Targeting Best Management Practices (BMPs) to Critical Portions of the Landscape: Using Selected Terrain Analysis Attributes to Identify High-Contributing Areas Relative to Nonpoint Source Pollution

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Funded by:
2007 Minnesota Department of Agriculture Clean (MDA) Water Legacy Funds

MINNESOTA DEPARTMENT OF AGRICULTURE

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Introduction

Digital terrain analysis is a geographic information system (GIS) tool that allows users to geospatially describe landscapes in a hydrological, biological, or geomorphological context. It has been used extensively in the past few decades for several different types of applications (Wilson and Gallant, 2000). Although the basis of the terrain analysis process has been essentially unchanged since its first applications, the quality of digital terrain data has advanced greatly since that time.

The following report details an investigation of the effectiveness of terrain analysis to identify areas that may be critical for restoring and protecting water quality. This investigation begins with analysis using coarse-scale (30-meter) elevation data that is available for the entire United States and concludes with analysis using fine-scale (3-meter) data that is becoming increasingly available for many areas. The effectiveness and feasibility of terrain analysis on these different scales is included.

Critical areas are defined as portions of the landscape that accumulate overland flow and are hydrologically connected to surface waters, either by an overland flow path or by sub-surface drainage. These areas have a higher likelihood of conveying contaminants to surface waters than other portions of the landscape. Using 30-m data, three different critical areas are identified: artificially drained upland depressions, riparian areas, and ravines. 3-m LiDAR data identified finer-scale features such as field gullies or side inlets. When present in an agricultural setting, critical areas contribute a disproportionate amount of contaminants such as sediments, nutrients, and pesticides, to nearby surface waters. Once identified by terrain analysis, BMPs can be applied to these features to mitigate their degradation of water quality. By identifying these features and targeting the areas with the highest priority, water quality benefits are maximized with the most efficient use of resources involved.

Chapter 1
Targeting Critical Areas
Using 30 Meter Elevation Data

Introduction

The historic landscape of the Minnesota River Basin was mainly comprised of wetlands and prairie. After settlement, many of the prairies were plowed and wetlands were drained to support agricultural activities. Nearly 90% of the basin is intensively farmed; agricultural tile lines drain more than 80% of wetlands that used to exist on these agricultural lands (Brezonik et al., 1999). The Minnesota River itself has been listed as one of the most polluted rivers in North America, partly due to agricultural runoff (American Rivers, 1997).

The Minnesota River flows into the Mississippi River near the Minneapolis-St. Paul metropolitan area. The Minnesota Basin is part of the Upper Mississippi River Basin, which contributes approximately 90,000,000 kg of Nitrogen to The Gulf of Mexico annually (Alexander et al., 2008), exacerbating the problem of hypoxia in the Gulf.

The Le Sueur River Watershed is one of 12 major watersheds in the Minnesota River Basin. It is located on the eastern edge of the basin (Fig. 1.1), and receives 250 millimeters more in mean annual rainfall than watersheds located on the western edge of the basin. The Le Sueur River drains 2,880 square kilometers (1,000 square miles) into the Minnesota River near Mankato, MN and contributes a disproportionate amount of non-point source pollution. According to Minnesota River Basin water quality data collected upstream of Jordan, MN, the Le Sueur watershed contributes 53% of the total suspended solids load, 31% of the total phosphorus load, and 20% of the nitrate-nitrogen load, despite comprising less than 7% of the total land surface area within the basin (MRBDC, 2005).

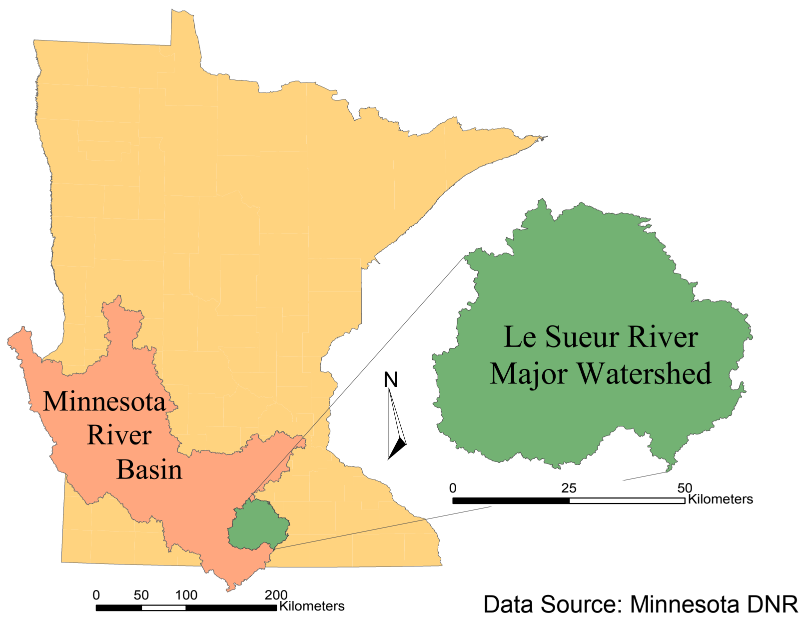

Fig. 1.1 Location of Le Sueur River Major Watershed within the Minnesota River Basin

Determining which landscapes are major sources of agricultural pollution within the watershed is complicated by the mechanisms of transport. Overland runoff is generated when the rate of precipitation exceeds the infiltration capacity of the soil. This runoff accumulates in certain areas based on landscape topography and contributes disproportionate amounts of flow and associated contaminants to surface waters. Small portions of the landscape that are conducive to overland flow and are also hydrologically connected to surface waters are referred to here as critical areas. Artificially drained upland depressions, ravines, and riparian areas are of focus for this project.

GIS and terrain analysis are utilized in this study to identify the locations of critical areas. Terrain attributes can be calculated from readily available 30-meter digital elevation models (DEMs). Applying thresholds to these attributes results in GIS data layers that help us identify different features on the landscape. In this study, various combinations of these data layers, along with ancillary GIS data, have been used to identify critical source areas intended to focus conservation efforts. Such areas include artificially drained upland depressions, ravines, and riparian areas.

Methods

Data

30-meter grid cell resolution DEMs were acquired from the US Geologic Survey's National Elevation Dataset (USGS, 2006). Terrain attributes were then derived using "Terrain Analysis Using Digital Elevation Models" (TAUDEM) software version 3.1 (Tarboton, 2005) and ESRI's ArcGIS software version 9.2.

Terrain Analysis Attributes

The attributes employed throughout this study include *slope, flow accumulation, profile curvature, stream power index* (*SPI*), and *compound topographic index* (*CTI*). These attributes have been used extensively to study topographic features of heterogeneous landscapes (Wilson and Gallant, 2000).

Unless otherwise noted, *slope* refers to the tangent of the slope angle. This is equivalent to slope in percent divided by 100. To avoid data errors in secondary attribute calculation, *slope* values of 0 were reclassified to 0.001.

