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EVALUATION OF METHODS FOR DELINEATING RIPARIAN ZONES IN A SEMI-ARID MONTANE WATERSHED[1]

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ABSTRACT: Riparian zones in semi-arid, mountainous regions provide a disproportionate amount of the available wildlife habitat and ecosystem services. Despite their importance, there is little guidance on the best way to map riparian zones for broad spatial extents (e.g., large watersheds) when detailed maps from field data or high-resolution imagery and terrain data are not available. Using well-established accuracy metrics (e.g., kappa, precision, computational complexity), we evaluated eight methods commonly used to map riparian zones. Focusing on a semi-arid, mountainous watershed, we found that the most accurate and robust method for mapping riparian zones combines data on upstream drainage area and valley topography. That method performed best regardless of stream order, and was most effective when implemented with fine resolution topographic and stream line data. Other commonly used methods to model riparian zones, such as those based on fixed-width buffers, yielded inaccurate results. We recommend that until very-high resolution (<1 m) elevation data are available at broad extents, models of riparian zones for semi-arid mountainous regions should incorporate drainage area, valley topography, and quantify uncertainty.

(KEY TERMS: riparian zone delineation; riparian ecology; geospatial analysis; spatial modeling; uniform and variable-width buffers; valley bottom topography; upstream drainage area.)

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INTRODUCTION

Riparian zones are the most biologically diverse, productive, and threatened ecosystems in many semi-arid regions (Poff *et al.*, 2011). Riparian zones can act as natural filters and storage areas for sediment, pollutants, and nutrients. They also regulate water and air temperature, dissipate energy during high flow events, and provide habitat and migration corridors for many species (Brauman *et al.*, 2007). Riparian zones have been defined as the interface between flowing aquatic and surrounding terrestrial ecosystems, often containing stream-side riparian vegetation. They extend from the edge of the stream channel to the edge of geomorphic features and soils and vegetation that are influenced by surface water and/or elevated groundwater (Gregory *et al.*, 1991; Naiman and Décamps, 1997; USFWS, 2009).

Here, we operationally define riparian zones as those areas that are adjacent to streams in relatively flat, moist areas that are strongly influenced by

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surface and subsurface water at a decadal to century time scale. Typically, these areas have vegetation that differs from the adjacent upland areas. However, where riparian zones have been modified by land use activities such as urban, residential, or agricultural development (e.g., where an agricultural field encroaches into the riparian zone of a stream), the land cover may differ from that of adjacent unmodified riparian zones. Modification could also be due to upstream water diversions or reservoirs, which can alter the downstream flow regime resulting in a reduction of the "natural" riparian vegetation, although relictual stands of riparian vegetation may remain. Given our definition, such areas of altered vegetation would still be considered part of the riparian zone. Alternative definitions of riparian zones exist that incorporate litter fall, wood recruitment and thermal energy to examine the lateral transfer of energy between aquatic and terrestrial ecosystems (e.g., Gregory *et al.*, 1991; Ilhardt *et al.*, 2000), though these definitions are better suited for mesic temperate forests in the western United States (U.S.) than the semi-arid zone that is our focus. Moreover, very-high resolution (<1 m) elevation data (e.g., from LiDAR) and extensive field work are required for such approaches, making them impractical for use in regional-scale mapping of riparian zones.

The prevailing geomorphic processes that influence the location and condition of riparian zones include erosion, channel migration, development of fluvial features, and sediment transport and deposition (Naiman *et al.*, 2005). Each of these processes varies in a systematic way as a function of catchment size and gradient, drainage density, and dominant sediment size (Schumm, 1977). The prevailing hydrologic processes include flow, infiltration, and evapotranspiration; and are characterized by precipitation magnitude and distribution, flow depth and velocity, the frequency, magnitude and duration of flooding, and the hydraulic conductivity and gradient of groundwater (Naiman *et al.*, 2005).

Geomorphic and hydrologic processes can be separated into three systems: longitudinal, lateral, and upslope (Reeves *et al.*, 2004). In delineating riparian zones, longitudinal processes, which transport water, sediment, and energy from upstream reaches, are frequently represented by upstream drainage area. Lateral processes, which influence riparian zone composition and extent roughly perpendicular to the flow of water, are represented by valley bottom topography, including the depth and width of the channel and the slope of the streambanks and valley floor. Upslope processes, such as sediment production and overland flow and delivery of sediment, are represented by overland flow processes, land cover, and human activity.

Despite the ecological importance of riparian zones, mapping them in a consistent, comprehensive way across broad landscapes remains a challenge (Congalton *et al.*, 2002; Goetz, 2006; Hollenhorst *et al.*, 2006). Although some localized areas (i.e., small watersheds) have been mapped from high-resolution aerial photography (e.g., Colorado Division of Wildlife, 1998) or even LiDAR (e.g., Johansen *et al.*, 2010), it is cost prohibitive to map broad expanses at high resolution. We are not aware of a consistent, high-resolution (<30 m) riparian map for any large basin in the U.S.

Because of the cost and difficulty of accurately mapping riparian zones over broad expanses, numerous methods have been developed to approximate the boundaries of riparian zones by modeling geomorphological aspects of valley bottoms and floodplains. For instance, to map riparian zones for ecosystem service applications, the U.S. Environmental Protection Agency (USEPA)'s EnviroAtlas currently delineates riparian zones by uniformly buffering streams, regardless of their size (i.e., headwaters to large rivers), by 30 m (USEPA, 2013 similar to Jones *et al.*, 2010). Clearly, such an approach ignores the influences of hydrologic and geomorphic processes. Additionally, researchers have found that different floodplain widths (e.g., 50-100 year) correspond with valley bottom width (Clarke *et al.*, 2008) and riparian zone extent (Dunne and Leopold, 1978 and Ilhardt *et al.*, 2000) and have used floodplain widths to delineate riparian zones. Agencies (e.g., U.S. Forest Service) have used floodplains to represent riparian zones when detailed riparian zone maps were not available (D. Merritt, personal communication). Floodplain mapping is similar to riparian zone mapping in that it strives to identify regions near streams and rivers influenced by streamflow. However, floodplain mapping is perhaps more tightly constrained due to regulatory uses that require very-high resolution elevation data and local precipitation data. Many other methods used to map riparian zones (e.g., Hemstrom *et al.*, 2002; Strager and Yuill, 2002; Theobald *et al.*, 2010) have been published in grey literature and governmental reports.

We examined the variety of ways that riparian zones have been modeled in the literature and categorized them into eight spatial modeling approaches (Table 1). These methods vary from including only limited lateral processes using simple fixed-width buffers around stream lines (e.g., Wickham *et al.*, 2011) to more advanced approaches that incorporate lateral and longitudinal processes by estimating valley bottom topography and upstream drainage area (e.g., Clarke *et al.*, 2008). Our overall goal in this article is to determine which of these modeling methods most accurately maps riparian zones in our study basin.

We selected 19 studies to represent the eight methods (Table 1). Fifteen of those studies present maps

TABLE 1. A Brief Description, Study Area, and Citation(s) for the Eight Spatial Modeling Methods for Mapping Riparian Zones.

