GIS MODELING OF RIPARIAN ZONES UTILIZING DIGITAL ELEVATION MODELS AND FLOOD HEIGHT DATA: AN INTELLIGENT APPROACH

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ABSTRACT

Riparian ecotones are unique, diverse networks of vegetation and soils in close proximity to freshwater streams, rivers and lakes. These ecotones are linked to the watercourse network via flooding and intercepting upland runoff. Vegetation communities along stream banks often delineate riparian boundaries. However, geology, soil chemistry, and hydrologic changes need to be considered as well. Previous approaches to riparian boundary delineation utilized fixed width buffers, but this methodology has proven to be inadequate as there are two factors that all riparian ecotones are dependent on: the watercourse and its associated floodplain. Using a fixed width riparian buffer only takes the watercourse into consideration. Past research has determined the 50-year floodplain is the optimal hydrologic descriptor of a riparian ecotone. By hydrologically defining a riparian ecotone to occur at the 50-year flood height and incorporating digital elevation data, the spatial modeling capabilities of GIS are utilized to map riparian zones accurately and efficiently. The objective of this study is to develop a GIS based model to delineate a variable-width riparian boundary that characterizes a stream's ecotone. This approach offers advantages over other previously used methods of riparian ecotone mapping by better characterizing the watercourse and its associated floodplain. The riparian zones delineated using 10 and 30 meter DEMs, along with stream course information from the National Hydrological Data were found to be statistically significant ($p < 0.001$). This approach to delineating riparian areas is easily implemented and customized within ArcMap.

INTRODUCTION

(Verry and others, 2004). The ecotone is linked to the watercourse network via flooding and intercepting upland runoff (Mitsch and others , 2000). It is important to note that riparian ecotones are typically defined by local conditions but respond to climatic and geological processes on continental scales via interconnecting watersheds. Hence any riparian zone delineation model must be scale independent. Vegetation communities along stream banks often delineate riparian boundaries. However, geology, soil chemistry, hydrologic changes and animal habitats also need to be considered (Naiman and McClain, 2005).

Previous approaches to riparian boundary delineation have utilized fixed width buffers, but this methodology has proven to be inadequate. Palik and others (2000) determined that fixed-width buffers do not emulate natural riparian corridors because they have no functional relationship to the naturally varying watercourse. Suggested buffer width guidelines from the Minnesota Forest Resources Council were evaluated by Skally and Sagor (2001) in a single-case pilot study. Their report described the difficulty in using the designated guidelines of fixed-width buffers because of many watercourse variables, such as site condition, water body type and forest management history need to be incorporated into the delineation process. Their research also concluded that the riparian ecotone boundary was on average 2.5 times farther from the stream than the suggested buffer width within the selected study area. Hanowski and others (2000) studied the effects of riparian buffers on breeding bird populations and used fixed-width buffers of 28.5 m and 57 m based on the spatial resolution of the Landsat TM sensor. The method was easy to use for the study, but did little to explain the relationship of buffer widths to the water bodies. Developing an all-encompassing definition for riparian ecotones, because of their high variability, is challenging. However, there are two factors that all riparian ecotones are dependent on: the watercourse and its associated floodplain. Using a fixed width riparian buffer only takes the watercourse into consideration and ignores the critical surrounding geomorphology.

Research by Ilhardt and others (2000) determined the 50-year floodplain was the optimal hydrologic descriptor of a riparian ecotone. This flood recurrence interval was selected because the 50-year flood elevation usually intersects the first terrace or other up sloping surface and supports the same microclimate and geomorphology as the stream channel. The 50-year flood plain also coincides with measurements that quantify a valley to its streams via two measurements: 1) the entrenchment ratio (valley width at the first terrace or up slope to the stream width at full bank), and 2) the belt width ratio visible on aerial photos or maps (Ilhardt and others, 2000).

Lakes are not as impacted by floodwaters compared to fast moving watercourses, but typically have a defined high water mark. This presents an issue of how to define a riparian ecotone boundary around standing, open water bodies. Within 100 ft of lakes, forest cover contributed 60-80% of its influencing habitat function, such as shade, woody debris recruitment, bank stability and litter fall as noted by Ilhardt and others (2000).

By hydrologically defining a riparian ecotone to occur at the 50-year flood height and incorporating digital elevation data, the spatial modeling capabilities of GIS can be utilized to map riparian zones accurately and efficiently. The objective of this study is to develop a GIS based model to delineate a variable-width riparian boundary that characterizes a stream's ecotone.

