Using Statistical Process Control Charts (SPCC) to Determine Optimum Resolution for Geomorphometric Analyses.

by

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ABSTRACT

Studying landscapes can give great insight into what geological processes lead to their current appearance. The use of digital elevation models (DEMs) helps scientists better understand the processes that created or modified landscapes, especially with study areas that are geographically extensive. As resolution has increased, scientists have started to notice more subtle details in features that have not been previously reported in coarser resolution studies. This study's focus was on assessing the impact of DEM resolution on the delineation of landforms. There were two main objectives of this thesis: (1) Determine the optimum resolution for measuring drumlins and (2) automating the analysis by customizing ArcGIS 9.3 for the morphometric measurements for use with Statistical Process Control Charts (SPCCs) to determine the optimum resolution of drumlins. SPCCs are primarily used for process and quality control in manufacturing and industrial applications. The principles of this method can be applied similarly to the problem of coarsening of DEM resolution. The problem was treated like an industrial process where the finest resolutions was treated as the control set, then as resolutions get coarser, a point is reached where the values exceed acceptable values and are deemed unreliable. The last resolution before the unreliable value is then deemed the optimum resolution. The study area was in Palmyra, NY, chosen due to the abundance of drumlins, which are streamlined glacial landforms that are easily recognizable on contour maps or DEMs. Results indicate that (1) 10 m DEMs were consistently within the control limits. (2) Morphometric drumlin analysis can be automated once drumlins are

delineated using a bounding container script. The only task not automated was delineating the drumlins themselves. This study's focus was on assessing the impact of DEM resolution on the delineation of landforms. SPCC helped give statistical significance to optimum resolution rather than more simplified methods (e.g., inflection point or relative error). All of this combined could lead to discoveries in landform delineations, patterns, or genesis of not only drumlins, but possibly other landforms or landscapes.

Chapter 1: Introduction

Introduction

Resolution is most simply defined as “the process or capability of distinguishing the individual parts of an object”, or “a measure of the sharpness of an image or of the fineness with which a device can produce or record such an image usually expressed as the total number or density of pixels in the image” (Merriam-Webster, 2005). There are four fundamental types of resolution referenced in landform studies (e.g., Shellito, 2012):

- Spatial: the size of the area on the ground being represented by one pixel’s worth of energy measurement.
- Spectral: the bands and wavelengths being measured by a sensor.
- Radiometric: the ability to determine fine differences in a band of energy measurements.
- Temporal: the length of time a sensor takes to come back and image the same location on the ground.

Although all types of resolution are critical to the appropriate use and analysis of satellite imagery, spatial resolution (i.e., the number of megapixels) is the focus of this thesis due to its importance in studies of landforms and landscapes. Frequently, resolution is used to characterize smart phones, digital cameras, and other portable electronics with cameras. Technological development toward increasing resolution is believed to equate to a better picture. Trends in remote sensing have also been toward increasingly higher spatial resolution (Woolard and Colby, 2002; Napieralski et al., 2013; Ely et al., 2016). For landform analysis, the question is whether a higher resolution yields “better results”.

Digital Surface Representation

A digital elevation model (DEM) is a numerical representation of surface elevations over a region of terrain. DEMs provide the same information as contour maps, but in a digital format suitable for processing by computer-based systems rather than in analog format (Cho and Lee, 2002). DEMs can be made by incorporating field observations, stereopairs, topographic maps, or remotely sensed observations (balloon, airplane, satellite, etc.) into a GIS (geographic information system). DEMs store aggregated ground data for each pixel in raster format. Many DEMs are developed from satellite data, which have gradually decreased in pixel cell size over time. For example, DEMs from early Landsat programs had a resolution of 80 m (i.e., 80 m x 80 m pixels), which produced a relatively coarse representation of Earth's surface. During the mid to late 1990s, the best available resolution for DEMs was 30 m, which was an improvement in resolution, but still left some ambiguity in accurately measuring a landform, especially if the landform was relatively small (e.g., 40 m wide). In the early 2000s, 10 m DEMs became readily available (Table 1.1), becoming the new standard for high DEM resolution (e.g., the National Elevation Datasets (NED) in the United States, Shellito, 2012). Now users have the ability to study micro-scale landforms, but due to limitations in computing power and storage capacity, many studies are not feasible because of the sheer volume of data and processing time. As technology advances, this gap should lesson to a point where it is negligible. Geomorphologists typically have to decide between studies with larger study areas and coarser resolutions or focusing on subsets of the landscape with finer resolution.

