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Modeling and monitoring riparian buffer zones using LiDAR data in South Carolina

Emre Akturk · Christopher Post ·
Elena A. Mikhailova

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Abstract Functional riparian areas protect water quality and conserve aquatic systems, plants, and wildlife. Laser-based remote sensing technology offers a high-resolution approach to both characterize and document changes in riparian buffer zones (RBZs). The objectives of this study were to demonstrate a rapid method and model to calculate riparian buffer widths on both sides of a stream using a LiDAR-derived slope variable, to classify riparian buffers and determine their quality, and to evaluate the appropriateness of using LiDAR in riparian buffer assessment. For this purpose, RBZs were delineated for Hunnicutt and King Creek, which are located in Oconee and Pickens counties, in South Carolina. Results show that LiDAR was effective in delineating required riparian buffer widths based on the topography slope of upstream areas, and in calculating the ratio of tree cover. This LiDAR-based assessment methodology could be applied to a wide-range of environments.

Keywords Riparian buffer · GIS · LiDAR · Water quality · Remote sensing

E. Akturk (✉)
Faculty of Forestry, Department of Forest Engineering, Kastamonu University, Kastamonu, Turkey
e-mail: eakturk@kastamonu.edu.tr

C. Post · E. A. Mikhailova
Department of Forestry and Environmental Conservation, Clemson University, Clemson, SC, USA

Introduction

It is critical to protect water quality and aquatic resources with appropriate riparian buffer zones. Urban, agricultural, and forestry activities change the structure of the landscape and can cause an increase in the quantity of sediments which reduce water quality and inhibit presence of aquatic organism (Robinson and Blyth 1982; Salomons 1985; Pimentel et al. 1987; Walker et al. 1999; Anbumozhi et al. 2005). Establishing or restoring functional riparian areas can be a solution to conserve and protect aquatic systems, plants, and wildlife. Riparian buffer zones (RBZs) can be defined as the neighboring areas to streams, lakes, and other surface waters (Narumalani et al. 1997). The word "buffer" is used to define zones or barriers to stop runoff and pollutants before they enter water sources via infiltration, absorption, filtering, and uptake (Narumalani et al. 1997). Riparian buffer zones have many important functions, such as improving surface water quality by reducing the amount of sediment, nutrients, and other environmental pollutants (Hession et al. 2000; Anbumozhi et al., 2004); stabilizing stream banks and helping to remove nitrogen fluxes from uplands (Sabater et al. 2003); storing water to prevent floods; and protecting habitat areas by enabling shade, shelter, and access to food for fish, birds, and other wildlife (Lathrop and Haag 2007). For instance, Lowrance and Sheridan (2005) found riparian forest buffers were effective in reducing non-point source pollution reporting reductions from 27% for total Kjeldahl N to 63% for P. In another study, 20 sites were differentiated by buffer width, slope, and vegetation to examine buffer zone effectiveness and found that all buffers reduced runoff volume by approximately 84% and buffer width was the most influential factor in trapping sediments (Abu-Zreig et al. 2004). In addition, riparian areas may provide access to waterways for activities such as swimming, boating, fishing, hunting, hiking, and nature observations for people (Klapproth and Johnson 2009).

Geographic information systems (GIS) and remote sensing techniques can be used to characterize RBZs. For example, Narumalani et al. (1997) conducted a GIS and remote sensing–based study to delineate riparian buffer zones and to qualify buffers by land use type. The analysis was composed of four stages: (1) image classification of RBZs using Landsat imagery, (2) obtaining stream network data via Digital Line Graph data, (3) making a decision about the riparian buffer zone width with the aid of Soil Capability Class method, and (4) analyzing buffer strips and their vegetation. As a result, GIS and remote sensing techniques were determined to be an efficient way to identify critical areas near water bodies with regard to buffer quality. However, datasets that were used in that study were dependent on low-resolution satellite images which likely introduced errors because of the coarseness of the data. In order to prevent errors due to low-resolution images, light detection and ranging (LiDAR) data can provide a more accurate horizontal and vertical representation of stream buffer areas.

LiDAR provides an accurate 3D representation of the ground and vegetation to determine ground cover characteristics. A LiDAR system uses light pulses to measure the distance based on the elapsed time of the reflected light from the target object back to the LiDAR instrument which allows 3D objects to be mapped and visualized (Akay et al. 2009; Dong and Chen 2017). This instrument also allows the creation of high-resolution digital surface models (DSM) and digital elevation models (DEM) that can be used to delineate the stream network, and to calculate the land slope (Poppenga et al. 2014). Accuracy, precision, and costs of these obtained data are very important factors for us. Therefore, a study was conducted on the accuracy and costs of these data by comparing with two different data sources (QuickBird and SPOT-5) to map riparian zones (Johansen et al. 2010). LiDAR data was found to be the most accurate way to measure RBZ widths ($R^2 = 0.91$), and the least expensive way to map large-extent riparian areas according to this article.