METHODS

Data Inputs and Study Areas

The study utilized ArcGIS Desktop 9.1 produced by ESRI, Inc. (ESRI,1999-2005) for all data manipulation, management and spatial analyses. Inputs into the model were setup as geodatabases. The riparian zone delineation model was developed using the coding language Python and is based on a procedure discussed by Aunan and others (2005). The model creates riparian ecotone boundaries based on stream and lake locations, digital elevation data and the 50-year flood height variable associated with each stream segments order. Specific data inputs and their sources are listed in Table 1.

The National Hydrography Dataset (NHD) was used in this study and is a feature-based dataset organized as ArcMap geodatabases. The data provides continuous, national coverage of stream reaches and water drainage systems and is overseen by the United States Geological Survey (USGS). Currently there is nation wide coverage at 1:100,000 with high-resolution coverage being developed at 1:24,000 and 1:12,000. For this study 1:24,000 data was used where available with data gaps filled in with information from the state supported GIS systems. The NHD is comprised of water-related entities such as natural river courses, lakes, ditches, industrial discharges, drinking water supplies, etc. Each entity has an assigned address that establishes its location and connections to other entities in the drainage network (USGS, 2005).

Table 1. Initial model inputs and sources

Input Data	Sources
Streams	USGS National Hydrography Dataset (NHD) Michigan Center for Geographic Information Minnesota DNR Data Deli
Lakes	Michigan Center for Geographic Information Minnesota DNR Data Deli
10 meter Digital Elevation Model	GIS Data Depot
30 meter Digital Elevation Model	USGS, The National Map

The USGS Digital Elevation Models (DEMs) are raster based elevation information sampled at regularly spaced ground locations and registered to the UTM projected coordinate system. DEMs with spatial resolutions of 10 and 30 meters were used for this study. The 10 meter DEM data were downloaded in a 7.5' quadrangle format from the GIS Data Depot (www.gisdatadepot.com) and mosaiced. The 30 meter DEMs were downloaded from The National Maps seamless dataset (http://nationalmap.gov/).

Flood height data was downloaded in a tabular format from the USGS Real-Time Water data site (http://waterdata.usgs.gov/nwis/rt). The USGS Real-Time water data collection system is composed of monitoring sites that record data at 15-60 minute intervals . The information is either stored onsite or transmitted to a USGS office between 1 and 4 hour increments. The data is transmitted via satellite, telephone, or radio, and is available for viewing within minutes of arrival. During critical events, recording and transmission times are more frequent.

The study sites are comprised of multiple watersheds in 3 locations: northeast Minnesota, the central Upper Peninsula (UP) of Michigan and the eastern Lower Peninsula (LP) of Michigan. These locations were selected based on 10m DEM data availability, which is more widely available in areas of federally owned lands.

Model Development

The first step in delineating the riparian ecotones is calculating flood heights to determine the 50-year flood event for all possible stream locations within each of the study areas. The heights are calculated from USGS stream measurements of annual average stream flow data which has a minimum of 30 years of data, a measured flow rate and a defined stream width at locations within the study areas. The annual average flow rate measurements are organized by year and sorted from fastest to slowest for each stream gauge location. After sorting, the annual flow rate measurements are ordinally ranked. The ranking is assigned so that the fastest flow rate receives a value of 1. To calculate the recurrence interval, the rank number is divided by the number of measurements. The flow rate is then plotted against the logarithmic recurrence interval to develop a flood occurrence regression (Bedient and Huber, 2002). Using the developed regression equation, 1-year (to provide a baseline) and 50-year flow rates are determined. Flow rate, velocity and channel width are used to calculate flood heights at each location for 1-year and 50-year events.

This flow rate plus velocity and channel width are used to determine the flood heights. Specifically, the flood heights are calculated by: 1) regressing the cross-sectional area vs. flow rate, 2) regressing the width vs. cross-sectional area, and 3) dividing stream flood height calculations by the stream width. An R-squared value of 0.85 or higher was noted for all calculations. The flood height calculation results ranged between 0.3 and 1.75 meters. As we wanted to use the same flood height for all of the study sites, an average flood height of 1 meter is utilized in the model. However, this height could be varied based on stream order or other information as the model has been written to utilize a varying flood height.

The modeling language Python was used to develop the GIS riparian delineation model. The model is composed of five modules to facilitate customization (Figure 1). Inputs must be in ArcMap geodatabase format and the user must have access to ArcMap's spatial analyst extension. The first module edits the streams and lakes feature classes for input (Figure 1, Module 1). The stream length is dissolved by reach code to remove extraneous nodes. Next, stream segments delineated within a lake or other open water body are erased as mapping of a riparian zone along these segments would be erroneous. Lastly, a 30.48 m (100 ft) buffer is computed around all lakes and other open water bodies based on the recommendations of Ilhardt and others (2000).