Method	Riparian Zone Determined By	Citation	Study Area	Terrain Resolution	Stream Representation
Fixed-width buffers	Fixed distance from the stream line	Baker *et al.* (2006)	Eastern U.S.	30	1:24,000
		Jones *et al.* (2010)	Conterminous U.S.	—	1:24,000
		Wickham *et al.* (2011)	Eastern U.S.	—	1:24,000
Variable fixed-width buffers	Variable fixed distance from the stream line	Li and Nigh (2011)	Central U.S.	—	Unknown
Elevation above stream	Simulates the inundation area surrounding a stream line with a specific flood depth	Grabs *et al.* (2010)	Semi-arid mountainous U.S.	10	Synthetic
		Kost and Dillon (2005)	Conterminous U.S.	30	
		Williams *et al.* (2000)	Semi-arid mountainous U.S.	30	1:100,000
		Benda *et al.* (2007)	Western U.S.	10	Synthetic
Variable elevation above stream	Simulates the inundation area surrounding a stream line with varying flood depths	Goetz (2001)	Semi-arid mountainous U.S.	30	1:100,000
		Ruefenacht *et al.* (2005)	Semi-arid mountainous U.S.	30	Synthetic
Bankfull depth	Empirical power functions relate upstream drainage area to bankfull depth. Multipliers (2.5 or 5) then applied to bankfull depth to create a flood depth	Castro and Jackson (2001)	Western U.S.	—	—
		Clarke *et al.* (2008)	Mesic western U.S.	10	Synthetic
		Dodov and Foufoula-Georgiou (2005)	Central U.S.	30	1:24,000
		Theobald *et al.* (2010)	Western U.S.	30	1:100,000
Topographic distance	Uses a combination of slope, elevation increase, and distance from the stream line	Benda *et al.* (2011)	Northern Spain	5	Synthetic
		Hemstrom *et al.* (2002)	Semi-arid mountainous U.S.	10	1:24,000
		Strager and Yuill (2002)	Eastern U.S.	30	1:100,000
Topography, discharge, and slope (TDS)	Uses a modified Euclidean distance (e.g., a buffer) computed using cost inputs that incorporate bankfull depth and slope	Theobald (unpublished)	Semi-arid mountainous U.S.	10	1:24,000
Multiple resolution valley bottom flatness (MRVBF)	Assumes riparian zones are low and flat relative to the surrounding topography, occur at a variety of scales. Large riparian zones tend to be flatter than smaller riparian zones	Gallant and Dowling (2003)	Australia	25	—

of riparian zones using GIS-based methods implemented with commonly available raster data and the other four studies map riparian zones using vector stream lines. Review of these 19 studies revealed two key ways in which the data they use differ, the first being the spatial resolution of the elevation data. Eight of the 15 raster-based riparian mapping studies used a 30 m resolution, which is too coarse to adequately map the narrow riparian zones of many headwater streams (Goetz, 2006), whereas others used a finer resolution (Table 1). Second, three different stream representations were used to delineate riparian zones: streams mapped at a scale of 1:100,000; streams mapped at a scale of 1:24,000; and synthetic stream lines derived from digital elevation models (DEMs). The source and scale of the stream dataset impacts the accuracy of riparian mapping in three ways: smaller scale representations of stream lines contain less detail than larger scale representations, potentially excluding smaller streams; mapped stream networks may not reflect the actual stream density present in watersheds (Elmore *et al.*, 2013); and errors in the location of mapped stream features may contribute to errors in the location of mapped riparian zones.

Despite the variety of approaches developed to delineate riparian zones, to our knowledge a systematic comparison of these methods has not been conducted (Goetz, 2006). Therefore, we evaluated the eight methods (Table 1) to determine which method best maps riparian zones, in a semi-arid, mountainous watershed, using free, readily available stream and elevation data. We did not evaluate very-high resolution (<1 m) elevation from LiDAR because those data were not available for our study area.

To evaluate those eight methods for mapping riparian zones over broad spatial extents, we: (1) characterized the conceptual basis (i.e., incorporation of processes) and computational complexity of each method; (2) implemented the algorithms on a standard platform (i.e., ArcGIS v10) to provide a consistent basis for comparison; (3) tested the performance of the various methods, including the effects of stream order, stream representation, and DEM resolution, against an independent validation dataset; and (4) summarized the quantitative accuracy and advantages/disadvantages of each approach.

METHODS

Study Area

Our study area is the Big Thompson watershed (Figure 1), which is located in the Northern Front Range of Colorado within the Southern Rockies Ecoregion. The Big Thompson watershed covers approximately 2,150 km^2, has roughly 3,000 m of topographic relief, and has an annual precipitation range of 1,194 mm in the headwaters to 375 mm at lower elevations (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, *accessed* June 15, 2012). Our analysis focused on the 1,794 km^2 mountainous portion of the watershed (~85%), which is west of 105° longitude and over 1,500 m in elevation, hereafter referred to as the study area. The study area is typical of forested areas in the Intermountain West and is characterized by a variety of land cover types: forest (53%), grass and shrublands (29%), croplands (5.5%), and developed areas (4.7%) including the towns of Estes Park and Loveland (National Land Cover Dataset v2011, http://www.mrlc.gov/nlcd06_data.php, *accessed* February 13, 2015).

Validation Data Set

We assessed the accuracy of each method by comparing the maps they produced with riparian zones interpreted from aerial photography at 100 plots (600 m × 600 m) within the study area. Plot size was selected to be large enough to capture the full width of the widest riparian zones in our study area, but small enough to limit the incidence of multiple riparian systems (i.e., confluences) within a given plot. We located the plots using a stratified random design (Theobald *et al.*, 2007) to ensure an equal representation of headwaters (Strahler stream order 1; S_1), mid-watershed (S_2), and larger streams ($>S_2$). Stream order was determined using the U.S. Geological Survey's National Hydrography Dataset (NHD) high-resolution scale dataset (i.e., 1:24,000). We delineated the edge of riparian zones from recent (>2010), summer, high-resolution (0.3 m) color aerial photography (ESRI, 2010 ESRI. World Imagery, http://services.arcgisonline.com/ArcGIS/rest/services/World_Imagery/MapServer, *accessed* June-October 2013), as well as slope and a topographic wetness index (Beven and Kirkby, 1979) created, using the LCAP tools in ArcGIS v10 (Theobald, 2007) at 10 m resolution (U.S. Geological Survey, National Elevation Dataset (NED), http://ned.usgs.gov/, *accessed* June 13, 2009).

