APPLICATION OF A DIGITAL TERRAIN MODEL FOR FOREST LAND CLASSIFICATION AND SOIL SURVEY

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Master of Science

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by

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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled:

APPLICATION OF A DIGITAL TERRAIN MODEL FOR FOREST
LAND CLASSIFICATION AND SOIL SURVEY

Presented by Christopher J. Fabian

A candidate for the degree of Master of Science

And hereby certify that in their opinion it is worthy of acceptance.

Richard D. Hammer

Randall J. Miles

John Kabrick

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ABSTRACT

Characterization and classification of the land is central to sound resource management. This includes: 1) defining different kinds of land, 2) locating transition areas (boundaries) from one kind to another, 3) assessing variability of characteristics within and among units, 4) determining appropriate and effective land uses, and 5) educating land managers and the general public on appropriate land uses. Classifications of forest lands have been inexact and difficult to apply because they have lacked sufficient detail, failed to delineate many important site factors, are heterogeneous relative to the important site factors, have failed to adequately describe the variances within classification units, and methods to effectively and economically apply classifications to large areas are not readily available. An ecological land classification system (ECS) has been offered as dynamic and comprehensive alternative to traditional classifications. In addition, scientists have encouraged the National Cooperative Soil Survey (NCSS) program to adopt more precise and flexible approaches to soil survey.

Landforms, because of their: i)influences on and covariances with a variety of site factors, ii) abilities to be modeled at different scales, iii) easily observable features, and iv) relative stability in the landscape, are a logical base for modeling landscape ecosystems. Much impetus for the development and improvement of our forest land classification efforts has revolved around the technologies of Geographic Information Systems (GIS) and Digital Elevation Models (DEM's), as systems to produce Digital terrain models (DTM's). This study investigated the potential for making accurate and operationally efficient DTM's as baselines for land classification systems such as ECS and Soil Survey.

GIS was used to evaluate the accuracy of DEM data and to develop digital terrain models (DTM's) that could portray important soil-geomorphic-ecological patterns in the Missouri Ozarks. Six DEM's were evaluated through analysis of visual portrayals of the landscape, slope and aspect accuracy and landform classifications. Digital Terrain Model's (DTM's) were created and compared with a soil-geomorphic field survey for two sites covering 1742 ha.

USGS level 2 DEM's and TOPOGRID DEM's created from USGS hypsography generated the most accurate slope, aspect and landform classifications. The correct slope class was predicted in 71.6% of observations and the correct aspect class was predicted in 84.6% of observations. A rule-based approach to landform classification provided the best results in classifying landforms, and classified landforms correctly on 71.2% of the "calibration" site and 64.3% on a test site when compared to the field survey.

The prime advantages of these methods include: the consistent delineation of landforms, an efficient method for applying soil-geomorphic-ecological relationships, a dynamic format that can be adjusted for different interpretations and updated as new information is gained, an efficient and cost-effective method for inventorying large areas, and an effective way to communicate soil-landscape-ecological relationships to land managers and planners.

CHAPTER 1

INTRODUCTION

A finite amount of land is available for food production, forest products, wildlife habitat, urban areas, and recreation. Population growth, urban sprawl, and increased per-capita consumption of resources are exerting accelerating pressures on land resources. With these pressures, land must be used more efficiently, recognizing that different kinds of land best support different uses.

Central to sound land management is the characterization and classification of the land. This includes: 1) defining different kinds of land (units), 2) locating transition areas (boundaries) from one kind to another, 3) assessing variability of land characteristics within and among units, 4) determining appropriate and effective land uses, and 5) educating land managers and the general public on appropriate land uses. However, shrinking budgets for natural resources management demand that these activities be performed efficiently with limited financial and human resources.

Among the earliest land classification efforts is the soil survey program began under the oversight of the Division of Soil over 100 years ago. Today soil survey is part of the multi-agency National Cooperative Soil Survey (NCSS) led by the Natural Resources Conservation Service (NRCS). Other land classification programs, such as multiple-factor Ecological Classification systems also have been developed in the United States, Canada and Europe. However, land classification systems have been inexact and difficult to apply for the following reasons:

i) insufficient detail of site characterizations make information gained through research and management experiences at one site difficult to extrapolate to other sites;

ii) classification systems often delineate land units that
   a) fail to include many important site characteristics;
   b) are heterogeneous relative to these important site factors; and c) fail to adequately describe the variances of site characteristics within classification units;

iii) methods to effectively and economically extrapolate accurately identified and characterized site factors are not readily available.

To effectively understand and model landscapes for natural resources management, some have proposed the landform as the basic element. Many important site factors show some relation to landforms. A landform is defined by its surface shape, its location in relation to other landforms, its underlying geologic materials, and its soil attributes (Hammer, 1997).

A collection of geomorphically related landforms composes a landscape (Hammer, 1997). Landforms delineate natural units for observation of ecosystems. Examples of landforms include loess-covered summits, steep sideslopes formed from residuum and hillslope sediments, and alluvial terraces. If the important site characteristics (soil properties, microclimate, etc.) can be understood in terms of their relationships with landforms, characterization of geomorphic properties may serve as a framework for predicting characteristics of unknown sites. Such a system would provide sound baseline information, since management questions such as vegetation composition, productivity potential, limitations of timber management and responses to disturbances are functions of environmental characteristics and management history on the site.

Much impetus for the development of new classification systems and the improvement of existing systems has revolved around new and improving technologies including Geographic Information Systems (GIS) and Digital Elevation Models (DEM's). A GIS is a "set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world for a particular set of purposes" (Burrough, 1986). DEM's are ordered arrays of numbers that represent the spatial distributions of elevation (Moore et al., 1991). These are the usual baseline data for a digital terrain model (DTM), which is a representation of the spatial distribution of terrain attributes (Moore et al., 1991). The GIS and DEM technologies have especially strong application potential in rugged and deeply dissected regions.

Areas of rugged topography are common. McNab and Avers (1994) identified 195 ecological sections for the United States. Approximately 46% of the U.S. (43% of the lower 48 states) is in ecological sections described as steeply to moderately dissected with local relief generally exceeding 100 meters and landforms that are observable from topographic information such as the United States Geological Service (USGS) 7.5 minute topographic sheets. Another 10 to 20% of the U.S. is moderately hilly sections such as the Southern Appalachian Piedmont and the Central Dissected Till Plains that contain landscapes that also have some potential to be modeled with digital terrain modeling techniques. Many rugged areas were neglected in past land surveys and require more intensive land characterizations. Additionally, many of these rugged lands are receiving new urbanization, development and recreational pressures.

Hypotheses

1. Digital elevation models (DEM's) can be used as accurate sources for computation of geomorphic characteristics such as slope gradient and slope aspect.
2. Terrain models produced from DEM's can be reliable information for landform classifications that can be used for determination of ecological landtypes, premapping for soil survey and soil survey updates.

3. The use of GIS and DEM technologies with a geomorphic-influenced approach can increase the accuracy, flexibility, and efficiency of land classification activities.

Objectives

1. Compare several sources and production techniques for producing DEM’s. Evaluate accuracy and usefulness of DEM products through analysis of visual portrayals of the landscape, slope and aspect measurements, and landform determinations.
2. Utilize DEM’s with GIS to develop DTM’s, experimenting with different terrain modeling methods. Compare these DTM’s to a detailed soil-geomorphic field survey.
3. Evaluate the operational potential of using the DTM approach for land classification activities including:
    a) ECS development and mapping,
    b) soil survey premapping,
    c) soil survey updates,
    d) stratification of landscape for soil and environmental sampling, and
    e) production of dynamic surveys that can be adjusted for specific uses or for different interpretations.

Project Background

Emphasis was placed on developing techniques to help with three ongoing projects: i) the development of an Ecological Classification System (ECS) for the Ozark region of Missouri, ii) assistance with site characterization for a long-term ecological research project known as the Missouri Forest Ecosystem Project (MOFEP), and iii) the Missouri soil survey program executed by the NRCS and the Missouri Department of Natural Resources (MDNR).

Ecological Classification Systems

Initial development of an ECS was executed for Mark Twain National Forest and the surrounding region by Miller (1981). Nigh et al. (1994) revised this system as a pilot study for the application of a statewide ECS in Missouri. An ECS is a method of classifying ecosystems and landform patterns. It is an integrative approach to classifying land that incorporates the major ecosystem factors including climate, geology, topography, soils, and vegetation. Potential goals for an ECS include the identification of land units that are similar relative to: 1) distributions of water and energy (Hammer and Henderson, 1994), 2) type, structure, and productivity of vegetation (Jones, 1991), and 3) responses to site disturbance and management (Hammer and Henderson, 1994; Hills, 1960).

Missouri Forest Ecosystem Project

The MOFEP project is a long-term ecological research project designed to monitor ecological response to forest management (Brookshire and Hauser, 1993). This project is being executed by the Missouri Department of Conservation (MDC) with assistance from several other state and federal agencies. The project is designed to monitor ecosystem changes over a 100-year period. Monitored components include wildlife, vegetation and soils. This thesis project has utilized much of these data, especially geomorphic and soils data collected by Meinert (Meinert et al., 1997; Meinert, 2001).

Soil Survey

The National Cooperative Soil Survey (NCSS) program requires new techniques that might increase the quality of soil survey. Techniques and approaches were investigated that could improve the accuracy, consistency, efficiency and flexibility of soil survey programs. This becomes important as the soil survey advances to the Major Land Resource Area (MLRA) “update” phase. The MLRA update will focus on refinement and modification of soil map units and soil-landform models.

Thesis Format

Chapters two and three are the experimental research chapters. Chapter two evaluates DEM’s produced from different sources for their effectiveness in portraying realistic looking landscapes, making slope and aspect measurements, and classifying landforms. Chapter three investigates using the USGS level 2 30-m DEM to produce DTM’s, experimenting with different methods and comparing these with a detailed field investigation.

Additional Literature Reviews

In addition to the two research chapters, two literature reviews were prepared. They are not included in the thesis because of their length, but are available upon request. The first literature review was prepared prior to the thesis research. It contains four sections. The first section reviews the research on soil-landscape relationships and presents the basis for the theory that modeling of geomorphic features can lead to successful characterization of soil characteristics and other environmental phenomenon. The second section focuses on how site and soil characteristics influence a particular ecosystem characteristic - tree growth. Site quality as measured by tree growth was chosen as the focus because forest management is a major land classification challenge, much quantifiable research has been published, and literature reviews on vegetation composition and characteristics were done by other project researchers involved with MOFEP and ECS. The third section is a review and critique of different land classification efforts with an emphasis on ECS. The final section of chapter two discusses and reviews applications of GIS and DEM technologies for land classification.

The second literature review was undertaken because of a request by the USDA Forest Service to review forest management impacts on soils in the Central Hardwood Region. This project deviated somewhat from the scope of the thesis and synthesizes research on the impact of timber harvesting on soils in the Central Hardwood Region. The USDA Forest Service is performing ongoing research to estimate the impacts of different timber management activities on soil characteristics in the Central Hardwood Region - a region that includes areas of primarily hardwood vegetation in the Midwest and Mid-South. A need was identified to review and synthesize related research in the Central Hardwood regions and similar landscapes to help facilitate management and research projects. Interest is primarily in the upland areas where natural vegetation is dominated by forest, including parts of Missouri, Arkansas, Illinois, Kentucky, Tennessee, Indiana, and Ohio. Subjects covered include the impacts of harvesting activities on soil disturbance, compaction, erosion, and water.

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CHAPTER 2

EVALUATION OF DEM ACCURACY

INTRODUCTION

Landforms are often the most important influence on ecosystem expression. A Landform is defined by its surface shape, its location in relation to other landforms, its underlying geologic materials, and its soil attributes (Hammer, 1997). The shapes and relative locations of landforms can be determined by modeling terrain attributes such as slope gradient, slope aspect, surface shape, slope length and relative slope position. Accurate and efficient modeling of these terrain attributes depends on the availability of accurate and precise spatial baseline information. Digital elevation Model’s (DEM’s) usually are the baseline data used for modeling terrain attributes. Quality considerations of a DEM include the grid resolution, source of elevation data, number of supporting survey points, techniques used in producing the DEM, and the skills of those producing the DEM. Source documents used for construction of DEM's include; 1) contour maps, 2) stereo aerial photography, 3) stereo satellite images, 4) Light Detection And Ranging (LIDAR) Radar, 5) Interferometric Synthetic Aperture Radar (IFSAR), 5) global positioning systems (GPS), and 6) ground survey data.

Despite the importance of accurate baseline information, few studies have validated DEM-derived products with field data. Bolstad and Stowe (1994) compared accuracy of elevation, slope, and aspect measurements derived from a United States Geological Service (USGS) 7.5 minute quadrangle 30-m DEM and a 30-m DEM created with images from the French satellite, *Le Systeme Pour l’Observation de la Terre* (SPOT), by STX Corporation. This analysis found the two DEM's similar in quality for elevation measurements. Both DEM’s were within the Root Mean

Squared Error (RMSE) accuracy target established by the USGS for Level 1 7.5-minute DEM's, which stipulates a vertical RMSE target of 7 meters and a maximum RMSE of 15 meters. Greater statistical differences in slope and aspect measurements were observed, with the USGS DEM significantly more accurate when measured on a per-point basis. Bolstad and Stowe (1994) speculated that much of the error in the SPOT DEM is probably due to difficulties in stereo-correlation in forested terrain.

Sasowsky et al. (1992) studied a region in Alaska with 250 m of relief in a 25 km^2 area. An elevation analysis was made between a large-scale DEM derived from low-flying aerial photography (assumed to be of high accuracy) and a SPOT-based DEM produced by STX Corporation. In this comparison, the RMSE elevation value was 19.3-m, the average residual was 17.5-m and the standard deviation was 18.5-m. However, despite these relatively large errors, Sasowsky et al. (1992) concluded that the slope and aspect data from the SPOT-based DEM were useful for ecosystem investigations in areas where topographic information was not previously available. Touton and Beaudoin (1995) used SPOT images to produce a DEM in the Canadian Rockies. Cell elevations were within 30 meters of DEM's generated from contour lines with a 90% confidence interval. The authors felt that with modifications of their techniques, differences of 15 to 20 meters would be attainable. Theodossiou and Dowman (1990) have speculated that SPOT-based DEM's might perform adequately for scales as large as 1:25,000.

Hammer et al. (1995) performed rigorous testing of slope determinations from DEM's of two different sources and from a standard Natural Resources Conservation Service (NRCS) soil survey in moderately sloping terrain with relief up to 43 m. They found that a 10-m DEM produced from aerial photographs produced slope estimations that were more accurate than the published soil survey. However USGS level 1 30-m DEM data were not so accurate as the soil survey data. Klingebiel et al. (1987) found that USGS level 1 30-m DEM data were useful for slope and aspect premaps for third-order soil surveys in Idaho, Nevada, and

Wyoming, but they did not believe these data were sufficiently accurate for more detailed second-order soil surveys.

The major questions investigated are:

1) Despite the published reports of USGS 30-m DEM's with level 1 accuracy, few reports have been found of data from USGS Level 2 DEM's. Do level 2 DEM's represent a significant increase in DEM quality over level 1 DEM's?

2) Several investigations have noted that SPOT data can be a useful source for DEM’s in areas without existing topographic data. Can SPOT-based DEM's be produced that surpass the accuracy of existing topographic data sources?

3) Many programs are available to convert elevation contours to grid-based DEM's. How accurate is one of the most common commercially available programs and does it offer quality increases over existing USGS level 1 and level 2 30-m DEM's?

4) Hammer et al. (1995) found a USGS Level 1 30-m DEM to lack sufficient resolution for accurate slope maps in northwestern Missouri. Do Level 1 DEM's have greater success in a more rugged area of the Missouri Ozarks?

DATA AND METHODS

Site Description

The research sites are in Shannon, Carter and Dent counties in the Lower Ozark region of southeastern Missouri (Nigh et al., 1994). The study region is within four USGS 7.5 minute quadrangles (Exchange, Powder Mill Ferry, Stegall Mountain and Van Buren North) covering an area of about 600 $km^{2.}$ Within this area are nine long-term research sites maintained by the Missouri Ozark Forest Ecosystem Project (MOFEP), ranging in size from 260 to 527 ha (657 to 1,300 ac) (Brookshire and Hauser, 1993) (Fig. 2.1). The MOFEP study is a long-term ecological research project administered by the Missouri Department of Conservation

(MDC) with cooperators from other state and federal agencies. The MOFEP study seeks to determine the effects of forest management activities on Missouri Ozark ecosystems.

The vegetation is part of the Oak-Hickory forest region (Braun, 1972). Important communities include oak-pine, mixed upland and bottomland hardwood forest, oak-savanna, and glades. This region is underlain mostly by eroded and uplifted sedimentary rocks composed of dolomites, limestones, sandstones and cherts with igneous intrusions on some upland areas. The topography is rugged and deeply dissected with elevations ranging from approximately 137 m to 414 m (450 feet to 1360 feet). Generally, the nine research sites have narrow, convex ridges or summits (less than 150 m wide) with slopes of less than 20%. Steep side slopes ranging from 15-20% to over 60% cover a majority of the study sites. Structural benches with slopes less than 20% and relatively narrow floodplains are other common features of the area. The Current River is the best known natural feature of the region, and flows northwest to southeast. The most rugged portions of the study region are generally closer to the Current River. Soils are formed primarily in hillslope sediments and residuum, with some areas of loess and alluvium. Soils generally are highly weathered and range in depths to bedrock. Bedrock outcrops and fragipans are common. Paleudults, Paleudalfs, Hapludalfs and Paleudults are common soil great groups and loamy-skeletal and loamy-skeletal over clayey are the most common particle size classes (Meinert et al., 1997; Soil Survey Staff, 2004).

MOFEP Research Sites

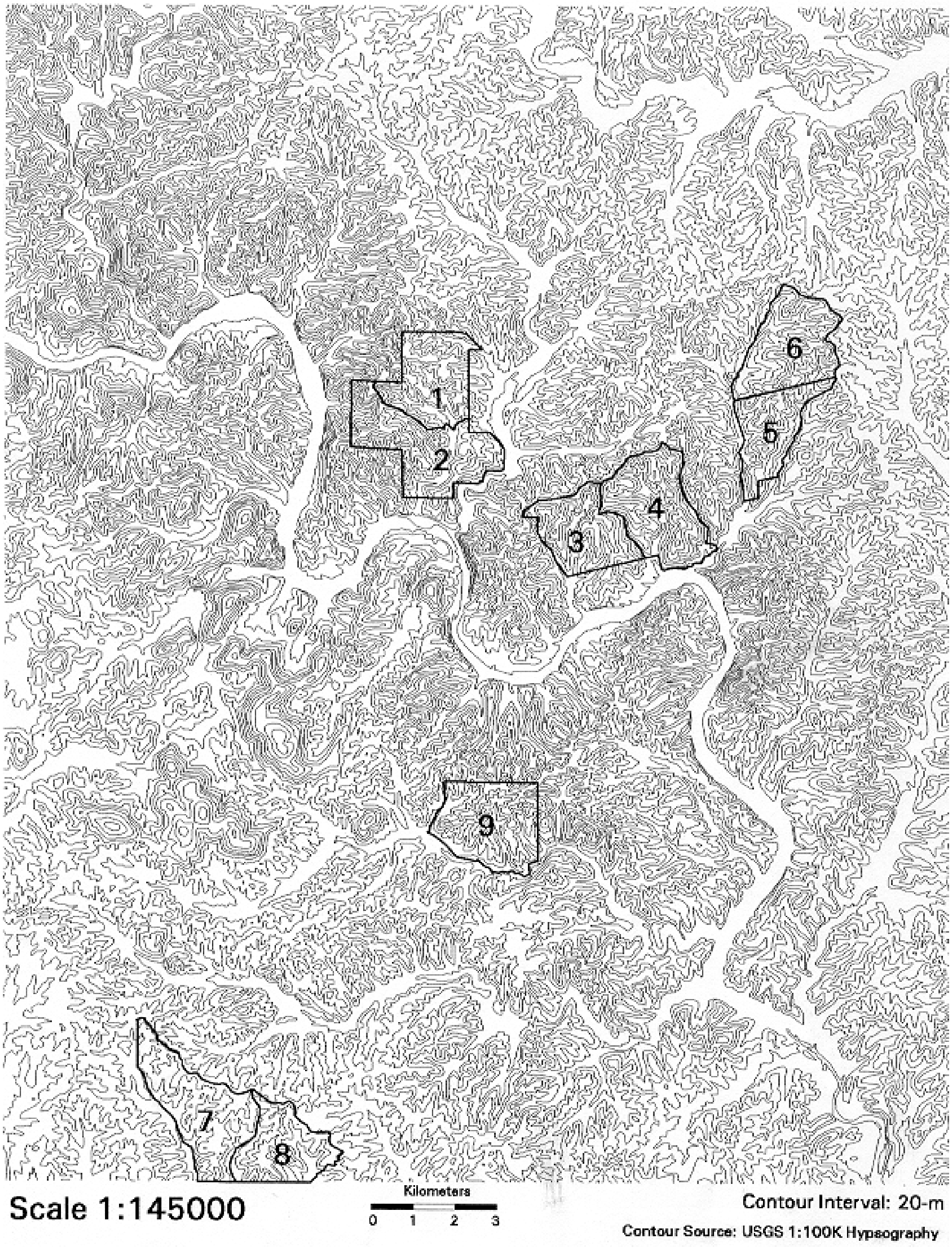

Figure 2.1 MOFEP research sites shown with region hypsography.

Evaluation Criteria

Four sources of DEM data were investigated: A) SPOT Image-based DEM, B) DEM's produced from elevation contours (referred to as TOPOGRID DEM’s), C) USGS level 1 DEM’s, and D) USGS level 2 30-m DEM’s (Table 2.1). The DEM coverage is not complete for all sites, except for the SPOT DEM (Table 2.2). The USGS Level 2 DEM covers six sites and the USGS Level 1 covers three sites. Hypsography data necessary for production of TOPOGRID DEM's were available for the northwest, northeast, and southeast sections of the study region, which includes sites 1 thorough 6. Because DEM coverages and data collected were not complete for the entire study, not all sites were used for all comparisons.

Evaluations were made of three common DEM products to determine the accuracy of each DEM with respect to visual quality, calculation of slope gradient and slope aspect, and execution of a supervised landform classification (Table 2.3). These data were analyzed with respect to four data sources for DEM’s. Because of incomplete DEM coverage of the study region and variable amounts of field data for each site, it was not possible to use all sites for all comparisons. The entire study region was used for initial small-scale visual observations and sites 3 through 9 were used more detailed investigations.

Table 2.1 DEM’s Tested for Accuracy

DEM	Data Source	DEM Abbreviation
USGS Level 1 30-m	Aerial Photographs	USGS-L1
USGS Level 2 30-m	USGS 1:24K Hypsography	USGS-L2
SPOT 15-m DEM	SPOT Satellite Images	SPOT
TOPOGRID 7.5-m DEM	USGS 1:24K Hypsography/Hydrology	TOPO7.5
TOPOGRID 15-m DEM	USGS 1:24K Hypsography/Hydrology	TOPO15
TOPOGRID 30-m DEM	USGS 1:24K Hypsography/Hydrology	TOPO30

Table 2.2 MOFEP Sites DEM Coverage

	USGS 30-m		SPOT 15-m	TOPOGRID		
Site #	**Level 1**	**Level 2**		**7.5-m**	**15-m**	**30-m**
1		X	X	X	X	X
2		X	X	X	X	X
3		X	X	X	X	X
4		X	X	X	X	X
5		X	X	X	X	X
6		X	X	X	X	X
7	X		X			
8	X		X			
9	X		X			

Table 2.3 DEM's evaluated and research area used for each type of comparison.

Type of Evaluation	DEM's Evaluated	Area of Comparison
Small-Scale Visual Assessment	ALL	Entire Extent of Each DEM
Large-Scale Visual Assessment	SPOT 15-m DEM	Site 4
	USGS Level 2 30-m	Site 4
	TOPOGRID 7.5-m	Site 4
	TOPOGRID 15-m	Site 4
	TOPOGRID 30-m	Site 4
Visual Assessment of Slope and Aspect Maps	SPOT 15-m DEM	Site 4
	USGS Level 2 30-m	Site 4
	TOPOGRID 7.5-m	Site 4
	TOPOGRID 15-m	Site 4
	TOPOGRID 30-m	Site 4
Quantitative Accuracy of Slope and Aspect Determinations	SPOT 15-m DEM	Sites 5 - 9
	USGS Level 1 30-m	Sites 7 - 9
	USGS Level 2 30-m	Sites 5 & 6
	TOPOGRID 7.5-m	Sites 5 & 6
	TOPOGRID 15-m	Sites 5 & 6
	TOPOGRID 30-m	Sites 5 & 6
Supervised Landform Classification	SPOT 15-m DEM	Sites 3 & 4
	USGS Level 2 30-m	Sites 3 & 4
	TOPOGRID 7.5-m	Sites 3 & 4
	TOPOGRID 15-m	Sites 3 & 4
	TOPOGRID 30-m	Sites 3 & 4

DEM Sources and Production

SPOT DEM

Stereo images from the satellites can be used to produce orthophotos and DEM's much in the same way as from conventional aerial photography. An advantage of satellite data over aerial photography is that it is cheaper, more easily obtained, and can be purchased in a digital form directly accessible by computers (Moore et al., 1991, Gugan and Dowman, 1988). The French earth observation satellite, SPOT, is the most common source of images for DEM's produced from satellite data.

Three versions of SPOT image-based DEM's were received from Autometric, Inc. Initially, a 15-m and 30-m DEM were received in October of 1995. Analyses of the DEM's indicated several problems. Especially notable was the poor visual portrayal of the landscape. Elevation values for entire drainages were lower than the lowest elevation in the region, and difficulties were encountered in properly registering the DEM. Because of these problems, Autometric, Inc. produced another 15-m DEM using the same images, which they delivered in March of 1996 (Fig. 2.2). Autometric, Inc. did not indicate if different techniques were used for the production of these DEM's. The second 15-m DEM was higher quality, so it was used for this project.

The 15-m SPOT DEM was derived from panchromatic stereopairs taken during leaf-off periods in early spring of 1994. Autometric, Inc. produced the original 15-m DEM using an image correlation algorithm with 1482 longitude post points and 1850 latitude post points for a total of 2,741,700 post points (equal to the total number of cells). The image quality appeared excellent except for some light cloud cover in the southwest area of the images. The DEM was delivered with elevations given in meters relative to National Geodetic Vertical Datum of 1929 (NGVD29), and cast on to zone 15 Universal Transverse Mercator UTM Projection using the North American Datum of 1927 (NAD27). For the initial 15-m DEM collection results, 40.5% were classified as good, 0.3% as fair and 17.7% as poor and 41.5% of the collection results were interpolated. Autometric Inc. did not indicate if collection results were significantly different for the second DEM. Further information about techniques was not provided by Automatic, Inc.

Contour-Based DEM's

Contours from topographic maps such as the USGS 7.5 minute quadrangles are becoming an important source for grid DEM. The lines from existing maps can be digitized automatically using raster scanning and vectorization processing. Many software packages convert contour lines to grid DEM's. One program was devised by Hutchinson (1989), and is called the Australian National University digital elevation model (ANUDEM). This method was later adopted into the TOPOGRID program available with Arc/Info (ESRI, 1994). The TOPOGRID program is a process of interpolating grid DEM's from contour line data or scattered point elevation data. This method has a drainage enforcement algorithm that automatically removes spurious sinks and calculates stream lines and ridge lines from points of locally maximum curvature. The TOPOGRID method is one command in Arc-Info with several sub commands that can define options such as number of iterations for the interpolations, depth of sinkhole tolerances, and optional input of stream coverages. In creating a DEM from contour information, it is important to note that the original source documents contain errors and that a DEM is no more accurate than the original source data (Carter, 1988, Moore et al., 1991).

A 7.5-m DEM was produced within the TOPOGRID module and was resampled to 15 and 30-m DEM's. Producing initial DEM's at coarser resolutions was not possible in much of the study region because the contour information was too dense for the TOPOGRID program. To produce DEM’s in this situation, it is necessary to either manually edit the areas of dense contour lines, or to produce a DEM at a high resolution (small cell size) and resample it to a larger cell size. The latter

SPOT 15-m DEM

Figure 2.2 SPOT 15-m DEM covering entire study region.

method was used. The 7.5-m resolution was chosen because it was the largest resolution that could be successfully used for the TOPOGRID program, and it represented a realistic minimum resolution, as finer resolutions are much more detailed than can be realistically gained given the initial 6.1 meter contour interval. In addition, finer resolutions would result in extremely computer-intensive operations. The 7.5-m cell size also was a suitable resolution to resample to 15 and 30-m resolutions.

Several options are available for producing DEM's within the TOPOGRID module in Arc/Info. Different parameters within the TOPOGRID module were tested to determine the most accurate methods, along with efforts by other investigators working with related projects (J. Krstansky and S. Westin, personal communication). These efforts are not reported in detail, however, they influenced the quality of the DEM produced. Evaluations were made based on histograms of the DEM elevation values, overlays of different DEM's, and calculations of slope and aspect values. The final parameters chosen for producing the 7.5-m DEM included using the USGS 7.5 minute hypsography, USGS 7.5 minute stream data edited so that arc arrows point downstream, with tolerances of 0.07, 0.30, and 0.60 for the drainage enforcement process.

The initial 7.5 m DEM produced from TOPOGRID contained several “sinks”, areas of the DEM that were represented as closed depressions such as sinkholes. The topographic maps showed that nearly all sinks were spurious data errors rather than true sinks. The majority of the sinks on the 7.5-m DEM were filled with the Arc/Info FILL command before using for further analysis or resampling to the 15 and 30-m DEM's. The FILL command fills all sinks to the specified level. All sinks 15-m deep and shallower were filled for this analysis. The 7.5-m DEM was resampled to DEM's of 15-m and 30-m resolution. The resampling to 15-m resolution was performed using a bilinear resampling technique. Every four cells in the 7.5 m DEM are interpolated to produce a 15-m DEM. The 30-m DEM was produced using a trilinear interpolation from the 7.5-m DEM where the nine 7.5-m cells located in the center of each 30-m DEM are interpolated.

USGS DEM’s

A third base for DEM data is the USGS 30-m DEM for 7.5 minute quadrangles. Those used in this study are USGS DEM's classified as either level 1 or level 2. Level 1 DEM's are no longer produced, however they remain the only available DEM in many areas.
New USGS DEM's for 7.5-minute quadrangles are usually released as level 2. An additional USGS product, level 3 DEM’s, meet higher accuracy standards but are not widely available. The level 1 designation is generally reserved for DEM data that are created photogrametrically by manual profiling or image correlation techniques from aerial photographs (USGS, 1996). The standard Gestalt Photomapper II was an instrument commonly used for the photogrammetric production of USGS level 1 DEM's. A minimum of 28 test points per DEM is required to compute the root mean square error (RMSE). The vertical accuracy is computed by a comparison of linear interpolated elevations in the DEM with corresponding known points. A vertical RMSE of 7 meters is the desired accuracy standard and a RMSE of 15 meters is the maximum permitted for level 1 DEM's. The absolute elevation error tolerance is 50 meters (approximately three times the 15-m RMSE). Any array of points in the DEM cannot encompass more than 49 contiguous elevations in error by more than 21 meters (three times the 7-m RMSE). Note that the USGS published accuracy specifications are general guidelines, and are not reported for specific quadrangles. The two southernmost quadrangles of the study, the Exchange and Van Buren North quadrangles, are level 1 DEM's. MOFEP sites 7, 8, and 9 are in these two quadrangles. Elevations for the DEM’s were given in meters relative to National Geodetic Vertical Datum of 1929 (NGVD29), and postings were cast on to the zone 15 UTM Projection using the North American Datum of 1927 (NAD27).

The level 2 designation includes DEM data derived from hypsoscopic DLG data or generated from vector data derived from scanned raster files of USGS 1:24,000-scale map series contour separates (USGS, 1996). Level 2 DEM's have been processed or smoothed for consistency and edited to remove identifiable systematic errors. An RMSE of one-half contour interval of the source map is the maximum permitted error. Systematic errors (those that follow some fixed pattern and represent an array of points) may not exceed one contour interval. Map accuracy standards for the original 7.5 minute quadrangles require that at least 90% of the tested points be within one-half contour interval of the correct value. Level 2 DEM's are becoming more commonly available. The northern-most quadrangles of the MOFEP area (Powder Mill Ferry and Exchange) are level 2 DEM's (Fig. 2.3). Six of the nine MOFEP sites (sites 1-6) are in these two quadrangles. These were provided in the same datum and projection as the level 1 DEM's cited above.

DEM Filtering

Filtering is a technique for improving the accuracy of DEM data. Low-pass filters smooth the lattice and reduce the significance of anomalous cells, while maintaining general surface patterns (ESRI, 1994). Filtering has been shown to improve the quality of DEM data (Hammer et al., 1995). One can adjust the amount of filtering by adjusting the values used in the filter and the number of iterations or passes that are made over the DEM. A detailed analysis of the filtering process effect on DEM quality was not performed in this investigation. However, it is important to know situations where filtering may be used and how it can affect DEM data.

USGS Level 2 30-m DEM’s

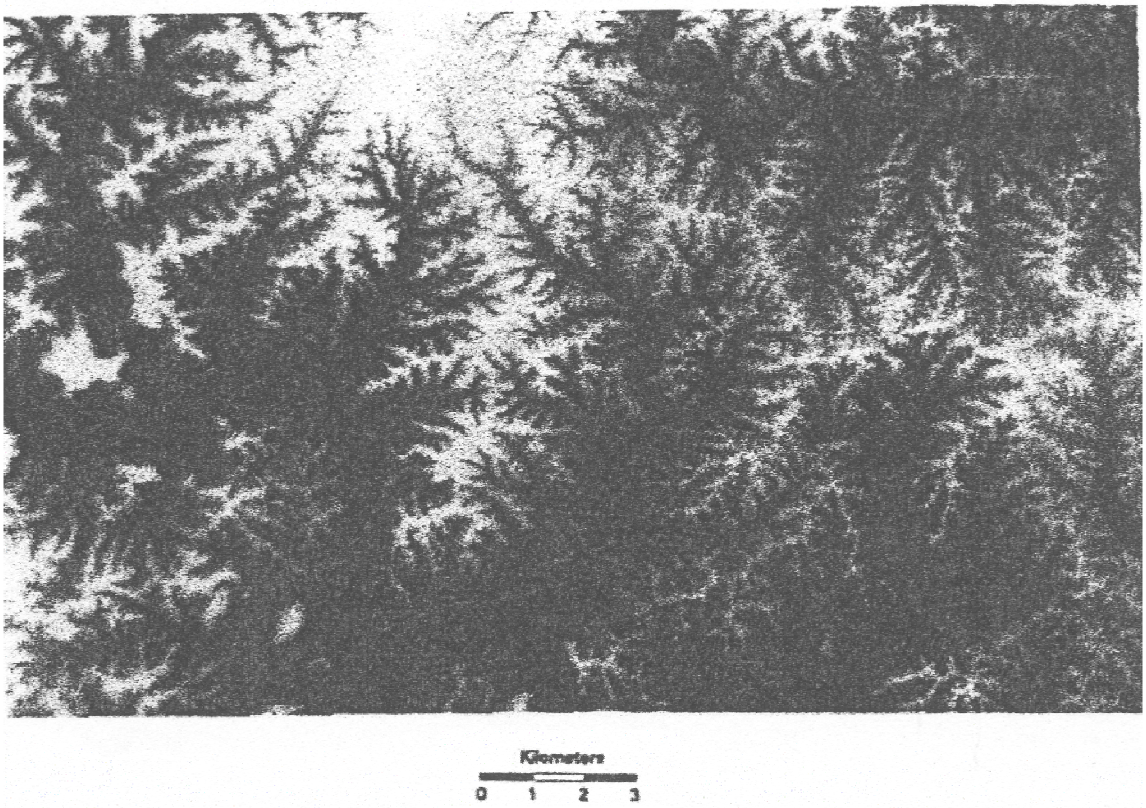

Figure 2.3 USGS Level 2 30-m DEM’s covering the northern two quadrangles (Exchange and Powder Mill Ferry) of study region.

