LAND COVER CHARACTERISTICS
IN THE
KARST REGION OF SOUTHEASTERN MINNESOTA

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ABSTRACT

Anthropogenic land-use activities can affect regional biophysical processes and functioning of neighboring land areas impacting the human and natural communities found in these areas. Karst landforms add complexity to land-use management. The term "karst" describes predominately limestone and dolostone landforms weathered primarily through a chemical dissolution process. Over geologic time, karst features including sinkholes, bedrock springs and fractures, sinking streams and caves form on and under the land surface. Studies that further our understanding of land cover and land use, especially in sensitive land areas can inform and improve land management and policy development for those areas. Through three projects, this thesis examined land and land-use characteristics in a regional karst landscape. Physical spring characteristics were analyzed to determine whether a subset of spring characteristics can discriminate springs into bedrock units or aquifer units. A subset of characteristics was found that discriminated the springs into both bedrock units and aquifer units. Springs had a clumped distribution on the landscape with most springs found at low elevations. For the second project, land pattern metrics were examined for a county-delineated land area and compared with pattern metrics in the major watershed overlying that county area. Differences between patterns of variation in metrics for the watershed versus the county area including greater fragmentation in the county landscape, fewer components of variation in the watershed and greater importance of land cover diversity in the watershed. For the last project, local municipal protection of regional natural resource processes was examined by determining the extent of local policy coverage on landscape functions and ecosystem services. Current coverage and gaps were

identified. Policy changes directed at incorporating landscape functions into land-use planning were presented. This research provides new information about spring characteristics, land pattern metrics, and policy coverage of natural resources and ecosystem services, contributing to the accumulation of knowledge of land use and land cover characteristics, especially for karst regions, including that found in southeast Minnesota.

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PROLOGUE

Karst landscapes add an underground dimension to land management. The term "karst" describes predominately limestone and dolostone landscapes primarily weathered through a chemical dissolution process. Over geologic time, karst bedrock features including springs, sinkholes and caves form on and under the landscape. Because these features focus storm-water or melt-water runoff quickly into the subsurface, little or no filtering of pollutants occur making these systems vulnerable to nonpoint source contamination. In the United States, approximately 25% of land is karst (Aley 2002). Globally, approximately 20% of the earth's land surface is karst (Gvozdetskii 1967 as cited by White 1988).

Karst features like springs, can influence and be influenced by regional land cover characteristics (Ryan and Meiman 1996). Springs are areas on land where the water table and land surface intersect, and ground water discharges to the surface. Quantity and quality of spring discharge is dependent upon the spring's spatial location and the regional land cover in the spring's recharge and discharge area. Some land use activities can contaminant ground-water systems. Conversely, natural land cover can filter water that recharges a spring or can provide cover to protect spring waters. Forests, for example, that surround springs and associated stream systems are important for keeping spring and stream water temperatures cool. Biophysical connections exist between forest cover, springs and cold-water ecosystems. These connections have implications for forest, spring and cold-water stream management.

Land-use policy and land management activities that promote the sustainability and viability of forest ecosystems also promote the sustainability of spring discharge and associated cold-water ecosystems. Evaluations of land cover composition and land patterns could help inform land and watershed planning and policy development. Land cover composition can characterize the primary matrix of land cover dominant in specific areas. Land cover patterns can characterize spatial arrangements of land cover and can potentially reveal information relating to the viability of natural resources. For example, patterns that indicate connections between size and connectivity for specific types of natural land cover suggest that sustainable spatial arrangements exist for that land cover type (Leitao et al. 2006). Comparisons of land cover composition and patterns in local politically-delineated areas versus overlying naturally-delineated areas could also help inform land and watershed planning and policy development. For example, if smaller patches of forest cover are found in the watershed than is seen in the overlying county, watershed policy might be created or modified to promote or mandate larger areas of forested springshed areas to better sustain springs and associated cold-water ecosystems.

In karst regions, land-use activities can easily degrade water resources. In a few karst regions, municipalities have developed ordinances to deal explicitly with problems associated with karst-related land-use and construction-related activities (LaMoreaux et al. 1997; Fischer 1999). However, despite the scientific and regulatory recognition of karst-related land-use problems, some karst land areas remain unprotected and unmanaged with respect to human activities.

Although our understanding of karst hydrogeology has grown in the last few decades, there are still important research gaps. For example, while some studies have examined the physical characteristics (Beck 1995; Peterson and Vondracek 2006), the spatial distribution (Dalgleish and Alexander 1984; Dalgleish 1985; Magdalene 1995; Magdalene and Alexander 1995; Witthuhn and Alexander 1995; Gao and Alexander 2003; Gao and et al. 2005; Gao and Alexander 2008) and the regulatory recognition (Quinlan 1986; Dinger and Rebmann 1991; Bade and Moss 1999; Fischer 1999) of sinkholes, there is little work examining these characteristics of springs. As a critical component supporting a multi-state, regional billion dollar fishing industry (Gartner et al. 2002; Hart 2008), characteristics useful for informing spring management should be better understood. Second, there is little work examining land cover patterns on small spatial scales where most land-use decisions are made. Examination and comparisons of local politically-delineated and watershed-delineated land patterns and land composition can help inform the decision-making process. Third, there are several reviews of local regulatory actions designed to prevent or mitigate environmental problems related to human development activities in karst areas (Beck, 1995; Ralston et al., 1999), but no reviews to evaluate the extent of policy coverage of landscape functions or the ecosystem services produced in karst areas. Policy protection of these natural processes should be implemented and reviewed in karst areas because problems associated with land-use activities in karst areas affect the physical and economic health of human communities, natural resources and wildlife.

To examine these objectives in areas where land use is primarily locally determined, each study is conducted in one of two counties in southeast Minnesota - Wabasha County or Winona County. The same bedrock formations cross both counties (Mossler and Book 1984; Mossler 2001). Both counties have similar land cover characteristics and are governed by five county commissioners and one county administrator. The dominant land cover in both counties is cultivated land (Wabasha 53%, Winona 43%) followed by forest (Wabasha 25%, Winona 35%) then hay/pasture/grassland (Wabasha 13%, Winona 14%). Both counties have comprehensive land plans and county ordinances available through their websites (Wabasha - http://www.co.wabasha.mn.us, Winona - www.co.winona.mn.us).

These similarities extend to the other counties in southeast Minnesota. Unlike the Minnesota counties outside of this region, southeast Minnesota counties primarily utilize bedrock sources of drinking water (DNR 2000). Sharing similar bedrock characteristics, a hydrogeologic framework of the entire southeast Minnesota region has been developed for environmental managers and scientific investigations (Runkel et al. 2003). These counties also share similar climate and annual average surface runoff (DNR 2000). In response to concerns about water quality and soil erosion, tillage best management practices for water quality protection have been developed specifically for the entire southeast Minnesota agriculturally-dominated region (Randall et al. 2002). All counties in this southeast region have documented springs and sinkholes in a karst feature database developed for southeast Minnesota (Gao et al. 2002). All counties except Dakota, Dodge and Houston have documented stream sinks listed in the karst feature database. All counties except Houston have a completed County Geologic Atlas.

Sharing similar physical, biological and geological characteristics, the counties in this southeast region of Minnesota also share recommended vision, goals and strategies for the land area (MFRC 2003) and for forest resource management (Class and Skally 2002). Because of these similarities, conclusions from these three case studies can apply broadly to the other counties in this region.

With the widespread use of geographic information systems (GIS) and free software available from the internet (i.e. Fragstats), these analyses can be carried out for most, if not all, karst regions in the United States (U.S.). In addition, many U.S. political units post ordinances and regulations on their community websites, freely available for download. Where electronic versions are not available, printed copies are generally available by request. These analyses could also be done for karst regions outside of the U.S., but they might be limited by the availability of spatial data layers (e.g. soils or elevation) or GIS software.

The goal of my research was to develop a better understanding of: (1) springs, a common, but not well-studied karst feature, (2) county-scale and watershed-scale land patterns and (3) policy coverage of landscape functions and ecosystem services in a local community in the karst region in southeast Minnesota. My dissertation, subdivided into three chapters, adds to studies investigating land cover characteristics and regulatory coverage in karst regions. My objectives were to: (1) examine characteristics that describe the physical locations of springs, and then to examine the potential use of those characteristics for classifying springs into their associated aquifer group or bedrock unit, (2) quantify and compare county-scale land cover patterns with land cover patterns in the overlying major watershed area, and (3) examine county and city ordinances for coverage of karst features, landscape functions and ecosystem services.

Chapter 1 - Spring Distributions in Winona County, Minnesota, USA.

Currently, in the southeast Minnesota karst region, sinkholes are the only surficial geologic feature that have been analyzed (Dalgleish and Alexander 1984; Dalgleish 1985; Magdalene 1995; Magdalene and Alexander 1995; Witthuhn and Alexander 1995; Gao and Alexander 2003; Gao et al. 2005; Peterson and Vondracek 2006; Gao and Alexander 2008). However, springs are also an important surficial geologic feature serving as: discharge points for aquifers, indicators of aquifer characteristics, water sources for streams and critical habitat components for cold-water aquatic ecosystems. Identification and protection of springs is needed for sustainable land and water management to support spring water quality and quantity, and subsequently for the conservation of cold-water aquatic populations. In addition, in southeast Minnesota, trout fishing and tourism form a multi-million dollar industry for human communities (Gartner et al. 2002; Hart 2008). In the larger four-state ecoregion encompassing this area, estimates of the total impact of trout anglers put regional economic contributions of the annual usage of this natural resource to be in excess of $1.1 billion dollars (Gartner et al. 2002; Hart 2008). A better understanding of characteristics describing spring locations could help natural resource managers mitigate activities affecting natural spring inputs to stream systems supporting both natural and economic processes.

For this first chapter, I examine the spatial pattern of spring distribution through a nearest neighbor analysis and then gather characteristics describing the physical locations of springs. I examine these physical location characteristics for their ability to discriminate springs into their associated surficial aquifer groups or bedrock units. My objectives are to conduct a nearest-neighbor analysis to examine the distribution of springs across the county and then use a discriminant function analysis to examine physical characteristics describing spring locations for their ability to discriminate springs into their associated surficial aquifer groups or bedrock units. My hypotheses are that springs are located randomly across the landscape and that there are no characteristics describing physical spring locations that can discriminate springs into surficial geologic groups - bedrock units or aquifer units. The study site, Winona County, was chosen because this county has spatially-explicit geologic and karst information in a geographic information database available for research use.

Chapter 2 – No county is an island: a comparison of watershed- and county-scale land pattern metrics in southeast Minnesota, U.S.A.

For this chapter, I examine and compare land pattern metrics in a county-delineated area with those in the overlying major watershed. Studies examining pattern metrics typically focus on land cover specific to urban areas, watersheds, riparian areas, forests or other plant communities. Rarely do studies examine and compare pattern metrics found in natural land areas with those in areas that geographically overlap but are delineated by political boundaries. This type of analysis can provide information relating to differences in land cover between the two areas. These extraterritorial (territory outside of delineated boundaries) considerations are needed because land-use decisions affect and are affected by the larger-scale physical environment and by the activities of neighboring communities.

The goal of this chapter is to identify and compare major gradients of variation in pattern metrics for a politically-delineated county area and its overlying major watershed. Specific objectives of this chapter are to (1) quantify pattern metrics for each area, (2) identify pattern metrics most useful for characterizing the land patterns in each area using factor analysis, and (3) identify and describe differences in primary pattern metrics between these two areas.

Chapter 3 – Thinking globally while governing locally: local regulation of ecological processes

Every landscape performs functions which can be related to the natural maintenance of the landscape in the absence of humans (e.g. Mitsch and Gosselink 2000). Conversely, ecosystem services describe natural landscape processes that produce goods and services directly used or consumed by humans (Daily et al. 1997). For the final objective, local municipal protection of regional natural resource processes is examined by determining the extent of local policy coverage on landscape functions and ecosystem services. I examine the extent to which municipal policies acknowledged or protected regional landscape functions and ecosystem services. Current coverage and gaps are identified. Policy changes directed at incorporating natural resource functions and ecosystem services into land planning are presented.

I wrote all three chapters in the form of manuscripts to be submitted to peer-reviewed journals for publication. Some of the data and analysis from chapter 3 have been published in the Summer 2008 *CURA Reporter*: Ziegler, S.S. and M.A. Williams. 2008. Land-Use Policy to Conserve Resources in Southeastern Minnesota. *CURA Reporter*. 38(2):13-21.

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Chapter 1

Spring distribution in Winona County, Minnesota, USA and the relationship with geologic strata in a karst landscape

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Springs, points where the landscape and water table intersect and ground water discharges, link aquifer systems with land surfaces and water bodies. As such, in many regions, they are critical to the viability of cold-water fish communities. A nearest neighbor analysis and a discriminant function analysis (DFA) of springs were conducted in Winona County, Minnesota, USA, a karst landscape, to better understand spatial distribution of springs and as a potential method for identifying variables that characterize aquifer or bedrock locations of springs. Twenty-two variables describing the locations of springs were analyzed to ascertain their ability to discriminate correct aquifer unit or bedrock unit classification for each spring. Springs were clumped with the highest densities in the lowest elevations. Springs were correctly assigned to aquifer units and bedrock units with eight and 11 landscape variables, respectively. Consideration of upland human activities on spring discharge, along with a better understanding of characteristics describing spring locations could lead to better management activities that protect springs and their important contributions to the ecohydrology of the region.

Keywords
karst, spring, nearest-neighbor analysis (NNA), discriminant function analysis (DFA), Minnesota

1. Introduction

Karst is predominately limestone and dolostone landforms primarily weathered through a chemical dissolution process. Globally, approximately 20% of the earth's land surface is karst (Gvozdetskii, 1967 as cited by White, 1988) and in the United States (U.S.), approximately 25% of bedrock is karst (Aley, 2002). Over geologic time, karst bedrock features such as springs, sinkholes, and caves form on and under the landscape adding an underground dimension to land and watershed management. Because these features focus storm-water or melt-water runoff quickly into the subsurface, little or no filtering of pollutants occur making these systems vulnerable to nonpoint source contamination.

Springs, points where the landscape and water table intersect and ground water discharges, link regional aquifer systems with land surfaces and water bodies. Springs in karst regions have been used to study discharge as a possible indicator of water quality (Mahler and Lynch, 1999; Wicks et al., 2004; Davis et al., 2005; Zhou, 2008), to study aquifer characteristics (Bonacci, 1993; Doerfliger et al., 1998; Amit et al., 2002; Toran et al., 2007), and to examine interactions between spring flow and biological activity (Bartodziej and Perry, 1990; Wilcox et al., 2005; Tenorio and Drezner, 2006).

In many karst regions, springs are a critical cold-water component for fish hatcheries and aquatic fish species, particularly trout (Anderson, 1983; McClendon and Rabeni, 1987; Thorn, 1988; Blann et al., 2002; Wicks et al., 2004; Whitledge et al., 2006; Brewer et al., 2007). In the midwestern U.S., hydrogeologic characteristics have been related to trout stream habitat quality (Poff and Allan, 1995; Richards et al., 1996). Characteristics describing geology and regional land use have also been linked to stream water quality, invertebrate production and trout population characteristics (Krueger and Waters, 1983; Troelstrup and Perry, 1989; Vondracek et al., 2000; Blann et al., 2002). In many karst regions, cold-water streams arise from or are supplemented by cold ground-water springs critical for trout.

Trout fishing is an important component of the regional economy, in many karst regions. Fishing activities contribute to tourist operations, local business success, fish hatchery operations, park visitations and local food markets (Gartner et al., 2002; Hart, 2008). Natural resource managers have long understood the need to conserve cold-water inputs to trout streams and research continues to inform the need for a better understanding of the fundamental relationships between land-use management and cold-water ecosystems. Consideration of human activities upland of spring discharge is important for informing management activities that could protect springs and their important contributions to the ecohydrology of the region. Tools useful for characterizing springs and areas where they are located could inform ordinance development (e.g. zoning), natural resource protection and water management.

The goal of this study was to improve our understanding of the distribution and landform characteristics of springs in an environmentally-sensitive karst region where springs are known to be a critical cold-water habitat component of trout streams. These trout streams support regional fishing activities that have recently been valued as a mult-million dollar economic industry for the human communities living in this area (Gartner et al., 2002; Hart, 2008). In the karst region of southeastern Minnesota, we chose to examine springs in Winona County because this county is similar in geology to the regional karst area and is one of the few counties in this region with a geographic information database containing spatially-explicit geologic and karst information.

Our objectives were to conduct a nearest-neighbor analysis to examine the distribution of springs across the county and then to use a discriminant function analysis to examine physical characteristics describing spring locations to discriminate springs into their associated surficial aquifer groups or bedrock units. Our hypotheses were that springs are located randomly across the landscape and that there are no characteristics describing spring locations that can discriminate springs into surficial geologic groups - bedrock units or aquifer units. However, if characteristics were found to be important for describing spring locations, these characteristics could be used to improve our understanding of spring systems, to improve the potential for locating springs not currently mapped, and for informing future land and water management activities in this area and in other karst regions.

2. Methods

2.1 Study Site

Winona County is located in the southeastern corner of the state of Minnesota (Figure 1). The topography in this county consists of a Paleozoic plateau dissected by deep valleys with streams tributary to the Mississippi River (Trimble, 1983). Unlike most of Minnesota, the southeastern corner of the state, including Winona County, escaped most coverage from the most recent North American glaciation, and with almost no glacial drift, is referred to as the Driftless Area Ecoregion (Omernik and Gallant, 1988). Between these tributaries lie areas that stand as level plateaus, composed primarily of karst and sandstone. Numerous karst features such as springs, sinkholes and caves have formed in this area. Currently, there are 300 documented springs in Winona County (Gao et al., 2002).

The eastern boundary of Winona County is the Mississippi River, which establishes the base elevation for the topography of the county. The entrenchment and lowering of the upper Mississippi River during the Pleistocene lowered the regional base level, resulting in upland plateaus subject to greater erosion and dissolution through fluvial processes. The development of Ordovician carbonates in the county is partially controlled by this base-level topography defined by the deep valleys cut into the Cambrian sandstones. These carbonates have been shaped over time from both karst and fluvial processes. With intermittent and perennial streams flowing across the landscape, both surface and ground water act as geomorphic agents in the evolution of the landscape. Sinkholes, joints, conduits, and fractures continually evolve as water courses over and through the landscape. Flooding events enhance these processes and point to the need for continual monitoring of the evolution of this landscape.

Karst in Winona County actively forms in lower and middle Ordovician dolostones and limestones (Table 1). The largest surface bedrock unit consists of the Prairie du Chien Group (Figure 2). The Galena-Decorah-Platteville Formations are found in the southwestern area of the county. The Ironton-Galesville Sandstones are the lowest exposed bedrock in the county.

2.2 Characteristics describing spring locations

As a result of regional hydrogeologic research, a karst feature database containing thousands of georeferenced karst features for southeastern Minnesota has been developed for use by researchers and land managers (Gao et al., 2002). All features in this database are recorded in a geographic information system (GIS) data layer and made freely available to researchers and land managers. These features include springs, stream sink/sieves, sinkholes, seeps and outcrops. Variables describing the location of the 300 springs (Gao et al., 2002) were derived by intersecting the point locations of spring from this database with GIS layers containing spatial land cover information for this county.

In this karst region, hydrogeologic research has revealed that certain juxtaposed bedrock units behave hydraulically as one aquifer unit (Kanivetsky, 1984). Therefore, characteristics describing the locations of springs were analyzed separately for potential classification into two geologic groups - bedrock units and aquifer units. Two variables were created as indicators of the physical connection between springs and cold-water streams. One variable was created to define the distance from the spring to the nearest stream segment and another variable was created to indicate whether or not the nearest stream segment was a designated trout stream. Distance from spring to nearest stream segment was determined using a Minnesota Department of Natural Resources (MNDNR) Arcview extension (Minnesota Department of Natural Resources, 2008a). Stream type ("P"=Perennial or "I"=Intermittent) and the stream's trout designation ("0"=not designated as a viable trout stream or "1"=designated trout stream or protected tributary to a designated trout stream) were determined from the nearest line segment in the stream line layer. Distance from spring to the nearest bedrock group was also determined using the MNDNR extension with the spring point layer and the bedrock geology layer.

Elevation and slope were derived from a United States Geological Survey (USGS) 1:24,000 scale Level 2, 30-meter digital elevation model (DEM) for the state of Minnesota. Land cover data were from the 1990 International Land Use/Land Cover data with an original nineteen category classification scheme reclassified into eight land cover categories - urban/rural development, cultivated land, hay/pasture/grassland, brushland, forest, water, bog/marsh/fen and mining. Geomorphological designations were derived from a Minnesota Geological Survey (MGS) 1:100,000 geomorphology data layer created for the state of Minnesota. Intersection of the spring and geomorphology layers produced a geomorphology code for each spring combining: a one-character geomorphic association (e.g. "F"=Fluvial), a two-character glacial phase designation (e.g. "Wi"=Wisconsinan), a single digit ordinal value expressing general terrain topography (e.g. "1"=Level) and a one-character designation for the sedimentary association (e.g. "A"=Alluvium).

Soil classification systems provide standard delineations of land areas and, as such, are useful for characterizing general locations of land features. For this study, the soil unit designation for each spring location was derived by intersecting the spring data layer with a general soils classification map of Minnesota (Cummins and Grigal, 1980). The soil units in this generalized map were delineated based on parent material, climate, topography, organisms and time.

Winona County has seven surficial bedrock units (Figure 2) comprising five aquifer units (Figure 3). Springs are currently documented in five of these bedrock units and in three of the aquifer units. As a comparison, the potential for discrimination using variables that described spring locations was analyzed separately for bedrock units and aquifer units.

The Galena and Decorah Shale bedrock units contain a low number of springs and were merged and treated as one bedrock unit for the bedrock unit discrimination. The Shakopee and Oneota bedrock units were also merged. Each of these two pairings is considered to behave as a single hydrologic unit (Kanivetsky, 1984).

2.3 Statistical analyses

A nearest-neighbor analysis of the 300 springs in Winona County was conducted using the ArcView 3.2 Nearest Neighbor Analyst v1.0 extension to test the null hypothesis that springs are located randomly across the landscape.

A Kruskal-Wallis test was used to test the hypothesis that there were no differences in elevation, nearest bedrock contact, nearest stream segment and slope (Table 3) among the bedrock units and among the aquifer units. When differences were found, a Duncan's multiple-range test was used to identify significant differences between units. Categorical characteristics were dummy-coded into separate variables for statistical analyses (Table 2).

Georeferenced spring points (Gao et al., 2002) along with an array of variables describing spring locations were used to conduct discriminate function analyses (DFA) to determine whether subsets of characteristics could be used to classify springs into geologic groups. The general steps in a DFA are to 1) identify the subset of variables most useful for discriminating between groups, 2) create and then evaluate a classification model using the identified subset of variables and 3) test or validate the classification model using a second independent data set.

A stepwise discriminant analysis (SAS v9.1) was conducted to identify which subset of variables discriminated best among the geologic groups to test the null hypothesis that no variables discriminate springs into geologic groups. A random drawing of 200 springs (60% of observations) was used to create and then evaluate a classification model. Remaining observations (n=100, 40% of observations) were used to validate discriminate functions, producing a predictive classification matrix with error count estimates.

3. Results

Nearest-neighbor analysis (R=0.45, t=18.21) indicated that the springs in Winona County are clumped (Figure 1). Mean spring elevation was 277 m above sea level with a 25% slope, and located 60 m from the nearest stream segment and 90 m from the nearest bedrock contact. The greatest number and density of springs and the longest length of trout streams were in the St. Lawrence-Franconia Formation bedrock unit and the St. Lawrence-Franconia-Ironton-Galesville aquifer unit (Table 3). Among the bedrock units, the Prairie du Chien bedrock unit had the largest area of land and the lowest spring density. Among the aquifer units, the Prairie du Chien-Jordan aquifer unit had the largest area of land and the lowest spring density. The Galena aquifer unit and Galena bedrock unit each represent the same spatial area. This area, the stratigraphically highest and spatially smallest unit, had the smallest length of total stream length and did not contain any trout stream segments.

3.1 Aquifer Units

The St. Lawrence-Franconia-Ironton Galesville aquifer unit had the highest density (0.78 springs/km^2) and the Prairie du Chien-Jordan had the lowest (0.06 springs/km^2) density of springs among the aquifer units (Table 3).

Significant differences were found between aquifer units for elevation (Kruskal-Wallis Test, H=85.6, 4 df, p<0.001), distance to nearest bedrock contact (Kruskal-Wallis Test, H=28.2, 4 df, p<0.001) and distance to nearest stream segment (Kruskal-Wallis Test, H=12.8, 4 df, p<0.002). For each of these variables, Duncan's multiple-range tests identified differences between the bedrock units (Table 3). Spring elevation was different (Duncan's multiple range test p<0.001) across aquifer units with the Galena Aquifer highest, the St. Lawrence-Franconia-Ironton-Galesville Aquifer lowest, and the Prairie du Chien-Jordan Aquifer intermediate. The mean distance to nearest bedrock was similar for the springs in the Galena Formation and springs in the lower elevation Prairie-Du Chien-Jordan aquifer group, but were greater than for the St. Lawrence-Franconia-Ironton-Galesville Aquifer. The Galena Formation had the greatest distance to nearest stream segment (Duncan's multiple range test p<0.05) relative to the other two aquifer units. Spring slope was not different among aquifer groups.