We followed the interpretation guidelines developed by the U.S. Fish and Wildlife Service (USFWS, 2009) to map riparian zones for the National Wetland Inventory, in which riparian zones were identified by the presence of mesic vegetation surrounding streams that appears greener and coarser in texture on the aerial photos than do upland areas. If riparian vegetation was not present adjacent to a stream due to human modification of the landscape, we then visually assessed the slope of the valley walls. We identified low values of slope (typical <1°) then found the first place where slope increased abruptly indicating a ridge, bank, or valley side away from the stream (Polvi *et al.*, 2011). In conjunction with areas of low slope, we used the topographic wetness index to evaluate where soils become less saturated (i.e., had locally lower values), similar to Grabs *et al.* (2009) who evaluated topographic wetness index as a method to map spatial patterns of wetlands. Due to natural variations in valley and stream types, we did not apply a threshold to either the slope or topographic wetness index. We conducted a preliminary evaluation of our techniques and ability to identify

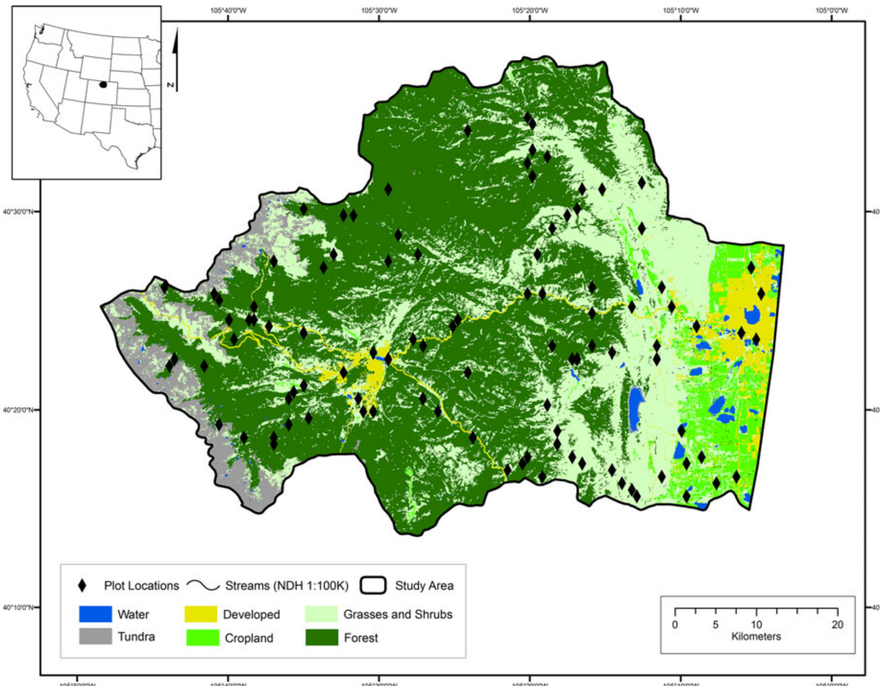

FIGURE 1. The Study Area Is the Mountainous Portion of the Big Thompson Watershed in the Northern Front Range of Colorado. Plot locations points indicate locations where validation data were collected.

the boundaries of riparian zones on the aerial photos by field checking 10 plots in a variety of valley types and stream orders following methods developed by Polvi *et al.* (2011). This allowed us to refine our interpretation methods, especially in identifying the edge of riparian zones in locations that had been modified by humans and distinguishing the riparian edge in locations dominated by herbaceous vegetation.

Methods to Map Riparian Zones

The eight modeling methods (Table 1) were applied to three different stream representations: synthetic stream lines developed from DEMs and two hydrographic datasets: the NHD high resolution (1:24,000; ftp://nhdftp.usgs.gov/, *accessed* July 23, 2008); and NHD medium resolution (1:100,000; USEPA and U.S. Geological Survey, NHDPlus, http://www.horizon-systems.com/nhdplus/, *accessed* July 23, 2008). Both NHD datasets were developed using U.S. Geological Survey hydrologic digital line graph and USEPA reach files, products that originate from topographic map and aerial photography interpretation and can be prone to error. The NHD requires that that 90% of mapped features are within specified distances from their true geographic locations: high-resolution features must be within 12.2 m of their true geographic location while medium-resolution features must be within 50.9 m. We converted NHD lines to raster (grid) representation using a thinning algorithm to avoid overrepresentation of stream cells. We created synthetic stream lines at both 10 and 30 m resolution using flow routing tools (flow direction and flow accumulation) in ArcGIS. Any cell that had a catchment area ≥40 ha in the flow accumulation raster was considered a stream cell. As is common in hydrologic modeling, we assumed the stream occupied the entire cell. Each stream representation was implemented at two terrain scales, 10 and 30 m NED (U.S. Geological Survey, NED, http://ned.usgs.gov/, *accessed* June 13, 2009). Following others (e.g., Williams *et al.*, 2000; Hemstrom *et al.*, 2002; Strager and Yuill, 2002), we did not recondition the DEMs, but we did use standard hydro-conditioning when creating the flow direction raster to remove "pits." In addition to the three stream representations and two DEM resolutions, a variety of model parameters were used with each of the methods, as described below, resulting in a total of 138 model-based maps of riparian zones.

Buffers. We analyzed three fixed-width buffers that are commonly used (100, 120, and 180 m), and to broaden the range of buffer widths we also analyzed three smaller buffers (40, 60, and 80 m). Each of these six fixed-width buffers were applied uniformly across the entire study area, regardless of stream order. For the variable fixed-width buffer method, we varied buffer width based on Strahler stream order (S), employing buffer widths of 15 m for S_1, 35 m for S_2 and S_3, and 70 m for $>S_3$ (following Li and Nigh, 2011).

Elevation above Stream. For the "elevation above stream" method, we mapped riparian zones as the area of a valley bottom that would be inundated at a specific stream discharge. Several researchers have applied this approach (Williams *et al.*, 2000; Kost and Dillon, 2005; Benda *et al.*, 2007; Grabs *et al.*, 2010), using fixed depths ranging from 2 to 15 m. We examined fixed depths of 2, 3, 5, 10, and 15 m, and one version of variable depths where depth was dependent on stream order as follows: 1 m for S_1, 3 m for S_2, 4 m for S_3, 5 m for S_4, 6 m for S_5, and 8 m for $>S_5$ (following Goetz, 2001).

Bankfull Depth. Leopold and Maddock (1953) developed power functions to describe channel geometry based on drainage area, which have been adapted to predict bankfull depth based on drainage area and regional coefficients (Castro and Jackson, 2001) as follows:

$$\text{Bankfull depth} = aD^b$$

where D is the drainage area (km^2), a and b are region-specific parameters, and bankfull depth is the average (or hydraulic) depth at a cross section.

Several researchers (e.g., Castro and Jackson, 2001; Dodov and Foufoula-Georgiou, 2005; Benda *et al.*, 2007; Clarke *et al.*, 2008; Theobald *et al.*, 2010) mapped riparian zones by applying a threshold or multiplier to the estimate of bankfull depth, equating the riparian zone with bankfull depth. Use of such multipliers relies, in part, on an analysis by Dunne and Leopold (1978) who found that riparian zones in arid, mountainous regions are similar to the extent of a 100-year flood, which typically occurs when the bankfull depth is exceeded by 2.2 times. Dodov and Foufoula-Georgiou (2005) related upstream drainage area to riparian zone extent by using two sets of values for parameters a and b, $0.6D^{0.34}$ for basins <700 km^2 and $0.6D^{0.02}$ for basins >700 km^2. Other researchers first estimate bankfull depth to incorporate the relative size and power of a stream and then multiply it by 2.5 (Theobald *et al.*, 2010) or 5 (Clarke *et al.*, 2008) to estimate the riparian zone. In addition to using equations developed by Dodov and Foufoula-Georgiou (2005), three sets of values for parameters a and b to calculate bankfull depth were used. Each set was developed by researchers for mountainous regions with geomorphology similar to that of the study area. These three sets are as follows: $a = 0.61$, $b = 0.33$ (Castro and Jackson, 2001); $a = 0.38$, $b = 0.25$ (Clarke *et al.*, 2008); and $a = 0.36$, $b = 0.20$ (Theobald *et al.*, 2010). We then multiplied each estimate of bankfull depth by 2.5 and 5.

