River Restoration in Milwaukee, WI:
Geomorphic Characterization and Classification of
Stream Segments in the Kinnickinnic River Basin

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Abstract
This GIS analysis examines the geomorphic and land cover characteristics of the Kinnickinnic River Basin in Milwaukee County, Wisconsin to develop a stream segment classification methodology. This classification scheme will provide a framework for targeted river restoration. The final classification of stream segments in the Kinnickinnic River Basin was summarized exclusively according to stream order and slope, while other geomorphic characteristics served to inform this classification method. The classification of stream segments by stream order and slope produces a framework for focused restoration with optimal classes to enhance restoration efforts.

Introduction
River restoration is a broad term that encompasses an array of environmental management activities, ranging from replanting native vegetation to dam removal and river channel redesign (Bernhardt et al., 2007). According to Bernhardt et al. (2005), river restoration may result in, “species recovery, improved inland and coastal water quality, and new areas for wildlife habitat and recreational activities.” Restoration efforts vary according to the site specific characteristics of each stream segment. This project will advise the restoration of the Kinnickinnic River Basin in Milwaukee, Wisconsin and other watersheds by developing a standard GIS methodology for stream segment characterization and classification. The methods will serve as a template to apply to other river restoration efforts in glaciated regions of North America. This project was developed in association with the United States Geological Survey (USGS) Wisconsin Water Science Center. It contributes to the effort to collect, analyze, and interpret water data to solve practical water problems (USGS, 2016). Specifically, this GIS analysis supports fluvial geomorphology research that aims to understand the geomorphic settings that shape streams and riparian zones.

The purpose of this project is to support river restoration by leveraging GIS to determine the characteristics of stream segments and group segments in optimal classes that accurately reflect geomorphology and site setting. The extent of this project includes: 1) gathering a range of data layers of the geographic area of interest, 2) describing and examining the data in relation to stream segments, 3) interpreting the most suitable characteristics for stream segment classification, and 4) development of a classification scheme for the Kinnickinnic River Basin.
Appropriate scale is essential to GIS analysis. A standard spatial hierarchy is used to study geomorphic processes in the hydrologic landscape. Fitzpatrick et al. (2006) notes, “three common spatial scales used to identify geomorphic characteristics and processes are a watershed or landscape scale, a segment scale, and a reach or channel scale.” This project aims to characterize a watershed by considering stream attributes on the segment scale. The segment scale considers a stream network as sections “bounded by confluences or physical or chemical discontinuities, such as major landforms, changes in slope, or point-source discharges” (Fitzpatrick et al., 2006). Reach represents the finest scale, defined as “a length of stream chosen to illustrate a set of uniform channel features” (Fitzpatrick et al., 2006). The segment scale was chosen for this project to capture variation while maintaining a manageable and meaningful number of stream segment units.

**Study Area**

The Kinnickinnic River is the shortest of three main rivers in Milwaukee, WI. It lies in the southern area of the city, running through urbanized residential and industrial neighborhoods before flowing into the Milwaukee Estuary and Lake Michigan. The relatively small size of the Kinnickinnic River Basin is ideal for a pilot project to develop a GIS methodology. The streams are affected by myriad geological and urbanization processes, resulting in high variability despite the relatively small geographic range of the watershed. River restoration in urban areas like the Kinnickinnic River Basin is especially useful for improving community safety during floods, increasing aquatic and riparian habitat and habitat connectivity, increasing species diversity, enhancing water quality, and improving aesthetics.

The climate of Milwaukee County is classified as humid continental, characterized by large seasonal temperature differences, from cold winters to hot, humid summers. Glaciation played a major role in forming the geology of Milwaukee County. This resulted in a range of glacial geological phenomena, which shape stream geomorphology in addition to affecting land cover and land use patterns (Milwaukee County, 2006).

