Deforestation and Flooding in the Lower Roanoke River Basin

by

Yingfan Zeng

Advisor: Nicolette Cagle, PhD

April 21, 2022

Masters project submitted in partial fulfillment of the requirements for the
Master of Environmental Management degree
in the Nicholas School of the Environment of
Duke University

Executive Summary

The large natural forest ecosystems in the Lower Roanoke River Basin, in northeast North Carolina, are home to numerous and diverse plant and animal species. However, these unique and precious forest ecosystems have been progressively threatened by deforestation and flooding in recent decades. Logging, agriculture, development, recreational use, and reservoir construction all could cause direct loss of floodplain forests. Changes in landscape, especially deforestation, conducted on the floodplains can cause indirect impacts on the floodplain hydrology. For example, flood events may occur with greater frequency in some areas due to increased upstream impervious surfaces and loss of vegetation buffers. At the same time, dams altered the natural flow, and in particular, have impacted the timing and intensity of overbank flow into the floodplain. This change in hydrology and flooding may lead to consequences for the floodplain plant and animal communities. The objectives of this project are to deepen the understanding of the 2 interacted factors of deforestation and flooding concerning the Roanoke River Basin by 1). investigating the deforestation trends in the past 20 years, 2). analyzing the flood frequencies and duration in recent years, and 3). mapping the flood extents by a remote sensing model.

Temporal and spatial trends of deforestation in the Lower Roanoke River were analyzed by the forest loss data from the Global Forest Change database accessed on Google Earth Engine, and the vegetation species of the removed forests were investigated. Over the past 20 years, there were about 1290 km2 of forest loss happened in the Lower Roanoke River Basin, of which 610 km2 in 2001-2010 and 680 km2 in 2011-2020. Over the same 10-year period, forest loss increased by 11.5% after 2010. Spatially, deforestation was mainly distributed on the downstream banks and increased in these areas after 2011. In the past 2 decades, 8.1% or 48 km2 of deforestation occurred in the 100-year floodplain. Similar to the total deforestation, the forest loss areas in floodplains also increased after 2011 but at a higher increase rate of 18.8%. The largest loss of vegetation species in deforestation areas was hardwood. Oak - Sweetgum Floodplain Forest was the most removed vegetation type in both the floodplains and it was also the second-largest vegetation type of the deforestation areas in the whole basin before and after 2010.

The flow in the Lower Roanoke River Basin is heavily dominated by 3 upstream dams. Given the dam capacity and empirical observations, a flood event was defined as a continuous period of that discharge of the Roanoke Rapids Dam above 20,000 cfs in this study. All such periods from 2016 to 2021 were screened, and there were 25 flood events in total. During the 6 years, the number of flood events ranged from 1 to 6, showing a seasonal trend of more flood events in winter and spring, and less in summer and autumn.

In addition to flood frequency, the inundation time in the floodplain forests was studied by the continuous water level data from 14 monitoring sites along the Roanoke River. For all the flood events, the time required for the forest to dry out varied widely, with an average of 25 days to 40 days. For the monitoring sites, the upstream monitoring ones were underwater for a longer time, the downstream sites needed a medium time, and the sites in the middle basin went back

dry the most quickly. Another important finding was the inundation in the forests needed a long time to recede. Even though the dam discharge periods were only about 1-2 weeks, the water remained on the floodplain for up to 57 days. In summary, the floodplain forests were under serious flooding pressure because of the long inundation time, which varied a lot, depending on location, flood events, topography, land cover, and other factors.

It is very necessary to understand where the inundated forests are during flood events to study how forest ecosystems respond to flooding stress. A remote sensing model using Sentinel-1 radar data was built to identify the flood extent of a specific flood event by a random forest machine-learning algorithm. The flood extents of 2 flood events in March 2019 and March 2021 were mapped. The resulted flood extent maps had high accuracies. The overall accuracy for March 2019 was 85.6% and that for March 2021 was 89.7%. The most common misclassification was between dry forest and flooded forest due to their similar remote sensing signatures in the predictor composites. Both flood extents overlapped well with the 100-year floodplain in the middle and lower basin, validating the 100-year floodplain was a good predictor of flood extent in this area. But there were areas flooded in both events but not on the floodplain, which needed special attention to flooding.

In conclusion, forest loss was accelerating in the Lower Roanoke River Basin, especially on the floodplains. The basin was still at high risk of flooding in winter and spring, and the floodplain forests would be under high flooding pressure because of the long time for water to recede. Remote sensing, in particular with radar data, had been proven as a feasible way to map the flood extent of a specific flood event, which can be a good reference for forest management and dam management. With deforestation and flooding both considered, the 100-year floodplain should be the focus of forest management and conservation work in the Lower Roanoke River Basin. Increased knowledge about shifts in forest practices, water flow responses, and flood extents may inform and benefit future land, forest, and dam management in the Lower Roanoke River Basin.

Contents

1. Introduction

1.1 Introduction

Deforestation is believed to have a negative impact on the hydrological balance. Forests play an important role in the resilience of watersheds in the face of disturbances such as hurricanes, by effectively absorbing flooding water, slowing wind speeds, and reducing flood control pressure on dams (Calder & Aylward, 2006). Globally speaking, there is a strong link between increased flood frequency and forest loss, as well as the intensity and duration of floods (Bradshaw, Sodhi, PEH, & Brook, 2007). Some watershed-scale studies have also shown that deforestation exacerbates flooding in these areas (Popa & Diaconu, 2019; Kim, Sohn, Kim, & Lee, 2019; Zeilhofer, Alcantara, & Fantim-Cruz, 2018; Gentry & Lopez-Parodi, 1980). Therefore, forest loss is an important factor in studying hydrological changes and reducing flood risk.

Flooding is one of the most dangerous natural disasters in the world, affecting societies, economies, and ecosystems. With climate change, floods are increasing in intensity and frequency (Bates, Kundzewicz, Wu, & Palutikof, 2008). Flooding is the main stressor for many ecosystems like forests. Globally speaking, there is a strong link between increased flood frequency and forest loss, as well as the intensity and duration of floods (Bradshaw, Sodhi, PEH, & Brook, 2007).

Roanoke River Basin is one of the most biodiverse ecosystems in the Southeast United States, but it is threatened by rapid forest loss and flooding. Beginning in the Blue Ridge Mountains and ending in the Albemarle Sound, the Roanoke River Basin covers 10,000 square miles and 3,500 square miles are within North Carolina (North Carolina Environmental Quality, n.d.). The Roanoke River has the most water volume among all the rivers in North Carolina, and also the widest floodplain (Burgess and Schott, 2008), and the basin is a typical southeastern alluvial system, contains the largest natural bottomland hardwood forests in the mid-Atlantic region and is home to a massive number of fish and wildlife species (The Nature Conservancy, n.d.; U.S. Fish & Wildlife Service, 2014).

Unfortunately, the active floodplain ecosystems along the Roanoke River are suffering forest loss. Logging, agriculture, development, recreational use, and reservoir construction all could cause direct loss of floodplain forests. This loss is seriously threatening the rich forests and biodiversity of the Roanoke Basin. Moreover, changes in the landscape, especially deforestation, conducted on the floodplains can cause indirect impacts on the floodplain hydrology. For example, flood events may occur with greater frequency in some areas due to increased upstream impervious surfaces and loss of vegetation buffers. However, how and where deforestation has happened in the Roanoke River Basin, especially in recent years, remains unclear.

In addition to deforestation, anthropic activities, such as dam construction, also significantly affect the hydrology of the Roanoke River and the ecosystems within the basin. Dams altered the natural flow, and in particular, have impacted the timing and intensity of overbank flow into the floodplain. This change in hydrology and flooding may lead to consequences for the floodplain plant and animal communities. A previous study assessed flooding stress on trees in the Lower Roanoke floodplains by measuring the growth rate change and surveying species composition of bottomland forests (Anderson, 2017). The results showed that smaller trees were more affected by flooding and the growth rate reduced in recent years. On this basis, it would be good to take forest loss into account and involve geospatial analysis.

With the 2 interacted factors of deforestation and flooding concerning the Roanoke River Basin, it is very important to study the shifts in forest practices, water flow responses, and flood extents to better maintain floodplain ecosystem health and function in the Lower Roanoke River Basin. In this project, I investigated How much deforestation has happened in the past 20 years in the Lower Roanoke Basin, characterized the flooding hydrology from the frequency and duration perspectives, and explored the methods of modeling flood extent at different dam discharge levels. This study would contribute to the understanding of ecological dynamics in the Lower Roanoke River Basin and provide references for conservation land management and dam management.

1.2 Study Area

The Lower Roanoke River Basin is in southern Virginia and northeastern North Carolina in the United States (Figure 1-1). Located between the John H. Kerr Dam and the Albemarle Sound, this 600000-ha basin contains over 200 km of the Roanoke River, with floodplains of about 5-10 km in width. There is more than 25000 ha of floodplain forests in the basin (Townsend, 2001), which are deeply affected by the floods of the Roanoke River.

The discharge of upstream dams is closely related to downstream flooding in the Lower Roanoke Basin. There are 6 major dams along the Roanoke River, and 3 of them located near the Virginia-North Carolina border are critical to the lower basin (Figure 3-1). Built and run by the U.S. Army Corps of Engineers, the John H. Kerr Dam started to operate in 1953 for the purposes of flood control and hydropower. Not far downstream, there are two smaller dams, the Gaston Dam and the Roanoke Rapids Dam, both owned by a private company Dominion Energy. They were completed in 1963 and 1955 respectively for hydroelectric power. There are no more major dams below the Roanoke Rapids Dam so the downstream Lower Roanoke River Basin is heavily dominated by these 3.

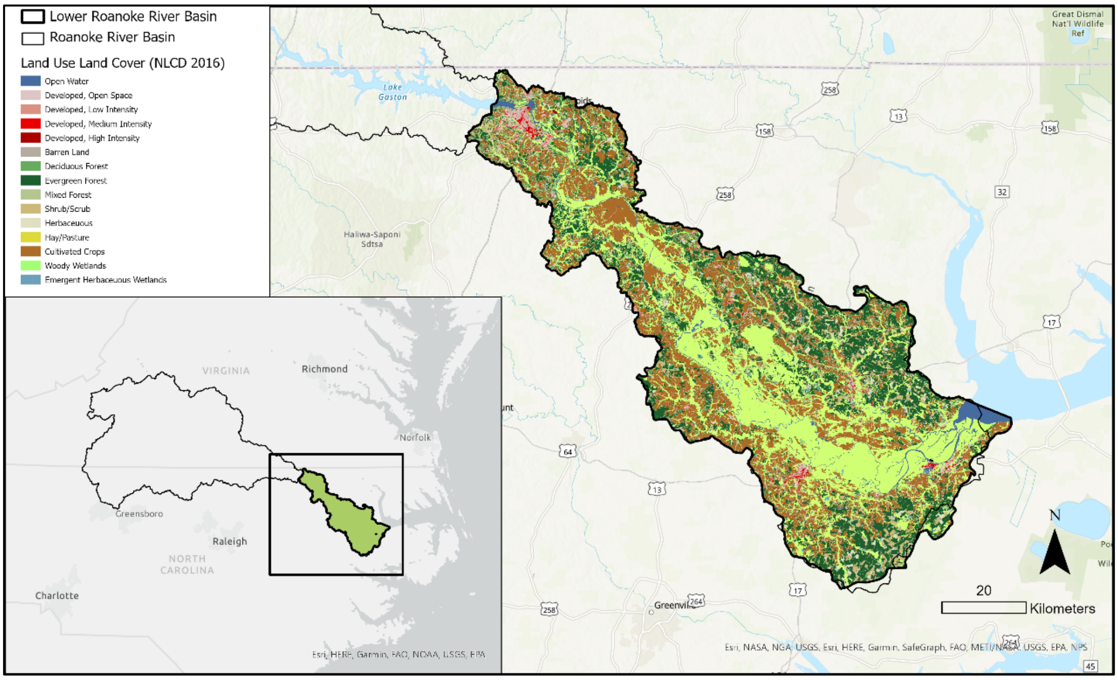

Figure 1-1. The study area of Lower Roanoke River Basin, featured by land use land cover data from NLCD 2016.