The second module calculates the x, y coordinates for the starting point of each transect (Figure 1, Module 2). Input parameters include the DEM's spatial resolution and a pixel ratio, expressed as a percentage of pixel size. The distance between sample points is set to a distance of 75% of the pixel's spatial resolution along each stream segment (Figure 2). This was done to minimize the influence of the DEM's spatial resolution on the distribution of the sample points along the stream course, but not assume a horizontal accuracy better than the data accuracy standard. Point spacing is calculated using Euclidean distance from one point to the next along the stream segment. The stream segments are treated as continuous features to avoid sampling gaps and maintain a constant spacing distance. Upon completion of the stream sample point calculations, the program retrieves the elevation for each sample point from the DEM and writes the value to the attribute table.

The third module (Figure 2, Module 3) produces transects perpendicular to the direction of the stream channel at each sample point (Figure 2). At the origin and termination of streams, transects are created in a circle around the nodes to add more sample points. This ensures a more realistic mapping of the riparian area as opposed to an abrupt

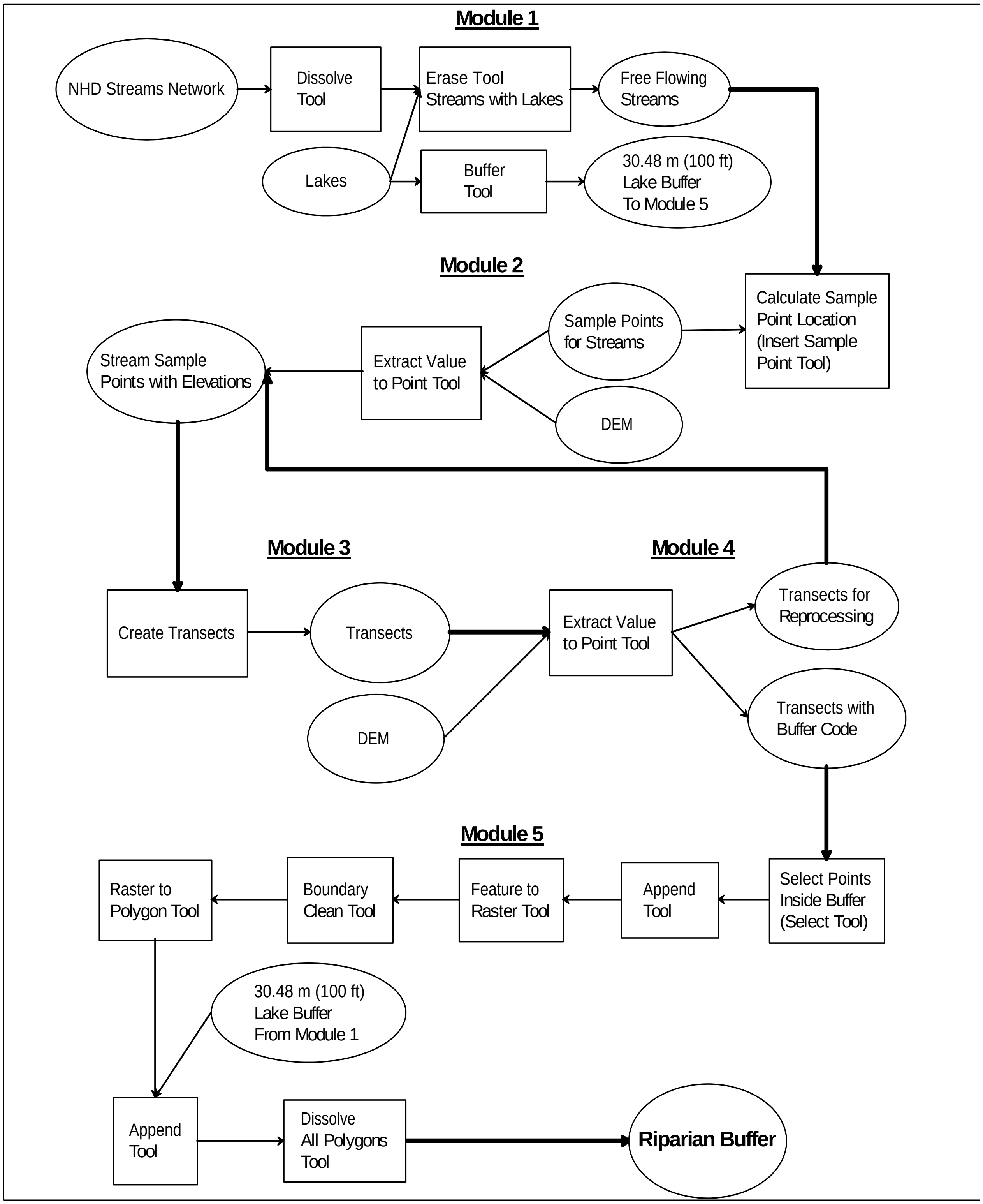

Figure 1. Flowchart of the riparian zone model. The model is composed of 5 modules to facilitate editing and customization.