Variables that best discriminated spring membership relative to aquifer units were two geomorphology types – TWp2B and Fwi1Rng, three soil types, elevation, forest land cover type, and distance to nearest bedrock contact (Table 4). Geomorphology variable TWp2B reflected contributions of Wisconsinan fluvial and dissected bedrock terrain characteristics to spring classification. Geomorphology variable FWi1Rng, describing fluvial, level topography characterized lower elevations of springs in older bedrock (Figure 4). Soil units 902, 903, and 908 discriminated springs in the aquifer units. Soil unit 902, representing hapludoll dominant soil groups on unglaciated or lightly glaciated slopes, terraces and floodplains (Cummins and Grigal, 1980), closely follows the spatial pattern of the Franconia-Ironton Galesville aquifer unit (Figure 5) encompassing most springs in the study area.

Soil units 903 and 908 were found in the southwestern area of the county. Soil unit 903 described hapludalf, haplaquoll, or hapludoll dominant soil groups on eroded till plain and bedrock. Soil unit 908 described hapludalfs, arigdolls, or hapludalfs on unglaciated or lightly glaciated uplands. All of the springs in the Galena bedrock unit and aquifer unit were located on one of these two soil units. On average, the springs in these soil units were at higher elevations, greater distances to the nearest bedrock contact and stream segment, and smaller slopes (Table 5).

The discriminant function analysis discriminated spring membership between aquifer units (Wilks' Lambda=0.13, $F_{16,380}$=41.01, $p < 0.001$). Using the subset of significant variables to create and calibrate a predictive classification matrix of springs classified into aquifer units using a random sample of 200 of the observations, 84% of the 200 observations were correctly classified. Correct classifications were obtained for 86% of the springs in the Galena aquifer unit, 84% in the Prairie du Chien-Jordan and 83% in the Franconia-Ironton Galesville (Table 6). Validating the predictive capabilities of the classification with the remaining 100 observations, 72% of the 100 observations were correctly classified. Correct classifications were obtained for 57% of the springs in the Galena aquifer unit, 86% in the Prairie du Chien-Jordan and 68% in the Franconia-Ironton Galesville (Table 7).

3.2 Bedrock Units

The St. Lawrence-Franconia Formation bedrock unit had the highest density (0.83 springs/km^2) of springs and the Prairie du Chien had the lowest density (0.03 springs/km^2) of springs.

Significant differences were found between bedrock units for elevation (Kruskal-Wallis Test, H=135.2, 4 df, $p<0.001$), distance to nearest bedrock contact (Kruskal-Wallis Test, H=63.1, 4 df, $p<0.001$) and distance to nearest stream segment (Kruskal-Wallis Test, H=15.4, 4 df, $p<0.001$). For each of these variables, Duncan's multiple-range tests identified differences between the bedrock units (Table 3). Elevation was different (Duncan's Test, $p < 0.001$) across all units. Springs in the Prairie du Chien bedrock unit, had the greatest distance to nearest bedrock contact and were significantly different (Duncan's Test, $p<0.001$) from the other units. Spring slope was similar among bedrock units.

Variables that best discriminated spring membership relative to bedrock units were elevation, four soil types, two geomorphology types – TWp2B and Fwi1Rng, forest land cover, trout designation of nearest stream segment and a nearby intermittent stream segment (Table 4). Soil units 419, 903, 908, and 912 characterized springs in the bedrock units. Soil unit 419 describes udorthent or hapludoll dominant groups on steep slopes adjacent to river terraces and floodplains. Soil unit 912 describes fluvaquents, udifluvents, or hapludolls on terraces and floodplains. Springs in these two soil units had the lowest mean slope elevations, shorter mean distances to the nearest bedrock contact and larger mean slopes (Table 5).

The discriminant function analysis discriminated spring membership into bedrock units (Wilks' Lambda=0.53, $F_{44,709}$=18.7, $p < 0.001$). Using the reduced set of variables to create a predictive classification matrix of springs classified into bedrock units using a random sample of 200 of the observations, 70% of observations were correctly classified. Correct classifications were obtained for 86% of the springs in the Galena bedrock unit, 40% in the Prairie du Chien, 83% in the Jordan Sandstones, 72% in the Franconia Formation and 59% in the Ironton Galesville (Table 6).

Validating the predictive capabilities of the classification with the remaining 100 observations, 57% of observations were correctly classified. Correct classifications were obtained for 57% of the springs in the Galena bedrock unit, 15% in the Prairie du Chien, 87% in the Jordan Sandstones, 59% in the St. Lawrence-Franconia Formation and 55% in the Ironton Galesville bedrock unit (Table 7).

4. Discussion

4.1 Spring Distributions

In Winona County, we found several characteristics of spring distributions that could be useful for informing land and water management. Springs were found to be clumped with the highest number and density of springs found in the lowest elevations. The highest density of springs and the longest length of trout streams occur in the St. Lawrence-Franconia Formation bedrock unit indicating the greater propensity in this specific land area for the occurrence of springs and viable trout stream segments.

A majority of springs are located on forested land, the only land cover variable important in the aquifer and bedrock unit classifications. Relationships among forest cover, springs and cold-water ecosystems reflect a physical connection having implications for forest, spring and trout stream management. Riparian forest cover that shades discharged spring water can aid in keeping water temperatures low in cold-water aquatic ecosystems. A recent study of land patterns in this area has indicated that mean forest patch area and gyration (a measure of the spatial spread of patches), were important components of land cover patterns that support viable forest processes in this area (Chapter 2). Land-use management could work to conserve this relationship to preserve regional forest processes to benefit spring and stream waters.

Conversely, land-use activities that might reduce forest cover around springs could increase surface runoff, sediment, pollution and warm-water contributions to streams, and can modify stream water chemistry (Arthur et al., 1998; Brooks et al., 2003). With potentially increased surface runoff and decreased recharge to springs, the mitigating effect of cold-water spring contributions to streams could diminish with subsequent degradation to cold-water ecosystems (Sullivan et al., 1987; Blann et al., 2002). Forest best management practices (BMP) that minimize or prevent changes to hydrological characteristics and sediment inputs to springs and stream segments could also minimize or eliminate loss of shading for these areas. Vegetated buffers, suggested as a water quality BMP for sinkholes (Peterson and Vondracek, 2006), could be used to protect springs in upland areas and their cold-water contributions to stream ecosystems.

Metrics important for describing spatial land patterns have been found to be different between landscapes delineated by county boundries and major watershed regions in this area (Chapter 2). Careful analyses of the distribution of land cover types and their relationships to surface water bodies with respect to their naturally-delineated watershed boundaries could help inform land-use decisions for sustainable water resource management. Lands could be targeted for forest ecosystem improvements, as water resource or fishing easements. Limestone ordinances exist to provide land-use policies protecting unique geological attributes, such as springs or sinkholes (LaMoreaux et al., 1997; Bade and Moss, 1999). These ordinances are absent in some karst communities (Ziegler and Williams, 2008; Chapter 3) and could be better developed and utilized for the protection of all karst lands.

After forest lands, springs are predominantly located on parcels designated as a hay/pasture/grassland land cover type. The fact that the bulk of springs are located on these cover types could be due to the methods used in the initial gathering of spring locations reflecting easily identifiable springs chosen on topographic maps (Gao et al., 2002). Thus, while these data are spatially accurate, they are not yet complete. With future additions and updates to the karst database, relationships between land cover type and other variables identified in this study could guide future exploration of relationships to spring distribution.

4.2 Spring Discrimination into Geologic Groups

Describing the location of springs, eleven and eight variables were important for classifying springs into bedrock units and aquifer units, respectively. Seven of these variables were the same indicating overlap in the geological attributes of aquifers and bedrock units. Elevation was significantly different between all bedrock units and aquifer units, and was an important classification variable for both geologic groups.

Geomorphic variable FWi1Rng, representing fluvial and level topography, characterized springs in the lower elevations of older bedrock. Discriminate variables for aquifer units included the soil unit 902 describing hapludoll dominant groups on unglaciated or lightly glaciated upland slopes, glacial terranes and floodplains (Cummins and Grigal, 1980). The distribution of this soil unit follows the spatial distribution of the lower elevation Franconia-Ironton Galesville aquifer group which had the highest number and density of springs. This soil type reflects impacts from the fluviokarst weathering processes that ultimately exposed bedrock openings in low elevations. Also important for classifications was shorter distances to nearest bedrock contact, which reflects the close boundaries of the upper Cambrian bedrock strata in the lower elevations (Table 1) due to fluviokarst weathering downward into the valleys.

Designation as a trout stream of the nearest stream segment aided in discrimination of springs in the bedrock units. In low elevations, for over half the springs, the nearest stream segment was a designated trout stream or a protected tributary to a designated trout stream. This association reflects the influence of cold-water springs in maintaining stream temperatures necessary to support viable trout populations in this area (Waters, 1977; Anderson, 1983), which would be consistent with findings in other regions (Bowlby and Roff, 1986; McClendon and Rabeni, 1987; Brabrand et al., 2002; Whitledge et al., 2006) and for other cold-water aquatic species (e.g. Alexander and Caissie, 2003; Brewer et al., 2007).

Classification rates for springs were higher for the three aquifer units than the five bedrock units. This association mainly reflected the larger sampling sizes from combining of data into the fewer aquifer units. Overlap in values for several variables also affected spring classification and reduced classification accuracy. For example, distance to nearest bedrock contact was significantly different across several of the bedrock units (Table 3). However, across all springs, the range for this variable was large and overlapping values were found across multiple bedrock units. Most springs, regardless of bedrock unit association, had a forested land cover. As well, between 24% and 64% of springs in the three lower elevation bedrock units were found with the FWi1R geomorphic designation. For future research, use of only this subset of the geomorphologic designations may better classify springs.

In addition to variables describing a spring's location, other variables may improve discrimination of springs relative to aquifer unit or bedrock unit. Spring aspect, for example, reflecting regional geologic dips (e.g. towards the southwest) and describing the direction of the slope where a spring is located (e.g. southwest) has potential for describing where springs can be located in karst regions (Day et al., 1994). Spring type (e.g. diffuse, conduit, bedrock spring, episodic, intermittent, perennial, etc.) combined with discharge chemistry characteristics could provide additional spring characterization and improve efforts to predict, classify, or characterize springs (Bartodziej and Perry, 1990; Bonacci, 1993; Alfaro and Wallace, 1994). However, neither spring aspect or spring type is currently documented for the springs in this region.

Conversely, some variables may not be useful for classification purposes. Slope was not significantly different between aquifer units or bedrock units and was not a relevant classification variable. Most springs are located on surfaces with less than a mean slope of 25%. Slope derived from a 30-meter DEM, however, may not provide adequate resolution for this region due to the widely distributed tributary valleys, streams and rivers. A DEM with higher resolution, when available, may be more useful for characterizing spring locations.

While this study examined spring characteristics in one county of the southeastern Minnesota karst region, the methods employed could be used for other counties in Minnesota or other karst regions (Figure 1) with hydrogeologic data available in GIS format. Geologic data are available for most counties in southeastern Minnesota and are organized for use with GIS to convey geologic and hydrogeologic information and interpretation, particularly to local governments (Minnesota Department of Natural Resources, 2008b).

The benefit of expanding knowledge and management of cold-water systems is great for human communities in this region. Studies of the total impact of trout anglers in the four-state Driftless Area estimate regional economic contributions of the annual usage of this natural resource to be in excess of $1.1 billion dollars (Gartner et al., 2002; Hart, 2008). As a critical habitat component for trout and subsequently an important component supporting the regional trout-fishing industry, quality and quantity of spring discharge could be managed as a regionally important natural resource. Current management of southeastern Minnesota cold-water ecosystems includes in-stream habitat protection and improvement, easement acquisitions, fisheries surveys, stocking, fisheries regulations and agency staff participation in watershed management projects. Regional goals include a statement of recognition of the need to protect and manage sources of cold water for these regional trout streams (Minnesota Department of Natural Resources, 2003). However, recent evaluation of county and city policy found no regulatory acknowledgement or protection of springs or spring discharge (Chapter 3) to guide zoning or land-use permits.

Springshed mapping, the mapping of spring recharge areas, is a growing research activity in the southeastern Minnesota karst region (Lopez et al., 2003; Green et al., 2005; Luhmann et al., 2008) and will provide valuable data concerning the connection between upland recharge areas, spring location, spring discharge characteristics and cold-water aquatic ecosystem health. This additional research in Minnesota and other karst regions will be valuable in pinpointing land areas that have significant impacts on the ecohydrology of a stream system.

5. Conclusions

Springs were found to be predominately clumped at low elevations indicating the importance of land management in recharge areas. A subset of variables was shown to be important for classifying springs into two regional geologic groups – bedrock and aquifer units. Classification of springs was most successful relative to aquifer units. However, trout designation of the nearest stream segment aided in discrimination of springs in the bedrock unit indicating a strong relationship between regional bedrock geology and biotic systems. These relationships indicate potential usefulness for the prediction of spring locations for informing land and water management activities such as zoning, easement purchases and development of best management practices in forested land areas.

In karst regions, surface features focus storm-water and melt-water runoff into the subsurface, where little or no filtering of pollutants occur making these hydrologic systems vulnerable to nonpoint source contamination. Thus, an understanding of spring characteristics can be especially important in karst regions as found in southeastern Minnesota. Analyses, such as those provided in this study, could provide land managers with a better understanding of characteristics describing or defining the locations of springs and can add to the growing karst hydrogeologic database. This knowledge can increase accuracy and usefulness of land and water management plans and improve predictability of water and pollutant transport.

Springs are not only a critical hydrogeologic component of cold-water streams and trout habitat, they also support strong regional social and economic activities. Consideration of upland human activities on spring discharge could lead to informed management activities that protect not only springs, but also their contributions and connections to the viability of regional ecosystems and socioeconomic infrastructure. With future mapping of additional springs and their subsequent entry into the karst spring database, additional research could aid in selecting variables that would improve our understanding of springs and their connections with natural and human communities.

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Table 1. Generalized stratigraphic column indicating delineations of bedrock units and associated aquifer units for Winona County, Minnesota (adapted from Mossler and Book 1984). The number of springs is based on currently known spring locations for this county in the regional karst feature database (Gao et al., 2002).

System	Series	BEDROCK UNIT	# OF SPRINGS	DESCRIPTION	AQUIFER UNIT	# OF SPRINGS
Middle Ordovician		Galena	14	Fine-grained fossiliferous limestone. Many shale partings in basal 15-20 feet.	Galena - Upper Carbonate Aquifer	14
		Decorah Shale, Platteville, Glenwood FM		Shale and thin interbeds of limestone. Commonly fossiliferous. Fine-grained fossilierous limestone. Sandy shale.		
		St Peter Sandstone	0	Fine- to medium-grained, poorly cemented, quartrose sandstone; basal contact minor erosional surface. Upper surface commonly iron crusted. Generally massive and unbedded.	St. Peter Aquifer	
Lower Ordovician	Prairie du Chien Group	Shakopee Formation	28	Thin-bedded and medium-bedded dolomite with thin sandstone and shale beds. Basal 20 to 30 feet is fine-grained quartzose sandstone. Local red iron staining. Basal contact minor erosional surface.	Prairie du Chien-Jordan Aquifer	72
		Oneota Dolomite		Thick-bedded to massive dolomite. Some sandy dolomite in basal 10 to 20 feet. Vugs filled with coarse calcite in upper part. Minor chert nodules. Upper part near contact with Shakopee commonly brecciated.		
Upper Cambrian		Jordan Sandstone	44	Sandstone. Top 30 feet is thin bedded and well cemented by calcite. Middle part is medium- to coarse-grained quartzose sandstone; generally uncemented and iron-stained in outcrop. Basal 35-40 feet is very fine to fine-grained sandstone.		
		St. Lawrence FM	176	Thin-bedded dolomitic siltstone. Minor shale partings.	St. Lawrence-Franconia-Ironton-Galesville Aquifer	214
		Franconia Formation		Thin-bedded, dolomite-cemented glauconitic sandstone. Very fine to fine grained. Contains minor dolomite beds near base and shale partings thorughout.		
		Ironton & Galesville Sandstones	38	Ironton: Poorly sorted, silty, fine- to medium-grained quartzose sandstone with minor glauconite. Galesville: Fine- to medium grained, well-sorted quartzose sandstone.		
		Eau Claire Formation	0	Very fine to fine-grained sandstone and siltstone. Some is glauconitic. Interbedded shale.	Confining Layer	
		Mt. Simon Sandstone	0	Fine- to very coarse-grained, poorly cemented sandstone. Contains pebbles in basal 20 to 40 feet. Sandstone generally moderately to well sorted. Greenish-gray shale mottled with grayish-red in basal third of formation. Basal contact major erosional surface.	Mt. Simon Aquifer	
Precambrian				Biotitic granite gneiss in eastern part. Poorly known in west.	Unknown	

Table 2. Landscape characteristics derived by intersecting locations of spring with spatial layers in a geographic information system.

Variable	Type*	Description
Aquifer Unit		*Geologic group or formation at spring location (see Figure 3)*
	D	Galena - Upper Carbonate aquifer unit
	D	Prairie du Chien-Jordan aquifer unit
	D	St. Lawrence-Franconia-Ironton Galesville aquifer unit
Dist_to_Bedrk	N	Distance from spring to closest bedrock boundary
Elevation	N	Elevation of spring in meters above sea level
Slope	N	Slope of the land where spring is located
Dist_to_Spring	N	Distance from spring to nearest stream segment
Bedrock Unit		*Geologic bedrock unit at spring location (see Figure 3)*
	D	Galena Formation
	D	Prairie du Chien
	D	Jordan Sandstone
	D	St. Lawrence-Franconia Formation
	D	Ironton Galesville Sandstones
Geomorphology		*Full landform code (see text for explanation of codes)*
FHo1A	D	Fluvial, Holocene, Level Topography, Alluvium Sedimentary Association
FWi1Rng	D	Fluvial, Wisconsinan, Level Topography, Terrace, Non-glacial Source
TWp2B	D	Dissected Bedrock Terrane, Pre-Wisconsinan, Rolling to Undulating Topography, Bedrock Dominated
TWp4Blo	D	Dissected Bedrock Terrane, Pre-Wisconsinan, Steep, Bedrock Dominated, Loess Mantled Sediment
TWp5Blo	D	Dissected Bedrock Terrane, Pre-Wisconsinan, Inclined Slopes Intermediate Between Rolling and Steep, Bedrock Dominated, Loess Mantled Sediment
Soils		*Minnesota soil unit associations*
419	D	Udorthent, Fine-loamy
902	D	Hapludoll, Fine-loamy/sandy
903	D	Hapludalf, Fine-silty
905	D	Paleudalf, Fine-silty
908	D	Hapludalf, Fine-loamy
912	D	Hapludoll, Coarse-loamy
LULC		*Land use / land cover of the land where the spring is located*
CL	D	Cultivated Land
FR	D	Forest
HP	D	Hay/Pasture/Grassland
UR	D	Urban
Strm_type		*Type of nearest stream segment*
S20	D	Perennial
S21	D	Intermittent
Trout_flag	D	*Presence (1) or absence (0) of trout population in nearest stream segment*

*Variable type indicates dummy variable (D) or numeric variable (N).

Table 3. Summary of spring distribution characteristics, stream and trout stream length, and mean (± s.d.) of variables used in the discriminant function analyses for both aquifer units and bedrock units.

	Number of Springs	% of Total Springs	Area *(km^2)*	Spring Density *($\#/km^2$)*	Total Streams *(km)*	Trout Streams *(km)*	Numeric Variables: Elevation *(m)*	Numeric Variables: Nearest Bedrock Contact *(m)*	Numeric Variables: Nearest Stream Segment *(m)*	Numeric Variables: Slope *(%)*
Aquifer Units										
Galena	14	5	51	0.28	18	0	381 (9) [A]	418 (257) [A]	110 (119) [A]	21 (7)
Prairie Du Chien-Jordan	72	24	1188	0.06	1180	99	298 (33) [B]	301 (671) [A]	51 (99) [B]	27 (19)
St. Lawrence Franconia-Ironton-Galesville	214	71	275	0.78	887	355	263 (28) [C]	90 (57) [B]	60 (79) [B]	24 (16)
Univariate F							<.001	<.001	0.068	0.355
Bedrock Units										
Galena	14	5	51	0.28	18	0	381 (9) [A]	418 (257) [B]	110 (119) [A]	21 (7)
Prairie Du Chien	28	9	1068	0.03	924	54	318 (32) [B]	702 (953) [A]	91 (148) [AB]	23 (19)
Jordan	44	15	120	0.37	256	45	284 (26) [C]	46 (53) [C]	25 (24) [C]	29 (19)
St. Lawrence-Franconia	176	59	212	0.83	659	219	270 (26) [D]	96 (55) [C]	56 (75) [BC]	25 (16)
Ironton & Galesville Sandstones	38	13	63	0.60	228	136	233 (14) [E]	62 (55) [C]	75 (98) [AB]	20 (13)
Univariate F							< .001	< .001	0.002	0.078

[a]Duncan's multiple-range tests identified significantly different groups ($p > 0.05$) as indicated by different superscript letters. For example, elevation is significantly different between all aquifer units.

Table 4. Statistical values for variables related to the aquifer and bedrock units based on a discriminate stepwise analysis.

Step	Variable(s)	Partial R-Square	F Value	Pr > F	Wilks' Lambda	Average Squared Canonical Correlation
Aquifer units						
1	S903	0.51	100.85	<.001	0.49	0.25
2	Elevation	0.32	46.10	<.001	0.34	0.36
3	S908	0.14	16.27	<.001	0.29	0.39
4	geoTWp2B	0.39	63.24	<.001	0.17	0.48
5	FR	0.12	13.52	<.001	0.15	0.53
6	geoFWi1Rng	0.06	5.77	0.00	0.14	0.55
7	Dist_Bdrk	0.03	3.05	0.05	0.14	0.55
8	S902	0.04	3.73	0.03	0.13	0.56
Bedrock Units						
1	Elevation	0.59	69.66	<.001	0.41	0.15
2	S903	0.42	34.87	<.001	0.24	0.22
3	S908	0.30	20.62	<.001	0.17	0.27
4	geoTWp2B	0.40	31.35	<.001	0.10	0.32
5	FR	0.13	6.98	<.001	0.09	0.35
6	S419	0.13	7.19	<.001	0.08	0.37
7	S912	0.11	5.84	0.00	0.07	0.39
8	Dist_Bdrk	0.08	4.22	0.00	0.06	0.41
9	geoFWi1Rng	0.06	3.07	0.02	0.06	0.42
10	trout	0.05	2.64	0.04	0.06	0.43
11	Strm21	0.06	2.81	0.03	0.05	0.44

Table 5. Summary statistics for the soil unit associations used in the discriminant function analyses. Soil unit 902 was an important discriminatory variable related to aquifers. Soil units 903 and 908 were important variables in both aquifer and bedrock unit analyses. Soil units 419 and 912 were important relative to bedrock units.

Soils	n		Elevation *(m)*	Distance to nearest Bedrock *(m)*	Distance to nearest Stream *(m)*	Slope *(%)*
902	153	*min*	215	2	0	0
		max	328	1,922	386	66
		mean	259	109	47	25
		sd	24	184	61	17
903	9	*min*	299	29	11	9
		max	391	772	287	34
		mean	365	363	92	22
		sd	29	244	104	9
908	14	*min*	322	60	9	0
		max	390	2,624	517	25
		mean	367	1,215	204	12
		sd	22	1,024	178	9
905	100	*min*	231	0	0	0
		max	358	392	326	63
		mean	293	82	42	26
		sd	25	66	56	17
912	12	*min*	238	1	3	5
		max	268	114	226	34
		mean	250	49	73	17
		std	9	38	64	10
419	12	*min*	202	2	7	3
		max	271	279	435	67
		mean	231	92	174	29
		sd	22	86	172	24

Table 6. Initial discriminate function classifications using a random sample of 60% of the 300 spring observations. Diagonal values indicate correctly classified number and percent of springs per geologic layer.

	Bedrock Units						Aquifer units			
	Galena	Prairie Du Chien	Jordan	St. Lawr-Franc	Irntn-Glsville	Total	Galena	Prairie Du Chien	St. Lawr-Franc	Total
Galena	6	1	0	0	0	7	6	1	0	7
	86	14	0	0	0	100	86	14	0	100
Prairie du Chien	1	6	7	1	0	15	1	37	6	44
	7	40	47	7	0	100	2	84	14	100
Jordan	0	0	24	5	0	29				
	0	0	83	17	0	100				
St. Lawrence-	0	1	26	88	7	122	0	25	124	149
Franconia	0	1	21	72	6	100	0	17	83	100
Ironton	0	0	2	9	16	27				
Galesville	0	0	7	33	59	100				
Total	7	8	59	103	23	200	7	63	130	200
	4	4	30	52	12	100	4	32	65	100
Error Count Estimates:										
Rate	0.14	0.60	0.17	0.28	0.41	0.32	0.14	0.16	0.17	0.16
Priors	0.20	0.20	0.20	0.20	0.20	0.20	0.33	0.33	0.33	0.33

Table 7. Classification of a random sample of 40% of the 300 spring observations. Diagonal values indicate correctly classified number and percent of springs per geologic layer.