Flow accumulation, also known as upslope contributing area or catchment area, represents the total upslope land area that drains into any single cell. Its estimation of drainage patterns makes it a valuable attribute for water resource applications. The attribute itself, as well as secondary attributes derived from it, have been used to predict overland runoff in a number of studies (Wilson and Gallant, 2000). *Flow accumulation* was calculated based on the D∞ algorithm of flow routing in the 30-meter analysis (Tarboton, 1997). For larger geographic areas or finer-scale data, the simplified ArcGIS default D8 method of flow routing is suggested.

Profile curvature refers to the change in slope down a flow path; it represents the rate of change in gradient and is useful in identifying areas with potential flow velocity changes (Wilson and Gallant, 2000).

Stream Power Index (*SPI*) is a secondary terrain attribute that measures the erosive power of flowing water (Wilson and Gallant, 2000). Stream power itself is a misnomer; this index does not quantify the power of streams, but the power of overland flow. It was calculated based on:

$$SPI = (Flow\ Accumulation) \times (Slope)$$

The *compound topographic index* (*CTI*), also known as the topographic wetness index, is a secondary terrain attribute which identifies areas on the landscape with a potential for ponding or saturation (Wilson and Gallant, 2000). It was calculated based on:

$$CTI = \ln(Flow\ Accumulation\ /\ Slope)$$

See appendix A for additional calculations.

Most 30-m terrain attributes were calculated by employing the D∞ flow direction method (Tarboten, 1997). This approach may be a more robust method of flow routing, but it is limited to raster datasets no larger than 7000 x 7000 grid cells. Attributes calculated for the Le Sueur River Watershed employed the D∞ method. However, some attributes were computed on larger datasets, and therefore the simplified D8 method of flow routing was employed.

Critical Areas

Three different landscape features are identified as critical source areas in this analysis: ravines, artificially drained upland depressions, and riparian areas. Each landscape is unique and is associated with different contaminant concerns. Ravines are generally found in forested areas adjacent to streams; the main concern of this landscape is sediment erosion. Artificially drained upland depressions are generally located in agricultural areas and are associated with tile drainage. In the absence of tile drains, these areas would likely be wetlands where water is stored and sediments and nutrients are removed. When present in an agricultural setting, tile drains in depressions route flows and their corresponding contaminant loads to nearby surface waters. Finally riparian areas area associated with high overland flows during runoff events and transport contaminants such as sediment and nutrients during these events.

Ravines

Ravines are active erosional features that contribute a significant amount of sediment to nearby waterways. They were identified with three attributes of the 30-m DEM: slope, aspect, and flow accumulation. A threshold of cells with slope greater than 7% was combined with the standard deviation of the aspect greater than 40. A 200-m buffer was applied to each cell with flow accumulation between 200 and 7400 cells, representing catchment areas between 140,000-m^2 and 5,000,000-m^2. A pixel was considered in the ravine critical area if it met all of these three criteria.

Terrain analysis was effective at identifying ravines. Sixty-five sites were visited in the field, and 90% of those were confirmed as active ravines. These sites were selected to represent different agroecoregions, a land classification system based on soil type, parent material, slope steepness, drainage characteristics, erosion potential, and climatic factors that affect crop productivity (Mulla, 1996). The majority of false positives occurred in the Coteau agroecoregion. Ravines cover only a small portion of the watershed, but are an important source of sediment from water erosion processes. An example of ravines identified using terrain analysis is illustrated in Fig. 1.2.

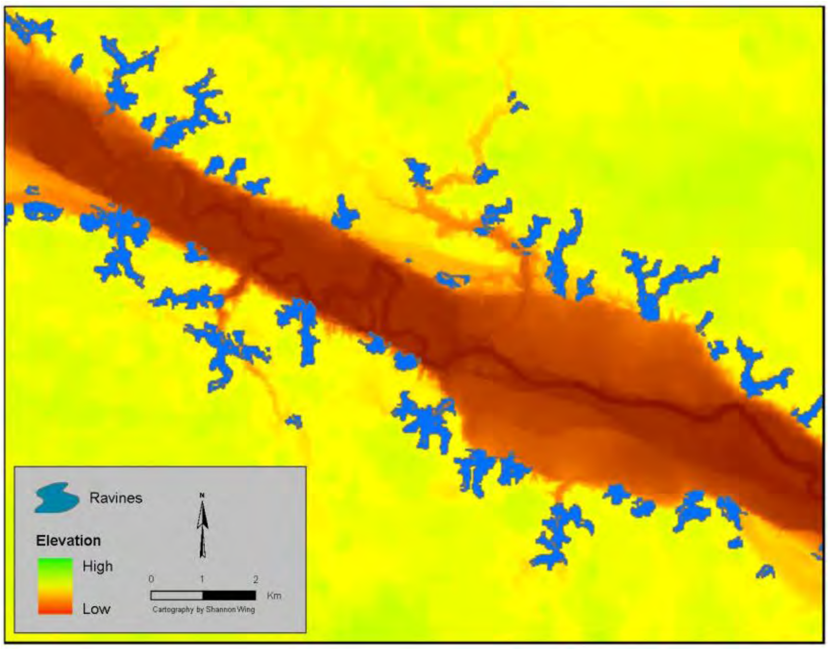

Fig. 1.2 Snapshot of ravines identified with 30-m terrain attributes in the Minnesota River Basin

Upland Depressions

Historically, a large number of wetlands existed in the Le Sueur River Watershed. Although a majority of these wetlands have been drained to accommodate agricultural practices, the soil and topographic features which were associated with wetlands still exist and continue to influence surface hydrology. Landscape features that were formerly wetlands or accumulate surface water are referred to as artificially drained upland depressions, or upland depressions for short.

Upland depressions were delineated using CTI values and soil drainage characteristics. Original CTI values were smoothed using a 3 x 3 grid cell low-pass filter.

A threshold of 11.5 was applied to the smoothed CTI values. This threshold was partly calibrated by field visits in the Beauford Minor Watershed located in the Le Sueur Watershed. NRCS Soil survey geographic (SSURGO) database drainage data further refined this threshold; SSURGO soil map units identified as "poorly drained" or "very poorly drained" were intersected with smoothed CTI values greater than 11.5 resulting in the upland depression critical area.

Terrain analysis was effective at identifying upland depressions. These features were verified in the Beauford minor watershed, which aided in determining attribute thresholds. In agricultural fields, these depressions are typically drained by open surface inlets installed to route water to subsurface drainage tiles. Prior to agricultural drainage, these depressions likely held water, reducing peak flows due to temporary storage and evapotranspiration and protected water quality by removing sediments and NO_3 (Skaggs et al. 1994). Water quality could be improved and peak flows reduced by replacing open surface inlets with rock inlets or French drains that regulate water flows and filter sediments or by controlling drainage flows to retain water longer (Evans et al. 1995). Identification of upland depressions is illustrated in Fig. 1.3.