2. Deforestation in the Lower Roanoke Basin

2.1 Introduction

Deforestation has been a big concern in North Carolina. In 2010, 60% of North Carolina was covered by natural forests, while about 23% of them were lost between 2001 and 2020 (Global Forest Watch, 2021). However, there is a lack of studies on deforestation in the Lower Roanoke River Basin, one of the largest and the most important natural forest contributing areas. In this section, I researched the forest practice changes in the Lower Roanoke River Basin by investigating the temporal and spatial trends of deforestation. I also examined the vegetation types in the deforestation areas to learn about the most threatened tree species.

2.2 Methods

Deforestation data was obtained from the Global Forest Change dataset (Hansen et al., 2013). The Global Forest Change dataset recorded forest change (gain or loss) globally at 30 meters resolution from Landsat 7 Enhanced Thematic Mapper Plus (ETM+) scenes. Annual data from 2001 to 2020 were currently available in the dataset. For the forest practice change in the Lower Roanoke Basin in the past 2 decades, I mainly focused on deforestation change and ignored the forest gain. The first reason was that the area of forest gain in the study area was far less than the area of forest loss. Also, it could take a long time for new forests to grow enough to affect the watershed and flooding, and 20 years was not enough. Forest loss or deforestation was defined as a disturbance that eliminates all trees taller than 5 meters in the stand. To see how the trend changed, I compared 2 time periods, 2001-2010 and 2011-2020. The raster images of forest loss for these 2 periods were exported from Google Earth Engine, where the Global Forest Change dataset was implanted.

Forest changes in floodplains may affect the extent of flooding. The 100-year floodplain, referring to areas with a 1% chance to be flooded in any given year, is important in disaster prevention, construction regulation, insurance, and importantly, conservation. The 500-year floodplain, which means there is a 0.2% chance of a flood occurring in any given year, is another important area when evaluating flood hazards. The 2 types of floodplain extents were a subset of the map of NC Flood Hazard Areas retrieved from the NC Flood Risk Information System (NC FRIS, 2000). The 100-year floodplain was subset by the zone ID of "AE", and the 500-year floodplain was filtered by the zone ID "0.2 PCT ANNUAL CHANCE FLOOD HAZARD".

To identify the tree species that were removed in the deforestation areas, I used the GAP/LANDFIRE National Terrestrial Ecosystems dataset from USGS (U.S. Geological Survey (USGS) Gap Analysis Project (GAP), 2018). I compared it with the National Land Cover Database (NLCD) (Dewitz, 2019) and decided the GAP dataset could serve our purpose better. The GAP dataset had a very detailed vegetation classification, but NLCD only had 3 classes of forests. In addition, according to a former study, NLCD appeared to be underestimated agricultural lands while the cropland in the GAP dataset was more comparable to the estimation reported by the USDA (Wardlow & Egbert, 2003). The latest GAP dataset was from 2011, which was the year of Enviva's entry. There were 7 levels of land cover classification in the GAP dataset, and we chose the National Vegetation Classification (NVC) group because of its appropriate level of detail.

All the geospatial analysis was conducted in ArcGIS Pro 2.6.3 (ESRI, 2011). The areas of deforestation in 2001-2010 and 2011-2020 were obtained, including those in the whole Lower Roanoke Basin, and within the 100-year and 500-year floodplains. For raster data, the areas were calculated by pixel number times pixel area. For feature class data, the areas were calculated by the Calculate Geometry command. The land use land cover and vegetation types of forest loss were determined by clipping the GAP map to the deforestation areas. The areas and percentage of each land cover type were further calculated and visualized in Microsoft Excel (Microsoft Corporation, 2018).

2.3 Results

Over the past 20 years, the annual amount of deforestation had not been constant. There was a low point around 2011, but there were two peaks in 2006 and 2016, with the loss of forest area reaching 74 km^2 and 84 km^2 respectively (Figure 2-1). Overall, deforestation was increasing in the recent decade. From 2001 to 2020, there were about 1290 km^2 of forest loss happened in the Lower Roanoke River Basin, of which 610 km^2 from 2001 to 2010 and 680 km^2 from 2011 to 2020 (Table 2-1). Over the same 10-year period, forest loss in the Lower Roanoke Basin area increased by 11.5% after 2010. Spatially, deforestation was mainly distributed on the downstream banks and increased in these areas after 2011 (Figure 2-2). In the past 2 decades, 8.1% or 48 km^2 of deforestation occurred within the 100-year floodplain. Similar to the total deforestation, the forest loss areas in floodplains also increased after 2011 but with a higher increase rate of 18.8% (Table 2-1).

The largest loss of vegetation species in deforestation areas was hardwood. Oak - Sweetgum Floodplain Forest was the most removed vegetation type in both the floodplains and it was also the second-largest vegetation type of the deforestation areas in the whole basin before and after 2010. Besides, Southeastern Native Ruderal Forest was one of the major vegetation in the forest loss areas after 2011, which proved that these areas were disturbed before. Areas of human activity, such as farmland and urban, were less affected by deforestation (Figure 2-3, Figure 2-4, Figure 2-5, Figure 2-6, Table 2-2).

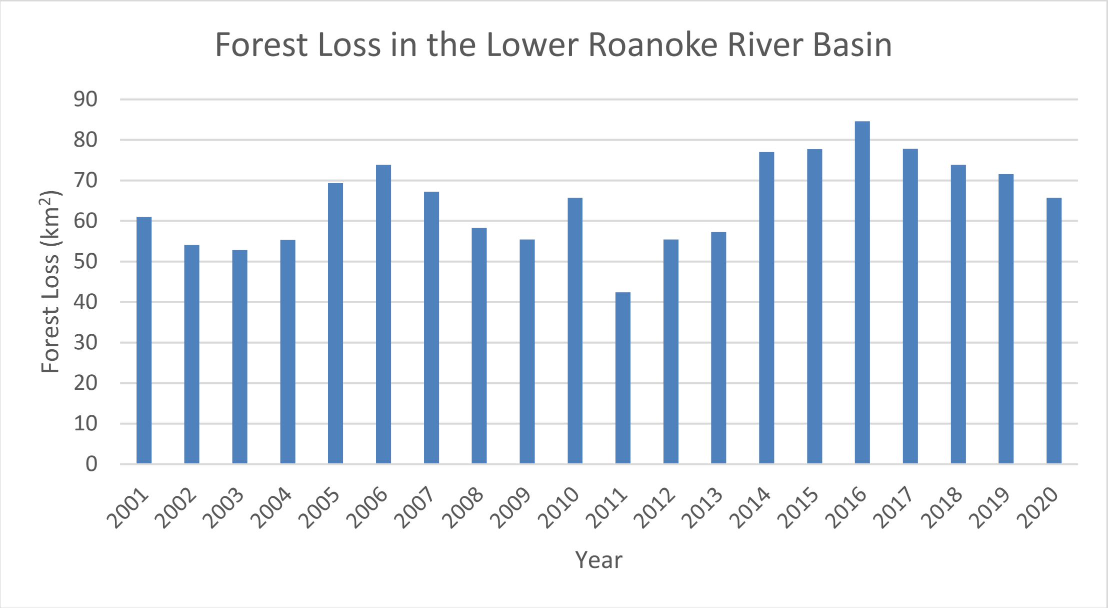

Figure 2-1. The annual forest loss area changes in the Lower Roanoke River Basin from 2001 to 2020.

Table 2-1. Comparison of deforestation areas between 2001-2010 and 2011-2020.

	Forest loss area (km^2)	**Forest loss in 100-year floodplain (km^2)**
2001-2010	610	48
2011-2020	680	57
Total	1290	105
Increase rate	11.5%	18.8%

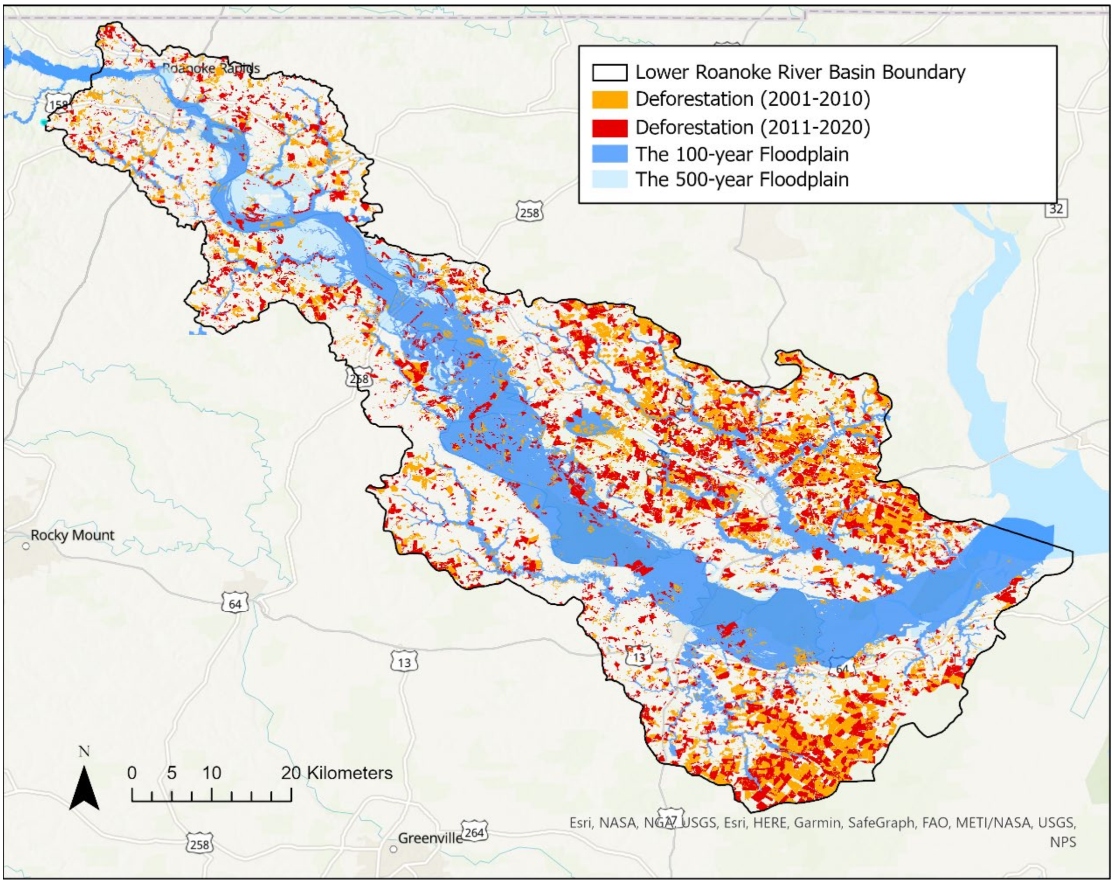

Figure 2-2. Deforestation occurred in 2001-2010 and 2011-2020 in the Lower Roanoke River Basin.