	Bedrock Units						Aquifer units			
	Galena	Prairie Du Chien	Jordan	St. Lawr-Franc	Irntn-Glsville	Total	Galena	Prairie Du Chien	St. Lawr-Franc	Total
Galena	4	3	0	0	0	7	4	3	0	7
	57	43	0	0	0	100	57	43	0	100
Prairie du Chien	2	2	9	0	0	13	2	24	2	28
	15	15	69	0	0	100	7	86	7	100
Jordan	0	0	13	2	0	15				
	0	0	87	13	0	100				
St. Lawrence-	0	0	19	32	3	54	0	21	44	65
Franconia	0	0	35	59	6	100	0	32	68	100
Ironton	0	0	1	4	6	11				
Galesville	0	0	9	36	55	100				
Total	6	5	42	38	9	100	6	48	46	100
	6	5	42	38	9	100	6	48	46	100
Error Count Estimates:										
Rate	0.43	0.85	0.13	0.41	0.45	0.45	0.43	0.14	0.32	0.30
Priors	0.20	0.20	0.20	0.20	0.20	0.20	0.33	0.33	0.33	0.33

Figures

Figure 1. Spring locations (Gao et al., 2002) and trout streams in Winona County, Minnesota (Minnesota Department of Natural Resources 2008c). Winona County is part of the southeastern Minnesota karst region.

Figure 2. Distributions of the seven bedrock units for Winona County, Minnesota.

Figure 3. Distribution of the five aquifer units located in Winona County, Minnesota.

Figure 4. Relationship of spring locations and distribution of geomorphology variable FWi1Rng describing fluvial, level topography. This landform is found at lower elevations in the county.

Figure 5. Distribution of the St. Lawrence-Franconia-Ironton Galesville aquifer unit and soil unit association 902 describing hapludoll dominant soil groups on unglaciated or lightly glaciated slopes, terraces and floodplains (Cummins and Grigal 1980). One third of all springs are defined by this soil unit association.

Figure 1.

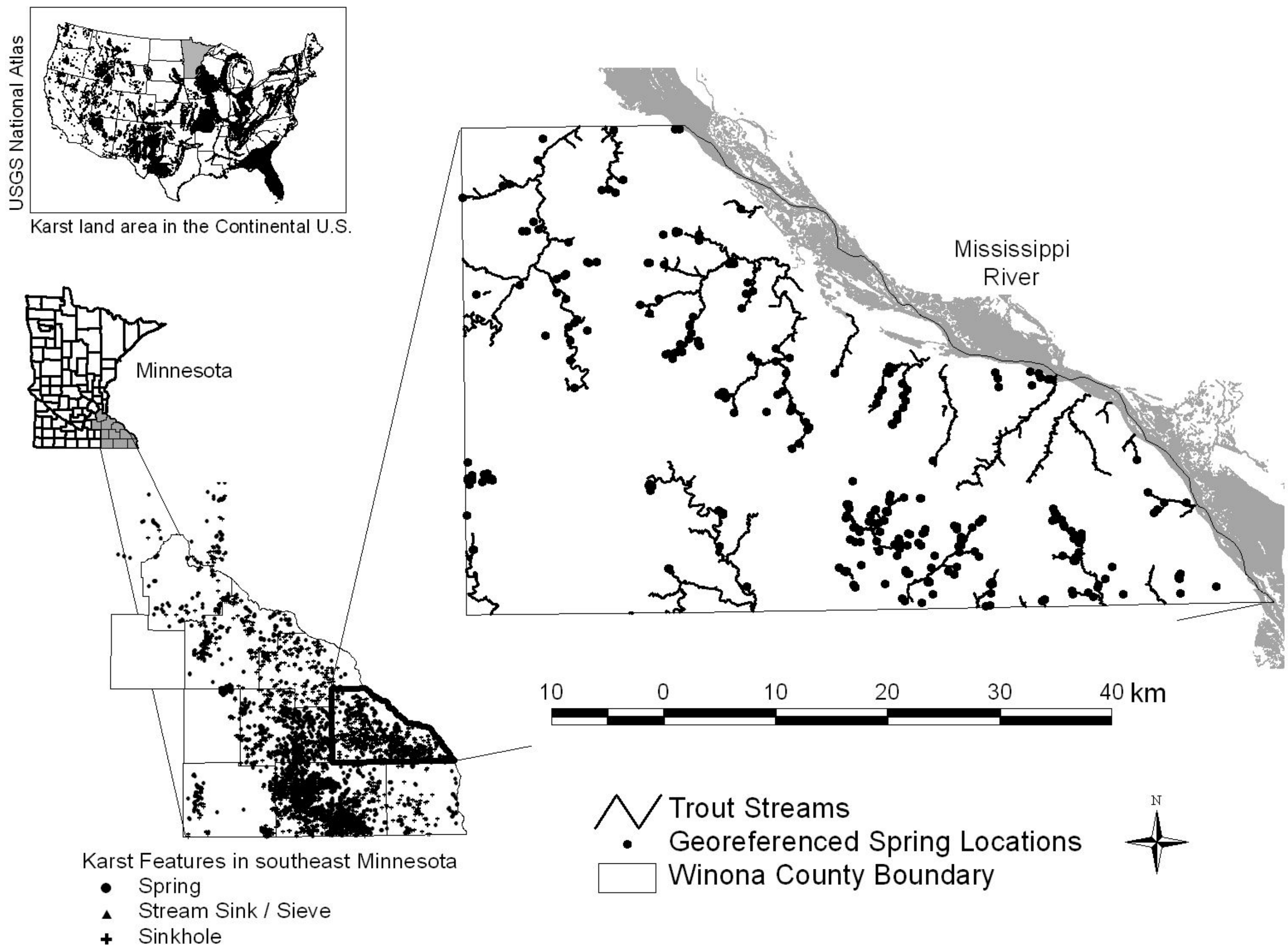
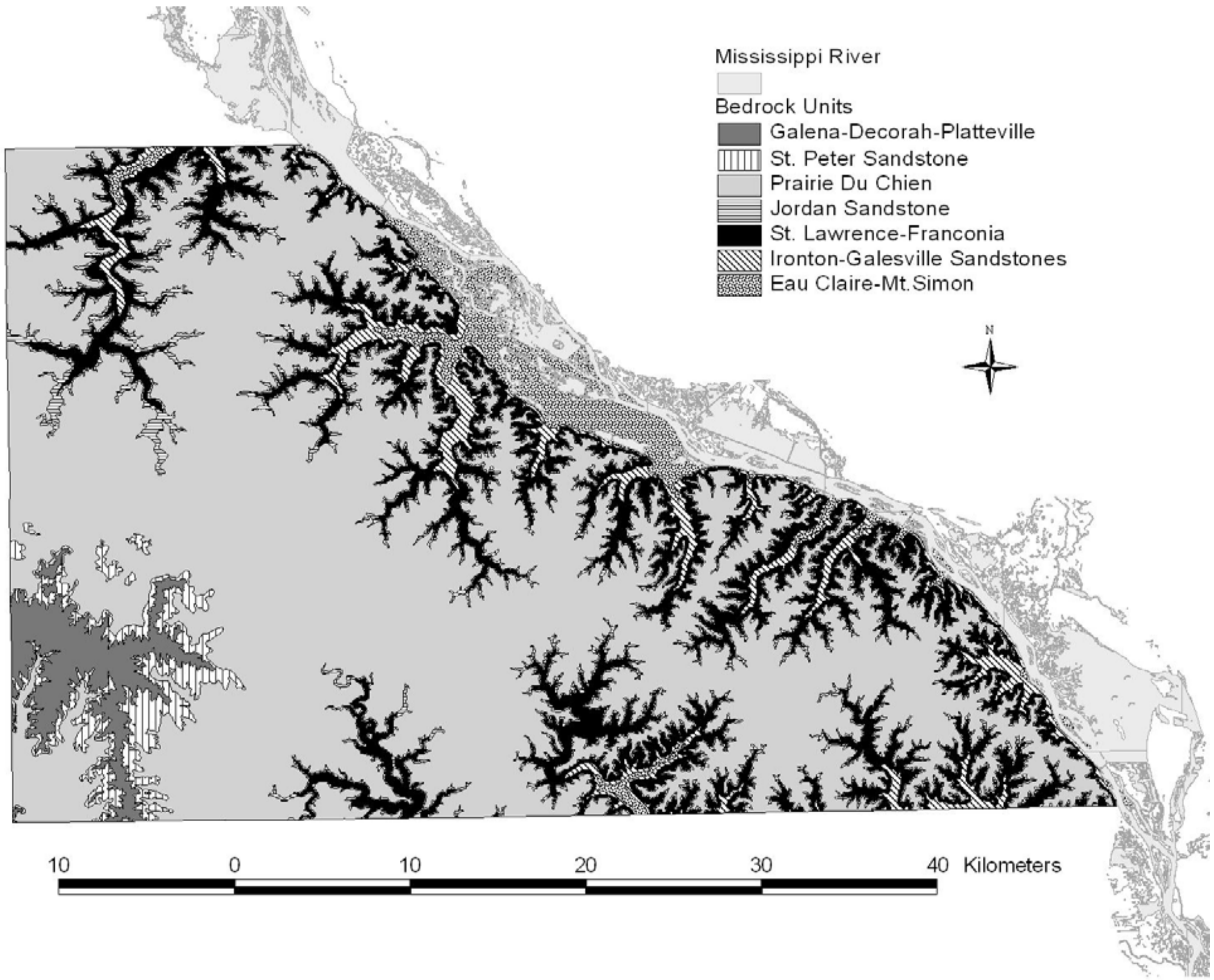

USGS National Atlas
Karst land area in the Continental U.S.
Minnesota
Karst Features in southeast Minnesota
Spring
Stream Sink / Sieve
Sinkhole
Mississippi
River
10 0 10 20 30 40 km
Trout Streams
Georeferenced Spring Locations
Winona County Boundary
N

Figure 2.


Mississippi River
Bedrock Units
Galena-Decorah-Platteville
St. Peter Sandstone
Prairie Du Chien
Jordan Sandstone
St. Lawrence-Franconia
Ironton-Galesville Sandstones
Eau Claire-Mt.Simon
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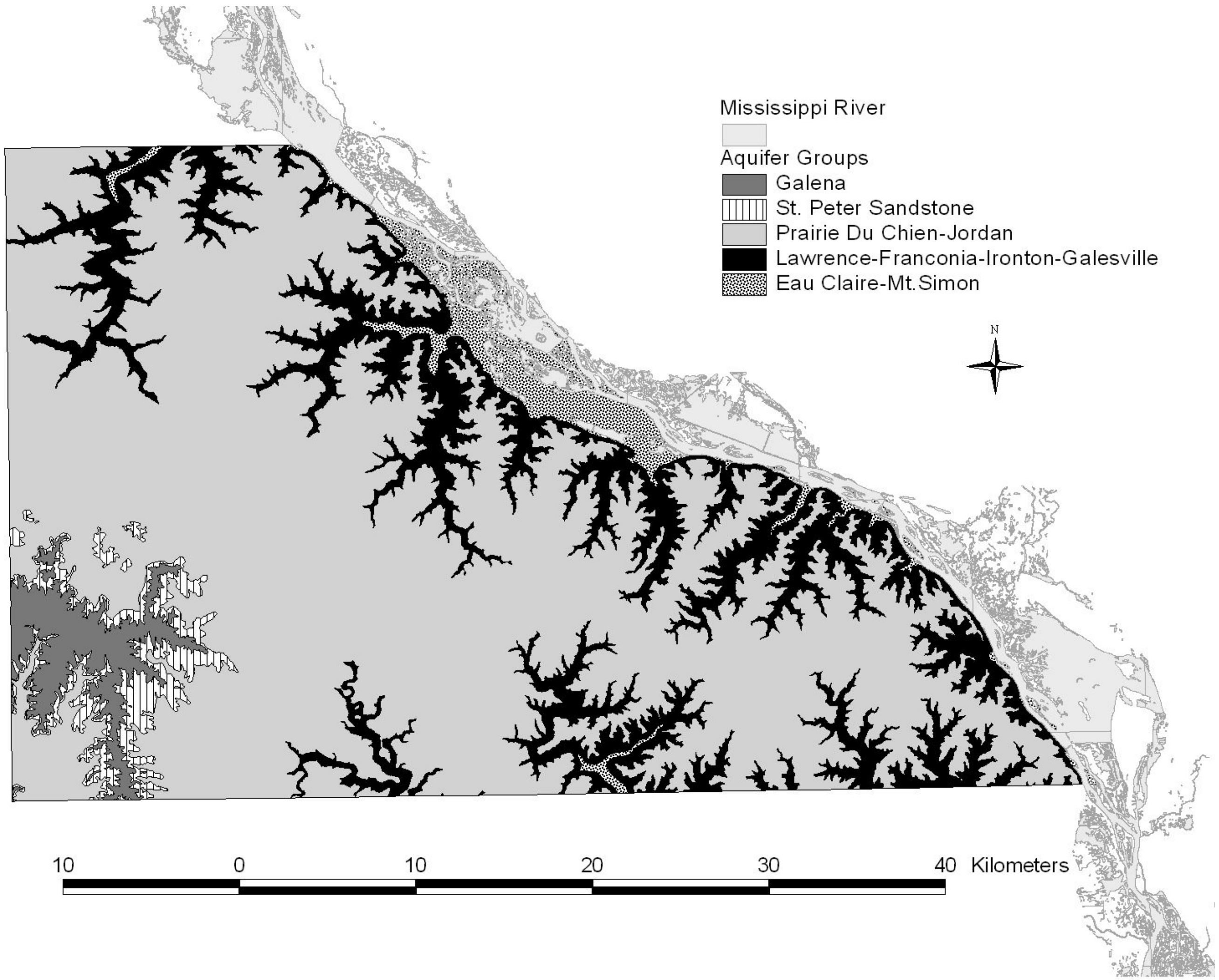
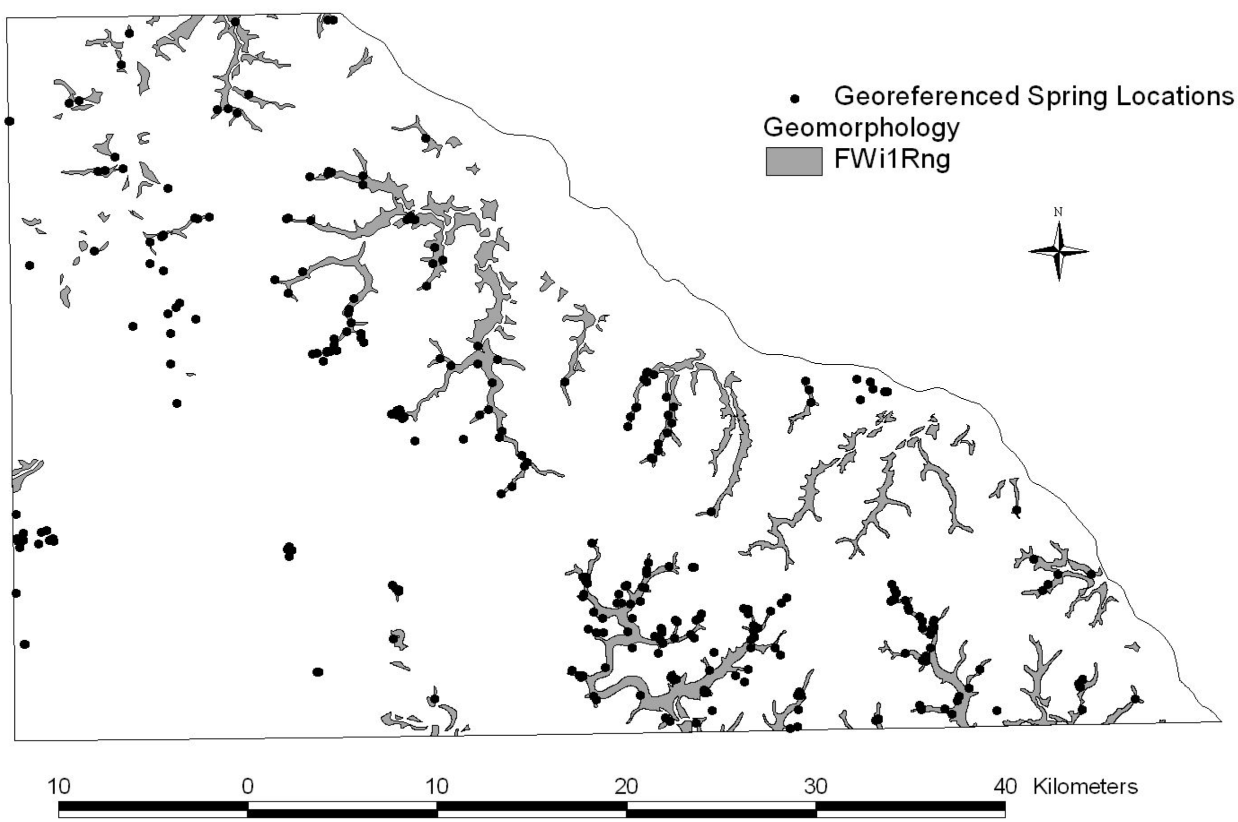
Kilometers

Figure 3.



Mississippi River
Aquifer Groups
Galena
St. Peter Sandstone
Prairie Du Chien-Jordan
Lawrence-Franconia-Ironton-Galesville
Eau Claire-Mt.Simon
N
10 0 10 20 30 40 Kilometers

Figure 4.



Georeferenced Spring Locations
Geomorphology
FWi1Rng
N
10
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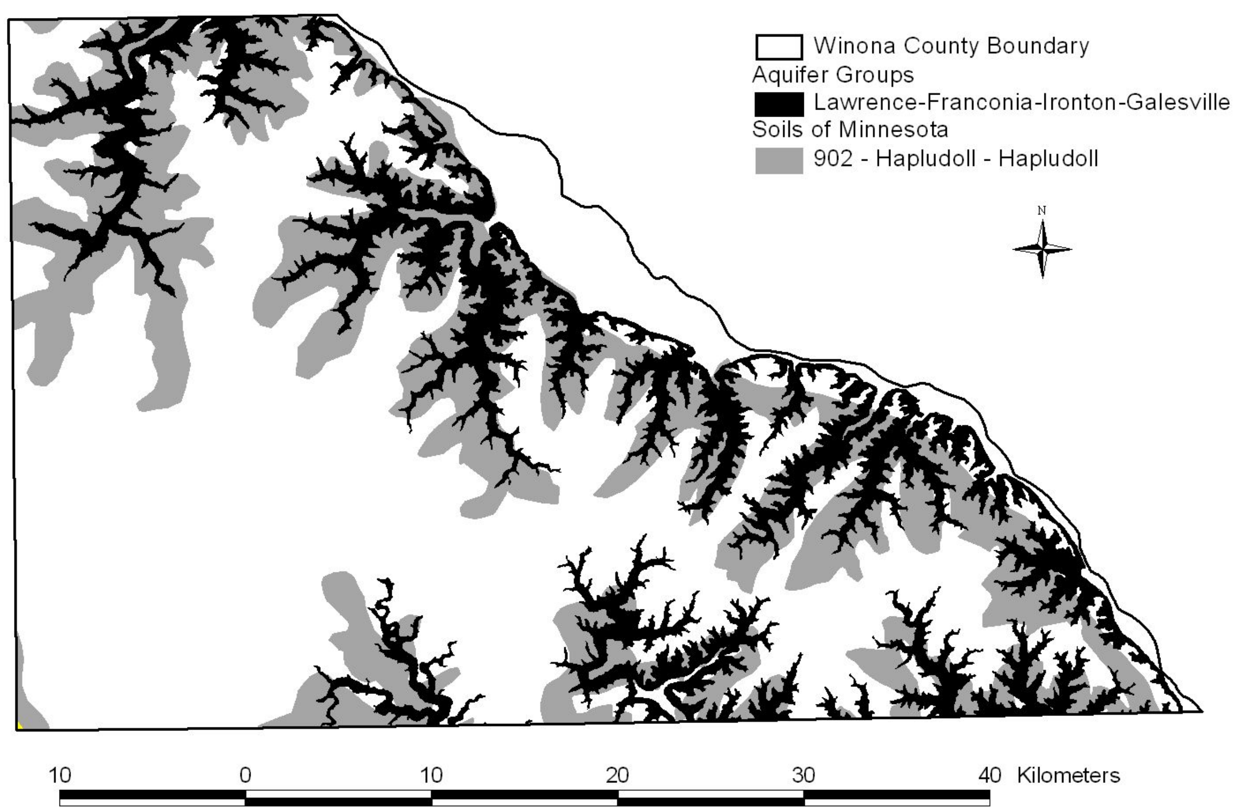
Figure 5.



Winona County Boundary
Aquifer Groups
Lawrence-Franconia-Ironton-Galesville
Soils of Minnesota
902 - Hapludoll - Hapludoll
N
10 0 10 20 30 40 Kilometers

CHAPTER 2

No County is an Island:
A Comparison of
Watershed- and County-scale
Landscape Patterns
in southeast Minnesota, U.S.A.

Mary A. Williams

This paper is formatted for submission to the journal *Landscape Ecology*.

Regional land cover patterns affect flows of energy, water, materials and animals along with various ecological processes at finer spatial scales. Rarely, however, does land and watershed planning at these finer spatial scales incorporate the larger physical environment into decision-making considerations. Quantifications and comparisons of patterns in local political land areas with those in the larger overlying natural areas could contribute to a better understanding of the impacts of land-use decisions both locally and across the larger spatial region.

For this study, land pattern metrics were calculated for a county in southeast Minnesota and compared with those patterns in the larger-scale major watershed land area overlying that county. For each of the two areas, twenty-five pattern metrics were calculated and analyzed using factor analysis. Descriptive metrics quantifying average patch size, patch density, large patch index and contagion indicated that the county was more fragmented than the watersheds. Six and seven factors explained 73% and 85% of the variance in watershed and county metrics, respectively. The top two dominant land cover types (forest and cultivated land) were significant in the first two county factors. Three land cover types (forest, urban and cultivated land) accounted for variations in the first two watershed factors. Analyses describing and comparing land cover composition and configuration for overlapping geographical areas can be used to inform multi-scale land or water management plans, to improve communications between planners and natural resource managers and to provide a quantitative basis for landscape change research, examining effects of land cover change in a political and a natural resource setting.

Introduction

Sustainable land planning has generally been defined as the planning for the development and maintenance of natural resources and spatial patterns of land use that are ecologically, socially and economically beneficial for the needs of the present without compromising the ability of future generations to meet their needs (World Commission on Environment and Development 1987; Leitao and Ahern 2002). Inherent in this definition is the incorporation of larger-scale land areas in the land planning process. Promoting this connection, a number of studies call for a greater inclusion of larger-scale environmental considerations in local land planning activities where many land-use decisions are made (Salzman 1998; Beatley 2000; Selman 2002; Theobald et al. 2005; Tscharntke et al. 2005; Fiedler et al. 2008). These larger-scale considerations are needed because land-use decisions affect and are affected by the larger-scale physical environment and by the activities of neighboring human communities.

Cross-scalar analyses of land patterns in local land planning units with an extraterritorial (territory outside of delineated boundaries) land area like a major watershed could provide land and watershed managers with a tool for the inclusion of larger-scale environmental considerations into land planning and policy development. For local political planners and policymakers, a cross-scalar analysis could provide a measure of how land cover differs between the local political unit and the larger naturally-delineated watershed area. For example, if small urban patches characterize land cover in the political unit, but large urban patches characterize land cover in the cross-boundary watershed unit, then local policy could be created or modified to direct urban growth away from the watershed or away from sensitive areas within that watershed. Watershed managers interested in wildlife, water and stream management could also use these analyses to inform watershed policy. If, for example, comparisons revealed smaller patches and lower connectivity of natural cover in the watershed, watershed policy could be modified or created to promote or mandate larger levels of specific types of native landscaping. Pattern metrics useful for informing planning and policy needs will depend on objectives (e.g. increase in urban or rural development) and context (e.g. growing human populations).

Differences in land patterns between a political unit and an overlying major watershed area would be expected due to the influence of centralized land-use ordinances in the political unit versus decentralized land-use decision-making across multiple political units in the watershed. A greater uniformity in zoning, land division and land conversion, for example, in a local political unit, could create smaller, more uniform patch areas, increasing patch diversity and land fragmentation (Croissant 2004). Conversely, watershed management and policy will typically strive to protect, restore or connect patches of diverse natural areas, increasing patch sizes, shapes and connectivities of natural areas (Steinman and Denning 2005).

Measures of land pattern metrics have been used as tools to characterize large-scale land cover heterogeneity in watersheds (Cain et al.1997; Miller et al. 1997; Aspinall and Pearson 2000; Wang et al. 2003) and political units (Griffith et al. 2000; Swenson and Franklin 2000). These spatial pattern analyses, however, are typically quantified using large-scale land units, whereas most land planning and policy development addresses land-use activities over small spatial areas. Changes in spatial scale could yield different insights for specific questions (Turner 1989). This study explores pattern variability at the smaller spatial scale using subwatersheds as units of analysis to quantify and examine land patterns in a local political unit and in an overlying extraterritorial area of land defined by major watershed boundaries. These subwatersheds constitute the spatial scale at which much policy and planning occur.