Currently, this technological evolution continues, as Light Detection and Ranging (LiDAR) technology can produce even higher resolution datasets (e.g., sub 1 m). LiDAR has advantages over satellite based data as it is typically gathered with the use of airplanes, which allow coverage of specific areas of interest. Meng et al. (2010) distinguished five different advantages of using LiDAR over traditional techniques. First, dense point clouds are generated (elevation values), which lead to highly accurate DEM data. Second, surface features can be delineated because a height context analysis in post processing allows the delineation of surface features (i.e. buildings, power lines, and trees). Third, the high-density point clouds allow even minimal changes in elevation to be easily mapped, even with subtle changes in vegetation canopies.

Fourth, vegetation canopies can be easily mapped because there are multiple signals sent; some penetrate the canopy while others can distinguish the top. And lastly, LiDAR can map ground elevations because it penetrates dense vegetation because of multiple signal returns. A disadvantage is that continuous coverage is not a likely option due to the high costs associated with gathering LiDAR data. Currently, LiDAR data sets are becoming more available to the public due to data being released by private and utility companies.

The Impact of Resolution on Geomorphometry

Many studies have attempted to understand the effects of resolution on landform and landscape characterization derived from DEMs. Clearly, too coarse a DEM resolution decreases the quality of landscape representation, and as a result, delineation and measurement. For example, coarse resolution creates a less defined representation of the landscape (i.e., landscape smoothing), filtering surface roughness and diminishing the accuracy of terrain attributes (Wolock and Price, 1994; Wolock and McCabe, 2000; Thomason et al., 2001; Usery et al., 2004; Claessens et al., 2005; Sorensen and Seibert, 2007; Wise, 2007; Coz et al., 2009; Ely et al., 2016). Additionally, coarse resolution alters slope length and angle, although this is dependent on local topographic variability (Zhang et al., 1999; Thomason et al., 2001; Cotter et al., 2003; Kienzle, 2004; Usery et al., 2004; Paz et al. 2008; Wu et al., 2008; Yu et al., 2015). Finally, the ability to identify and delineate the boundary of a landform (i.e., landform capture) is related to resolution, meaning the total number of landforms identified decreases when resolution decreases (Chaplot et al., 2000; Wu et al., 2008; Yu et al., 2015).

Furthermore, coarse resolution affects hydrologic model simulations of water flow, especially at the watershed scale. Watershed delineation becomes more uncertain when resolution decreases, as coarse resolutions tend to substantially alter watershed shape and size (Cotter et al., 2003). If watershed shape and size are altered, then the derivation of channel networks and flow routing is also impacted (Tang et al., 2003). Resolution also directly influences surface runoff (up to 200% variation) and sediment and nutrient loadings in hydrologic model predictions using TOPMODEL, the Soil and Water Assessment Tool (SWAT), and the Agricultural Non-Point Source Pollution Model (AGNPS) (Wolock and Price, 1994; Braun et al., 1997; Valeo and Moin, 2000; Cotter et al., 2003; Chaplot, 2005; Wise, 2007; Wu et al., 2008; Dixon and Earls, 2009;

Dixon and Earls, 2012; Tan et al., 2015). Finally, resolution affects estimates of topographic index and soil wetness index (i.e., soil moisture) (Thompson et al., 2000; Wolock and McCabe, 2000; Kienzle 2004; Wu et al., 2008; Tan et al., 2015) and rates of erosion and sedimentation (Schoorl et al., 2000; Woolard and Colby, 2002; Claessens et al., 2005; Hessel, 2005; Hu et al., 2015).

As resolution can have an impact on landscape studies and hydrologic analyses, scientists have sought to determine an "optimum resolution," which is defined as the coarsest resolution that yields results compairable to finer resolutions (Cotter et al., 2003; Chaplot, 2005; Dixon and Earls, 2009; Yu et al., 2015). Landform characteristics tend to stay relatively similar as resolution is coarsened, but beyond a particular resolution, there is a change in morphometric measurements. A compounding factor is that landforms are also difficult to define because landform boundaries are ambiguous and scientists use different methods to decide what constitutes a boundary. This lack of standardized methods for measuring landforms makes it difficult to compare the results of various landform studies (Dunlop and Clark, 2006; Migon et al., 2013).

Determining Optimum Resolution

To date, the research to determine optimum resolution has been limited. A few studies focused on quantifying the amount of error associated with digital elevation models (Garbrecht and Martz, 1994; Horritt and Bates, 2001; Cotter et al., 2003), and some methods have been as basic as looking for an obvious deviation from the normal pattern or an inflection point on a graph (Horritt and Bates, 2001). Garbrecht and Martz (1994) used the statistical test of relative error in their study, in which they used an arbitrary value of ±10% to determine if resolution is affecting the analysis. These methods were initially tested for this project, but the results were unsatisfactory and inconsistent in regards to the variety of parameters (area, perimeter, length, width, etc…).