An initial analysis of filtering was performed on the SPOT 15-m DEM. A low-pass filter was performed with different numbers of passes. Filtered DEM's were converted to contour lines and surface displays to assess possible improvement. The filtered SPOT DEM's did not appear to be reasonable representations of the landscape. The filtered DEM, while smoothing some of the inconsistencies, displayed no landscape detail. Because the initial analysis did not show filtering to offer noticeable improvements to the SPOT DEM, a more detailed analysis was not undertaken. Detailed analysis of filtering on the other DEM’s was also not investigated. Improvements from filtering are likely for the USGS Level 1 DEM’s, as this was observed by Hammer et al. (1995) in northwestern Missouri. Filtering may also have positive effects on the

TOPOGRID 7.5-m DEM. Filtering is less likely to have positive impacts on the USGS Level 2 30-m DEM since it undergoes a filtering process in its production, nor on the TOPOGRID 15-m and 30-m DEM's, since the resampling process serves to smooth these DEM's. Although filtering has potential to improve DEM data, it does not appear to make dramatic improvements in DEM accuracy, nor would it be expected to greatly change the relative accuracy of the DEM's presented in this chapter.

Collection of Field Measurements

The collection of field measurements was performed in connection with the MOFEP project (Brookshire and Hauser, 1993; Meinert et al., 1997). The MOFEP project has nine study sites with 70 to 74 plots each. Information on vegetation, wildlife, soils, geomorphology, microclimate, and other ecosystem data is collected. Among these data are slope gradient and slope aspect measurements.

Slope gradient was measured to the nearest percent on all 673 plots with a hand-held clinometer. Readings upslope from the plot center to the plot edge and downslope from the plot center to the plot edge were averaged to derive the slope gradient for each plot. The circular plots are 0.203 ha with a radius of 50.8 meters. By comparison, a 30-m DEM calculating slope with a 3 x 3 cell window uses distance of 60 meters from the center of the upslope cell through the center cell and to the center of the downslope cell. The plot size biases the comparisons towards larger cell sizes (i.e. favors 30-m DEM's over 7.5-m DEM's). Uncertainty of exact plot locations (an estimated 50% of plot centers within 4.5 to 8.5 meters of the true plot locations) might bias the estimates towards the coarser DEM's with larger cell sizes. Aspect was measured with a field compass from the center of each plot. All aspect measurements were rounded to the nearest 5^0. Some plots have variable slopes and aspects within plot boundaries, therefore any horizontal registration error would produce erroneous DEM slope and aspect estimates. The procedure for this study did not remove from the data plots situated on sites of variable slopes and aspects in order to avoid subjective decisions that might inflate the true accuracy of the DEM’s. However, with horizontal registration errors, lack of direct overlay of DEM and plot centers, and the small error usually expected with field measurements, the reported accuracy in this study is probably less than true accuracy.

Plot locations were determined using a Trimble Global Positioning System (GPS). This work was conducted in support of the MOFEP project by Missouri Department of Conservation and USDA Forest Service personnel (Brookshire and Hauser, 1993). Horizontal positions for the plots were determined using differentially corrected GPS data averaging at least 180 position fixes for each plot center. Data from 280 plots (of the 673 total MOFEP plots) were available when this project was executed.

Data collected with the field units contain several sources of error. Much of the error is from an artificial degradation, known as selective availability, of the satellite signal by the Department of Defense. The policy of artificial degradation was in effect at the time of the GPS data collection, although it was discontinued after April of 2000. Selective availability can cause horizontal errors of up to 100 meters in GPS positions (Trimble, 1994). This introduced error can be minimized by differential correction, which requires establishing an observed error of a receiver at a known location (i.e. the base station), and applying the observed error as a correction factor to rover receivers recording locations at the unknown locations (field plots). Data must be collected simultaneously at the base station and the unknown locations. The offset differences are used to determine errors in the field data and to remove these errors from the field receiver positions (Trimble, 1994). The base station data used were those of the Midwest Science Center in Columbia, Missouri. This base station is approximately 250 km from the field sites, which is within the recommended maximum distance of 500 km or less from the collection area (Trimble, 1994). However, this distance adds an additional 3.5

meters error to the data based on Trimble’s (1994) suggested formula that estimates a 10-mm degradation for every km between the base station and the rover or field GPS units.

The GPS position errors are commonly expressed as the circular error probable (CEP). This is a circle of a specific radius that encloses 50% of the data points. Trimble (1994) states that differentially corrected GPS data have CEP error of one to five meters, meaning that one-half of the points fall within a two-dimensional circle of radius one to five meters surrounding the true location and one-half of the points fall outside the circle. Combining the displacement error, estimated at 3.5 meters, with the other positional error, approximately 50% of the sampled plots fall within 4.5 to 8.5 meters of the true plot locations.

GIS Measurements

The GIS work was performed with Arc-Info version 7.02 software. The GIS measurements were taken to assess visual effectiveness of the DEM’s and their products, slope and aspect accuracy, and accuracy in classifying landforms. Initial evaluations determined the ability of each DEM to reasonably portray the landscape, and to display consistent geomorphic features such as connected streams and ridges. This procedure is important because effective portrayals of landscapes increase our understanding of geomorphic relationships. In addition, the visual effectiveness of a model often determines if the utilization of that model is accepted or rejected as a management or research aid. The three methods used to initially judge the quality of the DEM's were: 1) observations of gray-scale displays, 2) contour lines created from the DEM's, and 3) three-dimensional displays. In addition, selected slope and aspect maps were created for site 4 and visually assessed.

Accuracy of slope and aspect data were assessed by computing the slope and aspect values for each DEM and comparing these with field measurements. Slope identifies the maximum rate of change from each cell to its neighboring cells (ESRI, 1994). Slope was calculated as percent slope for a 3 x 3 neighborhood surrounding the processing or center cell using the average maximum technique (ESRI, 1994). The algorithm used was: rise/run = $((\Delta z/\Delta x)^2 + (\Delta z/\Delta y)^2)^{1/2}$ where a through i represent the elevation values of a 3 x 3 window used to calculate the deltas:

$$\begin{array}{ccc} a & b & c \\ d & e & f \\ g & h & i \end{array}$$

$$(\Delta z/\Delta x) = ((a + 2d + g) - (c + 2f + i)) / (8 * \text{x-mesh-spacing})$$

$$(\Delta z/\Delta y) = ((a + 2b + c) - (g + 2h + i)) / (8 * \text{y-mesh-spacing})$$

Aspect, or slope direction, identifies the down-slope direction of maximum rate of change from each cell (ESRI, 1994). The formula is $(-\Delta z/\Delta y)/(\Delta z/\Delta x)$. Slope values were rounded to the nearest one percent, while aspect values were rounded to the nearest five degrees.

To make accurate comparisons, two features of the data had to be accounted for: i) field plot centers did not directly align with the DEM cell centers, and ii) some horizontal registration errors occur with the plot centers (i.e., plot center locations are not exact). To minimize this effect, the values for slope and aspect were interpolated using a linear interpolation method with the LATTICESPOT command in Arc/Info (ESRI, 1994). This method determines the four closest cells to the sample point and then weights the value given to the sample point based on the distance of the four cell centers to the point (ESRI, 1994).

Slope and aspect accuracy were statistically assessed by comparing the SPOT 15-m, USGS Level 1 30-m, TOPOGRID 7.5-m, TOPOGRID 15-m, and TOPOGRID 30-m DEM's with field data from 141 plots on sites 5 and 6, and comparing the SPOT 15-m and USGS Level 30-m DEM's with field data from 139 plots on sites 7, 8, and 9. The field values were considered the "true" values for this assessment. Subtracting the DEM values from the field values give the signed residuals (errors), a measurement of the difference and direction of difference (> or <) of the DEM values from the field values. The absolute values of the residuals give the unsigned residuals, which is an indication of the absolute differences between the field values and the DEM values. The minimums, maximums, and means of the residuals were calculated. Pearson's correlation statistic was used to produce an index of correlation between the DEM values and the field values.

Slope values were separated into classes to answer the question, "Given important slope classes that have been determined from field investigations, how often are data derived from a particular DEM going to classify a cell into the correct class?" The slope classes were chosen based on an understanding of which slope breaks are important for identifying landforms and associated soil characteristics and are important for management interpretations. The slope classes were:

0-8%
8-20%
20-35%
35-60%

Also investigated were the accuracy of slope measurements within different slope classes and landform types. This was to determine if factors such as slope, surface shape or relative location of a landform affected accuracy.

Aspect classes were chosen based on breaks that appeared to be influencing vegetation characteristics (T. Nigh, 1996, personal communication) and soil characteristics (D. Meinert, 1996 personal communication). These breaks were:

Protected (340°-70°)
Neutral East (70°-160°)
Exposed (160°-250°)
Neutral West (250°-340°)

The frequency of agreement between the field-derived classes and the DEM-derived classes was calculated for each DEM.

Landform Classification Methods

A relatively straight-forward landform classification method, known as supervised classification, was performed on adjacent sites 3 and 4 to observe the utility of using each DEM as a base for landform classification. All the DEM's were used for the supervised classification comparison, with the exception of the USGS Level 1 30-m DEM, which does not cover sites 3 and 4. Supervised classification methods were used for this comparison because they could be performed in an objective manner that would not bias the results towards any one DEM. Analyses of different landform classification methods presented in chapter 4 found that supervised classification methods were not the most successful and practical methods. However, supervised methods are well-suited for an objective comparison of DEM quality. Supervised classification is a technique often used for classifying vegetation and land-cover from spectral data or a combination of spectral data and other data such as terrain features. Researchers have used supervised methods for vegetation classification (Treitz et al., 1992) but less extensively for landform classification (Hengl and Rossiter, 2003). Supervised classification was performed in Arc/Info. The supervised classifications were compared to a soil-geomorphic field survey by Meinert (2001). In an extremely detailed survey, Meinert identified 35 soil-geomorphic map units. These were aggregated into nine geomorphic map units that refer to a landform and/or geologic formation. The nine units are:

Eminence Waterway
Gasconade Waterway
Lower Gasconade Bench/Secondary Ridge
Eminence Bench/Secondary Ridge
Lower Gasconade/Eminence Backslope
Roubidoux/Upper Gasconade Backslope
Cliff/Steep Backslope
Roubidoux/Upper Gasconade Shoulder/Ridge
Roubidoux/Upper Gasconade Summit

Supervised classification requires the user to create prototypes for each class. The prototypes (training areas) in this case were the nine geomorphic classes. The interior portions of the geomorphic map units of the adjacent sites 3 and 4 were used as the training sites for the supervised classification. The training areas covered 29% of sites 3 and 4 (see Fig. 3.9 of next chapter), and were used to classify all of sites 3 and 4. A relatively successful landform classification should be expected with such extensive training sites. The methods used in Arc/Info statistically analyze the training areas to create a signature for each landform class and then classified the other 71% of sites 3 and 4 into one of the nine landform classes. Supervised landform classifications were created using all DEM's except the USGS level 1 DEM, which does not cover sites 3 and 4.

Grid stacks were created with the MAKESTACK command to use as inputs for each of the supervised models. The SAMPLE command was used to sample the training areas for the input grids. The SAMPLESIG command was used to create signature files of each input grid for each landform. The MLCLASSIFY command was used to classify each grid cell based on how it compared with the signature files for the training areas. Three attribute grids were used as inputs into the supervised classification: 1) elevation, 2) slope, and 3) surface curvature. These attributes were produced objectively, with the same methods used regardless of differences in the source DEM's. *A Priori* knowledge of the expected frequency of each landform class was inserted into the model. The *a priori* knowledge was developed by using the frequency of each landforms occurrence in the field survey. Each supervised classification classified each cell into one of nine classes.

RESULTS AND DISCUSSION

Visual Evaluations

Observations of gray-scales of all the DEM's at scales of 1:120,000 or smaller show the general landform patterns of the research area, as shown by the SPOT 15-m DEM of the entire study region (Fig. 2.2) and the two USGS level 2 30-m DEM’s of the northern half of the region (Fig. 2.3). However, when the DEM's were observed with more detail, large differences between the SPOT DEM and the other DEM's became apparent. Figures 2.4, 2.5 and 2.6 show hillshade views of site 4. The SPOT DEM shows a very poor portrayal of the landscape. The TOPOGRID 7.5-m DEM’s hillshade is a striking example of the advantage of finer scaled DEM’s to show more realistic and appealing views of the landscape. Finer-scaled DEM’s have clear advantages in portraying hillshades and three-dimensional views. Contour lines generated from the SPOT DEM (Fig. 2.7) do not convey landscape features nearly so detailed and realistic as the USGS 7.5 minute hypsography in figure 2.8 (this hypsography is the source data for both the USGS level 2 DEM and the TOPOGRID DEM’s).

Contour lines were created at increased intervals to determine if the SPOT DEM could be applied at coarser resolutions. Figure 2.9 shows contours produced from the SPOT DEM at a 20-m contour interval. These can be compared to 20-m contours produced from the USGS 7.5-minute DEM (Fig. 2.10), and from USGS 1:100,000 scale contours used in figure 2.1. Even at this scale, the major topographic patterns in the SPOT contour map are not observed. Several instances can be observed where streams cross the same contour line more than once on the SPOT contour map. It was only in the extremely coarse gray-scale (Fig. 2.2) that the SPOT DEM did not show serious flaws in displaying the landscape.

Hillshade Produced from SPOT 15-m DEM

SITE 4

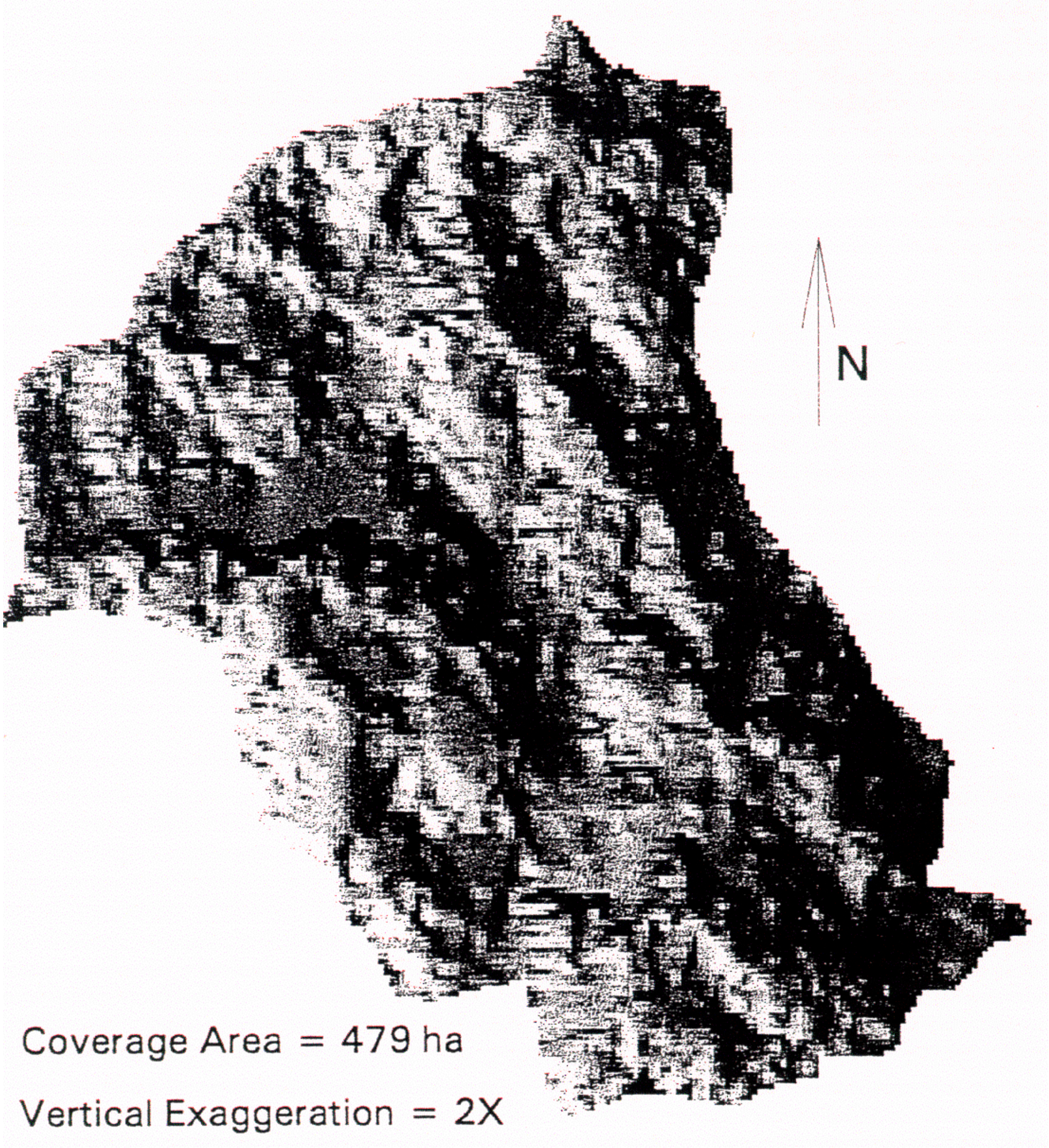

Figure 2.4 Hillshade of Site 4 produced from SPOT 15-m DEM.

Hillshade Produced from USGS Level 2 30-m DEM

SITE 4

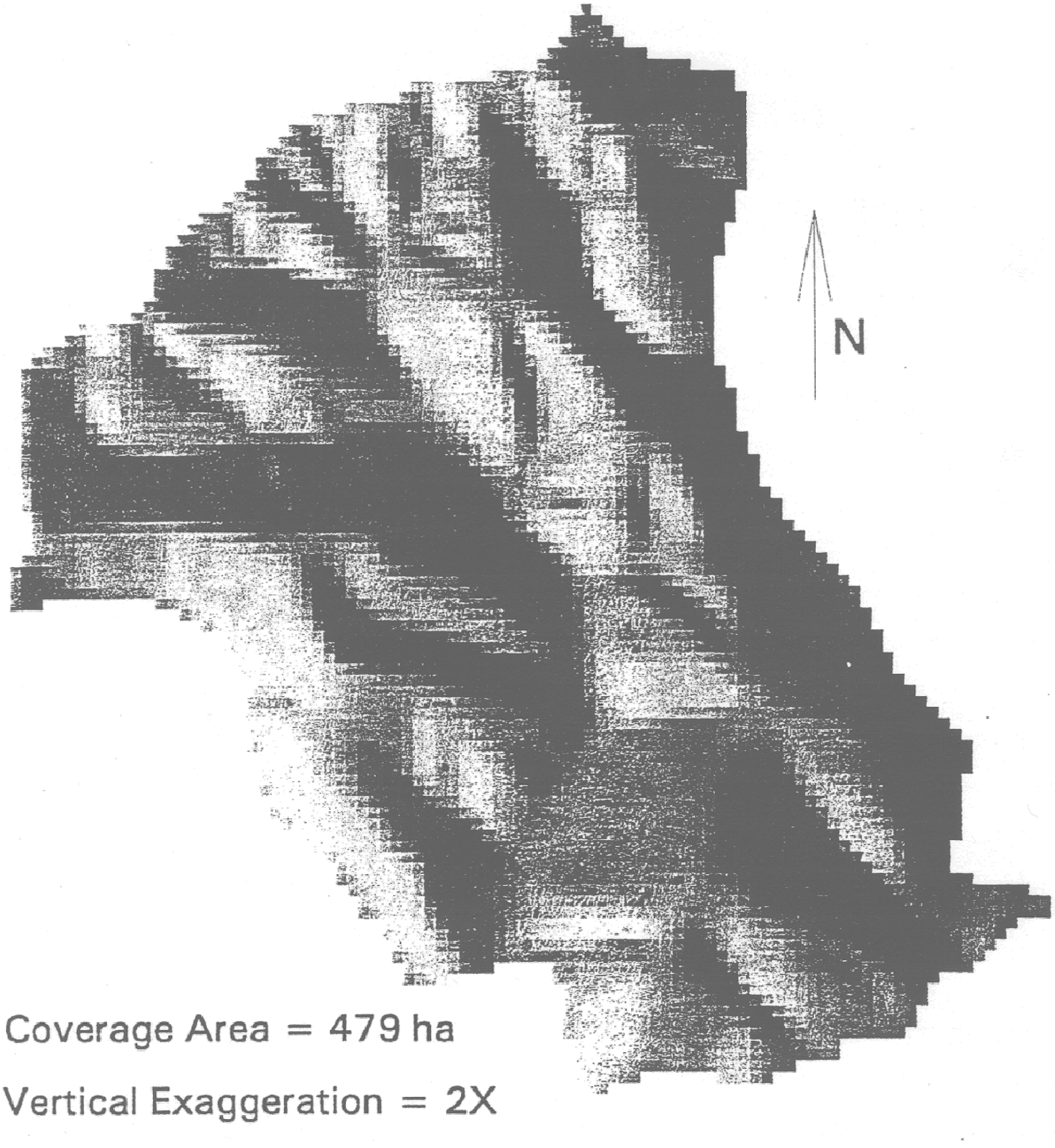

Figure 2.5 Hillshade of Site 4 produced from USGS Level 2 30-m DEM.

Hillshade Produced from **TOPOGRID 7.5**-m DEM

SITE 4

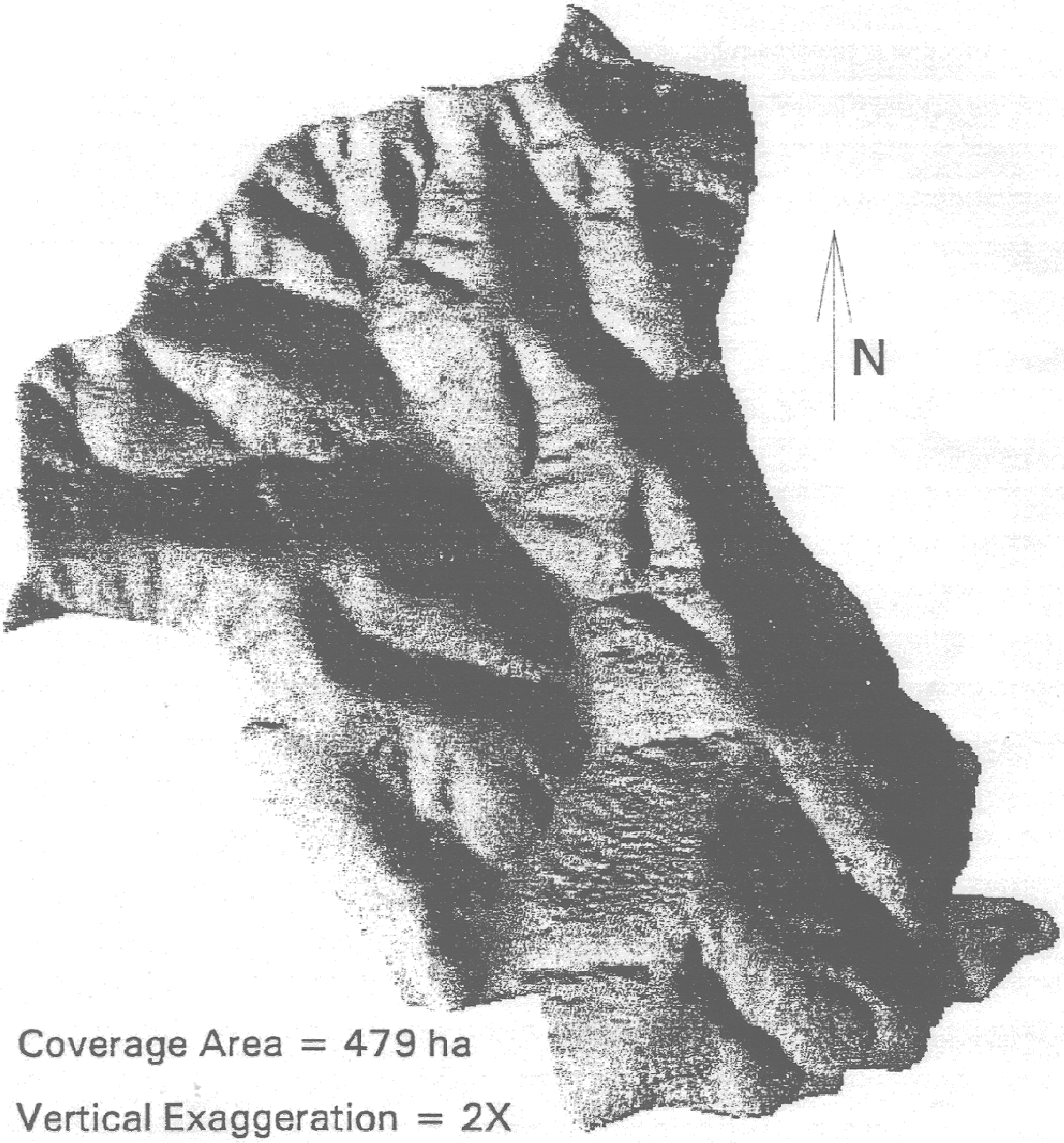

Figure 2.6 Hillshade of Site 4 produced from TOPOGRID 7.5-m DEM.

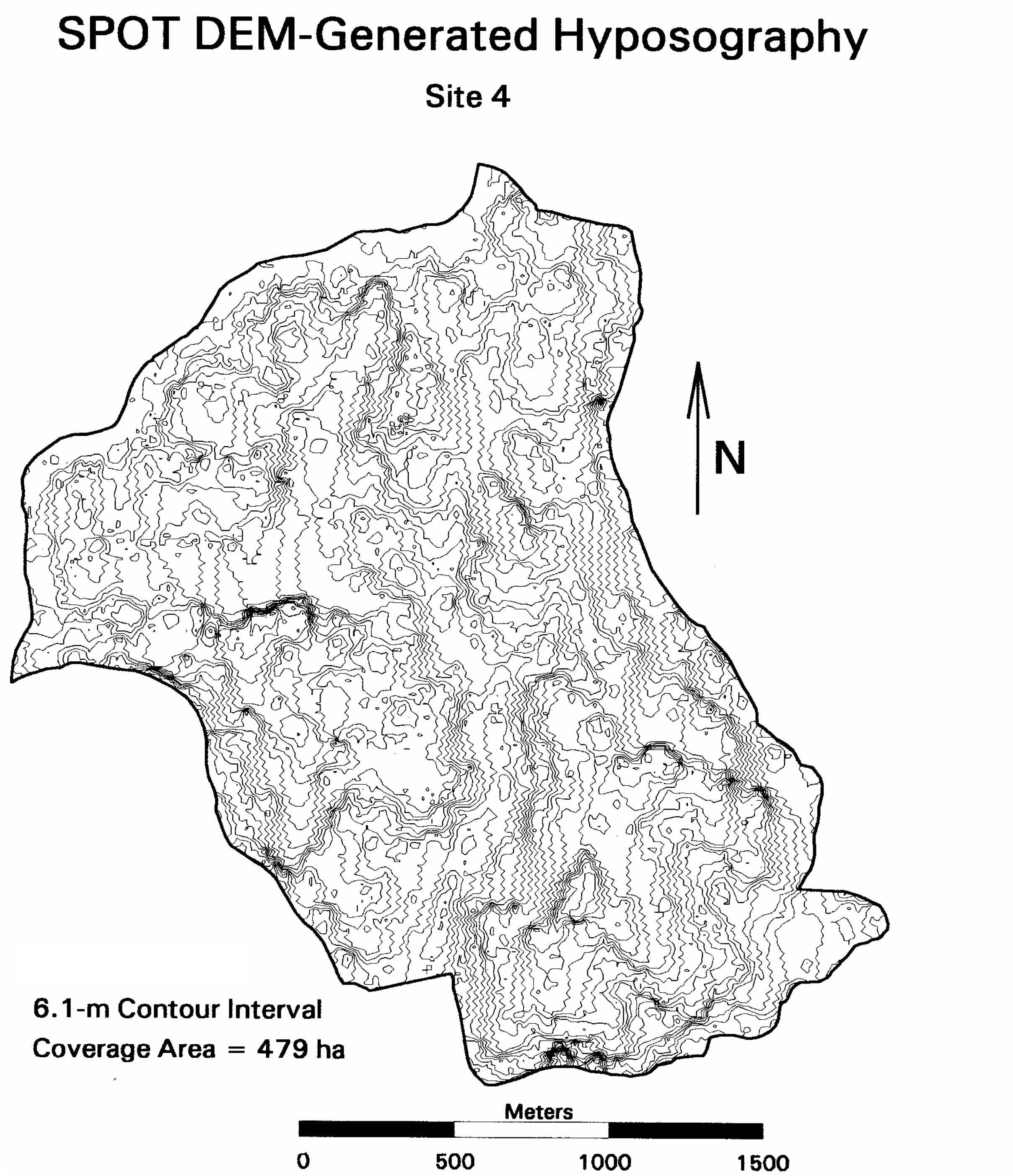

Figure 2.7 Hypsography generated from SPOT 15-m DEM for site 4. The 6.1-m contour interval is the same as the USGS 7.5-minute quadrangle

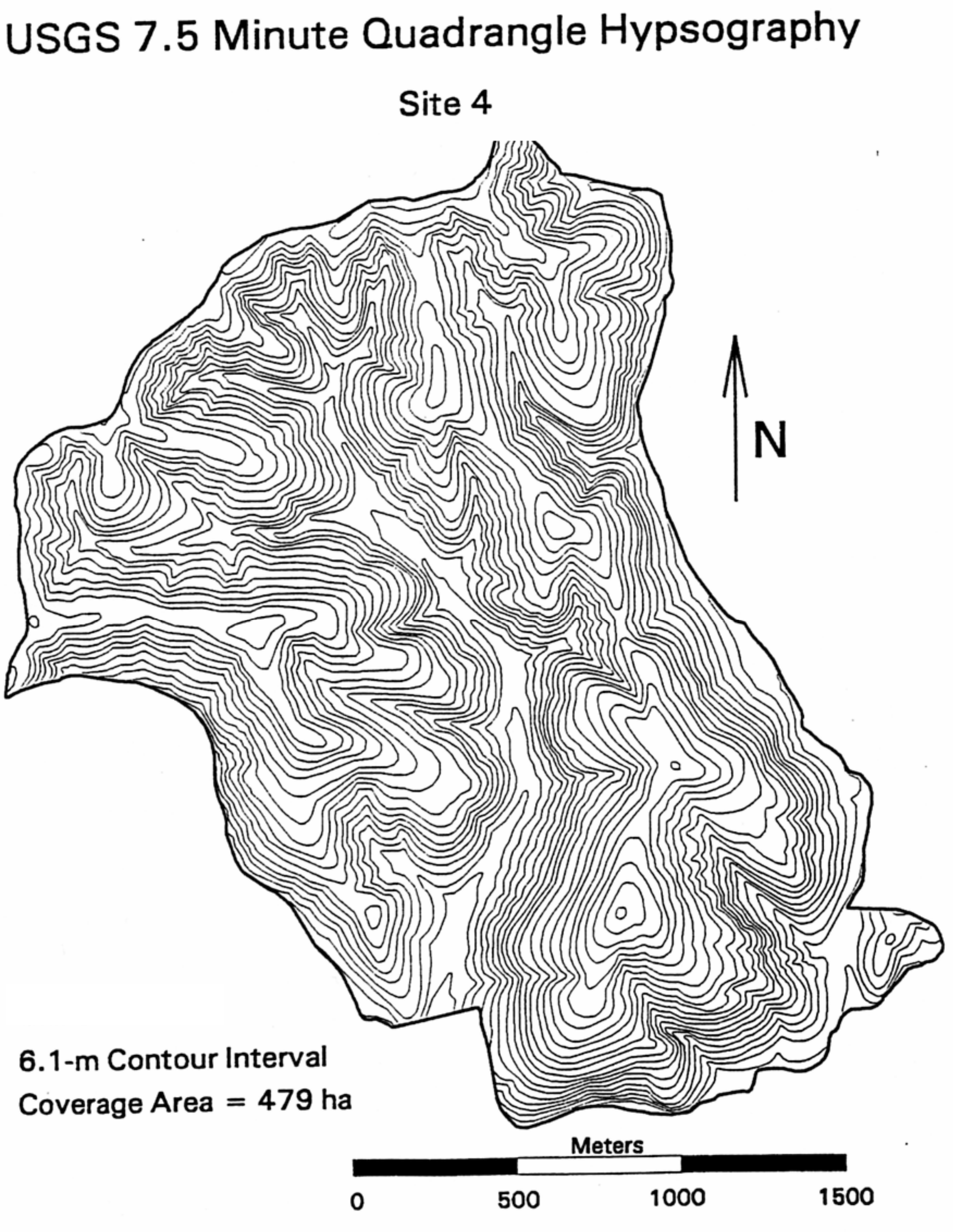

Figure 2.8 Hypsography for site 4 taken from a standard USGS 7.5-minute quadrangle. Contour interval is 6.1-m.

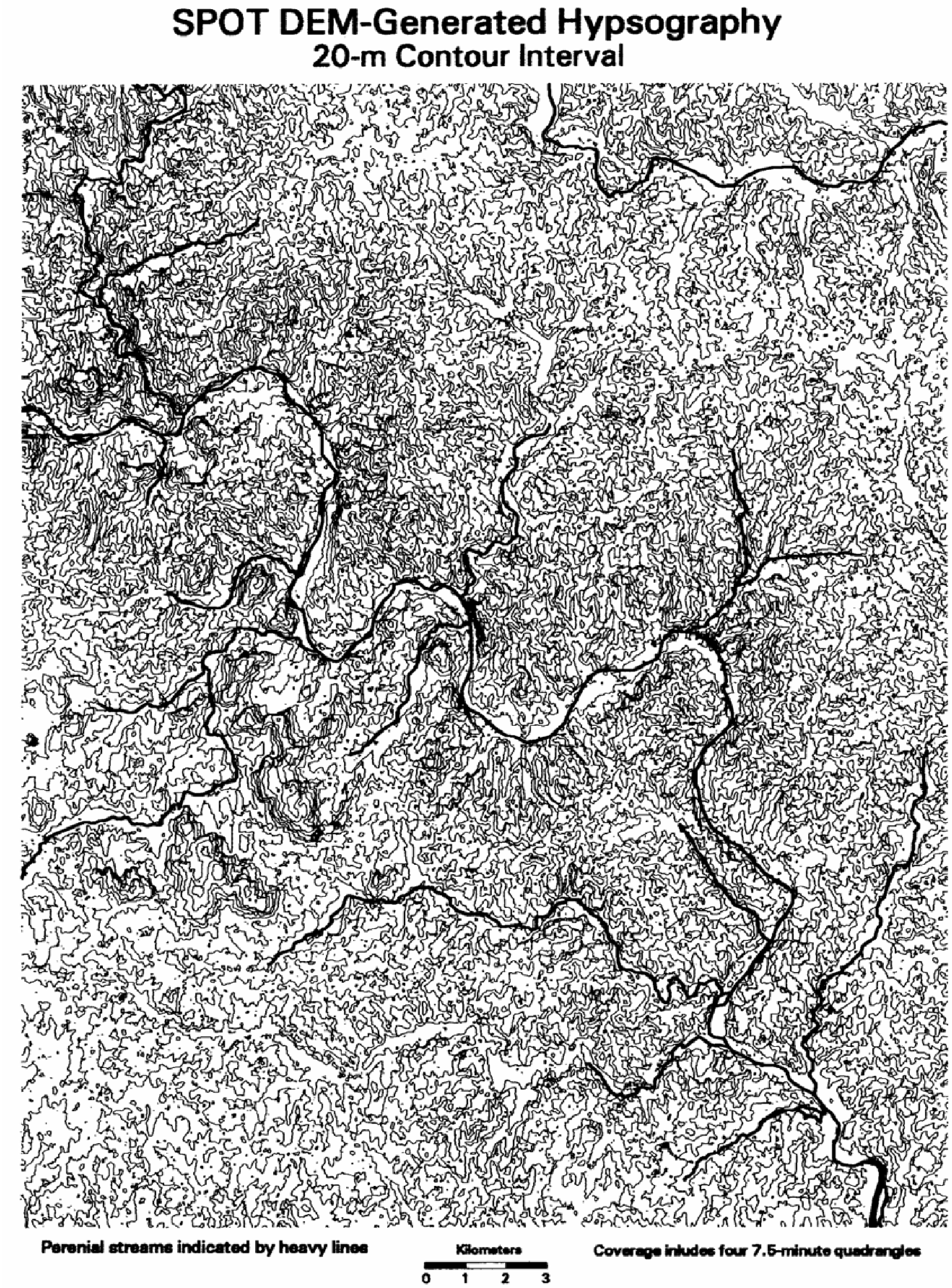

Figure 2.9 Hypsography generated from SPOT 15-m DEM at a 20-m contour interval for the entire study region.