**Methods**

The methods used to characterize and classify stream segments in the Kinnickinnic River Basin involved conceptualization and implementation modeling, data collection, GIS operations and analysis, the development of preliminary and final classifications, and cartographic presentation.
Conceptualization

Conceptual modeling is essential due to the complexity of the natural and cultural processes that shape Kinnickinnic River Basin hydrology. A conceptual model helps identify and describe the key components in a system and determine how they are related (Swannack et al., 2012). In addition, it provides a basis to implement an analysis. A standard GIS conceptualization framework was used for this project (fig. 5). The key concept of stream segment classification was divided into variables. A measurement value was applied to the variables to form operationalized variables. Finally, data layers were identified to guide data acquisition and derive the variables. The conceptualization process helped identify which variables are important to the project goal and how they are connected. It also served as a guide to the implementation process.

Key Concept

In a GIS methodology, the key concept is the main goal of the research question. For this project, stream segment classification based on geomorphic characterization was the objective.

Variables

A classification unit was required to accomplish the objective of this project. The watershed was divided into preliminary stream segments defined by existing Wisconsin Department of Natural Resources (DNR) hydrology data. The data was edited to improve accuracy based on consultation with the USGS. Stream lines were divided into stream segments by stream junctions, resulting in 45 stream segments (fig. 10-12).

Operationalization

The variables were separated into two main categories: stream and riparian (fig.1). Stream variables define characteristics of the stream itself, while riparian variables represent characteristics of an area 30 meters surrounding the stream on each side. Stream variables include stream order, slope, stream power index (SPI), and sinuosity. Riparian variables consist of Pleistocene geology, soil, presettlement vegetation, wetlands, and land use. Stream and riparian variables are operationalized in different ways. Stream variables are represented with a simple numerical value, while riparian variables are given as a percent coverage of the 30 meter buffer zone around each stream segment.

After applying the analysis, the values for each variable were summarized and classified based on frequency distribution and consultation with the USGS. The preliminary results
portrayed a detailed representation of the stream segment characteristics, which was used to select the optimal variables for stream segment classification.

**Implementation**

The implementation process was guided by the conceptual model developed during the conceptualization process. The implementation model illustrates the GIS methodology from input data layers to the final output. It guides the user through GIS operations to derive deliverables from the initial data layers (fig. 6).

**Data Collection**

Geographic data layers were assembled from an array of organizations and government agencies. Most were available for download on agency websites, although some required reaching out directly to organization staff (fig. 4). Data was compiled and loaded into GIS software for editing and analysis (Esri, Inc, 2016).

**GIS Procedures**

After loading data into GIS software for analysis, data layers were projected to the same coordinate system. The next step was to define the preliminary stream segments. Minor edits were applied to *DNR hydro flowlines and junctions* to ensure they accurately represented real-world conditions. The *DNR hydro flowlines* were segmented by the *DNR hydro stream junctions* to create 45 stream segments. A unique ID number was assigned to each stream segment, 1-45. After defining the preliminary stream segments, the values for the stream and riparian variables were calculated for each segment.

All riparian variables were downloaded in vector format, with the exception of the Milwaukee County Soil Map. This was digitized and converted to vector data to simplify calculations. For the riparian variables, a 30 meter buffer was applied to the stream segments using the buffer tool. The “no dissolve” option was selected so the buffered stream segments maintained their identity. The intersect tool was applied to the buffered stream segments layer and each riparian variable. The intersection of the buffered stream segments and the riparian variables allowed for the calculation of percent coverage. Percent coverage was calculated with the zonal statistics tool, resulting in values that represent the composition of the stream segments’ riparian zone. These values were added to a database to simplify data storage and access.
In contrast to the riparian variables, each stream variable was calculated using a different method. Length was calculated automatically for each segment using GIS software and stored in the attribute table of the stream segment layer. Visual inspection was used to assign stream order to each stream segment according to Strahler (1957).