This thesis investigated whether a more rigorous statistical method, Statistical Process Control Charts (SPCCs) can be adapted for use in geomorphic studies. (SPCCs) are widely used in manufacturing processes, but are becoming more common in almost all industries, even finding their way into managing and service orientated occupations (Bissel, 1994). The ability to use SPCCs to monitor short and long-term variability helps maintain a dynamic, changing system. They are designed to make sure products or processes are within specified control limits, which are dictated by a control set within the data. For example, a cereal company would use SPCC for monitoring how much cereal is put into boxes. Too much cereal would result in loss of profits, whereas too little cereal can result in dissatisfied customers. In either case, the use of control limits allows the company to set an acceptable range of product without the risk of losing money or customers.

SPCCs rely on basic statistical principles, including a control set, which is a series of values that are deemed acceptable. Once the control set is determined, the user calculates the amount of variability within the control set (Bissel, 1994). Typically, the analyst uses the amount of variability within the control set to establish a certain amount of standard deviations as control limits. Two to four standard deviations are commonly used, but the boundaries can be flexible if the analyst needs more or less variability to fit their particular needs. These control limits are applied to a base line value, usually the mean value for the control set, resulting in an upper control limit (UCL) and a lower control limit (LCL) that establish action limits. The first time a value exceeds either one, the process is deemed "out of control," and an action needs to occur to fix the problem. Since control sets are user defined, it is prudent to assess the impact control sets have on the output of the analysis (Napieralski and Nalepa, 2010).

Drumlin Analysis as Test Case

This study was conducted using drumlins as the landform for this DEM analysis. Drumlins are typically used in landform analyses and are easily identified because of their unique shape. They are long, elongated hills found in glaciated areas as a result of previous glacial activity. Generally tens of meters high, hundreds of meters long and typically <100 m wide but >20 m, they occur in "fields," which can cover vast areas such as most of Central and Western New York (>500 mi^2), or smaller fields such as a small localized area outside Traverse City Michigan (<40 mi^2) (Miller, 1972). Drumlins are of interest to the geographic community due to the distinct shape and distribution throughout the glaciated areas of the USA, Europe, Russia, and China.

Drumlins are of particular interest in this analysis, as they are delineated using the same contour line for each individual drumlin (1m-80m). This clear delineation makes it possible to isolate variations in drumlin measurements that are due to changes in DEM resolution, rather then the algorithm used to delineate the feature.

Thesis Objectives

The scope of this thesis was to first, determine the optimum DEM resolution for measuring drumlins. Second was to develop and modify a statistical test to determine when a resolution is too coarse for landform measurements. The results from this analysis will help guide other studies using SPCC in a DEM analysis of other landforms, possibly varying in magnitude and shape.

Thesis Format

This thesis is formatted in journal paper format, with two of the four chapters written in manuscript form for peer-reviewed scientific professional journals. As a result, there may be some overlap between explanations and discussions between chapters. Because many of these topics relate to one another within the larger objective of the thesis but must be explained in each chapter as they are intended to be stand-alone papers.

The first chapter “Introduction” describes the overall objectives and context of the research, and explains the format of the thesis and how the chapters are related.

The second chapter, “The Application of Control Charts to Determine the Effect of Grid Cell Size on Landform Morphometry,” was published in *Computers and Geosciences* (Napieralski and Nalepa, 2010). This chapter emphasizes the drumlin extraction technique and utilizes a wide range of variables with some being more complex (area, perimeter, elongation) than others (length, width, orientation).

The third chapter, “Optimizing Geomorphometry Using Statistical Process Control Methods” (Napieralski and Nalepa, 2012), was published as a book chapter in *Process Control: Problems, Techniques and Applications,* written primarily for industrial applications. The methodology focused on the design and application of SPCC and the impact user-defined input variables have on determining an optimum resolution. The results suggest that an optimum resolution does exist for most topographic features.

Chapter four reviews the results of this thesis and addresses overall applications of SPCC in geomorphometric applications. It identifies the strengths and weaknesses of the methods used and provides suggestions for future development and research.