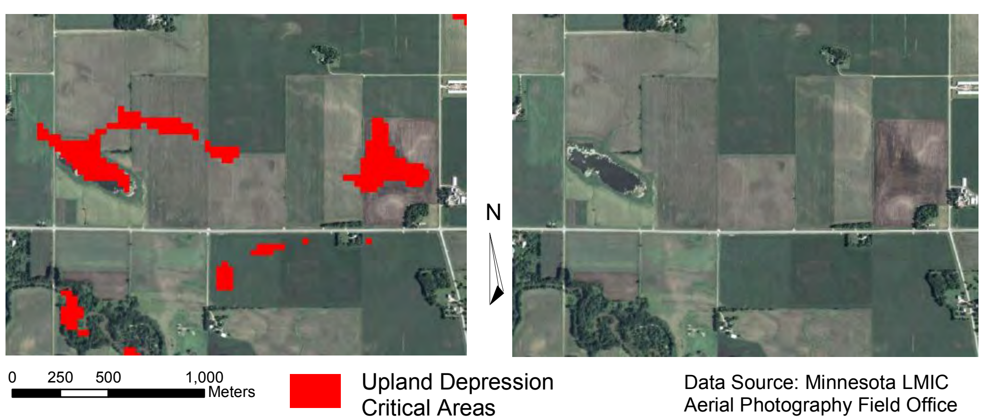

Fig. 1.3 Snapshot of Upland Depression Critical Areas identified with 30-m terrain attributes in the Beauford Minor Watershed

Artificially drained upland depressions also have a high potential to be sites for wetland restoration. The current approach to identifying restorable wetlands in Minnesota involves hand-digitizing stereo pair orthophotography, which can be a long and tedious process. With terrain analysis, similar areas can be delineated more rapidly, albeit at a coarser resolution. Broader upland depression features on the landscape show up well using terrain attributes derived from 30-m DEMs; however, this method fails to identify small polygons that have been accurately hand-digitized (Fig. 1.4). As previously mentioned, the Le Sueur watershed is a large source of NO_3 loading to the Gulf of Mexico. Restoring wetlands has been proposed as a method for reducing NO_3 discharge to the Gulf of Mexico (Mitsch et al., 2001).

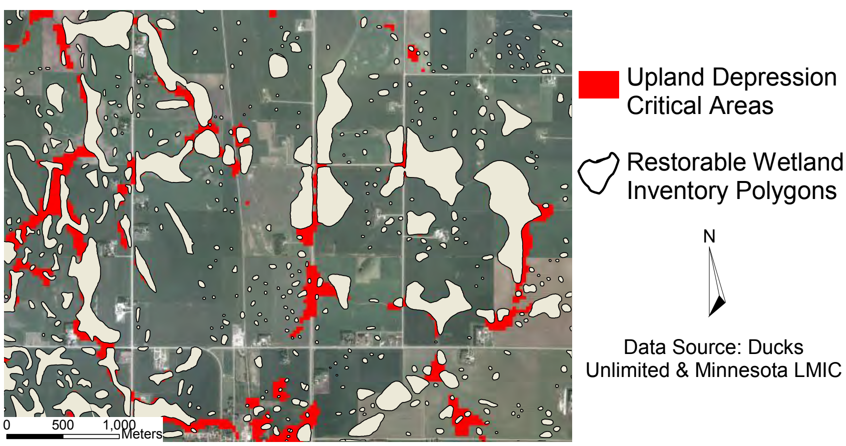

Fig. 1.4 Visual comparison of upland depressions identified with 30-m terrain attributes and hand-digitized restorable wetland polygons

Riparian Areas

During storm events, overland runoff is controlled largely by topography. Areas that accumulate flow due to topographic influences and have the potential to transport contaminants during storm events are termed riparian areas. SPI is used here to delineate areas of concentrated overland flow that would have the potential to transport contaminants during storm events.

SPI values were smoothed using a 3 x 3 grid cell low-pass filter. Smoothed SPI values greater than 10 were identified as critical riparian areas. Critical riparian areas were further sub-divided based on areas of slope greater than 3% to delineate what is termed priority riparian areas. These areas have both high stream power and a high potential for soil erosion by water.

Riparian critical areas are probable transport pathways for contaminants during periods of heavy rainfall or peak flows. Water quality can be improved by installing vegetative buffers in riparian areas, including grassed waterways within agricultural fields. The Beauford Minor Watershed, located within the Le Sueur River Watershed, was used as a pilot watershed to calibrate and validate applied thresholds for the terrain attributes used to identify riparian areas. Fig. 1.5 displays the minor watershed as well as potential transport pathways identified by riparian critical areas.

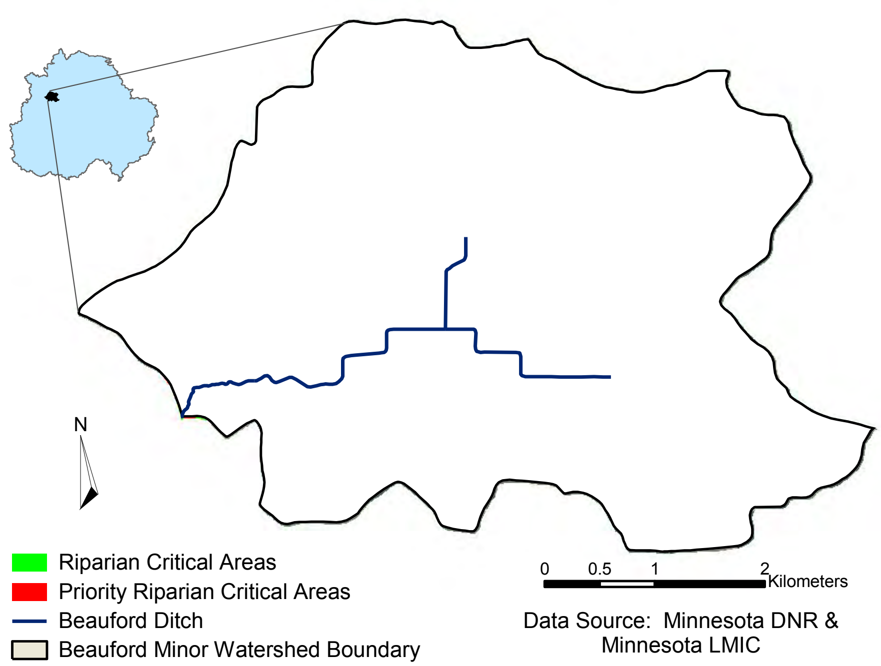

Fig. 1.5 Riparian areas and priority riparian areas (slopes greater than 3%) identified with 30-m terrain attributes in the Beauford Minor Watershed

Terrain attributes were also calculated for an additional watershed in northwestern Minnesota. The Wild Rice Watershed outlets into the Red River just north of Fargo, ND. The western portion of this watershed is contained in the Red River Valley and was determined to be too flat for a 30-m DEM to accurately describe flow patterns. Fig. 1.6 displays SPI values calculated for this watershed. Calibration of critical areas for this watershed was not in the scope of this analysis due to its proximity in the state.