Slope and Valley Bottom Topography. Slope and valley bottom topography methods incorporate upslope processes and valley bottom topography to map riparian zones. We evaluated three such methods: topographic-weighted distance from streams (Hemstrom *et al.*, 2002; Strager and Yuill, 2002); topography, discharge, and slope (TDS); and multiple resolution valley bottom flatness (MRVBF; Gallant and Dowling, 2003). Each of these methods uses subjective thresholds that are based on recommendations provided by the researchers who developed each method and are further informed by expert knowledge of the study area and visually comparing the modeled output to topography and aerial photographs in order to identify the boundary of riparian zones.

The topographic distance method calculates a topographically-weighted distance away from a stream, where the weights reflect valley bottom slope and distance from streams (Hemstrom *et al.*, 2002; Strager and Yuill, 2002). Following Strager and Yuill (2002), separate distance thresholds were used for each of the three groups of stream orders (i.e., 1-2, 3-4, and ≥5).

Building on the bankfull depth method (Castro and Jackson, 2001; Clarke *et al.*, 2008; Theobald *et al.*, 2010), the TDS method first calculates the bankfull depth using Castro and Jackson (2001) coefficients, but, instead of multiplying the bankfull depth by 2.5 or 5, this method incorporates the distance away from the stream line by applying weights that are based on the valley bottom slope accounting for the Euclidean distance. As steeper areas are encountered, the distance increases proportionately and a threshold, based on upstream watershed area, determines the elevation above bankfull depth at which riparian zones are defined. The three multipliers of the depth (1, 2, and 5) were selected to represent typical values that will approximate the 100-year flood magnitude (at value = 1). The other values, 2 and 5, are similar to those recommended by Clarke *et al.* (2008). Each of the threshold values was then determined using aerial photography at a variety of locations in the watershed.

The MRVBF method (Gallant and Dowling, 2003) identifies riparian zones based on topographic position by identifying areas that are low and flat relative to the surrounding topography. A continuous index is produced and thresholds are used to determine which values represent riparian zones. This method describes riparian zones as occurring at a variety of scales, with large riparian zones tending to be flatter than smaller riparian zones, and uses slope thresholds at a variety of scales to define riparian zones.

Following Gallant and Dowling's (2003) recommendations, the initial slope threshold was set at 8% for the 10 m DEM analysis and at 4% for the 30 m DEM analysis. We then visually inspected the results of the model and selected three different thresholds of the MRVBF index (<1, <0.75, and <0.5) that appeared to map riparian zones well.

Evaluation Process

We evaluated the methods by: (1) comparing the resulting riparian delineation to the validation dataset, (2) evaluating the sensitivity of each spatial modeling method to stream representation and terrain (DEM) resolution, (3) estimating algorithm complexity, (4) tracking processing time, and (5) comparing the resulting riparian maps visually.

Comparison to Validation Data

We compared our model-based delineations to those of the validation dataset using three metrics: a precision measure, the kappa coefficient (Cohen, 1960), and the percent of the study area that is classified as riparian. Precision is the proportion of the positive test results that are true positives; i.e., the proportion of estimated riparian cells in a plot that are also riparian in the validation dataset. The kappa coefficient utilizes information about not only true positives (i.e., riparian matches) but also true negatives (non-riparian matches). Thus, the kappa coefficient focuses not only on the riparian area but also on upland areas. The kappa coefficient and precision values were computed for each of the validation plots on a cell-by-cell basis, and the median across plots for the entire set of plots or for subsets of the plots containing streams of a particular size is reported. We tested for statistical differences among kappa coefficients and among precision values using a non-parametric analysis of variation test, the Friedman test (Friedman, 1940), with a post hoc analysis to determine which methods differ from each other. For the subsets of the plots (headwaters (S_1), mid-watershed (S_2), and larger ($>S_2$) streams) statistical differences were tested using the Mann-Whitney U test.

We calculated the percent of the entire study area that was mapped as riparian for each method. Our study constrained the plots to those containing streams, limiting the sampling frame to 39% (700 km^2) of the entire study area. To obtain an estimate of the percentage of the study area that was based on the validation data, the riparian percent found in the validation plots was multiplied by the proportion of the study area that was sampled (i.e., 0.39).

Effect of Stream Representation and DEM Resolution. We sought to determine if the accuracy of the methods was dependent on stream representation or DEM resolution. For every spatial modeling method, riparian zones were delineated using each of the six different combinations of stream representation and DEM resolution. We compared all of the resulting delineations with that of the validation set by computing kappa coefficients and precision values. We then evaluated the sets of kappa coefficients and precision values using the Friedman test with post hoc analysis.

Algorithm Complexity. Algorithm complexity of each spatial modeling method was evaluated using three metrics: the number of estimated parameters, the number of measured parameters, and the number of lines of Python code needed to implement the method.

Processing Time. Processing time was measured as the number of hours required to delineate riparian zones for the entire study area, using a personal computer running Windows XP with an Intel Core II CPU with 3.5 GB RAM and a 2.66 GHz processor.

RESULTS

Each of the eight methods for delineating riparian zones (Table 1) was implemented using several different parameterizations. Here we focus on the parameterizations that yielded the highest median kappa values when implemented using the most detailed DEM resolution (10 m) and stream data (NHD high resolution). Thus, we will discuss the following specific methods: 40 m fixed-width buffers, variable fixed-width buffers, elevation above stream 2 m, variable elevation above stream, bankfull DT 2.5 (Theobald *et al.*, 2010), topographic distance, TDS 1X, and MRVBF < 1. Results for all methods are described in the supporting information.

Characteristics of the Validation Plots

Our detailed mapping of the riparian zones in the 100 validation plots revealed that 7.9% of the plot area is occupied by riparian zones. When examined by stream order, we found that riparian zones occupy 6.7% of headwater stream (S_1) plots, 4.8% of mid-watershed (S_2) plots, and 11.9% of larger stream

($>S_2$) plots, on average. We estimate that 3.1% (i.e., 7.9×0.39) of the study area is occupied by riparian zones.

Effect of Stream Representation and DEM Resolution

For each of the spatial modeling methods, the kappa coefficient and precision values were used to evaluate the effect of stream representation and DEM resolution on the delineation of riparian zones with a given method and parameterization. Based on the kappa coefficients, only two methods, bankfull DT 2.5 and MRVBF < 1, did not exhibit significant differences among the different stream representations and DEMs ($p > 0.05$). For all other methods evaluated using the kappa coefficient, and for all methods except MRVBF < 1 when evaluated using the precision value, choice of stream representation or DEM produced results that had at least one significant difference ($p < 0.05$). However, there was no consistent pattern across the different methods, suggesting that no one stream representation or DEM is always superior. See supporting information for details.