Satellite	**Sensor**	**Bands**	**Spatial Resolution**	**Spectral Range**
Landsat 1-3	MSS	4	80	VNIR
Landsat 4, 5	TM	6	30	VNIR, SWIR
		1	120	TIR
Landsat 7	ETM	1	15	VNIR
		6	30	VNIR, SWIR
		1	60	TIR
Landsat 8	OLI	1	15	VNIR
		8	30	VNIR, SWIR
		2	30	TIR
EO-1	Hyperion	220	30	Hyperspectral
	Ali	1	10	Panchromatic
		9	30	VIR
SPOT 1-3	HRV	1	10	VIR
		3	20	VIR
SPOT 4	HRVIR	1	10	VIS
		4	20	VNIR, SWIR
SPOT 5	HRG	1	5, 2.5	VIS, VNIR
		3	10	VNIR
IKONOS	Panchromatic	1	1	VNIR
	MSS	4	4	VNIR
Quickbird	Panchromatic	1	0.61	VNIR
	MSS	4	2.44	VNIR
Terra	ASTER	3	15	VNIR
		6	30	SWIR
		5	90	TIR
Geoeye	HRG	1	0.4	Panchromatic
		4	1.65	VNIR
Envisat	ASAR	2	30	Microwave
ERSI/2		1	30	Microwave
TerraSAR-X		1	1, 3, 18	Microwave

Table 1.1. Summery of available satellite sensors used in landform mapping (A table modified from Napieralski et al, 2013).

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Chapter 2: The Application of Control Charts to Determine the Effect of Grid Cell Size on Landform Morphometry

Abstract

Geoscientists have become increasingly dependent on digital elevation models (DEMs) to delineate and measure landforms and landscapes. However, the DEM grid cell size available may not be the optimum resolution; this can mask subtle changes in measurements and lead to erroneous results. This paper presents a standardized statistical technique (i.e. statistical process control charts (SPCC)) for determining the optimum DEM resolution (i.e. the coarsest resolution in which detail is not sacrificed) for landforms (e.g. drumlins). For this study, forty-four DEM resolutions, ranging from 1 m to 80 m, were used to assess the effect of resolution on drumlin size, shape, and centroid. The results indicate that the optimum resolution for the size variables (width and length) was coarser than the optimum resolution for shape indices (elongation and rose curve). Drumlin location tends to drift in a predictable direction and rate as grid cell size coarsens above particular thresholds. The results prove that resolution plays a critical role in correctly evaluating drumlin morphometry and that care must be taken when utilizing DEMs to summarize drumlin characteristics. The creation of a standardized technique to describe drumlins will allow for scrutiny of previous work and straightforward comparative analyses between studies, while utilizing the optimum resolution will help decipher landform patterns, reveal relationships, and provide more insight into landform evolution.

Introduction

Digital elevation models (DEMs) are vital tools used in environmental, natural resource, and social applications due to the widespread availability and sources of elevation data, as well as their relative simplicity and computational efficiency. Studies of landforms and landscape processes (i.e. geomorphology) utilize DEMs to decipher patterns within a population of landforms (e.g. drumlins), reveal previously unrecognized relationships between landforms (e.g. ribbed moraines), and support or refute hypotheses for landform and landscape genesis and development. For example, glacial geomorphologists have long debated the environmental conditions under which ribbed moraines form (see Dunlop and Clark, 2006 for summary), with the lack of consensus driven in part by inconsistent descriptions and compilations of shapes and sizes documented from relatively localized studies. Dunlop and Clark (2006) addressed this issue by combining satellite imagery with DEMs to measure and compare the size, shape, pattern, and distribution of ribbed moraines formed by the Scandinavian, Laurentide, and Irish Ice Sheets. The results indicated that held assumptions regarding their formation were inaccurate or untrue, and that the morphological characteristics were more complex than previous studies had described. Therefore, DEMs promote opportunities to conduct large scale studies (greater than 50,000 km^2) of landforms in a rigorous, quantitative manner within a geographic information system (GIS), while also providing a tool that can supplement field mapping and interpretations from aerial photographs.

Drumlins have been well-studied for more than a century due to their relative ubiquity in North America and Europe and their distinctive shape, which has long generated attention regarding their genesis (Menzies 1984). Of special importance to this paper are the previous efforts that identified, measured, and described drumlin size, shape, and patterns. (e.g. Boyce and Eyles, 2000; Clark and Wilson, 1994; Stea and Brown, 1989). For example, drumlin shape has been related to similarly-shaped common objects, such as tear drops, torpedoes, and aircraft wings (Ebers, 1926; 1937), and described with mathematical curves, including lemniscate loop (Chorley, 1959), rose curve, and ellipsoids (Reed et al., 1962), and ratio variables, such as elongation (see Gardiner, 1983 for review). It is believed that drumlin shape is controlled by the underlying lithology and subglacial conditions, so understanding drumlin shape may lead to a better understanding and appreciation of their formative processes, such as how the degree of drumlin elongation is related to pressure or ice velocity (e.g. Briner, 2005; Menzies, 1979; Stokes and Clark, 2002). Moreover, the shape, size, and patterns of drumlins are frequently used as “building blocks” in paleo-ice sheet reconstructions (Boulton and Clark, 1990; Clark, 1997; Dongelmans, 1996; Kleman et al., 1997; Kleman et al., 2006; Stokes and Clark, 2002; Punkari, 1982;) and in the verification of numerical ice sheet models (Li et al., 2007; Napieralski, 2007;

Napieralski et al., 2007). Therefore, detailed morphometric and pattern analyses of drumlins and drumlin fields enhance reconstructions of paleo-environments.