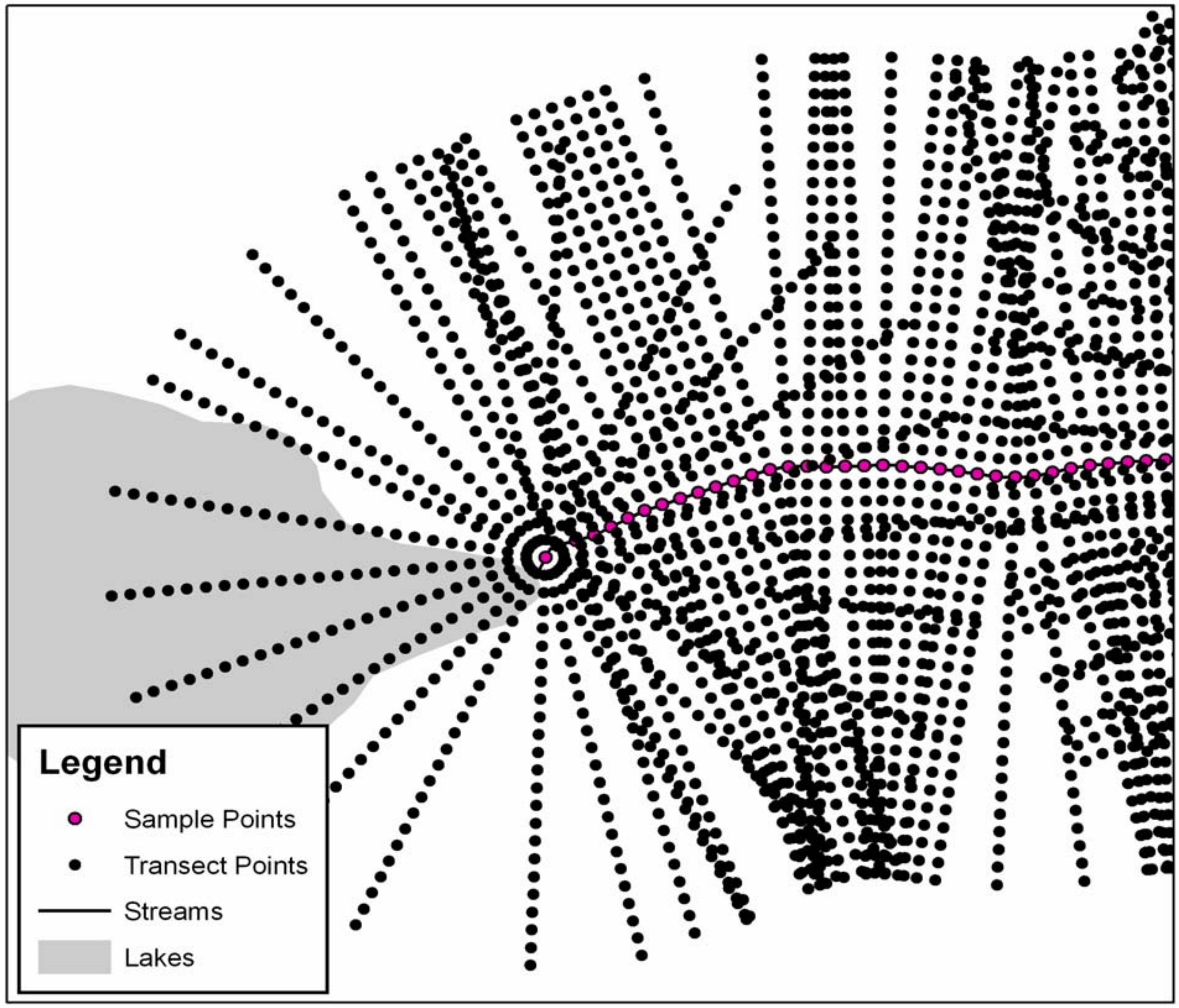

Figure 2. Sample points (shown in magenta) generated by Module 2 of the model. The black dots are the transect points generated in Module 3.

cutoff point which is a data analyses artifact. To optimize processing time, a maximum transect length was imposed. However, this may be changed by the user. If the transect did not find an elevation change within the maximum specified transect length, it was flagged for reprocessing without a length limitation.

