Mapping Sandbars in the Connecticut River Watershed through Aerial Images for Floodplain Conservation

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University of Massachusetts Amherst
MAPPING SANDBARS IN THE CONNECTICUT RIVER WATERSHED THROUGH AERIAL IMAGES FOR FLOODPLAIN CONSERVATION

A Thesis Presented

by

BOGUMILA BACKIEL

Submitted to the Graduate School of the University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

February 2018

Department of Environmental Conservation
MAPPING SANDBARS IN THE CONNECTICUT RIVER WATERSHED THROUGH AERIAL IMAGES FOR FLOODPLAIN CONSERVATION

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Approved as to style and content by:

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Keith H. Nislow, Chair

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Environmental Conservation
ACKNOWLEDGMENTS

First and foremost, I want to acknowledge my wonderful committee. Keith Nislow, thank you for your astonishing ideas and for being a role model that successful ecologists can come from the big city too. Christian Marks, thank you for the long hours you have patiently put into this research, your knowledge and detail have been invaluable. I have learned so much over the past two years which would not have been possible without both of your support and passion.

This project was funded by the Northeast Climate Science Center (NECSC). Thank you to Rick Palmer and Abigail Ericson for offering insight into engineering and providing a supportive group atmosphere that has led to success. To the other staff and students at NECSC and the Environmental Conservation department, I am forever thankful for your encouragement.

I am grateful to the team at the Nature Conservancy in Northampton. Kim Lutz, your enthusiasm and encouragement have been a driving force in this research and Katie Kennedy, thank you for providing help with statistics. To Jonathan Chipman from Dartmouth College, and Jason Coombs from the Forest Service, I am thankful for both of your assistance with GIS.

Thank you to my family, Halina and Waclaw, it is the incredible sacrifices you both have made in your lives that drive me to be successful and make you both proud.
ABSTRACT

MAPPING SANDBARS IN THE CONNECTICUT RIVER WATERSHED THROUGH AERIAL IMAGES FOR FLOODPLAIN CONSERVATION

FEBRUARY 2018

BOGUMILA BACKIEL

B.A., STATE UNIVERSITY OF NEW YORK, PURCHASE
M.S., UNIVERSITY OF MASSACHUSETTS, AMHERST

Directed by: Keith H. Nislow and Christian O. Marks

Active geomorphic features of rivers like sandbars provide habitat for endangered and threatened riparian plant and animal species. However, human development has altered flow and sediment regimes, thus impairing formation of sandbars and islands. Large scale mapping of the fluvial geomorphology in river ecosystems like the Connecticut River is necessary to understand the dynamics of these features and preserve habitat. Orthophotographs from 2012 from United States Department of Agriculture's Farm Service Agency (FSA), National Agriculture Imagery Program (NAIP) were used to develop a model in ArcGIS Pro to identify fluvial geomorphic features in the Connecticut River and 12 of its major tributaries. This multi-stage image classification model identifies and ranks pixels of proximity and similar color to identify and map sandbars and islands. Locations of sandbars distribution were mapped and analyzed for each river. In the majority of rivers, sandbar area per reach decreases downstream. For the mainstem, sandbar area decreased towards the mouth but with three increases of sandbars due to meandering and major tributary confluences of the White and Deerfield rivers. Dams tend to decrease sandbars downstream but the effect of dams
is context specific. Sandbars are stored upstream of the impoundment on the Black River as expected, sandbars appear downstream of a dam on the mainstem if a tributary confluence is present. Conservation of high sandbar area reaches and naturally eroding stream banks are necessary for preservation of endangered species. This spatial model for sandbar mapping can be applied in other river ecosystems across the region.
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CHAPTER 1

MAPPING SANDBARS AND ISLANDS IN THE CONNECTICUT RIVER WATERSHED USING AN OBJECT BASED SEGMENTATION MODEL ON AERIAL IMAGES

Abstract

Sediment in rivers has been decreasing worldwide due to construction of impoundments. Sediment deposition creates floodplains, wetlands and fluvial geomorphic features, like sandbars and islands. Sandbars are important because their early successional environment provides habitat for pioneer plant species that start a succession to a climax community of a forested floodplain. Sandbars are habitat for a variety of animals including freshwater turtles, insects and their associated eroding banks provide nesting sites for bank swallows and kingfishers. To map these critical sandbar habitats a model was developed on Connecticut River watershed using one meter resolution aerial images from the United States Department of Agriculture's Farm Service Agency (FSA), National Agriculture Imagery Program (NAIP). The aerial images were used to create a four step automated object based segmentation model in ArcGIS Pro. The river channels from the mainstem and 12 major tributaries were clipped from the FSA NAIP images. Pixels from each river channel image were segmented based on color and proximity, and automatically placed into five groups, with the group representing sandbars exported individually. The model ran on 83% of the 13 rivers total length due to overhanging vegetation and small channel size in tributaries. Sandbar accuracy was 93.4% for the watershed after polygons measuring over the mean size for each river were observed and deleted if an error. This spatial model provides researchers with a
methodology for geomorphological mapping that can be applied in other large river ecosystems.