Although drumlins are well documented and studied, the techniques used to identify, measure, and characterize drumlins have varied with very little consistency. Early methods used topographic maps to delineate and quantify drumlins on the basis of the enclosed contour line method. Miller (1972) utilized a contour interval of 6.1 m to characterize drumlin form while Trenhaile (1975) identified drumlins using 1:50,000 maps with a contour interval of 8.1 m, supplemented by the use of aerial photographs, to decipher smaller drumlins. It is likely that the use of these intervals was more of convenience, limited by the interval of the topographic maps. Rose (1989) used triangulation, precise leveling and plane tabling to create elevation data at a scale of 1:500 with a contour interval of 0.5 m. However, DEMs and aerial imagery now provide more flexibility with selecting appropriate contour intervals and resolutions to conduct a drumlin analysis (e.g. Kerr and Eyles 2007; Lanier and Norton, 2003; Smith and Wise, 2007). Many of the original drumlin studies required extensive field mapping or tedious plotting from topographic maps, but DEMs and GIS can be used to develop a drumlin delineation technique that is suitable for various geomorphmetric/physiographic conditions. Multi-resolution DEMs are useful in the accuracy assessment of delineated drumlins according to the differences quantified in drumlin parametric representation.

Despite the extensive history of drumlin descriptions and the resulting variability in drumlin analysis techniques, few studies have assessed how the results of drumlin morphometric studies are influenced by variations in grid cell size when analyzing drumlins on a DEM by employing the enclosed contour technique. Intuitively, relatively fine DEM resolutions resolve more detail and provide more reliable measurements (Gao, 1995; 1997; Ziadat, 2007). Ziadat (2007) found that the accuracy of landscape representation decreases as grid cell size increases. This conclusion is reflected in other studies (Gao, 1997; Kienzle, 2004; Lopez, 2000; Östman, 1987), although the decrease in accuracy is more pronounced with coarse (30 – 80 m) grid cell sizes (Gao, 1997), which may also conceal important morphological details. Smith and Wise (2007) found that increasing resolution from 30 m to 15 m increased the count of drumlins by 170%, indicating that coarse resolutions can obscure smaller landforms.

An increase in resolution, however, does not necessarily equate to an increase in detail or detectable landforms especially when far below the typical landform size; rather, very fine resolutions may simply produce more data and increase processing time without improving the quality of the analysis. Therefore, the coarsest resolution in which there is a negligible sacrifice in detail is an optimum resolution to conduct terrain analyses, particularly those related to drumlins.

Objective and Scope

The key objectives of this study are to: 1) present a method for drumlin delineation and parametric representation from multi-resolution DEMs and 2) determine the influence of DEM spatial resolution on the calculation of drumlin size, shape, and location. Changes in the basic morphometric variables (width, length, and orientation), shape indices (elongation and the rose curve), and location of drumlin center are all evaluated as the DEM grid cell size is altered. Optimum DEM resolution is defined as the resolution for which the pixel size influences calculations of drumlin variables.

Study Area

The study area covers a surface of approximately 3 km by 2 km, located south of Palmyra, New York. This particular study area was selected due to the abundance and density of well-defined drumlins that have been studied in depth for over a century (for review, see Menzies 1984). Sixteen drumlins were identified in the study area and extracted from the U.S.G.S. Palmyra 7.5-minute topographic quadrangle (Fig. 2.1). The sample size of drumlins was somewhat limited by the increase in the quantity of data and processing time generated when working with a 1 m DEM (although LiDAR DEMs are increasing in availability, coverage is limited in drumlinized areas). This limitation was considered acceptable as the overall goal of this study was to develop a statistical tool to evaluate changes in drumlin form as DEM resolution changed. Results from this study on a small population of drumlins can be used to guide future studies of large drumlin fields.