Although many studies have used remote sensing to characterize RBZs (Oetter et al. 2004; Dindaroğlu et al. 2015; Michez et al. 2016, 2017), there is still no rapid and uniform method that takes into account ground slope when identifying and characterizing riparian buffers with LiDAR. The objectives of this research are (1) to demonstrate a rapid method to calculate riparian buffer widths on both sides of streams using a LiDAR-derived slope estimate, (2) to classify RBZs based on their forest cover ratio and to evaluate the analysis with measured surface water quality metrics, and (3) to assess the appropriateness of using this instrument for riparian buffer assessment by completing an error assessment of its classification using high-resolution aerial imagery.

Material and method

Description of study fields

Hunnicutt Creek is one of several creeks in the Clemson University Campus and is located in Pickens County, SC, USA. The total watershed area is 4.89 km^2. The creek contains an extensive network of intermittent and ephemeral streams in addition to the perennial stream that covers a total length of 21 km in the watershed area. This stream discharges into Lake Hartwell which eventually drains through the Savannah River system into the Atlantic Ocean. The elevation of the study area ranges from 186 to 263 m above sea level. The watershed area is an urban environment which contains academic buildings, residential buildings, roads, and small forested areas.

King Creek is a forested watershed which covers 4.83 km^2 of Oconee County, SC, USA. The perennial, intermittent, and ephemeral stream branches of this watershed extent for 26 km. The elevation range of the watershed is significantly higher than that of the Hunnicutt Creek Watershed area, which ranges from 615 to 960 m above sea level.

Data and software

Data analysis was performed using ArcGIS 10.6 (ESRI, Redlands, CA, USA), using the Spatial Analyst, and 3D Analyst extensions to delineate RBZs and to calculate tree cover ratio within RBZs. Freely available LiDAR data was used in this analysis and Table 1 shows the

Table 1 Data layers, sources, types, and resolution

Data layer	Sources	Data type	Resolution/scale
LiDAR	US Geological Survey (USGS)	LAS data	n/a
NAIP Imagery	US Geological Survey (USGS)	Raster	1 m
Watershed Boundary	USGS National Hydrography Dataset	Polygon	n/a
World Imagery	ESRI	Raster	1 m

n/a not available

sources, data types, and resolution (scale) of data layers that were used in this work. In addition, earlier studies were used to evaluate surface water quality for Hunnicutt and King Creeks (English and Pike 2006; Dumrichob 2009). Eight water monitoring sites were in Hunnicutt Creek (Fig. 1) and seven water monitoring sites which were form King Creek were chosen (Fig. 2). The taxa richness and EPT index are the most commonly used indicators to monitor the quality of surface water. They are also useful because assemblage and identification of macroinvertebrates are easier when comparing with other habitats (Metcalfe 1989).

Riparian buffer zone width model

Buffer zone widths on both sides of streams were calculated based on the topographic slope of upstream areas using the South Carolina Best Management Practices (BMPs) regulations. This methodology allows for evaluation of stream side area based on guidelines for other states or regions. Several studies were examined in relation to RBZ width (Xiang 1996; Narumalani et al. 1997; Williams et al. 2003) and their effectiveness (Xiang 1993). Riparian buffer zone width can be either a fixed- or a standard-width value, based on slope, or a variable width that is based on many different components, such as vegetative cover condition, plant ages, their diversity, and soil characteristics. The presented methodology can be applied to a range of different types of BMPs as implemented through RMZs.

Best Management Practices are defined as a practical method to reduced point and non-point source pollutants at levels using management options (Helms 1998). In

