IDENTIFYING CRITICAL LANDSCAPE AREAS FOR PRECISION CONSERVATION IN THE MINNESOTA RIVER BASIN

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ABSTRACT

The Minnesota River Basin generates a disproportionately high amount of total suspended sediments to the Upper Mississippi River Basin. Many reaches in the Minnesota River Basin have impaired water quality due to turbidity. Critical landscapes can be divided into depressional areas, riparian areas, highly erodible lands, and areas susceptible to ephemeral gullies or ravines. Geographic Information Systems (GIS) were utilized, and terrain analysis was conducted using digital elevation models in an attempt to identify the locations and areal extent of these features in the Le Sueur River Watershed, one of the major watersheds in the Minnesota River Basin. Field verification showed that these methods were highly successful. Upland depressions cover 19,896 ha, which is roughly 7% of the watershed. Critical riparian areas cover 73,734 ha, which is about one fourth of the watershed. Forested ravines cover roughly 2,000 – 3,000 ha of the watershed (0.9%). Results from this research can be used to guide selection of locations for implementation of precision conservation strategies. These strategies can be tailored to specific landscape functions and transport pathways for contaminants.

Keywords; **GIS, DEM, Terrain Analysis, Precision Conservation**

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 relatively unpolluted Mississippi River near the Minneapolis-St. Paul metropolitan area. The Minnesota Basin is part of the Upper Mississippi River Basin, which is known for its disproportionate contribution of nitrate loading to the Gulf of Mexico, leading to the problem of

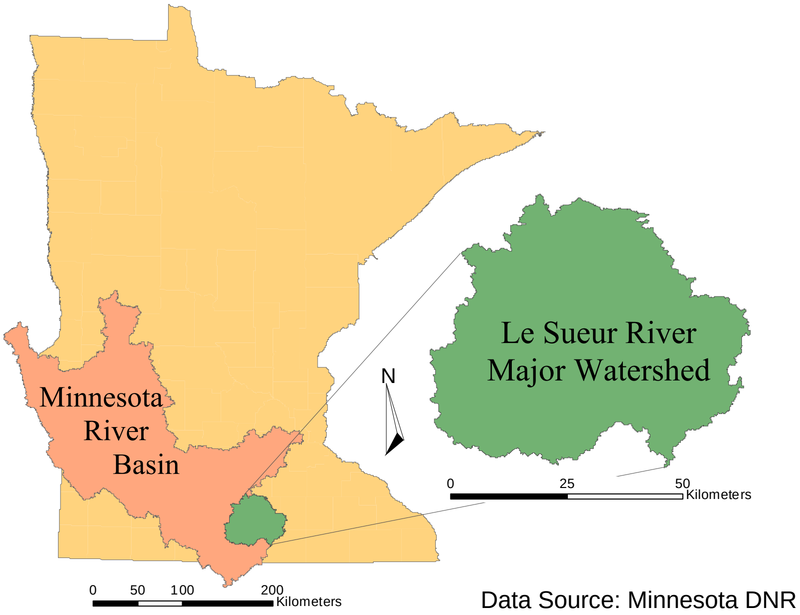


Fig. 1. Location of Le Sueur River Major Watershed within the Minnesota River Basin

hypoxia; over one-third of the nitrate loading to the Gulf of Mexico originates in this basin (Alexander et al., 1995).

The Le Sueur River Watershed is one of 12 major watersheds in the Minnesota River Basin. The Le Sueur River drains 2,880 square kilometers and flows into the Minnesota River near Mankato, MN and contributes a disproportionate amount of non-point source pollution. It is located on the eastern edge of the basin (Fig. 1), and receives 250 millimeters more in mean annual rainfall than watersheds located on the western edge of the basin. 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).