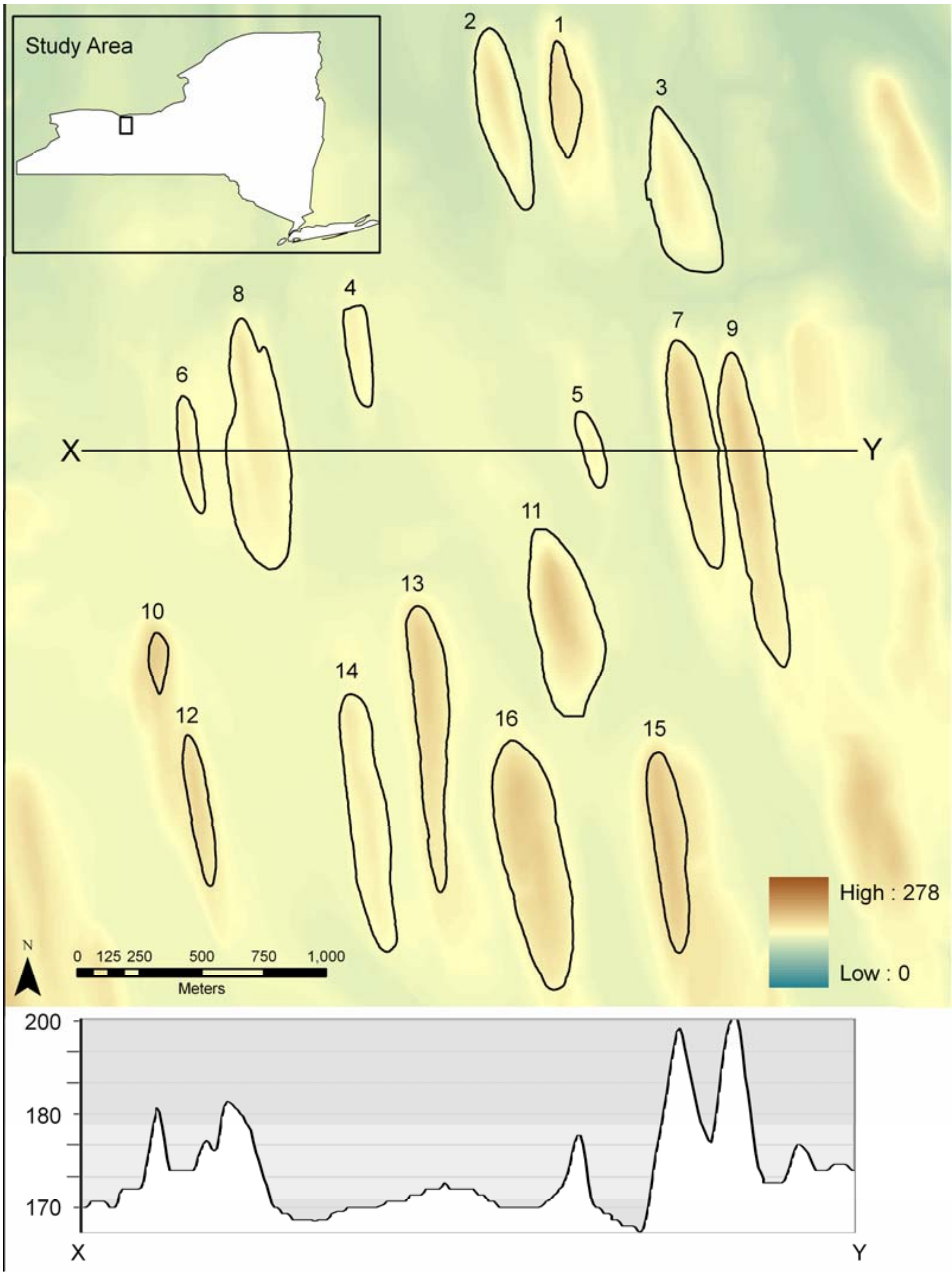


Figure 2.1. Digital elevation model (DEM) of study area, including 16 drumlins analyzed in this study. A vertical profile from X to Y illustrates the topographic characteristics and reveals a combination of subtle, low-relief drumlins and distinct, high-relief drumlins**.**

Methods

Drumlin Identification and Measurement

A 1 m DEM was generated from the Palmyra topographic map by digitizing the contour lines and interpolating a surface using ArcMap. This 1 m DEM was then sub-sampled to generate DEMs of 2 – 35 m (in increments of 1 m) and 35 – 80 m (in increments of 5 m). Digital contours with an interval equal to 1 m were derived from each sub-sampled DEM. A drumlin was identified using the lowest enclosed contour line (i.e. base elevation), as derived off the 1 m DEM. Individual drumlin boundaries were extracted using the same base elevation throughout the entire process, regardless of grid cell size. For the purpose of this study, closed contour lines shared by neighboring drumlins led to the use of the next highest contour line to denote the boundary of the two drumlins (see Fig. 2.2).