Based on elevation change, module 4 determines if the transect points are part of the riparian buffer (Figure 2, Module 4). If the elevation change is 1 meter (the average calculated flood height) or less between the transect's starting point and the point in question, the point is included in the riparian zone (inbuffer = 1). If the elevation change is greater than a meter, the point is considered to be outside the riparian zone (inbuffer = 2). The last "in" point is flagged (inbuffer = 3) to establish the location of the riparian boundary (Figure 3). If an elevation change does not occur, the transect is flagged and the original transect point coordinates are written to an output file for reprocessing with modules 3 and 4. The reprocessing elongates the original transect until the required elevation change is met. The output file (transects with buffer code) contains all of the sample points from all transects (Figure 3).

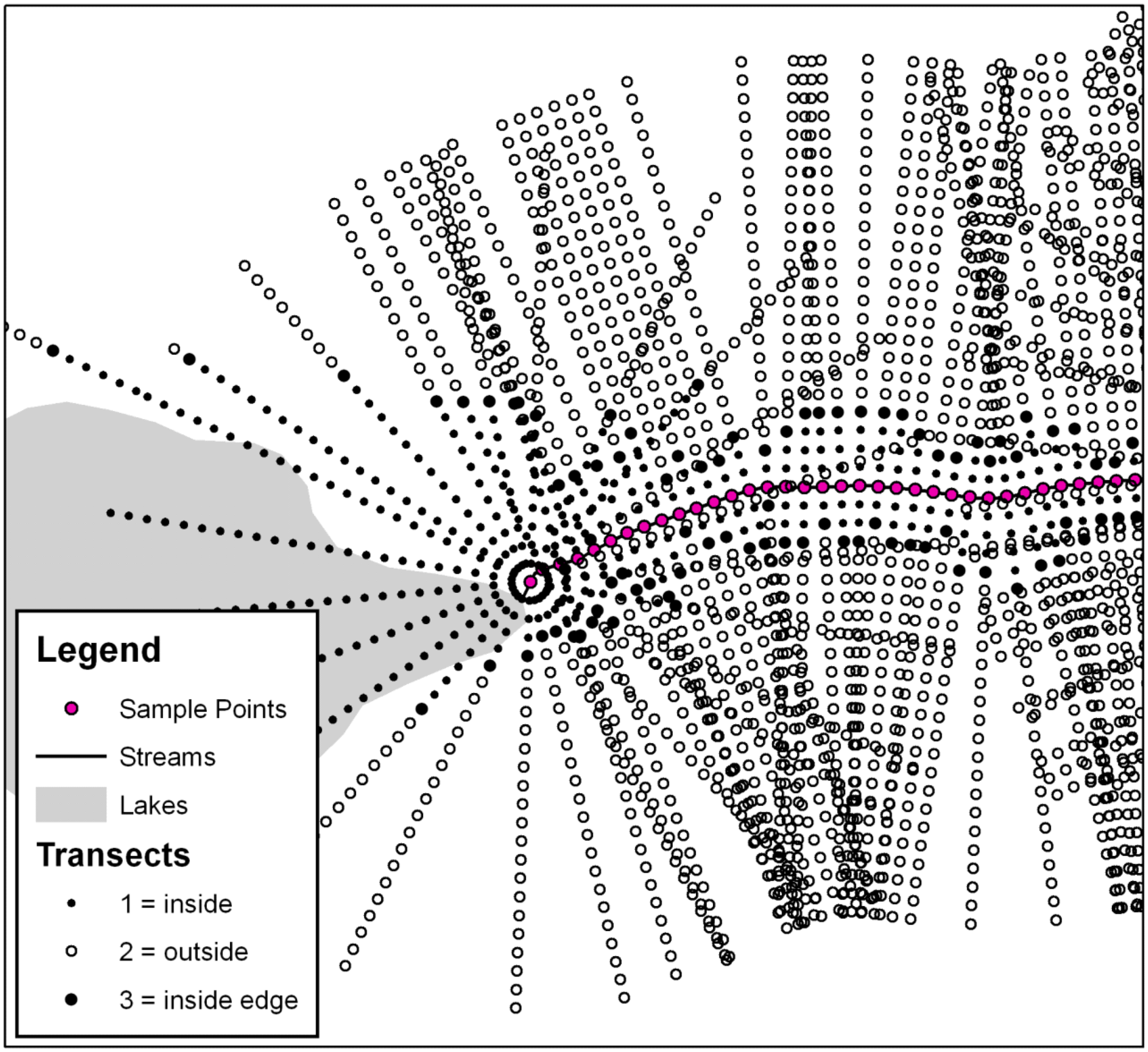

Figure 3. Boundary of the riparian area, shown as larger solid black points calculated in module 4 of the model. The magenta dots are the original sample points from which the transects originate and the hollow dots are transect points outside of the study area.