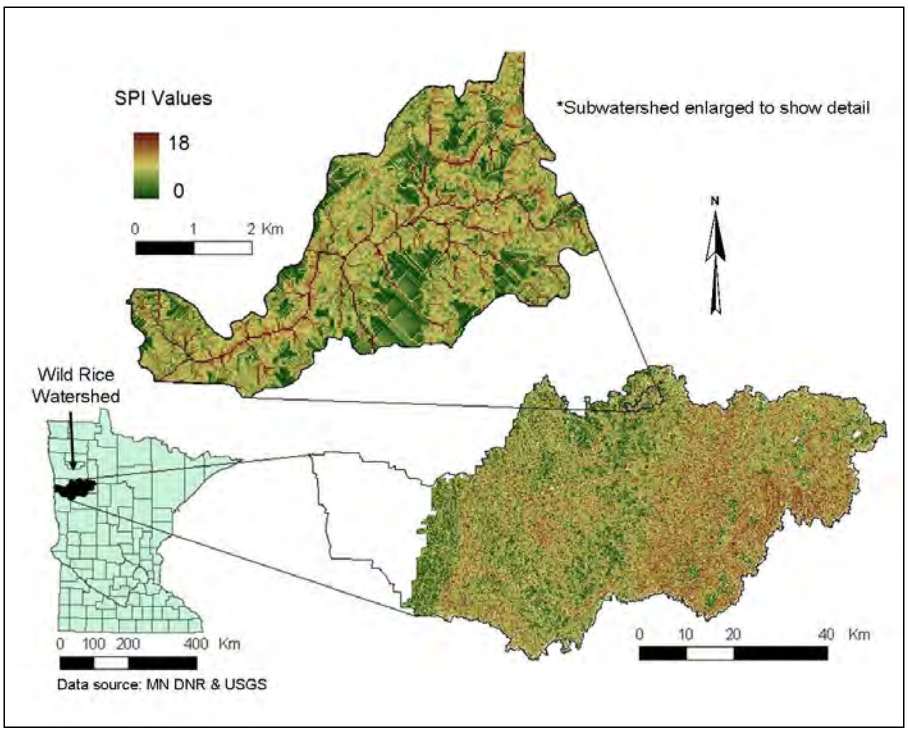

Fig. 1.6 SPI values calculated from a 30-m DEM in the Wild Rice Watershed

Results

Thresholds applied to terrain attributes were determined after analysis of aerial imagery (LMIC, 2003), field visits, and field data collection of runoff and water quality data (Khakural et al., 1999). Most terrain attributes were normalized for easier analysis, and applied threshold values corresponded closely to a value of the mean of the dataset plus one-half standard deviation. This cutoff level has been shown to be effective in delineating management zones in previous analyses (Mulla, 1993).

Terrain attributes derived from 30-m DEMs were used to identify critical areas in the entire Le Sueur River watershed. Upland depressions cover only 7% of the watershed, but a majority of these features (85%) are in agricultural production. Riparian areas make up more than one fourth of the watershed, and over half of these features (59%) are in agricultural lands. Also, one third of riparian areas have slopes greater than 3 percent, and are thus considered priority riparian areas. Table 1.1 gives descriptive statistics of critical area coverages in the Le Sueur River Watershed and their coincidence with agricultural areas. Figures 1.7 and 1.8 display the coverages within the watershed.

Critical Area	Total Area (Ha)	Proportion of Watershed	Area in Ag Production (Ha)	Proportion in Ag Production
Ravines	266	<1%	23	9%
Upland Depressions	19,896	7%	16,835	85%
Riparian	73,737	26%	43,795	59%
Priority Riparian	25,459	9%	13,206	52%

Table 1.1 Areal extent of critical areas identified with 30-m terrain attributes within the Le Sueur River Watershed; here agricultural production refers to national land cover dataset pixels classified as pasture or cultivated crop (EPA, 2001)

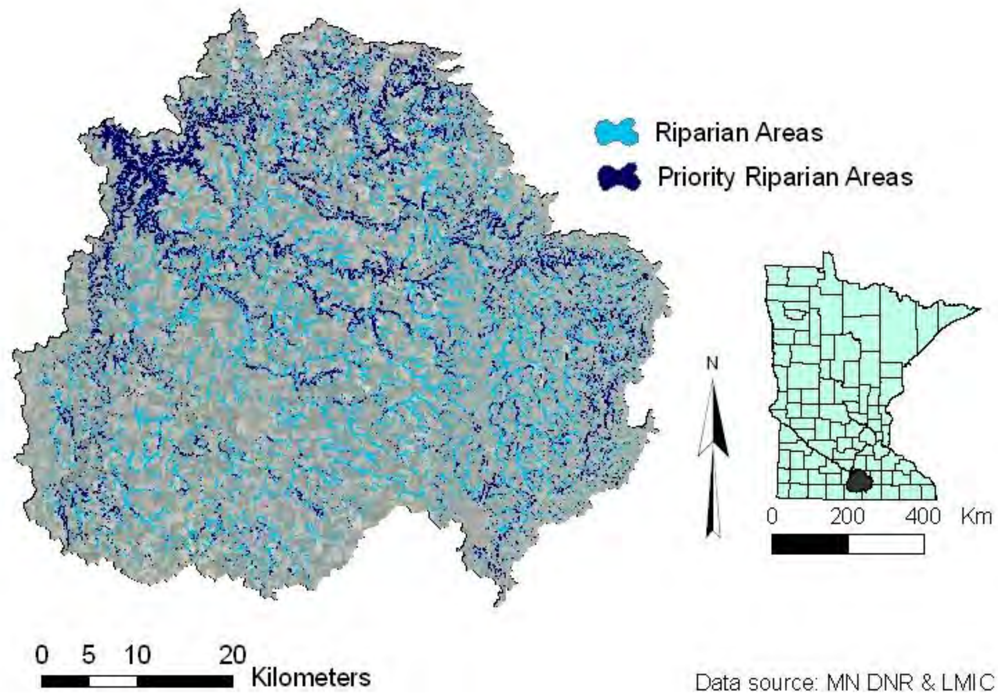

Fig. 1.7 Areal extent of riparian areas and priority riparian areas identified with 30-m terrain attributes within the Le Sueur Watershed