**Introduction**

Automated mapping of sediment deposition on a watershed scale is necessary for floodplain river conservation. Sediment has decreased in riverine systems worldwide due to anthropogenic factors (Syvitski et al. 2006; Walling and Fang, 2003) and has caused negative effects upon aquatic and riparian species habitat. Sediment budgets allow researchers to determine locations of increasing and decreasing sediment. Bars and islands can be used as a metric to quantify the sediment budget of a river (Wohl et al. 2015).

Active rivers create floodplains and sandbars including point bars, alternate bars, and islands (Gurnell et al. 2012). Different river channels have varying types of sandbars: alluvial islands are present in braided channels, side channel bars alternate in straight/sinuous channels and point bars occur in bends of meandering channels (Figure 1). Rivers meander and create natural bank erosion, which beings sediments into the river. For sediment to deposit and collect in river channels the flow of water needs to slow from either a reduction in stream gradient or discharge. Such reductions in stream gradient frequently occur at tributary confluences and the head of impoundments (Volke et al. 2015).

Sandbars provide vital riparian habitat and ensure future floodplain creation. Sandbars and islands are early successional habitats that allow for colonization and stabilization by pioneer plant species (Friedman and Auble, 2000; Gurnell, 2014). These
pioneers start a succession from a new sandbar into a vegetated floodplain or island. These forested floodplains provide ecosystem services to human communities by attenuating storm flood peaks through storing water (Posthumus et al. 2010). Sandbars and floodplains also provide critical habitat for riparian plant and animal species. In the Northeast United States, several species of conservation interest require sandbars and the surrounding land, including the endangered wood turtle (*Glyptemys insculpta*) (Jones, 2009), the puritan tiger beetle (*Cicindela puritana*) (Omland, 2004) and threatened river odonates (Collins and McIntyre, 2017). Sandbars provide habitat in other watersheds including the Missouri River, where the endangered least tern (*Sterna antillarum*) and threatened Piping Plover (*Charadrius melodus*) require sandbars for nesting (Sidle et al. 1992). Plant and animal species which depend on riverine sediment deposits are declining in numbers due to human activity.

Anthropogenic factors have caused the alteration and decline of sediment regimes. New England has the greatest density of dams in the United States (Graf, 1999). Both small tributary and large mainstem dams have changed flow conditions of the Connecticut River (Nislow et al. 2002), affecting sedimentation (Poff et al. 1997) and likely decreased formation of sandbars (Park et al. 2008). Channelization and bank hardening increases flow velocities (Gregory, 2006) thus not allowing for sediment to settle and accumulate into bars.

With the use of remote sensing, efforts can be made to conserve geomorphic processes and preserve habitat of endangered species (Wiens et al. 2009). Several approaches have been used to model fluvial geomorphology using aerial imagery including: hand digitizing sandbars within small portions of 145 kilometer reach in the
Platte River (Nelson, 2006) and reaches of the Missouri River (Sanford, 2007), and mapping river migrations from almost two centuries with the use of aerial imagery (Schook et al. 2017). However these approaches and others are time intensive due to the lack of automation, small in scale, and rely on images of coarse resolution.

No automated models have yet been developed that map the spatial distribution of geomorphic features across a watershed. Using fine resolution images of one meter resolution, from space borne sensors, allows for mapping in large and medium sized rivers (Gilvear and Bryan, 2016). Object-based image classification can offer differentiation and group similar pixels together from aerial images (Blaschke, 2010; Lee et al. 2010). Automation of models results in greater accuracy of results (Bulliner et al. 2013; Whited et al. 2002) which can be done through an unsupervised classification. The objective for this study was to inform river and floodplain conservation practice and policy by creating an automated object based spatial model that maps geomorphic features, like sandbars and islands, in the Connecticut River watershed.

**Methods**

**Study Region**

The Connecticut River is the largest river in New England, flowing 660 kilometers from its headwaters at the Canadian border to its mouth at the Long Island Sound in the Atlantic Ocean. The watershed encompasses 29,200 square kilometers. The Connecticut River receives precipitation year round, ranging from 900 to 1200 mm/year. Higher elevations of the watershed, including the Green Mountains in Vermont and the White Mountains in New Hampshire, receive greater amounts of precipitation mainly as
snow. During spring, snowmelt causes flooding along the mainstem. Storms like Hurricane Connie in 1955 and Tropical Storm Irene in 2011 have caused major flooding within the river and its tributaries (Anderson et al. 2010; Blake et al. 2007; Marks et al. 2014).

Materials

One meter resolution aerial images were provided from the United States Department of Agriculture's Farm Service Agency (FSA), The National Agriculture Imagery Program (NAIP) and downloaded from the United States Department of Agriculture (USDA) (https://gdg.sc.egov.usda.gov/). Photos were taken of Connecticut, Massachusetts, New Hampshire and Vermont during a one week period from the end of September into the beginning of October in 2012. These photos were selected because annual low flows in late summer and early fall expose bars. Images from 2012 were selected because they were the newest images available during the study period with the least amount of cloud cover.