The LiDar 5ft Digital Elevation Model (DEM) layer formed the basis for the segment slope, average slope, and stream power index (SPI) calculations. Prior to analyses, ArcHydro tools were used to “burn” the stream flowlines into the LiDar 5ft DEM to correct for bridge elevations over the stream segments. The calculation of segment slope values involved the use both raster and vector data. First, a new point feature class was created. Two custom fields were included. One corresponded to the segment ID of the segment, and the other denoted whether the point was the start or the end point of the segment. Start and endpoints were manually created using visual inspection based on the LiDar 5ft DEM layer and the stream segment layer. During point selection, segment ID and start or end point information was entered. After start and end were established for each segment, the extract values to points tool was used to extract the LiDar 5ft DEM elevation value for each point. Percent slope for each segment was calculated by subtracting the endpoint from the starting point (rise), dividing that value by the length of the stream (run), and multiplying by 100 (fig. 1).

\[
\text{Percent of Slope} = \frac{\text{Rise}}{\text{Run}} \times 100
\]

Figure 1. Slope Equation

Average slope was also calculated. For this project, average slope is defined as the average value of the slope values that compose a segment stream bed. Using the slope tool, a slope raster was derived from the LiDar 5ft DEM raster and expressed as percent rise for each pixel. The DNR hydro flowlines layer was converted to a raster and used to extract the pixel values of the slope layer that aligned with each segment stream bed. Using the zonal statistics tool, the average slope for the segment was calculated. After consultation with the USGS it was decided that segment slope was the most accurate characterization of slope for this project. However, the average slope method can be modified and applied to future analyses to characterize stream bank slope.
The Stream Power Index (SPI) is a measure of the water flowing out of a stream, or stream segment in the context of this project. It is derived by multiplying slope value and flow accumulation using raster math (Danielson, 2013). The calculation of the SPI involved a series of preliminary steps. As with average slope, the LiDar 5ft DEM layer was converted using the slope tool to create a slope raster layer expressed as percent rise.

Next, a flow accumulation raster was created according to methods described in Tarboton (2012). First a flowline raster was created from the vector flowlines feature. This was used to recondition the LiDar 5ft DEM using the raster calculator to run a map algebra expression representing the AGREE method (Tarboton 2012). A new slope raster was calculated from the reconditioned DEM. Next, the fill function in the hydrology toolset was applied to the reconditioned DEM. This step served to remove sinks in the raster to remove small imperfections in the data, so the flow accumulation will be represented continuously (Tarboton 2012). A flow direction raster was created next using the flow direction tool in the hydrology toolset.

Finally, the flow accumulation tool was used to calculate a flow accumulation raster using the flow direction raster as an input. Each cell on the output flow accumulation raster represents accumulated flow (Danielson 2013). Typically SPI is calculated using by applying raster math to the reconditioned slope raster and the flow accumulation raster. However, the flow accumulation raster captured ancillary flowlines not included in the analysis. To address this issue, a new point feature class was created to extract the flow accumulation values at the end points of each stream segment. A point feature class was also used to extract the corresponding slope values at the end points of the stream segments from the reconditioned DEM. After applying the extract values to points tool to each layer, the resulting data were exported to the database. Here, an SPI equation was applied to the data, resulting in the SPI index value (fig. 2).

\[
SPI = \ln(\text{flow accumulation}) \times \frac{\text{slope}}{100}
\]

*Figure 2. SPI Equation. Danielson, 2013.*

Sinuosity is a measure of the deviation a line from the shortest path. This is calculated by dividing total length (stream length) by the shortest possible path (valley length) (Esri, Inc, 2011). A sinuosity tool was applied to determine the sinuosity of each stream segment (Esri, Inc,
The code in the tool was modified to accurately reflect the standard sinuosity equation (fig. 3).

\[
\text{Sinuosity} = \frac{\text{Stream Length}}{\text{Valley Length}}
\]

\textbf{Figure 3. Sinuosity Equation}

\textbf{Stream Segment Classification}

The results of the above calculations and analyses were compiled in a database. First, the variables were classified by considering the frequency distribution of each variable. Each of the riparian variables was classified manually into three groups based on percent coverage: Dominant (1 category) \(>50\%\), Mix (2+ categories) \(10\%-50\%\), and Not Included \(<10\%\). The stream variables were classified independently. Stream order was concatenated with downstream stream order. Slope values were separated into three ranges: \(<0.3, 0.3-1, >1-2\), according to Fitzpatrick et al. (2006). SPI was reclassified using the reclassify tool to a range from 0-10. It was further classified into quartiles because it represents ordinal data. Sinuosity was classified into three categories: Low \(<1.2\), Moderate \((1.2-1.5)\), and High \(>1.5\) based on classification methods according to Rosgen (1994) and USGS consultation.