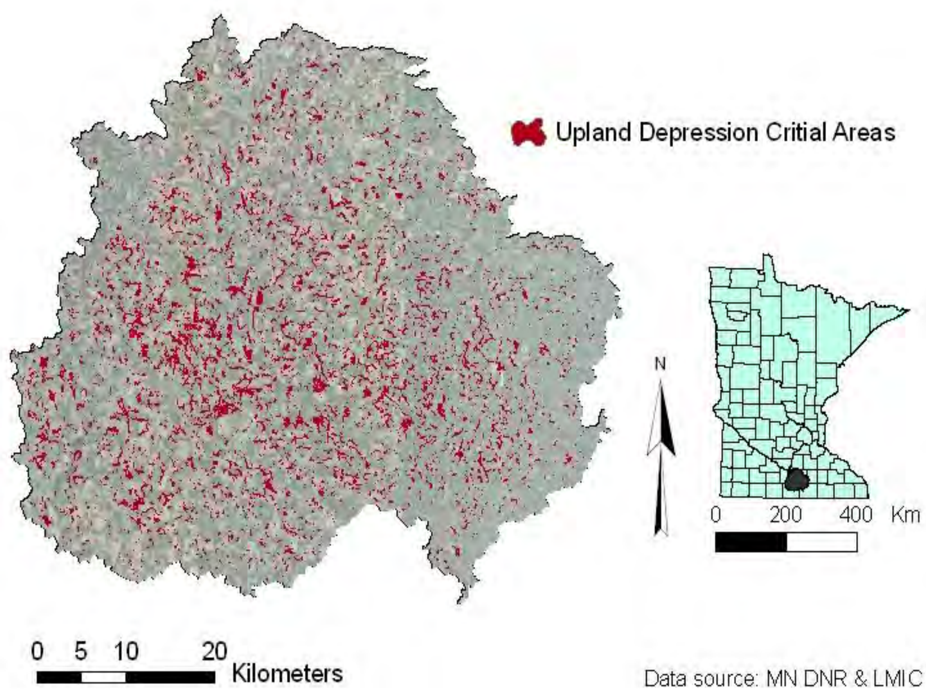

Fig. 1.8 Areal extent of upland depressions identified with 30-m terrain attributes within the Le Sueur Watershed

Discussion

Agricultural BMPs are more effective when placed in vulnerable portions of the landscape (Mulla et al., 2008). Government conservation programs often have limited funding and landowner participation is voluntary, which may not result in enrolling the most critical lands. An adjustable land classification system has been proposed in the past to overcome these limitations and institute a dynamic funding availability process that targets conservation funding to critical lands more effectively than a traditional first-come, first served approach (Larson et al., 1988). In this system, soil conservation practices were applied to the lands most susceptible to soil erosion based on best available spatial data. Terrain analysis used to identify critical areas could be used in conjunction with such an approach. Specifically, terrain attribute thresholds could be adjusted to determine the areal extent of critical lands that can be addressed with a predetermined amount of conservation program funding. Conversely, the same approach could be used to base conservation program funding requests on a selected areal extent of critical lands.

Terrain analysis using 30-m DEMs can only identify broad landscape features limited to that spatial resolution, but the approach is simple and it takes relatively little time to analyze large datasets, such as for an entire 8-digit watershed.

Conclusions

Precision conservation strategies involving terrain analysis and GIS may prove very helpful in the future to guide conservation efforts tailored to specific landscapes and to maximize efficiency of their placement. Also, as described in Chapter 2, with advances in LiDAR imagery and increased computing power, these methods can be employed at very fine spatial scales to identify critical areas with a high degree of accuracy.

Chapter 2
Targeting Areas of Concentrated Overland Flow Using LiDAR Elevation Data

Introduction

With the advancement of light detection and ranging (LiDAR) technologies, the topography of landscapes can be described with highly accurate elevation data. These data can be stored, processed, and analyzed in a geographic information system (GIS). Using GIS software, terrain attributes can readily be calculated from this data; these attributes can be used to find sensitive areas on the landscape very rapidly, which may guide field surveys and help find erosional features on the ground. Once identified, these features can be targeted with management practices, and their effects on surface water pollution can be minimized.

The potential applications of LiDAR based terrain attributes have been studied on two small watersheds located in the Minnesota River Basin. This study investigates the effectiveness of using LiDAR elevation data to identify areas of concentrated flow that are hydrologically connected to surface waters. Once identified, these critical areas can then be targeted with appropriate BMPs.

Methods

The Seven Mile Creek Watershed, located north of Mankato, MN, is an approximately 10,000 hectare (25,000 acre) watershed with low relief uplands transitioning into steep relief of the river channel near the outlet. This area was formed in glacial till deposited from the Des Moines lobe. The Beauford watershed is approximately 2,200 hectares (5000 acres) and is dominated by low relief lacustrine sediment deposited after the Des Moines Lobe retreat (Hobbs and Goebel 1982).

A digital elevation model (DEM) is the base layer for all terrain attributes in this analysis. To complete terrain analyses, DEM data should be obtained in raster grid format. LiDAR data for these study areas were acquired as two foot contour data by the Minnesota

Department of Agriculture from Blue Earth County. A portion of these data were delivered as a mass point file with breaklines and were converted into a hydrologically corrected DEM with 1-m grid cell resolution using the LP360 ArcGIS extension from QCoherent Software. These data were then resampled to a 3-m DEM to streamline processing times in subsequent analyses. Several spatial resolutions were considered; however, 3-m data was chosen because it demands less computing power than finer-scale data, while still maintaining a high level of accuracy. The majority of the LiDAR processing was done by Tim Loesch, Minnesota Department of Natural Resources GIS Operations Supervisor; processing assistance was provided by Joel Nelson, a GIS specialist with the University of Minnesota. If LiDAR data are delivered in the form of elevation contours, they can be converted to a DEM in order to conduct terrain analysis.

Once a DEM is acquired, all terrain attributes employed throughout this study can be derived from it. Our 3-m DEM was pit-filled to remove imperfections in the data and correct flow routing when small closed depressions may incorrectly terminate flow paths. Pit-filling essentially fills depressions with hypothetical water flow and forces drainage to the lowest possible outlet. The pit-filling process may not be appropriate for all areas, especially where water is held and evapotranspired in depressions; however, it is a more conservative approach because it tends to err on the side of overestimating rather than underestimating flows. For this reason, it is recommended in most situations. The Seven Mile Creek Watershed DEM was pit-filled with a z limit of 1-m based on the assumption that closed depressions of 1 meter or less would likely fill and overflow at the lowest cell edge during periods of high flows. The Beauford watershed was not pit-filled due to extremely low relief.

Terrain attributes at the 3-m scale are calculated just as attributes calculated on a 30-m scale. Refer to the method section of Chapter 1 for terrain attribute calculation details. Due to the larger file size of fine-scale LiDAR data, the D8 method of flow routing is used on all 3-m data. This method of flow routing may be less robust than more complicated methods, but it accommodates large datasets well and was found to provide highly accurate results in other studies (Fried, et al. 2000).