Data Preparation

The river channel of the main stem and 12 tributaries was hand digitized in ESRI ArcGIS. Hand digitization was done to limit processing time, by only having the model run on images of the channel. The mainstem was digitized from the headwaters in northern New Hampshire to the head of the estuary in southern Connecticut. The tributaries were digitized until their channels become too narrow to hand digitize and/or overhanging branches from ing trees on the riverbank obscured the channel (Figure 1.2).
Marinas, piers, boats, bridges and dams were not digitized in the river channel. Rather the polygon segments were digitized around this infrastructure to avoid them being mistaken for bars by the segmentation part of the model. The river channel polygons were used to clip the NAIP aerial images to only show the channel.

Identifying Sandbars

The aerial images of each river’s channel were segmented using a spatial detail of 14.5, with all other options as default (Figure 1.3b). Spatial detail values range from one to twenty, with a greater value providing greater classification of pixels. This segmented raster was then isoclustered through an unsupervised classification with a selection of five classes. Rather than training the model to distinguish between different objects in the river channel, the unsupervised option automated the model. The isoclustering created an Esri classifier definition file that was used to classify the segmented river channel and create a raster specifying five objects (Figure 1.3c). These raster objects were converted into polygons and the polygons representing sandbars were exported individually (Figure 1.3d). All rivers were not run together due to the large number of pixels from the segmentation step that is not supported by the ArcGIS isoclustering tool.

Quality assurance

By not hand digitizing human infrastructure like bridges in the river channel, several gaps were present in the channel polygons. After the segmentation model was run, gaps were filled in the channel polygons by using the 2012 NAIP aerial images to calculate channel area.
To determine the model accuracy, polygons that were identified as sandbars polygons measuring over the mean size for each river were observed. The mean and greater were selected because they were the source of outliers. If an error was present it was either deleted or if the sandbar was present in part of the polygon it was split for only the sandbar. The source of errors was from rapids that appeared the same pixel color as sandbars. These rapids tended to be larger, thus the reason for observing larger polygons.

**Results**

**Model**

The model successfully ran on 13 rivers including the mainstem and 12 major tributaries (Figure 1.4). Of the 13 rivers, 83% of their total length were hand digitized using the FSA NAIP aerial images and run through the model. For ten of the 13 rivers, over 3/4ths of their channels were digitized (Table 1.1).

During the automated isoclustering step the model identified four other groups that were not sandbars, these included the surrounding area, river channel, vegetation and errors. The error group included shadows from trees, rapids, and occasionally river channels.

**Quality Assessment**

The model had an 93.4% accuracy of mapping sandbars in the entire watershed (Table 1.2). After polygons which did not represent sandbars were deleted or split, the mean sandbar size in the watershed decreased by 20.8 square meters (Table 1.2). Accuracy varied depending on the river. The Chicopee and Ammonoosuc rivers had the
least amount of errors, while the Farmington and Ashuelot rivers had the greatest (Table 1.2).

**Discussion**

The model’s accuracy for selecting and grouping sandbars was over 90% in the watershed. This included an assortment of channels differing in size and location in the watershed. Thus, this model can be used on other river systems for sandbar and island modeling and would provide little to no errors.

Only major tributaries were chosen in this study due to their large channel sizes. In these major tributaries, channels were not hand digitized for their complete river length due to the decreasing stream size towards the headwaters and overhanging trees obscuring the channel. Mapping a metric like sandbars, in large rivers can offer insights into a river’s sediment regime. The use of fine scaled aerial images (one to five meter resolution) allows for accurate mapping of sandbars to determine the accuracy of their locations especially since these features can be very small in tributaries. Mapping limitations remain as aerial images from satellites can only be used for large and medium sized channel rivers due to canopy cover obscuring small rivers. Using drones and small hand held image sensors can be used to addressing sandbar modeling in smaller rivers (Gilvear and Bryan, 2016).

Our spatial model for mapping sandbars can be applied to other river systems. Our model worked on rivers in the Connecticut River watershed down to 15 meters in width on average. Thus large mainstem rivers and tributaries with a channel width around 15 meters are optimal study sites. Orthorectified aerial images of at least one meter
resolution from agencies like USGS should be used. High resolution will allow for
greater accuracy in locations of smaller sandbars and islands.

This model can be further applied in the Connecticut River watershed.
Investigating the influence of dams and other human development variables can aid in
determining the distribution of sediment deposition. Changes in sandbar distribution and
size after large storm events like Hurricane Irene can be detected by comparing images
before and after. In addition, drones can be used to capture aerial images of small
tributaries in the Connecticut River watershed and map them for sandbars, to provide a
better representation of sandbars in the watershed.

Automated large scale mapping of sediment regimes is necessary for river
conservation. Remote sensing through high resolution aerial images, LiDAR and
multispectral scanners are being used more in the field of geomorphology to quantity
features such as sediment (Wohl et al. 2016). Sediment budgets can aid researchers in
determining locations of increasing or decreasing sediment which can be used to create
policies that aid in a balancing sediment regimes (Wohl et al. 2015), and conserving these
fluvial geomorphic features for species habitat.
Conclusion

Combining locations of riverine sediment and data on flows is optimal for next generation river conservation (Wohl et al. 2015). This combination can aid in future work to determine areas of river conservation and restoration need. Large scale automated mapping of sandbars and islands, in major rivers such as the Connecticut, helps us understand the dynamics of these features and conserve the plants and animals that depend on these threatened habitats.
Literature Cited


Sanford, J.P., 2007. Dam Regulation Effects on Sand Bar Migration on the Missouri River: Southeastern South Dakota (Master degree thesis). the University of Montana Missoula, MT, USA.