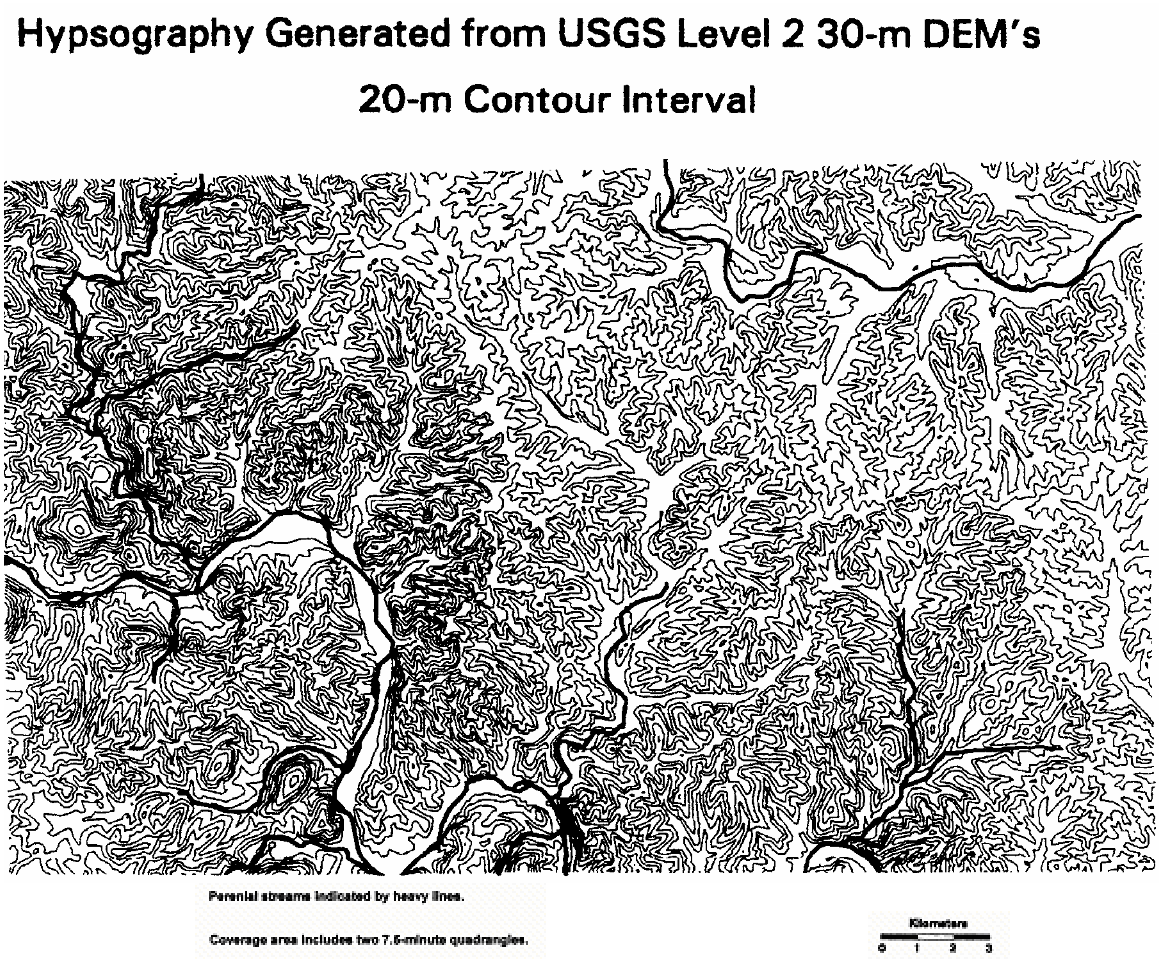

Figure 2.10 Hypsography generated from USGS Level 2 30-m DEM’s with a 20-m contour interval for the northern two quadrangle of study region.

Analysis of Slope Accuracy

Slope maps produced from three DEM's are shown for site 4 (Fig. 2.11, 2.12, and 2.13). Statistics for the residuals are shown in Table 2.4. The three TOPOGRID DEM's and the USGS Level 2 DEM's performed substantially better than the SPOT DEM on sites 5 and 6. The USGS Level 1 DEM performed much better than the SPOT DEM on sites 7, 8 and 9. However, the mean signed and unsigned errors were higher, and Pearson’s correlation coefficient was lower than the three TOPOGRID DEM's and the USGS Level 2 DEM from sites 5 and 6.

The DEM slope data were classified into the appropriate slope classes and compared to the field-determined slope classes (Table 2.5). The strongest agreement with the field slope classes was with the three TOPOGRID DEM's, where between 67.4% and 71.6% agreement was observed. The USGS Level 2 was next in accuracy followed by the SPOT DEM. The USGS Level 1 DEM was more accurate than the SPOT DEM on sites 7, 8 and 9. However, the USGS Level 1 DEM’s agreement with field-determined classes on sites 7, 8 and 9 was lower than all DEM's on sites 5 and 6, except the SPOT DEM.

Table 2.4 Slope error statistics comparing field-measured slopes and DEM-measured slopes.

	Source For Slope Determination						
Sites 5 & 6 n=141	**FIELD**	**USGS-L1**	**USGS-L2**	**TOPO7.5**	**TOPO15**	**TOPO30**	**SPOT**
Mean	24.2	-	23.1	24.7	24.6	24.7	21.4
Mean Signed Error	-	-	1.1	-0.6	-0.4	-0.6	2.7
Mean Unsigned Error	-	-	4.7	5.1	4.4	4.5	13.6
Max. Positive Error	-	-	16	17	16	16	39
Max. Negative Error	-	-	-12	-16	-15	-15	-88
Pearson’s Correlation	-	-	0.81	0.79	0.83	0.82	0.05
Sites 7, 8 & 9 n=139							
Mean	18.3	14.1	-	-	-	-	13.8
Mean Signed Error	-	4.5	-	-	-	-	4.5
Mean Unsigned Error	-	7.2	-	-	-	-	10.8
Max. Positive Error	-	25	-	-	-	-	39
Max. Negative Error	-	-13	-	-	-	-	-46
Pearson’s Correlation	-	0.65	-	-	-	-	0.18

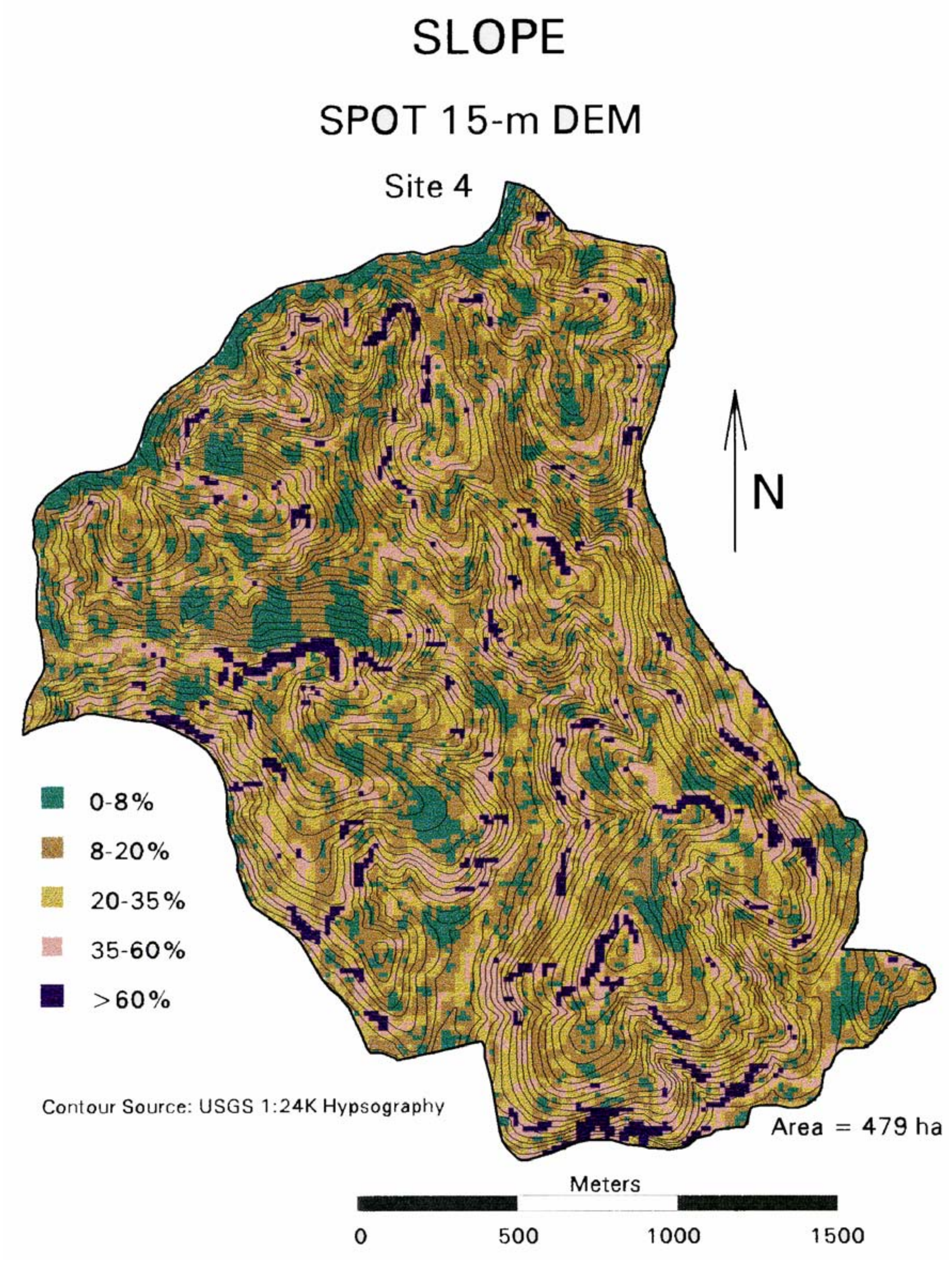

Figure 2.11 Slope classes derived from SPOT 15-m DEM for site 4. USGS 1:24K hypsography is overlayed at contour interval of 6.1-m (20 feet).

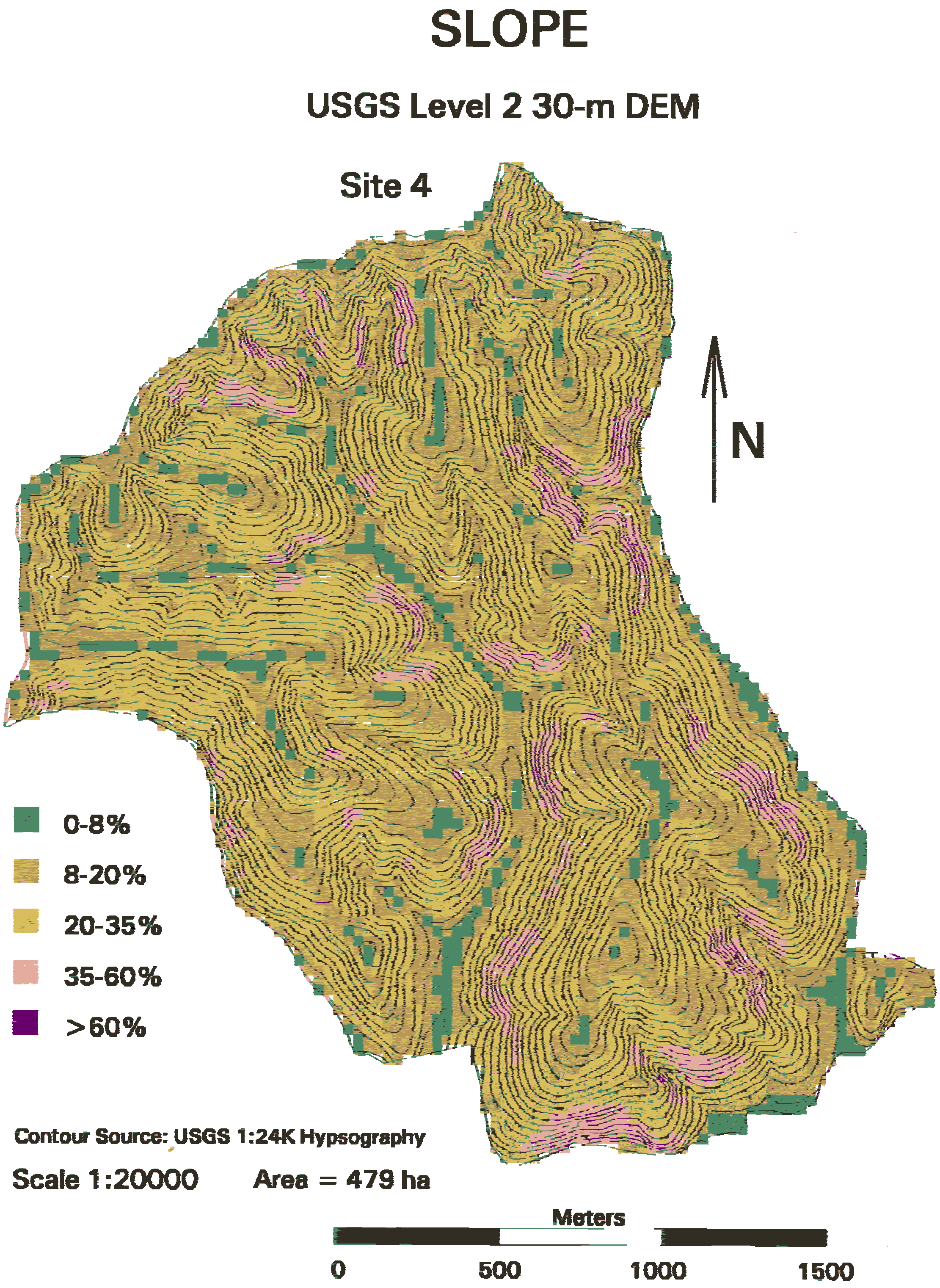

Figure 2.12 Slope classes derived from USGS Level 2 30-m DEM for site 4. USGS 1:24K hypsography is overlayed at contour interval of 6.1-m (20 feet).

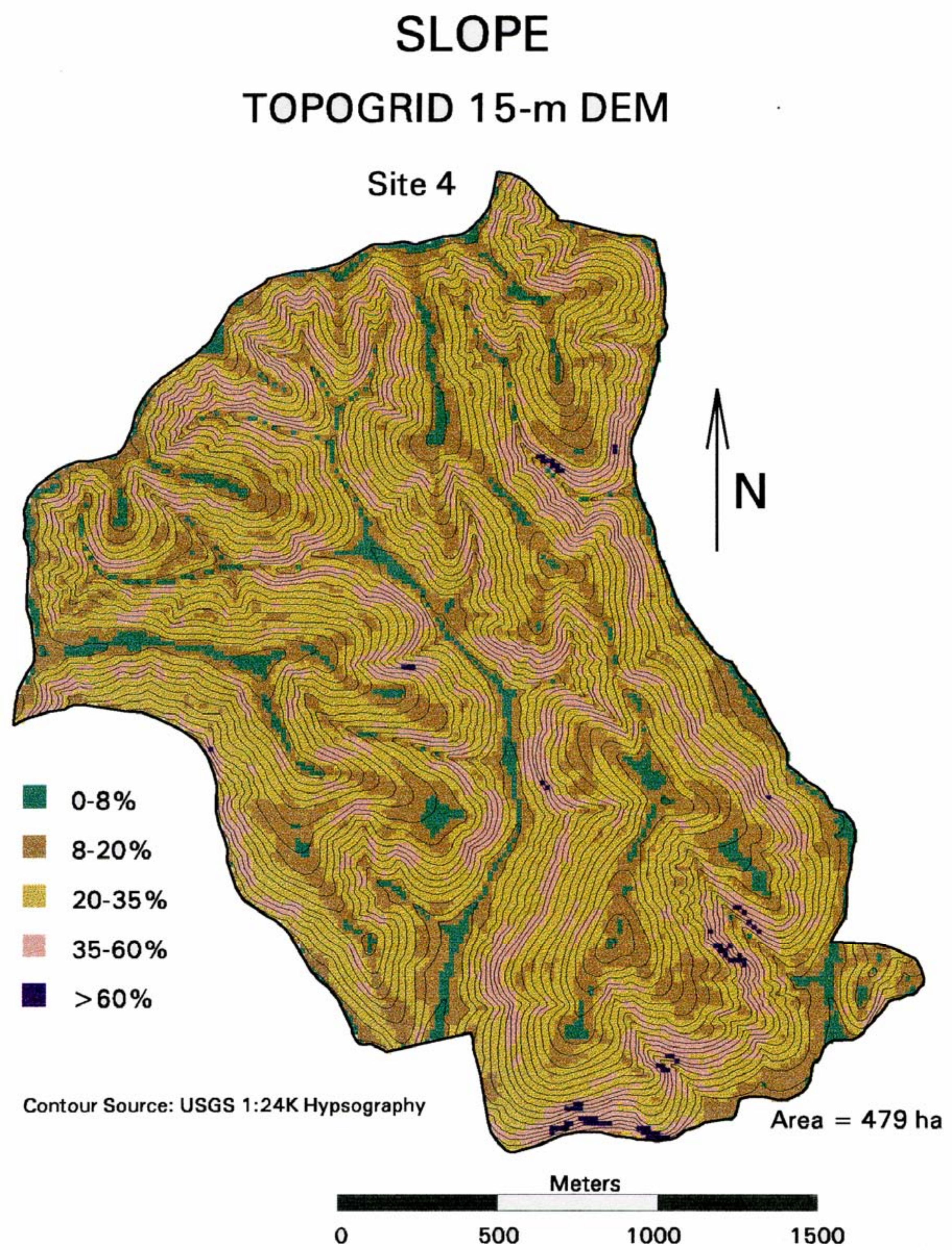

Figure 2.13 Slope classes derived from TOPOGRID 15-m DEM for site 4. USGS 1:24K hypsography is overlayed at contour interval of 6.1-m (20 feet).

Table 2.5 Slope class accuracy. Same class values indicate percent of DEM slope measurements in the same class as field measurements. The class difference columns indicate percent of DEM estimates that occurred at particular class differences from the field-measured DEM. Slope classes are: 0-8%, 8-20%, 20-35%, 35-60%.

Sites 5 & 6	**Source for Slope Determination**					
n=141	**USGS-L1**	**USGS-L2**	**TOPO7.5**	**TOPO15**	**TOPO30**	**SPOT**
	%					
Same Class	-	66.0	67.4	70.9	71.6	32.6
1 Class Difference	-	34.0	32.6	29.1	28.4	47.5
2 Class Difference	-	0.0	0.0	0.0	0.0	16.3
3 Class Difference	-	0.0	0.0	0.0	0.0	2.8
4 Class Difference	-	0.0	0.0	0.0	0.0	0.7
Sites 7, 8 & 9 **n=139**						
Same Class	46.0	-	-	-	-	32.4
1 Class Difference	48.9	-	-	-	-	48.2
2 Class Difference	5.0	-	-	-	-	18.7
3 Class Difference	0.0	-	-	-	-	0.7
4 Class Difference	0.0	-	-	-	-	0.0

Effects of landform characteristics on slope error

Pearson’s correlation value for slope versus slope error shows a strong relationship between slope gradient and slope error for the USGS Level 1 30-m DEM and weaker relationships for the USGS Level 2 30-m DEM and the SPOT DEM’s (Table 2.6). Table 2.7 also indicates greater error with steeper slopes for the USGS DEM’s. Both the USGS level 1 and level 2 DEM’s poorly classified the 35-60% slope classes with only 0.0% and 6.3% of those slope classes correctly classified. The DEM’s tended to perform with the greatest accuracy within the 20-35% slope class on sites 5 and 6 and the 8-20% slope class on sites 7, 8 and 9. Thus, the DEM’s performed best on the most common slope classes.

Table 2.6 Pearson's correlation values showing relationship between slope gradient and slope. Higher values indicate greater slope error on steeper slopes.

		Source For Slope Determination					
Sites	**Observations**	**USGS-L1**	**USGS-L2**	**TOPO7.5**	**TOPO15**	**TOPO30**	**SPOT**
5, 6	141	-	0.64	0.38	0.42	0.41	0.50
7, 8, 9	139	0.83	-	-	-	-	0.65

Table 2.7 Accuracy of DEM slope measurements for each field-measured slope class. Shown is the percent of each class correctly categorized by each DEM.

Sites 5 & 6		Source for Slope Determination					
Slope Class	**Observations**	**USGS-L1**	**USGS-L2**	**TOPO7.5**	**TOPO15**	**TOPO30**	**SPOT**
				%			
0-8%	9	-	44.4	77.8	55.6	55.6	0.0
8-20%	41	-	53.7	51.2	53.7	53.7	53.7
20-35%	75	-	88.0	76.0	85.3	85.3	28.0
35-60%	16	-	6.3	62.5	56.3	62.5	31.3
All slopes	141	-	66.0	67.4	70.9	71.6	33.1
Sites 7, 8 & 9							
0-8%	32	50.0	-	-	-	-	37.5
8-20%	36	86.1	-	-	-	-	47.2
20-35%	65	26.2	-	-	-	-	23.1
35-60%	6	0.0	-	-	-	-	0.0
All slopes	139	46.0	-	-	-	-	31.7

Mean signed errors within each slope class indicate a tendency for the DEM's to generalize the landscape and to overestimate the lower slope classes and underestimate the steeper slope classes (Table 2.8). However, the three TOPOGRID DEM's did not generalize the landscape to the degree of the other DEM's.

The three TOPOGRID DEM's follow a pattern of consistent amount of error, regardless of the slope class (Table 2.9). However the two USGS DEM's and the SPOT DEM from sites 7, 8 and 9 show some increases in error with the higher slope classes. This is consistent with the DEM's relatively high Pearson's correlation values from table 2.6.
The values of the USGS level 2 DEM's mean signed error and mean unsigned error for the 35-60% class were the same at 8.4. This indicates that the DEM consistently underestimated slope for the 35-60% class. While the error is sizable, the consistency of the underestimation indicates that adjustments in models may compensate for this error.

Average slope error associated with the seven most common landforms did not appear to vary significantly between landforms classes (Table 2.10). Landforms that occurred on the most common slope classes were the most accurately determined. The USGS Level 2 30-m DEM performed very poorly on steep backslopes. The USGS Level 2 30-m DEM actually performed better than the TOPOGRID DEM's with regard to slope error if steep backslopes are not included.

Table 2.8 Mean signed errors of slope measurements within each slope class. Values near zero indicate that DEM slope means were similar to field slope means for a given slope class. Positive numbers indicate that the DEM had tendency to underestimate slope and negative values indicate that the DEM had tendency to overestimate slope.

Sites 5 & 6		**Source for Slope Determination**					
Slope Class	**Observations**	**USGS-L1**	**USGS-L2**	**TOPO7.5**	**TOPO15**	**TOPO30**	**SPOT**
				%			
0-8%	9	-	-5.2	-2.9	-3.8	-3.7	-25.5
8-20%	41	-	-2.2	-2.8	-2.4	-2.5	-4.0
20-35%	75	-	2.1	-0.1	0.0	-0.1	8.1
35-60%	16	-	8.4	4.4	4.5	4.3	10.8
All slopes	141	-	1.1	-0.6	-0.4	-0.6	2.7
Sites 7, 8 & 9							
Slope Class							
0-8%	32	-3.8	-	-	-	-	-7.6
8-20%	36	0.3	-	-	-	-	1.2
20-35%	65	9.3	-	-	-	-	10.8
35-60%	6	22.3	-	-	-	-	21.9
All slopes	139	4.5	-	-	-	-	4.5

Table 2.9 Mean unsigned errors of slope measurements within each slope class. Lower values indicate DEM estimates similar to field measurements for a given slope class and high values indicate a greater deviation from the field measurements.

Sites 5 & 6		**Source for Slope Determination**					
Slope Class	**Observations**	**USGS-L1**	**USGS-L2**	**TOPO7.5**	**TOPO15**	**TOPO30**	**SPOT**
				%			
0-8%	9	-	5.2	3.7	4.1	4.1	25.5
8-20%	41	-	3.9	5.3	4.6	4.8	8.1
20-35%	75	-	4.1	5.0	4.1	4.2	13.7
35-60%	16	-	8.4	4.7	5.3	5.0	19.2
All slopes	141	-	4.7	5.1	4.4	4.5	13.6
Sites 7, 8 & 9							
Slope Class							
0-8%	32	4.2	-	-	-	-	8.2
8-20%	36	3.6	-	-	-	-	8.8
20-35%	65	9.5	-	-	-	-	12.5
35-60%	6	22.3	-	-	-	-	21.9
All slopes	139	7.2	-	-	-	-	10.8

Table 2.10 Accuracy of DEM slope measurements for seven common landforms. Shown is percent of correctly classified DEM slope measurements in each landform class.

Sites 5 & 6			**Source for Slope Determination**					
Landform Class	**Slope Class**	**Observations**	**USGS-L1**	**USGS-L2**	**TOPO7.5**	**TOPO15**	**TOPO30**	**SPOT**
			%					
Floodplain	**0-8%**	3	-	100.0	66.7	66.7	66.7	0.0
Backslope	**20-35%**	77	-	88.3	76.6	85.7	85.7	28.6
Steep Backslope	**35-60%**	16	-	6.3	62.5	56.3	62.5	31.3
Sloping Bench	**8-20%**	22	-	54.5	54.5	54.5	54.5	50.0
Shoulder	**8-20%**	4	-	75.0	75.0	75.0	75.0	75.0
Narrow Ridge	**8-20%**	11	-	54.5	45.5	45.5	45.5	45.5
Broad Summit	**0-8%**	5	-	20.0	80.0	60.0	60.0	0.0
All Landforms	**All**	138	-	67.6	69.1	71.9	72.7	33.1
Sites 7, 8 & 9								
Floodplain	**0-8%**	7	57.1	-	-	-	-	57.1
Backslope	**20-35%**	65	26.2	-	-	-	-	23.1
Steep Backslope	**35-60%**	6	0.0	-	-	-	-	0.0
Sloping Bench	**8-20%**	6	83.3	-	-	-	-	66.7
Shoulder	**8-20%**	14	85.7	-	-	-	-	50.0
Narrow Ridge	**8-20%**	14	85.7	-	-	-	-	42.9
Broad Summit	**0-8%**	19	47.4	-	-	-	-	31.6
All Landforms	**All**	131	44.4	-	-	-	-	31.9

* Totals (All Landforms) differ slightly from values in tables 2.5 (same class column) and 2.7 (all landforms column) because three observations from sites 5 and 6 and eight observations from sites 7, 8 and 9 occurred on less frequent landforms are not used in this comparison.

The directions (positive or negative) of slope errors were strongly related to the slope of each landform (Table 2.11). All DEM's tended to overestimate slopes of floodplains. The three TOPOGRID DEM's show no tendencies of under- or overestimating slope gradient for backslope positions. However, the USGS Level 2 30-m DEM had a slight tendency to underestimate slope and the USGS Level 1 30-m DEM and the SPOT DEM had strong tendencies to underestimate slope in backslope positions. Benches, shoulders, narrow ridges and broad ridges all tended to be overestimated by the DEM's.

Table 2.11 Mean signed errors of DEM slope measurements within each landform class. Values near zero indicate that DEM slope means were similar to field slope means for a given landform class. Positive numbers indicate that the DEM tended to underestimate slope and negative values indicate that the DEM tended to overestimate slope.

Sites 5 & 6			**Source for Slope Determination**					
Landform Class	**Slope Class**	**Observations**	**USGS-L1**	**USGS-L2**	**TOPO7.5**	**TOPO15**	**TOPO30**	**SPOT**
			%					
Floodplain	**0-8%**	3	-	-4.2	-4.0	-5.0	-5.0	-23.6
Backslope	**20-35%**	77	-	1.9	0.4	-0.2	-0.4	7.9
Steep Backslope	**35-60%**	16	-	8.4	4.4	4.5	4.3	10.8
Sloping Bench	**8-20%**	22	-	-2.2	-3.0	-2.7	-2.8	-1.6
Shoulder	**8-20%**	4	-	-2.0	-4.6	-2.5	-2.8	-5.3
Narrow Ridge	**8-20%**	11	-	-2.7	-0.6	-1.2	-1.3	-9.9
Broad Summit	**0-8%**	5	-	-5.8	-2.7	-3.3	-3.3	-30.6
All Landforms	**All**	138	-	1.1	-0.5	-0.4	-0.6	2.8
Sites 7, 8 & 9								
Floodplain	**0-8%**	7	-4.9	-	-	-	-	-4.5
Backslope	**20-35%**	65	9.3	-	-	-	-	10.8
Steep Backslope	**35-60%**	6	22.3	-	-	-	-	21.9
Sloping Bench	**8-20%**	6	-3.6	-	-	-	-	3.1
Shoulder	**8-20%**	14	1.5	-	-	-	-	-1.8
Narrow Ridge	**8-20%**	14	0.0	-	-	-	-	1.5
Broad Summit	**0-8%**	19	-3.1	-	-	-	-	-8.3
All Landforms	**All**	131	4.8	-	-	-	-	4.9

*Totals (All Landforms row) differ slightly from mean signed error values in tables 2.4 (mean signed error column) and 2.8 (all landforms column) because three observations from sites 5 and 6 and eight observations from sites 7, 8 and 9 occurred on landforms not used in this comparison.

Mean unsigned errors of the USGS Level 2 and the TOPOGRID DEM’s were similar, while increased mean unsigned errors occurred with the other DEM’s (Table 2.12). Mean unsigned errors were not larger at particular landscape positions for most of the DEM’s. However, note that for landforms with narrow slope ranges, mean unsigned errors are a more significant problem. For example, a 4% error associated with the backslope landforms, which have large slope ranges (20-35% and 35-60%), is less critical than the same 4% error associated with landforms that have narrow slope ranges such as summits and floodplains (0-8%).

Table 2.12 Mean unsigned errors of slope measurements within each landform class. Low values indicate DEM estimates similar to field measurements for a given landform class and high values indicate a greater deviation from the field values.

Sites 5 & 6			Source for Slope Determination					
Landform Class	**Slope Class**	**Observations**	**USGS-L1**	**USGS-L2**	**TOPO7.5**	**TOPO15**	**TOPO30**	**SPOT**
			m					
Floodplain	**0-8%**	3	-	4.2	5.4	5.0	5.0	23.6
Backslope	**20-35%**	77	-	4.2	5.2	4.2	4.3	13.7
Steep Backslope	**35-60%**	16	-	8.4	4.7	5.3	5.0	19.2
Sloping Bench	**8-20%**	22	-	3.4	4.9	4.4	4.5	6.3
Shoulder	**8-20%**	4	-	3.6	4.6	2.5	2.8	5.3
Narrow Ridge	**8-20%**	11	-	4.1	4.6	4.7	4.7	12.3
Broad Summit	**0-8%**	5	-	5.8	3.3	4.0	4.0	30.6
All Landforms	**All**	138	-	4.6	5.0	4.4	4.4	13.6
Sites 7, 8 & 9								
Floodplain	**0-8%**	7	4.9	-	-	-	-	4.8
Backslope	**20-35%**	65	9.5	-	-	-	-	12.5
Steep Backslope	**35-60%**	6	22.3	-	-	-	-	21.9
Sloping Bench	**8-20%**	6	4.5	-	-	-	-	4.9
Shoulder	**8-20%**	14	3.9	-	-	-	-	10.5
Narrow Ridge	**8-20%**	14	2.6	-	-	-	-	8.2
Broad Summit	**0-8%**	19	3.7	-	-	-	-	9.3
All Landforms	**All**	131	7.4	-	-	-	-	11.0

*Totals(All Landforms row) differ from mean unsigned error values in tables 2.4 (mean unsigned error column) and 2.9 (all slopes column) because three observations from sites 5 and 6 and eight observations from sites 7, 8 and 9 occurred on landforms not used in this comparison.

Analysis of Aspect Accuracy

USGS Level 2 and TOPOGRID DEM's portray more realistic displays of aspect than the SPOT DEM's (Fig. 2.14, 2.15, and 2.16). Statistics for the aspect residuals are in table 2.13. Mean unsigned error values were smaller for the TOPOGRID DEM's and the USGS Level 2 DEM than the SPOT DEM on sites 5 and 6. The mean unsigned residuals were smaller on sites 7, 8 and 9 for the USGS Level 1 DEM than the SPOT DEM. However, the USGS level 1 DEM had a larger mean unsigned error than the USGS level 2 and TOPOGRID DEM's from sites 5 and 6. Pearson's correlation value did not always indicate the same relative degree of precision as the other indices. Curiously, the value for the TOPOGRID 7.5-m DEM was 0.56. The Pearson's correlation values are not consistent with the other aspect data, most likely because the aspect data are circular (0 to 360°) rather than linear. For example, a field value of 5° and a DEM value of 355° are relatively similar values, but would not be considered as such for Pearson's correlation calculation.

Results from determination of aspect class accuracy are similar to those that found with slope class accuracy in the order TOPOGRID 15-m > TOPOGRID 30-m > TOPOGRID 7.5-m > USGS level 2 > USGS level 1 > SPOT DEM (Table 2.14). The SPOT DEM placed 16.2% of the plots in slope classes that were two classes different than determined by the field measurements - the maximum error possible.