Calibration

Surveys were conducted in both of the study watersheds along the riparian corridor to identify sources of erosion and overland flow paths hydrologically connected to surface water. All gullies and side inlets were recorded with a GPS receiver in the field, as well as the location of tile drain outlets. The Brown Nicollet Cottonwood Water Quality Board collected a large dataset for the Seven Mile Creek Watershed; a survey of the watershed identified 83 gullies along with other important drainage related features. The gullies found in this survey were given a sediment delivery potential (SDP) score in the field based on their likelihood of sediment transport. Data for the Beauford Watershed was collected by staff with the Minnesota Department of Agriculture. This area contains more side inlets and fewer gullies than in the Seven Mile Creek Watershed. Inlets are assumed to be installed at locations vulnerable to overland flow; also it was assumed larger flows must be accommodated with larger inlets so inlet size was recorded as a surrogate for runoff volume. See Fig. 2.1 for an example of both gully features and side inlets in the field.

Fig. 2.1 Example photos of a gully (left) and a side inlet (right) in the field

GPS data points were collected in the field and compared to calculated terrain attributes; 83 gullies were identified in the Seven Mile Creek Watershed, and 22 side inlets were identified in the Beauford Watershed. Where necessary, field GPS positions were edited so each point that appeared to be at the terminus of an SPI flow path was properly identified as such (Fig. 2.2). This accounted for any errors introduced by either the GPS or the terrain model and assured that any data extracted at that point would correspond to the correct location in the terrain model.

Fig. 2.2 Example of a field sample point correction based on 3-m SPI signatures

SPI flow paths are referred to here as "SPI signatures". These signatures represent the likely overland flow paths of surface flows during storm events. They are created by isolating only high values of SPI (discussed later). Figure 2.3 below displays an example of an SPI signature and its visual interpretation.

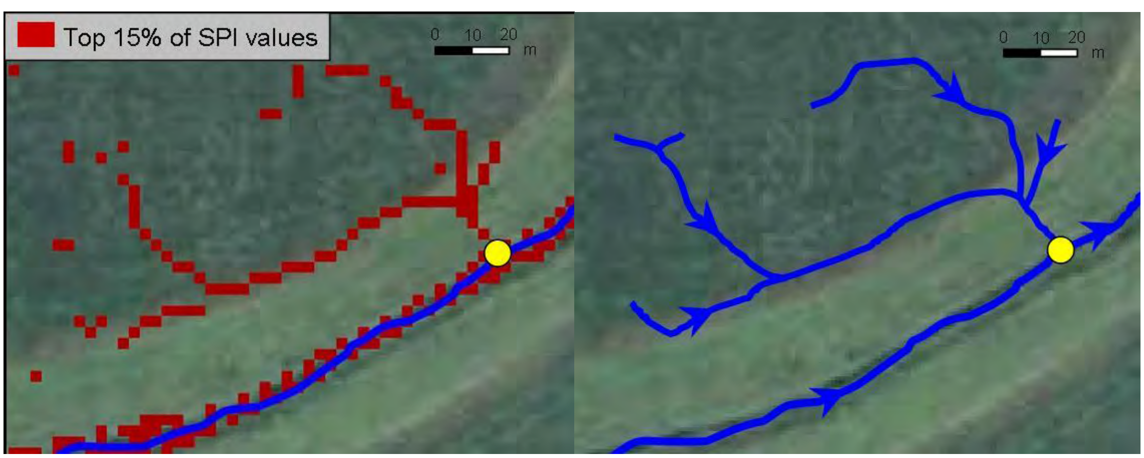

Figure 2.3 An example of a 3-m SPI signature (left) and its visual interpretation of flow (right). Note the yellow area; this represents an area where overland flow likely interfaces with the stream channel and should be visited in the field.

To determine the predictive power of each attribute, terrain data were sampled at each field surveyed point; each point therefore contained terrain data that corresponded to that 3 x 3 meter grid cell on the landscape. These data were processed with Statistica v. 8.0 so each point could be ranked among all points within the watershed. Similar analysis could be done in any statistical package that can accommodate large datasets; the datasets used in this analysis were on the order of ten million pixels. Once the data was ranked, a percentile value of each grid cell was calculated. Figure 2.4 displays a cumulative distribution plot of SPI values and their percentiles within the Seven Mile Creek watershed as well as the values that correspond with gully features. Terrain attributes calculated for an area should be compared relative to one another within an area of interest; they do not represent static values that correspond to a specific runoff volume or pollutant loading rate. Percentiles are used here in order to compare the attributes in relative terms. Since each landscape has unique characteristics, it is not suggested to apply static threshold values to terrain attributes.

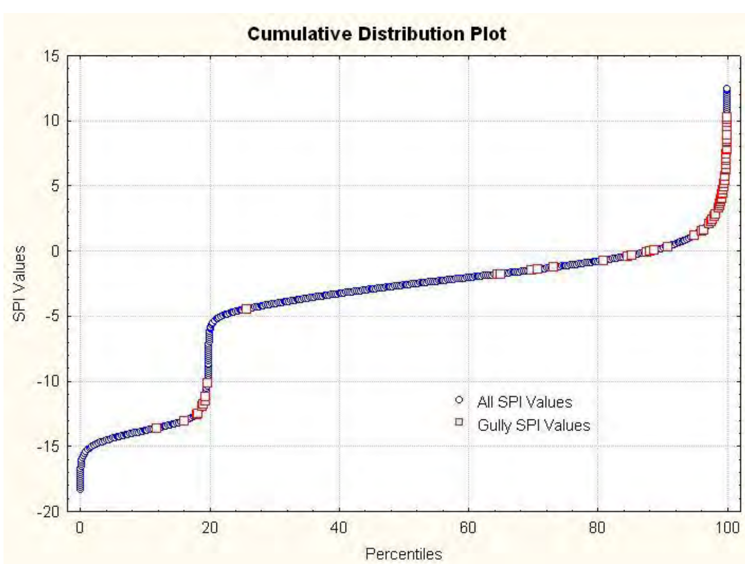

Fig. 2.4 Cumulative distribution plot of 3-m SPI values within the Seven Mile Creek watershed and SPI values that corresponded with a gully feature

Results

Percentile values for each attribute were summarized by watershed and further by SDP score and tile inlet size. For both watersheds, the average SPI values at field-surveyed sites were found to be the most useful for identifying these features. SPI essentially isolates areas with both a high catchment and a high slope. The inclusion of slope in the Beauford Watershed, being a flatter landscape, made only a small improvement in the predictive power of SPI. However, the Seven Mile Creek Watershed contains more topographic relief, and the addition of slope made a large difference in the percentile statistics (Table 2.1). Fig. 2.3 again displays SPI values of field verified gullies amongst all SPI values in the watershed.