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Tables

Table 1.1: List of rivers in the Connecticut River watershed modeled for sandbars and islands, with river lengths and basin size modeled.

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<th>River</th>
<th>Full (km)</th>
<th>Modeled (km)</th>
<th>Modeled (%)</th>
<th>Basin size (km²)</th>
<th>Modeled basin (km²)</th>
<th>Modeled (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonoosuc</td>
<td>89</td>
<td>81</td>
<td>91</td>
<td>1,036</td>
<td>828</td>
<td>80</td>
</tr>
<tr>
<td>Ashuelot</td>
<td>103</td>
<td>47</td>
<td>46</td>
<td>1,101</td>
<td>343</td>
<td>31</td>
</tr>
<tr>
<td>Black</td>
<td>66</td>
<td>58</td>
<td>88</td>
<td>520</td>
<td>393</td>
<td>76</td>
</tr>
<tr>
<td>Chicopee</td>
<td>29</td>
<td>29</td>
<td>100</td>
<td>1,870</td>
<td>1,823</td>
<td>97</td>
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<tr>
<td>Connecticut</td>
<td>654</td>
<td>574</td>
<td>88</td>
<td>29,200</td>
<td>28,808</td>
<td>99</td>
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<tr>
<td>Deerfield</td>
<td>122</td>
<td>113</td>
<td>93</td>
<td>1,722</td>
<td>1,153</td>
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<td>Farmington</td>
<td>75</td>
<td>57</td>
<td>76</td>
<td>1,559</td>
<td>583</td>
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<tr>
<td>Mascoma</td>
<td>51</td>
<td>33</td>
<td>65</td>
<td>505</td>
<td>341</td>
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<tr>
<td>Passumpsc</td>
<td>37</td>
<td>37</td>
<td>100</td>
<td>1,129</td>
<td>1129</td>
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<tr>
<td>Sugar</td>
<td>44</td>
<td>37</td>
<td>84</td>
<td>697</td>
<td>173</td>
<td>25</td>
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<tr>
<td>Upper Ammonoosuc</td>
<td>68</td>
<td>62</td>
<td>91</td>
<td>1,339</td>
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<tr>
<td>Westfield</td>
<td>126</td>
<td>77</td>
<td>61</td>
<td>1,339</td>
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<td>White</td>
<td>97</td>
<td>87</td>
<td>90</td>
<td>1,813</td>
<td>1,422</td>
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Table 1.2: The mean sandbar size for each river and the entire watershed, before and after resolving for errors.

<table>
<thead>
<tr>
<th>River</th>
<th>Mean sandbar size (sq m)</th>
<th>Mean sandbar size (sq m)</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonoosuc</td>
<td>324</td>
<td>320.7</td>
<td>99.0</td>
</tr>
<tr>
<td>Ashuelot</td>
<td>149.8</td>
<td>113.7</td>
<td>75.9</td>
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<tr>
<td>Black</td>
<td>343.2</td>
<td>340.8</td>
<td>99.3</td>
</tr>
<tr>
<td>Chicopee</td>
<td>281.9</td>
<td>281.9</td>
<td>100.0</td>
</tr>
<tr>
<td>Connecticut</td>
<td>579.5</td>
<td>537.8</td>
<td>92.8</td>
</tr>
<tr>
<td>Deerfield</td>
<td>220.2</td>
<td>216.2</td>
<td>98.2</td>
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<tr>
<td>Farmington</td>
<td>142.8</td>
<td>102.9</td>
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<td>Mascoma</td>
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<td>195.3</td>
<td>83.9</td>
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<td>269.4</td>
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<td>165</td>
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<tr>
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<td>242.8</td>
<td>241.4</td>
<td>99.4</td>
</tr>
<tr>
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<td>330.3</td>
<td>296.6</td>
<td>89.8</td>
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<tr>
<td>White</td>
<td>791.6</td>
<td>750.1</td>
<td>94.8</td>
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<tr>
<td>Average</td>
<td>314.2</td>
<td>293.4</td>
<td>93.4</td>
</tr>
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</table>
Figure 1.1: Types of channels and their associated sandbars seen in the Connecticut River watershed: (a.) Braided channels with islands, (b.) straight channels with alternating side channel bars, and (c.) meandering channels with point bars. Images are USGS NAIP, dated September 2012.
Figure 1.2: Study site of the Connecticut River watershed in New England, United States. Rivers in their complete length shown in orange, overlaid with blue representing the distance their channels were digitized.
Figure 1.3: The creation of an automated object based segmentation model in ArcGIS Pro for sandbar and island mapping: (1.) Mosaic aerial images and clip the river channel. (2.) Segment the river channel image with a spectral detail of 14.5 (with all other options as default). (3.) The result of an unsupervised isoclustering of the segmented image with a selection of five classes. (4.) Use the resulting Esri classification definition (.ecd) file to classify the raster, convert the resulting raster to a polygon and export the group representing sandbars/islands individually.
Figure 1.4: Polygons outlined in red showing sandbar mapping results in the (a.) White River near South Royalton, VT, (b.) Deerfield River near Charlemont, MA, and (c.) Upper Ammonoosuc River in Stark, NH.
CHAPTER 2
SANDBAR DISTRIBUTION IN THE CONNECTICUT RIVER WATERSHED