\textbf{Results and Discussion}

The results of the above preliminary classification were summarized and presented to the USGS. A final classification scheme was by drawing on the expertise and understanding the needs of the USGS. It represents the optimal grouping of stream segments based on the analysis of the Kinnickinnic River Basin. It includes five classes based on stream order and slope. It was determined that there was not a significant difference in first and second order streams in the Kinnickinnic River Basin, so these categories were merged for the final classification. The slope groups remained the same as in the preliminary classification. The final classifications are illustrated on the Stream Order and Slope Classification map (fig. 10). Pleistocene geology is included as a base layer to provide additional detail and illustrate how Pleistocene geology plays a significant role in stream segment geomorphology. The distribution of the number of stream segments among slope, stream order, and Pleistocene geology categories was summarized to inform the final classification scheme (fig. 8).
The GIS Analysis indicated that the variation of some variables was highly distributed across stream segments, while other variables showed distinct grouping among the segments (fig. 9). The collection and analysis of data produced a comprehensive representation of the stream segments in the study area. This representation was used to explore connections among the variables and groupings of the stream segments. Two of preliminary groupings were prepared and displayed to provide illustrative reference for the final classification.

The first, stream order and Pleistocene geology, resulted in eleven classes (fig. 11). The Pleistocene geology of the region contains three distinct features. Fine glacial till (FT), fine glacial till end moraine (FTE), and lacustrine clay and silt (LCS). These were merged with concatenated stream order to create eleven classes. This grouping of characteristics highlights the differences associated with stream order, including size and flow rate, while also considering geology. The second preliminary grouping, slope and Pleistocene geology, resulted in seven classes (fig. 12). In addition to characterizing streams based on geology, this classification also considers slope. Slope was merged with Pleistocene geology, resulting in classes that reflect the interactions of slope and geology on stream segments.

The final grouping of stream segments results in five classes based on stream order and slope (fig. 10). These variables were selected based on consultation with the USGS as well as guidance from previous studies. Fitzpatrick (2006) indicates that stream order and slope are the most useful, and the results revealed a similar pattern in this study. The length of stream segments among the five final classes is approximately evenly distributed, with the exception of the 3rd Order, 0.3-1.0 class (fig. 7). First and second order streams were merged due to high similarity between the first and second order streams in the Kinnickinnic River Basin. This is likely to be applicable in similar glacial watersheds in North America, but the specifics of each study area must be considered.

While only two variables ultimately made up the final classification scheme, analyzing and assessing the other variables was essential to developing an informed representation of this watershed. It provides stream segment specific data for future analyses. It also provides a method for narrowing down the variables included in a classification scheme based on the needs of the specific project. The preliminary classifications and the final classification will prove to be valuable tools for future projects.
Future research could incorporate a cost analysis model to the stream categories to identify and prioritize which areas would it would be most financially feasible to restore using a scoring system. A scoring system to determine restoration need based on water quality data could also be studied.

Additional studies could include reach scale characterization to a classification scheme, within a stream segment or a watershed. This would be helpful to further classify priority stream segments to identify areas that require different restoration considerations. According to Fitzpatrick (2006), “reach scale geomorphic conditions and processes can be used to infer conditions and processes for a given segment.”

**Conclusion**

This research project provides a GIS template for stream segment characterization. The methods will guide the restoration of the Kinnickinnic River Basin in Milwaukee, Wisconsin and other watersheds in glaciated regions of North America. This analysis demonstrated that among many different data layers stream order, slope, and Pleistocene geology are most significant in determining effective stream groupings. This project has shown that the first step in similar analyses is most likely determining the stream order and the slope.