Comparison to Validation Data

Results for each of the eight spatial modeling methods are presented in Tables 2-4 and Figures 2 and 3. We summarize the results first for the study area as a whole and then by stream order.

Study Area Comparison. When analyzing all plots, several significant differences ($p < 0.05$) occur between methods, specifically between methods that incorporate lateral and longitudinal processes and those that do not (Figure 2). Based on kappa coefficients (Table 2; Figure 2), TDS 1X performs better than all other methods ($p < 0.05$) except for bankfull DT 2.5 and topographic distance; MRVBF < 1 performs more poorly than all other methods ($p < 0.05$); and the 40 m buffer is statistically similar to all methods except for TDS 1X and MRVBF < 1. Based on precision values (Table 3; Figure 3), TDS 1X performs better than all other methods ($p < .002$) except for bankfull DT 2.5; MRVBF < 1 is not significantly different from 40 m buffers, elevation above stream 2 m, or variable elevation above stream; and the 40 m buffer is not statistically different from any other method except for bankfull depth DT 2.5 and TDS 1X. The percentage of the study area that each method estimates is riparian and the percentage estimated by the validation data are found in Table 4. When using a 10 m DEM, the percent of the study area estimated to be riparian zones varies from 5.1% (TDS 1X) to 18.8% (MRVBF < 1).

Stream Order Comparison. Using the same approach that was used for the full set of plots, the performance of each method was assessed at the plots for three stream orders, S_1, S_2, $>S_2$, at both the 10 and 30 m terrain scales (DEMs). Based on the kappa coefficients (Table 2), we found that 40 m buffers performed better along larger streams ($>S_2$) than smaller streams (S_1 or S_2) when mapped using either a 10 or 30 m DEM ($p < 0.002$); that variable fixed-width buffers performed better in $>S_2$ streams than in S_2 streams when mapped at 10 m ($p = 0.009$); that maps created using bankfull DT 2.5, elevation above stream, and topographic distance all performed better in $>S_2$ streams than in S_1 streams when mapped using at 10 m DEM ($p < 0.05$); and that the map created by TDS 1X using a 10 m DEM performed better than the map created using a 30 m DEM for S_2 and $>S_2$ streams ($p < 0.002$). The precision values

TABLE 2. Comparison of the Eight Methods to the Validation Data Using Median Kappa Coefficients for the 100 Plots for 10 and 30 m Digital Elevation Model.[1]

	Median Kappa Coefficient							
	S_1 Plots		S_2 Plots		$>S_2$ Plots		All Plots	
	10 m	30 m	10 m	30 m	10 m	30 m	10 m	30 m
Buffer 40 m	0.21	0.20	0.14	0.13	0.43	0.43	0.23	0.24
Variable fixed-width buffer	0.25	0.25	0.14	0.15	0.37	0.36	0.25	0.24
Elevation above stream 2 m	0.20	0.19	0.14	0.10	0.35	0.32	0.25	0.19
Variable elevation above stream	0.21	0.21	0.17	0.12	0.31	0.32	0.24	0.19
Bankfull DT 2.5	0.24	0.23	0.17	0.11	0.39	0.38	0.27	0.23
Topographic distance	0.19	0.28	0.24	0.17	0.40	0.38	0.29	0.28
TDS 1X	0.30	0.25	0.38	0.27	0.46	0.39	0.38	0.30
MRVBF < 1	0.10	0.14	0.10	0.11	0.16	0.17	0.13	0.15

Notes: S_1 and S_2 refer to Strahler stream order 1 and 2, respectively.
[1]Kappa and values are reported for selected spatial modeling methods calculated using National Hydrography Dataset high-resolution streams.

TABLE 3. Comparison of the Eight Methods to the Validation Data Using Median Precision for the 100 Plots for 10 and 30 m Digital Elevation Model.[1]

	Median Precision Values							
	S_1 Plots		S_2 Plots		$>S_2$ Plots		All Plots	
	10 m	30 m	10 m	30 m	10 m	30 m	10 m	30 m
Buffer 40 m	0.13	0.13	0.10	0.10	0.38	0.36	0.20	0.20
Variable fixed-width buffer	0.16	0.16	0.11	0.13	0.31	0.30	0.19	0.19
Elevation above stream 2 m	0.14	0.13	0.14	0.10	0.35	0.31	0.21	0.18
Variable elevation above stream	0.14	0.14	0.14	0.10	0.31	0.30	0.20	0.17
Bankfull DT 2.5	0.14	0.15	0.15	0.11	0.39	0.34	0.24	0.19
Topographic distance	0.18	0.19	0.17	0.14	0.34	0.35	0.24	0.22
TDS 1X	0.25	0.20	0.27	0.23	0.43	0.34	0.33	0.26
MRVBF < 1	0.09	0.11	0.11	0.11	0.24	0.24	0.14	0.16

Notes: S_1, and S_2 refer to Strahler stream order 1 and 2, respectively.
[1]Precision values are reported for selected spatial modeling methods calculated using National Hydrography Dataset high-resolution streams.

TABLE 4. Percent of the Study Area Estimated to Be a Riparian Zone for Each of the Eight Methods.[1]

	Percent of Study Area	
	10 m	30 m
Buffer 40 m	15.69	15.68
Variable fixed-width buffer	11.76	11.76
Elevation above stream 2 m	17.91	22.24
Variable elevation above stream	17.85	20.79
Bankfull DT 2.5	14.32	18.91
Topographic distance	11.07	11.65
TDS 1X	5.11	7.19
MRVBF < 1	18.77	17.41
Validation data	3.08	

[1]Values of percent of landscape are reported for selected spatial modeling methods calculated using National Hydrography Dataset high-resolution streams.

(Table 3) indicated that all methods, using either the 10 or 30 m DEM, perform better ($p < 0.05$) in $>S_2$ streams than in S_1 and S_2 streams and that choosing 10 m over a 30 m DEM resolution does not make a difference ($p > 0.05$) in the performance of the methods at any stream order (S_1, S_2, or $>S_2$). When analyzed by stream order and DEM resolution, all other methods performed statistically similarly ($p > 0.05$).

Algorithm Complexity and Processing Time

Across the methods, the number of estimated parameters ranged from 1 to 9, the number of measured parameters ranged from 0 to 2, processing times ranged from 0.02 to 3.0 h, and lines of code ranged from 19 to 149 (Table 5). For a given spatial modeling method, processing times varied little among the three stream representations.

Visual Comparison

For a stream segment near the center of the study area, we visually compared the modeled and validation estimates (Figure 4). Based on these eight comparisons, it is apparent that methods that incorporate valley bottom topography (elevation above stream 2 m, variable elevation above stream, bankfull, topographic distance, and TDS 1X methods) more accurately map the extent and spatial pattern of riparian zones.