Abstract

Unregulated rivers are vital for creating erosion and providing the material for sandbar and island creation. Sandbars, islands and their associated eroding banks are habitat for endangered freshwater turtles, insects and birds in the Connecticut River watershed. Sandbars and islands were mapped in the Connecticut River mainstem and 12 of its major tributaries including the Ammonoosuc, Ashuelot, Black, Chicopee, Deerfield, Farmington, Mascoma, Passumpsic, Upper Ammonoosuc, Westfield and White. The largest undammed river in the watershed, the White, had the greatest amount of sandbar area. Sandbar area in the watershed tended to decrease downstream. The mainstem had the second lowest amount of sandbars in the watershed, but showed three peaks of increased sandbars in meandering sections and at the confluences of the White and Deerfield rivers. The type of dam and its location in the watershed had an influence on sandbar formation. The Black River in Vermont showed sandbar loss downstream of the North Springfield dam, and stored sediment in the form of sandbars upstream. Tributary confluences on the mainstem created sandbars downstream of dams. Conversion to dry-bed dams or small dam removal can restore channel morphology and sediment loads in the watershed. Locations of high sandbar area can be used by policy makers to conserve reaches for ecological habitat. Naturally eroding banks should be conserved to ensure erosion and future sandbar creation.
Introduction

Sediment movement and transport in alluvial rivers creates migrating channels and floodplains. Unregulated rivers have migrating channels that meander and create erosion, bringing sediment into the river (Florsheim et al. 2008). Sediment deposition occurs with decreased stream power resulting from a lower stream slope or discharge. These deposits form into various types of sandbars (Gurnell et al. 2012).

Sediment deposition is one variable determining channel morphology. Braided channels contain islands that create side channels around it. Braided channels have a mixed load of sediment and steeper stream gradient (Leopold and Wolman, 1957). River reaches that appear relatively straight have sandbars that alternate on the sides of the channel, which are opposite of the reach’s deepest point, the thalweg. Alternate bars cause erosion in the outer banks, thus widening and meandering the channel. Point bars are found at the bends of meandering channels. These meandering channels are highly sinuous and have a low stream gradient (Leopold and Wolman, 1957; Rosgen, 1994).

River meandering is driven by the succession of sandbars into floodplains (Schuurman et al. 2016). Sediment accretion on bars is the beginning stage of succession to a vegetated floodplain or island. Succession of a sandbar starts with the establishment of pioneer plant species, like willows, since these features provide easy access to water, nutrients and sunlight (Corenbilt et al. 2007). These pioneers are often r-select species that use these newly created habitats to grow fast and produce many offspring (Pianka, 1970). Once these species have pioneered, they are overtaken by K-selected species, which are slower growing, in the later stage of succession (Pianka, 1970). Species succeed one another until a climax community is reached, such as a forested floodplain or
island (Young et al. 2001). Succession in fluvial features is not generally linear due to flooding that creates disturbances (Corenbilt et al. 2007). The increasingly larger vegetation on the bar helps to stabilize sediments (Corenbilt et al. 2007; Gurnell 2012). This succession of a sandbar into a floodplain forest creates a push onto the inner bank that allows channels to meander (Schuurman et al. 2016), thus creating erosion, the mechanism for sandbar growth and creation.

Sandbars and their associated eroding banks and floodplains provide ecosystems services and riparian species habitat. In New England, the wood turtle (*Glyptemys insculpta*) uses sandbars for nesting (Jones, 2009) and tiger beetles like the cobblestone (*Cicindela marginipennis*) and the puritan (*Cicindela puritana*) require sandbars to burrow and hunt over their entire life cycle (Omland, 2004). River meanders which create point bars of assorted sediment type support high numbers of benthic invertebrates (Garcia et al. 2012). Eroding banks, which provide sediment to the river, are used for nesting by bird species like the bank swallow (*Riparia riparia*) and the belted kingfisher (*Ceryle alcyon*) (Silver and Griffin, 2009). Floodplains are also important to human communities as they provide valuable ecosystem services such as attenuating flood peaks and absorbing excess nutrients (Posthumus et al. 2010).

Anthropogenically-induced geomorphic changes have caused declines in floodplain habitat and species dependent on those habitats (Burke et al., 2009; Conner and Brody, 1989; Friedman et al., 1998; Hughes 1990; Hunt et al., 2013; Johnson et al., 2012; Rood et al., 2010; Stallins et al., 2010). Damming of rivers has altered flows by changing characteristics of natural flooding which have altered sediment transport thus impairing geomorphic processes (Julian et al. 2015). New England has the greatest
density of dams in the United States (Graf, 1999). Many of these dams are old mills which don’t significantly alter flows but do collect sediment. Small tributary and large mainstem dams have altered flow conditions in the Connecticut River watershed by eradicating natural flooding, depending on the location of the dam and its operation (Magilligan and Nislow, 2001; Magilligan et al. 2008; Nislow et al. 2002). Altered flows have affected sedimentation (Poff et al. 1997) and likely decreased sediment deposition into sandbars (Park et al. 2008).