Unique regional attributes like bedrock geology add complexity to any scale of land management and planning. Karst, for example, describes predominately limestone and dolomite landscapes primarily weathered through chemical dissolution processes which, over geologic time, produces such features as sinkholes, caves and springs. Human activities on karst result in various land and water management concerns including flooding and water pollution (Mooers and Alexander 1994; Zhou, 2007). Approximately 20% of the earth's land surface is karst (Gvozdetskii 1967 as cited by White 1988) and approximately 25% of land in the United States is karst (Aley 2002).

This study quantifies and compares land pattern metrics in a county area (approximately 1414 km^2) and in the larger-scale major watershed area (approximately 5578 km^2) overlaying that county, in an environmentally sensitive karst region. The 39 subwatersheds covering the county and 137 subwatersheds covering the major watershed area were used as units for analysis. Specific objectives of this research were to (1) quantify pattern metrics for a politically-delineated county area and the overlying naturally-delineated major watershed area, (2) identify the pattern metrics most useful for characterizing the land patterns for each area using factor analysis and (3) identify differences in pattern metrics between these two areas.

Methods

Study site

Wabasha County is located in the southeastern corner of the state of Minnesota. Overlying Wabasha County are three major watersheds draining into the upper Mississippi River (Figure 1). These major watersheds, Lake Pepin (1568.8 km^2), Zumbro (3686.7 km^2) and Winona (1714.3 km^2), are characterized by karst landforms overlain primarily by loess resting on older till, weathered bedrock or fresh bedrock (Anderson et al. 2001).

Agriculture is the dominant land use in both the county-level land area and larger-scale major watershed land area. Forests are the second dominant land cover. Urban growth and sprawl are increasing in both areas. For example, Lake City is located at the northeastern edge of Wabasha County. In its comprehensive land plan, the Lake City projects a potential 1,635% increase in high density residential housing land area from 25.46 acres in 2000 to 441.84 acres in 2020 (Lake City 2001) with a projected 15.8% population increase by 2010. This increase in high density development will take place at the expense of current agriculture/rural land which is estimated to decrease by 95% (Lake City 2001).

For these analyses, Minnesota Land Use and Cover: 1990's Census of the Land data sets were downloaded from the Minnesota Land Management Information Center (LMIC). Major watershed and subwatershed boundaries were downloaded from the Minnesota Department of Natural Resources website. ArcView 3.3 was used to process all spatial datasets (ESRI 2007). Land cover type (LCT) describes the type of land use or land cover found on the land surface, defined as a specific type of land cover (e.g.

forest) by the Minnesota LMIC. Land cover was aggregated from eight into five LCTs for each subwatershed. Land cover "Urban and Rural Development" was combined with "Mining". "Hay/Pasture/Grassland", including fields that have been abandoned and have grown over with native vegetation, was combined with "Brushland", a land cover identified as areas with a combination of grass, shrubs and trees, often found adjacent to hay/pasture/grassland. Finally, land cover "Water" was combined with "Bog/Marsh/Fen". The resulting five LCTs were cultivated land (CL), forest (FR), hay/pasture/grassland (herein called 'hay/pasture' - HP), urban (UR) and water (WT).

Pattern metrics were separately quantified for subwatersheds in the county and then for those subwatersheds in the major watershed land area overlying the county. Because the Lake Pepin watershed had only 15 subwatersheds, its sample size precluded its inclusion in statistical analyses. However, several Lake Pepin subwatersheds are located in Wabasha County and are included in the calculation of Wabasha County landscape metrics. For the county subwatershed metric calculations, subwatersheds that physically crossed the county border were clipped at the county border. Metrics were then calculated for the delineated subwatersheds in Wabasha County. For the major watershed land area, subwatersheds were included from the Zumbro watershed and the Winona watershed. Subwatersheds averaged 36 km^2 in the county and 40 km^2 in the major watershed area.

Pattern Metrics & Statistical Analyses

Within landscape ecology, the term “landscape” refers to the spatial unit or area of analysis. The term “class” refers to the LCT represented in the landscape. A class metric, for example, is a pattern metric quantified for all patches of one specific LCT.

For this study, the two landscapes are the county and the major watershed area. Class metrics are defined for each of the five defined LCTs: cultivated land (CL), forest (FR), hay/pasture/grassland (HP), urban (UR) and water (WT).

Many analyses of spatial patterns through factor analysis have generally been inconsistent with regards to chosen metrics, defined landscapes, number and definition of land cover types and spatial scales (e.g. Riitters et al. 1995; Cain et al. 1997; Griffith et al. 2000; Cifaldi et al. 2004; Kearns et al. 2005). For this study, five landscape and twenty class metrics (Table 1), identified as contributors to a useful quantification of land use/land cover pattern analysis (Leitao and Ahern 2002; Cifaldi et al. 2004; Leitao et al. 2006) provided the basis for these analyses (Defined in Appendix II). Chosen metrics were quantified separately for the subwatersheds in the county and then for the subwatersheds in the watershed area using the Fragstats Spatial Pattern Analysis Program, version 3.3. (McGarigal and Marks 1994).

To characterize spatial heterogeneity and structural connectivity of patches, average patch gyration and average nearest neighbor values were calculated. Patch gyration quantifies the mean distance between each cell in the patch and the patch centroid. It provides a measure of patch extensiveness - how far across the landscape a patch extends. Patch variation was characterized by mean patch size, mean patch size coefficient of variation and mean patch shape. Four of these metrics were computed at the class level for each of the five LCTs.

Additional metrics were calculated to form descriptive metrics of each area (Table 1 - Defined in Appendix II). Mean patch size and patch density are redundant measures at the landscape level but not at the class level (McGarigal and Marks 1994).

Therefore, patch density was used as a descriptive measure at the landscape level. Patch interspersion was measured by a contagion index. Contagion quantifies the degree to which LCTs occur in clumped distributions (spatially aggregated or "contagious" areas) versus being dispersed in many smaller fragments. A higher value indicates clumped, or less diverse land cover. A lower value indicates a more diverse arrangement of land cover. Landscape fragmentation was further characterized by number of patches. Landscape diversity was described by patch richness density. A dominance metric, Shannon's Evenness Index (SHEI), was selected to characterize overall landscape composition. SHEI is a measure of patch distribution, or the measurement of the distribution of area among patch types within the landscape. SHEI is equal to zero when the observed patch distribution is low and approaches one when the distribution of patch types becomes more even.

These descriptive metrics, quantified for each area, were used to provide overviews of additional land patterns and were not included in the statistical analyses. SAS v9.1 was used to analyze the five landscape and twenty class metrics for each landscape. Metrics were assessed for normality using the Shapiro-Wilk test for normality with a p-value of 0.05. Some non-normally distributed variables were transformed. To examine data redundancy, pairwise correlation coefficients were calculated for all pairs of metric variables. One of each pair of variables with correlations greater than 0.90 were removed, a criterion used in previous metric studies (Griffith et al. 2000; Cifaldi et al. 2004). Remaining variables were retained for subsequent analyses.

For each study area, factor analysis (FA) was used to identify metrics with the highest within-group and lowest between-group correlations. FA is a tool used to reduce datasets with large numbers of variables to a smaller set of variables that most characterize the variance in the dataset. First, principal components was used to reduce the large number of variables in the dataset to a smaller set of variables that most characterize the variance. Then, principal components with eigenvalues greater than one were retained (Kaiser-Guttmann criterion - Shaw 2003 pg 109) and rotated using a varimax rotation to aid in interpretation. Variables with a rotated factor loading greater than 0.55 or less than -0.55 were retained for factor interpretation. These variables described at least 30% (0.55 squared) of the variance for that metric across factors. So that each variable is identified as an important metric of only one factor per analysis, each chosen variable for a retained factor was retained only if it had the highest loading across all factors. While these are common methods used in metric analyses, two caveats for interpretation of results are warranted – first, that a few loadings were similar in magnitude across several factors and second, there were two factors with less than three significantly-loaded variables.

Results and Discussion

Land Composition

Rank order of dominant land cover type was similar when comparing the county and the watershed areas, but the proportion of land cover differed between the two areas. Cultivated land was the dominant land cover type (LCT) in both areas covering 54% of Wabasha County and 61% of the watershed area (Table 2). Forest cover was the second dominant LCT in both areas with 25% in the county, but only 18% of the watershed area (Figure 3). Hay/pasture cover was the third dominant LCT in both areas with 13% in the county and 14% in the watershed area. Urban and water land cover were the smallest LCTs for Wabasha County and the watershed areas, respectively.

Karst and karst features can affect and be affected by land cover composition and land-use activities. For example, the presence of karst-inhabiting frugivores (bats) can affect seed dispersal and resulting land cover composition (Rivera et al. 1998). Agricultural activities can contribute to surface and subsurface water degradation (Ryan and Meiman 1996; Neill et al. 2004; Davis et al. 2005). Forest cover can aid in controlling nonpoint source pollution to streams, springs and aquifers (Arthur et al. 1998). Forest land cover can also be an important land cover type for sustainable spring discharge (Chapter 1). Urban and rural development can result in environmental, development and economic issues including failures of: impoundments and liner systems, foundation and slab, pipes and buried utilities, roadways (White et al. 1986; Beck 1995; Ralston et al. 1999). Sinkhole development can modify hydrology and influence the evolution of regional plant communities (Fetterman et al. 2003). Disturbances to land cover and regional hydrological processes can degrade cave and karst biota (Elliott 2000; Christman and Culver 2001; Olson 2001; Culver et al. 2003).

Factor Results

Seven factors explained 85% of the variation in metrics for Wabasha County and six factors explained 73% of the variance for the watershed area analysis. Each factor represented a gradient in metric values across the subwatersheds that can be visualized from examples of the subwatersheds with low and high factor scores (Figure 2). Analyses of spatial patterns through factor analysis have been inconsistent with regards to chosen metrics, defined study areas, land cover types and spatial scales (e.g. Riitters et al. 1995; Cain et al. 1997; Griffith et al. 2000; Cifaldi et al. 2004; Kearns et al. 2005). Therefore, direct comparisons of resulting factors and metric loadings cannot be made. However, comparisons can be made of the findings describing the number of unique dimensions of patterns across land areas. Riiters et al. (1995), for example, found that six factors, using 26 metrics, explained 87% of the land pattern variation measured across 85 maps derived from high-altitude land cover. Cifaldi et al. (2004) examined subwatershed metrics in two major basins in southeastern Michigan and found that five factors explained 77% of the variation in a basin characterized by suburban and undisturbed land area, five factors explained 83% of the variation in the Raisin River basins characterized by agriculture, and five factors explained 78% of the combined basins.

Watershed Pattern Metrics

In the watershed area analysis, the first factor described a gradient in urban patch size and forest patch shape with subwatersheds at the positive end characterized with larger mean urban patch areas, larger mean landscape patch gyration, and more extensive forest patches. Subwatersheds at this end were also characterized by smaller variations in mean landscape patch size, indicating that larger urban patch areas tended to occur where land cover diversity was higher and not dominated by agriculture. This result was also seen in a study comparing pattern metrics for a large agricultural and a large urbanized basin in Michigan (Cifaldi et al. 2004). The subwatersheds with the largest urban patches were located near urban areas with the four most urbanized subwatersheds overlapping with Rochester, Minnesota, the largest city in the study area.

Mean landscape patch size coefficient of variation was negatively correlated with this factor. For this factor, mean urban patch shape loaded with similar magnitude on components three and four so caution is warranted with this interpretation.

Factor two described a cultivated land gradient with smaller cultivated land patches at the negative end of the factor and subwatersheds dominated with larger, extensive cultivated land patches at the positive end.

Factors three and four identified water and hay/pasture gradients, respectively. Large mean water patches characterized subwatersheds at the positive end of factor three. Subwatersheds at the negative end were characterized by smaller mean water patches that occurred with smaller mean urban patch size variation. This finding indicated that larger water patches occurred where urban cover is not a dominate land cover type. Factor four described a gradient with smaller, more uniformly-shaped hay/pasture patches at the negative end and subwatersheds dominated by larger, slightly more complex-shaped hay/pasture patches at the positive end. Only two metrics loaded on this component which may not be enough to provide explanations of dynamics occurring with metrics on this factor.

Mean landscape patch size and mean landscape nearest neighbor distance were characterized in factor five. In addition, water patch shape was negatively-correlated with this factor. This inverse relationship indicated that subwatersheds with larger mean landscape patches had more uniformly-shaped water patches potentially shaped from land-use activities. Factor six described a forest gradient with larger mean forest patches but a lower diversity of hay/pasture patch sizes on the positive end. Larger average landscape patch shape also characterized the positive end of this factor indicating that more uniform hay/pasture patches were located near larger contiguous forest patches. For this factor, mean hay/pasture patch size coefficient of variation loaded with similar magnitude on component four so caution is warranted with this interpretation.

Wabasha County Pattern Metrics

In the Wabasha County analysis, the first factor characterized a gradient in mean landscape patch shape, gyration and mean forest patch characteristics with smaller, less-extensive patches, especially forest patches, at the negative end. Factor two identified a gradient characterizing variations in cultivated land patch characteristics. This was also seen for factor two in the watershed analysis indicating a common impact of this dominant land cover on land patterns across this region. In contrast to the watershed analysis, mean landscape patch area was also highly correlated with this factor. This indicates that subwatersheds with larger average landscape patches consisted predominately of cultivated land cover types.

Factor three identified a hay/pasture gradient, similar to factor four of the watershed analysis. Subwatersheds at the negative end were characterized by smaller hay/pasture patches. Emerging earlier on factor three in the county analysis indicated that hay/pasture patches are more important for describing land patterns in the county area. Factor four described a gradient of patch size diversity, especially for forest and cultivated land patches, with subwatersheds at the negative end of the factor having a lower diversity of land cover patch sizes.

Factor five described an urban cover gradient. Urban cover was the primary influence on describing variations in pattern metrics for the watershed area but emerged as much less important in this dataset. This factor described a gradient of smaller urban patches at the negative end and larger patch characteristics at the positive end. For this factor, mean urban patch shape loaded with similar magnitude on component one so caution is warranted with this interpretation. Factor six described smaller water patch size characteristics and hay/pasture patch diversity at the negative end. Factor seven described a gradient of smaller water patch shapes and more isolated (larger nearest neighbor values) landscape patches on the negative end. For this factor, the nearest neighbor metric loaded with similar magnitude on component two and only two metrics loaded on this component so caution is warranted with this interpretation.

Comparisons between county and watershed metrics

Gradients in mean landscape patch gyration and forest patch shape characteristics were characterized in factor one for both areas. In the first component of the watershed area, however, urban patch characteristics emerged as important descriptors of land pattern indicating that consideration of urban land patterns is more important in the watershed area. Often accompanying urban development, increasing impervious surface can negatively impact regional hydrology, especially in karst regions, reducing land surface recharge, exacerbating storm-water and pollutant runoff (Lastennet and Mudry 1997; Veni 1999), increasing flooding potential (Zhou 2007) and soil erosion (Ralston et al. 1999). These impacts result in the degradation of regional natural resources, aquatic ecosystems and karst hydrology (Veni 1999).

Cultivated land, the dominant land cover in both study areas, emerged as an important land pattern in the second factor in both study areas. Degradation of water quality by agricultural practices is well-studied, especially in karst regions (White 1988;

Berryhill 1989; Neill et al. 2004). These impacts have prompted the adoption in some regions of agricultural best management practices (BMPs) to mitigate any potential degradation to karst and other regional natural resources (e.g. Currens 2002). Unfortunately, natural resources and karst features are not legally protected in some karst areas (Chapter 3).

Wabasha County metrics described a more fragmented landscape than was seen in the major watershed area. For example, with a similar mean number of patches, Wabasha County had, on average, smaller patch sizes (area-weighted and non-weighted), larger patch densities, smaller large patch index measures and lower contagion values (Table 3). Given that Minnesota law confers responsibility of land-use planning and regulation to county government (Association of Minnesota Counties, 2002), this could be attributed to the effects of land parcelization similar to the effects found on county landscape patterns in south-central Indiana (Croissant 2004). Other human activities, agriculture and transportation as examples, are also attributable to increased landscape fragmentation and could be contributors to increased fragmentation in this county landscape (Forman 2000).

Although appearing more fragmented, for the Wabasha County area, both average forest patch area and average forest radius of gyration were positively correlated on the first factor indicating that connectivity of patches could be supported by adequate patch size for many forest processes (Leitao et al. 2006). In this region, forest land cover has been found to be the primary land cover important for describing where karst springs are located (Chapter 1). Forest cover is useful for protecting springs and streams, but forest ecosystem processes are also important for infiltration and recharge to springs and aquifers. This connection between forest patch area and radius of gyration was not seen in the watershed area analysis, potentially indicating that forest ecosystems, explicitly examined within a watershed context, may lack the connectivity needed for viable long-term forest processes.

Overall, the differences between the county and watershed areas included: 1) the county had the more fragmented land area; 2) urban patch size was important for describing variations in land patterns in the watershed area. Forest cover describes the most variation in land patterns in the county area. Cultivated land was of secondary importance in describing land patterns in both areas; 3) three land cover types (CL,FR,UR) accounted for metric variations in the top two factors of the watershed area analysis, whereas only two LCTs (CL,FR) accounted for variation in the first two factors for the county. Thus LCT diversity was more important for describing land patterns in the watershed area; 4) hay/pasture, the third dominant land cover, explained 14% of additional variance in the third factor of the county area, but only eight percent additional variance in the fourth factor of the watershed area. Thus, hay/pasture emerged as more important in describing land patterns in the county area; and 5) six factors explained the major gradients of variation in the watershed area, but seven were needed to explain the greater amount of variation in the metrics describing land patterns in the county area.

Implications for planning and policy

As a goal of land planning, land-use sustainability should include spatial planning for the conservation and protection of land and natural resources (Golley 1989; Forman 1995; Thorne et al. 2009). Landscape ecology concepts and examination of pattern metrics can be useful for addressing the spatial aspect in the planning and policy development process (Hersberger 1994; Forman 1995; Collinge 1996; Leitao and Ahern 2002). Different planning needs and policy applications will require their own solution sets of metrics and potentially differing scales of analyses (Ahern 1991; Leitao et al. 2006; Lovell and Johnston 2009).

County Planning and Policy

Compositional metrics can be used to inform county land planning and policy through analyses of land cover. For example, the degree of natural versus anthropogenic heterogeneity can be assessed by examination of compositional metrics. In this study, over half of the county is cultivated land. Zoning policy could zone natural land areas to be protected for the maintenance of natural physical (e.g. aquifer recharge) and ecological (e.g. wildlife habitat) processes, potentially targeting and protecting large natural areas using patch area metrics (Press et al. 1996). Mandated vegetated buffers around sinkholes could address nonpoint source pollution to karst aquifers (Peterson and Vondracek 2006). Regulatory limitations on the development of impervious surfaces could directly support hydrological processes and water pollution mitigation. This could include regulatory restrictions on road widths or prohibiting removal of native vegetation in easements or riparian areas.

Average urban patch size in the county area was approximately half of that seen in the watershed, indicating a greater influence of urban development in the watershed. County zoning policy could mandate the placement of urban or rural development away from sensitive hydrological areas in the watershed. Creating an overlay zone with sensitive hydrologic areas (e.g. sinkhole plains) and existing storm-water flow management methods (e.g. pipe and pond), county policy can incorporate stream or watershed peak flow restrictions with directed placement of urban or rural development to aid in water management goals within specific watersheds or subwatersheds.

Metric reduction through PCA could also provide useful information. For the county area, both average forest patch area and average forest radius of gyration were found to be positively correlated on the same PCA factor indicating potential viability (with appropriate size and connectivity) of forest patches in the county land area. To maintain this relationship to support healthy forest ecosystems, zoning policy could prohibit development in forest ecosystems, or could zone these areas for only low-impact land use (i.e. hiking, biking, hunting, greenways, open space). To support and maintain healthy forests, policy could mandate best management practices in all county forestry operations (Arthur 1998; Zwieniecki and Newton 1999).

Comparisons between the watershed and county metrics could also inform county planning and policy development. For example, in this study, county land cover was more fragmented than the major watershed area. Land fragmentation through development, agriculture and deforestation can have a negative impact on hydrology and ecological processes, including loss of native species, invasion of exotic species, soil erosion and decreased water quality (Collinge 1996; Di Giulio et al. 2009). In response to this finding, county policy could be updated or created to mandate the restoration, connectivity and protection of specific natural areas to restore, prevent or mitigate potential negative effects of land-use activities that might promote land fragmentation. County policy could additionally establish overlay zones that define, connect and protect land areas containing sensitive natural areas, known recharge areas and for this karst region, known karst features like sinkholes and cave systems. Variations of these types of policy instruments are not without precedent (Chapter 3).

Watershed Planning and Policy

Watershed policy is generally developed to guide what happens to snow melt and rain water that falls within a watershed's boundaries. However, no watershed exists in isolation and biophysical processes interact across watersheds to influence regional properties like aquifer recharge, land use and land cover. In karst regions, subsurface water flow can occur between watersheds, sharing nonpoint-source contaminants. Thus, knowledge of regional land-use cover and activities is important for all watersheds but is critical for karst watershed management (Veni 1999).

Comparisons between watershed and county metrics can help inform watershed planning and policy development. For example, in this study, the watershed lacked the indicators of sustainable forest land areas (with appropriate patch sizes and connectivity) that were shown to exist for the county. This finding could inform watershed policy for the need of enhanced restoration and connectivity of forests within the watershed. The watershed also had larger agricultural land patch sizes and smaller forest patch sizes than seen in the county. Watershed policy could be created or modified to mandate or promote agroforestry practices in agricultural land areas or could promote or restore native forest cover in rural and urban settings.

Conclusions

With increasing urbanization, land and watershed managers are faced with the need to develop appropriate and cost-effective assessment tools that can provide a comprehensive survey of land use and land cover, including water resources.

Sustainable land and watershed efforts need research and management tools that take into account the impacts of land cover alterations and subsequent consequences on natural systems (Luck and Wu 2002), including those that occur in karst regions (Veni 1999).

This study presents the results of the quantitative analysis and comparison of pattern metrics in a county area and in the major watershed area overlying the county area. A reduced set of pattern metrics was identified and compared for each of these two land areas. Results of analyses were compared and similarities and differences were identified. A similar result, for example, was that cultivated land, the dominant land cover in both the county and major watershed area, emerged only as a secondary (factor two) metric for describing land patterns in each area. Identifying a difference in land patterns between the county and watershed areas, descriptive metrics indicated that the county was more fragmented than the watershed. Additional descriptive metrics provided more context with which to compare the land cover patterns. These analyses of pattern metrics, applied separately to a county and major watershed area, identified multiple factors and specific metrics that explained a large amount of variance in each land cover dataset. These metrics provide a baseline description of landscape structure that could be used as a tool to quantitatively describe the landscape, to improve communications between planners and natural resource managers and to provide a quantitative basis for future landscape change research.

Comparisons of land patterns across political units and naturally-delineated land regions could contribute to a better understanding of impacts from anthropogenic activities on regional natural resource inventories, potentially improving land-use and land-management decisions. Research into land pattern quantification can provide a basis for understanding human impacts on biophysical environmental processes. The quantification and behavioral analysis of regional pattern metrics, like that provided in this study, in addition to studies evaluating temporal changes in pattern metrics, could be used by researchers and managers to more effectively manage and mitigate human impacts across overlapping naturally- and politically-delineated landscapes. These methods could be used for any politically-delineated region from smaller-scale cities to larger-scale political regions that spatially overlap with larger naturally-delineated land areas.

Karst geology integrates terrestrial and hydrologic systems. For any karst region in any country, research into land pattern quantification could provide information necessary for determining links between anthropogenic land use and implications for environmental processes. Metrics could be used to improve predictive capabilities of land use and land use change, especially for the integrity of unique and sensitive land areas and the human communities that inhabit them.

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Table 1. Metrics selected as descriptive pattern measures and for landscape and class pattern analyses. For each class metric, xx indicates the land cover type (LCT) metric where CL=cultivated land, FR=forests, HP=hay/pasture/grassland, UR=urban and WT=water land cover type.

Pattern Metric	Fragstats Acronym	Units
MEASURES INCLUDED IN PCA ANALYSES		
LANDSCAPE METRICS		
Area-weighted Mean Patch Size	AREA_MN	meters
Mean Patch Size Coefficient of Variation	AREA_CV	%
Mean Patch Shape	SHAPE_MN	none
Mean Patch Gyration - Average Patch Extensiveness	GYRATE_MN	meters
Mean Euclidean Nearest Neighbor	ENN_MN	meters
CLASS METRICS (per LCT for each of the 4 LCTs)*		
Mean Patch Size	xx_AREA_MN	meters
Mean Patch Size Coefficient of Variation	xx_AREA_CV	%
Mean Patch Shape	xx_SHAPE_MN	none
Mean Radius of Gyration	xx_GYRATE_MN	meters
DESCRIPTIVE MEASURES OF EACH LANDSCAPE		
Number of Patches	PN	none
Patch Density	PD	#/100 hectares
Patch Richness Density	PRD	#/100 hectares
Largest Patch Index	LPI	%
Landscape Shape Index	LSI	none
Shannon's Evenness Index	SHEI	none
Contagion Index	CONTAG	%
Area-weighted Mean Patch Size	AREA_AM	meters
Area-weighted Mean Patch Shape	SHAPE_AM	meters
Area-weighted Mean Euclidean Nearest Neighbor	ENN_AM	meters

* where xx indicates a class-level metric where cl=cultivated land, fr=forests, hp=hay/pasture/grassland and ur=urban.