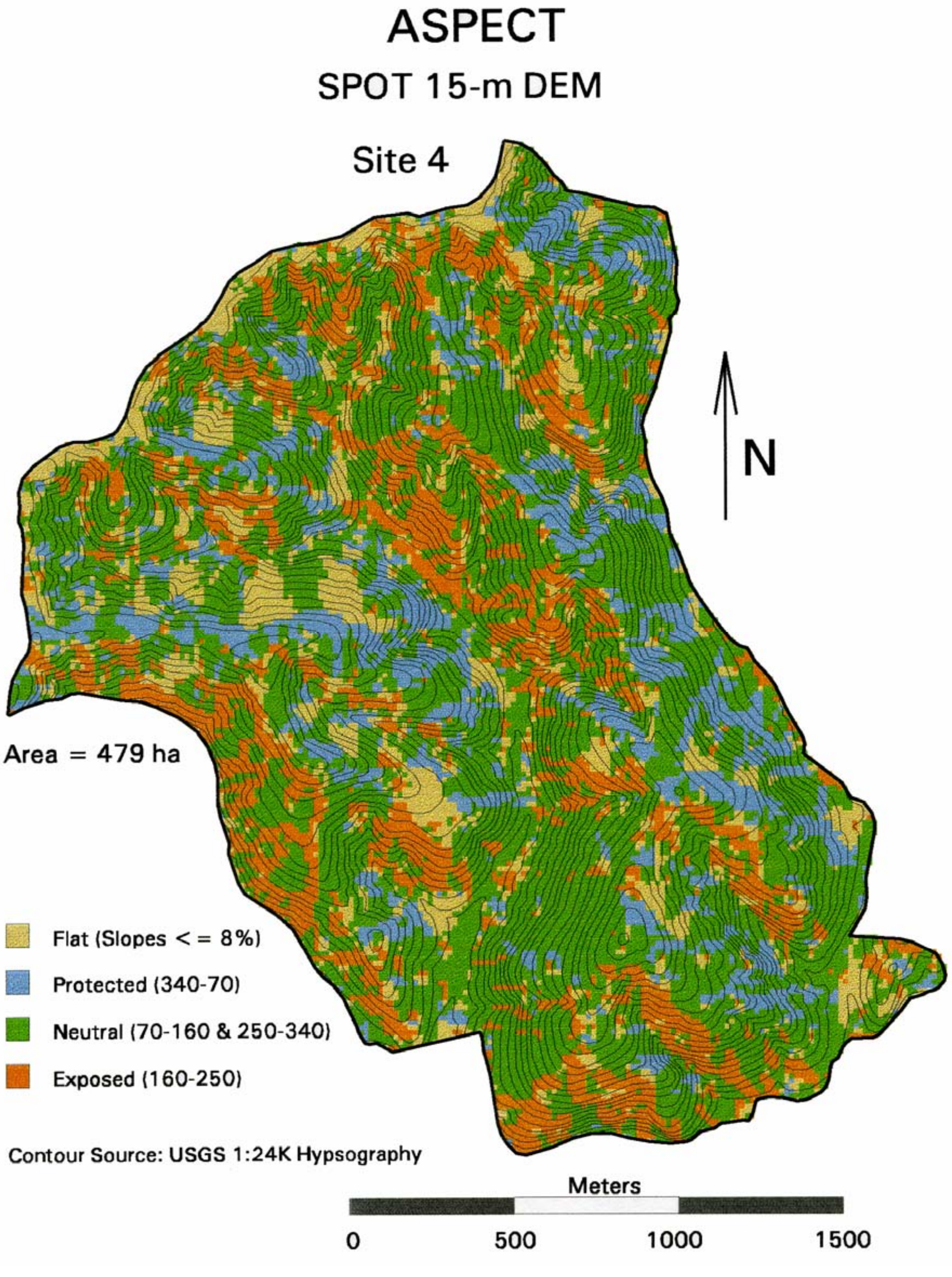

Figure 2.14 Aspect classes derived from SPOT 15-m DEM for site 4. USGS 1:24K hypsography is overlayed at contour interval of 6.1-m (20 feet).

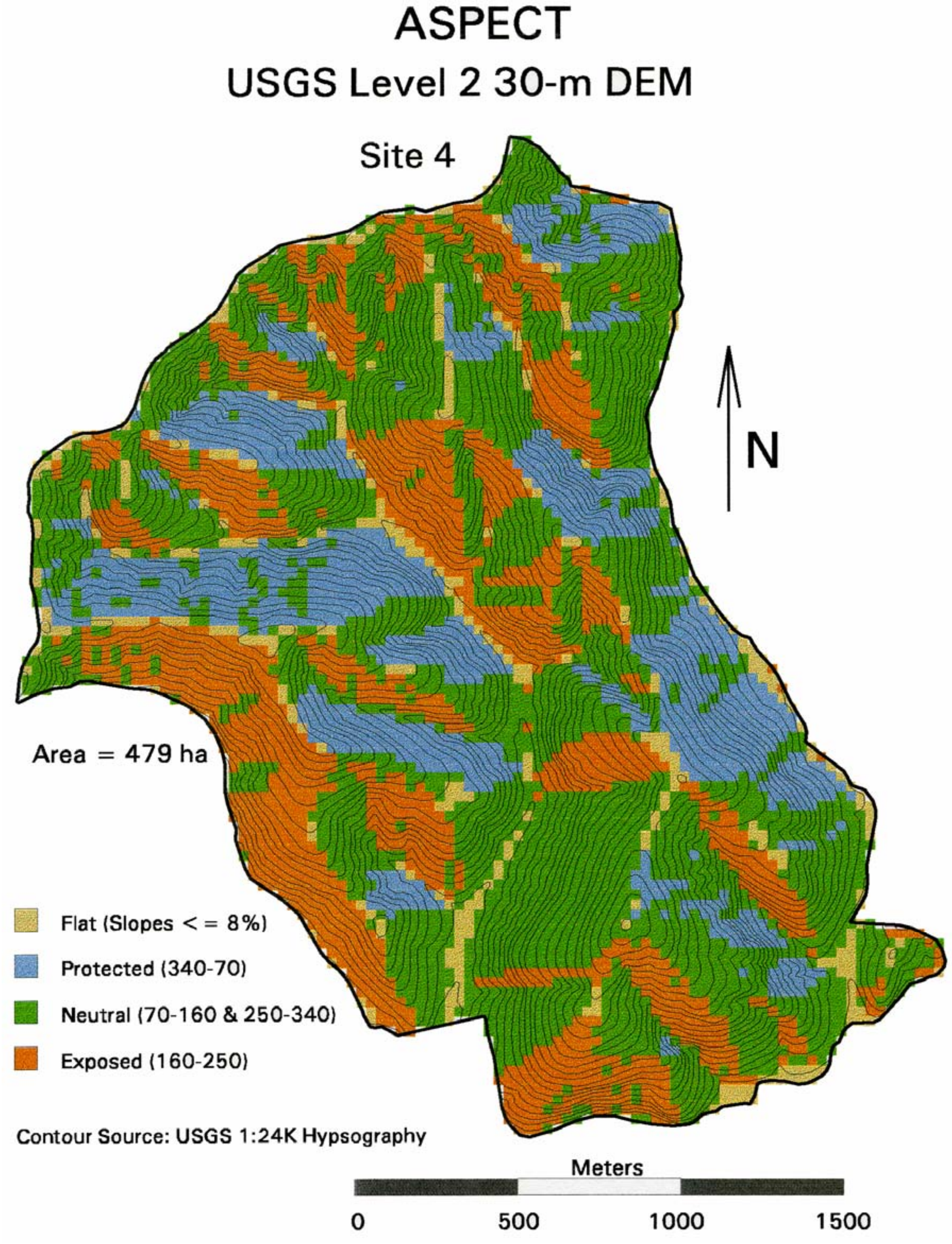

Figure 2.15 Aspect classes derived from USGS Level 2 30-m DEM for site 4. USGS 1:24K hypsography is overlayed at contour interval of 6.1-m (20 feet).

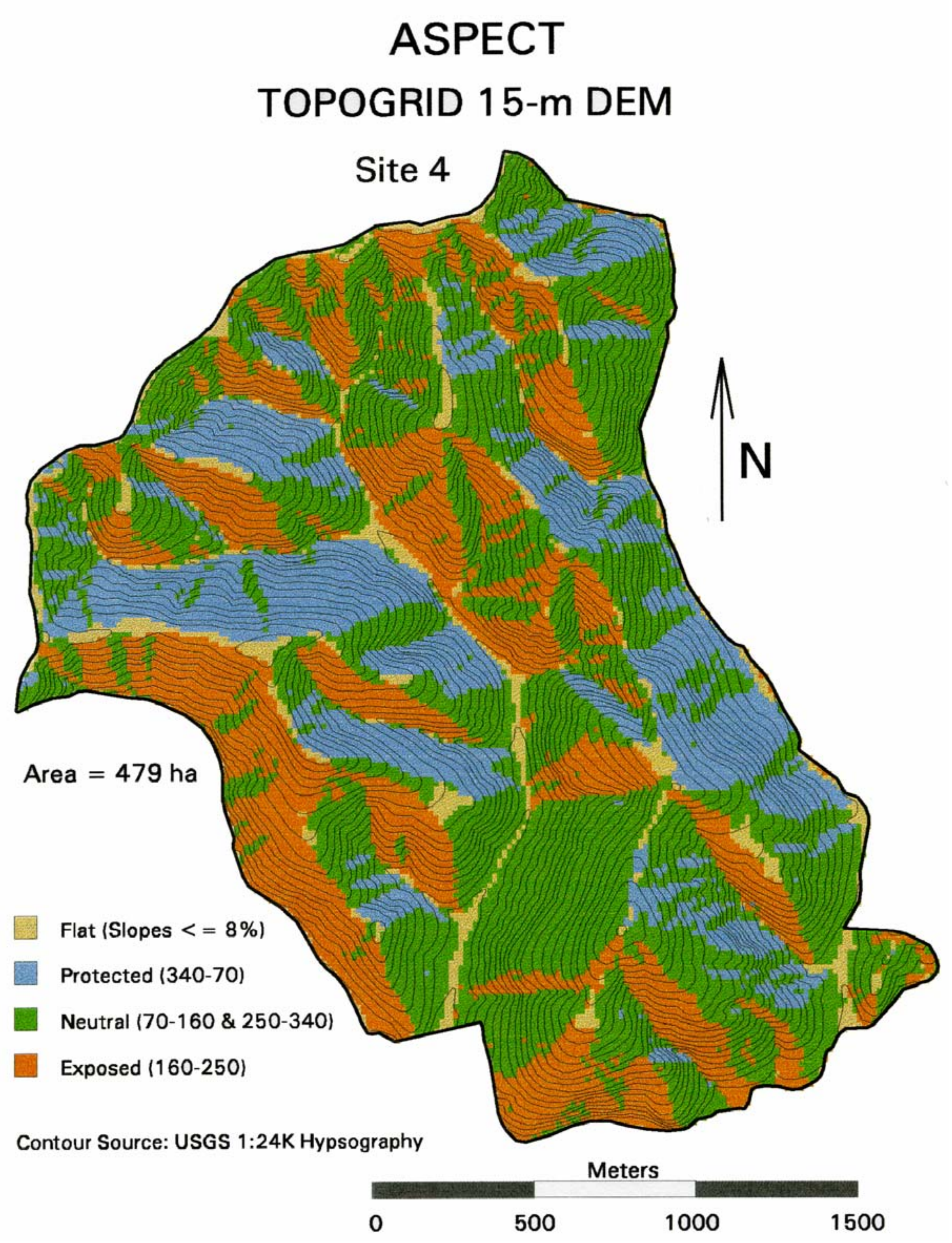

Figure 2.16 Aspect classes derived from TOPOGRID 15-m DEM for site 4. USGS 1:24K hypsography is overlayed at contour interval of 6.1-m (20feet).

Table 2.13 Aspect error statistics comparing field-measured aspect and DEM-measured aspect.

	Source For Aspect Determination						
Sites 5 & 6 **n=141**	**FIELD**	**USGS-L1**	**USGS-L2**	**TOPO7.5**	**TOPO15**	**TOPO30**	**SPOT**
Mean	179.0	-	195	190	189	188	198
Mean Unsigned Err.	-	-	20.5	19.4	20.2	20.8	51.1
Maximum Error.	-	-	157	112	132	130	177
Pearson's Correlation	-	-	0.69	0.56	0.65	0.67	0.59
Sites 7, 8 & 9 **n=139**							
Mean	195.2	200.3	-	-	-	-	187.6
Mean Unsigned Err.	-	26.8	-	-	-	-	55.0
Maximum Error	-	177	-	-	-	-	176
Pearson's Correlation	-	0.72	-	-	-	-	0.47

Table 2.14 Aspect class accuracy. Same class values indicates percent of DEM aspect measurements in the same class as field measurements. The class difference columns indicate percent of DEM estimates that occurred at particular class differences from the field-measured DEM. Aspect classes are: Protected (340°-70°), Neutral East (70°-160°), Exposed (160°-250°), and Neutral West (250°-340°).

	Source for Aspect Determination					
Sites 5 & 6 **n=141**	**USGS-L1**	**USGS-L2**	**TOPO7.5**	**TOPO15**	**TOPO30**	**SPOT**
Same Class	-	78.5	83.1	84.6	83.8	47.7
1 Class Difference	-	14.6	13.8	12.3	12.3	36.2
2 Class Difference	-	7.0	3.1	3.1	3.9	16.2
Sites 7, 8 & 9 **n=139**						
Same Class	73.1	-	-	-	-	45.4
1 Class Difference	21.3	-	-	-	-	43.5
2 Class Difference	5.5	-	-	-	-	11.1

Supervised Landform Classification Accuracy

Supervised classifications for all of the DEM's except the USGS Level 1 30-m DEM were performed on sites 3 and 4 (Figures 2.17 - 2.19). The supervised classification created with the TOPOGRID 30-m DEM had the best agreement with the field survey, followed closely by the USGS Level 2 DEM and the TOPOGRID 15-m DEM (Table 2.15). The TOPOGRID 7.5-m DEM had lower agreement with the field survey than the 15 and 30-m DEM's. Two possible explanations exist. The DEM's at 7.5-m resolution, produced from 6.1-m (20 feet) contour intervals, are finer than the resolution of the input data in all areas of the study region, except for areas with extremely steep slopes. Attributes created in this situation can produce unreliable data. For example, observation of a surface curvature map from a 7.5-m DEM shows more convexities in bands where contour lines existed, and more concavities occurring on areas in between the contour lines. This scenario would contribute to the misclassification of cells with the supervised classification, and a situation which not only produces unnecessary data replication, but also creates false data. The second possible explanation is that the 7.5-m DEM, when it does create more detailed data than what is created at coarser DEM's (i.e., areas of dense contour lines), contains information that is more detailed than that used in the field survey. In this case, the terrain model might class some cells at a finer resolution than even a detailed field survey.

Table 2.15 Agreement of Supervised Classifications performed using different DEM sources with the field survey classifications. The interior portions of field survey delineations were used as training sites for the supervised classifications.

DEM Source	**Agreement With Field Survey (%)**
SPOT 15-m	54.3
TOPOGRID 7.5-m	67.4
TOPOGRID 15-m	70.7
TOPOGRID 30-m	71.4
USGS Level 2 30-m	70.8

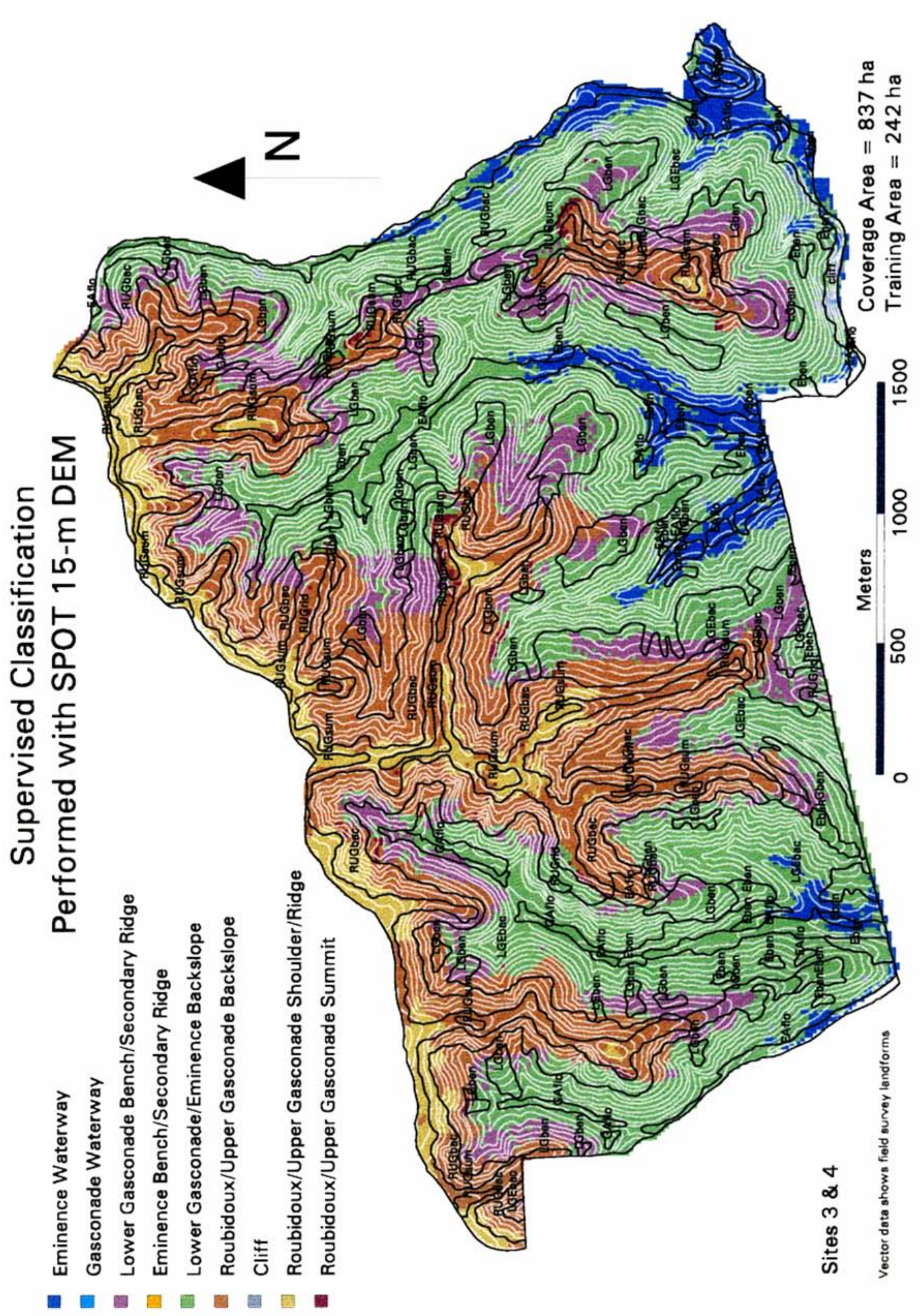

Figure 2.17 Supervised Classification performed with SPOT 15-m DEM data. Color-coded data shows supervised classification landforms and vector data shows field survey landforms.

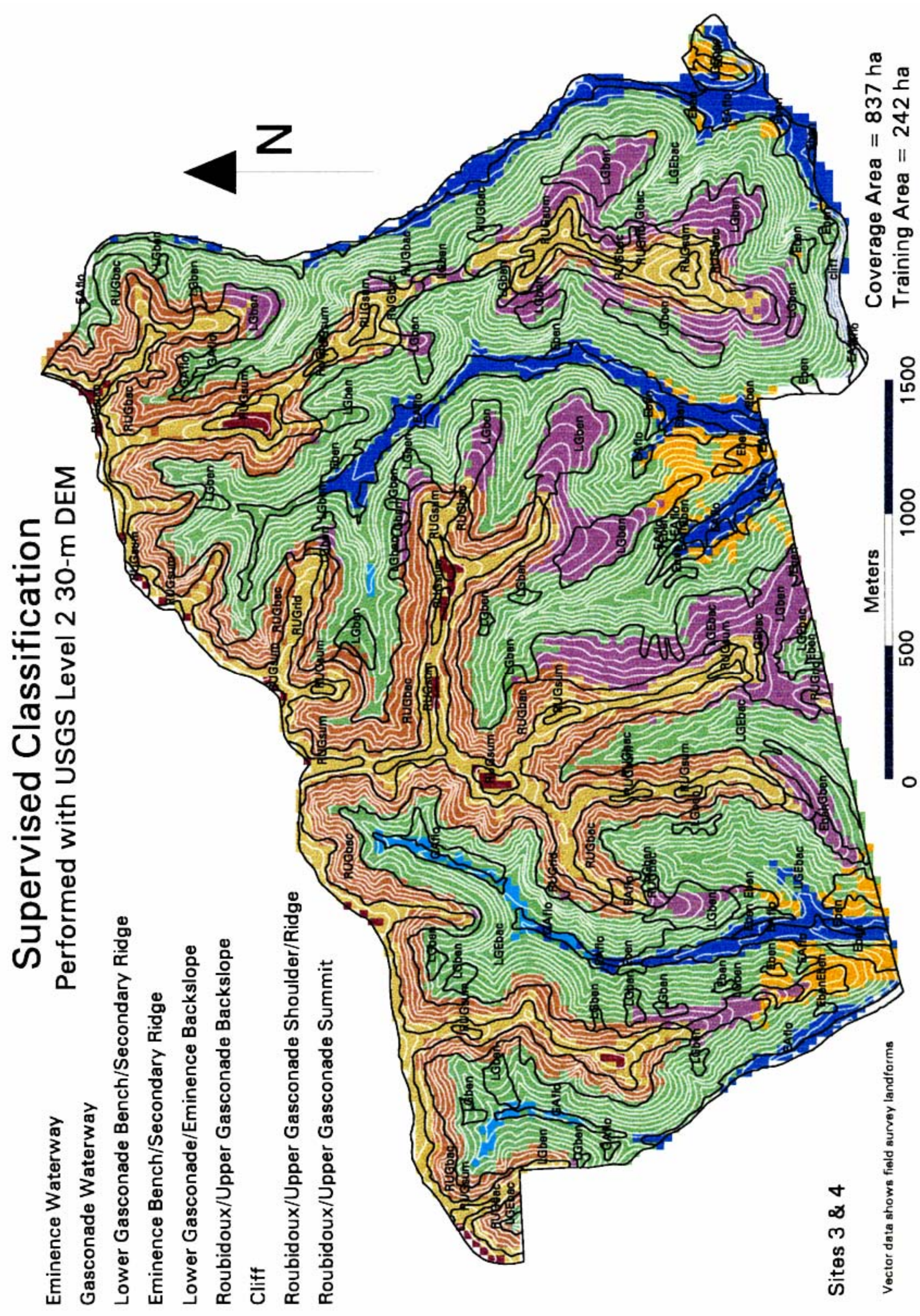

Figure 2.18 Supervised Classification performed with USGS Level 2 30-m DEM data. Color-coded data shows supervised classification landforms and vector data shows field survey landforms.

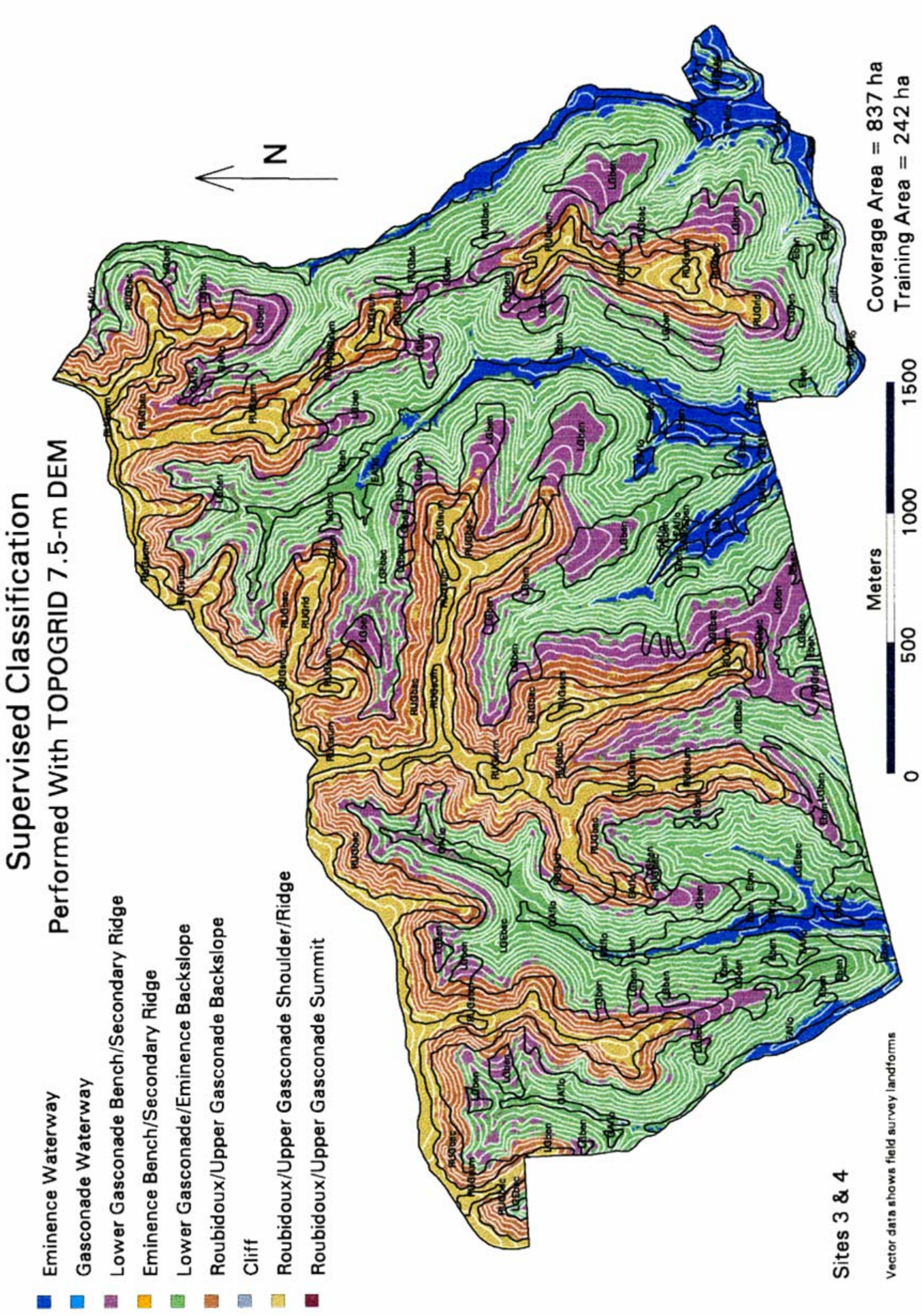

Figure 2.19 Supervised Classification performed with TOPOGRID 7.5-m DEM data. Color-coded data shows supervised classification landforms and vector data shows field survey landforms.

CONCLUSIONS

Visual displays of the landscape were generally similar with respect to the TOPOGRID and USGS level 2 DEM's. The visual display of the USGS level 1 DEM’s did not portray the landscape so well as the TOPOGRID and USGS level 2 DEM's. Some displays with the finer-scaled 7.5-m and 15-m DEM's are more aesthetically pleasing than those with larger cell sizes.

The DEM's that consistently produced strongest correlation with the field slope data were the TOPOGRID 15 and 30-m DEM's. The USGS level 2 DEM’s generally performed at an accuracy level slightly lower than the TOPOGRID 15 and 30-m DEM's and were relatively similar to the 7.5-m DEM. However, if steep backslopes (35-60% slopes) are not included in the comparison, the accuracy of the USGS Level 2 DEM’s is similar to the TOPOGRID 15 and 30-m DEM’s. The USGS level 1 DEM was less accurate than all DEM's except for the SPOT DEM. There was a tendency among all DEM’s to overestimate slope values for flatter slope classes and underestimate values for steeper slope classes. This tendency to generalize the landscape has been observed by other investigators with USGS 30-m DEM’s (Thompson et al., 2001).

The DEM's with strongest agreement with the field aspect data were the three TOPOGRID DEM's (83.5 to 84.6% in the correct aspect class), followed by the USGS level 2 DEM (78.5% in the correct aspect class). The SPOT DEM was least accurate on nearly all slope and aspect accuracy tests.

A supervised classification produced with the TOPOGRID 30-m DEM agreed most strongly with the field survey, followed closely by the USGS level 2 DEM and the TOPOGRID 15-m DEM. This example implies that finer-scaled DEM's are not necessarily better if the resolution is finer than the input data (the hypsography information) and if the resolution is finer than the phenomena that one is attempting to model.

The SPOT DEM shows landscape features only at the coarsest scales. At scales necessary to understand and model landforms, these data do not appear useful. Potential uses are difficult to visualize, even if the study region had no existing topographic databases. Systematic errors that could be corrected to make the DEM more useful for analyzing landscapes are not apparent. The observed accuracy difference between the USGS Level 1 30-m DEM and the SPOT DEM is much greater in this investigation than the study reported by Bolstad and Stowe (1994). The techniques and algorithms used by Autometric, Inc. may not have been appropriate or accurate. Experiences from this project suggest that potential users of SPOT-based DEM's should proceed with extreme caution.

The accuracy problems with SPOT DEM data shift the focus to the other sources for DEM's. These analyses suggest that if quality vector contour and hydrology information is available, the TOPOGRID module in Arc/Info would produce more accurate results than USGS Level 2 30-m DEM's, and USGS Level 1 30-m. In addition, improved techniques such as newer versions of the ANUDEM program (earlier versions of which were used as a basis for Arc/Info’s TOPOGRID program), appear to offer some improvements over the Arc/Info 7.0 TOPOGRID program. The drawbacks are that the DLGs are required and these are not yet as available as the USGS level 1 and 2 DEM's. The TOPOGRID DEM's, and other programs to create DEM’s from DLG information, require more time to produce. The module is slow, the stream data require editing, and the DEM must be tested with different parameters. For example, early efforts at creating DEM's without the stream data and without experimenting with different parameters resulted in DEM's of less accuracy than the USGS Level 2 DEM's. A user may decide that the possible increase in accuracy is not worth the increase in data processing time. While the USGS level 2 30-m DEM’s do appear acceptable in this research, the USGS level 1 30-m DEM’s appear to lack the detail necessary for intermediate scale applications. This finding reinforces other research by Hammer et al.

(1995) and Klingebiel et al. (1987) that showed the Level 1 DEM's have limited value for 2nd order soil surveys.

This project used some analyses similar to Bolstad and Stowe (1994), however, the results of the USGS Level 1 DEM and the SPOT DEM in this study are not as accurate as they reported. Shortcomings with the SPOT DEM used in this study are one obvious factor in the differences. Another factor that affects both the SPOT DEM and the USGS Level 1 DEM is that Bolstad and Stowe (1994) used points that were specifically chosen for the study to be well within the boundaries of each slope class. In this thesis however, field points were taken from plots not selected in this fashion. In order to avoid overly biasing the study, points that occurred on edges of landforms and slope classes were included in the analyses. Thus, one would not expect the results to be as good as those reported by Bolstad and Stowe (1994). Due to the problems of having plots on the edges of landforms and horizontal registration errors of plot locations mentioned in the Data and Methods section, the actual accuracy of the DEM's may be better than the results reported in this thesis.

It is common among users of DEM data to refer only to USGS DEM's without noting the accuracy, and many users of DEM data are not aware that different levels of USGS DEM accuracy exist. This research clearly shows that users of USGS data need to make special note on the accuracy (level 1, 2 or 3) of the USGS DEM being used, as this appears to be a very strong indicator of the DEM's usefulness.

A major consideration, if DLG's are available, is "at what cell size should DEM's be created from the DLG's?". It appears that the 30-m and 15-m DEM's have greater slope accuracy and perform better at supervised classifications than the 7.5-m DEM's, and perform similarly with respect to aspect as the 7.5-m DEM. However, note that the plot size used for the field data most closely approximates the 30-m and 15-m cell sizes. Thus, in situations where the 7.5-m DEM could interpret information at fine scales (i.e., steep slopes where contour information is very dense), DEM data would be finer than the field measurements and would not result in better agreement with the field data.

Time, disk storage, and computer processing required for DEM's with smaller cell sizes are important considerations. For example, a 7.5-m DEM requires 16 times more computation intensity, processing time, and disk storage requirements than a 30-m DEM. Visual portrayal of the landscape also is important. Coarser DEM data are not so visually pleasing, especially if converted to visuals at large-scales. Users may be less likely to accept a product with the blocky structure of coarse resolutions. Conversely, analyzing and displaying products at resolutions finer than the input data may mislead users about the “real” resolution and detail of the data. The phenomena being modeled should be considered. For example, if one is terrain-mapping an area with a minimum mapping unit of 1 hectare (2.41 acres or approximately 22 30-m cells), 7.5-m resolution data may not be logical. Considering all factors and present technology levels, results for this study region indicate that 15 to 20-m resolution is appropriate for the input resolution, fine enough resolution to be displayed effectively, and is an appropriate scale with regards to computational and disk space intensity.

The accurate prediction of slope gradient can have positive repercussions for soil survey, given that slope is a key component for several interpretations (Soil Survey Staff, 2003). Slope gradient affects many timber harvesting considerations including erosion risk, the amount of disturbance (compaction, rutting and exposed mineral soil) and the extensiveness and type of road and skid trial system that will be required. In addition, correlations have been observed between slope gradient and several soil properties including soil water storage (Helvey et al., 1972), soil drainage class (Bell et al., 1994), and “A” horizon thickness (Walker et al., 1968).

The reliability of aspect measurements in this investigation bodes well for models that attempt to predict forest site quality, soil properties and soil water. Strong correlations between tree growth (site index) of several tree species and slope aspect have been reported in the Ozarks (Graney and Ferguson, 1972; Hartung and Lloyd, 1969), and other areas of the central hardwood region (Carmean, 1965; Carmean, 1967; Hannah, 1968). Slope aspect often influences on the dynamics of soil water (Hanna et al., 1982), and has been correlated with thickness of the “A” horizon (Meinert, 2001), surface organic matter (Franzmeier et al., 1969; Daniels et al., 1987), and pedological development (Finney et al., 1962; Franzmeier et al., 1969) in forested regions. Accurate aspect measurements can help predict how timber harvesting and vegetation management activities will affect hydrologic properties such as stream flow and storm water production.

The relative accuracy of the DEM’s used in this investigation may likely be replicated in areas of similar terrain and data resolution. However, data regarding the actual accuracy of DEM’s should be extrapolated with care. Considerations such as the precision, scale and accuracy of the source data, variations in slope breaks and kinds of landforms, and the intensities of data needed mean that other regions may not show the same results as seen in this investigation.

LITERATURE CITED

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CHAPTER 3

A DIGITAL TERRAIN MODEL AS A BASELINE FOR FOREST LAND CLASSIFICATION AND SOIL SURVEY

INTRODUCTION

Landscape ecosystems include the air, water, soils, topography and biological components that comprise basic units of nature (Rowe, 1991). Ecosystem characteristics are responsible for land management potential and limitations and much variation of these characteristics occurs in landscapes.

Many environmental factors have been characterized, modeled, and classed in efforts to understand and predict variation. However, many of these classifications are overly narrow in scope and lack covariance with other ecosystem components, frustrating their utility for land management. Alternative classifications systems, such as ecological land classification (ECS) and other integrated multiple-factor systems, have been proposed as dynamic and comprehensive systems for characterizing landscape ecosystems (Nigh et al., 1994; Jones, 1991; Rowe, 1991; 1984; 1980; Smalley, 1991). In addition, scientists have encouraged the Natural Resources Conservation Service (NRCS) to adopt more precise and flexible approaches to soil survey (Hammer, 1991; Indorante et al., 1996; McSweeney et al., 1994).

Landforms, because of their: i)influence on and covariance with a variety of site factors, ii) abilities to be modeled at different scales, iii) easily observable features, and iv) relative stability in the landscape, are a logical base for modeling landscape ecosystems. The potential of digital terrain models (DTM's) to characterize landforms offers further impetus for the development of geomorphic-based land classification systems. This study investigates the potential for making accurate and operationally efficient DTM’s that can serve as a baseline for land classification systems such as ECS and Soil Survey.

Classification Systems

Single-factor classification systems contain valuable information that has been successfully applied to land management. However, these classifications have often proved too limited for a variety of applications. For example, soil surveys have had very limited success predicting forest productivity (Carmean, 1961; Broadfoot, 1969; Van Lear and Hosner, 1967). Traditional soil survey has an agricultural bias (Hammer, 1991), and often fails to consider other important uses and interpretations (Grigal, 1984). The strength of Soil Taxonomy is its ability to provide a comparative framework of soils across different regions, but sometimes this framework is too rigid to allow locally important properties of soils to be communicated in the soil survey. Instead, effort is made to fit mapping units into a preconceived classification system based on taxonomy (Grigal, 1984).