The analysis has demonstrated that all data is not equal. Data management is an important skill to developing a useful GIS. While this project was exploratory in nature in order to narrow down the ideal characteristics for stream classification, identifying priority data from the start is essential for an efficient analysis. The GIS methodology developed in this project provides a starting point for future research to prioritize stream order, slope, and geology when characterizing stream segments in similar watersheds.
Acknowledgments

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USGS Wisconsin Water Science Center

William Gartner, Senior Lecturer, Department of Geography
University of Wisconsin-Madison

Michelle Lutz, Physical Scientist
USGS Wisconsin Water Science Center

Karen Tuerk, GIS Certificate Program Manager
University of Wisconsin-Madison
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Daniel, T., 2013, Utilizing a High Resolution Digital Elevation Model (DEM) to Apply Stream Power Index (SPI) to Gilmore Creek Watershed in Winona County, Minnesota: Papers in Resource Analysis, Saint Mary’s University of Minnesota University Central Services Press, Winona, MN, v. 15, 11 p.

Esri, Inc, 2011, Calculate Sinuosity, accessed July 15, 2016 at https://www.arcgis.com/home/item.html?id=00e708a448b74810a0e805c4a97f9d46


## Data Layers

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<thead>
<tr>
<th>Data Layer</th>
<th>Source</th>
<th>URL</th>
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<tr>
<td>Regional Wetland Inventory</td>
<td>SEWRPC, WI DNR</td>
<td><a href="http://maps.sewrpc.org/regionallandinfo/metadata/2010_Wetland_Inventory.htm">http://maps.sewrpc.org/regionallandinfo/metadata/2010_Wetland_Inventory.htm</a></td>
</tr>
<tr>
<td>LiDar 5ft Digital Elevation Model</td>
<td>Milwaukee County GIS Database</td>
<td><a href="http://county.milwaukee.gov/mclio/geodata/elevation.html">http://county.milwaukee.gov/mclio/geodata/elevation.html</a></td>
</tr>
<tr>
<td>Current Land Use</td>
<td>SEWRPC</td>
<td><a href="http://maps.sewrpc.org/regionallandinfo/metadata/2010_Land_Use_Inventory.htm">http://maps.sewrpc.org/regionallandinfo/metadata/2010_Land_Use_Inventory.htm</a></td>
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<td>Milwaukee County Soil Map</td>
<td>Wisconsin Geological &amp; Natural History Survey</td>
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<td>Presettlement Vegetation</td>
<td>WI DNR</td>
<td>ftp://dnrftp01.wi.gov/geodata/orig_veg_cover/</td>
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*Figure 4. Data Layers and Sources*
Appendix I – Charts
Conceptualization

Figure 5. Conceptualization Diagram
Implementation

Figure 6. Implementation Diagram
Figure 7. Sum of Stream Segment Lengths (m) by Stream Classification

Selected Attributes by Category in Number of Segments

<table>
<thead>
<tr>
<th>Slope</th>
<th>Stream order</th>
<th>&lt;0.3</th>
<th>0.3 - 1.0</th>
<th>&gt;1.0 - 2.0</th>
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<tbody>
<tr>
<td></td>
<td>1st order</td>
<td>3</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>2nd order</td>
<td>8</td>
<td>4</td>
<td>1</td>
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<tr>
<td></td>
<td>3rd order</td>
<td>7</td>
<td>2</td>
<td>3</td>
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<table>
<thead>
<tr>
<th>Slope</th>
<th>Pleistocene geology</th>
<th>&lt;0.3</th>
<th>0.3 - 1.0</th>
<th>&gt;1.0 - 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FT</td>
<td>4</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>FTE</td>
<td>16</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>LCS</td>
<td>0</td>
<td>0</td>
<td>1</td>
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</table>