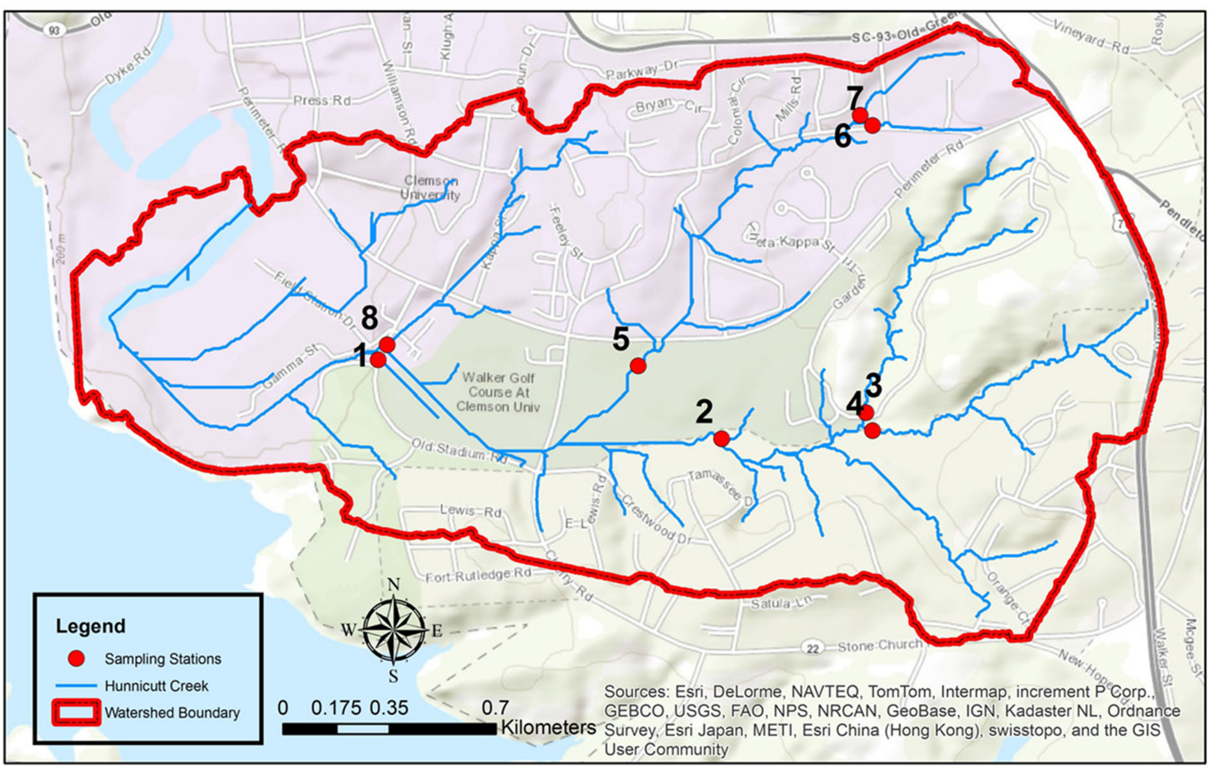

Fig. 1 Locations of water quality sampling sites in Hunnicutt Creek (Dumrichob 2009)