DISCUSSION

We found that using methods that incorporate dominant hydrologic processes and higher resolution improves the mapping of riparian zones. Riparian zones were identified better than a randomly generated map would have (i.e., $\kappa > 0$; Table 2) for all methods, but some methods were better than others at estimating riparian zones. First, based on kappa and precision values (Table 2 and 5; Figures 2 and 3), we found that methods incorporating both lateral and longitudinal processes (e.g., TDS and bankfull DT 2.5) are more accurate than methods (e.g., fixed- and variable fixed-width buffers) that do not incorporate landscape-level drivers. Second, the percent of the study area mapped as riparian most closely matches the validation dataset using only one method, TDS 1X (Table 4). Third, however, the improved accuracy comes at a price, in that the simplest methods to implement (e.g., buffers) typically take the shortest time to process and require the least amount of input data and fewest lines of code (Table 5). Furthermore, based on both kappa and

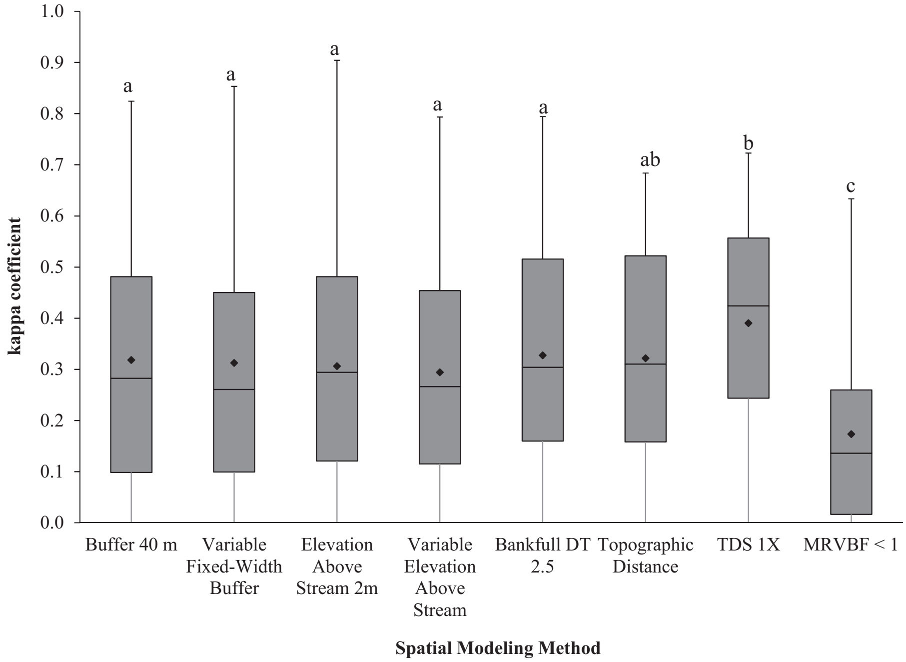

FIGURE 2. Box Plots of Kappa Coefficients for Selected Spatial Modeling Methods Calculated Using National Hydrography Dataset High-Resolution Streams and a 10 m Digital Elevation Model.

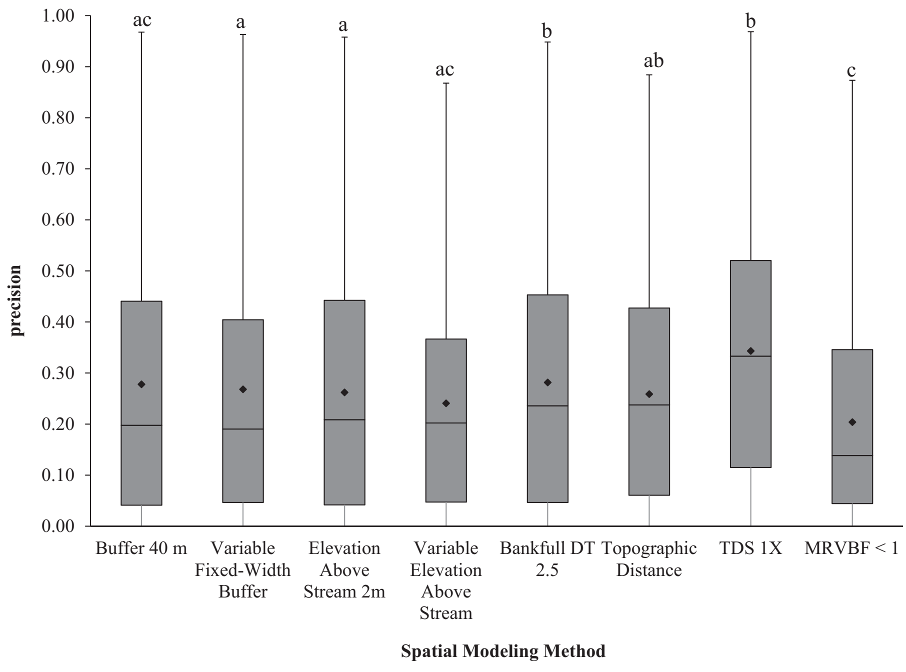

FIGURE 3. Box Plots of Precision Values for Selected Spatial Modeling Methods Calculated Using National Hydrography Dataset High-Resolution Streams and a 10 m Digital Elevation Model.

precision values (Tables 2 and 3), TDS 1X performed slightly better than bankfull depth DT 2.5 for the study area as a whole and also for each stream order group (although not significantly better at $p \geq 0.05$). Visual analysis and a higher kappa coefficient and precision value in $>S_2$ streams reveals that in areas with low topographic relief, the riparian zones mapped using TDS 1X were less likely than those created using bankfull methods to extend far from the stream and create riparian zones that are not connected to streams, thus better estimating riparian zones in flat regions. Based on the comparison to

TABLE 5. Algorithm Complexity and Processing Time of the Eight Methods.[1]

Method	Parameters		Processing Time (hours)	Lines of Code
	Estimated	Measured		
Fixed-width buffers	1	0	0.02	19
Variable fixed-width buffer	6	0	3.5	33
Elevation above stream	1	0	0.15	42
Variable elevation above stream	9	0	3.75	49
Bankfull depth	1	2	1.5	71
Topographic distance	3	0	3.5	76
TDS	6	2	3	149
MRVBF	2	0	1.25	84

[1]Processing time was computed using a 10 m digital elevation model and National Hydrography Dataset high-resolution streams.

validation data, the TDS 1X method using a 10 m DEM and NHD high-resolution stream lines was best suited to estimate riparian zones in our study area.

The algorithm for TDS 1X includes drainage area and streambank steepness, and thus maps the extent of the riparian zone using both longitudinal and lateral influences. Methods that do not include lateral and longitudinal influences (e.g., fixed-width buffers) can overestimate riparian zones in headwater streams and canyons and underestimate riparian width in larger streams with broad valley bottoms. Our study area has substantial topographic relief (3,000 m), large variations in stream gradient (0.01-19.29%), and a wide range of valley types, from low energy glacial valleys to steep mountain canyons. Models that include local stream gradient (such as TDS) performed well in this highly variable watershed but, might not apply as readily in areas with less vertical relief and natural variation in stream gradient or valley type.