The riparian zone layer including all the buffer areas around streams and lakes is calculated in Module 5 (Figure 2, Module 5). The program reads the attribute table and selects only the points inside the buffer, then adds the sample points along the streams to the file to prevent gaps in the center of the buffer. These points are rasterized with a spatial resolution equal to the DEM (Figure 4). The raster is cleaned using the Boundary Clean Tool with a one-way sort. One-way sorting enables the sample points on the stream segment to remain in the buffer after processing. Otherwise, if the buffer is only one pixel wide, it would be lost in a two-way sort. Once the raster is cleaned, it is converted to a polygon. The final riparian buffer consists of the stream riparian zone (polygon) merged with the 100 foot lake buffer created in module 1. The merged buffer is dissolved with the "all" option to create a continuous buffer around adjacent hydrologic features.

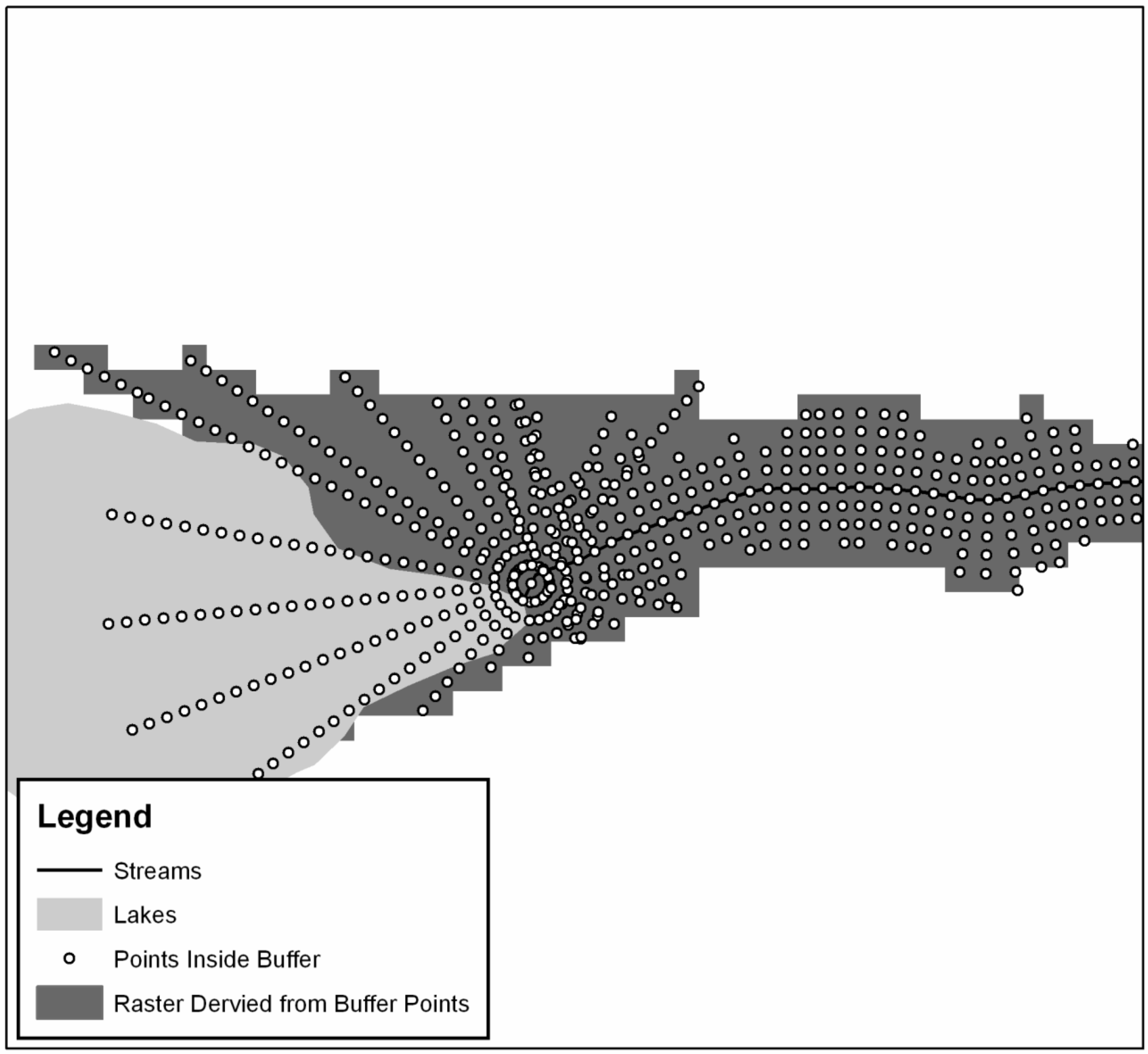

Figure 4. Rasterization of points within the riparian zone. The spatial resolution is equal to that of the DEM elevations used as input into the model. The raster is cleaned using the Boundary Clean Tool with a one-way sort.