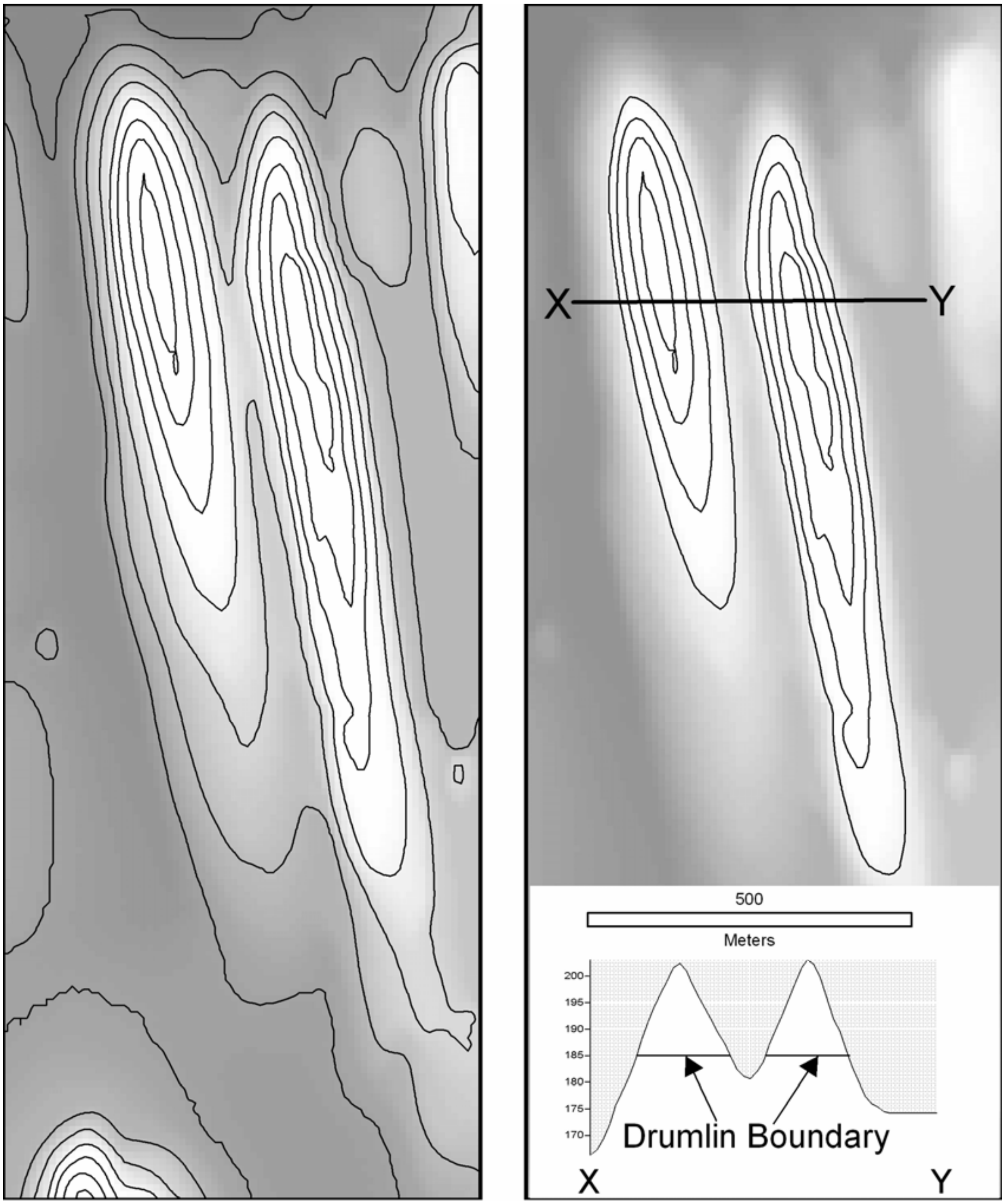


Figure 2.2. Illustration of technique (at least three enclosed contour lines) used to identify and extract drumlins using a contoured DEM. Note a vertical profile showing relief of the drumlins and where lowest enclosed contour line (5 m interval) is positioned on DEM.

Drumlin length, width, and orientation were calculated for each drumlin by generating a "bounding container" around each drumlin. A bounding container script was developed (and is available from http://arcscripts.esri.com/details.asp?dbid=14535) so that a rectangle was automatically generated around each feature (i.e. polygon or polyline) using ESRI's ArcGIS 9.2. Preparing features (contour lines) for the bounding container script requires the user to "clean up” the features by deleting unused contour lines. This study’s only contour lines of interest were the lowest enclosed contour lines which delineated the extent of each drumlin. The boundary of the container box is tangential to each side of a drumlin, such that the width, length, and orientation of the box represent the width, length, and orientation of the drumlin (Fig. 2.3). Elongation, area, and the rose curve were also calculated. Elongation is calculated using length/width, while area is simply length×width. The rose curve, which has been found to be a good description of drumlin form (Doornkamp and King, 1971), is defined by the following equation:

$$R = a \cos k$$

where a is the long axis length and k is a dimensionless constant that defines the elongation of a loop (Chorley, 1959), such that:

$$k = a^2/4A$$

where A is the drumlin area.