Our findings do not apply to riparian zones that are narrower than 10 m, which may occur especially along some headwater streams. In headwater streams (S_1), we found that variable methods (e.g., variable buffer width and variable elevation above stream) and methods that incorporate longitudinal processes (e.g., Bankfull DT 2.5 and TDS 1X) tend to work best (Tables 2 and 3). Variable methods allow for smaller buffer widths or increases in elevation (when using elevation above stream) along headwater streams than larger streams, resulting in more representative riparian zones. Methods that incorporate longitudinal processes, which are derived from drainage area, more appropriately capture the narrow riparian zones of headwater streams. Additionally in headwater reaches, smaller buffer widths (e.g., 40 m) and smaller increases in elevation above stream (e.g., 2-3 m) work better (supporting information online) than fixed methods with large buffer widths (e.g., >40 m) and large elevation increases (e.g., >3 m). Headwater streams generally support narrow riparian zones and applying large uniform buffers across entire watersheds, either determined by Euclidean distance or flood depths, often overestimate the width of narrow riparian zones.

In the middle reaches of the watershed (S_2), we found that the TDS 1X method worked well (Tables 2 and 3). Within our study area, the middle reaches of our watershed have a wide variety of valley types (e.g., canyons, glaciated floodplains, and moderate energy confined and unconfined valleys). This variation in valley types makes it difficult to map riparian zones without considering both longitudinal and lateral processes that have the ability to accurately map different valley types and the associated riparian zones. Although many methods (e.g., elevation above stream, bankfull DT 2.5 m, topographic distance) account for valley bottom topography, the inclusion of weights based on the valley bottom slope increases the accuracy of TDS 1X in narrow valleys with steep side-walls and in regions with low topographic relief. Applying a uniform buffer or increase in elevation fails to capture the natural variability within our watershed.

In larger streams and rivers ($>S_2$), all methods (Tables 2 and 3) map riparian zones more accurately than they do in middle reaches and headwater streams. This occurs because, within our study area, larger streams have wider riparian zones and less variation in valley type and riparian zone width. The 40 m buffer works well in larger streams because the width of the rivers supports a riparian zone of a similar size. However, the 40 m buffer may not work well in all situations, especially in regions with streams that are either larger or smaller than those in our study area.

Comparing Terrain Resolution and Stream Representation

The stream order analysis revealed that the kappa coefficients were larger (i.e., more accurate) for three of the methods (40 m buffers, variable fixed-width buffers, and TDS 1X) when calculated using a 10 m DEM than when using a 30 m DEM in S_1 and S_2 streams. This is to be expected as riparian zones are

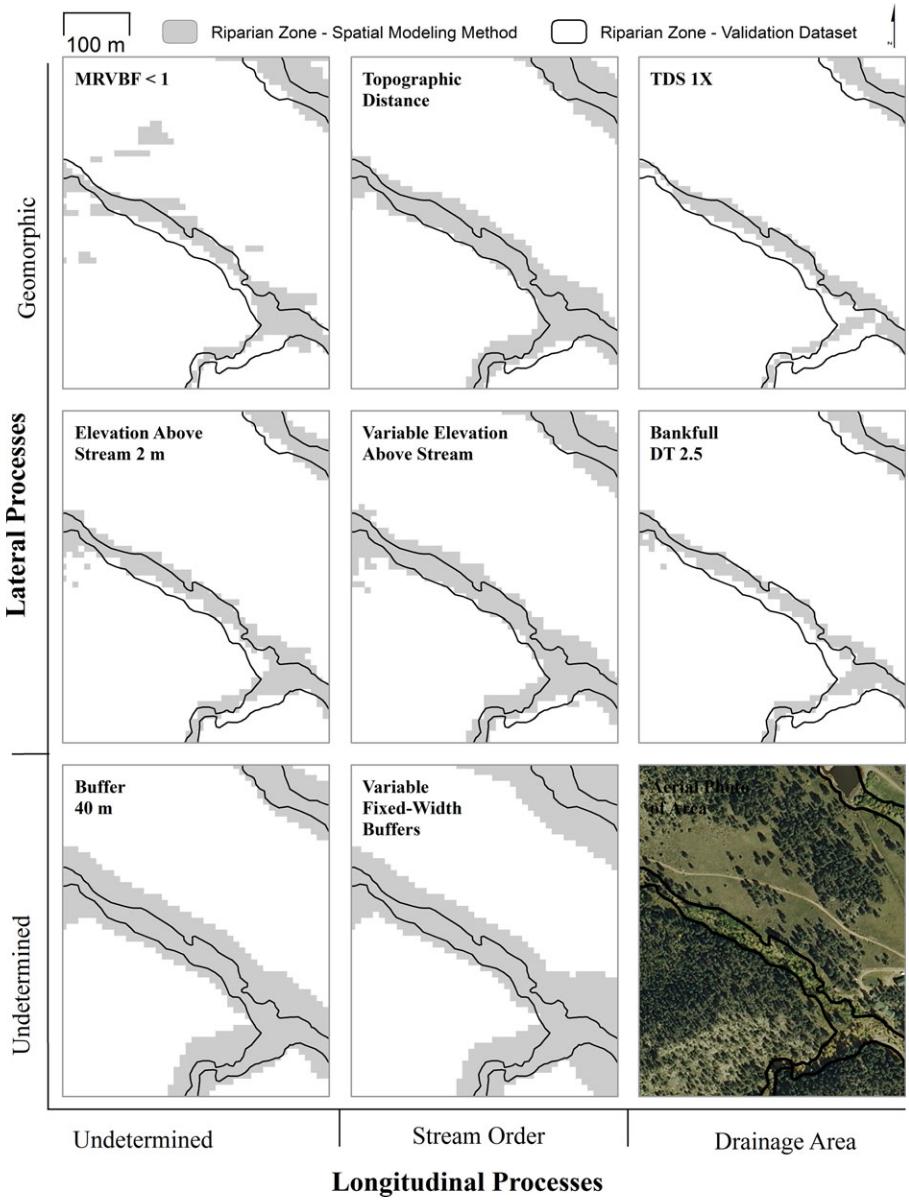

FIGURE 4. Illustration of Each Spatial Modeling at a Stream (Strahler stream order 2) in the Middle Reaches of the Big Thompson Watershed. The version of each method shown here is the one that achieved the best kappa value. By comparing the riparian (gray) areas to the validation data (black line), we see that many of the methods (especially 40 m buffer, MRVBF < 1, and variable fixed-width buffers) overestimate the riparian zone. Examples of spatial modeling methods calculated using 10 m digital elevation model and National Hydrography Dataset high-resolution streams.

narrow in headwater streams, which supports mapping riparian zones at a 10 m resolution or higher for headwater streams, and is consistent with other research that found mapping riparian zones with finer resolution data can produce maps with higher accuracy (Hollenhorst *et al.*, 2006; Baker *et al.*, 2007; Gergel *et al.*, 2007). In addition, the top performing method for estimating riparian zones in our study area, TDS 1X, performed best when using a 10 m DEM. Based on these findings, we recommend using at least a 10 m resolution to map riparian zones and, where appropriate, we limit our discussion to the results of the 10 m analysis.