Site index is the most widely accepted estimate of forest site quality in the United States (Carmean, 1975). Site index is the height of dominant and codominant trees of a stand projected to a standard age (Pritchett and Fisher, 1987). Site index is limited in that it conveys only information concerning the immediate stand, and it cannot be used for sites lacking suitable trees for measurement, or for the conversion to species other than those used in site index calculations (Pritchett and Fisher, 1987). Site index does not address management limitations or multiple-use possibilities such as biodiversity, wildlife habitat, or recreation potential. In addition, the products of site index calculations are graphs and equations; however, the tools necessary for forest management and planning are maps and inventories (Stone, 1978).

Vegetation-based methods are another popular method of classifying sites with respect to productivity, silvicultural options, or plant community classifications, and are based on ground vegetation types, community types and habitat types. Many of these classifications have been developed for the western U.S., such as those developed by Daubenmire (1976). However, vegetation-based classification systems have limited effectiveness in the eastern U.S. because of the history of disturbances such as logging, grazing and rooting of domesticated animals, fire, insect, and fungal infestations. In addition, vegetation classifications do not communicate other important information such as physical limitations to site management (compactability, erodability or equipment limitations).

The limitations of single-factor system classifications and modern management considerations have stimulated interest in flexible and scale-variable multiple-factor classifications. These characteristics could be developed with innovative soil surveys or alternative classification systems. A potential system for forested regions in Missouri is a multiple-factor ecological land classification system (ECS). An ECS is an integrative approach to classifying land that incorporates major site factors including climate, geology, topography, soils and vegetation. Examples of potential applications for an ECS include the modeling of distributions of water and energy (Hammer and Henderson, 1994), the type, structure, and productivity of vegetation (Jones, 1991), or the response to site disturbance and management (Hammer and Henderson, 1994; Hills, 1960). A first approximation of an ECS was developed by the USDA Forest Service for the Mark Twain National Forest and surrounding lands (Miller, 1981). Nigh et al. (1994) are revising this system as a pilot study for the statewide application of an ECS in Missouri.

Importance of Landforms

A Landform is defined by its surface shape, its location in relation to other landforms, its underlying geologic materials, and its soil attributes (Hammer, 1997a). A landscape is composed of geomorphically related landforms (Hammer, 1997). Many environmental factors influence the expression and management potential of ecosystems, but geomorphology synthesizes many of the other factors. Landforms influence, and show covariance with, a variety of site factors including micro-climate, vegetation composition (Host et al., 1987), tree growth (Smalley, 1991; Steinbrenner, 1975; Carmean, 1975), and soil characteristics (Bell et al., 1992; Finney et al., 1962; Franzmeier et al., 1969; Knox, 1965; Moore et al., 1993; Odeh et al., 1991). Ecosystem processes such as nitrogen cycling (Zak et al., 1986), successional pathways (Host et al., 1987), and total biomass (Host et al., 1988) often are associated with different landscape positions. In addition, landforms are the most permanent and stable feature of the ecosystem and are relatively easy to identify in the field. If the important site factors (soil characteristics, microclimate, vegetation frequencies, tree growth, etc.) can be correlated and understood in terms of their relationships with landforms, characterization of geomorphic properties may serve as excellent baseline information for understanding and managing landscapes.

GIS and DEM Technologies

Geographic Information Systems (GIS) and Digital Elevation Models (DEM’s) may make accurate, flexible, scale-variable, and economical land classifications a real possibility. A GIS can be defined as a “set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world for a particular set of purposes “ (Burrough, 1986). Digital elevation models (DEM’s) are of particular interest in terrain modeling and terrain-based land classification systems. A DEM is an “ordered array of numbers that represents the spatial distribution of elevations above some arbitrary datum in a landscape” (Moore et al., 1991). DTM’s will be defined as an “... ordered array of numbers that represents the spatial distribution of terrain attributes” (Moore et al., 1991). Thus, an example of a DTM might be a landform representation based on terrain attributes calculated from a DEM. Grid-based models are most widely used DTM's because of the computational and structural efficiency for the estimation of topographic attributes (Moore et al., 1991).

DEM's in conjunction with GIS have been used to estimate landform attributes (Bell et al., 1994; Hammer et al., 1995; Irvin et al., 1995; Klingbiel et al., 1987; Moore et al., 1993; Moore et al., 1991). Accurate terrain-based models can be useful for predicting important soil factors, vegetation productivity, management potential, and vegetation communities. Topographic parameters derived from a 10-m DEM were used to predict soil morphological data by Bell et al. (1994). Fifty-four percent and forty-nine percent correlations were found between the actual A-horizon depths and depth to carbonates and the model predictions. Bell et al. (1992) developed a terrain model from a DEM, stream data, and surficial and bedrock geological data. This model was 74% successful in predicting soil drainage class, compared to 69% success rate for the published soil survey. Gesler et al. (2000) investigated soil-geomorphic patterns at a 2-ha site in the southern California Coast Range using a high-resolution DEM. They found correlations between A horizon depth, soil depth, soil carbon and net primary production and terrain variables such as surface shape, flow accumulation, and a compound topographic index.

Several methods exist for creating digital terrain models. Three of these models were analyzed. Each classification method used a combination of terrain attributes to model landform features. The three classification methods were: 1) Rule-based classifications – classes are based on user-specified rules; 2) supervised classification – signatures are developed from prototype landforms and used to classify areas according to the landform signature they most resemble; and 3) unsupervised classification - natural clusters of cells are determined without the user setting boundaries or training areas.

Objectives:

Specific objectives of this research were to:

1) Develop landform classifications with different methods (rule-based, supervised and unsupervised) and compare these with a detailed soil-geomorphic survey developed by an experienced soil scientist. Determine which method is most applicable and successful in different situations.

2) Determine how accurately detailed information from one area can be extrapolated to another area with similar geomorphic and ecological patterns.

3) Determine if landform classifications are of sufficient accuracy and efficiency to be operationally used for premapping in soil or other land classification systems.

4) Determine if United States Geological Service (USGS) level 2 30-m DEM data are of sufficient detail to be used as baselines for ECS inventories at the ELT level or second-order soil surveys.

DATA AND METHODS

Site Description

The research sites are in Shannon County in the Lower Ozark region of southeastern Missouri (Nigh et al., 1994). The study region is within two USGS 7.5 minute quadrangles. Within the study region, nine research sites are maintained by the Missouri Ozark Forest Ecosystem Project (MOFEP). The MOFEP project is a long-term ecological research project directed by the Missouri Department of Conservation with cooperators from other state and federal agencies. The MOFEP research sites range in size from 260 to 527 hectares (657 to 1,300 acres) (Brookshire and Hauser, 1993) (See Figure 2.1). Four of the nine research sites were chosen for the Chapter 4 analysis. Of these four research sites, sites 3 and 4 are adjacent and occur on the Exchange USGS 7.5-m quadrangle, and sites 1 and 2 are adjacent on the Powder Mill

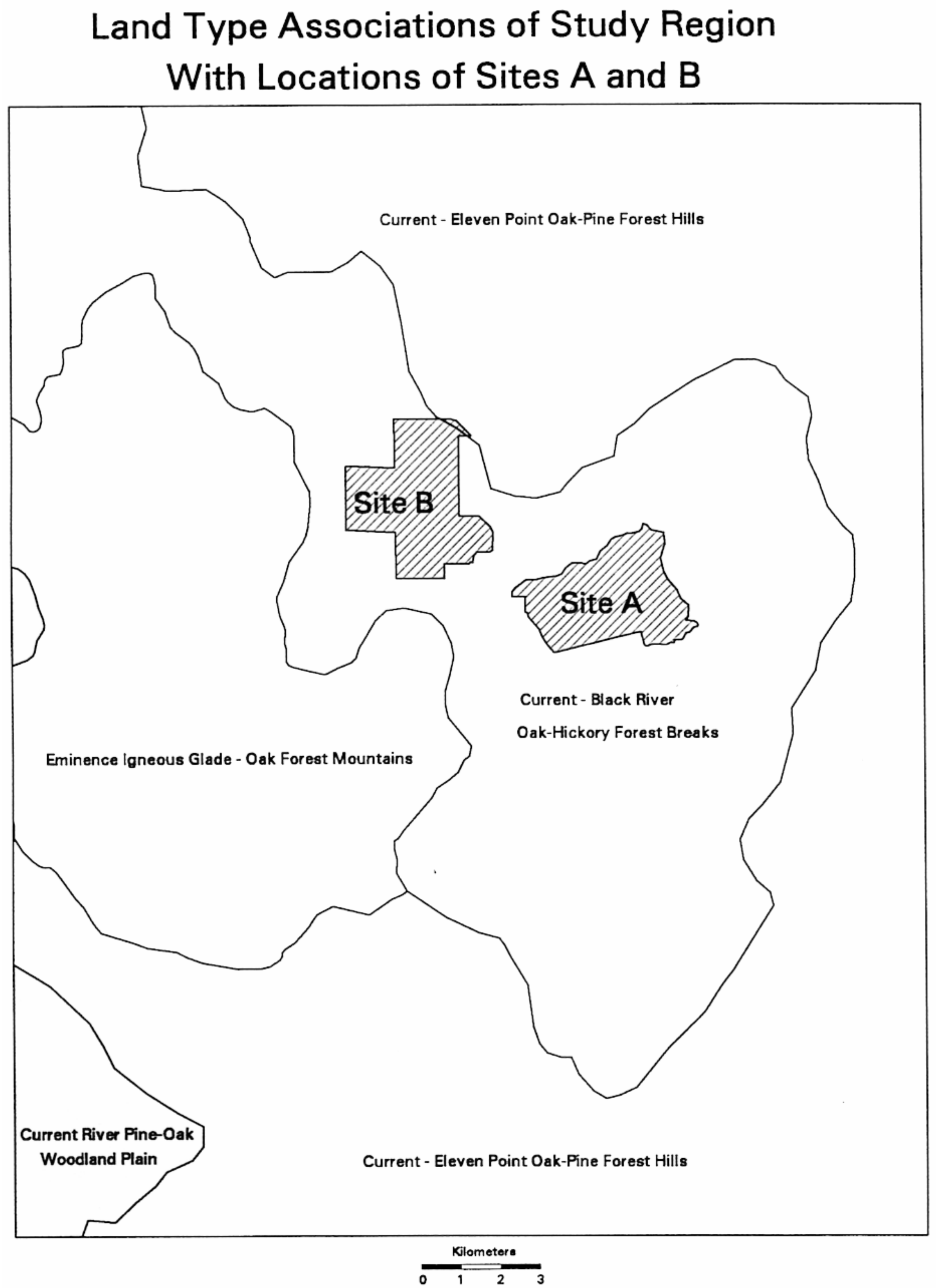


Figure 3.1 Landtype Associations of study region with locations of sites A and B.

Ferry 7.5-m quadrangle. Units 3 and 4 will be referred to as site A and units 1 and 2 as site B (Fig. 3.1). The centers of sites A and B are approximately 5 km apart and their closest borders are approximately 1 km apart.

The topography is rugged and deeply dissected with elevations ranging from approximately 137 m to 414 m (450 feet to 1360 feet). The research region is underlain mostly by eroded and uplifted sedimentary rocks composed of dolomites, limestones, sandstones, and cherts. Common landforms include narrow ridges (less than 150 m wide) with slopes of less than 20%. Steep side slopes ranging from 20% to over 60% are the most extensive feature of the study sites. Structural benches with slopes less than 20% and relatively narrow floodplains and colluvial bottoms are other common landforms. The Current River is the best-known natural feature of the region and flows near the western boundary of site B and forms part of the southern boundary of site A. The most rugged portions of the study region are closest to the Current River. Soils are formed primarily in hillslope sediments and residuum, with some areas of loess and alluvium. Soils generally are highly weathered and range in depths to bedrock. Bedrock outcrops and fragipans are common. Paleudults, Paleudalfs, Hapludalfs and Paleudults are common soil great groups and loamy-skeletal and loamy-skeletal over clayey are the most common particle size classes (Meinert et al., 1997; Soil Survey Staff, 2004). The vegetation is part of the Oak-Hickory region (Braun, 1972). Significant communities include oak-pine, mixed upland and bottomland deciduous hardwoods, oak-savanna, and glades.

DEM Production

Several DEM’s from various sources were investigated for their accuracy in producing elevation, slope and aspect measurements, and performing simple landform classifications (see Chapter 2). Analyses showed the USGS level 2 DEM to be more accurate than DEM's produced from SPOT imagery, more accurate than USGS level 1 DEM's and slightly less accurate than DEM's produced from elevation contours and hydrologic information using Arc/Info’s TOPOGRID program. The level 2 DEM's were available for Exchange and Powder Mill Ferry quadrangles for the production and analyses of the terrain model. Because their relative accuracy and increasing availability render these data useful for operational situations, they were chosen for this analysis.

The level 2 designation includes DEM data derived from hypsographic digital line graph (DLG) data or generated from vector data derived from scanned raster files of USGS 1:24,000-scale map series contour separates (USGS, 1996). Thus, the ultimate sources for DEM data are the contour lines from USGS 7.5-minute quadrangles (Fig. 3.2), and the DEM is an interpolation of these contour lines (Fig. 3.3). Level 2 DEM's are now the primary USGS DEM product for 7.5-minute quadrangles. They are smoothed for consistency and are edited to remove identifiable systematic errors. A RMSE of one-half contour interval of the source map is the maximum permitted error. Systematic errors (those that follow some fixed pattern and represent an array of points) may not exceed one contour interval. The contour coverages for the study region have a interval of 6.1-m (20 feet). Elevations from the DEM's were given in meters relative to National Geodetic Vertical Datum of 1929 (NGVD29). Postings were cast onto the zone 15 Universal Transverse Mercator (UTM) Projection using the North American Datum of 1927 (NAD27).

Terrain Attributes

Several terrain attributes were investigated for their potential in a landform classification (Table 3.1). All attributes were produced using Arc/Info version 7.0 software (usually in the GRID module), and all attributes were in raster format. Not all of the terrain attributes described were used in the classifications analyzed in this chapter. However, they are noted in this section because they may have utility for other terrain modeling procedures. To reduce confusion over Arc/Info commands and terms used to name some terrain attributes, upper

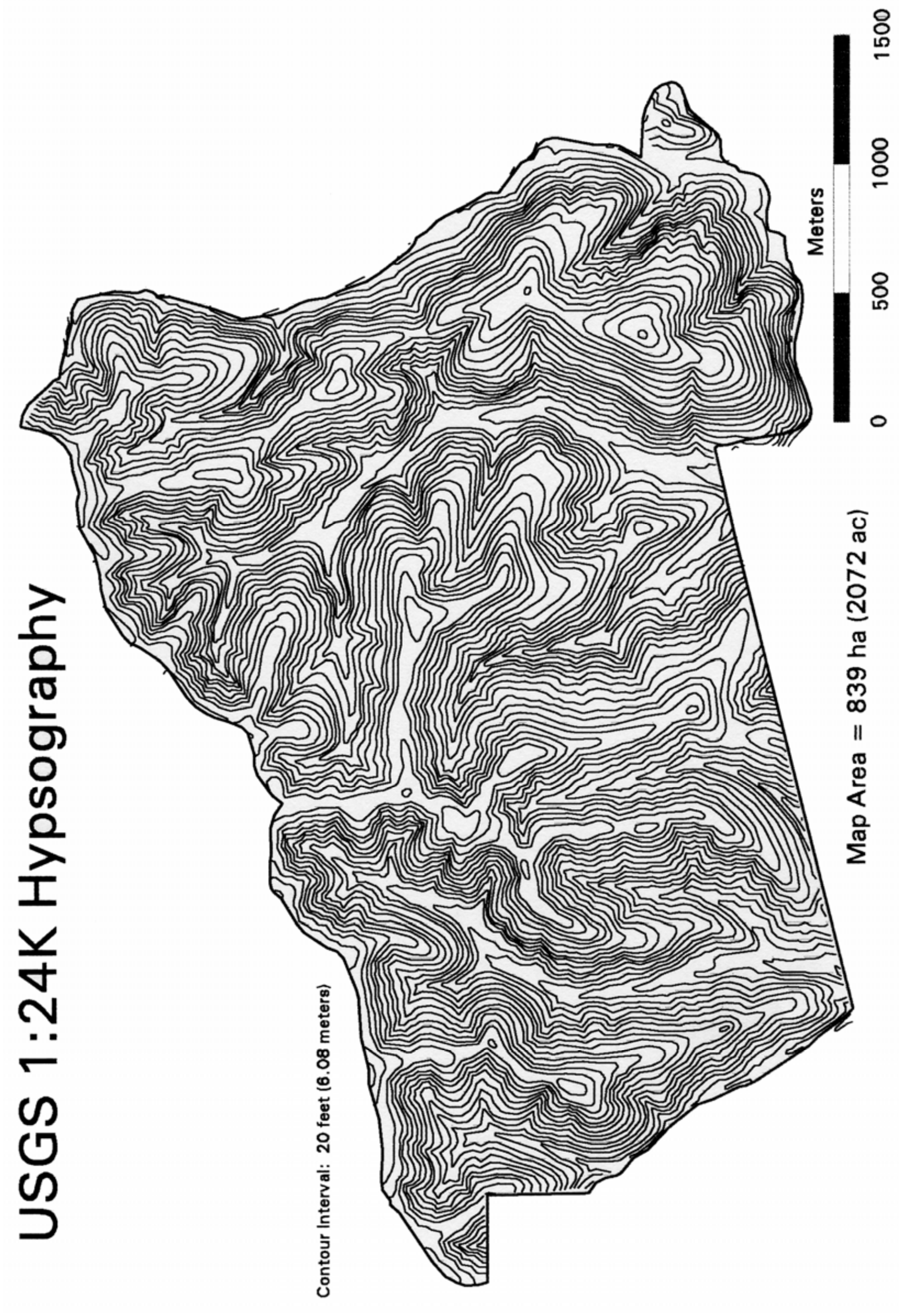


Figure 3.2 USGS 1:24,000 scale hypsography of site A.

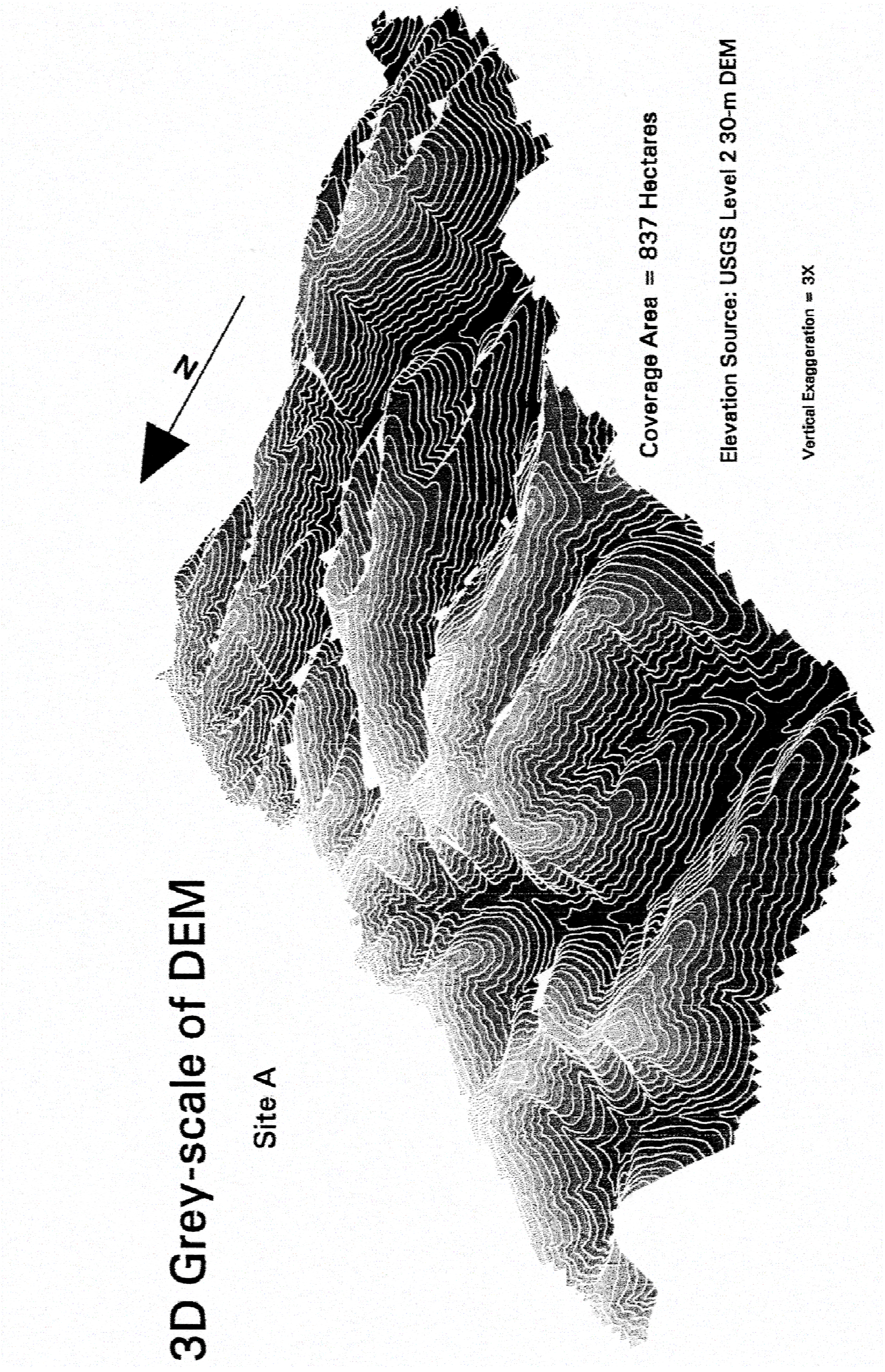


Figure 3.3 Three-dimensional gray-scale of Site A produced from the USGS level 2 30-m DEM. Contour lines are overlayed from USGS 1:24,000 hypsography. Contour interval is 6.1-m (20 feet).

Table 3.1 Terrain Attributes Created for Landform Classification

Attribute	**Abbreviation**	**Description**
Elevation	ELEV	Base terrain feature used to calculate other attributes.
Slope	SLOPE	Maximum rate of change from each cell to neighbor cells.
Aspect	ASPECT	Direction of maximum rate of change.
Curvature	CURVE	Calculates an average curvature for all directions for cells in a 3 x 3 window.
Plan Curvature	PLAN	Curvature along a direction parallel to the contour.
Profile Curvature	PRO	Curvature along a direction perpendicular to the contour.
Flow Accumulation	FLOW	Gives a value for each cell that equals the number of cells in the upslope area in which overland flow goes into that cell.
Stream Buffer	STREAMBUF	Indicates drainageways with high flow accumulation values and gently sloping areas adjacent to cells with high flow accumulation values.
Elevation Above Local Drainageway	ELEVLOCAL	The height above the closest local drainageway.
Elevation Above Major Drainageway	ELEVMAJOR	The height above the closest major drainageway.
Ridge/Summit	RIDGE	Areas that are local topographic highs with low flow accumulation values and slopes <= 20%.
Elevation Below Local Summit	ELEVRID	The height above the closest summit or ridge cell.
Elevation Above Local Minimum	ELEVMIN	The height above the lowest cell within a 450 m radius of each cell.
Elevation Below Local Maximum	ELEVMAX	The height below the highest cell within a 450 m radius of each cell.
Relative Location Below Summit	SUMX	Uses ELEVRIDGE and ELEVMAX to calculate a relative index
Relative Location Above Drainageway	DRAINX	Uses ELEVDRAIN, ELEVMAJOR, and ELEVMIN to calculate a relative index.

case letters are used to denote actual Arc/Info commands and italics denote the names of the more complex attributes created with combinations of Arc/Info commands and/or conditional and mathematical operators.

Slope gradient identifies the maximum rate of change from each cell to its neighbor cells (ESRI, 1994). The "SLOPE" command calculated percent slope for a 3 x 3 neighborhood surrounding the processing or center cell using the average maximum technique (ESRI, 1994). The algorithm used was:

$\text{rise/run} = ((\Delta z/\Delta x)^2 + (\Delta z/\Delta y)^2)^{1/2}$ where "a" through "i" are the elevation values of a 3 x 3 window used to calculate the deltas:

$$\begin{matrix} a & b & c \\ d & e & f \\ g & h & i \end{matrix}$$

$(\Delta z/\Delta x) = ((a + 2d + g) - (c + 2f + i)) / (8 * \text{x-mesh-spacing})$

$(\Delta z/\Delta y) = ((a + 2b + c) - (g + 2h + i)) / (8 * \text{x-mesh-spacing})$

Figure 3.4 shows a slope attribute map with the important slope breaks for the area. Aspect identifies the direction of maximum rate of change in elevation (also called slope direction) from each cell (ESRI, 1994). Although an important influence on some ecological factors in the area, aspect was not used in the DTM because the field model to which the DTM is being compared did not use aspect to delineate map units. However, aspect could be included in the DTM or used to separate some map units at a later stage after the initial DTM is performed.

Surface shape is characterized by three measurements: curvature, planform curvature and profile curvature. "CURVATURE" is calculated in Arc/Info on a cell-by-cell basis with a fourth-order polynomial of the form $Z = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Ay + I$, where cells A through H represent the surrounding cells and I represents the middle of the 3 x 3 window and Z represents the curvature value (ESRI, 1994). The Z values are presented as 1/100 Z units so that positive values are upwardly convex surfaces, negative values are upwardly concave surfaces,

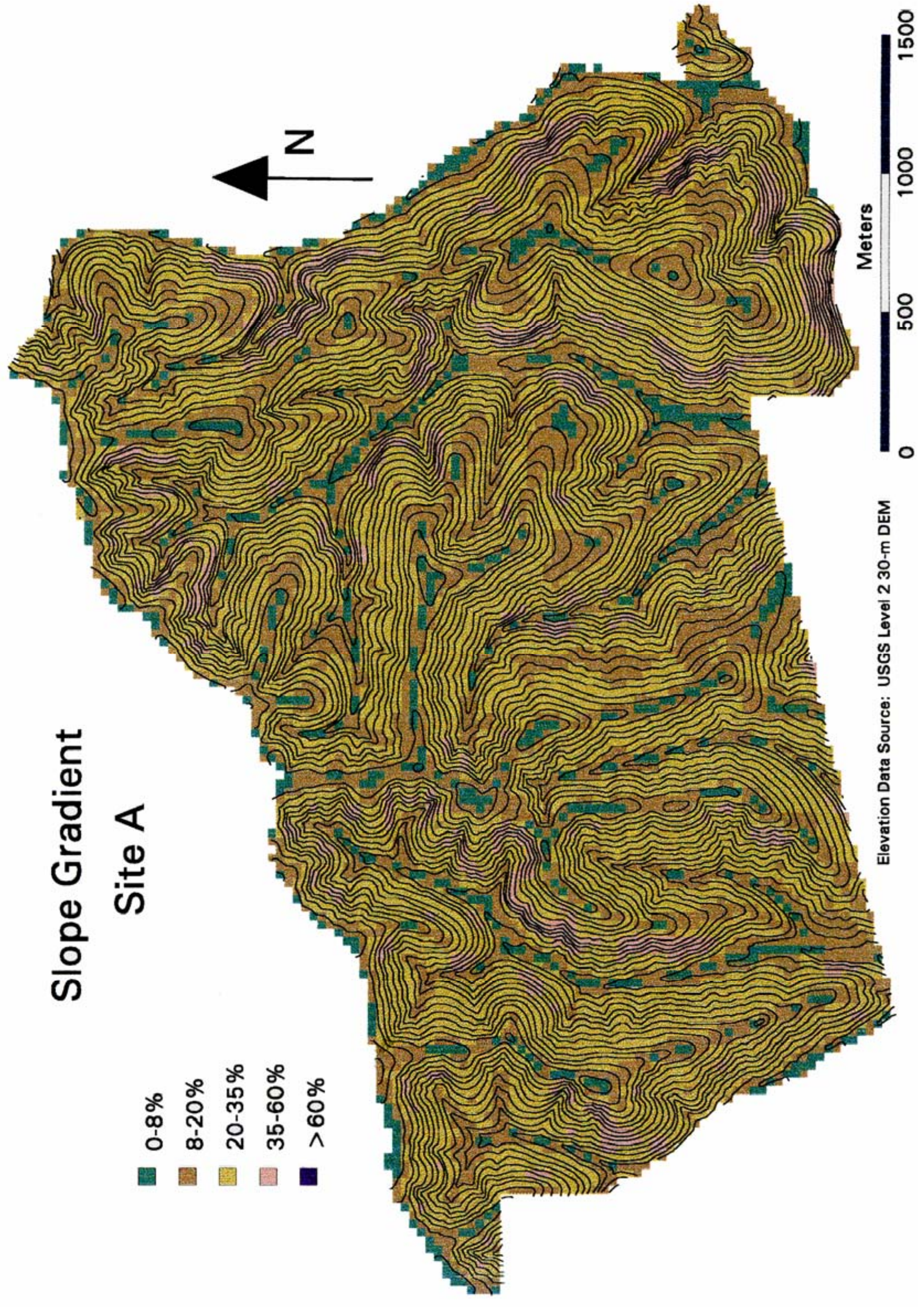


Figure 3.4 Slope gradient with five slope classes for site A. Slope gradient is measured in percent. Contour lines are overlayed from USGS 1:24,000 hypsography with contour interval of 6.1-m (20 feet).

and zero indicates flat surfaces. An example is shown of curvature divided into five classes (Fig. 3.5). Profile curvature determines the curvature along a line connecting the upslope, center, and down slope elevation cells and planform curvature determines shape parallel to the contour.

The Arc/Info “FLOW ACCUMULATION” command was used as part of several coverages created. This function calculates accumulated flow as the accumulation of all cells flowing into each down slope cell (ESRI 1994). In a nonweighted application, the value of the cells in the output grid is the number of cells that flow into each cell. For example, if a total of 15 cells flows directly or indirectly to a certain cell, then the value of that cell is 15.

Cells with a high FLOW ACCUMULATION value are areas of concentrated flow and cells with a FLOW ACCUMULATION of 0 are local topographic highs. Before creating the Flow Accumulation grid, the “FILL” command was used to fill all the sinks in the DEM, and FLOW DIRECTION determined the direction surface water would flow from each cell. FLOW ACCUMULATION was used as an input to several grids.

“*Elevation above local drainageway*” was calculated by first determining local drainageways by using the FLOW ACCUMULATION grid to select all cells with a value over 20 with a conditional statement in the CON function. Another CON statement was executed to create a grid composed only of drainageway cells with their elevations. The “EUCALLOCATION” command identified the closest local drainageway cell to all cells in the study region and gave these cells the elevation value of the closest drainageway cell. Then the closest drainageway cell’s elevation was subtracted from the elevation of each cell, and the difference was the height above the closest drainageway cell. “*Elevation above major drainageway*” was similarly calculated by first selecting large drainages by taking all cells with a value over 1000 in the FLOW ACCUMULATION grid with a CON statement. Following this, the same procedures as for the *elevation above local drainageway* grid were

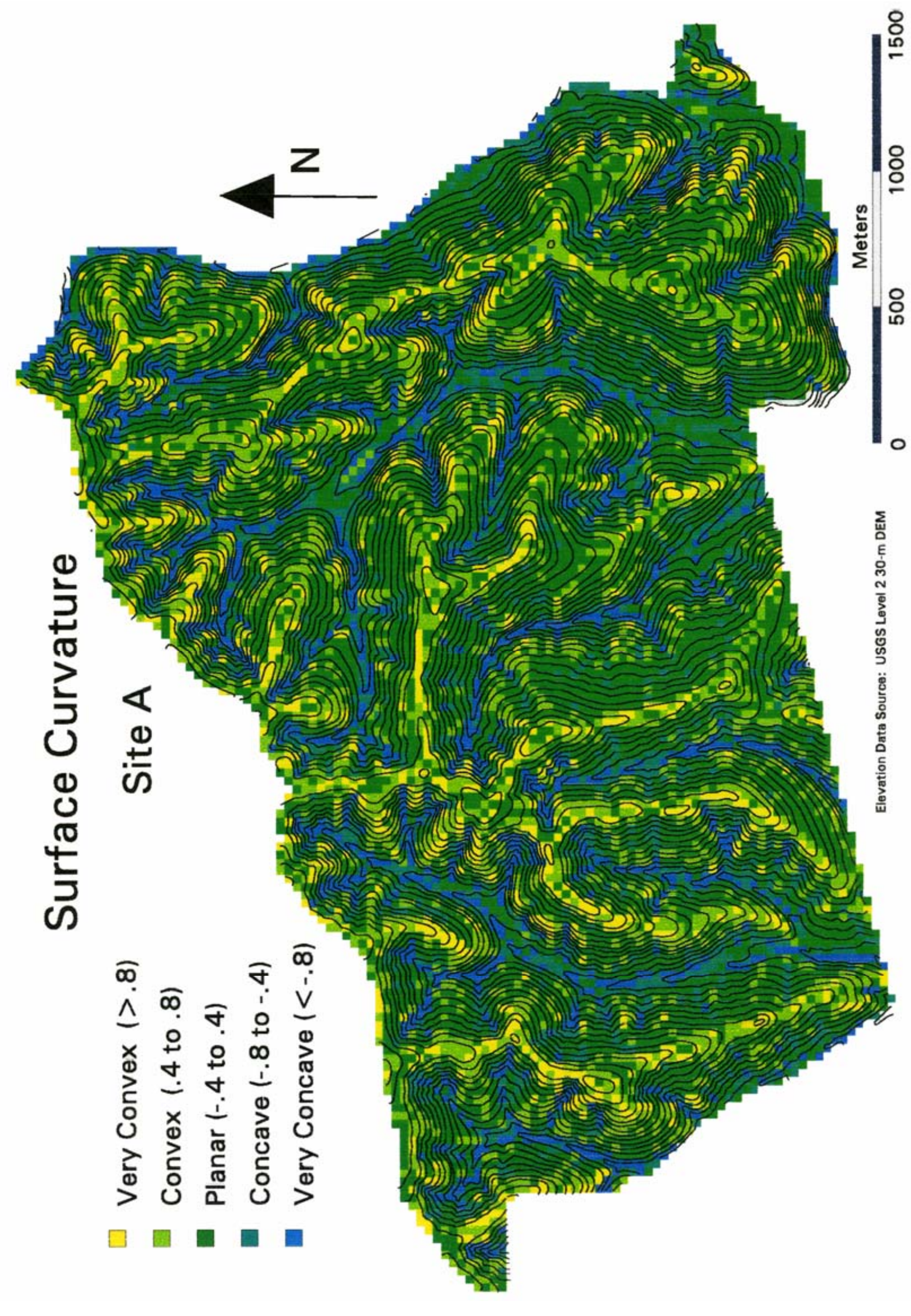


Figure 3.5 Surface Curvature of Site A. Positive values indicate convex areas, negative values indicate concave areas and values near zero indicate planar positions. Contour lines are overlayed from USGS 1:24,000 hypsography with contour interval of 6.1-m (20 feet).

used to determine *elevation above major drainageway*.

The "*ridge*" coverage was developed by first using a "CON" statement to identify all cells in the FLOW ACCUMULATION grid with a value of 0. Next, a CON statement was used to identify all cells with a FLOW ACCUMULATION value of 0 and a slope percent value of less than 20%. To eliminate low lying flat areas, all areas with *a height above local drainageway* of 25 meters or less were deleted from the grid. Then a series of filters was used with the "MAJORITYFILTER" command to eliminate non-ridge areas (such as shoulders). At this point many of the non-ridge areas had been eliminated as well as some ridge areas, so an "EXPAND" function (similar to "BUFFER" command in the vector environment) was used to increase the ridge file to include all potential ridge sources. Then, once again, all slopes > 20% were eliminated from the grid. It was necessary to run the MAJORITY FILTER, EXPAND, and CON statements several times until the grid included most of the ridge cells but not other cells. This was one of the more qualitative grids created in that the techniques were based on a visual estimation of the grid's effectiveness, and exact techniques are not easily executed for different areas.