Urban development is accountable for an increase in river channelization (Scott et al. 1986). The Connecticut River is one of many large river ecosystems with altered geomorphology due to human development (Poff et al. 1997; Ward et al. 1999). Channelization of river ecosystems has resulted in reduced channel area, wetland habitats and bars, oxbows, and islands (Missouri and Nebraska, 1998). Urban development along rivers is responsible for hardening channel banks thus impairing meandering, erosion and sandbar creation.

Studies in the Connecticut River watershed have addressed fluvial geomorphology but not the distribution of sediment features on a large scale. The floodplains in watershed have been mapped using multiple aerial images of flooding (Anderson et al. 2010) but they do not address nor map fluvial features prior to floodplain succession. The objectives of this research were to inform ecologists and policy makers on the spatial distribution of sandbars in the Connecticut River watershed by determining reaches of the rivers with the greatest amount of sandbars and islands that are potential habitat and future forested floodplains and to identify which landscape variables and human activities are influencing sandbar distribution in the watershed.
**Methods**

**Study Site**

The Connecticut is the largest river in New England, flowing over 660 kilometers from the Canadian border to the Long Island Sound. The headwaters begin at several lakes in northern New Hampshire, flows and meanders through farmland in the upper portion of the watershed and descends through major cities before joining Long Island Sound in Connecticut. The river’s watershed encompasses an area of over 28,000 square kilometers and spans four New England states.

**Data Collection**

Sandbar locations were mapped using an automated object based segmentation model in ArcGIS Pro. Locations include the Connecticut River mainstem and 12 major tributaries including the Ammonoosuc, Ashuelot, Black, Chicopee, Deerfield, Farmington, Mascoma, Passumpsic, Sugar, Upper Ammonoosuc, Westfield and White. The largest tributaries were selected for this study.

**Data Preparation**

A center line was created within each river’s channel polygon using ET GeoWizards (Tchoukanski, 2012). The line was split into reaches of approximately two kilometers. Points were created at the bottom of each line. The river channel polygons were split into two kilometer length segments, matching the length of the centerline.
Response Variable

The proportion of sandbar area to channel area, for each two kilometer length reach was used as the response variable. Sandbar area alone was not the response variable because it was not a linear relationship with channel size. Sandbar area was normalized for each reach in the watershed by its channel area (Figure 2.1).

Landscape Variables

Watershed area was delineated for each of the 13 rivers using a 10 m digital elevation model (DEM) from USGS (https://nationalmap.gov/). The 10m DEM was used to calculate stream gradient for every two km reach. Elevations were obtained for points spaced 0.05 kilometers apart within each reach and the slope of the elevation of the points going downstream was taken as an estimate of average stream gradient in the reach. If stream gradient was positive on the mainstem, it was recalculated using 1m DEM, if possible. If gradient was positive in a tributary, rather than downloading 1m DEMs due to the time restriction, the highest positive value and all values ranging to its negative equivalent, were turned into zeros. Information and locations of major dams was provided by Zimmerman and Lester, 2006.

Statistical Analysis

Data analysis was conducted in R 3.0.1 (R Core Team, 2010). An ANOVA and Tukey-post hoc test were conducted to determine pairwise differences in sandbar area per reach among the 13 rivers. Package “VIF” was used to determine variation inflation factors between explanatory variables. The package “MuMIn” was used for AIC model
selection to determine the top model describing sandbar area distribution downstream in the 13 rivers. Models within two delta AIC scores were determined equal. Package “mcgv” was used to model generalized additive models (GAM) and make predictions. Package “lattice” was used to create a box chart between mean sandbar sizes per river. An alpha of 0.05 was used for significance. Maps were made in ESRI ArcGIS Map.

Results
Watershed

The model was successfully applied to the mainstem and 12 of its major tributaries (Figure 1). In the modeled watershed the average cover of sandbar within a two kilometer reach was 6.33%, with an average of 2.81% for the mainstem and 13.06% for the all tributaries combined. There are a total of 1,906 sandbars in the watershed measuring 293 sq m and greater, which is the mean sandbar size (Table 2.1). One-fourth of these large sandbars were present in mainstem (count of 486, 26%) and three-fourths from the 12 tributaries combined (count of 1,420, 74%).

The White River has the greatest amount of sandbar area per reach compared to all rivers ($P < 0.001$, Table 2.3). The Deerfield has the second largest amount of sandbar area per reach compared to five rivers (Table 2.3). The Chicopee, Farmington, Ashuelot and mainstem have the lowest sandbar areas (Table 2.2). The White, Black and Ammonoosuc rivers had the largest sandbars in the watershed (Table 2.1), with all being greater than the watershed mean and all rivers present in upper part of the watershed (Figure 2.2). The highest count of sandbars measuring over the watershed mean were found in the White, Deerfield and Ammonoosuc rivers (Table 2.1).
Mainstem

Sandbar area per reach in the mainstem decreased downstream towards the mouth, with three peaks of increased sandbar area. The first sandbar peak is present in the upper portion of the watershed where the river naturally meanders and is the size of a tributary. The second peak is present below the confluence of the White River, the tributary with the greatest sandbar area in the watershed. The third peak is below the Deerfield River confluence, the tributary with the second greatest sandbar area in the watershed. These peaks decrease in size downstream towards the mouth (Figure 2.4).