Figure 8. Selected Attributes by Category in Number of Segments
<table>
<thead>
<tr>
<th>Attribute</th>
<th>1st-2nd order, &lt; 0.3</th>
<th>1st-2nd order, 0.3-1.0</th>
<th>1st-2nd order, &gt;1.0-2.0</th>
<th>3rd order, &lt;0.3</th>
<th>3rd order, 0.3-1.0</th>
<th>Total</th>
</tr>
</thead>
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<tr>
<td>Sum of Segment Lengths</td>
<td>11,384</td>
<td>10,359</td>
<td>8,978</td>
<td>11,090</td>
<td>2,623</td>
<td>44,434</td>
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<tr>
<td>SPI (Min. - 1st quartile)</td>
<td>578</td>
<td>1,470</td>
<td>5,671</td>
<td>265</td>
<td>0</td>
<td>7,985</td>
</tr>
<tr>
<td>SPI (1st quartile - 2nd quartile)</td>
<td>5,622</td>
<td>2,323</td>
<td>1,233</td>
<td>5,043</td>
<td>187</td>
<td>14,408</td>
</tr>
<tr>
<td>SPI (2nd quartile - 3rd quartile)</td>
<td>4,319</td>
<td>4,650</td>
<td>3,455</td>
<td>5,586</td>
<td>2,436</td>
<td>20,445</td>
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<tr>
<td>SPI (3rd quartile - Max.)</td>
<td>865</td>
<td>534</td>
<td>0</td>
<td>196</td>
<td>0</td>
<td>1,596</td>
</tr>
<tr>
<td>Sinuosity - Low</td>
<td>9,513</td>
<td>5,367</td>
<td>6,768</td>
<td>5,931</td>
<td>681</td>
<td>28,260</td>
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<tr>
<td>Sinuosity - Moderate</td>
<td>1,871</td>
<td>3,148</td>
<td>3,591</td>
<td>5,159</td>
<td>1,942</td>
<td>15,711</td>
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<tr>
<td>Sinuosity - High</td>
<td>0</td>
<td>463</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>463</td>
</tr>
<tr>
<td>Land Use - Mixed</td>
<td>399</td>
<td>4,051</td>
<td>3,627</td>
<td>1,030</td>
<td>1,942</td>
<td>11,050</td>
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<tr>
<td>Land Use - Natural/unused</td>
<td>977</td>
<td>2,323</td>
<td>2,700</td>
<td>4,195</td>
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<td>10,195</td>
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<tr>
<td>Land Use - Transportation</td>
<td>8,625</td>
<td>2,841</td>
<td>1,153</td>
<td>4,043</td>
<td>494</td>
<td>13,556</td>
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<tr>
<td>Land Use - Other Open Land</td>
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<td>0</td>
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<td>3,755</td>
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<td>Land Use - Water</td>
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<td>Land Use - Residential</td>
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<td>1,497</td>
<td>0</td>
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<td>2,342</td>
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<tr>
<td>Wetland (0)</td>
<td>2,103</td>
<td>1,996</td>
<td>3,456</td>
<td>3,964</td>
<td>494</td>
<td>12,012</td>
</tr>
<tr>
<td>Wetland (0-10%)</td>
<td>9,281</td>
<td>3,896</td>
<td>2,049</td>
<td>5,931</td>
<td>2,129</td>
<td>23,287</td>
</tr>
<tr>
<td>Wetland (10-20%)</td>
<td>0</td>
<td>299</td>
<td>4,409</td>
<td>1,916</td>
<td>0</td>
<td>6,624</td>
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<tr>
<td>Wetland (20-30%)</td>
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<td>463</td>
<td>1,697</td>
<td>0</td>
<td>0</td>
<td>2,161</td>
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<td>Wetland (&gt;30)</td>
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<td>2,323</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2,323</td>
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<td>Presettlement Vegetation - Oak Forest</td>
<td>256</td>
<td>463</td>
<td>2,851</td>
<td>0</td>
<td>0</td>
<td>3,570</td>
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<tr>
<td>Presettlement Vegetation - Conifer Swamp</td>
<td>865</td>
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<td>0</td>
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<td>18,362</td>
<td>313,013</td>
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*Figure 9. Attributes by Category in Summed Stream Length (m)*
Appendix II – Cartographic Output

Final Classification: Stream Order and Slope

Figure 10. Final Classification: Stream Order and Slope
Preliminary Classification: Stream Order and Pleistocene Geology

Figure 11. Preliminary Classification: Stream Order and Pleistocene Geology
Preliminary Classification: Slope and Pleistocene Geology

Figure 12. Preliminary Classification: Slope and Pleistocene Geology

Base from WI DNR, Milwaukee County, USGS, and Natural Earth.
Scale: Main: 1:50,000. Inset: 1:750,000. Transverse Mercator Projection, NAD 83