Land Cover and Vegetation Types in the Deforestation Areas in the Lower Roanoke River Basin

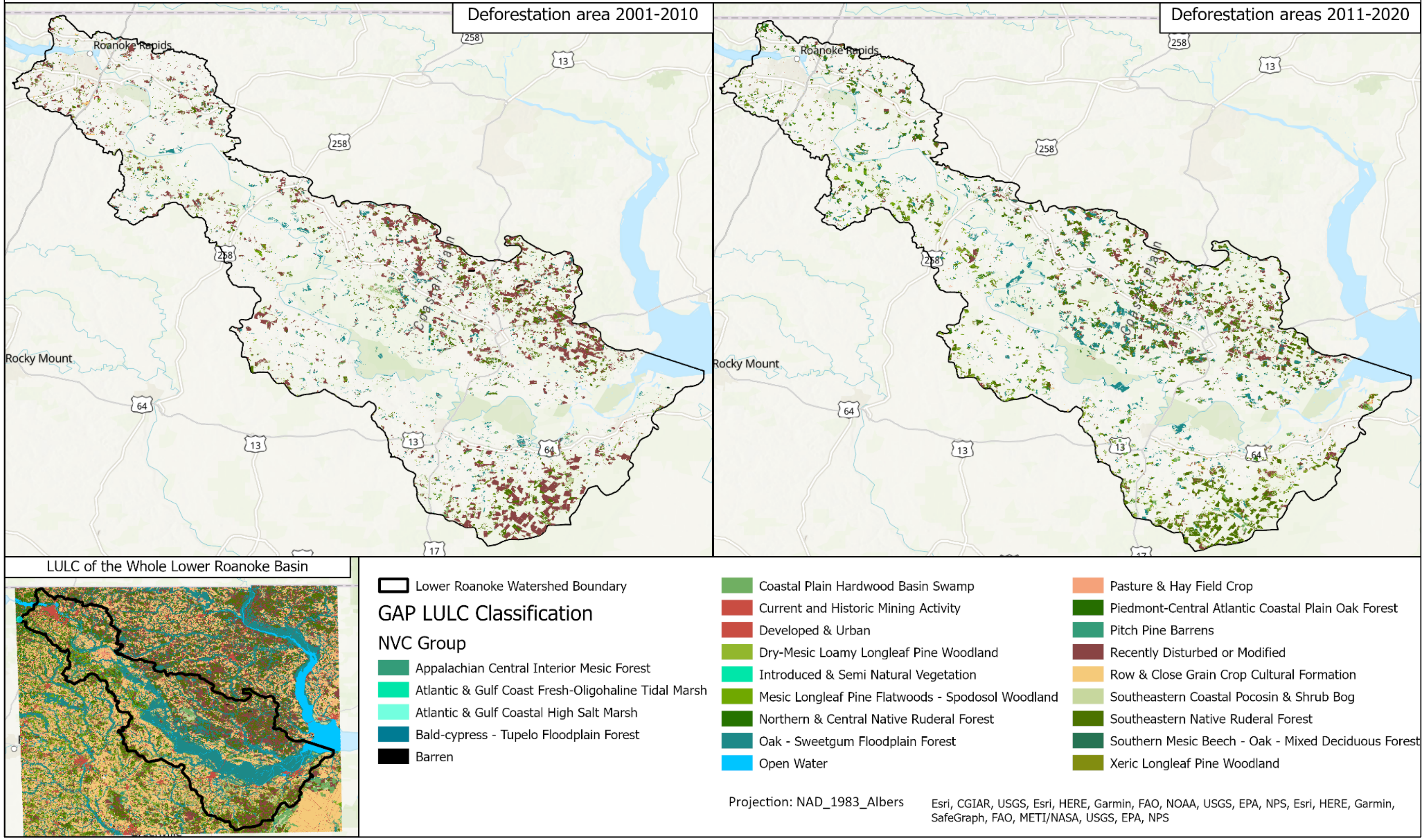

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Figure 2-3. Land Cover and Vegetation Types in the Deforestation Areas of the Lower Roanoke River Basin.

Table 2-2. The land cover types of deforestation areas in the Lower Roanoke River Basin.

National Vegetation Classification (NVC) Groups	Land Use/Land Cover of Deforestation Areas											
	Whole basin 2001-2010		Whole basin 2011-2020		100-year floodplain 2001-2010		100-year floodplain 2011-2020		500-year floodplain 2001-2010		500-year floodplain 2011-2020	
	Area (km^2)	Percentage	Area (km^2)	Percentage	Area (km^2)	Percentage	Area (km^2)	Percentage	Area (km^2)	Percentage	Area (km^2)	Percentage
Dry-Mesic Loamy Longleaf Pine Woodland	13	3.3%	32	7.3%	0	0.8%	1	1.9%	0	5.1%	1	6.1%
Southeastern Native Ruderal Forest	80	20.6%	166	37.9%	2	6.3%	6	11.2%	1	19.8%	3	27.7%
Piedmont-Central Atlantic Coastal Plain Oak Forest	7	1.9%	23	5.3%	1	1.6%	2	3.0%	0	4.3%	1	6.9%
Southern Mesic Beech - Oak - Mixed Deciduous Forest	4	1.1%	15	3.4%	0	0.8%	1	2.5%	0	1.3%	0	3.0%
Oak - Sweetgum Floodplain Forest	46	11.8%	80	18.1%	24	59.8%	36	65.5%	2	24.4%	4	32.3%
Coastal Plain Hardwood Basin Swamp	11	2.7%	13	3.0%	3	6.4%	2	2.8%	0	1.9%	0	1.9%
Mesic Longleaf Pine Flatwoods - Spodosol Woodland	3	0.9%	6	1.4%	0	1.1%	1	2.2%	0	7.1%	1	5.9%
Southeastern Coastal Pocosin & Shrub Bog	6	1.5%	7	1.7%	2	4.7%	1	1.9%	0	0.2%	0	1.2%
Barren	1	0.2%	0	0.0%	0	0.1%	0	0.0%	0	1.0%	0	0.0%
Row & Close Grain Crop Cultural Formation	5	1.2%	9	2.1%	0	1.1%	1	1.3%	0	2.2%	1	4.4%
Pasture & Hay Field Crop	0	0.1%	2	0.3%	0	0.1%	0	0.4%	0	0.2%	0	0.6%
Recently Disturbed or Modified	204	52.3%	74	17.0%	6	16.0%	3	5.7%	2	30.6%	1	8.1%
Developed & Urban	9	2.2%	11	2.5%	0	1.1%	1	1.3%	0	1.7%	0	1.8%
Sum	390	100.0%	439	100.0%	39	100.0%	54	100.0%	6	100.0%	11	100.0%

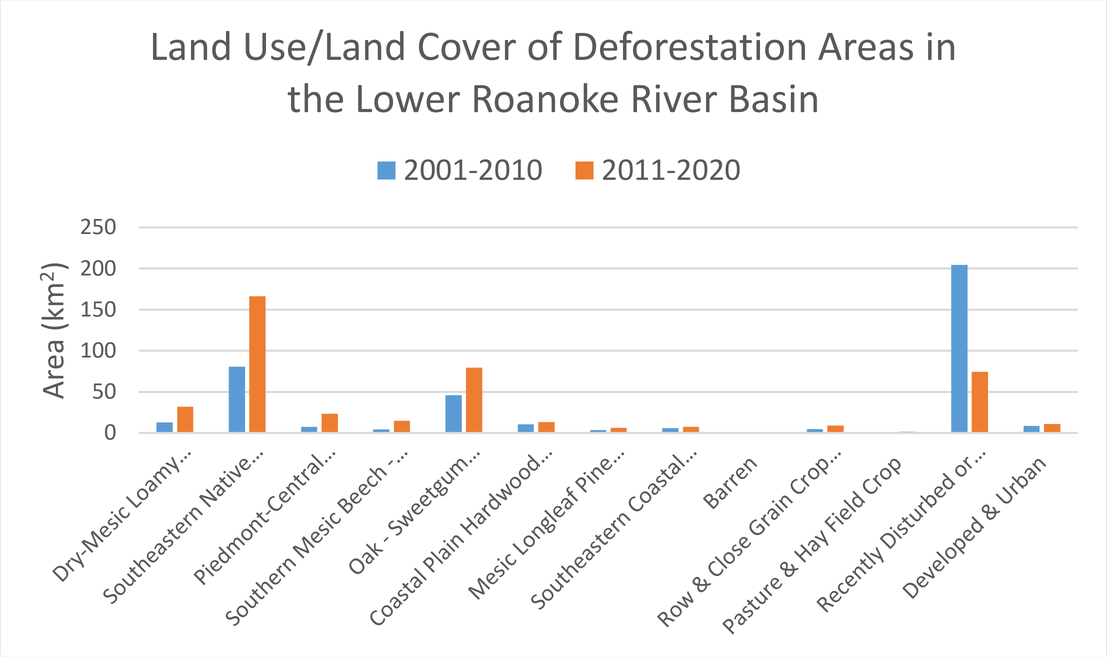


Figure 2-4. Land Use/Land Cover of Deforestation Areas in the Lower Roanoke River Basin.

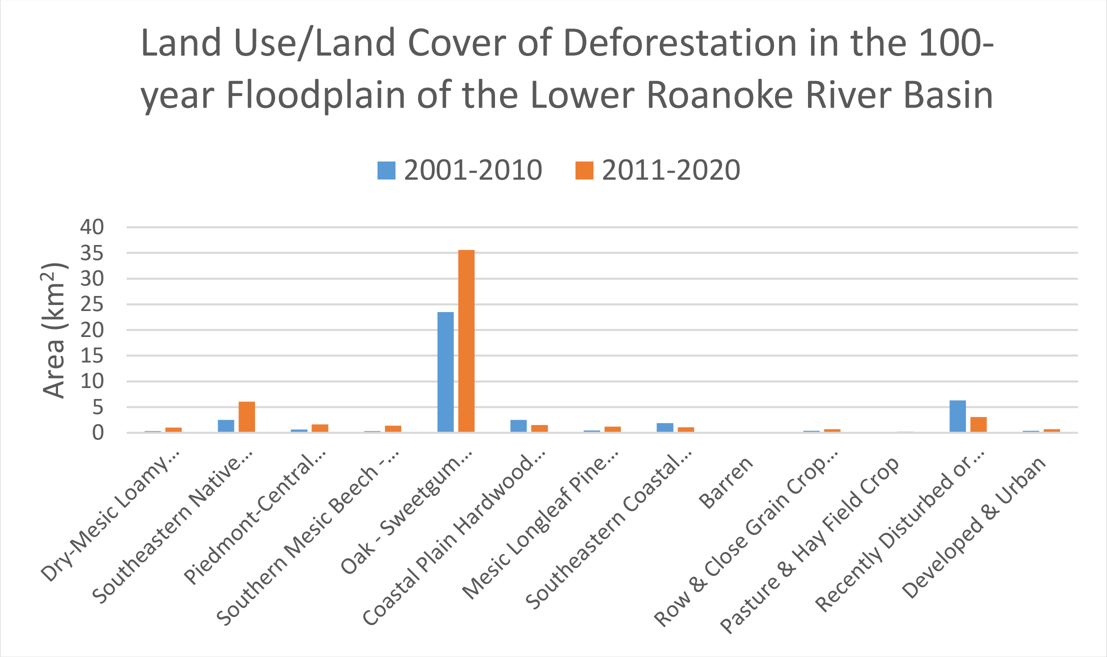


Figure 2-5. Land Use/Land Cover of Deforestation in the 100-year Floodplain of the Lower Roanoke River Basin.