Tributaries

Sandbar area per reach decreased downstream towards the mainstem for eight tributaries (Figure 2.5). Decrease in sandbar area downstream occurred either linearly or with high sandbar area peaks such seen in the White, Black and Deerfield rivers. The White River in Vermont had a reduction of sandbar area downstream towards the confluence but with an increase peak in the middle where stream gradient increases. The Black and Deerfield rivers experience peaks due to impoundments. Four tributaries had an increase in sandbar area downstream to the mainstem, which include the Ammonoosuc, Chicopee, Mascoma and Sugar rivers, all on eastern side of the watershed (Figure 2.1). All tributary increases in sandbar area downstream were linear (Figure 2.4). All tributaries, regardless if sandbar area if increasing or decreasing, had a reach at the confluence with less than 20% of its channel containing sandbars (Figure 2.4).
Dam Effects on Sandbars

In the Black River sandbar area is high upstream of the North Springfield dam and low downstream of it (Figure 2.4). The dam creates two peaks of increase sandbar area going downstream, below a reduction following the dam (Figure 2.4). Sandbars are present downstream of Wilder dam in Vermont, where the confluences of the White and Mascoma rivers merge (Figure 2.7.2). Sandbars are present upstream and downstream of the Knightville dry-bed dam in Massachusetts (Figure 2.7.3), however sandbar area decreased towards the confluence following the sandbar peak after the dam (Figure 2.4).

Discussion

Meandering and major tributary confluences resulted in the largest sandbar areas in the mainstem. Tributaries with the largest sandbar area provided the greatest amount of sandbars to the mainstem. Studies have shown tributaries are a source of sediment into the Connecticut mainstem (Svendsen et al. 2009). Sandbar area decreased downstream towards a confluence or mouth because sandbars are formed going downstream, in the middle sections of rivers, thus limiting the sediment material downstream. In addition, the large tributaries in the lower portion of the watershed had the lowest sandbar areas, which were not providing sediment to the lower mainstem. Rivers with the largest mean sandbar size were found in the northern part of the watershed possibly due to their sediment material being larger such as cobble.

The White River has greatest amount of sandbars in the watershed and is the largest unregulated river within the study watershed. Dams have altered sandbar distributions by storing sediment in the form of sandbars upstream, and depriving sandbar
formation downstream. Unregulated rivers have large amounts sediment that can drive stream meandering (Constantine et al. 2014). This locations of sandbars caused by dams affects river channel migration, future bank erosion and the distribution of future floodplain forests.

Sandbar area was high in the Deerfield River due to tropical storm Irene, which occurred on August 31, 2011, one year before the aerial images analyzed in this study were taken. The storm caused between a 100 year and a 500 year flood on the Deerfield River resulting in high erosion and great sediment deposition throughout the river including upstream and downstream of its major dams (Yellen et al. 2014). In some Deerfield River floodplains the Irene sediments measured over 50 cm thick (Brian Yellen and Christian Marks, personal communication). Other rivers draining the Green Mountains such as the West, Black and White Rivers also saw exceptional high flood peaks during Irene.

Tributary confluences below dams can deliver sediments that replenish sediments downstream of the dam. Our study only looks at sediment deposition and specifically in the form sandbars and islands which are present above the water. The majority of sediment that is captured by dams is often accumulated and stored under the water due to the fine size (Kasprak et al. 2008).

Dam Management Implications

Changing to dry-bed dams for flood control could potentially allow more sediment to pass through the reservoir downstream. Dry bed dams would be a compromise as removing water from upstream of dams will reduce recreation activities
but it also increase storage capacity for flood control. Removing small dams in the watershed can increase sediment downstream in the short run (Poff and Hart, 2002) and thus alter the channel morphology such as into braided channels (East et al. 2015).

Placement and design should be a top priority for the creation of new dams. Low level gates can be installed that allow the release sediment downstream, when water levels are low in the reservoir, and would eliminate the build up of sediment behind the dam (Kondolf et al. 2014). Building dams directly above a confluence of a major tributary which has a large sediment load can mitigate the loss of sediment below the dam. Altering dam operations or removing dams on tributaries can transport sediment and create sandbars in the mainstem.

Conservation

Reaches of the rivers with large amounts of sandbar areas should be conserved to preserve habitat for pioneer plants as well as rare and threatened turtles and insects. Our results show locations of sandbars which are not shaded by overhanging trees. This is specifically important because several pioneer plant species are shade intolerant like the eastern cottonwood and animals require habitats with minimal canopy cover, such as the wood turtle for basking (Sherwood and Wu, 2012) and tiger beetles for hunting of prey (Omland, 2002). Human activity including camping and off roading on sandbars disrupts habitat (US Fish and Wildlife Service 1993) and should be limited to maintain population numbers of these critical species.