Statistical Assessment

Riparian areas were calculated using both the 10 meter and 30 meter DEMs. The riparin zone area for each of the 3 study sites, excluding lake surface area, is calculated and placed in an attribute table. Additional fields in this table include a unique ID for each watershed and the DEM spatial resolution. This information is input into the program R for Statistical Computing (R, 2006) and analyzed to ascertain if there is a statistically significant difference between the riparian areas delineated with the 10 meter versus the 30 meter DEMs. The analysis is done as a repeated-measures analysis of variance. The delineated riparian area is the response, the DEM spatial resolution is the treatment effect. The watersheds are the subject effect and are assumed random. The data are tested using linear mixed-effects techniques in R. Normality is assessed using normal probability plots and assumptions of within-subject variance homogeneity and additivity.

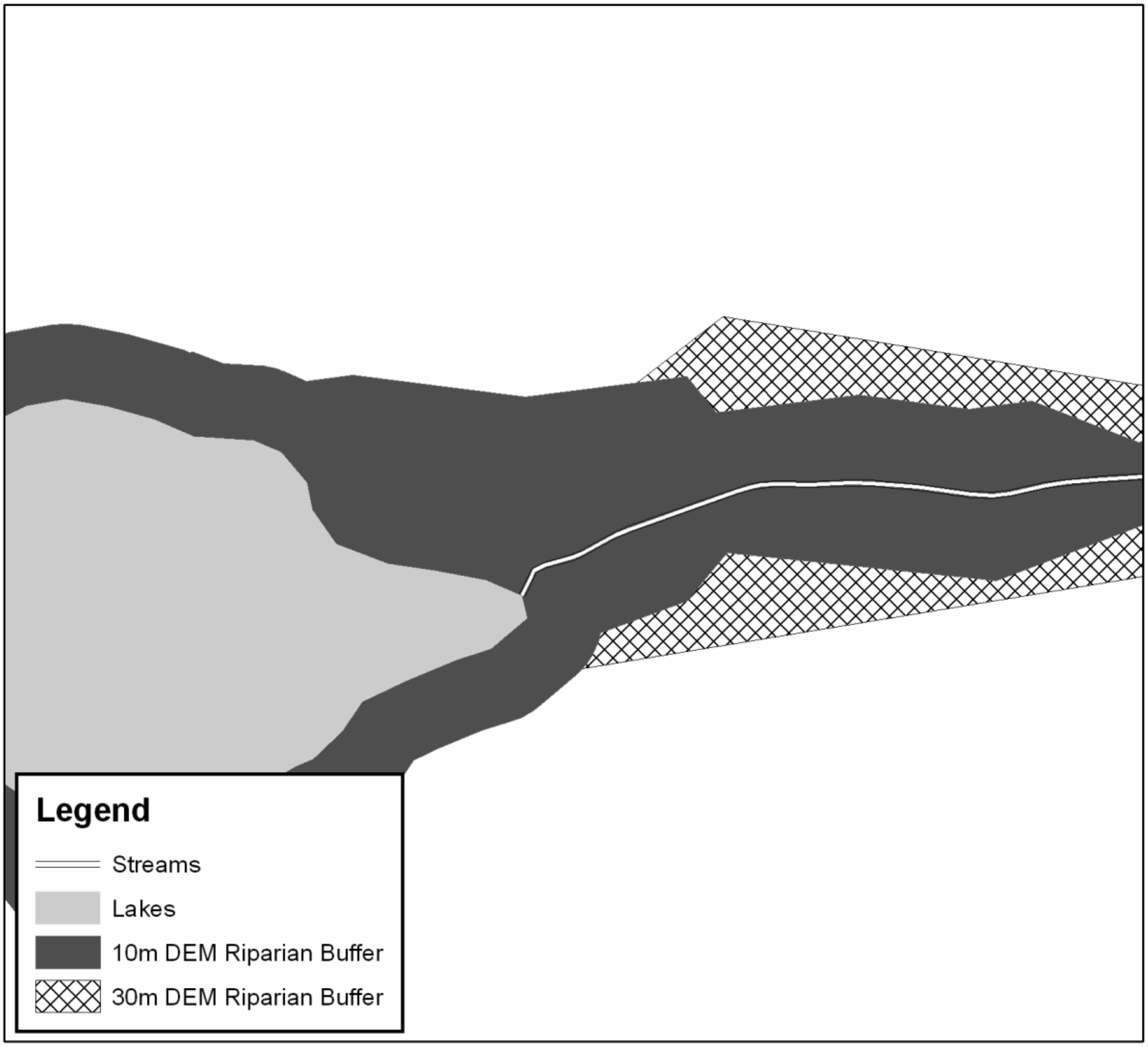

Figure 5. A representative sample contrasting the spatial extent of the riparian zones calculated from the 10 and 30 meter DEMS.

Fixed Width Buffers

Fixed width buffers of 30 and 60 meters were generated to compare to the results from the model. These widths were chosen based on the recommendations by Palik and others (2004), and permits a direct comparison to their findings.

RESULTS AND DISCUSSION

The variable-width riparian areas calculated from the 10 meter and 30 meter DEMs produce very different area totals and spatial extents (Figure 5). For all of the watersheds in the 3 study areas, the riparian areas derived from the 30 meter DEM are larger than those calculated using the 10 meter data (Table 2). Based on a qualitative

Table 2. Area summaries for the 3 study sites using the variable-width buffer model and fixed width buffers of 30 and 60 meters.

		Study Sites	Minnesota	Upper Peninsula Michigan	Lower Peninsula Michigan
		Total Watershed Area (Ha)	168,642	92,009	59,274
Variable-width Buffer	10m DEM	Buffer Area (Ha)	16,359	17,014	6,130
		% of Watershed	9.70%	18.49%	10.34%
	30m DEM	Buffer Area (Ha)	20,454	28,503	10,063
		% of Watershed	12.13%	30.98%	16.98%
Fixed-width Buffer	30m Buffer	Buffer Area (Ha)	4,279	3,563	2,880
		% of Watershed	2.54%	3.87%	4.86%
	60m Buffer	Buffer Area (Ha)	8,726	6,896	5,704
		% of Watershed	5.17%	7.49%	9.62%

