purposes of flood mitigation and hazard management, results from this research consistently indicate that lower impervious values lead to lower surface runoff flow rates, although backwater effects can affect the degree to which this is true.

Smaller storms are where local-scale human actions can have the greatest potential for impact. Land cover composition loses some importance for larger storms, especially in flat, low-lying watersheds such as the Amite Basin which also receive high annual levels of precipitation. From a design perspective, this suggests that exceptionally large storms will likely be out of reach of most design interventions, but that the benefit of mitigation measures will likely be to lessen the impact of smaller, more frequent flooding events. Large-scale engineering interventions such as the Comite Diversion Canal, and especially the proposed Darlington Dam, may be able to help limit damages from larger storms.

Additionally, the total amount of developed area in the greater Baton Rouge region that lies within the 100-year FEMA flood zone has increased significantly from 11.3 to 99.1 square miles between 1938 and 2016. In terms of urban planning, these results would seem to support developing with water and hydrology in mind. Building on floodplains puts residents directly in harm’s way; it may also reduce the ability of those floodplains to
mitigate flooding for smaller, more frequent storms, but further analysis would be needed to confirm this. It would thus seem reasonable to question the rapid, sprawling development patterns in such a flood-prone area, as described by Colten (2017), Jacobsen (2017), and Mosby and Birch (2019). The results of this thesis project support consideration of hydrology when new housing developments are planned for construction in flood-prone areas; building on floodplains positions residents closer to floodwaters and may reduce the ability of those floodplains to mitigate flooding in certain cases.

There are myriad possibilities for future work to build on the results presented here. More rigorous studies of the effects of land cover change on flooding could also consider combining these changes with the effects of channel modification or restoration of floodplains. Re-introducing meanders to straightened channels can lengthen the path that water must take through a subbasin, reducing velocity and attenuating peak (Harris, 2020). Creating a more complete network of restored wetlands and storage areas around these larger channels to reduce velocities and store flow excess could prove effective at curbing some flooding. As urban expansion in the greater Baton Rouge region has caused a loss in the ecosystem services provided by floodplains for flood abatement, the results of this study suggest that some of those services may be able to be recuperated with the introduction of new parks and green areas to existing urban areas. Incorporation of accelerated estimates of climate change could potentially give better predictions for future conditions. Further possibilities for expansion of this research include human impact assessments via HEC-FIA (Flood Impact Analysis), tree canopy analysis in HEC-HMS, examination of additional land use scenarios, and introduction of large engineering projects like the CRDC and Darlington Dam.
References


Vita

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