Watershed	Average SPI Percentile	Average FA Percentile
Beauford	89	88
7 Mile Creek	85	67

Table 2.1 Average percentiles of 3-m SPI and Flow Accumulation (FA) for the Beauford Watershed's 22 side inlet locations and the Seven Mile Creek Watershed's 83 gully locations

Percentile statistics were also used in attempt to analyze the relationship between terrain attributes and size of an erosional feature. For example, percentiles were summarized based on SDP scores in the Seven Mile Creek Watershed and by tile inlet size in the Beauford Watershed (see Tables 2.2 & 2.3).

SDP Score	Average Percentile of SPI
High (SDP = 3)	97.4
Moderate (SDP = 2)	83.8
Low (SDP = 1)	72.8

Table 2.2 Average percentiles of 3-m SPI for the Seven Mile Creek Watershed's 83 gully locations summarized by sediment delivery potential score

Side Inlet Size	Average Percentile of SPI
Large (24 - 36 inches)	98.9
Medium (14 - 18 inches)	93.3
Small (4 - 12 inches)	81

Table 2.3 Average percentiles of 3-m SPI for the Beauford Watershed's 22 side inlet locations summarized by inlet size

Although insufficient data are available to create a quantitative relationship, these data lead to the conclusion that values for terrain attribute such as SPI can be used to infer the ordinal size of erosional features and target management practices to the largest features. Further study is needed to attempt to quantify the relationship between SPI values and the size of erosion features.

In attempt to evaluate the effectiveness of this methodology, an exhaustive GIS-based field survey was conducted in the Seven Mile Creek Watershed. An SPI layer was overlaid with a streams layer. The SPI layer was first manipulated so only signatures in the 85th percentile or higher were visible. This threshold was chosen because it was the average percentile for field surveyed data points. Wherever an SPI signature had connectivity to the stream corridor, a new sample point was placed (see Fig. 2.5).

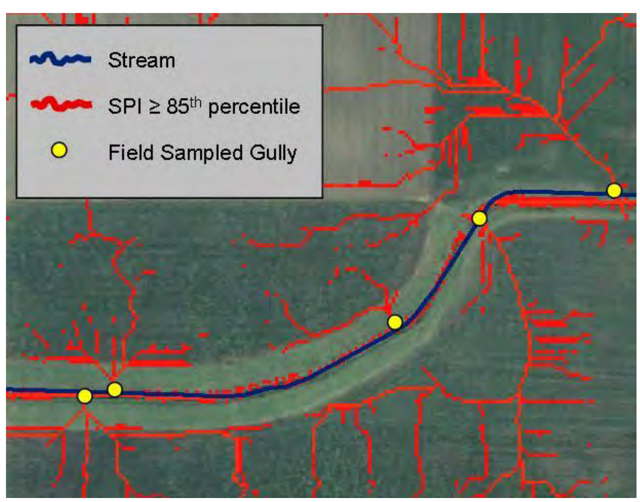

Fig. 2.5 Displays an example of how points were created at the interface of a 3-m SPI signature and the riparian corridor

122 points were created at these SPI signature interfaces denoting areas that should be field surveyed for validation. 43 of these 122 points (35%) were not closely related to an erosional feature in the exhaustive field survey. These can be interpreted as type 1 commission errors, or false positives. 14 features (11%) that were identified in the GIS survey were identified in field survey as either a tile outlet location or stream bank erosion. 65 of the 83 gullies were identified within the watershed using only the top 15 percent of SPI data; in other words, nearly 80 percent of the gullies in the watershed were identified by this threshold. When focusing on the largest contributors in the watershed or only high SDP score gullies, 31 of 32 were identified. Also, 12 of the 18 type 2 omission errors had an SDP score of 1, which represents the smallest gullies in the watershed (Table 2.4).

	Identified	Not Identified	Total Present
SDP 3 Gully	31	1	32
SDP 2 Gully	17	5	22
SDP 1 Gully	17	12	29
Total*	65	18 (Type II Error)	83
No Feature	43 (Type I Error)		

Table 2.4 Summary of GIS survey data

*14 additional features were identified as either tile outlets or stream bank erosion

Discussion

The accuracy of the results is partially based on prior knowledge of the watershed. It is known that a large portion of the erosion occurring near the mouth of the watershed occurs in forested ravines. These features were excluded from this survey with the aide of aerial photography. There are also a few extremely flat areas within the watershed where terrain models may fail to accurately describe surface flows, as illustrated in Fig. 2.6. Features located in such areas were also excluded. Prior knowledge of a specific study area will help guide the use of terrain attributes and ultimately increase the effectiveness of their applications.

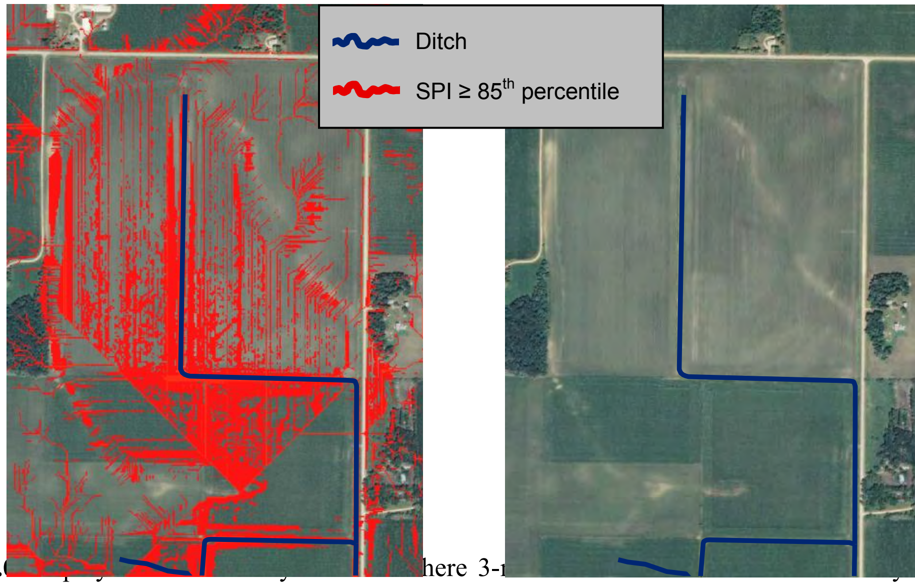

Fig. 2.[illegible] here 3-[illegible] describe surface flow (SPI signatures removed from right image). Notice the outline of a former flat land, likely a drained wetland, where SPI signatures appear parallel. This area may not contribute water to surface flows, but enforcing drainage out of this depression is a conservative approach and is recommended in similar areas.

The study area for most of this analysis lies in moderate to low relief areas created in glacial till and lacustrine sediments. In theory, greater relief areas would be easier to describe with terrain analysis because overland flow would follow predicted flow paths more accurately. Extremely low relief areas, however, may not be accurately described. Further research is needed to determine whether this method can be applied in areas with different geomorphologies. Also, due to stark differences in topography and other landscape influences, the 85th percentile is not likely a transferrable threshold to every watershed in the state, or even in similar landscapes for that matter. Further research is needed to quantify the relationship between terrain attribute percentiles and the size of erosional features.