The "*inverse flow accumulation*" grid was created as another indicator of ridges. First, the elevation grid was multiplied by -1 to produce an inverse grid. Then FLOW DIRECTION and FLOW ACCUMULATION were calculated on the inverse elevation grid to obtain an *inverse flow accumulation*. In this grid, higher values had the potential of being ridge cells. Those FLOW ACCUMULATION values > 10 along with slope values < 20% and *elevation below local maximum* (described later in this section) values < 25 were selected initially. Then a series of MAJORITY FILTER, EXPAND, and CON functions were used as described for the ridge file (above) to produce the inverse ridge file.

Two attributes were created that determined the relative location of a cell in relation to the surrounding landscape. For the "*elevation above local minimum*" grid, the minimum elevation within a 450 meter radius (64 hectare area) of each cell was identified with the “FOCALMIN” command. Then, the minimum elevation was subtracted from each cell in the grid to get the elevation of each cell above the localized minimum. The grid “*elevation below the local maximum*” was created in the same fashion by identifying the maximum elevation within a 450 meter radius using FOCALMAX. Each cell elevation was then subtracted from the maximum elevation in the neighborhood to identify the elevation of each cell below the localized maximum.

Two landscape position indices were created with combinations of other grids. The *relative location above drainageway* grid was created from the *height above local drainageway*, *height above major drainageway*, and *height above localized minimum* grids. The Arc/Info command “SLICE” was used on each input grid. Relative ratings of reading from 1 to 100 were produced for each grid. The three grids were added and the SLICE command was again performed. The resultant grid varied from 1 to 100 with lower value cells located in close vertical proximity to slope bottoms and higher value cells located higher on the slopes (Fig. 3.6). *The relative location below local ridge* was created by performing a SLICE command on *the elevation below summit* and *elevation below localized maximum* grids. The two sliced grids were added, and SLICE was performed again to create a grid in which lower value cells were in close vertical proximity to ridges and higher value cells were farther down the slopes from the local ridges (Fig. 3.7). Both the *relative elevation above drainageway index* and the *relative elevation below local ridge index* seemed to give a more realistic picture of the index than their input grids alone. This probably is because each input grid contained situations on the landscape, in which the input grids performed inadequately, but when combined, the errors in the different indices were compensated by the other input attributes.

Two data sets were investigated for their usefulness in interpreting geology. First, a 1:62,000 scale geology map produced in

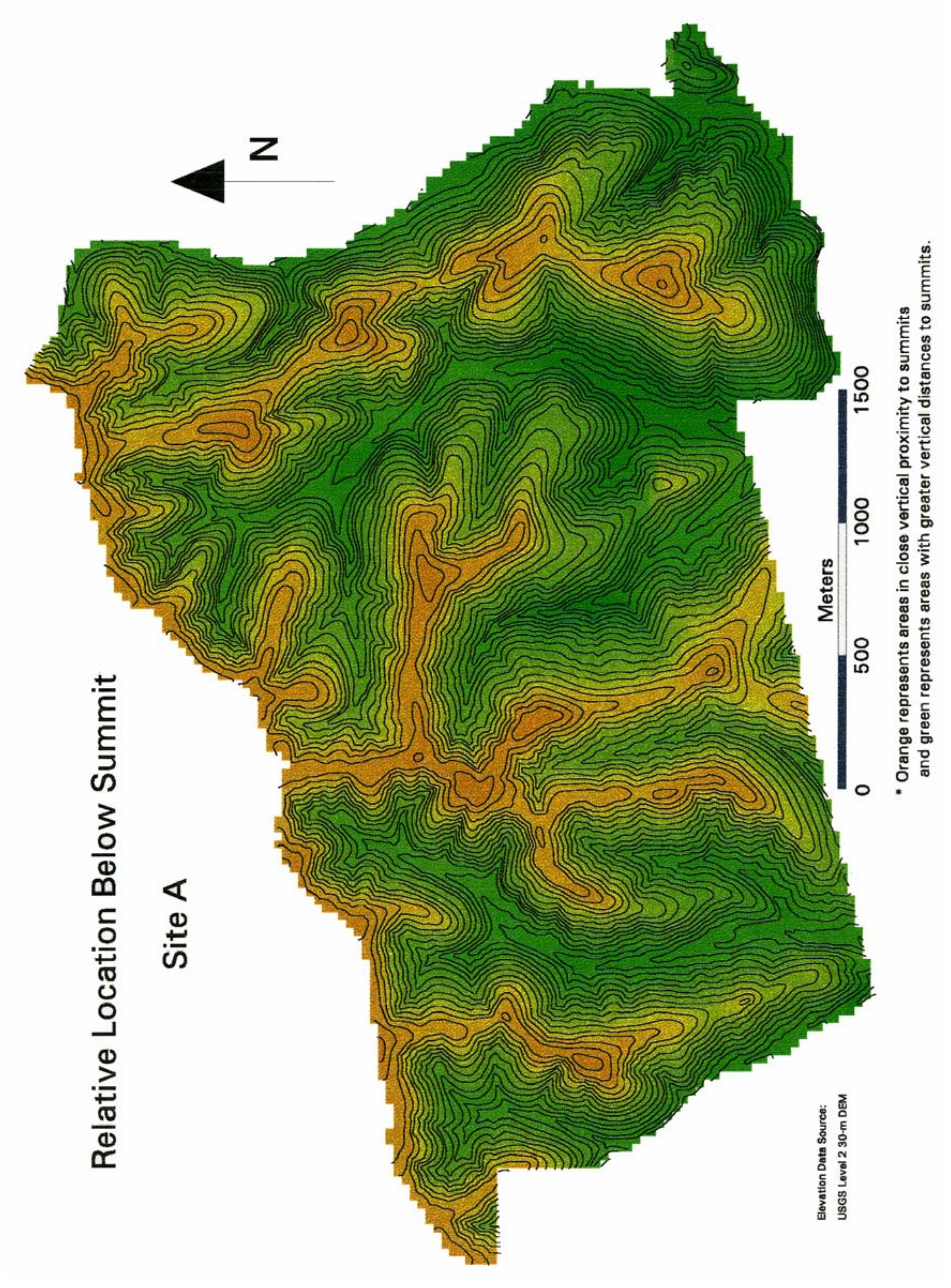


Figure 3.6 Relative location below summit. Orange cells have close vertical proximity of summits and green values having greater vertical distance to summits. Contour lines are overlayed from USGS 1:24,000 hypsography with contour interval of 6.1-m (20 feet).

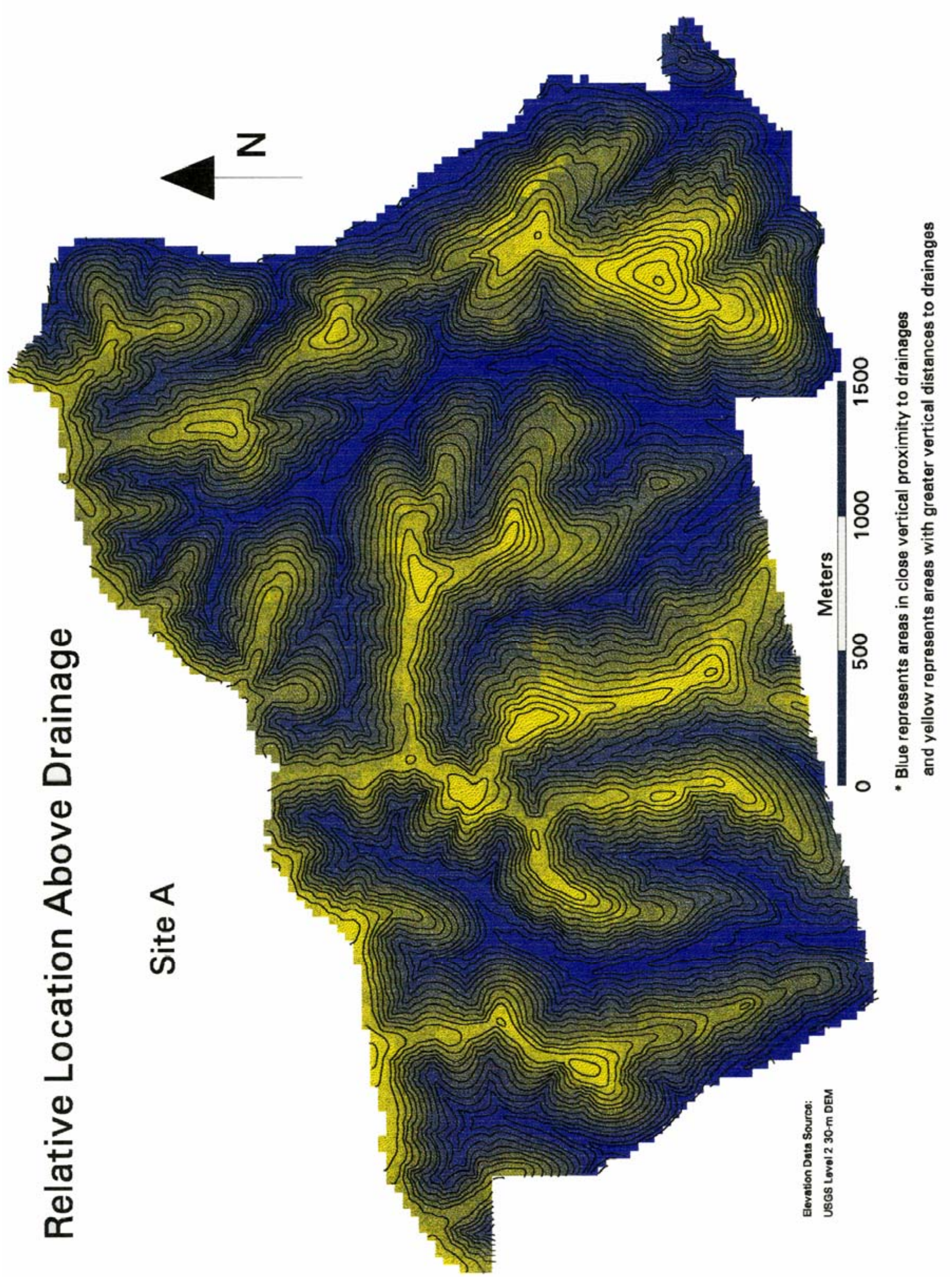


Figure 3.7. Relative location above drainageway. Blue cells indicate close vertical proximity to drainageways and yellow cells indicate greater vertical distance to drainageways. Contour lines are overlayed from USGS 1:24,000 hypsography with contour interval of 6.1-m (20 feet).

1929 was digitized. The map, although useful for interpreting geology in the field, proved insufficient for this type of GIS analysis for these reasons: the map scale was 1:62,000 and the other data were 1:24,000 scale topographic quadrangles; the map was on a 1925 hypsography base that is different from recent topographic interpretations; and the source map used for digitizing was of poor quality.

An alternative to using the 1929 map was to use geology information sampled at MOFEP plots to make a geology database. Sites A and B each contain 144 plots that were sampled for physiographic, geologic and soils data in connection with the MOFEP project (Meinert, 2001). The plot data were used to determine elevations at which geologic strata change. Geologic formation is correlated with elevation at both sites. However, a tilt of approximately 1^0 and small faults and dips in the strata make elevation alone a less than perfect geology source.

Separate geology layers were created for site A and site B. The resultant geology database was rechecked with the 144 samples on each site. Approximately 85% of the plots occur in the correct geologic material. In addition, the use of elevation was aided by knowledge that certain topographic features were keys to changes in stratigraphy.

Landform Classification Methods

Three methods identified landforms with GIS: 1) rule-based classification, 2) supervised classification, and 3) unsupervised classification. Each method was performed with Arc/Info 7.0 software (ESRI, 1994). Each method was compared to a detailed soil-geomorphic field survey.

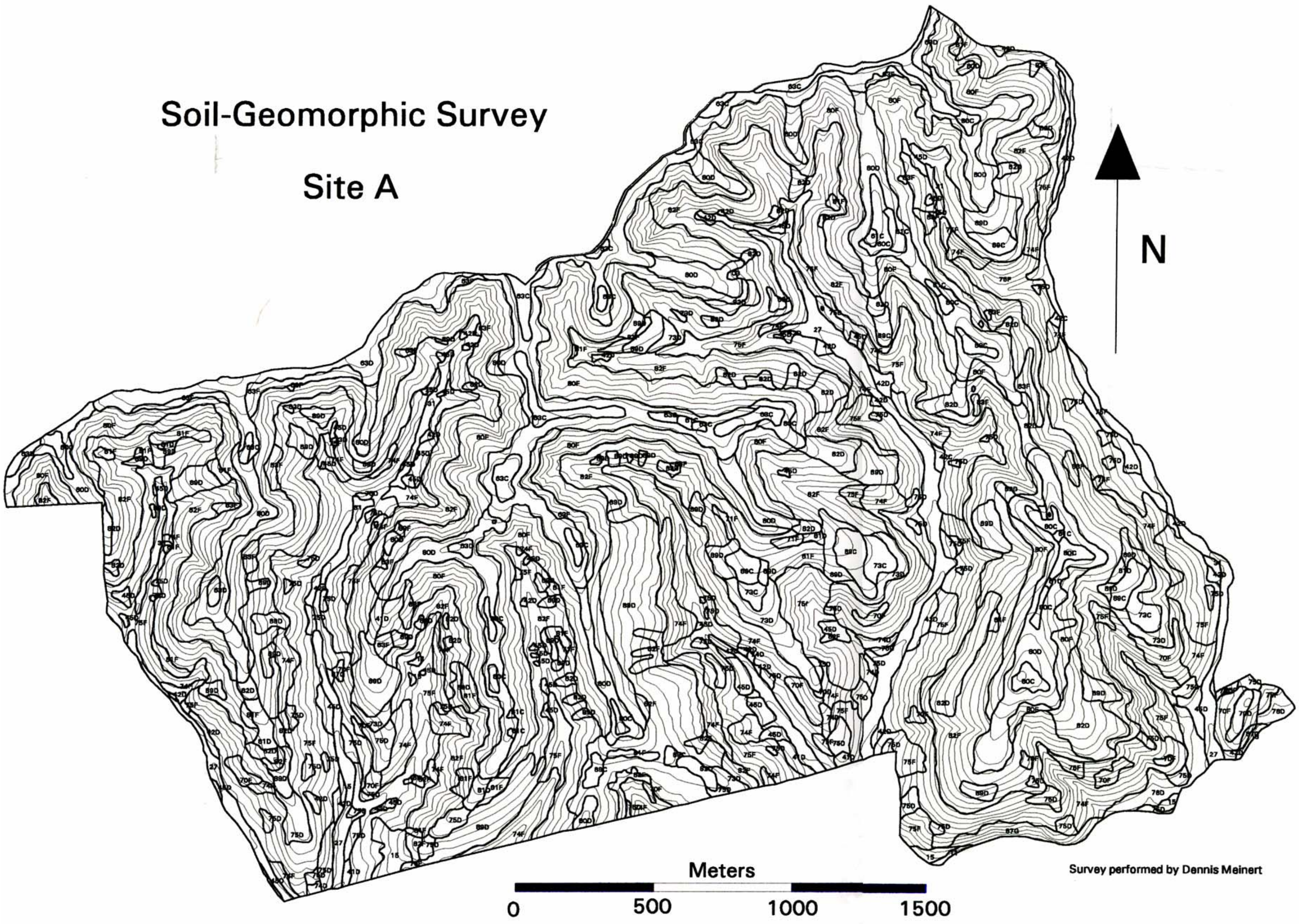
Soil-geomorphic Field Survey

The field soil-geomorphic survey was a first order survey at 1:12000 scale (Fig. 3.8). The survey had 34 map units (table 3.2), with delineations as small as 0.1 ha. The survey was conducted with NRCS soil survey techniques with several variations: i) the scale was finer than standard first order soil surveys; ii) the map unit design incorporated geomorphic and geologic attributes more aggressively than typical soil surveys; iii) the map unit design incorporated interpretations specific for multiple use forest planning; iv) the survey was designed to be a component in an ECS; and v) soil taxonomy was not used to set property boundaries for map units. The soil-geomorphic surveys of sites A and B were digitized by Missouri Department of Conservation personnel. The field survey was at a finer scale than currently available DEM data. Soil-geomorphic units with the same landforms were aggregated into landform units to develop a field model to compare with the DTM. In addition, alluvial landforms such as terraces and alluvial fans that could not be delineated with 30-m DEM data were combined into larger landform units. The aggregation contained 9 landform units (table 3.3 and Figure 3.9). The composition of the nine aggregated landform units by soil-geomorphic units is shown in table 3.4. The aggregated soil-geomorphic survey was converted from polygon format to a 5-m cell size grid format to facilitate comparisons with the terrain model.

Figure 3.8 (Following page) Soil-Geomorphic survey performed by Meinert (2001) for site A. Field mapping scale was 1:12,000, however map is displayed at smaller scale to conform to the page. Map unit characteristics are given in table 3.2.

Soil-Geomorphic Survey

Site A



Survey performed by Dennis Meinert

Table 3.2 Soil-Geomorphic units delineated in field survey of Site A. Shown are geology, landform, slope class, soil characteristics and common soil series for each map unit.

	Soil Series+	**Depth**	**Drainage**	**Particle-size Classes**	**Taxonomic Subgroup+**
03	*Sinkholes of Roubidoux formation, 1-3% slopes*				
	Not named	VD	WD	FL	Not determined
15	*Low terraces, alluvium, 1-3% slopes*				
	Secesh	VD	WD	FL	Ultic Hapludalfs
27	*Upland alluvial drainagways of Eminence formation, 1-4% slopes*				
	Waben-variant	VD	WD	LS	Mollic Hapludalfs
31	*Narrow alluvial floodplains, 1-3% slopes*				
	Midco	VD	SED	LS	Mollic Udifluvents
41D	*High strath terraces with colluvium over alluvium 3-8% slopes*				
	Pomme	VD	WD	FL	Typic Paleudalfs
42C	*Alluvial fans, 3-8% slopes*				
	Waben	VD	WD	LS	Ultic Hapludalfs
42D	*Alluvial fans, 3-15% slopes*				
	Waben	VD	WD	LS	Ultic Hapludalfs
45D	*Colluvial foot slopes, 3-15% slopes*				
	Not named	VD	MWD	FL	Typic Paleudults
	Pomme	VD	WD	FL	Typic Paleudalfs
61C	*Roubidoux formation summits, 1-8% slopes*				
	Hogcreek	VD	WD	FL	Typic Fragiudalfs
63C	*Roubidoux formation summits, 1-8% slopes*				
	Bendavis	MD	WD	LS	Typic Hapludults
	Poynor	VD	WD	LS/clay	Typic Paleudults
63D	*Roubidoux narrow ridges and shoulders, 8-20% slopes*				
	Bendavis	MD	WD	LS	Typic Hapludults
	Poynor	VD	WD	LS/clay	Typic Paleudults
63F	*Roubidoux formation sideslopes, 20-60% slopes*				
	Bendavis	MD	WD	LS	Typic Hapludults
	Clarksville	VD	SED	LS	Typic Paleudults
	Poynor	VD	WD	LS/clay	Typic Paleudults
70D	*Eminence formation narrow ridges with rock outcrop, 8-20% slopes*				
	Moko	SH	WD	LS	Lithic Hapludolls
70F	*Eminence Backslopes, 20-60% slopes*				
	Moko	SH	WD	LS	Lithic Hapludolls
71F	*Gasconade Backslopes, 20-60% slopes*				
	Moko	SH	WD	LS	Lithic Hapludolls
73C	Lower *Gasconade Benches, 1-8% slopes*				
	Viraton	VD	MWD	FL	Oxyaquic Fragiudalfs
73D	Lower *Gasconade Benches, 8-20% slopes*				
	Bendavis	MD	WD	LS	Typic Hapludults
74D	*Eminence Narrow Ridges with rock outcrops, 8-20% slopes*				
	Arkana	MD	WD	VF	Mollic Hapludalfs
	Ramsey	SH	SED	LO	Lithic Dystrudepts
	Niangua	D	WD	VF	Typic Hapludalfs
74F	*Eminence backslopes with rock outcrops, 20-60% slopes*				
	Arkana	MD	WD	VF	Mollic Hapludalfs
	Ramsey	SH	SED	LO	Lithic Dystrudepts
	Niangua	D	WD	VF	Typic Hapludalfs
75D	*Eminence secondondary ridges, 8-20% slopes*				
	Alred	VD	WD	LS/Clay	Typic Paleudalfs
	Rueter	VD	SED	LS	Typic Paleudalfs
75F	*Eminence back slopes, 20-60% slopes*				
	Rueter	VD	SED	LS	Typic Paleudalfs
	Alred	VD	WD	LS/Clay	Typic Paleudalfs
78D	*Colluvial footslopes along major rivers, 8-20% slopes*				
	Unamed	VD	WD	FL	Typic Paleudults
80C	*Gasconade summits, 1-8% slopes*				
	Clarksville	VD	SED	LS	Typic Paleudults
	Poynor	VD	WD	LS/clay	Typic Paleudults
	Scholten	VD	MWD	LS	Typic Fragiudults
80D	*Gasconade shoulders and narrow ridges, 8-20% slopes*				
	Clarksville	VD	SED	LS	Typic Paleudults
	Poynor	VD	WD	LS/clay	Typic Paleudults
	Scholten	VD	MWD	LS	Typic Fragiudults

Table 3.2 - continued

	Soil Series+	**Depth**	**Drainage**	**Particle-size Classes**	**Taxonomic Subgroup***
80F	*Gasconade backslopes, 20-60% slopes*				
	Clarksville	VD	SED	LS	Typic Paleudults
81D	*Gasconade shoulders & narrow ridges with rock outcrop, 8-20% slopes*				
	Bardley	MD	WD	VF	Typic Hapludalfs
	Gatewood	MD	MWD	VF	Oxyaquic Hapludalfs
81F	*Gasconade backslopes with rock outcrop, 20-60% slopes*				
	Bardley	MD	WD	VF	Typic Hapludalfs
	Gatewood	MD	MWD	VF	Oxyaquic Hapludalfs
82D	*Gasconade narrow ridges, 8-20% slopes*				
	Alred	VD	WD	LS/Clay	Typic Paleudalfs
	Rueter	VD	SED	LS	Typic Paleudalfs
82F	Gasconade backslope, 20-60% slopes				
	Alred	VD	WD	LS/Clay	Typic Paleudalfs
	Rueter	VD	SED	LS	Typic Paleudalfs
83F	*Gasconade backslopes & headslopes, loess & colluvium, 20-60% slopes*				
	Not Named	VD	MWD	FL	Typic Paleudult
87G	*Gasconade and Eminence cliffs with rock outcrop, slopes > 60%*				
	Not Named	SH-MD	MW-WD	LS	Not Classified
89C	*Lower Gasconade benches, 1-8% slopes*				
	Mano	VD	MWD	LS/Clay	Oxyaquic Hapludalfs
89D	*Lower Gasconade benches, 8-20% slopes*				
	Mano	VD	MWD	LS/Clay	Oxyaquic Hapludalfs

Particle Size Classes: SS = sandy-skeletal, LS = loamy-skeletal, CS = clayey-skeletal, S = sandy, L = Loamy, CL = course-loamy, FL = fine-loamy, CS = coarse-silty, FS = fine-silty, F = fine (clayey), VF = very fine (clayey), LS/Clay = Loamy-skeletal over clayey.

Drainage Definitions: WD = well-drained, MWD = moderately well-drained, SED somewhat excessively drained, ED = excessively drained.

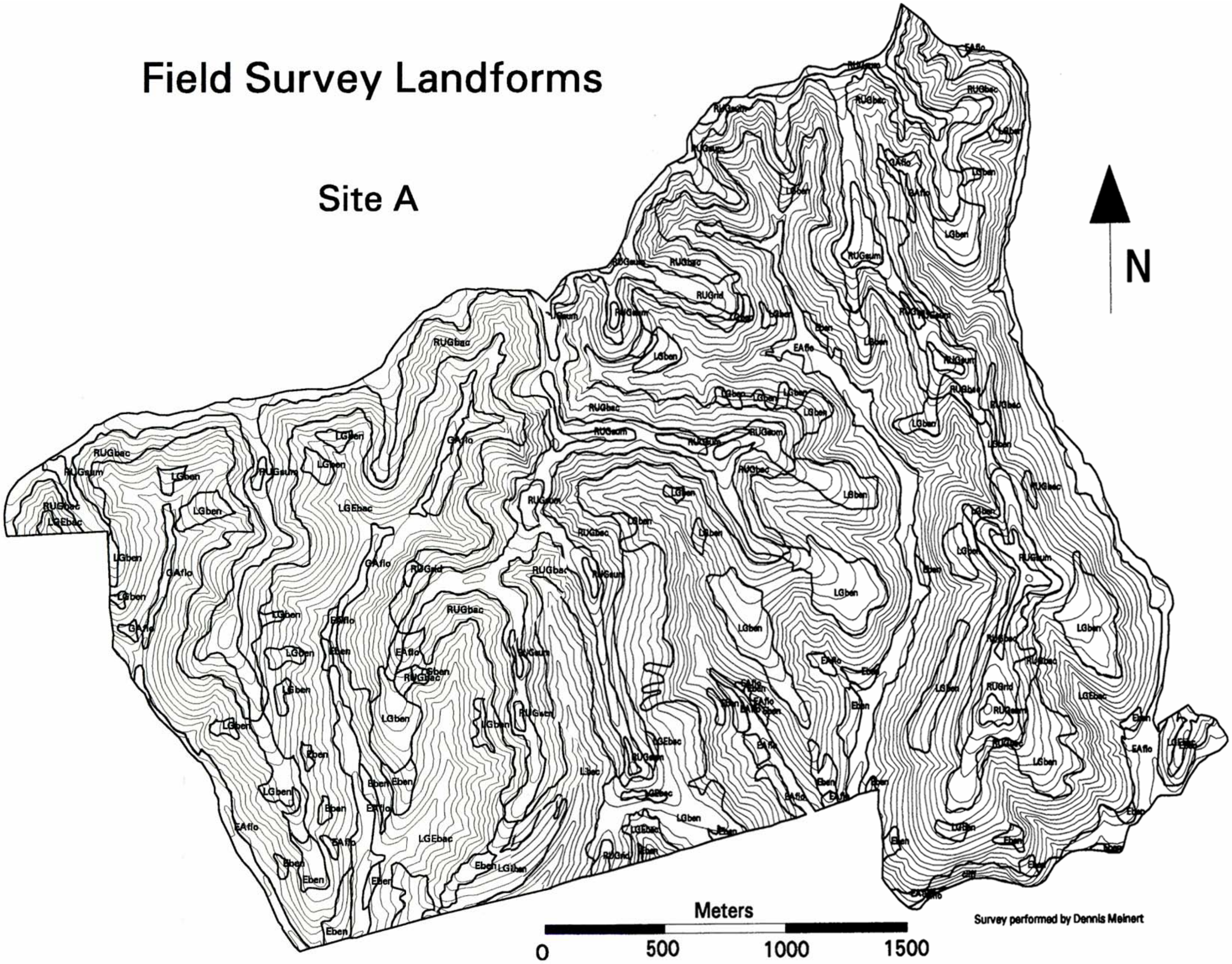
Depth Definitions: VD = very deep (> 152 cm), D = Deep (102-152 cm), MD = moderately deep (51-102) cm, SH = shallow (< 51 cm).

*Adapted from Meinert et al. (1997), Meinert (2001), and Soil Survey Staff (2004). Map units 1 and 13 are not shown because of insufficient data to characterize those units.
+Common soil series are named. Generally, soil series that occur in at least 15% of each map unit are named. Soil taxonomy was not used as criteria for soil mapping units, but is shown here to give examples of common taxonomic units that occur in each map unit. Soil series names with variant listed in the name are not official soil survey series. All soil series are in mesic temperature regime.

Figure 3.9 (following page) Field survey landforms created by aggregating 35 field survey map units into nine major landforms units. The nine abbreviations for the field-delineated landforms are: Eflo = Eminence Waterway, Gflo = Gasconade Waterway, LGben = Lower Gasconade Bench/Secondary Ridge, RUGbac = Roubidoux/Upper Gasconade Backslope, Cliff = Cliff, RUGrid = Roubidoux/Upper Gasconade Ridge, RUGsum = Roubidoux/Upper Gasconade Summit.

Field Survey Landforms

Site A



Survey performed by Dennis Meinert

Table 3.3 Meso-scale Landforms of the Current River Breaks

Landform	**Description**	**Inclusions or variations**	**Field survey Map units**
Roubidoux/Upper Gasconade Summit	Highest portion of hillslope with slopes <= 8% for a width > 60 meters and linear to slightly convex shapes.		03, 61C, 63C, 80C
Roubidoux/Upper Gasconade Ridge or Shoulder	<u>Ridge</u> - a convex stream divide on the highest portion of the hillslope with no portion of the landform containing slopes <= 8% for a width of > 60 m. Slopes <= 20% <u>Shoulder</u> -the convex zone of the landscape connecting a summit or ridge with a backslope. Slopes are 8 - 20%.	*Cryptozoan Reef benches occurring in upper gasconade geology with slopes <= 20%.	63D, 80D
Roubidoux/Upper Gasconade Backslope	Steepest portion of a hillslope with linear to slightly convex shape and slopes 20 to 60%. Occurring in the Roubidoux or Upper Gasconade geologic formations.	*Narrow, upland concavities with slopes <= 20%	63F, 80F, 83F
Lower Gasconade/ Eminence Backslope	Occurring in the lower gasconade (Van Buren and Gunter) geologic formation.	*Narrow, upland concavities with slopes <= 20%	70F, 71F, 74F, 75F, 81F, 82F
Cliff/Bluff	Steep, perpendicular or overhanging faces with slopes > 60%.		87G
Lower Gasconade Bench/Secondary Ridge	<u>Bench</u> - gently inclined surface occurring in Van Buren or Gunter formations held by resistant Gunter sandstone occurring on slopes <= 20%. <u>Secondary Ridge</u> - a lower ridge in Van Buren or Gunter materials separated from upper ridges or summits by more sloping landforms. Surfaces are convex and slopes are <= 20%.		73C, 73D, 81D, 82D, 89C, 89D
Eminence Secondary Ridge/Bench	Secondary ridges or Bench landforms that occasionally occur on Eminence materials with slopes <= 20%		70D, 74D, 75D
Gasconade Waterway	Relatively narrow drainageway formed from alluvial or hillslope deposits with slopes less than 20% and occurring in the gasconade geologic formation. Almost always a low order stream with intermittent water flow.	*Terraces *Strath terraces *Alluvial fans *colluvial footslopes	13, 15, 31, 41D, 42C, 42D, 45D, 78D
Eminence Waterway	Relatively narrow drainageway occurring in the eminence geologic formation. Usually a low order stream with intermittent water flow.	*Terraces *Strath terraces *Alluvial fans *Colluvial footslopes	27, 13, 15, 41D, 42C, 42D, 45D, 78D

Table 3.4 Map unit composition of aggregated landform units of Site A.

	Soil Map unit Area			**Landform Area**	
Landforms	**Unit**	**ha**	**%**	**ha**	**%**
Roubidoux/Upper Gasconade Summit	03	0.1	0.0		
	61C	1.5	0.2		
	63C	10.8	1.3		
	80C	8.6	1.1	21.0	2.6
Roubidoux/Upper Gasconade Ridge/Shoulder	63D	33.9	4.1		
	80D	54.9	6.7	88.8	10.9
Roubidoux/Upper Gasconade Backslope	63F	5.5	0.7		
	80F	142.9	17.5		
	83F	5.4	0.7	153.8	18.8
Lower Gasconade/ Eminence Backslope	70F	8.4	1.0		
	71F	0.9	0.1		
	74F	72.2	8.8		
	75F	108.6	13.3		
	81F	11.9	1.5		
	82F	175.5	21.5	377.5	46.3
Cliff/Bluff	87G	2.7	0.3	2.70	0.3
Lower Gasconade Bench/ Secondary Ridge	73C	3.6	0.4		
	73D	9.6	1.2		
	81D	2.4	0.3		
	82D	22.4	2.7		
	89C	7.1	0.9		
	89D	54.5	6.7	99.6	12.2
Eminence Secondary Ridge/Bench	70D	0.9	0.1		
	74D	1.6	0.2		
	75D	17.9	2.2	20.4	2.5
Gasconade Waterway	31	4.7	0.6	4.70	0.6
Eminence Waterway	27	25.1	3.1		
	1	0.3	0.0	25.4	3.1
Other Alluvial/Colluvial Soils (aggregated with either Eminence or Gasconade Waterways	13	0.3	0.0		
	15	2.9	0.4		
	41D	1.2	0.1		
	42C	0.4	0.0		
	42D	6.5	0.8		
	45D	6.6	0.8		
	78D	4.4	0.5	22.3	2.7
TOTALS		816.2	99.8*	816.2	100.0

*rounding error results in totals different from 100.

Rule-based Classification

“Rule-based classification” is defined here as a classification in which the user determines the class composition with respect to user knowledge of soil-geomorphic-ecological relationships. This classification used conditional and mathematical operators entered into a file with a text editor and then processed in Arc/Info GRID with the DOCELL command. The DOCELL command processes conditional statements similar to an Arc/Info AML. A simple rule-based classification based on three input grids (elevation, slope gradient, and surface curvature) might be:

```
DOCELL
if (slopegrid < 8 & elevationgrid >= 249) landform = 1
else if (slopegrid >= 8 & slopegrid < 20 & elevationgrid > 249 &
curvegrid > .2) landform = 2 else if (slopegrid >= 20 ) landform = 3
else if (slopegrid < 20 & elevationgrid < 249 & curvegrid >= .2)
landform = 4
else if (slopegrid < 20 & elevationgrid < 249 & curvegrid < .2) landform
= 5
END
```

“where 1 = flat summit, 2 = narrow ridge or shoulder, 3 = sideslopes, 4 = structural bench, 5 = floodplain”.

The rule-based classification analyses used site A for model development and site B for model verification. An initial DTM was produced and compared to the site A field survey. The DTM was modified to more closely replicate the field survey. These modifications involved global commands to alter the elevation breaks used to distinguish geologic formations, slope breaks used to distinguish landforms, and the values used with the *elevation above local drainageway* and *relative location below local ridge* grids to indicate relative landscape position. The modifications did not adjust the kind or calculation of terrain attributes used in the model. After fine-tuning the DTM for site A, it was appled to site B with the only adjustment being the elevation breaks used to distinguish geology formations.

Supervised Classification

Supervised classification involves the user defining classes and creating training samples that characterize the values of all input grids for each class. The signatures of the training samples are used to classify the region. Supervised classification techniques often are used for classifying vegetation and land-cover from spectral data or a combination of spectral data and other data such as terrain features. Researchers have used supervised methods for vegetation classification (Treitz et al., 1992) but less extensively for landform classification (Hengl and Rossiter, 2003).

The supervised classification was performed in Arc/Info (ESRI 1994). The prototypes (training areas) for the classification were from the soil-geomorphic survey of site A. The larger aggregated soil-geomorphic map units were used as training sites. Each map unit was buffered to the inside by the "SHRINK" command in Arc/Info GRID module, so the resulting training areas contained sites well within the boundaries of each map unit. This procedure minimized problems due to edge effect, digitizing errors or positional errors.