Table 2. Summary statistics of each land cover type in Wabasha County and in the watershed area. Kruskal-Wallis tests between class means found all class means to be significantly different except for the Hay/Pasture/Grassland class.

Land Cover Class		Wabasha County	Combined Watersheds
Percent of total land area			
Cultivated Land		53.93	60.60
Forests		25.30	18.42
Hay/Pasture/Grassland		13.20	13.55
Urban		2.67	4.94
Water		4.91	2.53
Averaged over subwatersheds			
Cultivated Land			
	Minimum	6.71	7.76
	Maximum	82.58	95.24
	Mean	54.27	61.72
Forests			
	Minimum	2.62	0.86
	Maximum	55.36	61.84
	Mean	25.69	17.27
Hay/Pasture/Grassland			
	Minimum	5.67	1.75
	Maximum	43.27	57.00
	Mean	13.53	14.59
Urban			
	Minimum	0.90	0.41
	Maximum	9.57	67.00
	Mean	2.69	5.30
Water			
	Minimum	0.00	0.00
	Maximum	54.20	30.40
	Mean	3.82	1.17

Table 3. Summary statistics of landscape and class metrics calculated for the subwatersheds in Wabasha County and in the major watershed area. For each class metric, CL=cultivated land, FR=forests, HP=hay/pasture/grassland, UR=urban and WT=water land cover type.

Pattern Metric		Wabasha County Mean	Wabasha County Stdev	Major Watershed Area Mean	Major Watershed Area Stdev
NP		292.31	163.93	274.24	213.45
PD		8.64	1.77	7.32	2.18
PRD		0.25	0.28	0.18	0.15
LPI		46.08	16.62	52.75	22.86
LSI		10.57	3.32	9.65	3.56
SHEI		0.63	0.12	0.56	0.17
CONTAG		63.25	6.67	67.57	9.74
AREA_AM		1005.70	834.73	1397.39	1425.84
SHAPE_AM		5.33	1.39	5.11	1.39
ENN_AM		60.05	25.63	61.20	31.88
AREA_MN		12.07	2.63	15.05	5.04
AREA_CV		824.91	320.50	881.08	364.90
SHAPE_MN		1.52	0.08	1.48	0.08
GYRATE_MN		78.88	10.14	83.26	20.83
ENN_MN		179.38	34.24	198.55	52.03
AREA_MN	CL	102.08	87.01	296.31	668.20
	FR	13.10	13.92	9.78	10.99
	HP	5.41	2.90	9.37	14.57
	UR	1.49	0.89	2.91	6.21
	WT	5.73	18.01	2.55	10.05
AREA_CV	CL	278.91	114.05	256.28	98.82
	FR	664.89	293.04	480.96	292.87
	HP	227.16	82.15	241.15	89.27
	UR	182.74	155.96	210.96	192.32
	WT	162.57	155.14	124.94	147.13
GYRATE_MN	CL	267.39	85.49	399.40	425.06
	FR	63.91	30.07	64.33	31.11
	HP	87.25	13.66	102.44	35.52
	UR	41.87	7.02	47.38	15.94
	WT	40.97	36.40	34.55	35.12
SHAPE_MN	CL	1.95	0.24	2.05	0.45
	FR	1.48	0.15	1.45	0.14
	HP	1.65	0.08	1.67	0.11
	UR	1.28	0.06	1.26	0.05
	WT	1.38	0.27	1.32	0.23

Table 4. Varimax rotated axes and loadings for each land area. Loadings less than 0.40 are deleted for reading clarity. Loadings used for component interpretation are in bold.

	(1) Wabasha County							(2) Major Watershed Area					
Metrics	1	2	3	4	5	6	7	1	2	3	4	5	6
area_cv	-0.41			**0.79**				**-0.74**					
area_mn		**0.64**		0.40								**0.72**	
cl_area_cv				**0.87**					**-0.72**				
cl_area_mn	-0.52	**0.67**							**0.83**				
cl_gyrate_mn		**0.92**							**0.90**				
cl_shape_mn		**0.92**							**0.88**				
enn_mn		0.51					**-0.52**					**0.71**	
fr_area_cv				**0.82**				-0.44					**0.59**
fr_area_mn	**0.74**		-0.42										**0.76**
fr_gyrate_mn	**0.76**							**0.89**					
fr_shape_mn	**0.83**							**0.82**					
gyrate_mn	**0.85**							**0.81**			0.43		
hp_area_cv						**0.73**					0.42		**-0.43**
hp_area_mn			**0.79**								**0.70**		
hp_gyrate_mn			**0.90**										
hp_shape_mn			**0.75**								**0.76**		
shape_mn	**0.88**							0.57					**0.58**
ur_area_cv					**0.89**					**0.76**			
ur_area_mn					**0.95**			**0.68**					
ur_shape_mn	0.42				**0.45**			**0.43**		0.43			
wt_area_cv						**0.74**				**0.82**			
wt_area_mn						**0.80**				**0.66**			
wt_shape_mn							**0.75**					**-0.59**	
Eigenvalue	4.5	3.4	2.7	2.6	2.3	2.3	1.7	4.5	3.2	2.3	2.1	2.0	1.9
%Variance	19.6	14.6	11.7	11.3	10.1	10.1	7.3	20.5	14.6	10.7	9.7	9.0	8.7
Cum %Variance	19.6	34.2	45.9	57.2	67.4	77.4	84.7	20.5	35.1	45.8	55.5	64.5	73.2

Figures

Figure 1. Approximately 25% of the United States land is karst including Wabasha County in southeast Minnesota (Aley 2002). This county is overlain by three major watersheds all draining to the Mississippi River.

Figure 2. Subwatersheds representative of the lowest (on the left) and highest (on the right) factor scores for the first two factors from the watershed area factor analysis. Subwatersheds show (a) for factor one, subwatersheds having less-complex forest patch shapes and smaller mean urban patch areas at the negative end of the factor. Subwatersheds with higher factor scores are characterized as having large variations in mean landscape patch size; (b) for factor two, describes a gradient with smaller mean cultivated land patch sizes with less-complex cultivated land patch shapes with low factor scores. Larger mean cultivated land patch sizes with small variations in mean patch size characterize subwatersheds with higher factor scores.

Figure 3. Agriculture, forest and urban land cover in the major watershed area overlying the two study areas.

Figure 1.

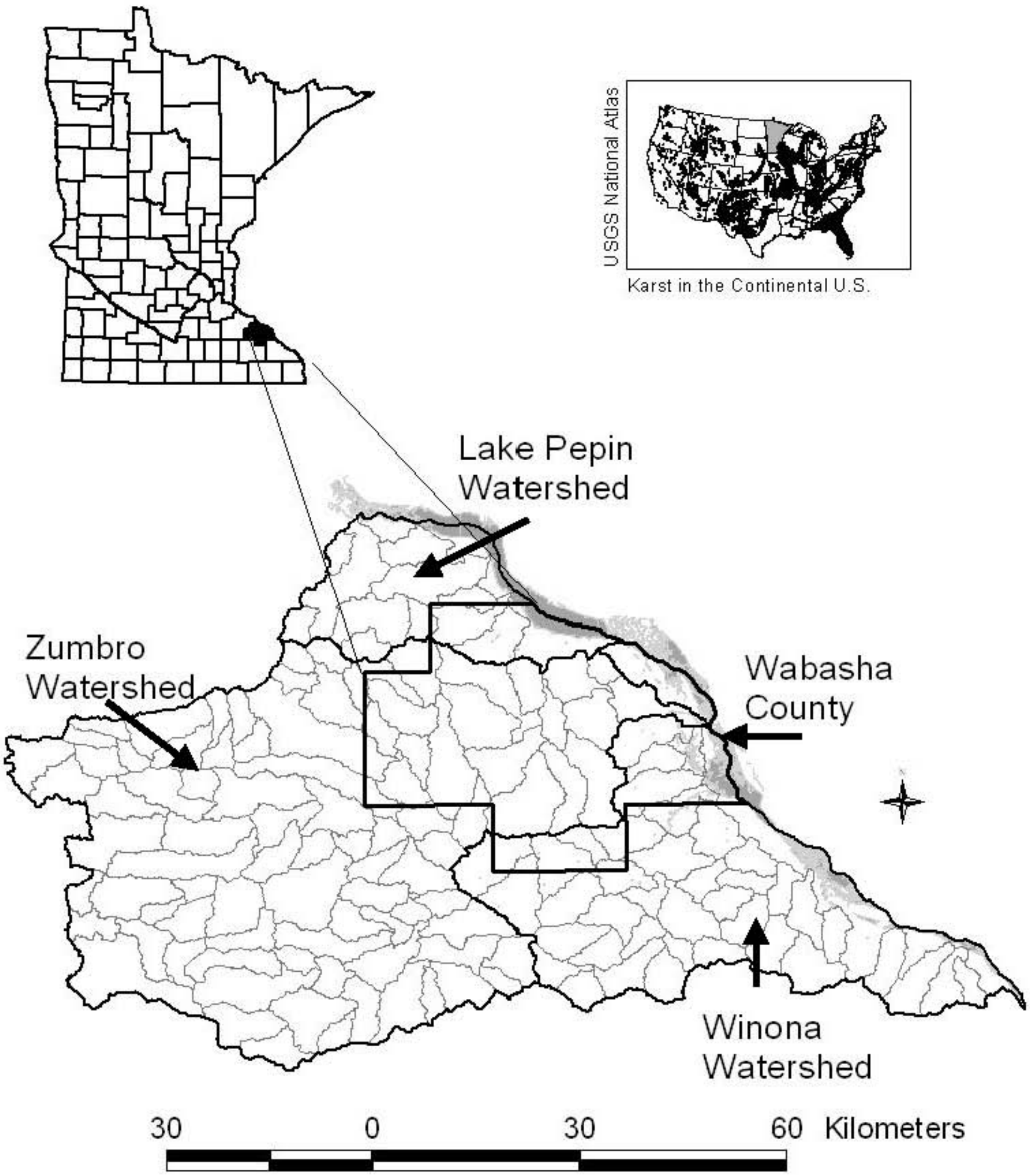

USGS National Atlas
Karst in the Continental U.S.
Lake Pepin
Watershed
Zumbro
Watershed
Wabasha
County
Winona
Watershed
30
0
30
60
Kilometers

Figure 2.

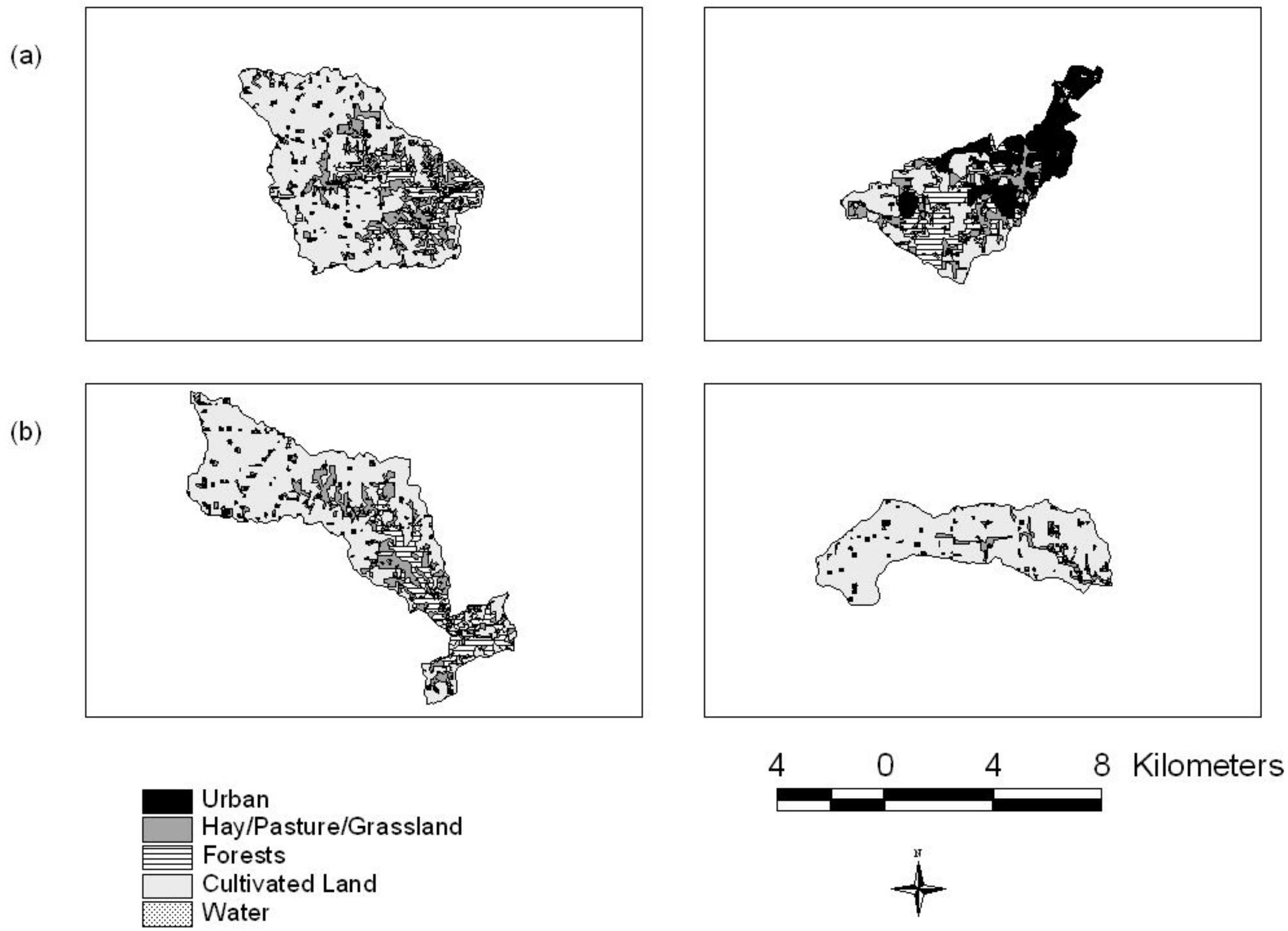
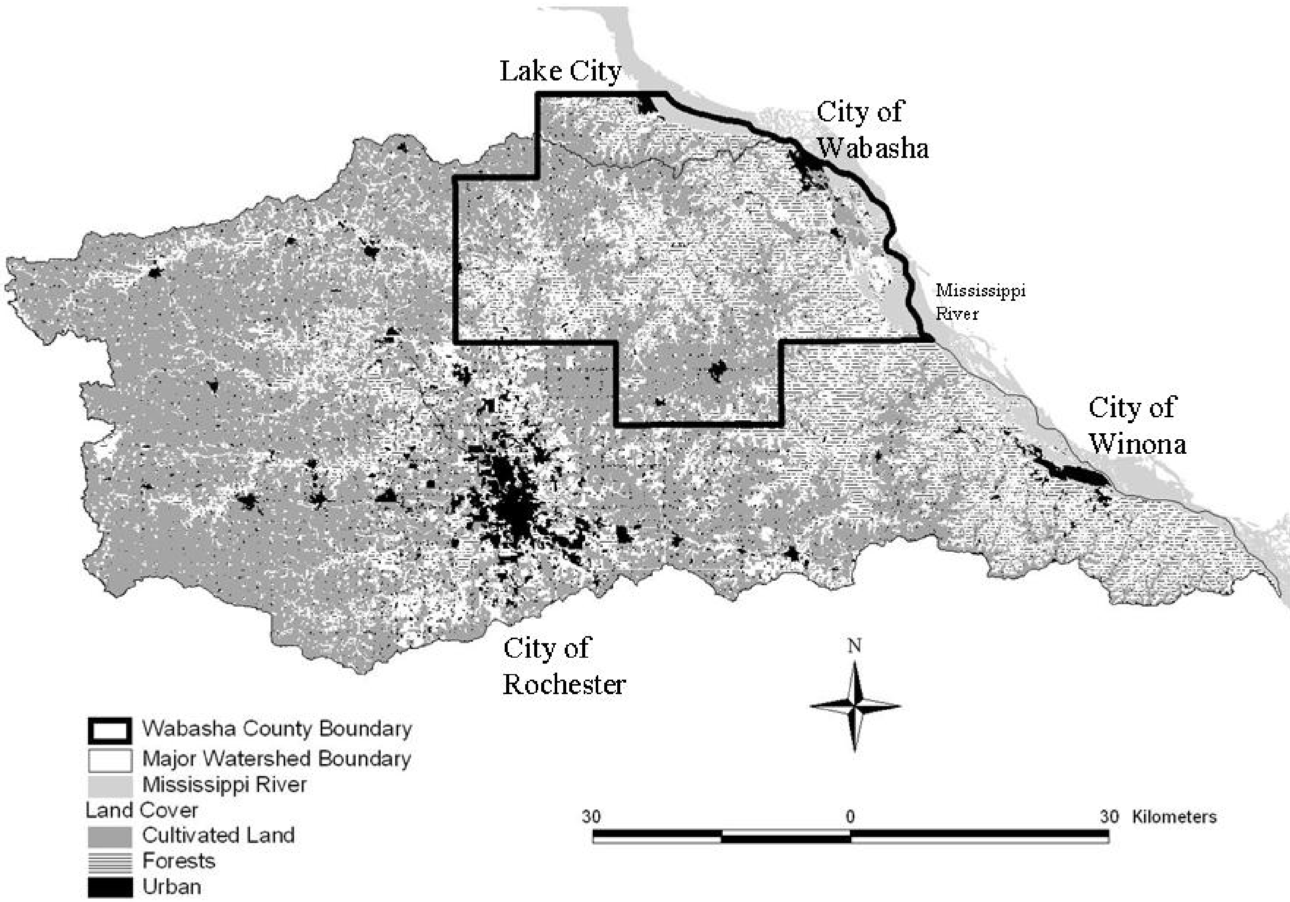

(a)
(b)
Urban
Hay/Pasture/Grassland
Forests
Cultivated Land
Water
4 0 4 8 Kilometers
N

Figure 3.


Lake City
City of Wabasha
Mississippi River
City of Winona
City of Rochester
N
Wabasha County Boundary
Major Watershed Boundary
Mississippi River
Land Cover
Cultivated Land
Forests
Urban
30
0
30 Kilometers

Chapter 3

Thinking globally while governing locally:

local regulation of ecological processes

MARY A. WILLIAMS

SUSY SVATEK ZIEGLER

Sustainable land-use planning and sustainable development are slowly gaining momentum because of social concerns, environmental objectives and socioeconomic needs. For these reasons, planning decisions and policy development increasingly depend on best available science, which may encompass multiple disciplines such as hydrology to address water issues, ecology to identify and protect environmentally sensitive areas, and public health for concerns such as pollution abatement. Less prominent, however, is the incorporation of holistic views of how larger-scale natural land areas function and are necessary to produce ecosystem services that provide goods and services to sustain human communities. Even with long-term knowledge of watershed and ecological processes, and the importance of ecosystem services to human communities, most land-use decisions and policy instruments are still focused on guiding activities on small-scale parcels of land.

To examine the current relationship between local land-use policy and larger-scale environmental functions, we examined municipal ordinances for a county and three cities within that county in a karst region in southeastern Minnesota to identify policy references to environmentally sensitive karst features, regional landscape functions and ecosystem services provided in that region. Multiple ordinances referenced and protected several ecosystem services, but landscape functions were rarely mentioned. Only one ordinance referenced a karst feature. We identified gaps in policy coverage and proposed additional policies and planning methods that could support and enhance sustainable land planning and policy development for these and other municipalities found in karst regions. We concluded that larger-scale views of land planning beyond the parcel scale are needed in this and other regions. With most land-use decisions made at the local scale, analyses such as this one are critical for identifying gaps in natural resource management and for providing initial steps towards incorporating larger-scale environmental processes into land-use planning and policy.

Key words: ecosystem services; karst; land-use policy; landscape functions; landscape planning; Minnesota, USA; ordinance; sustainable development; Wabasha County.

INTRODUCTION

In the United States, land-use decisions are made primarily on local or parcel-level scales (Porter 2008) where environmental effects of land planning and development can affect and be affected by the larger-scale environment (Dale et al. 2000; Beatley 2000; Selman 2002; Tscharntke et al. 2005; Fiedler et al. 2008). Studies have examined and continue to call for evaluation of larger-scale environmental interactions between local planning and policy development with landscape functions, ecosystem services (Salzman 1998; Woolf and Somner 2004; Chan et al. 2006) and biodiversity conservation (Press et al. 1996; Azerrad and Nilon 2006; Milder et al. 2008; Miller et al. 2008).

Policies developed to guide sustainable land planning and development should be tailored to the regional environment and what is useful in one region of the country may not apply to other regions. This geographic variability can be a problem when uniform standards and codes are applied blindly to all settings (Ben-Joseph 2004).

Unique regional attributes like bedrock geology contribute environmental variability. Karst landscapes, for example, add complexity to landscape management. The term "karst" describes predominately limestone and dolostone landscapes primarily weathered through a chemical dissolution process. Over geologic time, karst features like sinkholes, bedrock springs and fractures, sinking streams and caves form on and under the land surface.

Approximately 20% of the earth's land surface is karst (Gvozdetskii 1967 as cited by White 1988), and in the United States, approximately 25% of land is karst (USGS 2003). Anthropogenic land-use activities on karst result in various environmental, development and economic issues including failures of foundation and slab, pipes and buried utilities, impoundments and liner systems, and roadways (Beck 1995; Ralston et al. 1999). Environmental concerns include flooding (Zhou 2007) and spring water degradation (Mahler and Lynch 1999; Wicks et al. 2004; Davis et al. 2005).

Based on historical problems with land use on karst landscapes, published regulatory reviews reveal evolving guidelines for policy development in various karst communities in the United States (see review by LaMoreaux et al. 1997). Despite this legal recognition of karst sensitivities from some municipalities, however, other karst landscapes remain legally unprotected from human activities.

For a geologically and ecologically sensitive karst landscape in southeast Minnesota, we evaluated city and county municipal policy for regulatory recognition of karst features, landscape functions and ecosystem services. Our goal was to measure the extent of regulatory coverage of regional ecological processes on the local scale where most land-use decisions are made.

We first identified regional landscape functions and ecosystem services, then asked three questions regarding the extent of their regulatory coverage: (1) How is this feature, function or service tied to the karst nature of the landscape?, (2) Was the function or service directly or indirectly referenced by any of the municipal ordinances?, and (3) Could an ordinance elsewhere serve as a better ordinance? Apparent gaps in policy coverage of these elements were identified.

Although other studies have discussed the need for the development of local policy measures and infrastructure to better protect specific environmental processes (Woolf and Sommer 2004; Lankao 2007), they have done so without referencing how the proposed policies would fit in or complement existing policies. We examined existing policies and proposed additional policies and landscape planning methods that could support and enhance current policy and sustainable land planning for these and other similar municipalities.

This study is not a review of forces shaping land-use decisions. It is a qualitative examination of local regulatory coverage of a specific list of landscape functions and ecosystem services. This type of analysis can be repeated in any politically delineated unit and could be especially useful in other karst regions. We do not state or infer that the county or city ordinances were the only policies that determine land use in this particular area. An in-depth discussion of the full range of land-use policy from local to federal levels is beyond the scope of this paper.

METHODS

Study sites

Ordinances were reviewed for a county and three municipalities in southeast Minnesota, located on karst landforms (Fig. 1). This region has scenic blufflands created by the Mississippi River and its tributaries, multiple river valley plateaus and a variety of ecosystems including oak savannas, floodplain forests, shrub wetlands, open wetlands and prairies. Natural resource inventories revealed that this region, comprising only three percent of Minnesota's total area, contains habitat for 43% of Minnesota's plant and animal species listed as endangered, threatened or of special concern (McCormick 2007).

Karst landforms provide an important land and water management component to this region. In southeast Minnesota, more than 10,000 karst features have been located, georeferenced and included in a geographic information database created and maintained by the Minnesota Geological Survey (MGS) (Gao et al. 2002). These features include sinkholes, stream sinks, seeps and springs.

From this region, Wabasha County and three cities within this county were selected for this study because they are located on karst, their municipal ordinances were freely available for download over the Internet, and they represented a range of urban, exurban and rural communities (Table 1). Regional stakeholders included The Nature Conservancy, the U.S. Army Corps of Engineers and The Upper Mississippi River National Wildlife & Fish Refuge. Wabasha County encompasses or shares a boundary with land owned by all of these organizations. Across Wabasha County, 200 sinkholes, 45 springs and two stream sinks have been georeferenced and entered into the MGS karst database (Fig. 1). Further complicating land management activities, several extensive subsurface cave systems have also been mapped in this county (Tipping 2002).

This county and all three cities are underlain at least in part by karst. Lake City land area is 2% karst and the City of Wabasha land area is 20% karst. The City of Plainview sits entirely over karst. Expanding into defined growth boundaries will eventually increase the amount of karst land area in both Lake City and the City of Wabasha.

Most of the drinking water in Wabasha County comes from wells drilled into nine subsurface karst aquifers. Although the aquifer units have varying geologic characteristics, two different ground-water systems are recognized in the county: the upland area system and the river valley system. The majority of the rural residents living in Wabasha County have wells in the upland areas of the county. These upland areas are recognized as regions of ground-water recharge. The river valley system is a major area of ground-water discharge. Springs in this valley system are a major point of ground-water discharge. These springs are an important component of regional cold-water aquatic habitats and could become degraded with polluted or reduced ground-water discharge (Chapter 1).