Determining which landscapes are major sources of agricultural pollution within the watershed is complicated by the mechanisms of transport. The variable source area concept (Brooks et al., 2003) explains how small portions of the landscape can contribute disproportionately to runoff and peak flows. Variable source areas are typically regions on the landscape located near streams and waterways that become saturated due to runoff and interflow from upper landscape areas. Precipitation falling on variable source areas generates runoff more quickly than at other landscape positions. These variable source areas are referred to as critical source areas for the purposes of this paper.

Due to a greatly expanding world population, there will be increased demands on agriculture in the future for food, feed, fiber, fuel, fowl and pheasants. These demands for a multifunctional landscape require a new approach to conservation, termed precision conservation. Precision conservation allows small portions of the landscape that have a disproportionate effect on water quality or wildlife habitat to be targeted with Best Management Practices (BMPs). Precision conservation can help alleviate the strain on our soil and water resources (Berry, et al., 2003). Precision conservation uses a set of spatial technologies and mapping approaches that account for spatial and temporal variability in topography, hydrology, and other natural resource parameters across natural and agricultural landscapes (Berry et al., 2003). Such technologies often involve remotely sensed data, terrain analysis and GIS to identify risky areas, reduce off-site transport of contaminants and direct management practices to buffer areas, water channels, and other areas of the landscape (Berry et al., 2003).

GIS and terrain analysis are utilized in this study to identify the locations of critical source areas that may contribute disproportionate amounts of agricultural pollution. Terrain attributes can be calculated from readily available digital elevation models (DEMs). Thresholds applied to these attributes create GIS data layers that can target 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.

METHODS

Thirty 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.

Most terrain attributes were calculated by employing the D∞ flow direction method (Tarboten, 1997). This approach 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 a larger scale, and therefore employed the D8 method of determining flow direction.

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 effective in delineating management zones in different types of analyses (Mulla, 1993).

Terrain Analysis Attributes

The attributes employed throughout this study include slope (S), specific catchment area (SCA), profile curvature, stream power index (SPI), and compound topographic index (CTI). These attributes have been used extensively to study topographic features of varying landscapes (Wilson and Gallant, 2000).

Unless otherwise noted, slope (S) 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.

Specific catchment area (SCA), also known as contributing area or flow accumulation, represents the total upslope land area that drains into any single cell. SCA was calculated based on the D∞ algorithm of flow routing (Tarboton, 1997).

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:

$$SPI = (SCA) \times (S)$$

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:

$$CTI = \ln(SCA / S)$$

Critical Source Area Classes

Ravines

Ravines are active erosional features that contribute a significant amount of sediments to nearby waterways. Ravines were delineated using the following parameters: natural log of SCA > 5.5, profile curvature > 0, degrees of slope > 10, and SPI > 7. Ancillary GIS data was used to further refine this approach; ravines were restricted to only those areas which were forested according to the national land cover dataset (EPA, 2001).

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 and accumulate surface water are referred to as upland depressions.

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 and validated by field visits in the Beauford Minor Watershed located in the Le Sueur Watershed. SSURGO 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.