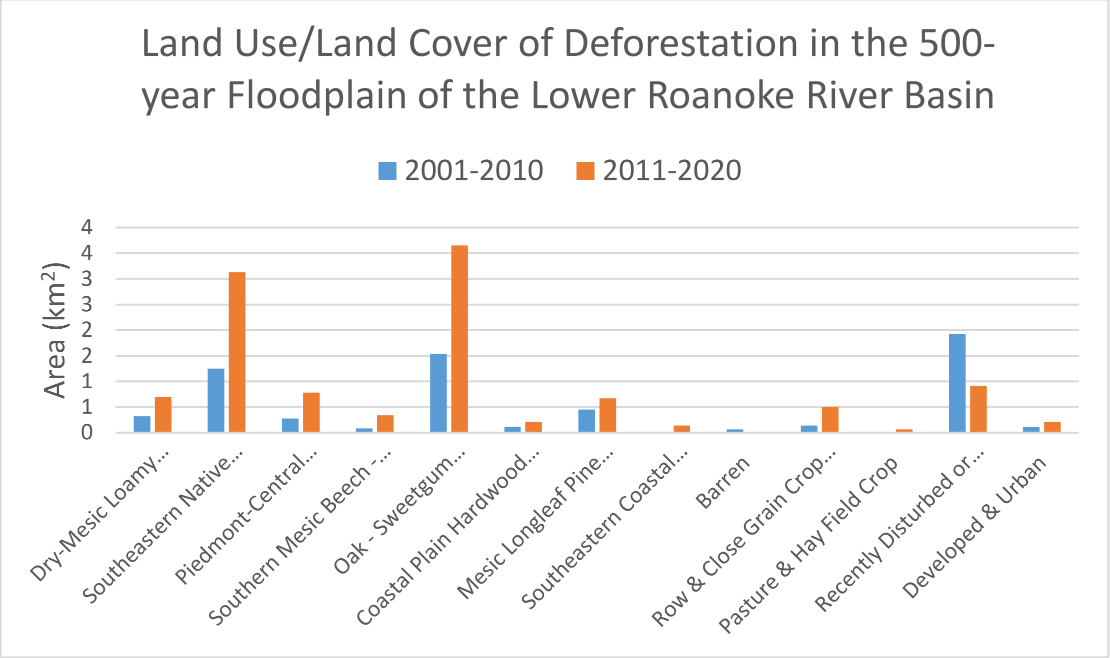


Figure 2-6. Land Use/Land Cover of Deforestation in the 500-year Floodplain of the Lower Roanoke River Basin.

2.4 Discussion

Deforestation in the Lower Roanoke River Watershed increased in 2011-2020 compared with 2001-2010. In another word, the rate of forest loss raised after Enviva entered this region in 2011. In particular, the increasing trend was more pronounced in floodplains, indicating that deforestation in the last decade had been closer to river channels. At the same time, the proportion of hardwood trees, like oak, being cut had increased significantly since 2011. Interestingly, 2010 was the year that the wood pellet biomass industry entered North Carolina, and this industry had a preference for hardwoods. The increased proportion of hardwood in the tree species being felled also suggested that the wood pellet industry might have encouraged the forest to disappear in the Lower Roanoke River Basin.

I used the USGS GAP dataset for the deforested vegetation types and land use land cover in the basin. The latest GAP data, which was also the data we used, was collected in 2011. Especially for the pre-Enviva period, a large area of forest loss was classified as recently disturbed or ruderal forest, which was the first plant to colonize disturbed lands. This was because at the time GAP data was collected, the land had just been deforested. Although the GAP dataset and the Global Forest Change dataset cross-proved each other's accuracy, the species of vegetation before they were cleared could not be known. Besides, a small number of areas deforested were classified as agricultural lands and urban. One possibility was that these areas were turned into farmlands and developed areas after the forests were removed. Another possibility, which was also the cause of some other errors, was that the classification algorithm was not accurate. The overall accuracy of 87% for the GAP dataset had been reported (Wardlow & Egbert, 2003). This was a relatively high accuracy rate among all the land use classifications, but there could still be some errors. The most ideal way to determine deforested vegetation could be to compare each year's forest loss with the previous year's vegetation classification, requiring a high amount of data and high data accuracy.

3. Flooding in the Lower Roanoke River Basin

3.1 Flood events in 2016-2021

The flow in the Lower Roanoke River Basin is heavily dominated by 3 dams, John H. Kerr Dam, Gaston Dam, and Roanoke Rapids Dam (Figure 3-1), and there is no more dam downstream of Roanoke Rapids. They have played a huge role in flood control. Before the dams were built in the 1950s, the basin suffered a lot from extreme flows and flooding, while the situations had been greatly alleviated since the dam construction. Nevertheless, the biggest dam among the 3, John H Kerr Dam, has a maximum turbine discharge of 35,000 cubic feet per second (cfs), while the turbine capacity of the other 2 dams, Gaston Dam and the Roanoke Rapids Dam, is only 20,000 cfs. Empirical observations had shown the downstream basin would be flooded when the discharge at the Roanoke Rapids Dam was above 20,000 cfs. Therefore, in this study, a flood event was defined as a continuous period of the discharge of the Roanoke Rapids Dam above 20,000 cfs.

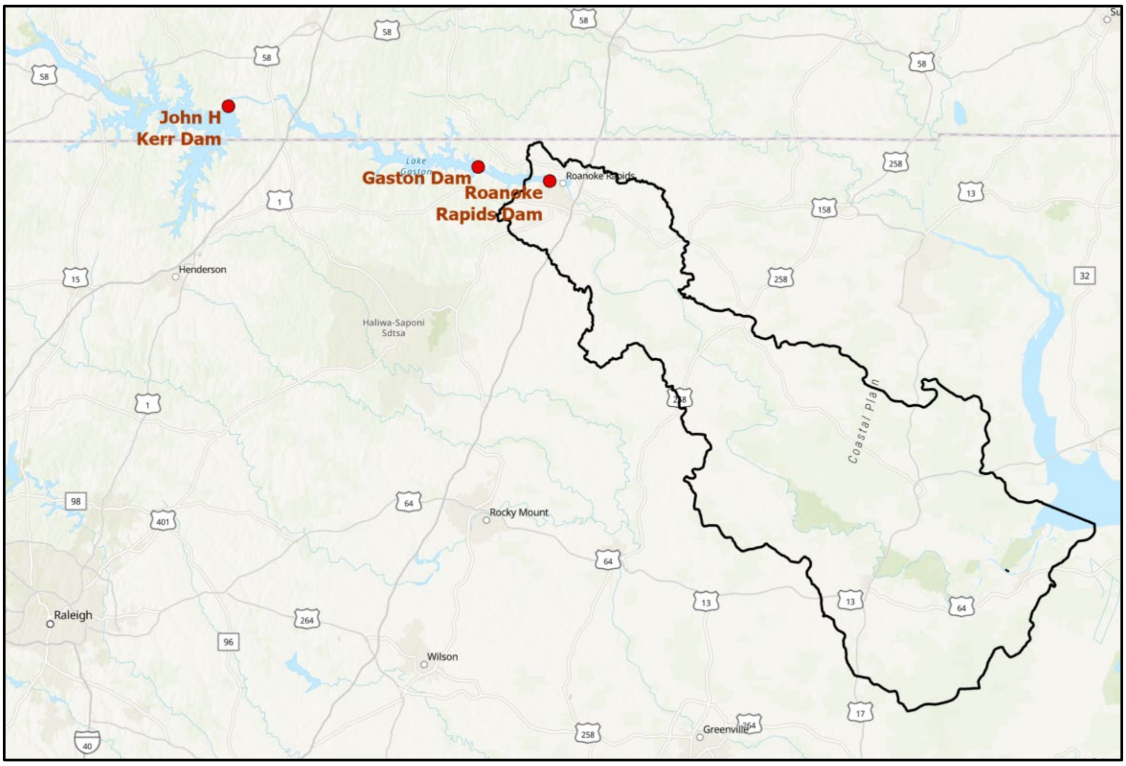


Figure 3-1. The locations of major dams dominating the Lower Roanoke River Basin.

I selected all the flood events that the discharge at USGS gage 02080500 Roanoke River at Roanoke Rapids was above 20,000 cfs during 2016-2021. During this time frame, there were 427 days that the dam discharge reached the flooding threshold, from 25 individual flood events (Table 3-1).

Table 3-1. The flood events in the Lower Roanoke River Basin in 2016-2021.

No.	Date	Dam Release (cfs)	Release Period
1	Jan 2016	20,000	1/1/2016-1/23/2016
2	Jan 2016	20,000	1/25/2016-2/1/2016
3	Feb 2016	20,000	2/6/2016-2/23/2016
4	Feb 2016	20,000	2/27/2016-3/12/2016
5	May 2016	20,000	5/10/2016-5/28/2016
6	Oct 2016	25,000	10/15/2016-10/22/2016
7	Jan 2017	23,000	1/28/2017-2/3/2017
8	Apr 2017	35,000	4/28/2017-5/10/2017
9	May 2017	27,000	5/27/2017-6/4/2017
10	Apr 2018	20,000	4/28/2018-5/4/2018
11	May 2018	25,000	5/22/2018-5/30/2018
12	Sep 2018	30,000	9/22/2018-10/5/2018
13	Oct 2018	35,000	10/18/2018-10/28/2018
14	Nov 2018	35,000	11/22/2018-12/2/2018
15	Dec 2018	35,000	12/22/2018-1/11/2019
16	Feb 2019	20,000	2/2/2019-2/8/2019
17	Mar 2019	35,000	2/27/2019-3/11/2019
18	Jun 2019	20,000	6/15/2019-6/24/2019
19	Feb 2020	35,000	2/11/2020-2/23/2020
20	May 2020	20,000	5/2/2020-5/8/2020
21	May 2020	35,000	5/29/2020-6/9/2020
22	Jun 2020	27,000	6/19/2020-7/4/2020
23	Nov 2020	35,000	11/3/2020-11/24/2020
24	Dec 2020	25,000	12/3/2020-1/13/2021
25	Mar 2021	20,000	3/22/2021-4/7/2021

Flood frequency is characterized by annual and seasonal trends. From 2016 to 2021, the number of flood events ranged from 1 to 6 (Figure 3-2). In most years, the Lower Roanoke River Basin can expect about 3-6 flood events each year. Seasonally speaking, the flood frequency is low in spring and autumn, while high in winter and spring (Figure 3-3). The flood risk is very low in July, August, and September in particular, with only 1 flood event over the 6 years occurring in these 3 months over the 6 years. In contrast, January, February, and May had a high frequency of flooding, with about half of the flood events (12 out of 25) happening in these 3 months during the study period.