Intersecting this county is a regional ground-water recharge zone where ground water discharges quickly from upper non-confined aquifers through this recharge zone into underlying aquifers (Runkel et al. 2003). Land use over this area directly affects the quality and quantity of water recharge into regional karst aquifers, the Mississippi River and eastern Zumbro River valley Quaternary sediments. These areas contain multiple municipal wells that provide drinking water for city and county residents. The susceptibility of ground water to pollution from land-use activities has been rated high to very high over most of this area (Peterson 2005).

Land planning

Wabasha County is governed by five county commissioners coordinated by a county administrator. This county has a published comprehensive land-use plan and has established zoning ordinances for all county land areas. Counties in Minnesota have no legal land-use authority in city boundaries, except when requested by a city (Association of Minnesota Counties 2002*a*). Through zoning ordinances, Minnesota counties and cities have complete control over land-use activities except for minimum state-required regulations for shorelands, floodplains, sewage treatment systems and building codes. Local municipalities are allowed to pass regulations stricter than any federal or state regulations.

Under state law, Minnesota county commissions plan county land-use (Association of Minnesota Counties 2002*b*). Wabasha County has a planning commission that meets regularly to assess zoning ordinance issues. Through open public meetings and based on recommendations from the county engineer's office and the county planning commission, the Wabasha County Commission makes all final decisions on land-use activities in the county for areas outside of city boundaries.

Minnesota state law requires city governments to regulate certain activities including: the use of streets and other public grounds; planting and protection of vegetation on city property; and zoning and land-use controls (Handbook for Minnesota Cities 2007*a*). Cities are not required to get voter approval to enact ordinance.

Each city in this study has a Mayor–City Council form of government with a planning commission designated to review land-use requests (Table 1). The mayor has the same power as a council member to make, second and vote on motions (Handbook for Minnesota Cities 2007*b*). Through open public meetings and based on recommendations from city staff and the city planning commission, each city council makes all final decisions on land-use activities in their respective cities.

Policy analysis

All ordinances published on the respective governmental websites were downloaded and examined for references to a list of landscape functions and ecosystem services (Table 2). Specific ordinance sections that referenced landscape functions, ecosystem services or karst features were recorded in a table for each city and the county. Ordinance numbers were cataloged to allow any person to find the specific ordinance. For example, under the Wabasha County column in Table 3, "A13S9(4A;14)ZO" refers to Wabasha County ordinance Article 13, Section 9, Subdivision 4A, page 14 in their Zoning Ordinance. Only subdivisions and page numbers were common to all ordinances and are in parentheses for ordinances listed across all municipalities. Ordinances without subdivisions have only a semi-colon before the page number (e.g. (;5)).

An ordinance that directly specifies the existence, need, maintenance or protection of a landscape function or ecosystem service was listed under the "Direct" column for the specific city or the county (Table 3). For example, City of Wabasha ordinance 335.37(1;17) states that "When possible, existing natural drainage ways, wetlands, and vegetated soil surfaces must be used to convey, store, filter, and retain storm-water runoff before discharge to public waters." This ordinance directly refers to the storm-water management functions of the natural landscape.

The "Indirect" column indicates ordinances that indirectly referenced the need for, maintenance of, or protection of a function or service (Table 4). The aesthetic beauty of natural views, for example, is an important ecosystem service that adds economic value to properties and improves community well-being (Daily 1997). Wabasha County ordinance A3S10(1A;4)ZO governing the development of a junkyard indirectly references the importance of a natural view when it states, "All reasonable means shall be taken to screen the use from adjacent properties and roads. Natural vegetation and earth forms shall be the preferred method of screening, with the actual design of screening to be determined by the Planning Commission as part of their review of the Conditional Use application." This ordinance implies that "natural" views are best, but does not mandate that the view has to be native landscape. The implication that views are important is clear, however, so it was included in the "Indirect" column.

These (like most other) ordinances are written as general rules to guide human behavior and most lack supporting or explanatory documentation. So, for this study, the interpretations of the purpose, goal or meaning of ordinances were literal (following the "letter of the law") and are, admittedly, somewhat subjective.

RESULTS AND DISCUSSION

Karst Features and Landscape Functions

Function, for the purpose of this paper, is specifically defined as a process (e.g. water recharge) that directly results from one or more physical actions (e.g. water infiltration) or states (e.g. percent pervious surface). So, for example, aquifer recharge is a function of precipitation, vegetation cover, topography, infiltration and percent pervious surface. An ecosystem function can be delineated in a specific setting. For example, in Glacier Bay, Alaska, in a recently deglaciated river, increased inputs of large woody debris led to high quality fish habitat (Naiman et al., 1997). In this spatially-delineated riverine system, provision of fish habitat is a function of the amount of large woody debris. Because ecosystems are not independent of neighboring spaces, landscape function is defined as a function which can be defined or delineated over two or more distinct ecosystems. Provision of habitat for migratory wildlife is another landscape function.

Karst features - Karst features are either surficial (like springs or sinkholes) and thus easy to see, or they are hidden from view (like covered sinkholes, bedrock fractures, vertical or horizontal conduits, and caves). Knowledge of subsurface karst features is virtually impossible without a surficial expression (like an entrance to a cave), and understanding the hydrogeologic interconnections through karst topography is challenging even for seasoned hydrogeologists. It is this very nature of the complex hydrogeologic character of karst that makes land and water management in karst topography a challenge for land-planners and policymakers.

Ralston et al. (1999) identified two categories of what they deemed to be relevant karst land-planning and ordinance legislation: storm-water management ordinances and land-development control ordinances. These types of ordinances generally control land-use decisions on individual parcels of land. Although almost all published ordinances fell into one of these two categories, scientists argue that because of the highly permeable and enigmatic above and below-ground interconnected nature of karst, land management in karst landscapes should not be conducted on a parcel basis, but rather should be viewed on a regional or watershed scale (LaMoreaux et al. 1997; Veni 1999; Zhou 2007). In this karst region of southeastern Minnesota, examination of land cover patterns have shown differing land cover patterns in the county versus major watershed areas (Chapter 2). Studies revealing regional land cover characteristics can help inform water and land management across large-scale areas.

Due to the rapid infiltration of surface water into subsurface aquifers, polluted storm-water runoff is of special concern in karst areas. Successful management of karst environments, particularly in urban areas, will involve the natural, undeveloped preservation of the most vulnerable areas of regional karst landscapes in conjunction with region-wide efforts to reduce point or non-point pollution loading to regional aquifers (Veni 1999). Springs in this region are clumped at low elevations where aquifer discharge is typically focused (Chapter 1). Pollution loading into these aquifers could discharge from the springs and degrade aquatic ecosystems. These cold-water aquatic systems support a multi-million dollar fishing industry and efforts to keep the aquifers pollution-free would translate to cleaner waters for aquatic ecosystems and continued support for the regional fishing industry (Chapter 1).

All municipalities in this study contain these two types of ordinances, but none explicitly referenced karst or karst features. The Wabasha County comprehensive land-use plan stated that "Wabasha County is located in a Karst topography region," but otherwise did not directly address the sensitivities of karst. As the single municipal ordinance that referenced a karst feature, Wabasha County zoning ordinance Article 5 stated that "No new feedlot shall be within 300 feet of any sinkhole." No other comprehensive land-use plan or ordinance in any of these municipalities directly referenced karst landscapes. This oversight is surprising given the legal, environmental and financial problems historically faced by several neighboring municipalities over karst-related ground-water contamination in southeast Minnesota (e.g. Alexander and Book 1984; Jannik et al. 1991; Alexander et al. 1993; Alexander et al. 2005).

This lack of regulatory coverage for karst features is problematic because anthropogenic land-use activities are known to affect and to be influenced by karst features. Land development in karst often creates or exacerbates regional socioeconomic and environmental problems by inducing sinkhole development, modifying storm-water runoff and vegetation cover, generating water-table draw downs and adding point and non-point source pollution (e.g. White et al. 1986; Neill et al. 2004; Alexander et al. 2005). One aspect of the socioeconomic problem is in the management of cold-water fisheries. Residents in the area fish to procure food and the fishing industry is an important part of the regional economy. Modifications of surface water processes including increases in impervious surfaces, pollution from construction activities, and subsequent changes in the raising or lowering of the regional water table aggregate over space and time, degrading regional surface and subsurface water bodies for regional and downstream citizens and wildlife (White et al. 1986; Veni 1999). Any effects causing a reduction in aquifer recharge will affect cold-water aquatic systems and subsequently, regional economies.

In response to these issues, several municipalities elsewhere have modified or developed ordinances and land-use plans to incorporate the definition of karst. For example, the Monroe County, Illinois, Comprehensive Development Plan, as part of its Comprehensive Land Plan, has an entire section on karst topography and a map marking sinkhole plain areas (Bade and Moss 1999). As one method for integrating the recognition of karst features into their ordinances, Monroe County officials added a definition for "sinkhole" for every ordinance, then additionally modified the Monroe County Subdivision Ordinance and Public Health Private Sewage Disposal Licensing Act and Code to improve safeguards against pollutant discharge into known karst features.

These evolving regulatory recognitions of karst influence, labeled "limestone ordinances" (Fischer 1999), while recognizing the inherent complexities of karst, simply regulate certain construction activities in the immediate vicinity of known surficial karst features (Table 5). However, parcel-level regulations do not recognize or protect the larger-scale interconnected hydrological processes found in karst landscapes.

On a larger watershed scale, the Texas Edwards Underground Water District and regional water management districts in Florida view their associated karst systems on aquifer-wide spatial scales and regulate activities with an eye on pollution prevention and long-term water quantity conservation (LaMoreaux et al. 1997).

In karst areas, rather than focus on land management of individual parcels through storm-water and construction management, land-planners could consider the importance of karst in land-planning activities. In our study area, for reasons unknown, regulations did not recognize karst, and they did not restrict or prohibit land use over known recharge areas. Incorporation of limestone ordinances could protect these natural resources, the landscape functions they support and the subsequent ecosystem services produced.

Evaluated over a larger land area, sustainable land planning would first recognize these environmentally sensitive land features and processes. Land planning activities could then incorporate protection of sensitive land areas while permitting heavier development where it is not likely to interfere with important land functions.

Aquifer recharge.—Most land in Wabasha County acts predominantly as an aquifer recharge area (Peterson 2005). Aquifer recharge is an important landscape function supporting above and below-ground biodiversity, terrestrial and aquatic habitats, biotic communities, nutrient cycling and geomorphologic stream and river processes.

Karst features facilitate aquifer recharge by focusing water flow into and through the subsurface, so that sustainable long-term recharge areas and recharge processes depend on the normal functioning of land features through space and time. Disruptions to the capacity of the upland area to recharge aquifers reduce the ability of the landscape to support recharge processes and subsequently to support other natural landscape and ecosystem processes. Springs, cold-water ecosystems and regional economic activity based on the fishing industry would be directly affected by any disruptions to aquifer recharge (Chapter 1).

None of the reviewed ordinances directly referred to the maintenance or protection of aquifer recharge. Several ordinances indirectly addressed this function through efforts to control the percentage of impervious land surface on development plots. Management of aquifer recharge on a parcel basis becomes ineffective when the amount of impervious land cover grows and significantly decreases the infiltration and recharge capabilities of the land surface and karst features (White et al. 1986; Scheuler 1994). Grant et al. (1996) advocate for strong regulatory limitations on the amount of paved surfaces and suggest that another way to foster adequate aquifer recharge is to maintain a low ratio of developed to undeveloped land leaving a high proportion of land area free from potential degradation.

As a result of incorporating a larger-scale view of land planning, Broward County, located over a karst aquifer in south Florida (Manda and Gross 2006), developed a "Drainage and Natural Aquifer Groundwater Recharge" guidelines designed to guide storm-water management activities. These activities are to, in part, "promote recharge to the Biscayne Aquifer" based on storm-water management guidelines over watershed scales (Broward County 2006). Although these guidelines are directed at parcel-level activities, the overarching purpose and goal incorporates a larger-scale view of land processes for the long-term sustainability of regionally-recognized natural resources.

Plant communities and wildlife habitat.—The natural development and maintenance of plant communities and wildlife habitat is an important landscape function, especially in complex spatially-heterogeneous landscapes (Pastor 2005). Karst adds to this complexity through its impacts on regional ecohydrological processes affecting the development of plant and animal populations (e.g. Furley and Newey 1979; Culver et al. 2000; Fetterman et al. 2003; Kobza et al. 2004).

Several ordinances indirectly addressed the natural development and maintenance of plant communities and wildlife habitat by requiring the preservation or restoration of natural vegetation to the greatest extent possible during development projects (e.g. Wabasha County ordinance A6S6(5;5)ZO and Lake City ordinance A6S7(A;3)). Decisions, however, are made on a parcel basis and generally cover engineering or construction issues (e.g. screening or erosion control). No ordinances mandated management, protection or connectivity of plant communities, ecosystems or wildlife habitats.

Forest ecosystems are important because they: provide wildlife habitat, aid in ground-water recharge, mitigate surface runoff pollution, mitigate stream temperatures and protect springs. Forested riparian areas mitigate soil erosion, pollution, water temperatures, water quality and water quantity for stream systems (Arthur et al. 1998; Brooks et al. 2003) which, in turn, support cold-water ecosystems and economically important cold-water fish species (Chapter 1). We found that neither forests nor springs received regulatory protection. Policies to protect or restore forest ecosystems or forested riparian areas could help to sustain these resources and subsequently to sustain the economical benefits that human communities derive from them. Zoning ordinances could mandate protection or restoration of native forest areas. Park and recreation areas could be zoned in forest ecosystems permitting only light, low-impact land use (e.g. hiking, greenways, open space). Characterizing land cover and land patterns could aid land managers in understanding how forest cover is allocated and connected across land areas (Chapter 2).

Cave systems and associated cave wildlife are found in many karst regions. Although research has highlighted the varieties of obligate karst biota found in the United States, including a high number of threatened or endangered species (e.g. Culver et al. 2000;

Elliot 2000), little published work describes cave biota of Minnesota. We located only one scientific study listing 11 species of troglophiles, two species of troglobites and two species of trogloxenes living in caves in Wabasha and Fillmore counties in southeastern Minnesota (Peck and Christiansen 1988). In this same karst region, cave explorers have recently identified bones of large prehistoric animals whose existence in this area was previously unknown to the scientific community (Mather 2009). Given this and other findings of new cave species in other karst regions of the United States (e.g. Christiansen and Bellinger 1996*a*; Christiansen and Bellinger 1996*b*; Lewis et al. 2003), the potential for new scientific discovery in this and other karst regions is very high. However, expanding settlements and land development could, potentially, deprive the region of natural resources and the scientific community of new findings before they can be thoroughly investigated.

Caves are known habitat for a variety of fauna. At least twenty-two states have passed cave protection acts (Huppert 1995; LaMoreaux et al. 1997), but neither Minnesota nor any of its county or local municipalities have followed suit. Austin, Texas, in contrast, developed watershed regulations with incorporated language that protects groundwater, caves and associated biota (Austin City Connection 2007). These ordinances have evolved over time to reflect science-based knowledge of karst hydrology and to cover land area and associated caves in all of the 45 watersheds within the city's planning boundaries. In the karst region of southeast Minnesota, the adoption of a comprehensive ground-water and cave protection ordinance could strengthen current ground-water protection efforts on a greater spatial and temporal scale and would protect the sensitive underground systems that are currently neglected from regulatory protection.

Ecosystem services

Ecosystem services are those goods and services produced by a landscape or ecosystem that contribute directly to human well-being. To recognize an ecosystem good or service is to acknowledge that a natural landscape or ecosystem function produced a free good or service for the direct well-being or consumption of humans. Although not directly using the label "ecosystem good or service," many ordinances in this region are written to reduce potential contamination of several ecosystem goods and services.

Drinking water.—In this karst region, the land surface is directly connected to ground water (Tipping 2002), and many ecosystem goods and services depend directly on the regional hydrogeology. Drinking water, for example, comes primarily from karst aquifers. To pump drinking water from regional aquifers requires an adequate supply (quantity) and it has to be potable (quality).

Recharge, the process by which water moves to the water table, supplies water to aquifers. A component of recharge is precipitation that percolates through the pervious soil matrix or that travels through karst features (sinkholes, fractures, conduits) to the subsurface aquifer systems. In Minnesota, over the long term, recharge is generally balanced by discharge, although this balance can be altered locally by factors including land use, impervious surfaces, pumping activities and climate change (Delin and Falteisek 2007).

Potable water is produced from filtration through natural landscapes. For runoff infiltrating quickly through karst features, the landscape between the point where the precipitation fell and where it intercepts an individual karst feature must have low or no pollution present in the flow area. In many areas, however, fertilizers and pesticides related to agriculture can and do enter the groundwater (Christensen 2007).

Municipalities recognized the need to protect the quality of this ecosystem good through ordinances developed to reduce or prevent pollution to both surface and ground water. The City of Plainview, for example, had a written wellhead protection plan to guide land use and development projects around sensitive wellheads and recharge areas. The goal of this plan was to reduce or prevent pollution from entering the city's source of drinking water. The other cities and the county had ordinances referencing the need to protect ground water or surface water, but had few mandated pollution prevention ordinances. An alternative storm-water management practice of using the natural land area to service municipal storm-water runoff to mitigate pollution was explicitly written in many ordinances. This written alternative is an explicit recognition of the ecosystem service of water filtration.

We found some regulations that addressed protect ground-water quality but none that targeted ground-water quantity. Surface and ground-water supplies are directly connected in karst systems, thus water quality and quantity should have concurrent consideration for proper management (Veni 1999; Bonacci et al. 2008). When not managed concurrently, protective efforts for one can be negated through neglect of the other. For example, caves and sinkholes might be given proper protection to maintain aquifer recharge, but land-use activities a short distance away could result in contamination of the same aquifers.

All of the ordinances we examined were directed at construction activities to reduce pollution discharges to water bodies, reduce lawn fertilizers and pesticides, and manage animal-feedlot operations and septic-tank installations. We did not locate any ordinances that mentioned the need to protect karst features that can direct run-off directly to ground-water aquifers.

In contrast, the state of Washington has developed a "Critical Aquifer Recharge Area" ordinance with the goal of "providing local governments with a mechanism to protect the functions and values of a community's drinking water by preventing pollution and maintaining supply" (Washington State 2007). King County, Washington, subsequently developed a "Critical Areas Ordinance as applied to Urban Properties in Unincorporated King County." Within that county, this ordinance defines areas of land that pose risk to aquifer water levels and aquifer water quality, prohibiting or restricting land-use activities in those areas. Although many of the individual ordinances are targeted toward plot-level construction activities, land management was initiated with a larger-scale watershed view of the regional natural processes that need to be conserved and protected.

Provision of wildlife populations.—Another ecosystem service acknowledged in each of the four comprehensive land-use plans in Wabasha County was the provision of wildlife populations that contribute directly to personal, cultural and socioeconomic well-being in this region. In southeastern Minnesota, cold ground-water springs contribute to viable cold-water trout habitat and subsequently to a profitable fishing industry (Waters 1977; Thorn et al. 1997; Gartner et al. 2002; Hart 2008). The juxtaposition of a cold-water spring to a stream strongly influences the ecosystem service of the provision of cold-water fish species for human consumption. Other regional wildlife populations like pollinator species are important for native plant reproduction and they support or enhance various agricultural activities in the county. Crop pests in this agricultural region, including various insects, rodents and nematodes, are controlled by natural enemies such as birds, spiders and ladybugs. Soil biota decompose waste, recycle nutrients and aid in waste removal and soil development. Migratory animals aid in seed dispersal and nutrient cycling across the landscape. These natural wildlife processes interact in complex ways and provide many ecosystem services to human communities (Daily 1997). Multiple ordinances referenced the need to provide wildlife habitat although none was found to mandate protection for specific animals, animal species or populations.

City of Plainview ordinance 604 (Storm water Management) section 7.11 (Additional Special Trout Stream and Outstanding Resource Value Water Requirements) identified that trout streams require special consideration when land is developed. This ordinance gave more specific guidelines for controlling potential water or sediment discharges from development activities for the protection of a nearby trout stream. Only Wabasha County and the City of Wabasha explicitly listed a function of wetlands as providing "fish and wildlife habitat." Lake City ordinance A7S7(B4c;7) stated that golf courses shall be designed with consideration of the "use of landscaping and site layout to preserve and enhance wildlife habitat." This ordinance did not mandate the preservation of natural landscape to provide the service of supporting and maintaining wildlife habitat, but indirectly acknowledged that wildlife populations are important ecosystem goods in this region. Trout populations are an ecosystem good in this region, forming a solid socioeconomic base as a multi-million dollar industry in southeast Minnesota (Gartner et al. 2002; Hart 2008). Degradation of these wildlife resources would be detrimental to the economy of this region. Also, as a predominantly agricultural county, elimination of pollinators and decomposer communities could reduce or degrade primary productivity, both on and off the farm.

As one example of what other communities have done to provide regulatory protection for regional wildlife populations, the City of Tampa, Florida, has developed an "Upland Habitat" ordinance that seeks to protect remaining upland xeric and mesic habitats in the city limits of Tampa that "constitute significant wildlife habitat, necessary to retain remaining habitat diversity and wildlife corridors and to maintain healthy and diverse populations of wildlife" (Municipal Code Online Library 2008).

The cities and the county in our study could examine their dependence on these ecosystem goods and services and follow up with regulatory mandates to preserve the environmental processes supporting the long-term socioeconomic health and sustainability of their communities.

Flood mitigation.—Although water drains quickly through karst areas, these areas can still flood. Floods are generally less severe but have a higher variability of flood peaks than streams in non-karst landscapes. Zhou (2007) lists three general types of karst-related flooding: recharge-related sinkhole flooding, flow-related flooding and discharge-related flooding. Flooding can exacerbate water pollution problems, induce sinkholes and cause damage to residential, commercial and public properties (Kemmerly 1993; Halihan et al. 1998; Zhou 2007). Costs associated with these damages are borne by private citizens, businesses and taxpayers. These costs can unexpectedly balloon with litigation (for an overview of multiple karst sinkhole litigation case examples, see

Quinlan 1986). Stream and river floodplain ecosystems evolve over time in karst landscapes because of naturally-occurring floods.

We did not find a county land-use plan or ordinance that recognizes or acknowledges the problems that sinkhole flooding could incur for citizens or communities. Wabasha County and the City of Wabasha did, however, list the function of wetlands for "storage of surface runoff to prevent or reduce flood damage," providing the ecosystem service of natural flood mitigation for county residents. Less than half of one percent of the land area in Wabasha County consists of wetlands, however, so this protection of wetlands would provide little natural flood mitigation for residents.

To recognize floodplain hazard areas, Wabasha County established Article 14 "Floodplain Management Regulations", which acknowledged that flooding in this area can result in potential loss of life and property. This ordinance established guidelines for minimum elevation and other plot-scale development codes within an established floodplain overlay district. A variety of conditional uses and variances are allowed. Lake City and the City of Wabasha had similar published floodplain management ordinances.

The lack of recognition of and protection for sinkhole flooding in the county can cause environmental and public health problems because sinkholes act simultaneously as collection basins for runoff and as points for aquifer recharge. Surface water, especially in flooded conditions, picks up and carries surface contaminates that can easily follow the water flow into and through aquifers then to springs, streams and river ecosystems. Land development increases impervious surfaces and surface runoff, which in turn increases flooding (Crawford 1984; Scheuler 1994; Mileti and Peek-Gottschlich 2001; Rogers and Defee 2005).

The lack of mandated protection for floodplains is an environmental and socioeconomic problem because any development in the floodplain alters ecohydrological functions both locally and downstream (Hughes and Cass 1997; Poff et al. 1997; Rogers and DeFee 2005). No ordinances reviewed in this study had designated any zones of "no development" that could allow the landscape and associated floodplains to mitigate floodwaters naturally and reduce loss of life and property. Flooding increases and becomes a greater hazard to human communities and the surrounding natural communities as the floodplain is further developed (Rogers and Defee 2005).

We did not find any existing ordinances that provided floodplain protection by mandating the complete prohibition of development in floodplains or even by restricting floodplain use to light, low-impact land use (e.g. hiking, biking, hunting, greenways, open space). Regulatory instruments that will sustain floodplain mitigation services over space and time will severely reduce or prohibit development on the floodplain and will protect those floodplain and riparian processes that support regional processes of flood-water storage and mitigation.

Undeveloped floodplains can support high floodplain biodiversity, mitigate flooding and prevent or minimize damage to and loss of property (Hughes and Cass 1997; Poff et al. 1997). Maintaining floodplains in their natural and unfragmented state with associated riparian areas allows these landscapes to fulfill their functions of storm or flood-water storage, aquatic ecosystem provision and maintenance, water filtration, and maintenance of water quality as water travels through the landscape then downstream through multiple watersheds and human communities.

LAND-USE PLANNING VERSUS LANDSCAPE PLANNING

In this study, all municipalities acknowledged or addressed at least one landscape function and ecosystem service through policy instruments, most typically through zoning policy directed at parcel-scale, land-use activities. Landscape planning will require that planners and policymakers take a larger-scale view of land use and community development. To incorporate extraterritorial areas in land and watershed management, planners could use various tools like geographic information systems and remote sensing to examine their larger physical environment (Lathrop and Bognar 1998; Stoorvogel and Antle 2001; Bacic et al. 2006). Assessments of ecosystem services could provide a baseline inventory for monitoring changes over time (e.g. Guo et al. 2000; Shelton et al. 2001). Incorporation of non-traditional development projects can promote sustainable residential neighborhoods (Milder et al. 2008). Outreach from scientific communities can provide environmental education and guidance for land managers (Brown and Kockelman 1996; Dale et al. 2000).