Conservation of sandbars will allow succession to occur into a forested floodplain or island. For future development and expansion of sandbars, natural eroding banks
should be preserved and not hardened or developed (Florsheim et al. 2008; Shankman, 1993). Natural bank erosion is the mechanism required to create the material for sandbar creation. In addition, conserving eroding stream banks will preserve habitats for several nesting birds. Reducing human development along rivers and conserving and restoring floodplains will allow the rivers to meander, erode stream banks and provide material for future sandbars. River meandering ensures the creation of point bars, and allowing for a diverse group of sandbar types in the watershed.

Tributaries supply ample sediments needed for development of floodplain forests, while the mainstem provides flooding that is needed for the floodplain forests to support a vegetation that is distinct from upland forests (Marks et al. 2014). The tributaries lack sufficient flooding because flood duration increases with watershed area and decreases with stream gradient (Marks et al. 2014). Thus the confluence area with both ample flooding and ample sediment are key to conservation of distinct floodplain vegetation assemblages such as silver maple floodplain forest.

This study was been in collaboration with hydrologists at the University of Massachusetts, Amherst, Civil Engineering Department. Restoring floodplains in areas like Maidstone, Vermont can reduce flow peaks and flooding hazards to downstream communities (Ericson, 2017). Several large floodplains remain in the watershed (Figure 2.8), which in the past have coincided with sediment deposition and coincide somewhat presently. For the development of future floodplains and for best flood hazard management, river reaches of sandbars and floodplains should be conserved together.
Conclusion

Sandbar and island distribution varies throughout the Connecticut River watershed. Tributaries such as the White and Deerfield have the greatest sandbar area and bring sediment into portions of the mainstem. Natural meandering and bank erosion lead to a high number of sandbars in those mainstem reaches. Dams have altered sandbar distributions by storing them upstream of the dam. Changes dams to dry-beds or removing smaller dams can restore sediment transport and deposition. Locations of large amount of sandbars and islands are important to conserving habitat of endangered species and locating future floodplain forests.
**Literature Cited**


Tchoukanski, I. 2012. ET GeoWizards version 10.2.


Tables
Table 2.1: The mean size of a sandbar and the count of sandbars over the watershed size for each of the 13 rivers.

<table>
<thead>
<tr>
<th>River</th>
<th>Mean sandbar size (sq m)</th>
<th>Count of Sandbars</th>
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<tr>
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<td>Ashuelot</td>
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<td><strong>Average</strong></td>
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Table 2.2: A pairwise comparison of mean sandbar area per reach between all rivers. Colored areas represent significant differences ($P < 0.05$), with blue as negatives and red as positives differences in mean sandbar area per reach between rivers. Means are bolded for each river.

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36
Figure 2.1: The proportion of sandbar area to channel area for each of the 20 reaches in the Passumpsic River.
Figure 2.2: The spatial distribution of sandbar area per two kilometer reach in the Connecticut River watershed. Thicker lines denote greater area of sandbars within a two kilometer reach.
Figure 2.3: Sandbar area per two kilometer reach decreased downstream in the mainstem. The generalized additive model had all the weight compared to a generalized linear model and the null in an AIC model selection. Three notable peaks are present in the GAM.
Figure 2.4: Proportion of sandbar area going downstream in 12 major tributaries in the Connecticut River watershed. Lines represent predictions from top model from AIC model selection.
Figure 2.5: Spatial distribution of sandbar area with locations of major dams in the Connecticut River watershed: (1.) Springfield dam used for flood control on the Black River in Vermont, illustrating how sediments can become trapped in impoundments (2.) Wilder dam, used for hydropower, on the mainstem in Vermont/New Hampshire, illustrating how major tributary confluences can mitigate for dam impacts (3.) Knightville dam, a dry-bed used for flood control, on the Westfield River in Massachusetts, illustrating how some types of dams can allow passage of sediments.
Figure 2.6: The largest current floodplains in the Connecticut River watershed mapped alongside sandbar distribution (Connecticut River Basin..., 1994; Ericson, 2017).
CHAPTER 3

CONCLUSION

Large scaled automated mapping of geomorphic features like sandbars and islands is necessary for successful floodplain and habitat conservation. Locations of sandbars allow scientists to understand dynamics of sediment deposition in rivers, and policy makers to select reaches to conserve. Fluvial geomorphic features are habitat for a variety of organisms including freshwater turtles, insects and migrating birds. Conservation of these early successional features will ensure future floodplain forests, which will reduce flooding damage to human communities, and support and increase the population of currently threatened and endangered riparian species.
APPENDIX A

SEDIMENT TO CHANNEL AREA PROPORTIONS

[Two scatter plots showing the relationship between log-transformed channel area and area of sediment per reach (sq m).]
APPENDIX B

SANDBAR DISTRIBUTION MODEL SELECTIONS

[Graphs showing sandbar area per reach as a function of distance downstream, with model comparisons indicated by GLM (AICc = 273.1, R² = 0.27) and GAM (AICc = 266.0, R² = 0.42).]

[Graphs showing sandbar area per reach as a function of distance downstream, with model comparisons indicated by GLM (AICc = 126.3, R² = 0.11) and GAM (AICc = 120.5, R² = 0.60).]
APPENDIX C

STREAM SLOPE OF RIVER DISTANCE
APPENDIX D

SANDBAR AND GRADIENT CORRELATIONS


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