Advances in LiDAR technologies are allowing us to create elevation models with ever increasing precision, however, the processing of this data is also becoming more intensive. Processing times for LiDAR datasets on the order of 10,000 hectares (25,000 acres) were similar to processing times of coarser 30-m data on the order of 100,000 hectares (250,000 acres). DEMs were created from LiDAR data in this analysis to have the spatial resolution of 3-m. This ensured that each pixel was accurately described by LiDAR sampled elevations. Although a DEM with a smaller spatial resolution may provide finer scale results, it will also require longer processing times. With adequate computing power, 3-m terrain attributes for watersheds on the order of 10,000,000 pixels (7,000 acres) can be calculated in a matter of hours. A similar time scale could be expected when calculating 30-m terrain attributes for an area on the order of 100,000 hectares (250,000 acres).

A terrain analysis guided ditch survey was completed to further test the effectiveness of this method. As part of a Minnesota State University study performed for the Crystal Loon Mills Clean Water Partnership, County Ditch 56 located southwest of Mankato, MN was field surveyed to locate areas of potential erosion. Prior to the field survey conducted in November of 2008, the student organizing the survey was provided a shapefile of points that were to be investigated as potential sources of erosion. These points were created using the LiDAR terrain analysis method described in this report. Of the 15 points that were visited by the field survey crew, 14 identified features associated with a potential erosion risk; 7 of these features were gullies. During this survey, two additional gullies were located that were not identified by terrain analysis. Several other erosion concerns were located; however, the majority of concerns were exposed tiles which may not be closely related to the terrain of surrounding landscapes. As a result of this survey, it was reinforced that LiDAR terrain analysis can effectively identify gully erosion features and can serve as a valuable guide for natural resource planners.

Conclusion

This study focused on identifying critical areas that contribute a disproportionate amount of nonpoint source pollution so their effects on water quality can be mitigated or minimized with the installation of BMPs. In this chapter, 3-m LiDAR terrain attributes were used to accurately identify fine-scale gullies and side inlets. With a certain amount of user knowledge and a high quality LiDAR DEM, terrain analysis can rapidly and accurately identify in field features where overland flow accumulates and is hydrologically connected to surface waters. These features are probable sources of contaminants associated with agricultural practices such as sediments, nutrients, and pesticides. BMPs targeted to these features can maximize their benefits on water quality and also maximize the efficiency of funding used for conservation.

The fact that erosional feature size can be inferred from terrain attributes has valuable implications. Targeting efforts can be matched to financial and temporal constraints with a high likelihood of capturing the largest contaminant producing features, maximizing the efficiency of all resources involved. With an ever increasing availability of LiDAR data, terrain analysis may prove very useful in the future for natural resource management.

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Appendix A

Secondary Terrain Attribute Calculations

- Stream Power Index
    - Calculated in “Raster Calculator” (Spatial Analyst) as:

    SPI = Ln (([FlowAccumulation_grid] + 0.001) * (([Slope_percent_grid]/100) + 0.001))

    - Any “No Data” pixels must first be reclassed to 0 using “Reclassify” (Spatial Analyst)
    - 0.001 added to each attribute to remove errors caused by 0 valued pixels
    - Natural Logarithm taken to normalize data

- Compound Topographic Index
    - Calculated in “Raster Calculator” (Spatial Analyst) as:

CTI = Ln (([FlowAccumulation_grid] + 0.001) / (([Slope_percent_grid]/100) + 0.001))

    - Any “No Data” pixels must first be reclassed to 0 using “Reclassify” (Spatial Analyst)
    - 0.001 added to each attribute to remove errors caused by 0 valued pixels

Appendix B

Field Survey Data Sheets

Site ID#	Streambank Location	Discharges to…	Feature	Flow Orientation	% Crop Residue	Land Use	Tillage Direction	Tile Style	Tile Size (inches)
   Date (xx/xx/xxxx)	Left Bank Right Bank Note: while looking downstream	Perennial Stream Intermittent Stream Grassed Waterway Other: ________	Culvert Drop structure Gully Grassed Waterway Open intake Side inlet Slumping Exposed tile Other: ________	N NE E SE S SW W NW		Corn Soybean Alfafa Wheat Pasture Forest ________	N NE E SE S SW W NW	Clay Corrugated Metal Pipe Concrete Plastic	

Vegetative Buffer	Buffer Condition	Buffer Width (ft.)	Gully/Slumping Width (ft.)	Gully/Slumping Depth (ft.)	Gully/Slumping Length (ft.)	Intake Distance (ft.)	Intake Size (inches)	Photo #
Yes No	0 1 2 3 4							

Comments:

Appendix C

This project also explored the use of terrain attributes to analyze the risk of water pollution from feedlots based on number of animal units and SPI values. Feedlot locations (point data) were acquired from the Minnesota Pollution Control Agency, which included the number of animal units present at each location. Assuming that the manure will be spread locally, a 1 mile buffer was applied to each feedlot site. Feedlots were ranked based on size (number of animal units) and the size values were assigned weighted values from 1 (smallest) to 5 (largest). This value was applied to the area within the 1 mile buffer around each feedlot. SPI values within the watershed were also ranked and classified on a 1 to 5 scale, the largest SPI values having the highest weight. The animal unit weighted values were multiplied by the SPI weight grid and the product of these data was summarized by minor watershed (10 digit hydrologic unit code) to produce a feedlot risk assessment map (below). This simple analysis took only minutes to finish, yet it may have valuable implications when applying resources within the watershed.

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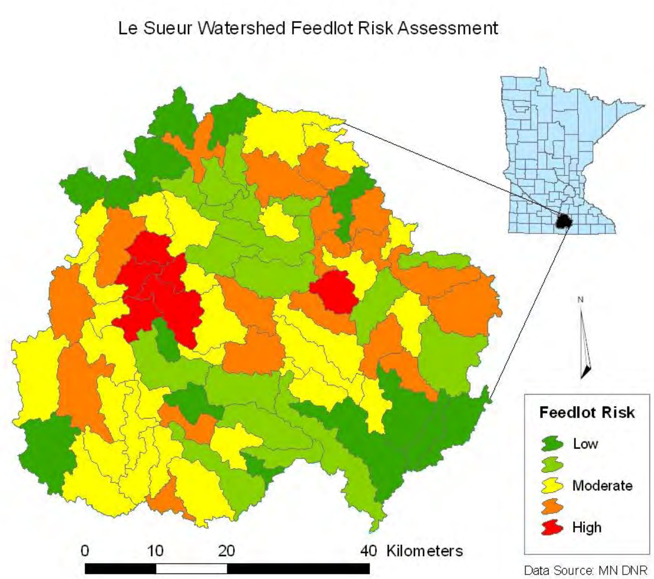

Subwatershed feedlot risk assessment map