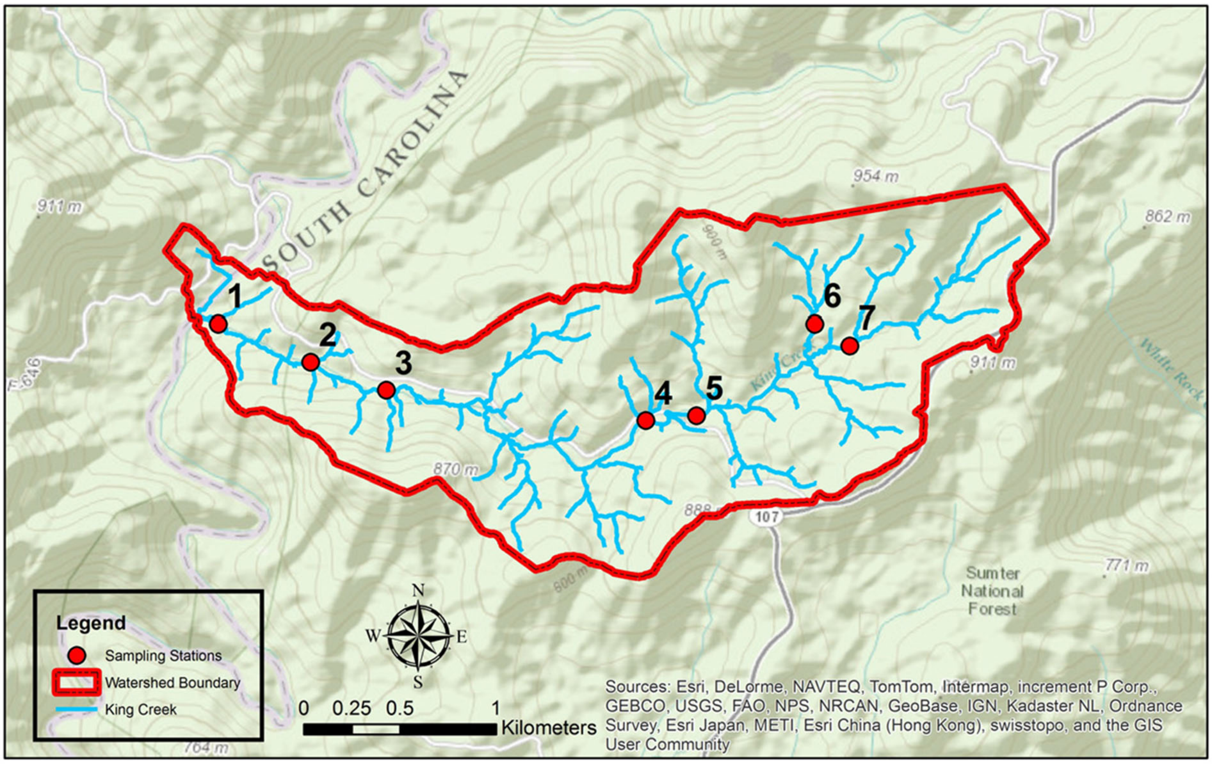

Fig. 2 Locations of water quality sampling sites in King Creek (English and Pike 2006)

1996, 47 states decided to develop BMPs in to minimize the environmental impact of forestry activities, which are performed adjacent to water bodies like non-point source pollution due to timber harvesting, and protect water quality (Blinn and Kilgore 2001). The effectiveness of BMPs on water quality was assessed by Anderson and Lockaby (2011) with results indicating that BMPs regulations substantially reduce effects of forest management on water quality.

According to South Carolina's BMPs, RBZs should be examined in two sections: primary zone and secondary zone, taking into account the slope of upstream areas. Buffer width does not change in any slope value for primary zone and the minimum buffer width is assigned as 12 m (40 ft) for these areas directly adjacent to a stream. No secondary buffer zone is required if the slope is less than 5%. Alternatively, RBZs widths should be at least 48 m (160 ft) if the slope value is greater than 40% (Table 2). In order to be most effective, buffers must cover all stream types, such as perennial, intermittent, and ephemeral streams (SC BMPs 1995).

Two former studies and their models developed by Lipscomb and Williams (2000) and Williams et al. (2003) were modified and then used to build a model in a GIS environment to delineate RBZs for Hunnicutt and King Creeks. The RBZ model basically consists of two main parts: (1) stream and watershed delineation; and (2) estimation of RBZ width, based on slope. This study used the complete stream network (including perennial, intermittent, and ephemeral streams) before starting RBZ width estimation analysis, which is the most conservative approach to protecting water quality. The ArcGIS 10.6 Hydrology toolset was used to map streams and watershed boundaries, using the previously created high-resolution LiDAR DEM. Slope areas were determined by buffering 30 m from the left and right of upstream areas. Then, the DEM was used to calculate the percentage of slope rise for those locations. Each raster cell was calculated as the steepest ridge of the eight adjacent cells. Average slope statistics for each input cell based on their neighborhood cell values was calculated. Raster slope data was classified based on BMP regulations (Table 2) providing a recommended RBZ width.

Estimated tree cover ratio

The effectiveness of RBZs can be assessed by measuring nutrient and sediment removal, which is dependent

Table 2 Minimum recommended South Carolina forestry RBZ width based on slope (SC BMPs, 1995)

Slope (%)	Width of RBZs on each side (m)	
	Primary	Secondary
< 5	12	0
5–20	12	12
21–40	12	24
> 40	12	36

on many variables, such as buffer width and extent, soil type, and vegetation type (Wenger 1999). Two vegetation types were used as a variable to define the efficiency of buffer zones in this study: (1) grassed buffers and (2) forested buffers. According to a US Environmental Protection Agency's (EPA) report, the buffer vegetation type was determined to be a highly effective variable in eliminating nitrogen ($n = 66$; $p = 0.002$) (Mayer et al. 2005). They also found that forest buffers are considerably better than grass buffers in blocking nitrogen to water sources (Mayer et al. 2005). Lowrance et al. (1984) had a similar conclusion and found that forested buffers were effective in stopping nutrient discharge which comes from adjacent agricultural fields.

A canopy height model, representing only the height of objects on the ground, was created by subtracting the DEM from the DSM. The resulting layer was classified as tree, shrub, or other based on the global forest resources assessment document from the Food and Agriculture Organization (FAO) that states that trees must be at least 5 m tall, while shrubs should be taller than 0.5 m and shorter than 5 m (FAO 2005). This methodology can easily be modified based on the required BMP. Commonly, this methodology presents some erroneous interpretations in a developed area or developing areas. Buildings can be classified as trees because their height is often higher than 5 m, similar to the height of trees. Buildings or other impervious surfaces should be delineated and reassigned as a different type of cover to prevent this issue.