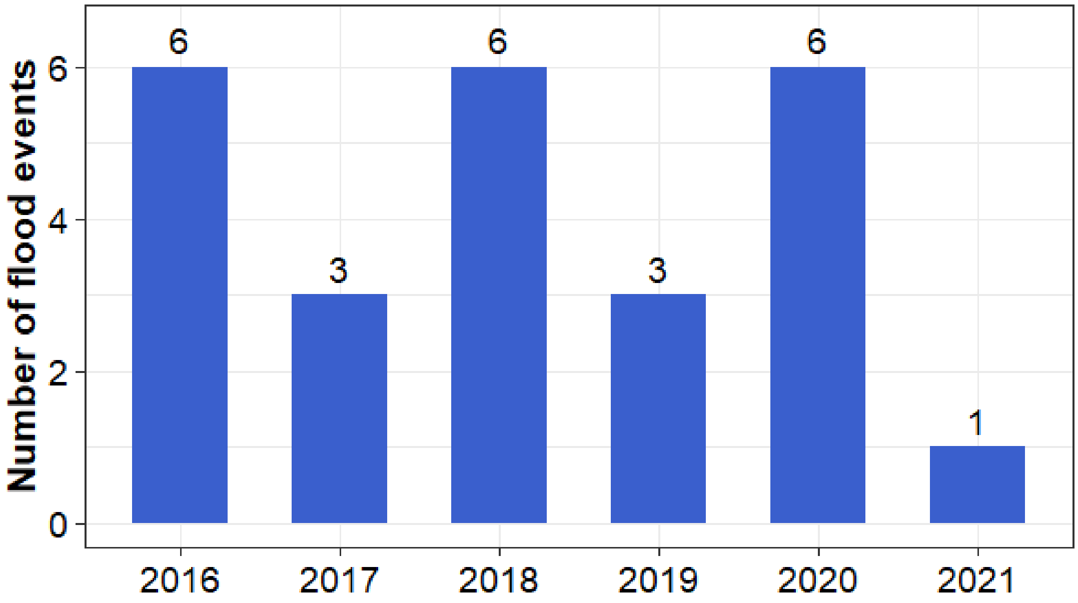


Figure 3-2. The number of flood events by year in 2016-2021.

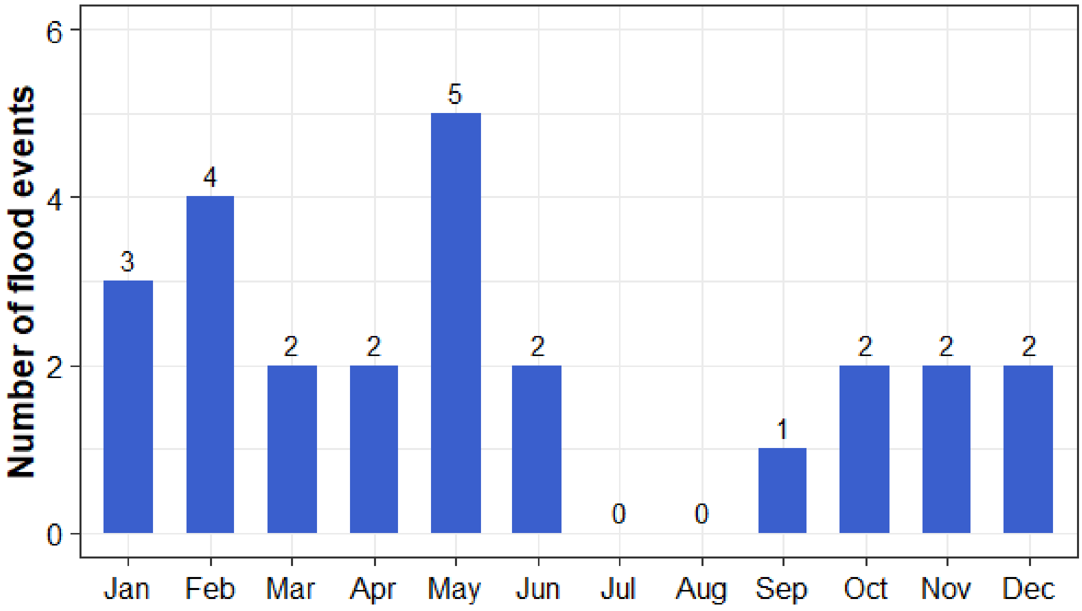


Figure 3-3. The number of flood events by month in 2016-2021.

3.2 Floodplain inundation

The periods and volumes of the dam release were controlled, whereas the time for the inundation from the overbank flow on the floodplain to recede was uncertain. This could depend on factors like topography, land cover, proximity to the river, and so on, so there would be a spatial difference in inundation time for different locations on the floodplain after each flood event.

To get an idea of actual inundation time in the floodplain forests, TNC had set up 14 monitoring sites along the Roanoke River (Figure 3-4). The monitoring sites recorded water height in feet. They were all on the floodplain and were not supposed to be underwater at a normal time, so data around or below 0 meant dry or no water, while significantly above 0 meant inundated. Most monitoring sites had water level data from 2008 to 2019, with minor gaps due to battery issues. Because these sites were distributed up and down the entire floodplain and had a continuous record of water level changes, they can help us understand the variation of floods and the differences in hydrology at different geographical locations in the basin.

For each of the flooding periods, I studied the trend of water level change at the 14 monitoring sites. If data allowed, I calculated the daily average water level at each monitoring site, from 10 days before the large dam release began to the day that water level was restored to the pre-dam-release level. I plotted the water level changes and counted the days it took for the water height to return to the normal level at the 14 monitoring sites. The statistical analysis for the TNC monitoring sites was done in R and Excel 2016.

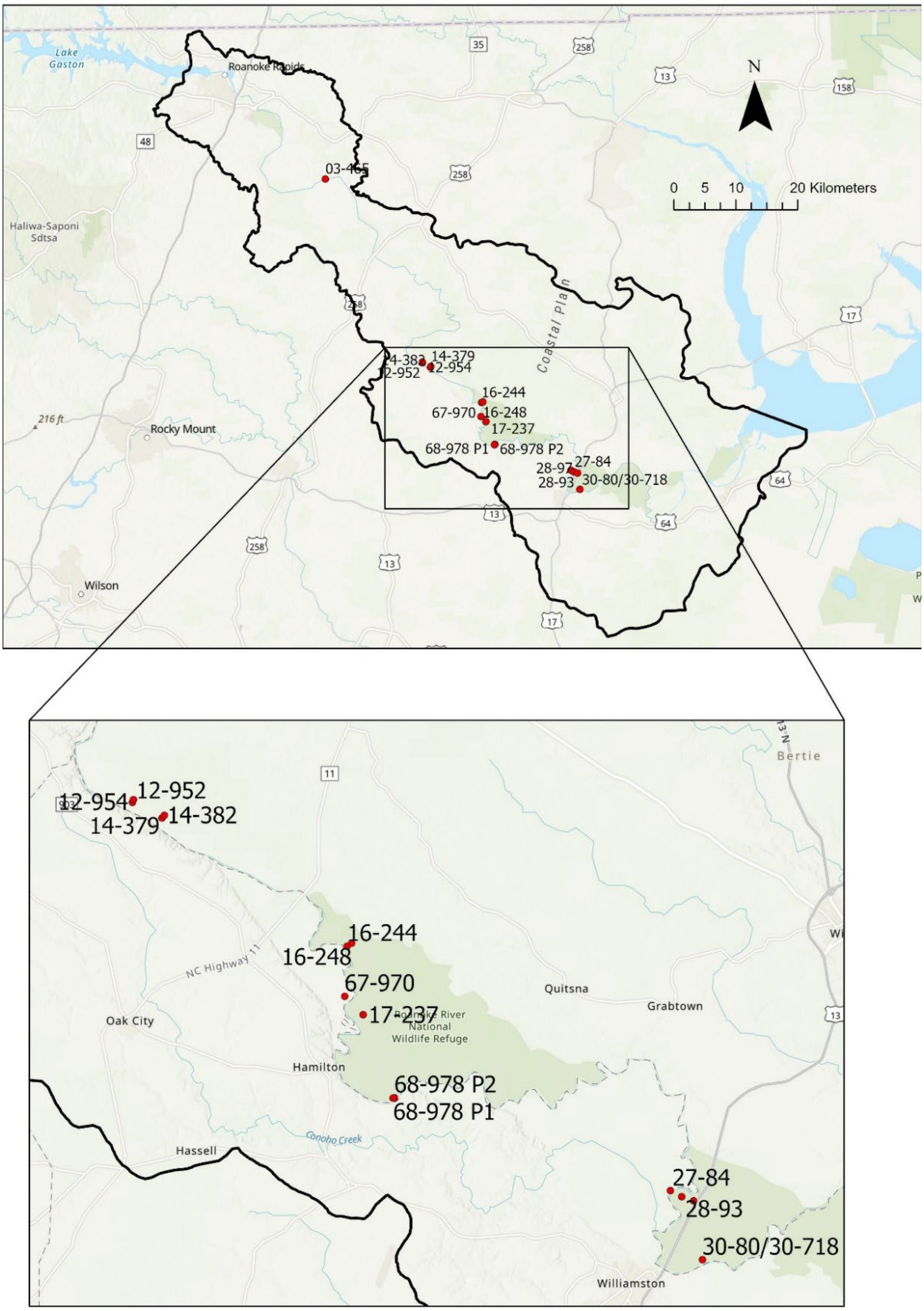


Figure 3-4. The TNC water level monitoring site locations.

Some temporal and spatial characteristics of the inundation time at these monitoring sites were found. First, water levels at some monitoring sites were always higher than at others. The water level at most sites was under 1 foot before the flooding and could reach about 5-10 feet during the floods. The water level of gages 12-954 and 14-379 were mostly among the highest, both during flood events and normal dry periods. Both gages were in the middle of the basin, further upstream than most other sites (Figure 3-4). Interestingly, they both had a paired gage that was located close to them but slightly further from the river channel (gages 12-952 and 14-382). The water height and change trends of the paired gages were very different. This suggested that specific conditions such as topography and land cover had a greater effect on the duration of inundation at a particular point. Second, the time of water level receding after floods were various at different gages. Depending on floods and monitoring sites, it could take as short as 7 days to as long as more than 50 days for the water to drop from the peak to the usual level. Among all the gages, it usually took the longest time at 12-954 and 14-379, which also located the most upstream than other gages. Lastly, at different dam discharge levels, the time for the water level to drop or for the flood to recede was different. For 35,000 discharge events, it took about 2 weeks for the water level to fall and the time at different sites was relatively close. When the floods were smaller with a discharge of 20,000 cfs or 25,000 cfs, some sites needed a very long time to about 50 days while the other gages only took less than 1 week. However, there was no clear trend showing a correlation between the dam discharge level and the duration of inundation. The location of specific sites and actual conditions before and after the flood, such as rain, had a greater effect.