assessment of key locations in the 3 study areas, the riparian buffers generated with the 30 meter DEM are located beyond the boundary of the actual riparian area. This result was anticipated given that the spatial resolution of the 30 meter DEM is 9X larger than the 10 meter. But what is more important is the fact that we have effectively shown the inadequacies of the 30 meter DEM to accurately map elevation changes in a landscape heavily impacted by glaciation which has resulted in significant elevation differences over short distances (in this study, less than 30 meters). Note we plan on conducting a quantitative assessment to validate our initial conclusions. However, the statistical assessment does confirm that the riparian areas produced from 10 meter and from 30 meter DEMs are significantly different ($p < 0.001$).

The study also supports the conclusions of Palik and others (2004) that riparian areas determined via fixed width buffers do not begin to accurately delineate riparian areas since they do not incorporate landscape features such as changes in elevation. The 30 and 60 meter fixed-width buffers delineated around all streams of the 3 study areas consistently underestimated the total riparian area, and also did an inadequate job of accurately delineating the spatial location of the boundary. Buffers generated in this manner do not protect enough of the riparian ecotone to maintain natural corridors. The variable-width buffer characterizes the stream better by considering the landform change around the stream and protecting that area which highly influences the stream. Once again this initial assessment is qualitative with plans to conduct a quantitative assessment.

CONCLUSIONS

The task of delineating a accurate variable-width riparian zone utilizing 50 year flood heights and digital elevation data was successful. The modeling is computational intensive, but can be accomplished within a reasonable amount of time. It is important to remember that the quality and accuracy of the ouput is dependent on the quality of the inputs. Factors to consider include age and quality of stream digitization, scale of the vector based stream data and DEM spatial resolution. The ease of using the NHD as it is in geodatabase format cannot be discounted, and the quality of the data is consistent over large geographic areas.

Analysis of 3 representative study sites in the Upper Midwest illustrates that a model can be designed to accurately and within a reasonable amount of computing time, delineate riparian areas based on elevation and hydrographic data. This approach offers advantages over other previously used methods of riparian zone mapping by better characterizing the watercourse.

As land development continues and water resources become scarcer, it is important these areas are protected and maintained for future generations. This method of delineating riparian areas is easily implemented by any GIS user. With the addition of higher resolution DEMs and additonal hydrologic information, even more detailed delineations could be accomplished.

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