Active collaborations with regional stakeholders like neighboring municipalities, and federal, state, watershed or non-profit organizations could highlight regional environmental issues and reveal information supporting sustainable land planning and decision-making (Beatley 2000; Bacic et al. 2006). In this region over the past decade, several public workshops have been held by the Minnesota Department of Natural Resources and the University of Minnesota Department of Geology to provide community education about karst land areas, geology and water flow in these systems.

Conservation planning workshops have been held to bring regional stakeholders together to discuss conservation needs, viability of and critical threats to conservation targets, and strategies for mitigating threats for sustainable management of important natural resources. Stakeholders could additionally interact with regional agencies like the Center for Regional and Urban Affairs, located at the University of Minnesota in St. Paul, Minnesota. One of many useful services from this organization is a free subscription to applied policy-oriented research reports covering urban and regional issues like land management (e.g. Ziegler and Williams, 2008).

Implementation mechanisms to address ecosystem services and landscape functions could include such actions as direct management of sensitive land projects, provision of financial incentives to land managers, policy creation for preservation or restoration of environmentally sensitive lands, adaptive modifications of land-use policy to incorporate advances in science and technology, provision of information and monitoring for the support of specific services and functions, as well as for public education purposes, and the initiation of workshops to build collaboration and exchange of information among regional stakeholders.

With the critical goal of protecting human health through protection of landscape functions and ecosystem services, Grant et al. (1996) have suggested objectives and principles for sustainable landscape planning (Table 6). Meeting these objectives could improve environmental and public health, benefit personal and community socioeconomics, preserve biodiversity, and enhance the ability of the land to respond to natural and anthropogenic changes and pressures.

CONCLUSIONS

Through published ordinances, municipalities in this study recognized more ecosystem services than landscape functions, undoubtedly because ecosystem services relate directly to human needs. There was little regulatory protection for ecosystem services and the land functions that support those services. Review of comprehensive land plans revealed that basic environmental protection is recognized as an element of local and regional environmental sustainability. However, ordinance development has not yet followed this recognition. These municipalities could do more to protect ecosystem services and, equally as important, they could recognize the larger-scale land functions that support the production of all ecosystem goods and services.

Humans derive resources from natural environmental processes. Through landscape planning, municipalities can prevent or minimize flood damage, disease or pest outbreaks, polluted water and air, decaying ecosystems, degradation of livelihoods and featureless landscapes. Policies developed for sustainable use of larger regional areas could provide protection and maintenance for natural functions and subsequent provisions of ecosystem services. Scholars have demonstrated that healthy environments support healthy human communities and that good environmental policy is good socioeconomic policy (Guidotti 2003; Pretty 2003; Diaz et al. 2006; Naidoo and Ricketts 2006; Kaplan 2007; Tzoulas et al. 2007). Municipalities that incorporate landscape planning for environmental and social health could justify their goals, purposes and reasons for specific ordinances by backing them up with the wealth of knowledge about planning healthy landscapes and healthy communities.

Standard codes and rules have evolved with the implementation of building and development codes and are now contentiously labeled "Urban Genetic Code". This name is applied because these standards are copied and shared resulting in a uniform look for communities across the nation (Ben-Joseph 2004). Our review of ordinances in Wabasha County and the three municipalities has provided a sense of localized replication of standardized land-planning code. Many of the city and county ordinances shared similar or identical language. However, only one ordinance targeted protection of one karst feature from one specific type of land-use activity. Other karst features, which geologists have studied for decades, are not protected. The lack of protection of karst features in this region suggests that local land planning is out of sync with the natural land area.

Evaluations of policy coverage of natural features, landscape functions and ecosystem services can be conducted in any karst region. Many ordinances and regulations are now being posted on governmental websites and many government agencies make their published regulations available in print form for public review, so these analyses can be carried out for many regions. Identified gaps could be used to promote policy protection of natural processes because land-use problems affect the physical and economic health of human communities, natural resources and wildlife.

Landscape functions, ecosystem services and any unique regional geography must be recognized when people attempt to balance the conservation of natural resources with serving the public good. In support of local, regional and global well-being of society and the environment, sustainable community development requires that we plan our land use within the context of land functions and the ecosystem services we receive from healthy landscapes. Instead of managing our lands, we should actively seek to manage human activities and interactions with our natural environment (Kay and Schneider 1994).

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TABLE 1. County and city regulatory and demographic characteristics. Each municipality has a hired administrator to oversee regulatory affairs and a planning commission that acts in an advisory capacity to the city council or county commission. This regulatory structure is common throughout the United States.

Demographic or Land Cover Characteristic[1,2]	City of Wabasha	City of Plainview	Lake City[3]	Wabasha County
Regulatory Structure	Mayor, six Council Members	Mayor, four Council Members	Mayor, six Council Members	Five Commissioners
Population	2,559	3,190	4,950	21,610
Population Density (per mi^2)	318.40	1,452.50	1,169.90	41.20
Number of housing units	1,166	1,223	2,347	9,066
House unit density (per mi^2)	142.90	556.90	553.30	17.30
Municipal Engineer	No[4]	No[4]	No[4]	Yes
Land Cover (mi^2) - Total	9.25	2.20	4.30	549.00
Deciduous Forest	3.24	0.02	1.15	139.03
Exposed Soil; Sand dunes	0.01	0.00	0.00	0.19
Grassland	0.29	0.04	0.35	71.77
Grassland-Shrub-Tree	0.06	0.00	0.03	1.03
Gravel Pits; Open Mines	0.15	0.00	0.03	0.52
Rural	2.31	1.10	0.82	304.69

Urban and Industrial	2.13	0.92	2.01	5.65
Unclassified	0.00	0.00	0.00	0.08
Water	1.04	0.01	0.04	24.15
Wetlands	0.01	0.00	0.00	2.03

[1]All data except for land cover data are from 2000 Census.

[2]Land cover data from 1990 International Coalition Land Use/Land Cover GIS dataset. Total of individual land areas does not equal "Overall Land Area" due to rounding.

[3]Includes the portion of the city in Goodhue County

[4]Not listed through their website, although often the public works director is a certified civil engineer and serves in the capacity as the municipal engineer.

TABLE 2. Partial listing of regional landscape functions and ecosystem services that formed the base of this policy analysis designed to assess degree of local protection or acknowledgement of regional natural resources. Landscape functions support physical and biological processes fundamental to the self-maintenance of the biosphere. Ecosystem goods and services describe the benefits that humans receive from landscape functions.

Landscape or Ecosystem Functions	Associated Natural Resources
Aquifer discharge/recharge	Plant communities; Soils; Water
Climate interactions	Biotic and abiotic land features
Erosion control	Plant communities; Soils
Flood mitigation	Wetlands; Soils; Streams
Nutrient Cycling	Plant communities; Soils; Water; Wetlands
Provision of aquatic habitat	Abiotic land features; Riparian communities; Streams
Provision of plant habitat	Soils; Upland, riparian, wetland communities; Water
Provision of wildlife habitat	Upland, riparian, wetland communities; Wildlife
Soil Formation	Biotic and abiotic land features
Storm-water management	Plant communities; Soils; Streams; Wetlands
Water Temp Moderation	Abiotic land features; Riparian communities; Water
Water Filtration	Upland, riparian, wetland communities; Soils
Ecosystem Goods and Services	Provisions to Human Communities
Biodiversity	Fishing; Hunting; Birding; Education
Bird populations	Birding; Public Health; Education
Clean air	Public health

Clean groundwater	Drinking water; Crop Irrigation
Clean surfacewater	Drinking water; Swimming areas
Fish populations	Food; Fishing; Public Health; Education
Flood mitigation	Risk reduction; Public Health
Game populations	Food; Hunting; Public Health
Natural ecosystems / viewsheds	Cultural values; Education; Fishing Fuel; Hunting; Public Health
Pollinator Populations	Pollination services for human crops
Shelter and Shade	Air conditioning; Physical health;
Soil quality	Growth medium for human crops
Storm-water management	Risk reduction; Water management; Public Health
Surface Water Bodies	Education; Fishing; Swimming; Skiing; Public Health
Timber	Timber products for human use
Waste assimilation	Animal waste disposal/composting; Soil development

TABLE 3. County and city ordinances found to directly reference the existence, need, maintenance or protection of a landscape function or ecosystem service. Functions and ecosystem services with no direct policy references are not listed.

	City of Wabasha	City of Plainview	Lake City	Wabasha County
Landscape Functions				
Water management	335.37(1&3;17)	604(7.7A,B;14)		A13S9(4A;14)ZO
Erosion control			A6S7(A;3)	A6S6(5;5)ZO
			A6S8(;3)	
			A6S9(;4)	
Animal habitat	335.33(4A;16)		A6S5(;2)	
Climate			A6S8(;3)	
			A6S9(;4)	

Water Temperature Moderation				A13S9(1B2b;11)ZO
Karst water flow				A5S5(4;2)ZO
Stream habitat	325(5.55;10)			A13S9(2D1;12)ZO
	335.33(4A;16)	604(7.10;14)	A6S5(;2)	
Wetlands[1]	335.65(4;25)			A13S9(4A;14)ZO
Ecosystem Services or Goods				
Clean	505.15(3;7)	602(;3)	A7S9(A7b;10)	
groundwater[2]		619(1;54)	A7S9(B7;12)	
		704(2C;3)		
Clean	335.33(4D;16)	311(7;10)		A13S9(1C;11)ZO
surfacewater[2]		401(2.8;5)	A7S9(A7b;10)	
		602(;3)	A7S9(B7;12)	
		604(12.4;19)		
		619(1;54)		
Surface Water		311(7;10)	A7S7(B4b;6)	A3S12(6;7)ZO

Bodies[2]		401(2.8;5)	
		604(12;18)	
Wildlife populations		604(7.11;15)	
Flood mitigation	335.33(4A;16)		A14(;1)
Natural ecosystems	300.23(3;12)		
or Viewsheds	305.09(5A2;25)		
	335.33(4A;16)		
Soil quality			A6S6(6;5)ZO
Shelter and Shade	415.07(11;3)		
Waste assimilation			A5S1(;1)ZO
Stormwater Management	335.37(1;17)		A13S9(4A;14)ZO

[1]Multiple functions were directly acknowledged in wetland ordinances.

[2]Pollution prevention to ground or surface water supplies is considered a direct recognition of this ecosystem good.

TABLE 4. Policy instruments that indirectly referenced the existence, need, maintenance or protection of a landscape function or ecosystem service. Functions and ecosystem services with no indirect policy references are not listed.

	City of Wabasha	City of Plainview	Lake City	Wabasha County
Landscape Functions				
Aquifer recharge		604(7.6r;13)	A9S4(C8;5)	
			A10S3(e;5)	
Plant habitat			A6S8(;3)	
			A6S9(;4)	
Animal habitat			A6S8(;3)	
			A6S9(;4)	
			A7S7(B4c;7)	
Water Filtration				A3S10(4;5)ZO
Ecosystem Services or Goods				
Clean air			A6S11(G;10)	
Clean groundwater	335.57(2;22)			A3S11(2A;6)ZO
Clean	335.27(5;14)			
surfacewater	335.31(2A;15)			
	335.33(4D;16)			
Surface Water		604(7.5;10)		
Bodies		604(7.6p;12)		
Natural ecosystems	335.27(2C;13)			A3S10(1A;4)ZO
or Viewsheds[1]	335.27(5;14)			A13S8(3B3;6)ZO

	335.35(1;17)	A13S8(4E;8)ZO
	335.73(4;29)	A13S8(5B3;9)ZO
		A13S8(5E;10)ZO
		A13S9(3A;14)ZO
Shelter and Shade		A6S8(;4)

[1]Policy encouraging but not requiring the use of vegetation or topography as screening is viewed as an indirect reference to viewsheds.

TABLE 5. Examples of existing or proposed limestone ordinances in the United States. This table originally appeared in Susy Svatek Ziegler and Mary A. Williams, "Landscape Planning and Land-Use Policy to Conserve Natural Resources in Southeastern Minnesota," *CURA Reporter* 38,2 (Summer 2008): 19. Reprinted with permission of the Center for Urban and Regional Affairs (CURA), University of Minnesota.

Parcel-scale development activities
Prohibit infill of sinkholes and limit development outside of specific sinkhole boundaries[1]
Prohibit discharge of storm water into sinkholes[1,2]
Prohibit the dumping of trash into sinkholes[1]
Compensate developers who lose portions of land due to sensitive karst features[1]
Allow non-developable karst areas like sinkholes to be set aside for open space, parks or green belts (as safety allows)[1]
Allow higher density residential buildings for lands which lose area due to karst sensitivities[1]
Prohibit development on any property with waste deposits in sinkholes[2]
Define elevation segments of sinkholes, sinkhole divides and immediate sinkhole drainage area[2]

Size subsurface seepage systems installed in a karst soil based on the results of an on-site soil investigation[2]

No private sewage disposal systems or components permitted within the lower elevation segments of sinkholes[2]

Prohibit surface discharges within 50 feet of an immediate sinkhole drainage area[2]

Prohibit surface discharge systems in sinkhole plain areas (areas where all of the surface drainage leads to the subsurface)[2]

Prohibit subsurface seepage fields within 75 feet of the point where the slope of a sinkhole side exceeds 5%[2]

Landscape-scale development activities

Define, delineate and avoid development around sinkholes, sinkhole drainage areas and potential sinkhole cluster areas[1,2]

Define "Karst Overlay Zoning Districts" and prohibit development in hydrogeologically- or biologically-sensitive land areas[3]

Follow comprehensive land planning incorporating springshed boundaries and preservation of karst hydrogeologic functions[3]

Enhance public education efforts about sustainability of karst features, natural landscape functions and ecosystem services[3]

Note: Ordinance language was either taken directly from reference or as an idea generated by reviewing published references.

[1]Dinger and Rebmann, 1991.

[2]Fischer, 1999.

[3]Ziegler and Williams, 2008.

TABLE 6. Landscape planning methods to promote sustainable land activities in human communities while maintaining landscape and ecosystem health, promoting the production of ecosystem goods and services and conserving regional natural resources.

General sustainable planning methods useful for any regional or local community
Inventory regional ecosystem goods and services every 5-10 years
Define and protect land areas and natural resource processes needed to sustain regional ecosystem goods and services
Develop policy and action plans for the protection of landscape features and functions, ecosystem services and goods
Examine land patterns to help inform land plans and to use for the evaluation of future land plans
Maintain a landscape matrix that includes and connects all habitats representative of, or special to, an area
Examine how adjoining jurisdictions are managing their lands to help inform land-use decisions
Collaborate with adjoining jurisdictions and stakeholders to create and manage land activities beneficial to regional processes
Invest in public education and involvement in promoting sustainability of natural resources, ecosystem goods and services
Hire a city/county ecologist on equal stature to the city/county engineer to balance quality of life with environmental quality
Educate city councils/county boards on natural resource inventories, land-use activities and current issues

Evaluate all urban renewal projects in terms of local and regional natural resource and ecosystem service sustainability

Locate development where it will conserve important natural resources including air, land and water[1]

Require all development plans to include a section describing development impacts to the larger-scale physical land area

Require that only indigenous species are allowed on all land areas, including indigenous grasses

Evaluate zoning every 10 years to evaluate anthropogenic activities and impacts over the larger land area

Insert language in government documents to establish a goal of maintaining ecological integrity over many generations

Promote healthy physical and social environments through planned sustainable community developments[1]

Incorporate building development into indigenous landscapes[1]

Maintain a low ratio of developed to natural landscape leaving more natural land to perform environmental functions[1]

Promote landscaping, even in urban areas, to develop or support forest growth, wildlife habitat or food production.

Additional methods for use in karst regions

Incorporate current karst hydrogeology knowledge into all land plans and land planning activities

Incorporate karst knowledge into land-use policy (e.g. prohibit trash fill into sinkholes)

Incorporate best management practices for protection of landscape features, landscape functions, ecosystem services and goods (e.g. riparian zones for springs and sinkholes)

Require karst education for all land developers

Require karst education for government staff education on karst-related processes impacted by regional activities

Develop and promote karst education workshops for the public including urban residents, private landowners, business owners and the farming community

Examine limestone ordinances useful in other karst communities to improve human interactions within the regional karst area

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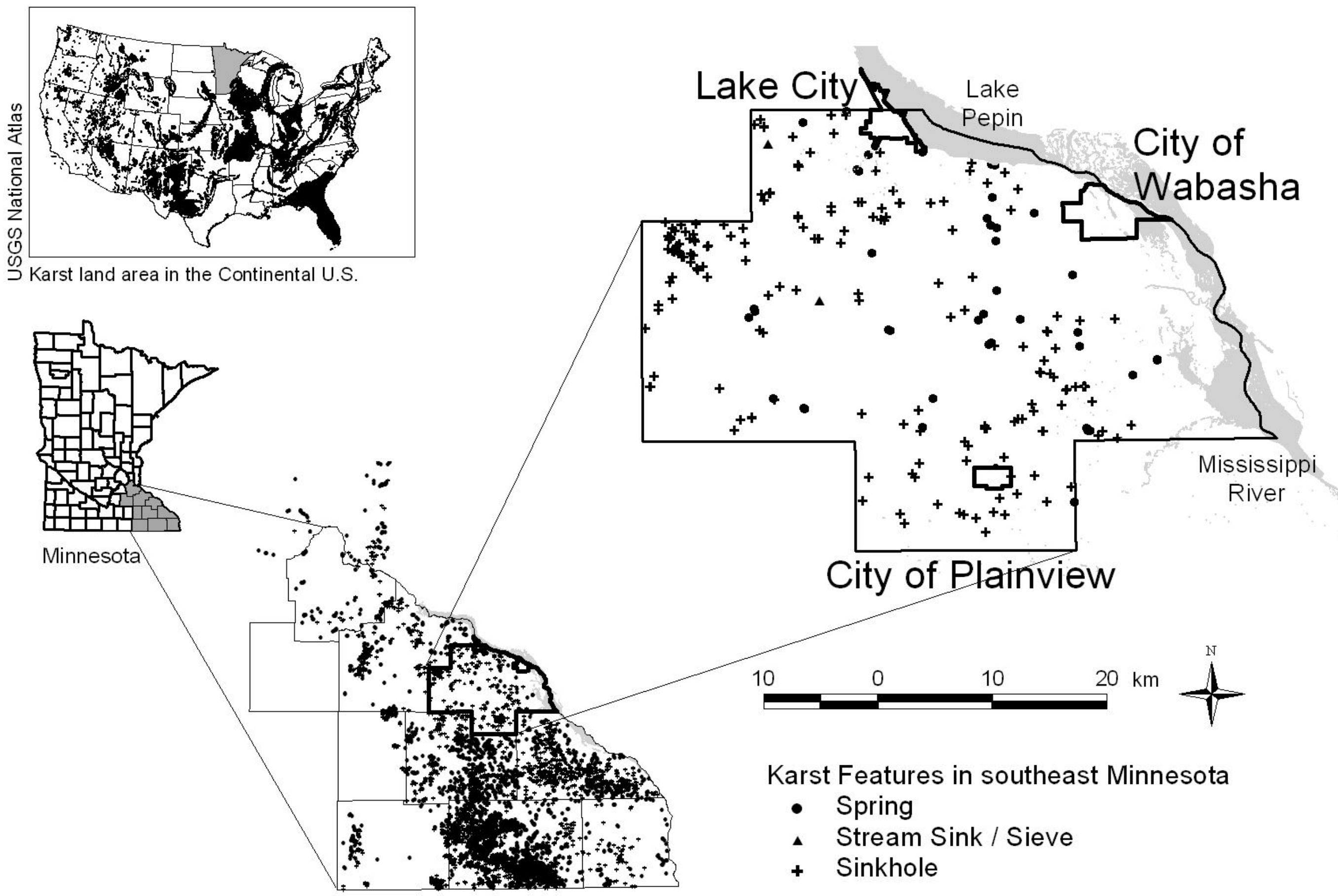
[1]Modified from Grant et al. 1996. All other ideas are from the authors.

FIG 1. Approximately 25% of land area in the continental United States is karst (inset map – USGS 2003). In southeast Minnesota, more than 10,000 karst features have been located, georeferenced and included in a geographic information database created and maintained by the Minnesota Geological Survey (Gao et al. 2002). Wabasha County, located in this region, has more than 20,000 people in 10 incorporated cities and two unincorporated villages. More than 240 karst features have been located in this county.


USGS National Atlas
Karst land area in the Continental U.S.
Minnesota
Lake City
Lake
Pepin
City of
Wabasha
Mississippi
River
City of Plainview
10
0
10
20
km
N
Karst Features in southeast Minnesota
Spring
Stream Sink / Sieve
Sinkhole

EPILOGUE

Anthropogenic land-use activities can affect the natural functioning of neighboring downstream land areas including human and natural communities. My research in an environmentally sensitive karst region in southeast Minnesota advances our knowledge of biophysical processes, land patterns and policy development through three studies that evaluate land cover information and land-use policies. Across these projects, I found that forest land cover is a primary indicator of spring distribution and regional land pattern, but, even as a known provider of various land functions (e.g. habitat, climate provision), ecosystem goods (e.g. timber) and services (e.g. shelter and shade), forests receive no regulatory protection.

I conducted three projects to evaluate land cover characteristics in a regional karst landscape. For these projects, (1) physical spring characteristics were analyzed to determine if a subset of spring characteristics can discriminate springs into bedrock units or aquifer groups, (2) land pattern metrics were examined for a county area and compared with pattern metrics in the major watershed overlying that county area, and (3) local policy was analyzed for coverage of karst features, landscape functions and ecosystem services.

Key findings of the three projects

Spring distributions Springs are clumped primarily at low elevations in forested areas. Elevation is significantly different between all bedrock and aquifer units indicating the usefulness of the elevation characteristic for describing where springs are located. Slope, however, is not useful for characterizing the physical location of springs or for classifying springs into geologic groups.

For over half the springs in the lower elevations, the nearest stream segment was a designated trout stream or a protected tributary to a designated trout stream. This association reflects the influence of cold-water springs in maintaining cooler stream temperatures necessary to support viable trout populations in this area. Forest land cover aids in spring recharge, maintains cool spring water temperatures and maintains cool stream water temperatures.

Eleven and eight variables describing the physical locations of springs are important for classifying springs into bedrock units and aquifer units, respectively. Seven variables are common between the classifications indicating overlap in the usefulness of characteristics for classifying springs into different geologic groups. Two variables identifying trout designation of the nearest stream segment and forest land cover type are additionally useful for classifying springs into bedrock units.

Land pattern metrics Wabasha County has a more spatially-fragmented land area than the major watershed area overlying the county. Wabasha County also has, on average, smaller patch sizes (area-weighted and non-weighted), larger patch densities, smaller large patch index measures and lower contagion values. For the Wabasha County area, average forest patch area and average forest radius of gyration are positively correlated indicating that spatial connectivity of forest patches is supported by adequate patch size to support viable and sustainable forest processes.

The county and major watershed area differ in other ways: forest cover describes the most variation in land patterns in the county area; land cover diversity is more important for describing land patterns in the watershed area; hay/pasture/grassland land cover type is more important in describing land patterns in the county area; six components explain the major gradients of variation in the watershed area, but seven are needed to explain variation in the county metrics.

Policy coverage of karst features, land functions and ecosystem services In this environmentally sensitive karst area, there is more regulatory protection for ecosystem services than the land functions that support those services. Ordinances typically cover anthropogenic activities (e.g. construction) or human needs (e.g. drinking water). Only one county ordinance targets protection of one karst feature by requiring a setback from individual sinkholes. There is, however, a lack of recognition of and protection for sinkhole flooding and there are no other ordinances referencing or protecting other karst features.

No ordinances mandate management, protection or connectivity of plant communities, ecosystems or wildlife habitats, including caves or cave biota. Multiple ordinances referenced the need to provide wildlife habitat although none mandate protection for specific animals, animal species or animal populations. Several ordinances indirectly address the natural development and maintenance of plant communities and wildlife habitat by requiring the preservation or restoration of natural vegetation to the greatest extent possible during development projects. Decisions, however, are made on a parcel basis and generally refer to engineering or construction issues (e.g. screening or erosion control).

Municipalities recognize the need to protect the quality of drinking water through ordinances developed to reduce or prevent pollution to both surface and ground water. However, there are no ordinances to protect or promote the quantity of ground-water supplies. No ordinances restrict or prohibit land use over known aquifer recharge areas.

Management and conservation recommendations

Forested land areas protect and maintain cold-water spring discharge. Both forests and springs sustain cold-water aquatic ecosystems, which support important regional economic activities. Policy and planning could actively manage and protect cold-water springs, the lands on which they are found and the recharge areas which contribute to their discharge. Policy could zone these areas for protection or for low-impact land use. Management practices could include easement purchases and promotion of best management practices that minimize or prevent changes to hydrological characteristics and sediment inputs to springs and stream segments. These conservation efforts could help produce sustainable quantity and quality of water supporting improved predictability of water and pollutant transport, healthier cold-water ecosystems and downstream biotic communities, all of which support important regional economic activities like fishing and tourism.