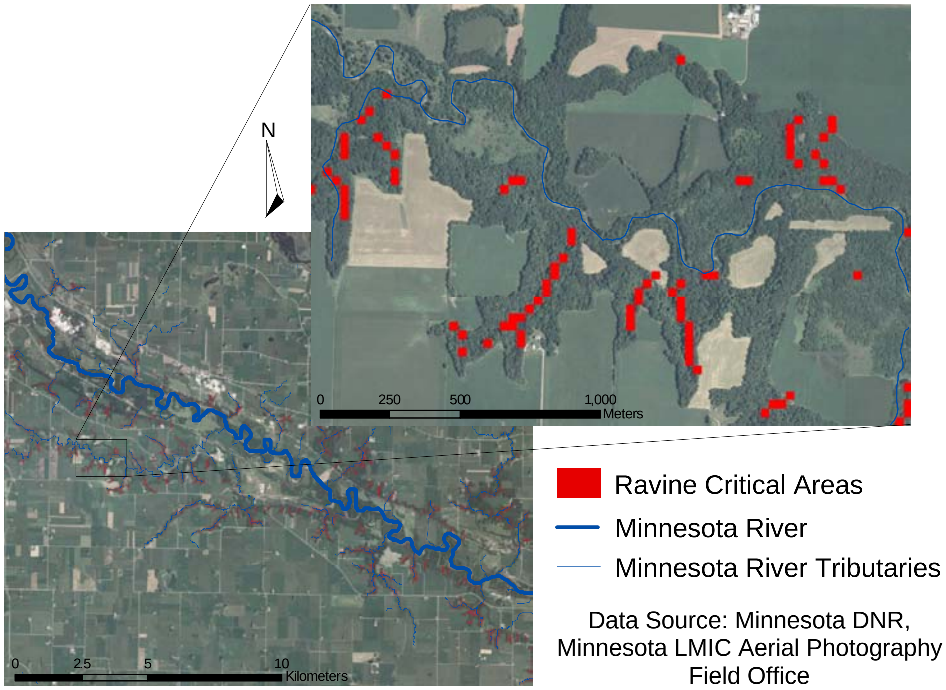
Riparian Areas

As mentioned earlier, the introduction of agricultural drainage has altered the surface hydrology of the Minnesota River Basin. Fewer wetlands that hold and evapotranspire water translate into increased overland flows. SPI is used here to delineate areas of high 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 into an even riskier landscape component. Smoothed SPI values greater than 10 were combined with areas of slope greater than 3 degrees to delineate what is termed priority riparian areas. These areas have both high stream power and a high potential for soil erosion by water.

RESULTS

Terrain analysis was effective at identifying ravines. A variety of sites were chosen for ravine field verification. Sixty-five sites were visited in the field, and 90% of those were confirmed as active ravines. These sites were distributed among 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. Delineation of ravines is illustrated in Fig. 2.



Data Source: Minnesota DNR, Minnesota LMIC Aerial Photography Field Office

Fig. 2. Example of Ravine Critical Areas located along the Minnesota River near Mankato, MN.

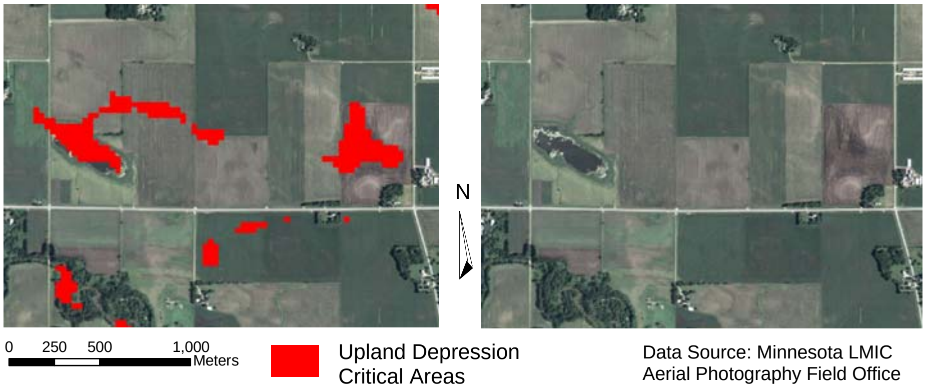


Fig. 3. Upland Depression Critical Areas located in the Beauford Minor Watershed.

Terrain analysis was effective at identifying upland depressions. These features were verified in the Beauford minor watershed, which aided in determining attribute thresholds. When present in an agricultural field, these depressional features are typically dealt with by installing open surface inlets that route water underground to subsurface drain tiles. Prior to agricultural drainage, these topographic features held water, which reduced peak flows due to temporary storage and evapotranspiration. These features also improved the quality of water by removing sediments and NO_3. Open surface inlets increase the volume of water generated from the landscape and also decrease the natural ability of these landscape features to improve water quality. These areas could benefit by replacing drain inlets with rock inlets or French drains that regulate water flows and filter sediments. Delineation of upland depressions is illustrated in Fig. 3.