Three sizes of training data were used for site A: 1) a large training set of 242 ha (29.1% of site A), a medium-sized training set of 83 ha (9.9% of site A), and 3) a small training set of 46 ha (5.6% of site A) (Fig. 3.10). The "SAMPLE" command was used to sample the training areas for all of the input grids. The "SAMPLESIG" command was used to create signature files of the training areas for each input grid for each landform class. A stack was created with "MAKESTACK" command to use as an input for each of the classification attempts. The "MLCLASSIFY" command was used to classify each grid cell based on a comparison with the signature files. Several supervised classification models were attempted using 24 different combinations of input grids. However, ten combinations of input grids were unsuccessful. Reasons

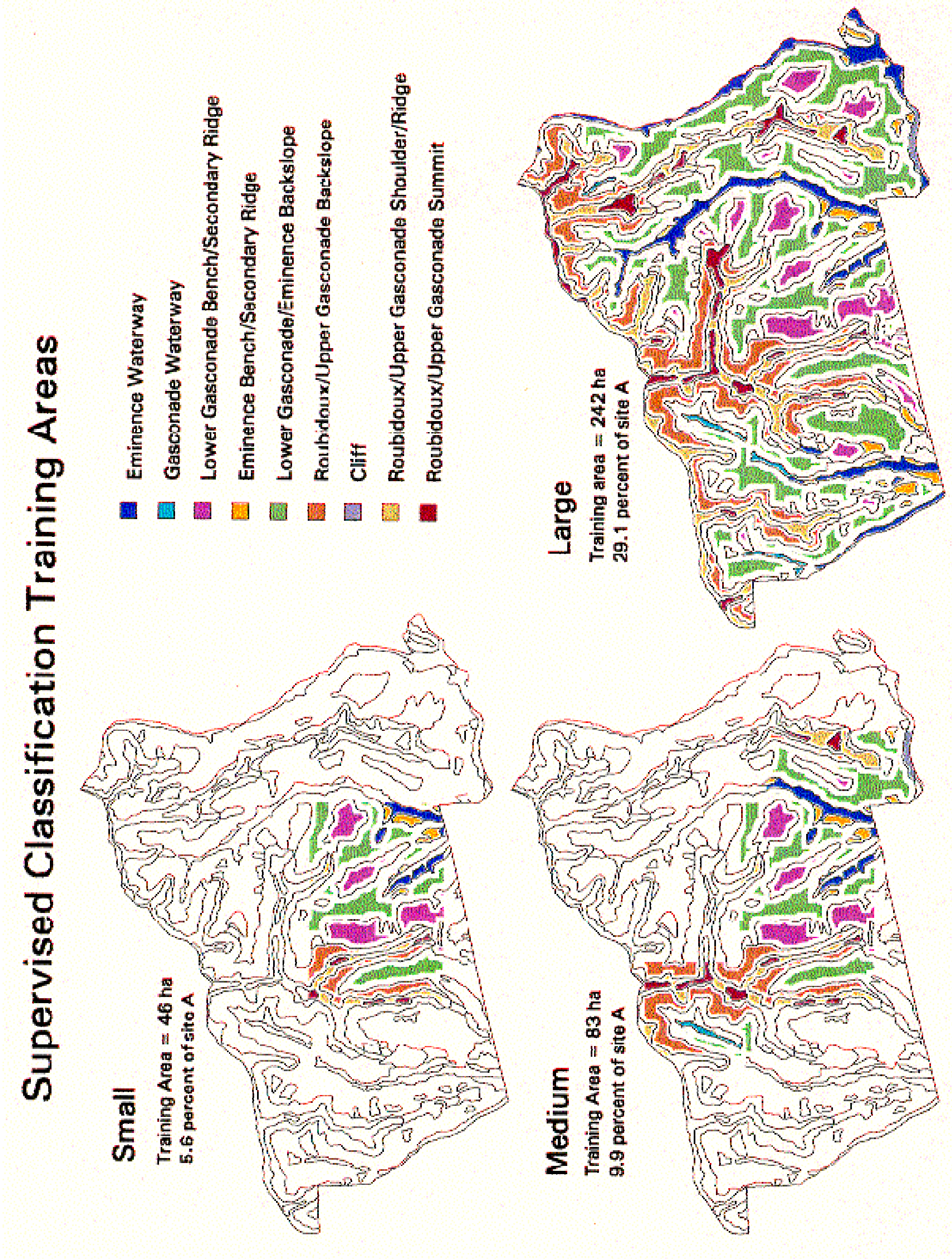


Figure 3.10 Supervised classification training areas with three levels of training area intensity.

for the unsuccessful classifications are unclear, however, problems with the Arc/Info supervised classification commands have been noted by other users (ESRI listserve; October, 1996). The 14 successful supervised classification models compared with the aggregated soil-geomorphic units from the field survey. Classifications were compared with and without *a priori* knowledge. *A Priori* knowledge can be included in the model if the modeler knows approximate frequencies of landforms.

A second analysis of supervised methods used the large training set of site A (covering 29.1% of site A) as a training set for site B. Each site B cell was classified based on the signature files developed from site A. *A Priori* class frequency knowledge was inserted into the model assuming the same frequency of landform occurrence as used for site A.

Unsupervised Classification

Unsupervised classification is a common method of vegetation and landcover classifications (Woodcock et al., 1994), in which spectral signatures from multiple wavelengths are used to determine classes. It also has potential for landform classification as demonstrated by Irvin et al. (1995) on a 50-hectare site in Wisconsin, where automated unsupervised classification produced higher detail resolution than manual classification with air photo stereopairs.

The unsupervised classification was performed only on site A. The set of attributes with the greatest success in the supervised classification was used for the unsupervised classification. A grid stack was created with the MAKESTACK command, and “ISOCLUSTER” was used to create signature files based on natural groupings of data points. The MLCLASSIFY command was used to classify each cell on the basis of which cluster of data points it most resembled.

Comparisons

Table 3.5 summarizes the methods used to compare DTM’s and the comparisons made for this chapter. A limited time period was available for completion of the GIS work on the Arc/Info GIS station. While the site A field data became available early in the GIS work, the site B data only became available towards the end of the GIS work, meaning that more intensive analyses was performed on site A than site B.

DTM’s developed with rule-based methods were done initially on site A. The site A field survey was used as a reference during the development of the rule-based model, thus site A was considered the training site for the rule-based model. The agreement of the landforms delineated on the rule-based model and the field survey were analyzed in detail. In addition, the rule-based model developed on site A was applied to site B. The overall agreement of the site B rule-based model and the field survey was determined, however, the agreement of landform class between the model and the field survey was not analyzed. Initially 14 different supervised models were performed on site A using large-sized training areas. Three of the supervised classifications were used to observe the effect of *a priori* information on the success of each model. Supervised classification model #3 was analyzed in detail with the agreement of the landforms delineated by supervised model #3 and the field survey observed. Additionally, supervised model #3 was performed using three different training area intensities. The final test of supervised classification was to apply supervised model #3 to the test site (B). The field survey was not available at the time the GIS work was performed, thus only a qualitative analyses was performed. In addition, an unsupervised classification was performed on site A. It was visually assessed by comparison to the site A field survey.

Table 3.5 Procedures used for DTM evaluations.

DTM TECHNIQUE	EVALUATION METHOD	SITE
Rule-based Classification (training site model)	Performed with access to field classification. The accuracy of each landform class was assessed by comparison to the field survey.	A
Rule-based Classification (test site model)	Application of model developed on the training (site A) to the test site (site B). The model was compared to the field survey.	B
Supervised Classification (comparison of different models)	14 different supervised models were developed from the large-sized training area and compared to the field classification.	A
Supervised Classification (*Priori* influences)	Comparisons were made of 3 supervised models performed with and without *Priori* information.	A
Supervised Classification (Accuracy of Landform classes)	The accuracy of each landform class in supervised model #3 was compared to the field survey.	A
Supervised Classification (comparison of training area intensity)	Supervised model #3 was performed using 3 different training area intensities.	A
Supervised Classification (test site)	Supervised model #3 developed on site A with the large training area was applied to site B. Results were qualitatively assessed.	B
Unsupervised Classification	Unsupervised classification was qualitatively compared to field classification.	A

RESULTS AND DISCUSSION

Rule-Based Classification

The final model used five grid databases, including elevation, slope, curvature, *elevation above local drainageway*, and *relative location above local ridge*. Five grids required several conditional statements for all potential situations, and a total of 30 conditional statements were used for the final rule-based classification (Table 3.6). Initial model development and results from chapter 3 showed that the DEM often overestimated gentle slopes and underestimated steeper

Table 3.6 The digital terrain model of Site A using rule-based methods.

```
“comments are in quotes”
“80 = Roubidoux/Upper Gasconade Summit”
“70 = Roubidoux/Upper Gasconade Ridge/Shoulder”
“51 = Eminence Secondary Ridge/Bench”
“50 = Lower Gasconade Bench/Secondary Ridge”
“42 = Cliff/Bluff or Steep Slope”
“41 = Lower Gasconade/Eminence Backslope”
“40 = Roubidoux/Upper Gasconade Backslope”
“11 = Eminence Waterway”
“10 = Gasconade Waterway”

docell

“for elevations >= to 255 meters”
if ( SLOPE <= 11 & ELEVATION >= 255 & SUMX >= 89 ) LANDFORM = 80
else if (SLOPE <= 11 & ELEVATION >= 255 & SUMX < 89 ) LANDFORM = 70
else if ( SLOPE > 11 & SLOPE <= 21 & ELEVATION >= 255 ) LANDFORM = 70
else if ( SLOPE > 21 & SLOPE <= 47 & ELEVATION >= 255 ) LANDFORM = 40

“for elevations >= 249 and < 255 meters”
else if ( ELEVDRAIN > 3 & SLOPE <= 23 & ELEVATION >= 249 & ELEVATION < 255 &
CURVATURE > -.5 )  LANDFORM = 50
else if ( ELEVDRAIN > 3 & SLOPE <= 23 & ELEVATION >= 249 & ELEVATION < 255 &
CURVATURE <= -.5 ) LANDFORM = 40
else if  ( SLOPE <= 23 & ELEVDRAIN <= 3 & ELEVATION >= 249 & ELEVATION < 255 )
LANDFORM = 40
else if ( SLOPE > 23 & SLOPE <= 47 & ELEVATION >= 249 & ELEVATION < 255 )
LANDFORM = 40

“for elevations < 249 and >= 216 meters”
else if ( ELEVDRAIN > 3 & SLOPE <= 23 & ELEVATION < 249 & ELEVATION >= 216 &
CURVATURE > -.5 )  LANDFORM = 50
else if ( ELEVDRAIN > 3 & SLOPE <= 23 & ELEVATION < 249 & ELEVATION >= 216 &
CURVATURE <= -.5 )  LANDFORM = 41
else if ( SLOPE > 23 & SLOPE <= 47 & ELEVATION < 249 & ELEVATION >= 216 )
LANDFORM = 41
else if ( ELEVDRAIN <= 3 & SLOPE <= 23 & SLOPE > 15 & ELEVATION < 249 &
ELEVATION >= 216 & CURVATURE > -.5 )  LANDFORM = 50
else if ( ELEVDRAIN <= 3 & SLOPE <= 23 & SLOPE > 15 & ELEVATION < 249 &
ELEVATION >= 216 & CURVATURE <= -.5 )  LANDFORM = 41
else if ( ELEVDRAIN <= 3 & SLOPE <= 15 & ELEVATION < 249 & ELEVATION >= 216 &
ACCUMBUFFER <= 2 )  LANDFORM = 41
else if ( ELEVDRAIN <= 3 & ELEVDRAIN > 2 & SLOPE <= 15 & SLOPE > 6 & ELEVATION <
249 & ELEVATION >= 216 & ACCUMBUFFER > 2 )  LANDFORM = 41
else if ( ELEVDRAIN <= 2 & SLOPE <= 15 & SLOPE > 6 & ELEVATION < 249 & ELEVATION
>= 216 & ACCUMBUFFER > 2 )  LANDFORM = 10
else if ( ELEVDRAIN <= 3 & ELEVDRAIN > 2  & SLOPE <= 6 & ELEVATION < 249 &
ELEVATION >= 216 & ACCUMBUFFER > 2 )  LANDFORM = 10
else if ( ELEVDRAIN <= 2  & SLOPE <= 6 & ELEVATION < 249 & ELEVATION >= 216 &
ACCUMBUFFER > 2 )  LANDFORM = 10

“for elevations < 216 meters”
else if  ( ELEVDRAIN > 3 & SLOPE <= 21 & ELEVATION < 216 & CURVATURE <= -.5 )
LANDFORM = 41
else if  ( ELEVDRAIN > 3 & SLOPE <= 21 & ELEVATION < 216  & CURVATURE > -.5 )
LANDFORM = 51
else if ( ELEVDRAIN > 3 & SLOPE > 21 & SLOPE <= 47 & ELEVATION < 216  ) LANDFORM
= 41
else if  ( ELEVDRAIN <= 3  & SLOPE <= 21 & ACCUMBUFFER <= 2 & ELEVATION < 216 )
LANDFORM = 41
else if  ( ELEVDRAIN <= 3  & ELEVDRAIN > 2 & SLOPE <= 21 & SLOPE > 15 &
ACCUMBUFFER > 2 & ELEVATION < 216 ) LANDFORM = 41
else if  ( ELEVDRAIN <= 3  & ELEVDRAIN > 2 & ACCUMBUFFER > 2 & SLOPE <= 15 &
SLOPE > 6 & ELEVATION < 216 ) LANDFORM = 41
else if  ( ACCUMBUFFER > 2 & SLOPE > 15 & ELEVATION < 216 ) LANDFORM = 41
```

Table 3.6 - continued

```
“for elevations < 216 meters and >= 211 meters”
else if  ( ELEVDRAIN <= 2 & ACCUMBUFFER > 2 & SLOPE <= 15 & ELEVATION < 216 &
ELEVATION >= 211 ) LANDFORM = 10
else if  ( ELEVDRAIN <= 3  & ELEVDRAIN > 2 & ACCUMBUFFER > 2 & SLOPE <= 15 &
SLOPE > 6  & ELEVATION < 216 & ELEVATION >= 211 ) LANDFORM = 10

“for elevations < 211 meters”
else if ( SLOPE <= 6 & ELEVDRAIN <= 3 & ELEVDRAIN > 2 & ELEVATION < 211 &
ACCUMBUFFER > 2 ) LANDFORM = 11
else if  ( ELEVDRAIN <= 2 & SLOPE <= 15  & ELEVATION < 211 & ACCUMBUFFER > 2 )
LANDFORM = 11

“for all slopes > 47%”
else if ( SLOPE > 47 ) LANDFORM = 42

end
```

slopes, tending to over-generalize the landscape. To compensate, model slope breaks were adjusted to match field-determined slope breaks. For example, the field survey found bench landforms to have slopes from 8 to 20%. The terrain model did not identify many of the structural benches, so a slope break from 10 to 23% was chosen to delineate them. Increasing the limits for slope breaks was also necessary to identify summits and ridges/shoulders. Steeper slopes were identified by compensating for the terrain model’s underestimation of steep slopes. Cliffs and bluffs were identified in the model as all areas > 47% slope, whereas the field survey identified all slopes > 60%. In addition to the DEM error, another reason that these adjustments may have been necessary is that the natural slope breaks that distinguished different soil-geomorphic units may not have been exactly the same as the slope breaks. For example, the bench landforms may have tended to occur on slopes as steep as 22 or 23% rather than the 20% breaks setup in the field-survey legend.

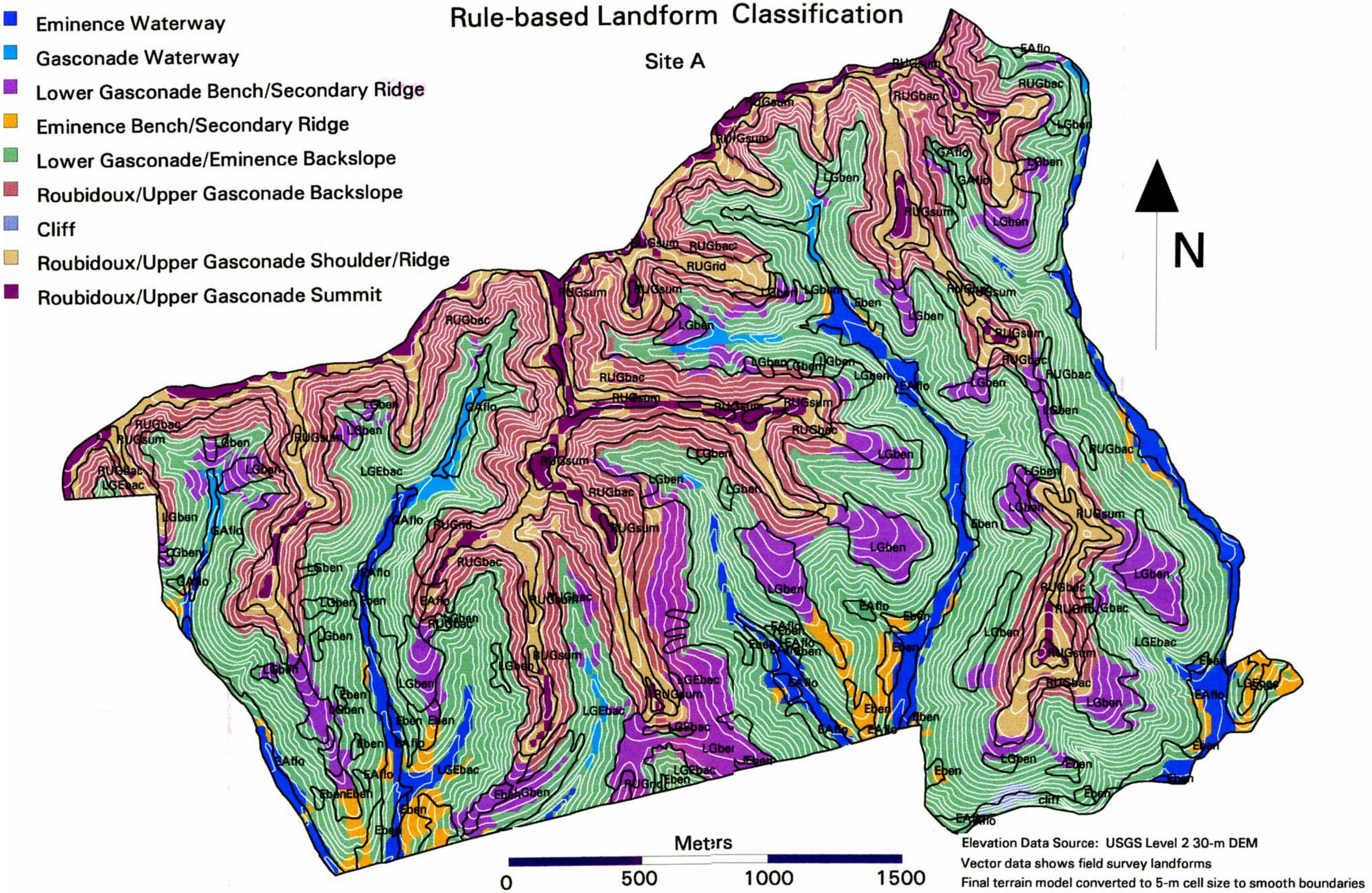
The final rule-based classification on site A had 71.2% agreement with the field survey (Fig. 3.11). The success of predicting different landform classes varied considerably according to the class in question (Table 3.7, Fig. 3.12). Generally, the landscape features with the largest extent were the easiest to predict. The two backslope landforms had the highest agreement. More than 50% successful classification also was reported for the Lower Gasconade bench/secondary ridges, the Eminence Alluvial Waterways, the Roubidoux/Upper Gasconade Ridge/Shoulders, and the Roubidoux/Upper Gasconade Summits. Agreements < 50% were found for Gasconade Alluvial Waterways, Eminence Secondary Ridge/Benches, and Cliff/Bluffs. The adjustment of slope classes described previously, still resulted in only 25.7% of the cliff/bluffs being correctly identified. However, cliff/bluff landforms are not extensive, covering only 3.7 ha (0.3%) of site A (table 3.4). Results indicate a further aggregation of land units might be considered. The summit landform occurs in small areas and probably will not be managed much differently than the ridge landforms, so these might be combined. When these two are combined, the model predicts 77.6% of the landform classes the same as the field survey.

Error in the rule-based model showed some patterns (Table 3.7). Misclassified bench landform units were most commonly classified as backslopes, probably because many of the benches delineated in the field were relatively steep (approximately 17-23% slopes) and difficult to distinguish topographically from the surrounding sideslopes. Waterways were misclassified because it was difficult to predict when a concave, gently sloping area would have sizable alluvial deposits and when these areas were V-shaped drains with insignificant amounts of alluvial sediments.

Figure 3.11 (following page). Rule-based landform classification of site A. Different colored classes show the nine landforms predicted by the rule-based model. Vector data show the nine landform classes determined in the field. Abbreviations for the field-delineated landforms are: Eflo = Eminence Waterway, Gflo = Gasconade Waterway, LGben = Lower Gasconade Bench/Secondary Ridge, RUGbac = Roubidoux/Upper Gasconade Backslope, Cliff = Cliff, RUGrid = Roubidoux/Upper Gasconade Ridge, RUGsum = Roubidoux/Upper Gasconade Summit.

Rule-based Landform Classification

Site A



Elevation Data Source: USGS Level 2 30-m DEM
Vector data shows field survey landforms
Final terrain model converted to 5-m cell size to smooth boundaries

Table 3.7 Landform Class Accuracy of Rule-based Classification on site A. Figures in bold indicate the percent agreement between field-determined landforms and DTM landforms. Other figures show the major misclassifications for each landform. Misclassifications < 1.5% are listed under "all others" category.

Field Landform	**DTM Landform**	**% of Class**
Roubidoux/Upper Gasconade Summit (RUGsum)	**RUGsum**	**51.1%**
	RUGrid	45.5%
	RUGbac	3.6%
Roubidoux/Upper Gasconade Ridge or Shoulder (RUGrid)	**RUGrid**	**58.9%**
	RUGbac	23.0%
	RUGsum	14.4%
	LGben	3.1%
	all others	0.5%
Roubidoux/Upper Gasconade Backslope (RUGbac)	**RUGbac**	**79.1%**
	RUGrid	10.6%
	LGEbac	8.1%
	LGben	1.8%
	all others	0.4%
Lower Gasconade/ Eminence Backslope	**LGEbac**	**77.8%**
	RUGbac	9.7%
	LGben	5.6%
	Eflo	2.6%
	Eben	2.3%
	all others	1.9%
Cliff/Bluff (cliff)	**Cliff**	**25.7%**
	LGEbac	74.3%
Lower Gasconade Bench/Secondary Ridge (LGben)	**LGben**	**61.3%**
	LGEbac	27.4%
	RUGbac	6.5%
	RUGrid	3.4%
	all others	1.3%
Eminence Secondary Ridge/Bench (Eben)	**Eben**	**32.6%**
	LGEbac	41.4%
	LGben	14.5%
	Eflo	11.5%
Gasconade Waterway (Gflo)	**Gflo**	**34.4%**
	LGEbac	34.7%
	Eflo	27.0%
	LGben	1.9%
	all others	2.0%
Eminence Waterway (Eflo)	**Eflo**	**59.6%**
	LGEbac	30.1%
	Eben	7.2%
	Gflo	1.8%
	all others	1.3%

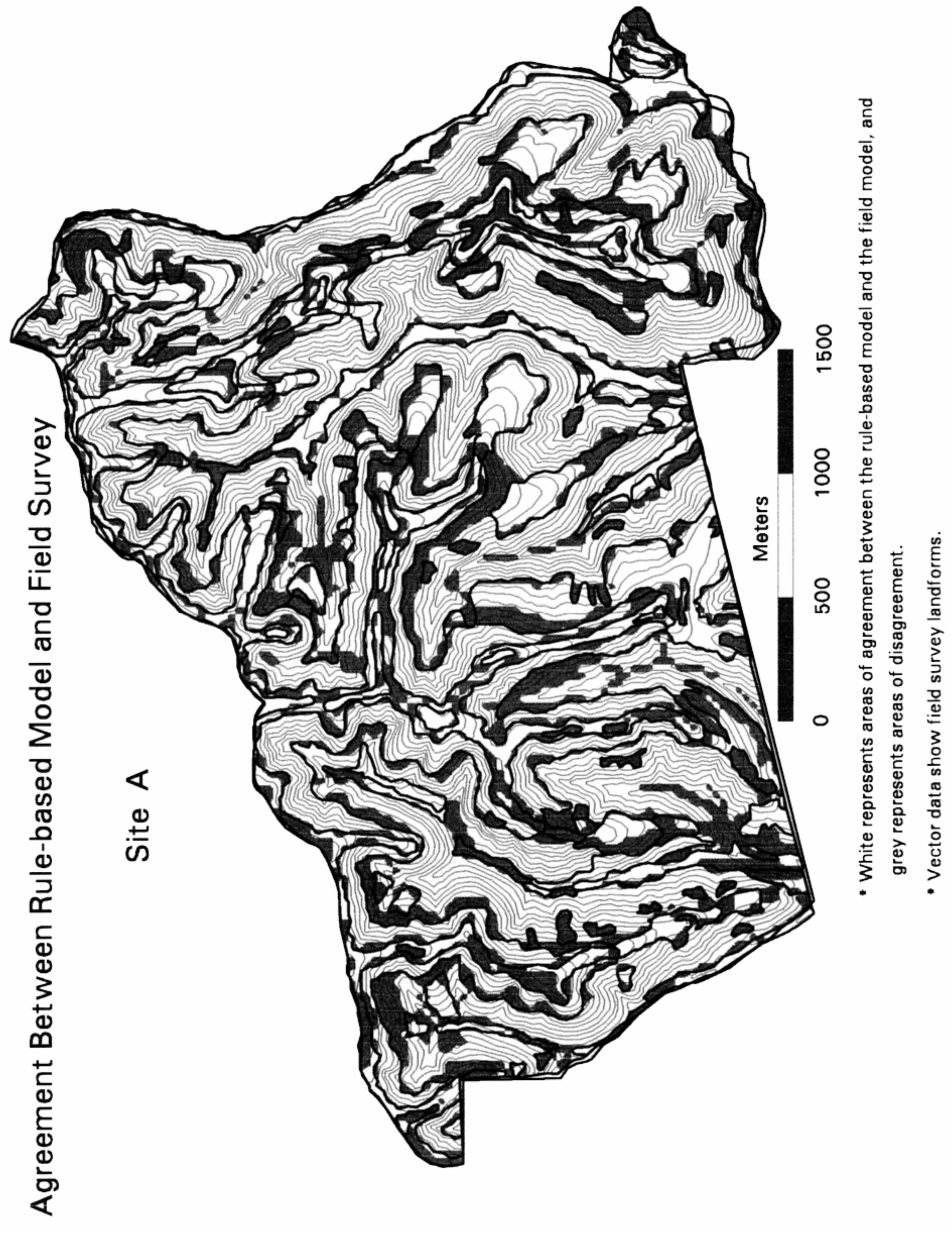


Figure 3.12 Agreement between rule-base model and field survey for site A. White shows areas of agreement and grey shows area of disagreement between the rule-based model and the field survey.

The rule-based methods on site A were applied to site B with the only changes occurring in the elevation breaks used to denote different geologic formations (Fig. 3.13). The site B terrain model was compared to the site B field survey. The terrain model had 64.3% agreement with the field survey. Unfortunately, the site B field survey was not available until after the figures for this chapter were produced, so there is no accompanying figure showing the field survey and the terrain overlaid, as was shown for site A. The types of errors in the site B model were not investigated in detail, however, errors associated with the less predictable geology of site B were the most visible. The other errors associated with the site B model appeared to be similar as those occurring on site A.

Supervised Classification

There were 14 successful attempts at supervised classification with various combinations of terrain attributes (Table 3.8), using the large training set (Fig. 3.10). The classification was most successful when *a priori* information about class frequency was included in the model. Supervised classifications with *priori* knowledge had agreements with the field model seven to ten percentage points higher than those models without *a priori* information (Table 3.9). Many models with different attributes produced similar agreement with the field model (Table 3.8). Supervised classifications combining elevation and slope with at least one other attribute had at least 68.6% agreement with the field survey. Increasing the number of terrain attributes after a certain point did not necessarily improve model accuracy. For example, model number eight was not so successful as models two and three, even though model eight included all attributes of models two and three plus additional attributes (Table 3.8).

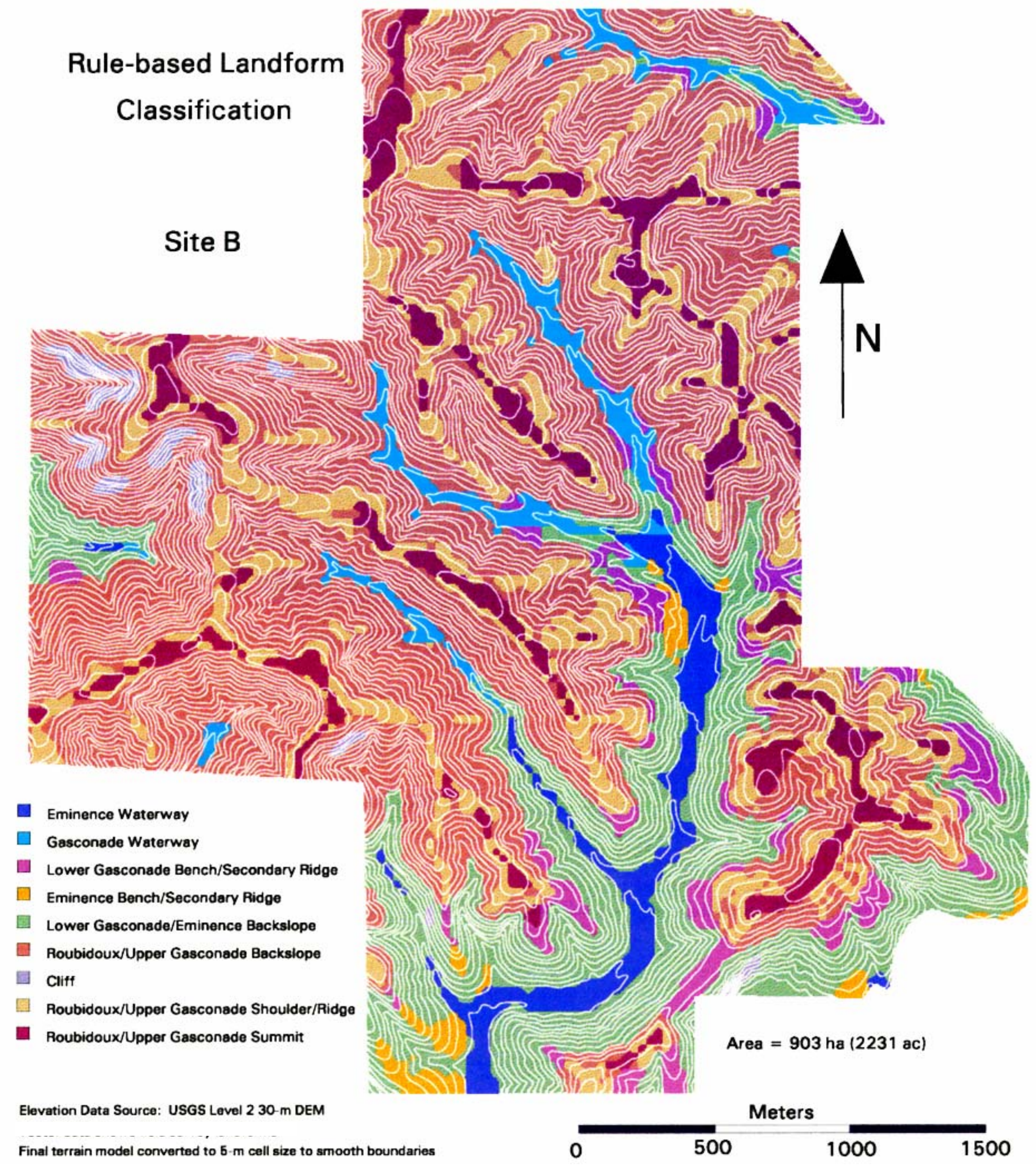


Figure 3.13 Rule-based classification for site B. Different colored classes show the nine landforms predicted by the rule-based model.

Table 3.8 Agreement between supervised classification models and the field survey. Terrain attributes that were used for each model are noted by an x in the attribute column. Model agreement with the field survey is noted in the last column. A priori knowledge of class probabilities was used for all supervised classifications.

	Terrain Attributes											
MODEL#	**ELEV**	**SLOPE**	**CURVE**	**PRO**	**PLAN**	**ELEV-DRAIN**	**ELEV-RIDGE**	**ELEV-MIN**	**ELEV-MAX**	**SUMX**	**DRAINX**	**%Agreement**
1	x	x	x			x				x		70.9
2	x	x	x									70.8
3	x	x	x							x	X	71.6
4		x								x	X	68.6
5	x	x							x			69.6
6	x	x						x				71.3
7	x	x						x		x	X	70.7
8	x	x	x			x		x		x	X	70.5
9	x	x				x						71.0
10	x	x								x		69.2
11	x	x									X	71.2
12	x	x	x			x					X	70.1
13	x	x	x					x			X	70.5
14	x	x				x		x			X	69.5

*Terrain attribute abbreviations: ELEV = elevation; SLOPE = slope gradient; CURVE = curvature; PRO = profile curvature; PLAN = plan curvature; ELEVDRAIN = elevation above local drainageway; ELEVMAJOR = elevation above major drainageway; ELEVRIDGE = elevation below local ridge; ELEVMIN = elevation above localized minimum; ELEVMAX = elevation below localized maximum; SUMX = relative location below summit; DRAINX = relative location above drainageway.

Table 3.9 Effect of *a priori* knowledge on success of three supervised classification models.

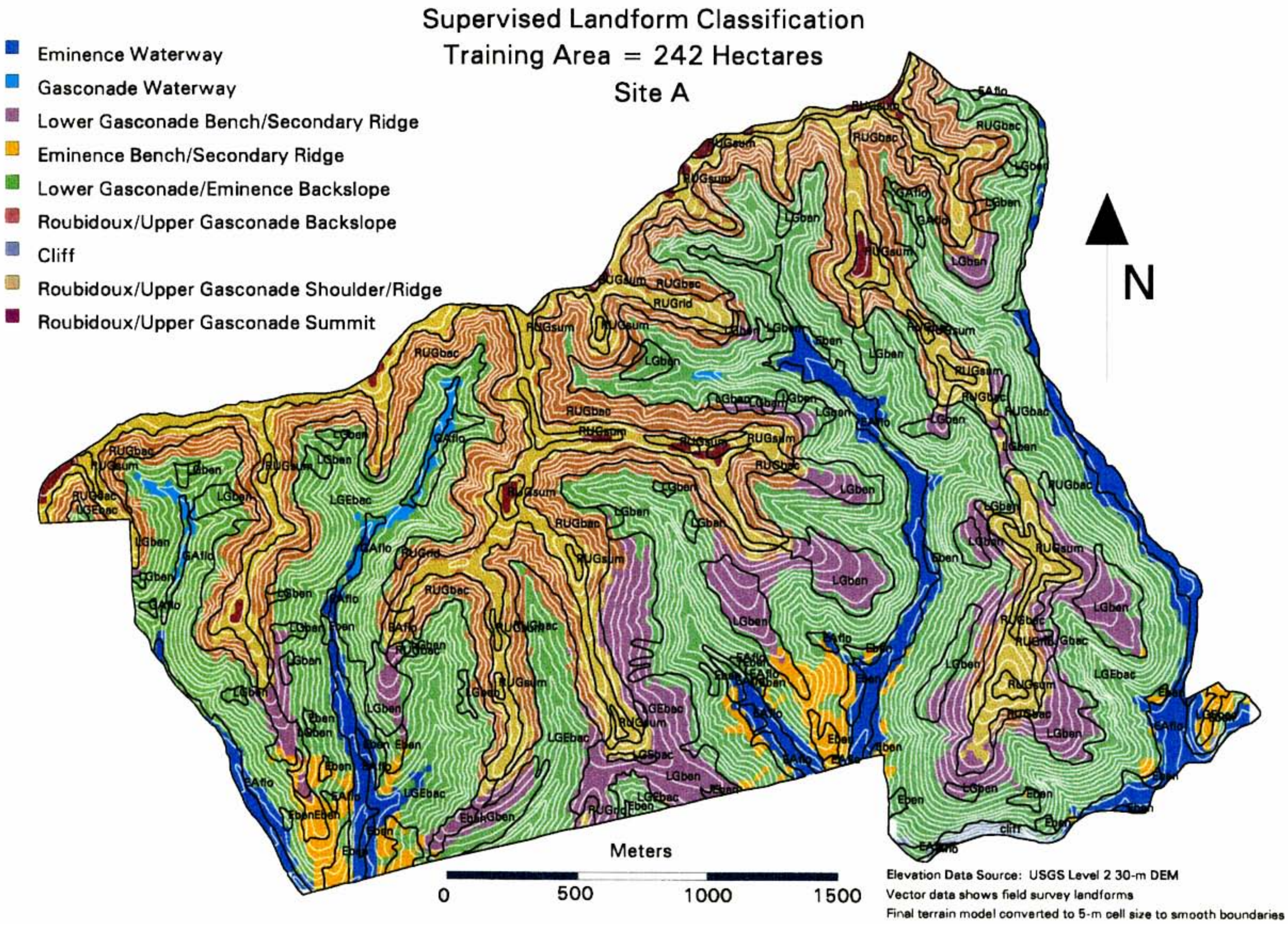
Model #	**Input Grids**	**Agreement Without *A Priori***	**Agreement with *A Priori***
1	ELEV, SLOPE, CURVE, ELEVDRAIN, SUMX	62.0%	70.9%
2	ELEV, SLOPE, CURVE	61.2%	70.8%
3	ELEV, SLOPE, CURVE, SUMX, DRAINX	64.2%	71.6%

*Terrain attribute abbreviations: ELEV = elevation; SLOPE = slope gradient; CURVE = curvature; ELEVDRAIN = elevation above local drainageway; SUMX = relative location below summit; DRAINX = relative location above drainageway.