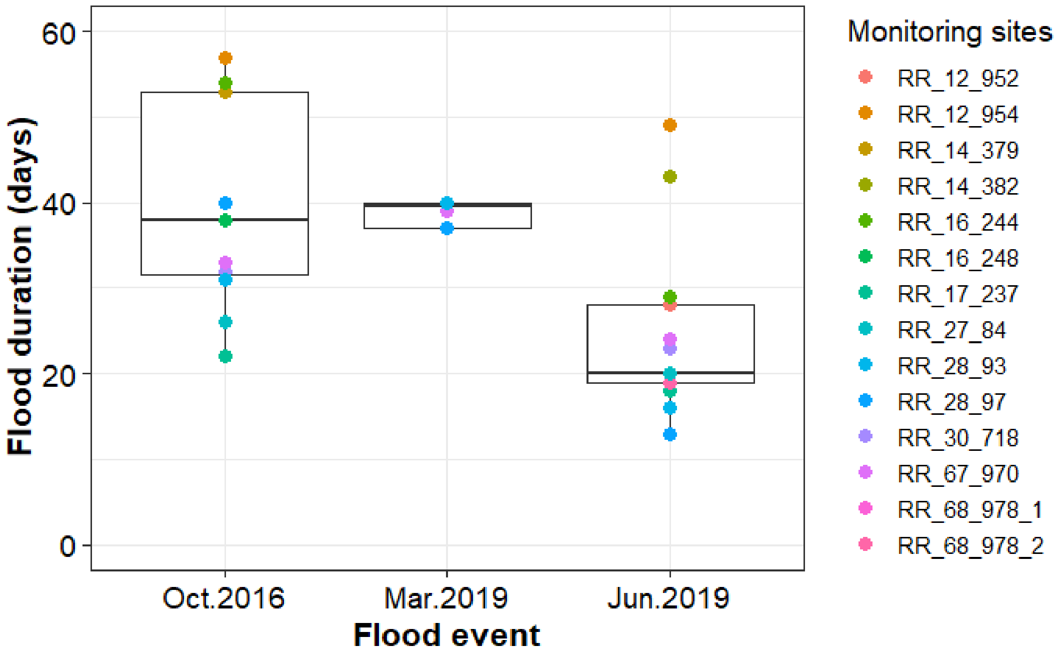


Figure 3-5. The flood duration (inundation days) after the flood events in October 2015, March 2019, and June 2019 at the 14 water level monitoring sites.

Table 3-2. The flood duration (inundation days) statistics after the flood events in October 2015, March 2019, and June 2019 at the 14 water level monitoring sites.

Flood duration (days)	**Oct 2016**	**Mar 2019**	**Jun 2019**
Dam discharge (reference)	8	13	10
Maximum	57	40	49
Minimum	22	37	13
Mean	40	39	25

I selected 3 typical flood events with the most available data to take a closer look. They were the flood events in October 2016, March 2019, and June 2019. The inundation duration for these 3 flood events at all the 14 monitoring sites was calculated (Figure 3-5). For the 3 flood events, the time required for the forest to dry out varied widely, with an average of 25 days to 40 days (Table 3-2). As the sites were arranged from upstream to downstream (from 12-952 to 68-978-2), the upstream sites were underwater for a longer time, the downstream sites needed a medium time, and the sites in the middle went back dry the most quickly (Figure 3-5). Another important finding was the inundation in the forests needed a long time to recede. Even though the dam discharge periods were only about 1-2 weeks, the water remained on the floodplain for up to 57 days (the maximum inundation duration of the flood event in October 2016) (Table 3-2). This means that even if the dam discharge period was very short, the downstream forest would still suffer from the inundation pressure for a long time.

The water height data from TNC monitor sites were very helpful in understanding general trends of floodplain inundation. However, there were also some concerns about this analysis. When I counted the number of days it took for the water level to fall, there were no clear criteria for the initial dry state. For some sites, the water levels were -1 feet or lower during dry periods, while some were around 0. This was also affected by flooding events and local weather events. If there was precipitation after a flood event, or during a very wet season, some sites might remain wet for months before the water level dropped back to dry again, making it difficult to count the inundation days caused by a single flood event. Despite efforts to avoid the influence of subjective factors, there might still be standard inconsistencies among different gages and different flood events. Therefore, the days were for qualitative reference only. That was why the 3 selected flood events (October 2016, March 2019, and June 2019) were important. They had the most abundant data across monitoring sites, and clear start and end date at most sites, so their flood duration days were the most accurate. For future studies, the next step could be to explore the spatial variation of inundation duration, including the difference between upstream and downstream, the effects of distance from the main channel, and the influence of topological terrains, such as why the data of paired gages close to each other were not similar.

4. Mapping the flood extent in the Lower Roanoke River Basin

4.1 Introduction

In the previous section, I studied the frequency of flooding and the duration of forest inundation caused by flooding in the Lower Roanoke River Basin. In addition to temporal trends, geospatial characteristics are also important. To study how forest ecosystems respond to flooding stress, it is very necessary to understand where the actual inundated forests are during flood events, which is to map flood extent.

Remote sensing provides an efficient and low-cost method to assess flooding compared with a traditional on-site or overflights survey. Early attempts to quantify the extent of flooding began before 2000, often by combining satellite images like Landsat with elevation and precipitation data. With the iteration of technology, the quantity and quality of remote sensing data are also increasing, and many models for long-term flood monitoring using advanced data have emerged (Lin et. al. 2016; Domeneghetti, Schumann, & Tarpanelli, 2019). Some of these surface water models, such as the Global Surface Water Database (Pekel, Cottam, Gorelick & Belward, 2016) and Global Surface Water Dynamics database (Pickens et. al., 2020), do a good job of showing seasonal changes in flooding, but not sensitive enough to inundation under vegetation. In recent years, sentinel-1 radar data has been used to solve this problem, because radar can be unaffected by clouds and detect water beneath forests (Schaffer-Smith et. al., 2020; Tsyganskaya, Martinis, Marzahn, & Ludwig, 2018). However, creating accurate and reliable flood extent maps, particularly for detecting water under vegetation, remains a challenge.

In this section, a remote sensing model was built to identify the flood extent of a specific flood event by a random forest machine-learning algorithm. As discussed in the previous section, the area of flooding for each specific flood event might be different, and the location of inundation depends on factors such as the topography and land coverage. As a result, the actual flooded area may not be the same as the pre-mapped floodplains. Alternatively, the downstream flow is heavily controlled by the dam release. Hence, different dam releases and flows may also have an impact on the flooded area. The object of this study was to map the flood extent of the Roanoke River, especially inundated forest areas, by radar imagery and other remote sensing data, aiming to explore the feasibility of identifying the flooded area within a short time frame by remote sensing, understand the actual flooded area in the Lower Roanoke River Basin and how the dam release levels influence the flood extents. This work would provide a reference for forest management and conservation in the Roanoke River Basin.

4.2 Methods

4.2.1 Flood event selection

The 2 flood events studied in this section were in Mar 2019 and Mar 2021. In terms of seasons, I preferred those in the pre- and post-growing seasons (spring and winter) to minimize the effects of vegetation change. Also, the chosen flood events should not be close to another flood event, with prolonged inundation or with much precipitation before or after, or the flood extent could be inaccurate. Most importantly, there needed to be enough good-quality satellite imagery within the about 10-day flooding time frame for the chosen events to perform classification. Among all the 25 flood events between 2016 and 2021 (Table 3-1), I selected the flood events of Mar 2019 and Mar 2021 because they met the above conditions, and were located in the same month so it would be good to compare, and respectively had the maximum dam discharge (35,000 cfs in March 2019) and the minimum flooding dam discharge (20,000 cfs in March 2021), representing the 2 extreme situations of flooding in the basin.

4.2.2 Data Collection and Pre-processing

I integrated 3 types of imagery data as predictors for flood extent classification: real-time remote sensing data during the flood events, land use land cover data, and elevation data. For both events, 10-meter Sentinel-1 Synthetic Aperture Radar (SAR) Ground Range Data (GRD) (Copernicus Sentinel-1 data, 2021) C-band radar data was used. For the March 2021 event, 10-

meter Sentinel-2 Multispectral Instrument (MSI) data (Copernicus Sentinel-2 data, 2022) was added because it has data available during the time window. The 30-meter land use land cover data was from National Land Cover Database (NLCD) 2016 (Dewitz, 2019), and the 10-meter elevation data was from the 3-Demensial Elevation Program (3DEP) (U.S. Geological Survey (USGS), 2019) as topographic information. All the data were obtained from the Google Earth Engine (GEE) platform (Gorelick et. al., 2017).

The remote sensing data, Sentinel-1 and Sentinel-2 for the 2 flood events were inquired within the dam release periods and the Lower Roanoke River Basin boundary. For March 2019, the time window was from February 26 to March 12, 2019. In this time frame, it had images taken on March 1 and March 6. Since the image on March 6 covered less area, I only retained the image on March 1 that basically completely covered the study area. For March 2021, the time frame was between March 22 and April 7, 2021. The eligible Sentinel-1 imagery was from March 26, 2021, and the Sentinel-2 imagery was from April 5, 2021.

I used the bands of ascending vertical transmit and vertical receive (VV) and ascending vertical transmit and horizontal receive (VH) polarization of the Sentinel-1 data. For the Sentinel-2 data for the second flood event, Band 2 (blue), Band 3 (green), Band 4 (red), Band 5 (Visible and Near-Infrared 1), Band 6 (Visible and Near-Infrared 2), Band 7 (Visible and Near-Infrared 3), Band 8 (Visible and Near Infrared), and Band 8A (Visible and Near-Infrared 4) were used. The Sentinel-1 and Sentinel-2 data accessed through GEE had been pre-processed, including applying orbit files, thermal noise removal, radiometric calibration, and terrain correction (Google Earth Engine, 2021). Thus, no more pre-processing steps were conducted.

I obtained the latest NLCD 2016 data with a 30-meter resolution. In addition to the land use land cover (LULC) layer, we extracted the properties of tree cover percentage and impervious cover percentage as separate layers. To simplify it and make it more relevant to flooding, I combined some land cover classes to just 6 (Appendix 1). The 3D Elevation Program is a national elevation database produced by USGS lidar surveys. The elevation data served as a flow property was important to the flood extents.

These layers were combined into a single stacked predictor composite for each flood event in GEE. The predictor composite for the flood event in March 2019 included 6 layers: Sentinel-1 VV and VH, LULC, tree cover percentage, impervious percentage, and elevation. The predictor composite for March 2021 had 14 layers, adding 8 Sentinel-2 layers (B2, B3, B4, B5, B6, B7, B8, and B8A) to the other 6. Except for the Sentinel-1 and Sentinel-2 images, none of the other layers was clipped to the study area because the classification model would automatically drop pixels that did not include all layers.

4.2.3 Training and Testing Samples

I used 3-meter Planet Scope 3-band multispectral imageries (Planet Team, 2017) as reference data to select training and testing samples for the supervised classification. A filter was applied to select images with a cloud coverage of less than 30% and were captured within the study area and dam release periods. The reference images for both flood events were collected within the dam release periods, which were collected on March 7, 2019, for the flood event in March 2019, and on April 4, 2021, for the March 2021 flood event.

Since flooded forest areas were the study focus, I set 4 classes: 1. Open water; 2. Open ground; 3. Dry forest; 4. Flooded forest. Training and testing sites for the 4 classes were manually selected in ArcGIS Pro (ESRI, 2011) and imported to GEE. Based on the reference Planet images, I created at least 1500 training pixels and 150 testing pixels for each class (Table 4-1).

Table 4-1. The number of training pixels and testing pixels used in the remote sensing models for the 2 flood events.

Flood event		Number of training pixels		Number of testing pixels	
		Mar 2019	Mar 2021	Mar 2019	Mar 2021
Class	Open water	23675	4185	154	621

	Open ground	2456	6025	199	813
	Dry forest	5988	3940	152	600
	Flooded forest	1868	15887	239	1652
Total		33987	30037	744	3686

4.2.4 Classification

I conducted a supervised classification with the random forest algorithm in Google Earth Engine. To train the model, I ran a random forest classifier with 100 decision trees and 2 variables per split by the manually created training pixels. The classifier then was used to perform supervised classification on the predictor composites. For accuracy assessment, confusion matrices for the testing pixels were created to calculate the accuracy.

4.2.5 Comparison with the 100-year floodplain

The flooded forest areas of the 2 flood events generated by the remote sensing model were compared with the 100-year floodplain in ArcGIS Pro. They were compared by stacking the extents and the floodplain layers in different colors to show overlapped areas and not-overlapped areas.