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

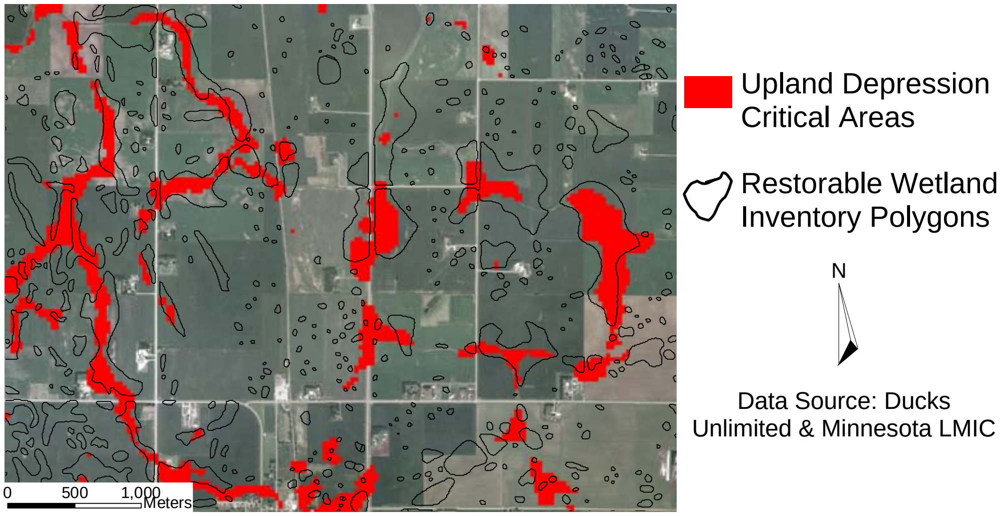


Fig. 4. Visual comparison of upland depression critical areas and hand-digitized restorable wetland inventory polygons.

rapidly, albeit at a coarser resolution. Broader upland depression features on the landscape show up well using terrain attributes derived from 30 meter DEMs; however, this method fails to identify small polygons that have been accurately hand-digitized (Fig. 4). As previously mentioned, the Le Sueur watershed is amongst the top contributors to 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).

Riparian critical areas can be used to locate probable transport pathways for contaminants during periods of heavy rainfall or peak flows. These features would benefit from conservation efforts such as vegetative buffers or when present in an agricultural field, they may be sites well suited for becoming grassed waterways. The Beauford Minor Watershed, located within the Le Sueur River Watershed, was used as a pilot watershed to calibrate and validate applied thresholds. Fig. 5 displays the minor watershed as well as potential transport pathways identified by riparian critical areas.