Model number three, with the ELEV, SLOPE, CURVE, SUMX, and DRAINX attributes as inputs, most completely agreed (71%) with the field survey (Table 3.8). This model was chosen for a more in-depth analysis of the supervised classification. However, an argument could be made for choosing a simpler model. For example, model two, with only three attributes (ELEV, SLOPE, and CURVE), had 70.8% agreement with the field survey. Model three identified a high percentage of backslope units (Fig. 3.14 and Table 3.10). Supervised techniques delineated alluvial waterways and ridge/shoulder units more accurately than the rule-based classification, although the latter was at the expense of successfully identifying summit landforms. The supervised classification less successfully delineated the Gasconade Alluvial Waterways and the two bench landforms than the rule-based classification.

The size of the training sets most influenced supervised classification’s success (Table 3.11). Model three with a large training set agreed 71.6% with the field survey (Fig. 3.14), while the same model attributes with the medium and small training sets, respectively, had agreements of 68.8% (Fig 3.15) and 64.3% (Fig 3.16) (Table 3.11). The necessity of large training areas for reasonably accurate landform classifications makes the operational potential of supervised classification techniques questionable.

Figure 3.14 (following page). Supervised landform classification of model #3 using the large (242 ha) training area. Different colored classes show the nine landforms predicted by the rule-based model. Vector data shows the nine landform classes determined in the field. The nine abbreviations for the field-delineated landforms are: Eflo = Eminence Waterway, Gflo = Gasconade Waterway, LGben = Lower Gasconade Bench/Secondary Ridge, RUGbac = Roubidoux/Upper Gasconade Backslope, Cliff = Cliff, RUGrid = Roubidoux/Upper Gasconade Ridge, RUGsum = Roubidoux/Upper Gasconade Summit.



Supervised Landform Classification
Training Area = 242 Hectares
Site A

Elevation Data Source: USGS Level 2 30-m DEM
Vector data shows field survey landforms
Final terrain model converted to 5-m cell size to smooth boundaries

Table 3.10 Landform Class Accuracy of Supervised Classification Model #3. Figures in bold indicate the percent agreement between field-determined landforms and DTM landforms. Other figures show the major misclassifications for each landform. Misclassifications < 1.5% are listed under "all others" category.

Field Landform	**DTM Landform**	**% of Class**
Roubidoux/Upper Gasconade Summit (RUGsum)	**RUGsum**	**26.7%**
	RUGrid	71.5%
	RUGbac	1.8%
Roubidoux/Upper Gasconade Ridge or Shoulder (RUGrid)	**RUGrid**	**76.9%**
	RUGbac	15.8%
	RUGsum	4.0%
	LGben	2.6%
	all others	0.7%
Roubidoux/Upper Gasconade Backslope (RUGbac)	**RUGbac**	**71.1%**
	RUGrid	16.1%
	LGEbac	10.0%
	LGben	2.7%
Lower Gasconade/ Eminence Backslope	**LGEbac**	**77.7%**
	RUGbac	7.9%
	LGEben	5.0%
	Eflo	4.2%
	Eben	3.1%
	all others	2.1%
Cliff/Bluff (cliff)	**cliff**	**77.8%**
	LGEbac	17.5%
	Eflo	2.5%
	Eben	2.2%
Lower Gasconade Bench/Secondary Ridge (LGben)	**LGben**	**58.1%**
	LGEbac	32.7%
	RUGrid	4.1%
	RUGbac	3.2%
	all others	1.9%
Eminence Secondary Ridge/Bench (Eben)	**Eben**	**33.9%**
	LGEbac	35.6%
	Eflo	20.1%
	LGben	10.2%
	all others	0.2
Gasconade Waterway (Gflo)	**Gflo**	**45.4%**
	LGEbac	46.9%
	Eflo	6.8%
	RUGbac	0.9%
Eminence Waterway (Eflo)	**Eflo**	**74.9%**
	LGEbac	17.5%
	Eben	3.8%
	Gflo	1.8%
	all others	1.9%

*Terrain attribute inputs into model #3 were: ELEV (elevation); SLOPE (slope gradient); CURVE (curvature); SUMX (relative location below summit); DRAINX (relative location above drainageway).

Table 3.11 Effect of training set size on success of supervised classification model #3.

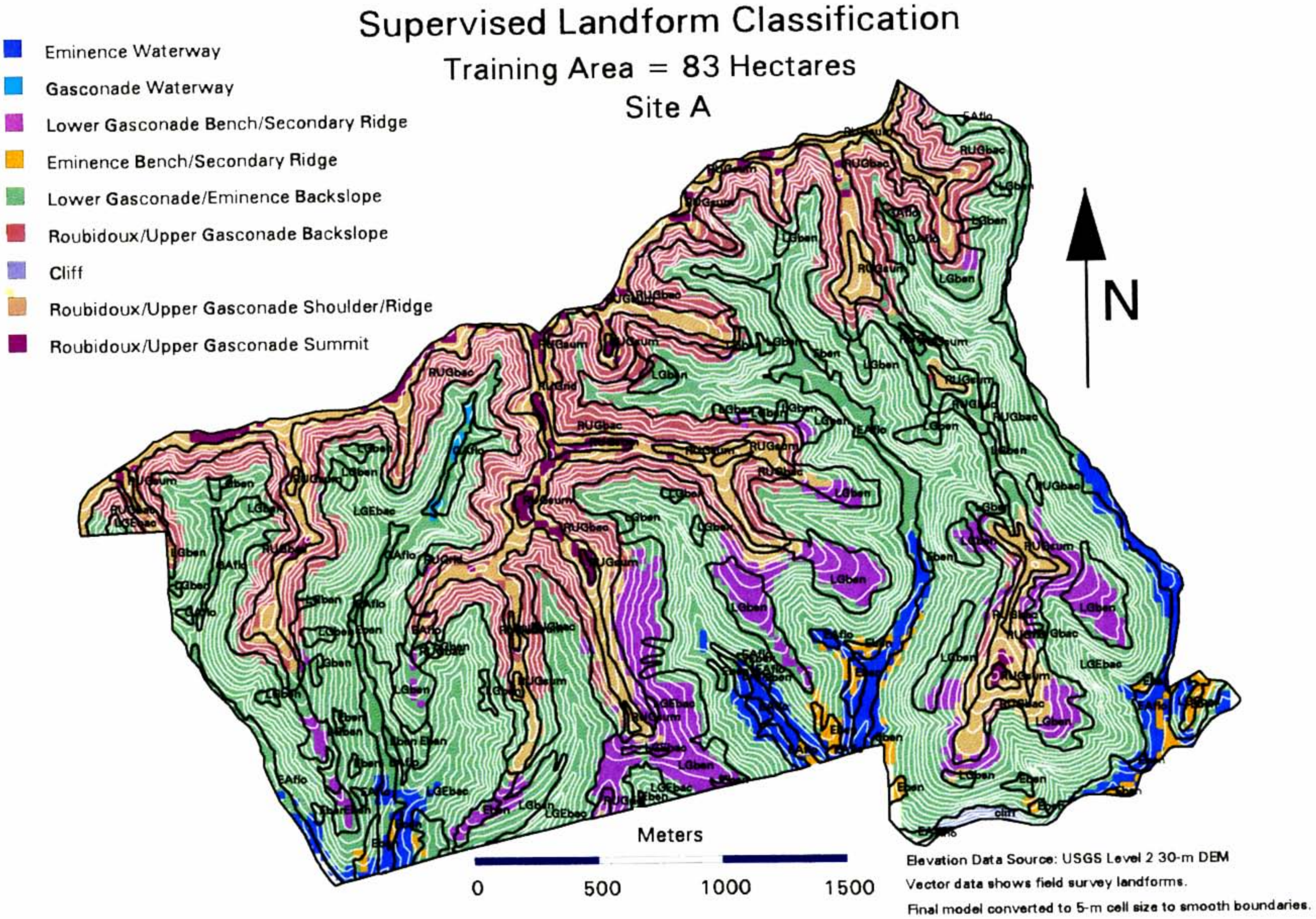
Training Set Size	**Training set size as % of Site A**	**Model Agreement with Field Survey**
46 ha (small)	5.6%	63.3%
83 ha (medium)	9.9%	68.8%
242 ha (large)	29.0%	71.6%

*Terrain attribute inputs into model #3 were: ELEV (elevation); SLOPE (slope gradient); CURVE (curvature); SUMX (relative location below summit); DRAINX (relative location above drainageway).

**A priori knowledge of class probabilities was used for all supervised classifications listed above.

Figure 3.15 (page 113). Supervised landform classification using the medium-sized (83 ha) training area. Different colored classes show the nine landforms predicted by the rule-based model. Vector data shows the nine landform classes determined in the field. The nine abbreviations for the field-delineated landforms are: Eflo = Eminence Waterway, Gflo = Gasconade Waterway, LGben = Lower Gasconade Bench/Secondary Ridge, RUGbac = Roubidoux/Upper Gasconade Backslope, Cliff = Cliff, RUGrid = Roubidoux/Upper Gasconade Ridge, RUGsum = Roubidoux/Upper Gasconade Summit.

Figure 3.16 (page 114). Supervised landform classification using the small-sized (43 ha) training area. Different colored classes show the nine landforms predicted by the rule-based model. Vector data shows the nine landform classes determined in the field. The nine abbreviations for the field-delineated landforms are: Eflo = Eminence Waterway, Gflo = Gasconade Waterway, LGben = Lower Gasconade Bench/Secondary Ridge, RUGbac = Roubidoux/Upper Gasconade Backslope, Cliff = Cliff, RUGrid = Roubidoux/Upper Gasconade Ridge, RUGsum = Roubidoux/Upper Gasconade Summit.

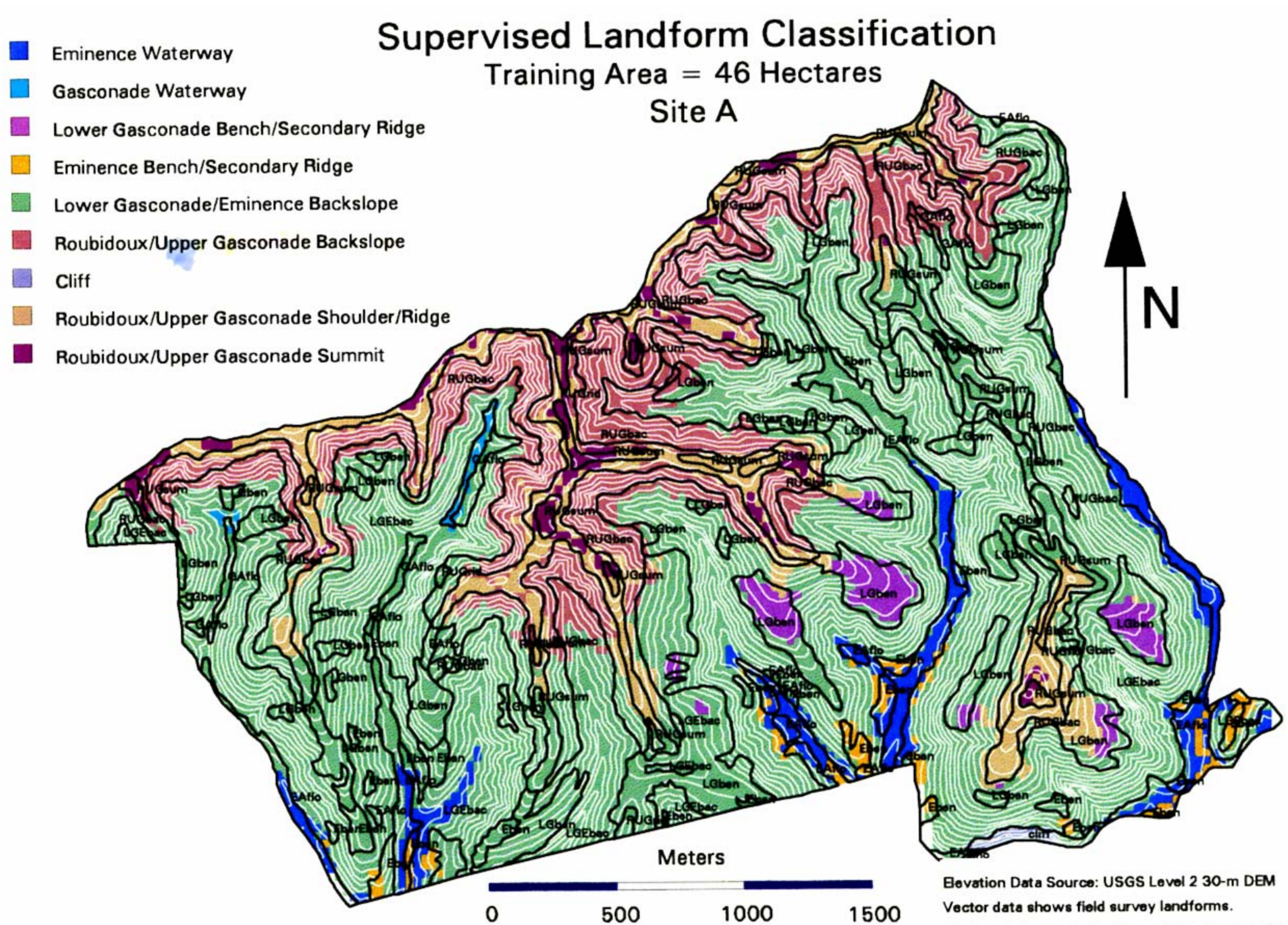


Elevation Data Source: USGS Level 2 30-m DEM
Vector data shows field survey landforms.
Final model converted to 5-m cell size to smooth boundaries.

Supervised Landform Classification

Training Area = 46 Hectares

Site A



Elevation Data Source: USGS Level 2 30-m DEM

Vector data shows field survey landforms.

Final model converted to 5-m cell size to smooth boundaries.

Another test of supervised classification was executed using the large training set for site A (Fig. 3.10) on site B. The supervised classification for site B was performed with the most successful combination of site A inputs (ELEV, SLOPE, CURVE, SUMX, and DRAINX). The supervised model was visually assessed since the field survey was not available at the time of GIS analysis. The visual assessment shows several problems that appear evident with the Ridge/Shoulder and Roubidoux/Upper Gasconade Backslope units (Figure 3.17). Another source of problems appears to be the elevation change in the occurrence of the geologic formations. The formations occur on site B occur at higher elevations than site A. The supervised classification appeared unable to adjust to these differences. In the rule-based classification, breaks in geologic formations were changed in the model on the basis of changes in surficial geology. No mechanism exists for changing elevation breaks in the supervised classification signature files. *A Priori* information from site A was used for the supervised classification on site B, and this may have had negative influence on its success. Landform frequencies are not the same for each site. Landforms of Roubidoux/Upper Gasconade geologic materials are more abundant and those of Lower Gasconade/Eminence materials are less abundant on site B than site A. The requirement of precise *a priori* knowledge for accurate classifications further limits the applicability of supervised classifications. It appears that supervised classifications are not suitable to accurately delineate landforms unless extensive training areas are located throughout the area being classified. Training sites only 1 to 3 km away from the test area did not appear to successfully delineate landforms.

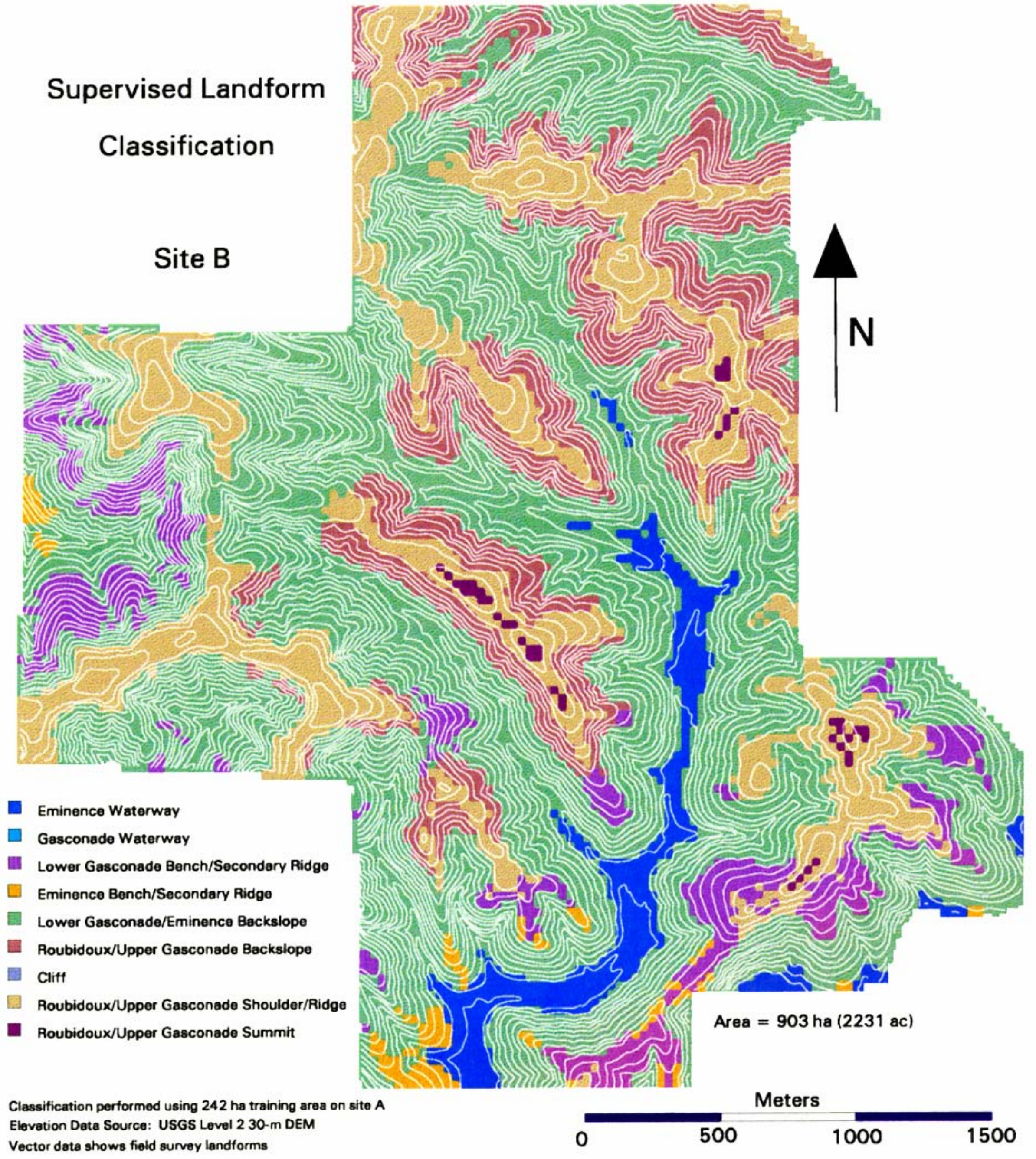


Figure 3.17 Supervised landform classification using the large (242 ha) training area for site B. Different colored classes show the nine landforms predicted by the supervised model.

A modified supervised classification might improve accuracy. For example, the use of elevation confounded the supervised model because of the changes from site A to site B of the elevations where stratigraphic breaks occur. Adding the geologic breaks after the supervised classification is performed would help remedy that problem. The Missouri ECS project has had more success using supervised classification than that shown in this project (T.A. Nigh, personal communication).

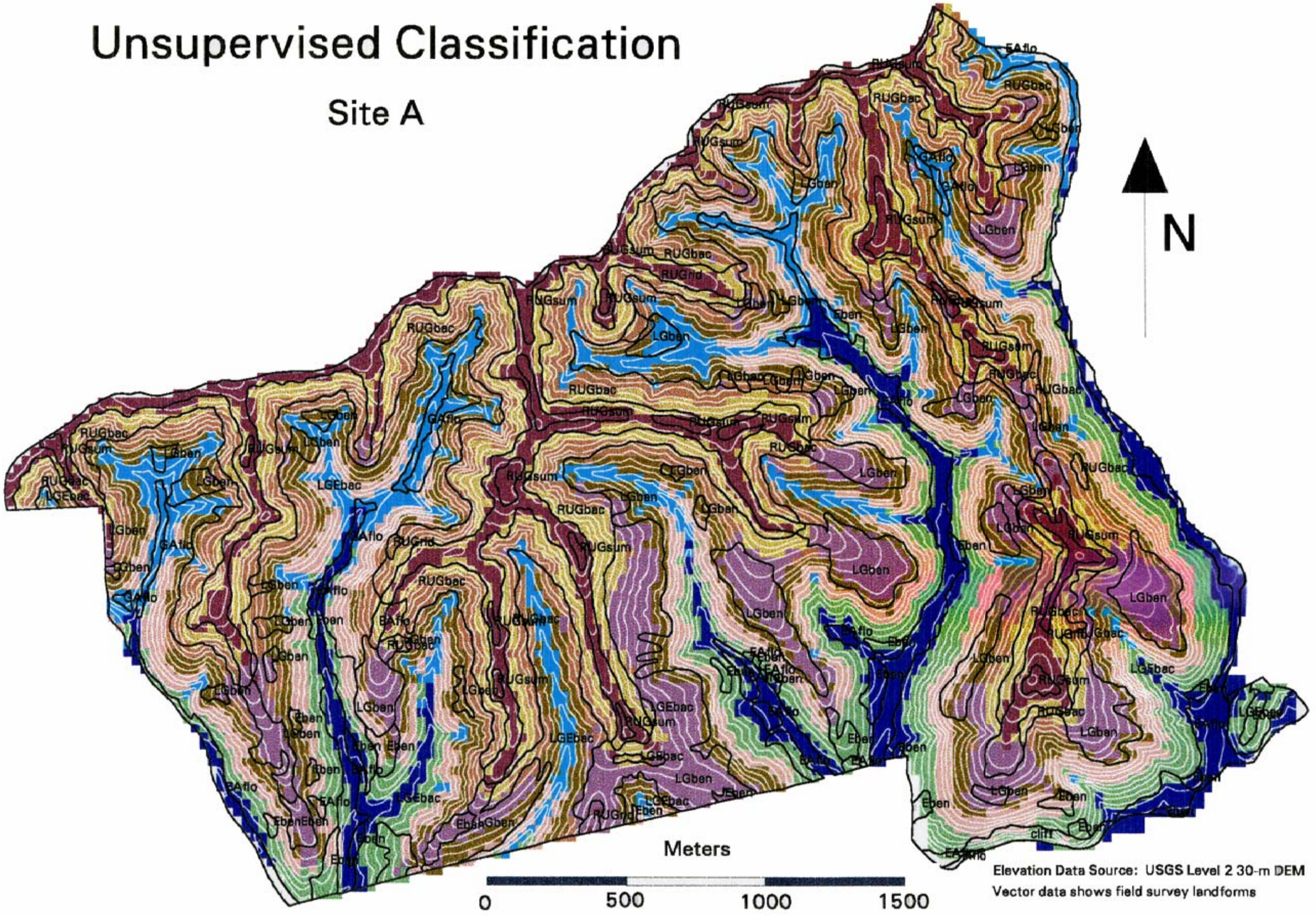
Unsupervised Classification

The unsupervised classification was performed using the same inputs as the most successful supervised classification, the ELEV, SLOPE, CURVE, SUMX, and DRAINX attributes. This model showed some interesting patterns in the landscape (Fig. 3.18). Results of unsupervised classification are difficult to interpret. Despite the limitations of the unsupervised method, the classification is relatively simple to produce and it has merits for initial screening in a new area. Unsupervised classification shows what potentially may be delineated with other classification methods. If an unsupervised method identifies potentially meaningful units, then more controlled methods such as a rule-based classification will be useful. For example, Figure 3.18 shows that drainages, benches, and various backslope landforms can be identified. However, the model combines ridges and summits into one unit, which indicates the difficulty of separating summits and ridges with this resolution DEM data, as was observed with both the rule-based and supervised classifications. In addition, the unsupervised classification can identify landforms that are potentially relevant to ecological site characteristics. A more thorough understanding of the region can determine which landform units identified in the unsupervised classification are significant influences on the ecosystem or management potential of a site.

Figure 3.18 (following page). Unsupervised classification of site A. Different colored classes show nine . Vector data shows the nine landform classes determined in the field. The nine abbreviations for the field-delineated landforms are: Eflo = Eminence Waterway, Gflo = Gasconade Waterway, LGben = Lower Gasconade Bench/Secondary Ridge, RUGbac = Roubidoux/Upper Gasconade Backslope, Cliff = Cliff, RUGrid = Roubidoux/Upper Gasconade Ridge, RUGsum = Roubidoux/Upper Gasconade Summit.

Unsupervised Classification

Site A



Elevation Data Source: USGS Level 2 30-m DEM
Vector data shows field survey landforms

CONCLUSIONS

Rule-based classification is superior for extrapolating information from a known site to an unknown site. However, rule-based classification is more complex and time-consuming than supervised or unsupervised classification. The requirement of extensive training sites and the difficulties in extrapolating information to different sites make supervised classification less practical in operational situations. The benefits of unsupervised classification are identification of terrain features that may be delineated with DEM-based technologies and usefulness in screening a region for terrain characteristics that merit field investigation. However, unsupervised classification was best used as a supplemental classification tool rather than the definitive classification method.

Rule-based classification requires the user to understand the landforms in question or work in close contact with the field scientists. Soil-geomorphic-ecological relationships in the lower Ozarks are very complex and it is not possible to develop classification algorithms for large expanses of land without field verification. For example, this study applied concepts from an 839 ha site to a nearby 903 ha site within the same Landtype Association (areas of similar geomorphic and ecological patterns). Even at this close distance, it was necessary to adjust algorithms for geologic differences. The most successful classifications required working intuitively with the terrain model.

In summary, six errors might explain situations where the rule-based terrain model occurring on sites A and B did not agree with the field survey: 1) inaccuracy of baseline DEM data; 2) inaccuracy of DTM in calculating geomorphic attributes; 3) error associated with the compilation of the field map onto the orthophoto quads; 4) errors in digitizing finished map into a digital version; 5) stretching of landform units to fit the soils (soils do not always fit exactly on the landforms or within pre-determined slope classes, and the field scientist may, for example, include an area into a bench soil because it has bench soil characteristics even though its slope may exceed the 20% slope limit associated with the bench soil); and 6) surveyor error - even with a detailed survey it is unreasonable to expect 100% accuracy. The first two errors listed concern the terrain modeling process and are responsible for most of the differences in the field survey and the terrain model. However, the compilation and digitizing errors associated with producing the field survey are responsible for some of the differences. The field scientist noted after looking at the model, that in some places the terrain model delineations were closer to what the field scientist intended that the final field survey, because of problems the field scientist had with compiling onto the orthophotos (the dark backgrounds made compilation difficult) and errors that occurred in the digitizing process. In this context, the agreement between the terrain model and the field survey for both site A and site B can be considered to be proficient. Employing the terrain model with four to five days of field checking and computer editing per 800 hectare site (approximately the size of site A) might be expected to produce an agreement of 85 to 90%, a level of consistency that most managers of ECS or soil survey projects would probably consider excellent.

The ECS Landtype Association (LTA) concept has utility for DTM’s, because it identifies regions of similar geomorphic and ecological patterns where detailed information from a site may be extrapolated to different sites. However, within the study region’s LTA, adjustments must be made to a model that is developed in one location and applied to another. It does not appear possible to apply algorithms from a studied area of a few hundred hectares to an entire 10 to 40,000 ha LTA without field verification and fine-tuning. Finer partitioning of LTA’s is necessary. This delineation need not be a new hierarchy in the classification system. Several hierarchies are in existence and more might add confusion and limitations to adoption of the system. However, this partition can be a tool the terrain modeler uses to stratify the landscape. A possible framework is to partition LTA’s into smaller units of 1000 to 3000 ha. A DTM can be developed with rule-based methods from one portion of the LTA and applied with small modifications (tweaking) to other parts of the partitioned areas.

Database limitations affect the accuracy of DTM’s. In this study, the geology was complex and variable, but had important influences on the soils and vegetation. The lack of a geology base coverage tied to the same base and hypsography as the other data made stratigraphy difficult to predict, resulting in much of the model error. Modeling colluvial and alluvial drains was also difficult. The limiting factor with drainageway areas was the contour interval, the source data of the USGS level 2 DEM's, as these are less intensive in flat areas such as floodplains and broad summits. In addition, floodplains are extremely variable over short distances. Thus, it is no surprise the DTM performed poorly in these areas, which often require more intensive sampling than other landforms. In environments with similar topography as the study region, intensive sampling might be possible on floodplains because they cover a moderate amount of the total landscape (6.42% of site A).

Implications

The ability to model individual terrain attributes and to effectively combine these attributes into models that predict landforms provides prospects for numerous applications related to ECS, soil survey, forest management and understanding soil-geomorphic-ecological relationships.

Generally in highly dissected terrain tree growth of most species is normally better on lower slopes, north and east aspects, concave slopes and well-drained bottomlands (Carmean, 1975, Carmean, 1967; Trimble, 1964). In Missouri and other sites in the central hardwoods region, strong correlations with *Quercus* (Oak) species and *Pinus* *echinata* (shortleaf pine) have been shown with slope aspect (Graney and Ferguson, 1972; Hartung and Lloyd, 1969), slope position (Hannah, 1968; Carmean, 1965; Carmean, 1967; Trimble, 1964), and surface shape (Hannah, 1968; Graney and Ferguson, 1972; McNab, 1989).

Many of these topographic relationships with site index are prevalent because of their impact on soil water. The dynamics of soil water is a fundamental control on tree growth (Pritchett and Fisher 1987). Seasonal availability of water has been shown to be affected by slope position (Helvey et al., 1972; Hanna et al., 1982), slope gradient (Helvey et al., 1972), surface shape (Wright et al., 1990) and slope aspect (Hanna et al., 1982). Terrain features accurately portrayed in this investigation such as *elevation above local drainageway* and *elevation below local summit, surface curvature*, *slope gradient* and *slope aspect* can be used in models to predict the spatial and temporal dynamics of soil water.

The ability to predict slope gradient enhances timber harvesting interpretations. Steeper slopes generally result in greater areas of disturbance (compaction, rutting and exposed mineral soil) (Bockheim, 1975) and greater requirements for more extensive road and skid trial systems (Bockheim, 1975; Anderson et al., 1976). Forest roads in steep watersheds generally have caused twice the increased sedimentation as roads in moderately sloping watersheds (Anderson et al. 1976). Models that predict soil erosion due to timber harvesting are strongly influenced by slope gradient (Dissmeyer and Foster, 1984). On steep land, practical reasons limit the types of environmentally sensitive harvesting that is available. While adding to the cost of logging operations, "careful planning" can increase of efficiency of the logging operation, limit environmental damage and increase post logging tree growth (Anderson et al., 1976; Froehlich et al., 1981). GIS along with terrain modeling technology could play a prominent role in planning environmental sensitive timber harvesting operations.

Timber harvesting in areas where there is more abundant soil moisture such as north-facing aspects, lower landscape position, and areas of shallow water tables will cause increased hydrologic responses (increases in stream flow and storm water production) compared with harvesting trees from drier parts of the landscape (Doauglass and Swank, 1972; Lee, 1972). Landform characteristics influence soil water, so the increase in predictive abilities from terrain modeling attributes can enhance the predictions of the impact of timber harvesting on water yield and stream flow.

In addition, GIS and terrain modeling tools offer potential to develop models to aid natural resource managers with predicting and controlling plant competition, predicting nutrient limitations, selecting vegetation species, and managing controlled burning and wildfire.

Both in interpretations related to forest and non-forest uses, soil survey can be improved from adoption of terrain modeling applications. Potential advances due to accurate slope measurements alone are substantial. A review of soil survey interpretations developed in the National Soils Handbook (Soil Survey Staff, 2003), illustrates that slope gradient is the single most prevalent and influential input. Slope is a major influence on many timber management interpretations, prime farmland, universal soil loss equations, septic tank absorption field suitability, limitations for dwellings and small commercial buildings, and a host of others. Therefore, methods that show even modest increases in slope determinations positively influence soil survey interpretations for most uses.

Research (Hammer, 1997b, Meinert et al., 1997; Meinert, 2001) and ongoing soil survey work in the Missouri Ozarks have revealed many soil properties to have distributions related soil to topographic, geologic, and geomorphic features. Geomorphic characteristics show some correlation with soil OM, base saturation, clay mineralogy, texture, cation exchange capacity, fragipan development, A horizon thickness, pH, soil OM concentrations and available soil phosphorus concentrations. Many of these relationships have not been thoroughly explored and quantified, but evidence suggest that there is potential to statistical quantify the relationships of soil properties with terrain attributes and then apply these relationships with GIS technologies to predict values across the landscape. Just as this chapter tested the hypothesis that terrain modeling techniques can reliably predict landforms, the spatial distribution of individual soil properties can be tested with similar methods.

Profiting from terrain modeling's capabilities may demand looking beyond a "one delineation fits all" approach to soil survey and ecological land classifications. Many interpretations might be best expressed in special use or interpretation models that focus on individual interpretations such as site index or erosion hazard.

The fundamental advantages of adopting GIS and terrain modeling approaches for soil survey and ecological forest land classifications include the:

1. consistent application of the soil-landscape model.
2. efficiency in premapping;
3. consistent framework for evaluating and updating existing soil surveys and land classifications;
4. dynamic and updatable format that can incorporate new information and new databases;
5. means for effectively extrapolating soils and ecological information from one site to different but similar sites;
6. increase in efficiency of operations; and
7. ability to communicate soil-landscape-ecological relationships in ways that encourages land managers and planners to adopt information that otherwise might go unused.

Hudson (1992) presented the soil-landscape paradigm, the model that field soil scientists in the United States have used as the foundation for soil survey for several decades. This model is largely developed through tacit knowledge, that gained by experience, and it is rarely effectively communicated to others outside of the profession. The use of GIS and terrain modeling to understand, predict and quantify soil-geomorphic-ecological relationships can help fulfill Hudson’s appeal for the soil-landscape paradigm to be documented and communicated to the scientific community and the general public.

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