Quantification and evaluation of land patterns between a local politically-delineated land area and the overlying major watershed area could inform sustainable land and watershed management through the comparison of land cover and land pattern information. For example, land fragmentation through the processes of development, agriculture and deforestation can have a negative impact on hydrology and ecological processes (Collinge 1996; Di Giulio et al. 2009). If one area is found to be more fragmented in comparison to the other land area, municipal or watershed policy could be updated or created to mandate the restoration, connectivity and protection of specific areas to prevent or mitigate potential negative effects of land-use activities that might further promote land fragmentation. Policies could additionally establish overlay zones that define, connect and protect land areas containing sensitive natural areas, known recharge areas and for this karst region, known karst features like sinkholes and cave systems. Zoning policy could increase the amount of natural land areas for the maintenance of natural physical (e.g. aquifer recharge) and ecological (e.g. wildlife habitat) processes, potentially targeting and protecting large natural areas using patch area metrics (Press et al. 1996). Regulatory limitations on the development of impervious surfaces could directly support hydrological processes and water pollution mitigation. This could include regulatory restrictions on road widths or prohibiting removal of native vegetation in easements or riparian areas.

There are many identified gaps in coverage for landscape functions and ecosystem services. Land and watershed managers, and county or municipal policymakers could work to establish a list of regional ecosystem goods and services and the land functions needed to sustain them. They could then collaborate on ways of conserving these resources that are valuable to human communities as well as regional animal and plant communities.

Future directions

Future work should continue to examine the relationship between springs, forest land cover and the sustainability of cold-water ecosystems. Cold-water natural communities and regional economies in the human communities are dependent upon the conservation of this relationship. Additional studies are needed to refine spring characteristics more useful for predicting the physical location of springs. Established relationships could help land and watershed managers better direct land-use activities. Research and examination of best management practices (BMP) for springs could promote spring conservation. Vegetated buffers, for example, have been suggested as a water quality BMP for sinkholes (Peterson and Vondracek 2006) and could be studied as a useful BMP for protecting springs. Metric analyses applied to other politically-delineated area and major watersheds could add to the analyses of pattern metrics on smaller spatial scales. Land pattern analyses directed at specific land-use management needs could help tie land patterns with specific land or watershed management processes informing specific policy needs. The complex hydrogeologic character of karst makes land and watershed management in karst regions a challenge. Studies like these can highlight gaps and needs in local and regional knowledge in science and policy for better protection of natural and physical features and processes along with the resulting ecological services provided to human communities.

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APPENDICES

Appendix I. List of geomorphic landform codes – Geomorphic Association, Glacial Phase, Sedimentary Association, Topographic Expression and any qualifiers.

Geo_Assoc

Geomorphic Association

A	Lake Agassiz	N	River Warren
B	Glacial Lake Minnesota	O	Organic Deposits
C	Scoured Bedrock Uplands	P	Pre-Wisconsinan Till Plains
D	Des Moines Lobe	Q	Glacial Lake Benson
E	Obscure glacial landscape, no glacial landforms present	R	Rainy Lobe
F	Fluvial	S	Superior Lobe
G	Grantsburg Lobe	T	Dissected Bedrock Terranes
H	Lake Duluth	U	Lake Upham/Aitkin
I	Iowan Erosion Surface	V	Red River Lobe
J	Lake and pond sediment	W	Wadena Lobe
K	Koochiching Lobe	X	Mines
L	St. Louis Lobe	Y	Water
M	Upper Mississippi river	_	Undifferentiated

Phase

Glacial phase, ice margin association or age

Al	Altamont	Kn	Knife
An	Ann	Ko	Koochiching Phase
Ar	Archean	Mi	Milnor Phase
Be	Bemis Phase	Ml	Mille Lacs
Bs	Big Stone	Ne	Nemadji
Ca	Campbell Phase	Ni	Nickerson
Cu	Culver	No	Norcross Phase
De	Dent	Ou	Outing
Du	Duluth	Pc	Pine City
Er	Erskine	Pr	Proterozoic
Fz	Frazee	Sr	Split Rock
Gu	Guthrie	St	St. Croix
He	Hewitt	Ti	Tintah Phase
Hi	Highland	Ve	Verdi
Ho	Holocene	Wi	Wisconsinan
Hr	Herman Phase	Wp	Pre-Wisconsinan
It	Itasca		

Sed_Assoc

Sedimentary Association / Rock Type

A	Alluvium	M	Metamorphic
B	Bedrock dominated	O	Outwash
C	Outlets	P	Peat
D	Sedimentary	R	Terrace
G	Igneous	S	Supraglacial Drift Complex
I	Ice Contact	T	Till Plain

L Lacustrine

Topo

General Topographic Expression

1 Level. Includes areas of little relief relative to adjacent topography such as lake and outwash plain

2 Rolling to Undulating. Areas exhibiting variable relief over broad reaches including till plains and drumlinized terrain.

3 Hummocky. Includes areas of highly variable relief relative to adjacent topography. Typically supraglacial complexes, esker complexes and end moraines (kame-kettle topo)

4 Steep. Used primarily for glacially-scoured or stream-dissected bedrock terranes.

5 Inclined slopes intermediate between rolling and steep; predominantly sloping in one direction; no undrained depressions

Qual *Additional Information or Qualifiers*

ag Anorthositic Gabbro Troctolite

ar Argillite

be Beach or Strandline. Elongate form representing past lake stage.

fe Banded Iron Formation

ch Outwash Channel or Outlet Channel

co collapsed or palimpsest outwash

di Disintigration ridge

dw Deep Water Facies Offshore deep water lake clays.

dr Drumlin or Flutes

dc Duluth Complex

es Esker

eg Ely Greenstone

fp floodplain

fn Fan. Fan -shaped features including glacial outwash fans, alluvial fans, some deltas.

gr Granite

gi Giants Range Granite

gv gravel

ic Predominately ice-contact deposits

iw Ice-Walled Lake Plains Abundant

ka Kame

ks karst

lm Lake Modified and/or wave-planed till. Reworking but usually not eliminating original landform characteristics.

lo Loess mantled sediment

ma Mantled by a veneer of younger drift

ms Metasedimentary

mv Metavolcanic

no Non-glacial source (terrace)

ns North Shore Volcanic Group

od outwash derived (terrace)

po Predominately Outwash

pa Peat Deposits Abundant

rb Raised Bog

rl river channel

ro Rove Formation

st stream washed

sw Shallow Water Facies. Near shore lake sands.

sg Saganaga Granite

th Thrust

tm Till Mantled

tr	Trommald Formation
tv	Tunnel Valley
vg	Vermilion Granite
em	Eolian Modification (windblown dunes)
vl	Unknown (currently under investigation)

Appendix II. Definitions of the pattern metrics selected as descriptive landscape measures and for landscape and class pattern analyes in chapter two. Metrics were calculated for each subwatershed within the defined boundaries of interest - Wabasha County and the Combined watershed area. Metrics are listed in the order found on Table 2-1. The metric name is given and followed in parenthesis by the Fragstats acronym. Definitions are adapted from the Fragstats manual.

MEASURES INCLUDED IN PCA ANALYSES

Mean Patch Size (AREA_MN)

Landscape and Class

For class-level (per each land cover type - LCT): this equals the sum of patch areas across all patches in a specific LCT, divided by the number n of patches in that LCT.

$$AREA\_MN = \frac{\sum_{j=1}^{n} a_{ij}}{n_i}$$

i = LCT i

j = patch j of n patches in LCT i

a_{ij} = Area (m^2) of patch j in LCT i

n_i = Number of patches in LCT i

For landscape-level mean patch size: this value equals the sum of all patches in the landscape (subwatershed for this study) divided by the number of patches N in the subwatershed.

$$AREA\_MN = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}}{N}$$

i = LCT i of m LCTs

j = patch j of n patches

a_{ij} = Area (m^2) of patch j in LCT i

N = Number of patches in the landscape.

Mean Patch Size Coefficient of Variation (AREA_CV)

Landscape and Class

This metric divides AREA_SD (patch size standard deviation) by AREA_MN normalizing the variability by the mean. This metric is proposed to be most useful for comparisons of variability among different landscapes or among different classes with different mean patch sizes.

$$AREA\_CV = \frac{Mean - Patch - Size - StdDev}{Area\_MN}$$

where,

$$\text{Mean Patch Size Standard Deviation} = \sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[a_{ij} - \left(\frac{A}{N}\right)\right]^2}{N}}\left(\frac{1}{10{,}000}\right)$$

where,

i = LCT i of *m* LCTs

j = patch j of *n* patches

a_{ij} = Area (m^2) of patch j in LCT i

A = Total landscape area (m^2)

N = Number of patches in the landscape.

<u>Mean Patch Shape (SHAPE_MN)</u>

Landscape and Class

This metric is a measure of the geometric complexity of a patch. It is a measure of the spatial character of patches. It is the ratio of actual patch perimeter to the perimeter of the theoretically most compact patch. It is the smallest for square patches (if using raster data) or circular patches (if using vector data). As the shape becomes more complex, the value increases.

Class-level calculation:

$$SHAPE\_MN = \frac{\sum_{j=1}^{n} \frac{p_{ij}}{\min p_{ij}}}{n_i}$$

where,

i = LCT i of m LCTs

j = patch j

n_i = number of patches for LCT i

p_{ij} = perimeter of patch j in LCT i

min p_{ij} = minimum perimeter of patch ij in terms of number of cell edges

Landscape-level calculation:

$$SHAPE\_MN = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} \frac{p_{ij}}{\min p_{ij}}}{N}$$

where,

N = Number of patches in the landscape.

Mean Patch Gyration (GYRATE_MN)

Landscape and Class

This metric quantifies the mean distance between each cell in a cluster of contiguous cells (a patch) and the the patch centroid (calculated as the average x and y coordinates for all the cells in the patch). It provides a useful measure of patch extensiveness - how far across the landscape a patch extends. It is calculated for every patch and aggregated at the class and landscape level.

Class-level calculation:

$$GYRATE\_MN = \sum_{j=1}^{n}\left[\sum_{r=1}^{z}\left(\frac{h_{ijr}}{z}\right)\left(\frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}}\right)\right]$$

Landscape-level calculation:

$$GYRATE\_MN = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[\sum_{r=1}^{z}\left(\frac{h_{ijr}}{z}\right)\left(\frac{a_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}}\right)\right]$$

Mean Euclidean Nearest Neighbor (ENN_MN)

Landscape

This metric quantifies the shortest Euclidean distance from one patch to another patch of the same land cover type (LCT). This is calculated at the patch level and aggregated at the class and landscape levels.

$$ENN\_MN = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} h_{ij}}{N}$$

where,

hij = the distance to the nearest neighboring patch of LCT i for patch j, based on the shortest distance between patch edges,

N = total number of patches of all LCTs.

DESCRIPTIVE MEASURES OF EACH LANDSCAPE

Number of Patches (PN)

Landscape

This metric quantifies the number of patches across the land area. This metric conveys no information about area, distribution or density of patches.

PN = N

where,

N = total number of patches of all LCTs

Patch Density (PD)

Landscape

This metric quantifies number of patches per unit area across the land area. This metric is calculated by taking the number of patches in the land area, dividing by the total land area (m^2), multiplying by 10,000, then multiplying times 100 (to convert to hectares).

PD expresses number of patches on a per unit area basis that facilitates comparisons among landscapes of varying size.

$$PD = \frac{N}{A} * (10{,}000)\frac{m^2}{ha} * 100$$

where,

N = total number of patches of all LCTs, and

A = total landscape area (m^2)

Patch Richness Density (PRD)

Number of different LCTs per unit of area. PRD expresses number of different LCTs per unit of area allowing comparative analysis of different sized land areas or map extents.

$$PRD = \frac{m}{A} * (10{,}000)\frac{m^2}{ha} * 100$$

where,

m = number of LCTs, and

A = total landscape area (m^2)

Largest Patch Index (LPI)

This metric quantifies the percentage of total landscape area comprised by the largest patch. It is a simple measure of dominance. LPI is calculated by taking the area of the largest patch of the corresponding patch type, dividing by the total land area (m2), then multiplying by 100 to convert to percentage.

LPI approaches zero (0) when the largest patch is increasingly small. LPI approaches 100 when the entire land area consists of a single LCT patch.

$$LPI = \frac{\max_{j=1}^{n}(a_{ij})}{A}(100)$$

Landscape Shape Index (LSI)

This metric equals the total length of edge (or perimeter), divided by a circle standard.

$$LSI = \frac{e_i}{2 * \sqrt{A * \pi}}$$

where,

e_i = total perimeter around the area plus any linear edge within the area,

A = total area,

π = 3.1416

This is an edge metric, best considered as representing landscape configuration, even though they are not spatially explicit. LSI measures the perimeter-to-area ratio for the landscape as a whole.

If the landscape boundary represents shape of the land area, then the LSI can be useful when comparing landscapes of varying sizes.

Shannon's Evenness Index (SHEI)

SHEI equals minus the sum, across all patch types, of the proportional abundance of each patch type multiplied by that proportion, divided by the logarithm of the number of patch types. Note, P_i is based on total landscape area (A) excluding any internal background present.

SHEI is expressed such that an even distribution of area among LCTs results in maximum evenness. As such, evenness is the complement of dominance.

SHEI is a measure of patch distribution, or the measurement of the distribution of area among patch types within the landscape. Shannon's evenness index is equal to zero when the observed patch distribution is low and approaches one when the distribution of patch types becomes more even. Shannon's evenness index is only available at the landscape level. SHEI quantifies evenness among landscapes.

$$SHEI = \frac{-\sum_{i=1}^{m} P_i * \ln(P_i)}{\ln(m)}$$

where,

P_i = proportion of the landscape occupied by land cover type i,

m = number of land cover types present in the landscape

Evenness measures the other aspect of landscape diversity--the distribution of area among patch types. There are numerous ways to quantify evenness and most diversity indices have a corresponding evenness index derived from them.

In addition, evenness can be expressed as its compliment--dominance (i.e., evenness = 1 - dominance). Indeed, dominance has often been the chosen form in landscape ecological investigations (e.g., O'Neill et al. 1988, Turner et al. 1989, Turner 1990a), although evenness is sometimes preferred because larger values imply greater landscape diversity (McGarigal and Marks 1995).

Maximum diversity for any level of richness is achieved when there is an equal distribution of area among LCTs. Therefore, the observed diversity divided by the maximum diversity (i.e., equal distribution) for a given number of LCTs represents the proportional reduction in the diversity index attributed to lack of perfect evenness.

As the evenness index approaches 1, the observed diversity approaches perfect evenness. Because evenness is represented as a proportion of maximum evenness, Shannon's evenness index does not suffer from the limitation of Shannon's diversity index with respect to interpretability.

<u>Contagion Index (CONTAG)</u>

This metric quantifies the degree to which LCTs occur in clumped distributions (spatially aggregated or "contagious" areas) versus being dispersed in many smaller fragments.

$$\text{CONTAG} = \left[1 + \frac{\displaystyle\sum_{i=1}^{m}\sum_{k=1}^{m}\left[\left\{P_i\left(\frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}}\right)\right\}\bullet\left\{\ln(P_i)\left(\frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}}\right)\right\}\right]}{2\ln(m)}\right](100)$$

CONTAG equals one plus the sum of:

the proportional abundance of each patch type (P_i) multiplied by the proportion of adjacencies between cells of that LCT ($g_{ik}/\Sigma g_{ik}$), multiplied by the logarithm of the same quantity, summed over each unique adjacency type (k=1 to m) and patch type (i=1 to m),

divided by: 2 times the logarithm of the number of patch types (m), and

all of the above multiplied by 100 to convert to a percentage.

The denominator, 2*ln(m) is the maximum possible value for contagion given m number of LCTS. Dividing the numerator (the actual value of shared edge variety) by the maximum contagion value, normalizes this metric, removing the effect of the number of LCTs on the metric value, thus allowing comparisons of landscapes with differing numbers of LCTS (Gergel and Turner 2003 pg 88).

A higher value indicates clumped, or less diverse land cover. A lower value indicates a more diverse arrangement of land cover.

Contagion is a measure of landscape configuration. It deals with the spatial distribution of land cover types.

Area-weighted Mean Patch Size (AREA_AM)

This metric quantifies the average patch area - weighted by the size relative to the total class area. Larger patches are weighted more heavily than smaller patches and contribute more to this value.

$$AREA\_AM = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[\frac{a_{ij}}{N}\left(\frac{a_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n}a_{ij}}\right)\right]$$

where,

i = LCT i of m LCTs

j = patch j of n patches

a_{ij} = Area (m2) of patch j in LCT i

N = Number of patches in the landscape.

Area-weighted Mean Patch Shape (SHAPE_AM)

At the landscape level, this metric is a measure of the area-weighted mean shape for all patches across all LCTs in a landscape. It describes the overall complexity of patch shape for the entire landscape mosaic.

$$SHAPE\_AM = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[\frac{p_{ij}}{\min p_{ij}}\left(\frac{a_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n}a_{ij}}\right)\right]$$

Area-weighted Mean Euclidean Nearest Neighbor (ENN_AM)

At the landscape level, this metric is a measure of the area-weighted mean shape for all patches:

$$ENN\_AM = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[h_{ij}\left(\frac{a_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n}a_{ij}}\right)\right]$$

where,

hij = the distance to the nearest neighboring patch of LCT i for patch j, based on the shortest distance between patch edges.

Appendix III. Summary statistics of all landscape and class metrics derived for Wabasha County and the major watersheds overlying the county.

		Wabasha County				Combined Watershed			
Pattern Metric		Min	Max	**Mean**	Stdev	Min	Max	**Mean**	Stdev
NP		35	692	292.31	163.93	35	2183	274.24	213.45
PD		4.75	12.40	8.64	1.77	3.32	13.95	7.32	2.18
PRD		0.06	1.61	0.25	0.28	0.02	1.61	0.18	0.15
LPI		18.95	82.39	46.08	16.62	11.16	95.23	52.75	22.86
LSI		4.68	18.59	10.57	3.32	3.81	32.07	9.65	3.56
SHEI		0.39	0.91	0.63	0.12	0.15	0.91	0.56	0.17
CONTAG		47.93	77.77	63.25	6.67	47.93	90.98	67.57	9.74
AREA_AM		51.52	3323.02	1005.70	834.73	51.52	10241.91	1397.39	1425.84
SHAPE_AM		2.40	7.77	5.33	1.39	2.40	8.79	5.11	1.39
ENN_AM		37.84	162.69	60.05	25.63	15.69	309.46	61.20	31.88
AREA_MN		8.06	21.07	12.07	2.63	7.17	30.14	15.05	5.04
AREA_CV		219.59	1664.64	824.91	320.50	219.59	1925.66	881.08	364.90
SHAPE_MN		1.39	1.75	1.52	0.08	1.31	1.75	1.48	0.08
GYRATE_MN		61.07	98.82	78.88	10.14	51.12	146.12	83.26	20.83
ENN_MN		100.51	238.12	179.38	34.24	107.57	393.20	198.55	52.03
AREA_MN	CL	6.88	461.46	102.08	87.01	13.05	5377.83	296.31	668.20
	FR	1.04	67.26	13.10	13.92	0.45	67.26	9.78	10.99
	HP	2.45	19.47	5.41	2.90	1.39	150.95	9.37	14.57
	UR	0.75	4.81	1.49	0.89	0.70	62.91	2.91	6.21
	WT	0.04	93.58	5.73	18.01	0.05	93.58	2.55	10.05
AREA_CV	CL	75.59	619.19	278.91	114.05	0.00	619.19	256.28	98.82
	FR	227.49	1229.08	664.89	293.04	93.83	1229.08	480.96	292.87
	HP	131.46	576.84	227.16	82.15	92.49	549.95	241.15	89.27
	UR	52.95	662.73	182.74	155.96	44.91	1497.75	210.96	192.32
	WT	0.00	689.80	162.57	155.14	0.00	1349.27	124.94	147.13
GYRATE_MN	CL	104.92	500.32	267.39	85.49	137.46	3796.61	399.40	425.06
	FR	37.66	210.93	63.91	30.07	29.27	193.15	64.33	31.11
	HP	62.93	119.99	87.25	13.66	49.08	327.33	102.44	35.52
	UR	31.72	63.42	41.87	7.02	31.39	150.64	47.38	15.94
	WT	7.07	151.13	40.97	36.40	8.49	214.04	34.55	35.12
SHAPE_MN	CL	1.51	2.45	1.95	0.24	1.54	5.15	2.05	0.45
	FR	1.30	2.08	1.48	0.15	1.19	2.03	1.45	0.14
	HP	1.45	1.83	1.65	0.08	1.33	2.11	1.67	0.11
	UR	1.17	1.48	1.28	0.06	1.15	1.47	1.26	0.05
	WT	1.00	2.15	1.38	0.27	1.00	2.42	1.32	0.23

Appendix IV. Varimax rotated principal component axes and loadings for each study area. Loadings used for component interpretation are in bold. Dashes indicate metrics dropped due to high correlations with other variables.

	Wabasha County							Combined Watersheds					
Metrics	1	2	3	4	5	6	7	1	2	3	4	5	6
area_cv	-0.41	0.15	0.12	**0.79**	-0.09	0.14	-0.20	**-0.74**	0.13	0.11	-0.22	0.31	0.06
area_mn	0.02	**0.64**	0.02	0.40	0.33	0.33	-0.27	0.24	0.27	0.05	0.38	**0.72**	-0.26
cl_area_cv	-0.23	-0.21	0.11	**0.87**	0.05	-0.16	-0.18	-0.28	**-0.72**	0.20	0.06	0.12	0.01
cl_area_mn	-0.52	**0.67**	0.12	0.26	0.14	-0.24	-0.25	-0.23	**0.83**	0.03	-0.09	0.23	-0.16
cl_gyrate_mn	-0.28	**0.92**	-0.02	-0.11	0.09	-0.08	-0.07	-0.21	**0.90**	-0.01	-0.05	0.19	-0.14
cl_shape_mn	0.10	**0.92**	-0.14	0.00	-0.01	-0.10	-0.05	-0.22	**0.88**	-0.07	0.05	0.12	0.07
enn_mn	-0.09	0.51	-0.19	0.10	-0.01	-0.38	**-0.52**	-0.06	0.26	-0.28	0.30	**0.71**	-0.23
fr_area_cv	-0.13	0.22	0.08	**0.82**	0.03	0.05	0.39	-0.44	-0.31	0.25	-0.16	-0.09	**0.59**
fr_area_mn	**0.74**	0.05	-0.42	0.15	-0.09	0.11	0.36	0.33	-0.09	0.08	0.02	-0.09	**0.76**
fr_gyrate_mn	**0.76**	-0.25	-0.30	-0.22	-0.09	0.12	-0.14	**0.89**	-0.13	0.06	0.12	0.02	0.09
fr_shape_mn	**0.83**	-0.30	0.02	-0.26	-0.05	0.13	-0.10	**0.82**	-0.05	0.11	0.14	-0.17	0.17
gyrate_mn	**0.85**	0.08	0.02	-0.27	0.12	0.06	0.20	**0.81**	-0.14	0.11	0.43	0.15	-0.05
hp_area_cv	0.04	-0.32	0.31	-0.05	-0.21	**0.73**	-0.05	0.25	-0.17	0.25	0.42	-0.12	**-0.43**
hp_area_mn	-0.28	-0.23	**0.79**	0.07	-0.07	0.25	0.03	0.25	-0.09	-0.04	**0.70**	0.19	-0.24
hp_gyrate_mn	-0.15	-0.04	**0.90**	0.11	0.12	0.07	0.02	-	-	-	-	-	-
hp_shape_mn	0.40	0.09	**0.75**	0.13	0.08	-0.07	0.10	0.13	-0.01	0.07	**0.76**	0.07	0.20
shape_mn	**0.88**	-0.01	0.21	-0.18	0.03	0.04	0.24	0.57	-0.13	0.21	0.23	-0.32	**0.58**
ur_area_cv	-0.03	0.10	0.00	0.04	**0.89**	0.12	0.21	0.23	-0.17	**0.76**	-0.06	-0.01	-0.08
ur_area_mn	-0.04	0.10	0.09	-0.01	**0.95**	0.05	-0.10	**0.68**	-0.04	0.21	-0.36	0.32	-0.05
ur_gyrate_mn	-	-	-	-	-	-	-	-	-	-	-	-	-
ur_shape_mn	0.42	-0.09	0.37	-0.07	**0.45**	0.26	-0.21	**0.43**	-0.09	0.43	-0.39	-0.11	0.26
wt_area_cv	0.32	-0.11	0.12	0.07	0.17	**0.74**	0.33	0.00	-0.07	**0.82**	0.10	-0.24	0.24
wt_area_mn	0.07	0.10	-0.10	0.00	**0.38**	0.80	0.05	-0.03	0.04	**0.66**	0.05	-0.04	0.02
wt_gyrate_mn	-	-	-	-	-	-	-	-	-	-	-	-	-
wt_shape_mn	0.24	-0.27	0.03	-0.03	0.05	0.11	**0.75**	0.30	-0.04	0.29	0.10	**-0.59**	-0.14
Eigenvalue	4.5	3.4	2.7	2.6	2.3	2.3	1.7	4.5	3.2	2.3	2.1	2.0	1.9
%Variance	19.6	14.6	11.7	11.3	10.1	10.1	7.3	20.5	14.6	10.7	9.7	9.0	8.7
Cum %Variance	19.6	34.2	45.9	57.2	67.4	77.4	84.7	20.5	35.1	45.8	55.5	64.5	73.2