National Agriculture Imagery Program (NAIP) high-resolution (1 m) digital orthophoto images were used to augment the information from the LiDAR-based DSM classification, by using the imagery to classify the land cover types to help pick out the impervious and man-made structures. For the Hunnicutt Creek watershed area, three main cover forms were assigned: (1) trees; (2) impervious; and (3) pasture, hay, and agriculture. The only difference for the King Creek watershed area is the elimination of pasture, hay, and agriculture cover types, because these cover types did not exist around King Creek. Supervised classification techniques were used to individually classify each high-resolution aerial orthophoto.

Results

Stream and riparian buffer zone delineation

Streams and buffer zones were delineated based on ground topography of the SC forestry recommendations (Figs. 3 and 4). Length of streams and the size of the

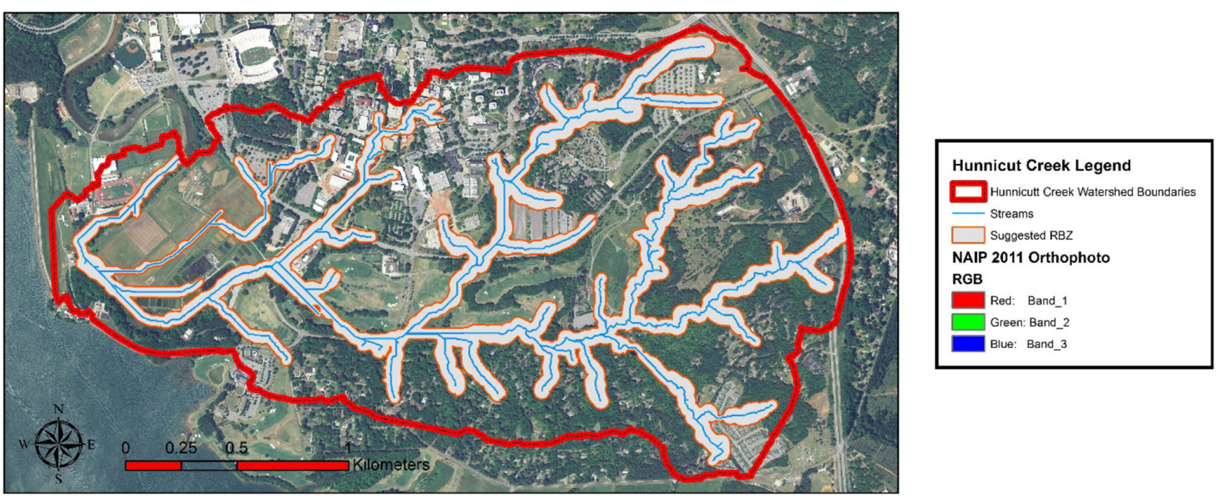

Fig. 3 Estimated riparian buffer zones (RBZs) for perennial, ephemeral, and intermittent streams for Hunnicutt Creek

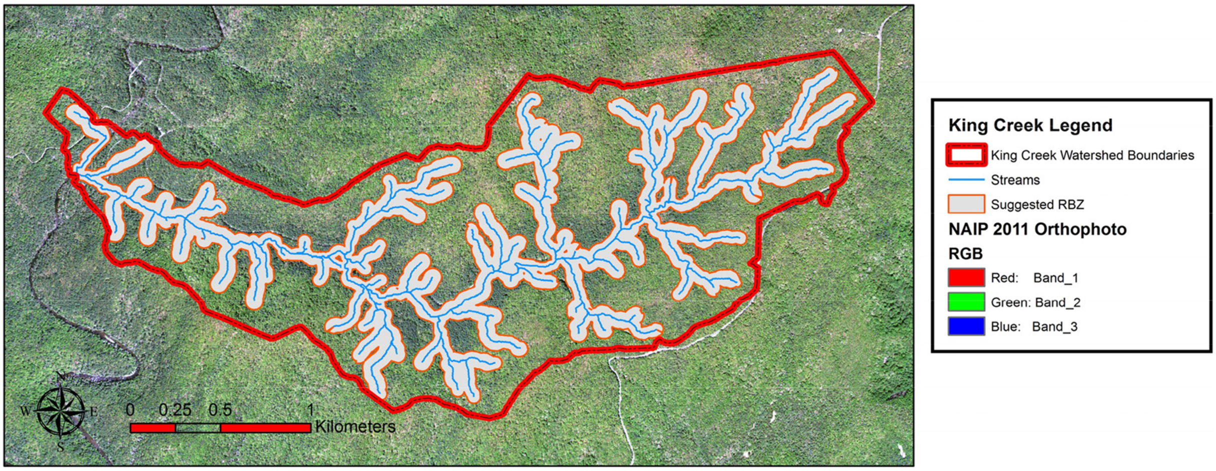

Fig. 4 Estimated riparian buffer zones (RBZs) for perennial, ephemeral, and intermittent streams for King Creek

required buffer zones varied considerably between the two study areas (Table 3). King Creek has approximately 4.5 km more in estimated stream length. The average slope values for King Creek were