We found varying results when comparing how different stream representations and DEM resolutions impact the kappa coefficients and precision values for a specific method. In contrast to the TDS 1X method, which performed best when using a 10 m DEM and NHD high-resolution stream lines, the kappa coefficients for the bankfull DT 2.5 method did not reveal any significant differences ($p > 0.05$) among any of the stream representation and DEM combinations. We did not find statistical evidence that supports improved mapping results when changing only DEM resolution or stream representations. However, we observed that using a 10 m DEM with NHD high-resolution stream lines produced the most realistic riparian zone maps. Fine resolution DEM data may better identify riparian zones because stream and valley gradients and patterns of connection (Baker *et al.*, 2007) can be detected more readily than with coarser resolution DEM data. These results demonstrate the importance of testing how each method performs with different stream representations and DEM resolutions before choosing the best method to map riparian zones in a specific area. However, only 24% of riparian zones mapped using aerial photography for this study have a width >60 m, suggesting that a 30 m resolution may be too coarse to delineate riparian zones in headwater streams of semi-arid, mountainous regions.

Our validation dataset of 100 plots shows that 48% of the riparian zones in those plots had widths of <30 m and 88% had widths of <90 m. If our data were used in a raster format with 30 m cells, the widths of 88% of the mapped riparian zones would be represented by only 1-3 cells, leading to omission errors when using automated mapping techniques. If riparian zones were represented using 10 m cells, 48% of the mapped riparian zones would be represented by only 1-3 cells, reducing omission errors.

Future Opportunities and Limitations

Expanded access to sub-meter elevation and canopy data from LiDAR would allow significant further improvements in riparian zone mapping. Where available, such data are already being used to include factors such as woody debris recruitment and to shade different delineations of the riparian zone (NetMap, 2015). However, one potential limitation is that these precise delineations of riparian zones, obtained using higher resolution data, can be so sensitive to dynamics on a decadal time frame that subsequent high flow or other disturbance events can render the delineations inaccurate, requiring frequent updating.

If LiDAR data were available for broad spatial extents, researchers would be able to produce maps of riparian zones across large watersheds that would incorporate fine-grain patterns and processes such as litter fall, wood recruitment, thermal energy, and forest structure. Resulting maps would, of course, be more useful for fine-scale management purposes than those examined herein. However, until LiDAR is available for broad spatial extents, large scale maps of riparian zones will be unable to depict the fine-grain processes that LiDAR data can represent. At this point in time, we believe that using a method such as TDS 1X to map riparian zones over broad spatial extents would produce an improved estimate of riparian zones for conservation, management, and restoration purposes than those that currently exist (e.g., Jones *et al.*, 2010; USEPA, 2013).

We recognize that riparian zones remain challenging to map, largely because they reflect multi-scale hydro-geomorphic processes. In many mountainous regions, streams are often narrow (<1 m in width) and have low flows or are ephemeral, making the associated riparian zones difficult to resolve in medium to coarse resolution remotely-sensed data (≥30 m) (Congalton *et al.*, 2002). Additionally, the influence of interannual flow, diversions, and dam releases is an important component to consider when mapping the location of riparian zones, but is difficult to model over large geographic extents and we were not able to account for these variables. Moreover, riparian zones are frequently obscured from above by the forest canopy of adjacent terrestrial ecosystems. Advances, especially in LiDAR, offer great potential to respond to these challenges.

The impacts of land use legacy are also an important issue in the ecology and conservation of aquatic resources (Foster *et al.*, 2003; Pijanowski *et al.*, 2007), and in particular, for mountain streams (Wohl, 2001). However, mapping the impact of land use legacy is a difficult task (Pijanowski *et al.*, 2007) and was not an element of any of the mapping methods we evaluated. The question arises then, could land use legacy effects have compromised our evaluation of the mapping methods? Based on an ad hoc comparison of sample locations to reference condition sites (e.g., wilderness areas), we concluded that historic land use did not greatly impact our evaluation of riparian zone mapping methods. We applied the commonly used idea of “reference condition” that has been reproduced in several research efforts (e.g., Stoddard *et al.*, 2006; Carlisle *et al.*, 2010; Falcone *et al.*, 2010; Poff *et al.*, 2010). In addition, the process we used for identifying riparian zones from aerial photos for our validation dataset was not limited to examining land cover, as we also included topographic wetness index, slope, and local topography to identify riparian zones. Our field exercise took place along streams in all areas of the watershed, including upstream and downstream of the Alva A. Adams Tunnel outlet. That said, we recognize that our evaluation of methods for mapping “natural” riparian zones is potentially subject to some error introduced by the effects of past land and water use on riparian zones in our study area.

CONCLUSION

Within our study area, we found methods that incorporated lateral and longitudinal processes were significantly better at estimating riparian zones than simpler methods based on buffers alone, and that the TDS 1X method performed best in mapping riparian zones. We recommend using the TDS 1X method implemented using a 10 m DEM and NHD high-resolution streams to map riparian zones in semi-arid mountainous regions with dendritic drainage patterns. TDS 1X was best at matching the validation data, is scalable to stream size, and incorporates lateral and longitudinal processes. TDS 1X utilized regressions developed from field work in arid, mountainous ecosystems that are available for other regions (Castro and Jackson, 2001; Faustini *et al.*, 2009) or can be developed through additional field work. Our case study basin is illustrative of the broader basin and ecoregion. Thus, our findings are relevant to other efforts to map riparian zones in semi-arid regions with watersheds that have perennial streams, a variety of valley types, dendritic drainage patterns, and relatively shallow soils. In other regions and for ephemeral and intermittent streams, it would be necessary to replicate our evaluation process to test the variety of riparian zone mapping techniques using available terrain and stream data.

A commonly cited statistic is that riparian zones occupy <2% of land in the West; however, the basis for this estimate is unclear (McKinstry *et al.*, 2004; Theobald *et al.*, 2010; Poff *et al.*, 2011). And for Colorado, Dahl (1990) estimated that historical riparian zones accounted for 3% of the total land area. Our estimates from the validation data indicate that riparian zones occupy 3.1% of the study area. All but one of the methods we tested overestimated the extent of the riparian zone of the study area by over 300%, and the TDS 1X method estimated that 5.1% of the study area is a riparian zone (Table 4).

Riparian zones are currently threatened by multiple stressors, and will likely face further stresses associated with climate change and additional water withdrawals due to population growth (Theobald *et al.*, 2010). Consequently, it is imperative to understand the current location and extent of riparian zones. It is also valuable to understand what processes are controlling riparian zones, as a means to understand both current conditions and vulnerabilities to land use and climate change, as well as to project how various management options might protect or restore these ecosystems. This research is a first step toward understanding how improved maps of detailed riparian zones can be generated, with the intent of informing decision making in forestry, grazing, conservation, and resource management. Until detailed riparian maps from updated very-high resolution imagery and terrain data can be created for large ecoregional extents, our procedure can be used to identify the best method(s) to map riparian zones that produce reasonable, credible, and consistent estimates. We recommend caution using some commonly employed methods, including uniform buffering and elevation above stream, because these methods require subjective estimations that are scale dependent and likely will perform poorly for an entire watershed or for watersheds with different-sized rivers. Methods that incorporate detailed geomorphological patterns and dominant hydrological processes can improve estimates of riparian zones and can be used to inform scientists and managers of riparian location and of potential threats to riparian zones.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Full results of complete analysis for this article.

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