4.3 Results

The supervised classification map with a 10-m resolution did well mapping the flood extents for the flood events in March 2019 and March 2021 in the Lower Roanoke River Basin (Figure 4-1 and Figure 4-2). The forest areas were mostly aligned with the NLCD 2016 land use land cover data (Figure 1-1), and all the rivers were accurately mapped. Flooded forests were concentrated along rivers, and the flooded area was smaller around rivers with high stream levels than that around rivers with lower stream levels. For example, the flooded forest stripe of the Cashie River, a tributary of Roanoke, was narrower than that of the Roanoke River.

The resulted flood extent maps had high accuracies. The overall accuracy for March 2019 was 85.6%, with user accuracies of 100.0%, 84.9%, 73.7%, and 84.5% for the class of open water, open ground, dry forest, and flooded forest respectively (Table 4-2). The overall accuracy for March 2021 was 89.7%, which was higher than that of March 2019. The user accuracies for open water, open ground, dry forest, and flooded forest for this event were 100.0%, 100.0%, 99.5%, and 77.3% (Table 4-3). The most common misclassification was between dry forest and flooded forest as expected, due to their similar remote sensing signatures in the predictor composites. There was also a slight underestimation of open ground for the March 2019 event, classifying open ground as open water or dry forest.

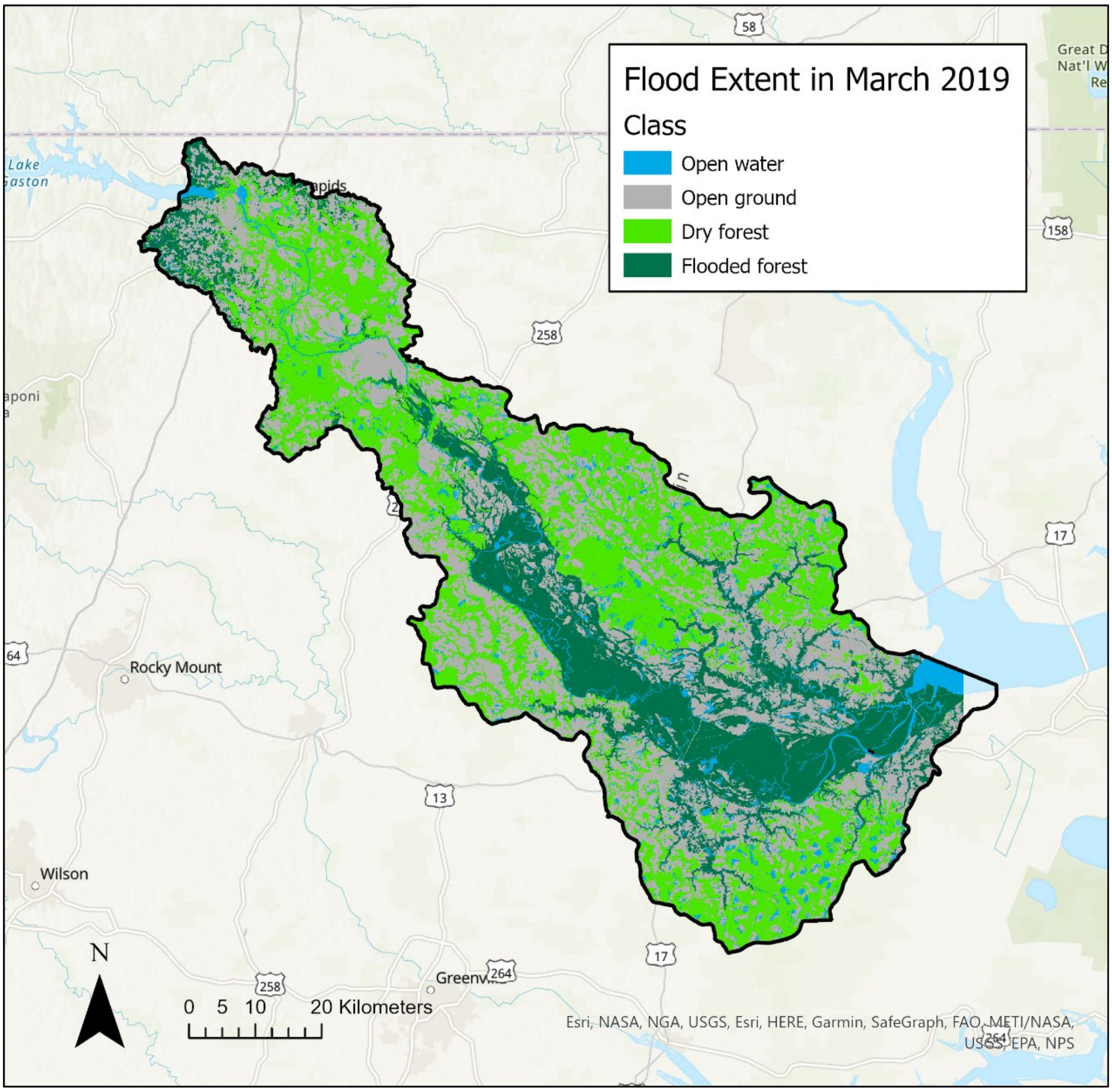
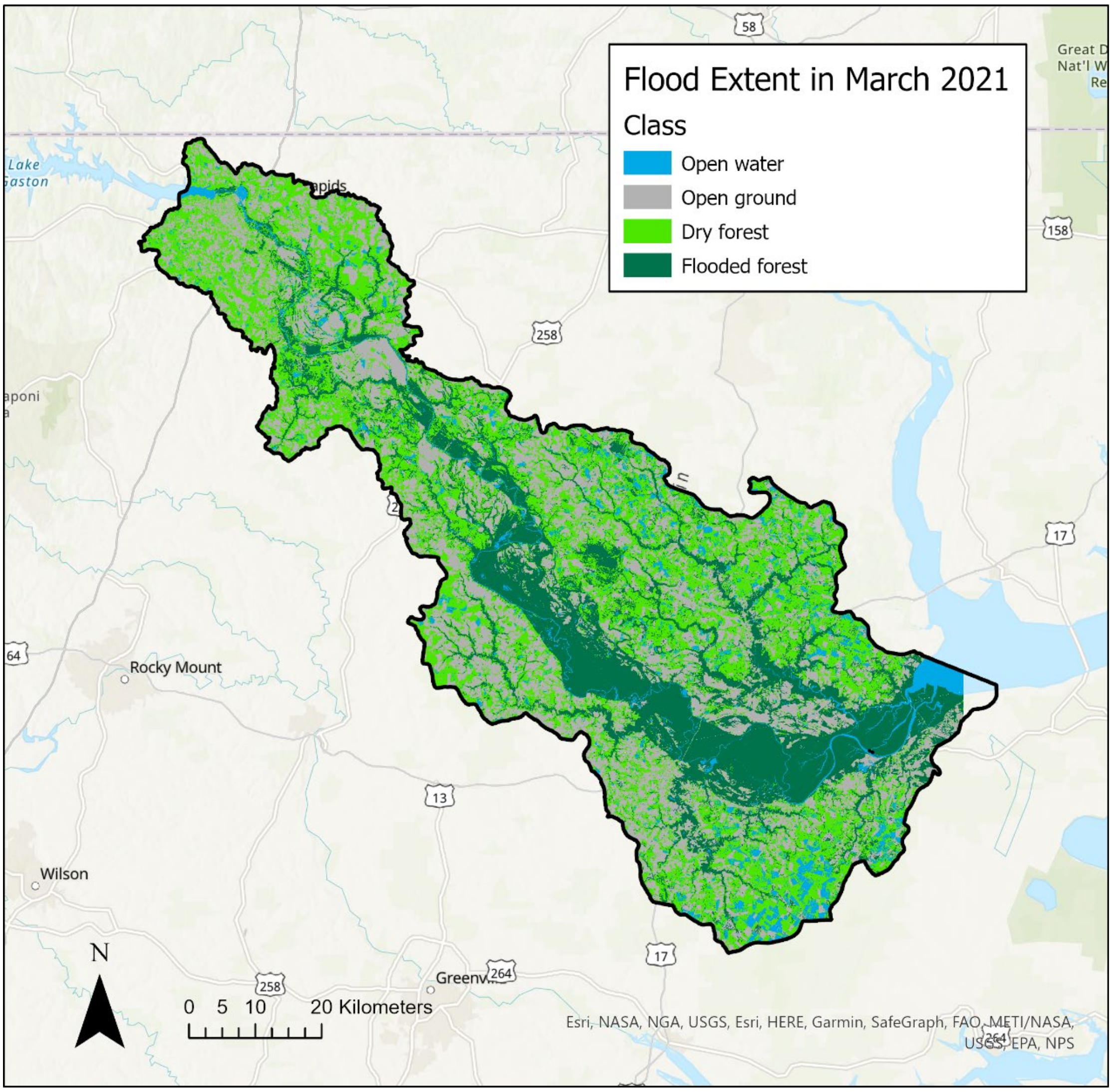


Figure 4-1. Map of the flood extent classification in the Lower Roanoke River Basin in March 2019.

Table 4-2. Accuracy assessment for the flood extent classification in the Lower Roanoke River Basin in March 2019.

Class		**Classification**					**User accuracy**
		Open water	**Open ground**	**Dry forest**	**Flooded forest**	**Sum**	
Testing samples	**Open water**	154	0	0	0	154	100.0%
	Open ground	19	169	11	0	199	84.9%
	Dry forest	1	1	112	38	152	73.7%
	Flooded forest	0	2	35	202	239	84.5%
	Sum	174	172	158	240	**Kappa**	80.6%
Producer accuracy		88.5%	98.3%	70.9%	84.2%	**Overall accuracy**	85.6%



Esri, NASA, NGA, USGS, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA, NPS

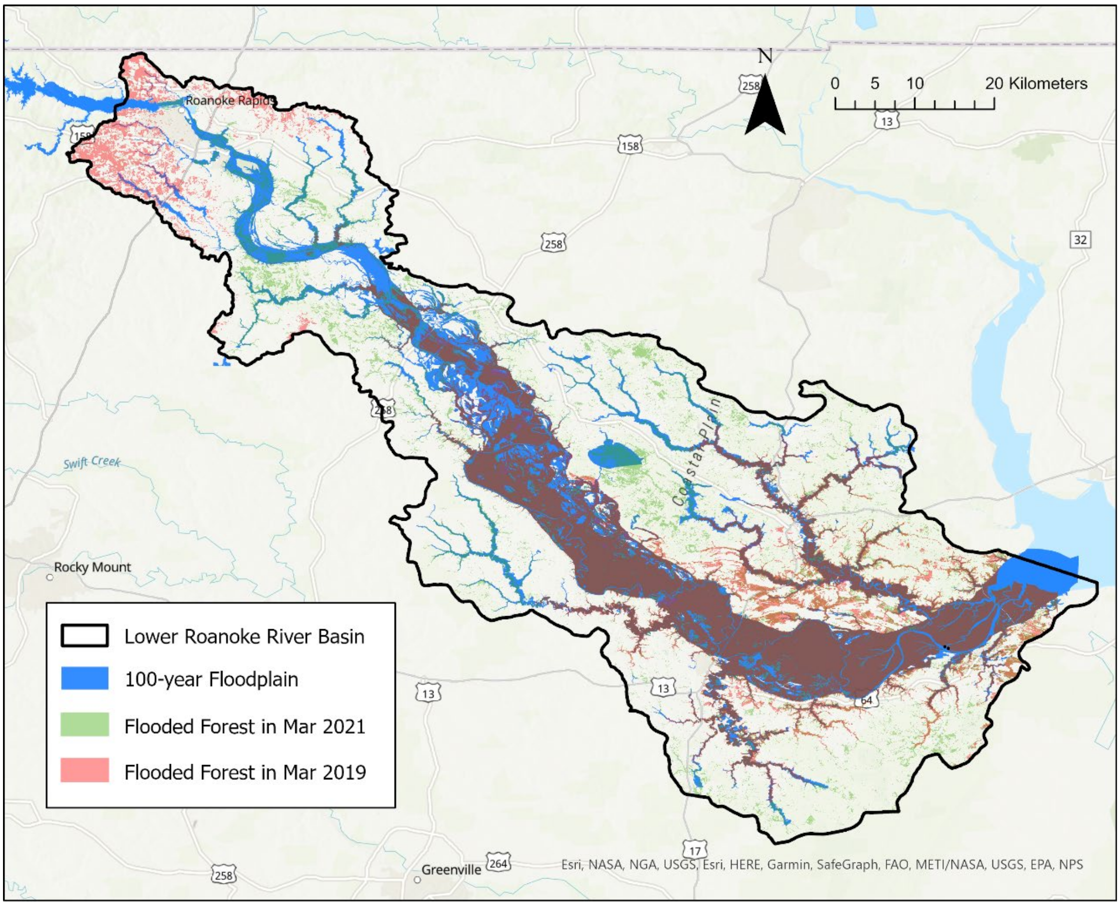
Figure 4-2. Map of the flood extent classification in the Lower Roanoke River Basin in March 2021.