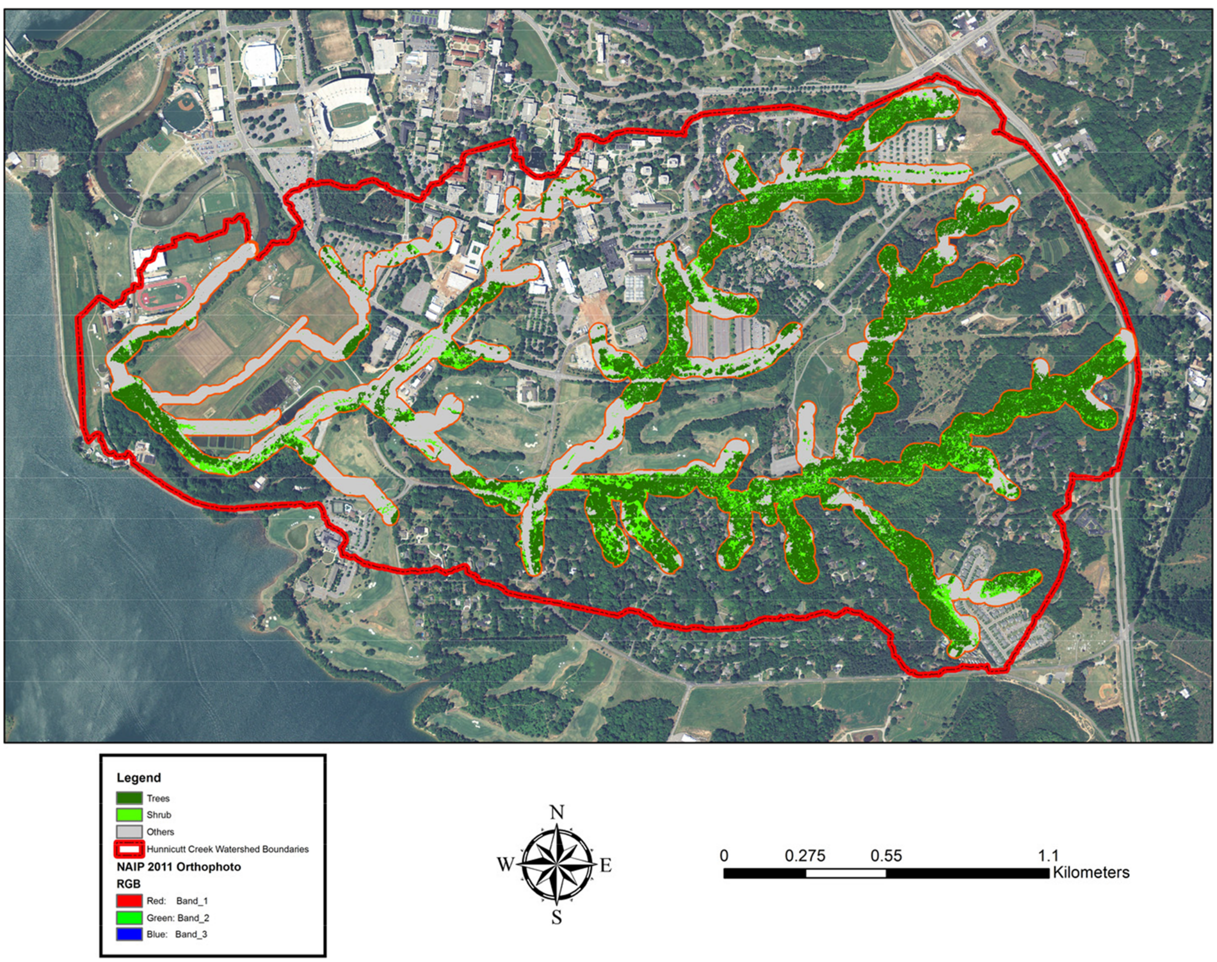

Fig. 5 Representation of tree, shrub, and other cover types within RBZs of Hunnicutt Creek

approximately 35% higher than those for Hunnicutt creek, which lead to a higher average suggested RBZ width for King Creek (43.85 m) vs. Hunnicutt (31.09 m). The recommended buffer width has a linear correlation with slope variable, based on the change in the recommended secondary RBZ with slope.