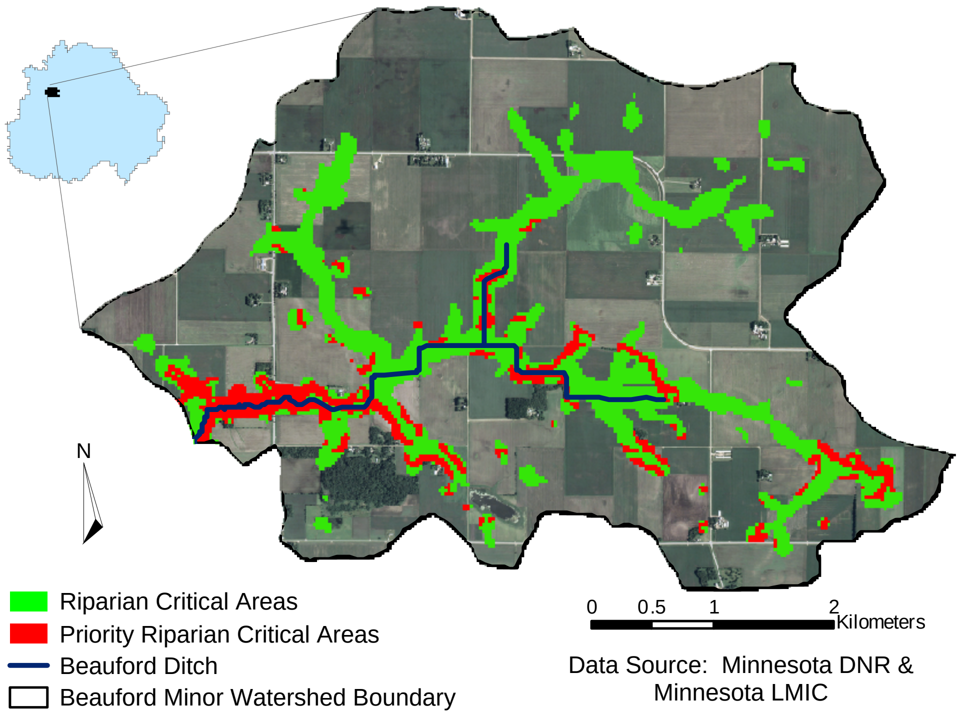


Fig. 5. Riparian critical areas in the Beauford Minor Watershed and its location within the Le Sueur River Major Watershed.

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. Areal extent of critical areas within the Le Sueur River Watershed. Here agricultural production refers to national land cover dataset pixels in either a pasture or cultivated crop condition (EPA, 2001).

Upland depressions cover only 7% of the watershed, but a majority of these features are in agricultural production. Riparian areas make up more than one fourth of the watershed, and over half of these features 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 gives descriptive statistics of critical area coverages in the Le Sueur River Watershed.

DISCUSSION

The effectiveness of best management practices (BMPs) depends on placing them in vulnerable portions of the landscape (Mulla et al., 2008). Typical government funded conservation efforts are often limited in funding amounts and are based on voluntary sign-ups which may not enroll the most vulnerable portions of the landscape. An adjustable land classification system has been proposed in the past to overcome these limitations and institute a dynamic funding availability process (Larson et al., 1988). Terrain analysis could be used in conjunction with such an approach to identify the most critical landscapes for conservation programs. A system could be employed that would match the amount of conservation funding to the extent of critical lands. Adjustable terrain attribute thresholds could rapidly refine or expand such land classification. Funding set aside for eligible lands may target conservation efforts more effectively than a traditional first-come first-served basis.

Terrain analysis is not necessarily the best method for identifying critical landscape features. More detailed methods can produce highly accurate landscape analyses; however, these methods can become time consuming or may produce results at a fine resolution, but limited spatial scale. Terrain analyses only identify broad landscape features limited to the spatial resolution of the DEM they were derived from, but these methods are simple to employ and take relatively short processing times to analyze large datasets. When very fine spatial resolution is not required or analysis of large land surface areas are needed, terrain analysis may minimize data processing times and maximize efficiency of conservation placement on the landscape.

Terrain analysis of finer resolution elevation data is being investigated. 1 and 3 meter LIDAR data have been acquired for a limited area within the Minnesota

River Basin. A full suite of terrain attributes have been calculated and are currently being analyzed. Preliminary results show these data can be very effective at locating erosional features at the field scale. However, when employing the D∞ method for flow routing (Tarboton, 1997), grids must be smaller than 7000 x 7000 cells. This can be as small as an area of 5000 hectares with fine resolution data. Terrain analysis with high resolution LIDAR data is limited by software and hardware constraints, so that it is not currently feasible at a major watershed scale.

CONCLUSIONS

To accommodate an ever increasing world population, the use of natural resources must be better managed in order to achieve sustainability. 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. Not only are these strategies relatively easy to employ, but the increasing availability of highly accurate digital elevation models allow these strategies to be employed in nearly any location in the world. Also, with the advances in LIDAR imagery and increased computing power, these methods can be employed at very fine spatial scales with accurate results.

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