Table 4-3. Accuracy assessment for the flood extent classification in the Lower Roanoke River Basin in March 2021.

Class		**Classification**					**User accuracy**
		Open water	**Open ground**	**Dry forest**	**Flooded forest**	**Sum**	
Testing samples	**Open water**	621	0	0	0	621	100.0%
	Open ground	0	813	0	0	813	100.0%
	Dry forest	3	0	597	0	600	99.5%
	Flooded forest	5	0	370	1277	1652	77.3%
	Sum	629	813	967	1277	**Kappa**	85.8%
Producer accuracy		98.7%	100.0%	61.7%	100.0%	**Overall accuracy**	89.7%

The flood extents in March 2019 and March 2021 were compared with the 100-year floodplain (Figure 4-3). The pre-mapped 100-year floodplain by NC Flood Risk Information System (FRIS) was in solid blue on the map. The flooded forest extent in March 2019 was in red and the flood extent for March 2021 was in green. These 2 flood extent layers were set to be 50% transparent so that the overlapped areas could be seen through. For example, a purely red area meant it was only flooded in March 2019, and a purely green area meant only flooded in March 2021. Near the Roanoke Rapids, there was no flooded forest in neither the flood events on the 100-year floodplain here. This might be because the area is mainly urban and agricultural and was classified as open ground by the model. The large maroon area along the downstream river was the area flooded in both flood events and also on the 100-year floodplain. The good overlapping validated that the 100-year floodplain is a good predictor of flood extent in this area. It is worth noting that there were some orange patches in the downstream basin, which were areas flooded in both events but not on the 100-year floodplain. These areas needed special attention to flooding.

Figure 4-3. The comparison of the flooded forest extents in March 2019 and March 2021 and the 100-year floodplain in the Lower Roanoke River Basin.



4.4 Discussion

The classification result in the Lower Roanoke River Basin proved that the method of mapping the flood extent of a certain flood event with remote sensing data is feasible. The classification had high overall accuracy. The forest cover in the classification map was also reasonable and consistent with the NLCD land cover data, and the flooded area was close to the flooding extent during 2 hurricanes in the same area in a previous study (Schaffer-Smith et. al., 2020). The classification of open water and open ground worked well, while the main misclassification occurred between dry forest and flooded forest.

I chose Sentinel data for its high temporal and spatial resolution. Because flood events were time-sensitive, lasting only about 10 days, Sentinel satellites' 5- or 6-day revisit intervals gave me a higher chance of getting images during a specific flood event. At the same time, their high resolution of 10 meters also allowed a more accurate flood extent. Although not from the study period, land cover types and elevation data significantly improved the classification results compared to the trial run results with radar data only. Unfortunately, I could not obtain enough cloud-free Sentinel-2 or Landsat images for the flood event in March 2019. The classification could be better with the presence of these multispectral data as the March 2021 flood extent map had a higher accuracy with Sentinel-2 data. Related indices, like Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI), could also help with the classification.

Another possible cause of classification errors in the training samples. There was a time difference between the reference Planet images to select training samples and the Sentinel-1 radar data and Sentinel-2 multispectral data to perform the classification. During this time difference, the flood extent might have changed, resulting in an inaccurate flood extent. Notably, we categorized all areas with no vegetation or water, including urban and agriculture, as open ground when creating the training samples, and the classification nicely combined them compared with the NLCD data.

There was no clear evidence showing that a higher dam discharge would lead to a larger flooded area and vice versa. Most of the flooded forests in March 2019 under a 35,000 cfs dam discharge overlapped with the March 2021 flooded forests, including areas outside of the 100-year floodplain (Figure 4-3). There were many flooded patches scattered around in the basin not connected to the mainstem flooding. These patches were most likely the results of local rainfalls. Although they could be inundated by a certain amount of rainfall, they were not necessarily related to the Roanoke River flooding and the dam discharge upstream. Similar situations applied to tributary flooding, too. The tributaries in the Lower Roanoke River Basin were not controlled by the dams, such as the Cashie River, so the flooded zones along the tributaries had no correlation with the dam discharge levels. In order to focus on only the Roanoke River mainstem and removed the tributaries and isolated inundated patches, Hydrological Unit Code (HUC) 12 could be used to exclude them.

This study explored a remote sensing method to map the flooded extent of a certain flood event, especially the area of inundated forest, which is important for investigating the response of forest ecosystems to flood threats. The method demonstrated the benefits of cloud-independent high-resolution Sentinel-1 radar data and the aids from land cover and topography information in flood extent classification. The random forest algorithm also had been proved very effective.

5. Conclusions

This study deepened the understanding of the floodplain ecosystems in the Lower Roanoke River Basin from the perspectives of deforestation and flooding. The lower Roanoke River Basin is a unique basin with rich biodiversity, while the ecosystems are mostly on active floodplains. The change of landscape has an impact on the floodplain ecosystems so it is important to study the overacting changing hydrology of the river and its interactions between deforestation and dam management. Increased knowledge about shifts in forest practices, water flow responses, and flood extents may inform and benefit future land, forest, and dam management in the Lower Roanoke River Basin.

Forest loss is accelerating in the Lower Roanoke River Basin, especially on the floodplains. Deforestation increased 11.5% between 2011 and 2020, compared with 2001-2010, and the forest loss in the 100-year floodplain was 18.8% after 2010 (Table 2-1). Interestingly, 2010 was the year that the wood pellet biomass industry entered North Carolina. In the removed forests, there was a higher proportion of hardwood, while the wood pellet producers also had a preference for hardwood. The wood pellet industry might be correlated to the increased deforestation in the Lower Roanoke River Basin.

Although the dams did a good job of controlling the flooding, the Lower Roanoke River Basin is still at high risk of flooding, especially in winter and spring. In the recent 6 years, the frequency of floods ranged from 1 to 6 per year. The floodplain forests would be under serious flooding pressure because of the long time for water to recede after a flood event. However, the inundation time in the floodplain forests varied a lot, depending on location, flood events, topography, land cover, and other factors.

Remote sensing, in particular with radar data, had been proven as a feasible way to map the flood extent of a specific flood event, which can be a good reference for forest management and dam management. Although this approach was still limited by image availability and might not be able to perform high-quality modeling of every flood extent, the Sentinel-1 radar data showed great advantages when mapping the flooded forest extent for a specific flood event within a short time window due to its high temporal resolution, could-free images, and sensitivity to water underneath vegetations.

With deforestation and flooding both considered, the 100-year floodplain should be the focus of forest management and conservation work in the Lower Roanoke River Basin. Recent forest loss had been more severe in the 100-year floodplain, where the loss of vegetation buffers could make the rest of the forests more vulnerable to flooding. On the other hand, the actual flooded forest areas largely overlapped with the 100-year floodplain, indicating that the floodplain was indeed more at risk of inundation. In this case, the future land and forest conservation work should pay more attention to the 100-year floodplain.

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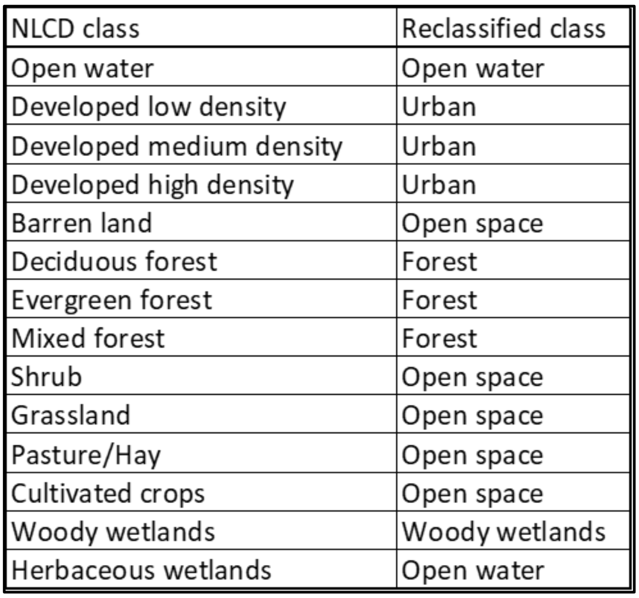
Acknowledgments

I would love to give special thanks to my advisor Dr. Nicolette Cagle for her patient guidance and endless support throughout this project. I also want to thank Dr. Julie DeMeester from The Nature Conservancy for providing me the incredible opportunity to participate in this project as well as countless guidance and encouragement. I would like to thank Dr. Jennifer Swenson for her instructions and advice on remote sensing methods. I am very grateful to Dr. Danica Schaffer-Smith and Ankita Gupta for their generosity in time helping me master Google Earth Engine. I really appreciate Steven Anderson for his insights into the project and for always being supportive. Lastly, I would like to express thanks to John Fay for helping me with all kinds of technical problems, big or small. The project would not be completed without any of you.

Appendixes

Appendix 1 – Simplified land use land cover classes as a layer in the predictor composites for the remote sensing flood extent model



NLCD class	Reclassified class
Open water	Open water
Developed low density	Urban
Developed medium density	Urban
Developed high density	Urban
Barren land	Open space
Deciduous forest	Forest
Evergreen forest	Forest
Mixed forest	Forest
Shrub	Open space
Grassland	Open space
Pasture/Hay	Open space
Cultivated crops	Open space
Woody wetlands	Woody wetlands
Herbaceous wetlands	Open water

Appendix 2 – JavaScript script in Google Earth Engine for the forest loss analysis

https://code.earthengine.google.com/a8ab95b7f97b06a9c7148921ccf6ebe9

Appendix 3 - JavaScript script in Google Earth Engine for the remote sensing flood extent model

Flood event in March 2019:

https://code.earthengine.google.com/c9168670d6a8a918c8e9a388e47444fe

Flood event in March 2021:

https://code.earthengine.google.com/15ee97f9a674c3a11d246c14bb4870a6