Tree cover ratio and impervious surfaces

Buffer zones of both creeks were classified into three land cover forms which are (1) trees, (2) shrubs, and (3) others (agriculture fields, pasture, hay, buildings, and roads). Furthermore, the map representations were shown in Figs. 5 and 6. Trees cover the biggest part of the RBZs of Hunnicutt Creek (46.69%), followed by others (41.41%) and shrubs (11.90%) respectively (Table 3). Many areas besides tributaries contain impervious, urban, and agricultural areas. An estimate of impervious land cover for the Hunnicutt Creek Watershed was calculated as 1.067 km^2 which covers 21.84% of the whole watershed area. In contrast to Hunnicutt Creek, almost the whole area of the King Creek stream side zones was protected by forests (97.14%) (Table 3). Since there are no agriculture fields, pastures, hay, or buildings within the King Creek Watershed boundary, the impervious surfaces (only roads) were much less prevalent (0.14%). The highly-forested and intact RBZs of King Creek would predict a higher level of water quality.

To determine the accuracy of the combined LiDAR and orthophoto classification, 100 sample cells were picked randomly from NAIP imagery for each land cover type assigned as forest and others (agriculture fields, pasture, hay, buildings, and roads). Accuracy assessment of the classification method indicated that 97.5% of the LiDAR-derived land cover map was

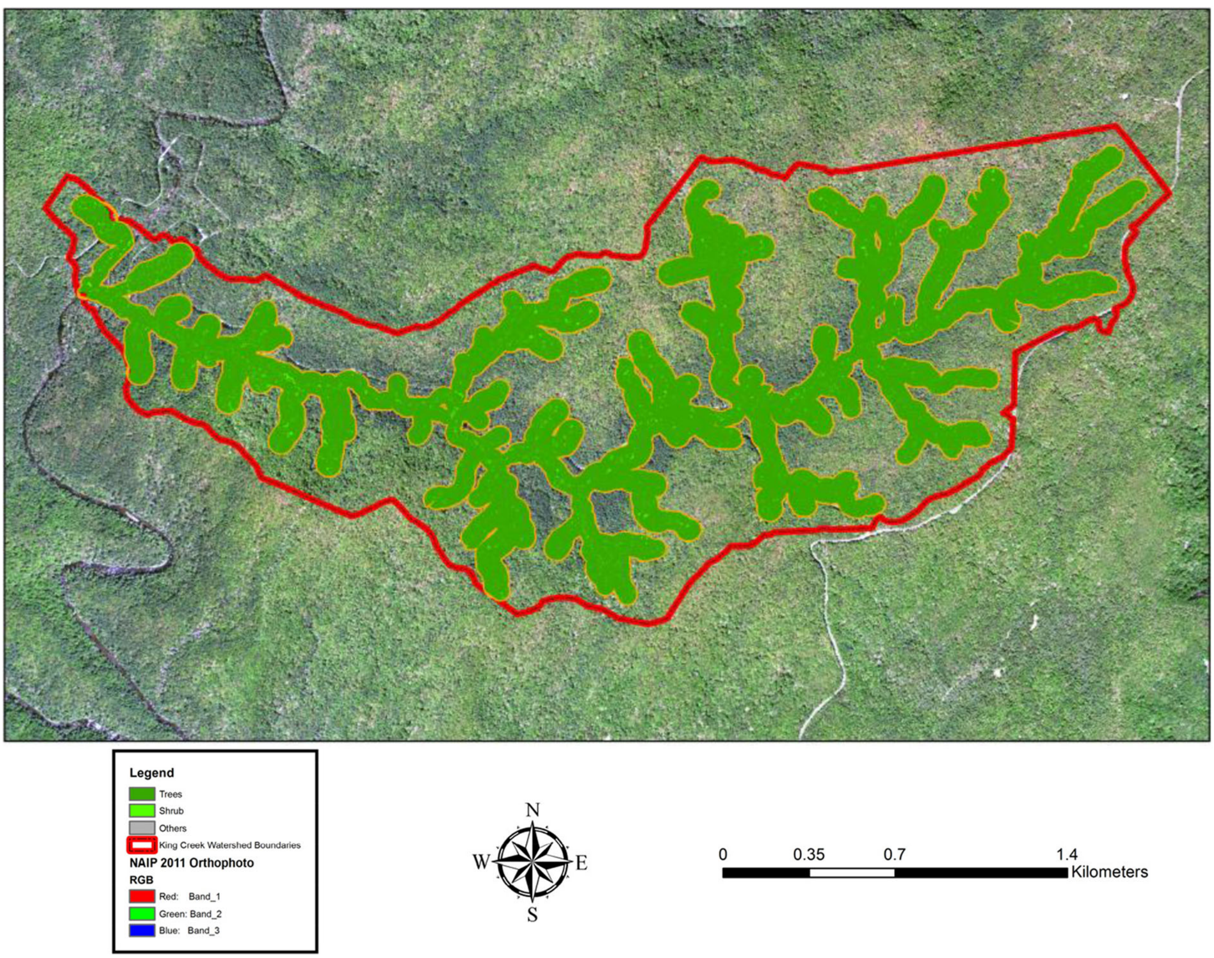

Fig. 6 Representation of tree, shrub, and other cover types within RBZs of King Creek

Table 3 Stream and RBZ characteristics

Total area of cover forms (m^2)							Proportion (%)		
Creek	Stream length (m)	Total RBZ area (m^2)	Average RBZ width (m)	Tree	Shrub	Others	Tree	Shrub	Others
Hunnicutt	21,533	1,196,197	31.09	558,504	142,312	495,381	46.69	11.90	41.41
King	25,938	1,894,130	43.85	1,839,961	51,529	2640	97.14	2.72	0.14

correctly classified with a Cohen's kappa coefficient of 0.95 for Hunnicutt Creek. In addition, overall accuracy of LiDAR-derived land cover map for King Creek was found to be 94.5% with Cohen's kappa coefficient of 0.89. Even though Hunnicutt Creek had much more complicated land cover, overall accuracy of land cover analysis in King Creek is lower than that of Hunnicutt Creek. This decrease in accuracy of land cover map can be explained by occurring pixel confliction due to having an intense tree cover and the resulting shade.

Discussion and conclusion

This research was conducted to provide further information about conditions of RBZs, which are important for maintaining water quality. The tree cover ratio analysis results (Table 3) showed that the water quality of King Creek would be expected to be higher than the water quality of Hunnicutt Creek based on the intact forest buffer in the King Creek watershed.

Aquatic macroinvertebrates spend most of their lives living in water and function as cumulative indictors of water quality. A high number of taxa or taxa richness indicates better water quality. The average taxa richness in King Creek watershed (87.86) was much greater than the average taxa richness in the Hunnicutt Creek Watershed (13.91). The EPT richness is a commonly used biological indicator of water quality. Higher EPT richness indicates better water quality. The studies by Dumrichob (2009) and English and Pike (2006) showed that King Creek watershed had an average EPT richness of 36.28 compared with that of Hunnicutt Creek watershed that had an average EPT richness of 5.50. This indicates that King Creek had better water quality than Hunnicutt Creek. These macroinvertebrate data support the RBZ classification suggesting that King Creek Watershed has a buffer with more trees and less impervious surface. Additionally, water monitoring sites for two studies were used as pour points to delineate different watersheds based on these points. All land cover results within RBZs were clipped by these watersheds and calculated. Table 4 shows the tree cover and related macroinvertebrate taxis richness, demonstrating a relationship between watershed cover and the water quality metrics.

Riparian buffer zones represent documented ways to protect these ecosystems, and establishing or restoring functional riparian areas can be a solution to conserve aquatic ecosystems. This study demonstrated a rapid method to use spatially accurate LiDAR data to classify RBZ land cover based on South Carolina's BMPs buffer size recommendations. Efficiency of these zones to prevent surface runoff was estimated by using tree cover ratio analysis. According to the results, almost all of the King Creek streams side zones were covered by forests

Table 4 Land cover proportions and previously reported water quality indicators (Taxa Richness and EPT Index) for watersheds derived from water monitoring sites (Dumrichob 2009; English and Pike 2006)

Location	Tree cover (%)	Shrub cover (%)	Other cover types (%)	Taxa Richness	EPT Index
H-1	23.10	4.71	72.19	10.8	2.7
H-2	37.31	10.38	37.31	15.3	7.1
H-3	71.96	6.12	21.92	25.3	11.9
H-4	70.19	16.51	13.30	19.6	10.1
H-5	51.69	11.04	37.27	12.7	5.0
H-6	7.71	6.51	85.78	n/a	n/a
H-7	61.43	15.25	23.32	8.0	1.7
H-8	43.87	15.33	40.80	5.7	0.8
K-1	96.06	3.37	0.57	110	45
K-2	95.05	4.82	0.13	72	32
K-3	97.14	2.85	0.01	85	41
K-4	97.45	2.55	n/a	93	38
K-5	98.04	1.96	n/a	83	39
K-6	97.76	2.24	n/a	91	29
K-7	97.90	2.10	n/a	81	30

n/a not available

(97.14%). In contrast, tree cover ratio was calculated lower for Hunnicutt Creek (46.69%). The accuracy assessment of the classification method indicated that 97.5% and 94.5% of the LiDAR-derived land cover maps were correctly classified with Cohen's kappa coefficients of 0.95 and 0.89 for Hunnicutt Creek and King Creek, respectively. These results showed that this LiDAR-based classification method has potential for use across different types of forested or partially forested watersheds.

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