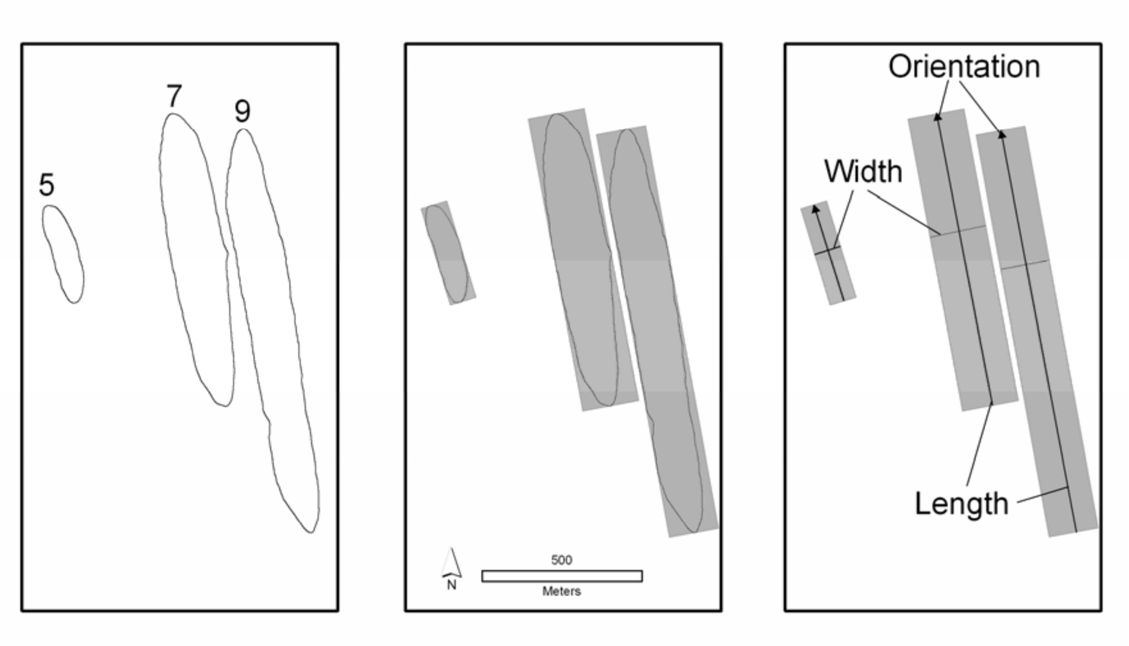


Figure 2.3. Technique used to measure basic drumlin characteristics utilized a series of bounding containers that automatically calculated the width, length, and orientation of each drumlin.

Finally, the influence of grid cell size on the spatial location of drumlins was investigated by generating a centroid per drumlin at every sub-sampled resolution. The "drift" (i.e. relative movement of the centroid) and drift direction was analyzed because we expect grid cell size to also effect spatial pattern analyses (e.g. cluster analyses), which provide data on the spatial distribution of drumlins and relationships and correlations between drumlins and surface/subsurface variables.

Statistical Technique

The relationship between resolution and length, width, and orientation were analyzed using statistical process control charts. Control charts are commonly used in manufacturing and industry to statistically analyze the performance of a production process in order to forecast deviations that may result in product rejection (e.g. Augustin and Minvielle, 2008; Bissel, 1994; Kolesar, 1993). For example, industries that package and ship precise volumes or weights of material use control charts to determine if the variation of a product is "in control", and thus acceptable, and those that are "out of control" and are rejected and considered a waste product (i.e. financial loss or missing product). We developed a control chart to forecast deviations in calculations of drumlin morphometry as resolutions coarsen. As the true size of drumlin is considered unknown, we assume the finest DEM (1 m) generates the most accurate representation of the landscape and that the reliability of the measurements decrease as the resolution coarsens.

Control charts include two key variables: a range and a set of control limits (upper and lower). The range (R) is calculated from a control set for each drumlin, which in this case is based on the first five resolutions (1–5 m):

$$R = \max - \min$$

where max and min are the maximum and minimum values within the control set (Fig. 2.4). The mean ($\bar{U}$) range values for the sixteen drumlins were used establish an upper and lower control limit based on a standard deviation (σ):

$$\sigma = \bar{U}/1.023$$

Upper and lower control limits, commonly referred to as action lines, are defined by $\pm 4\sigma$ and added to the mean variability within the control set for each drumlin. The first measurement that falls outside the upper control limit (UCL) or lower control limit (LCL) is considered “unreliable” data (Bissel, 1994). Thus, the last consecutive measurement that falls within the control limits is selected as the optimum resolution for that drumlin (Fig. 2.4).

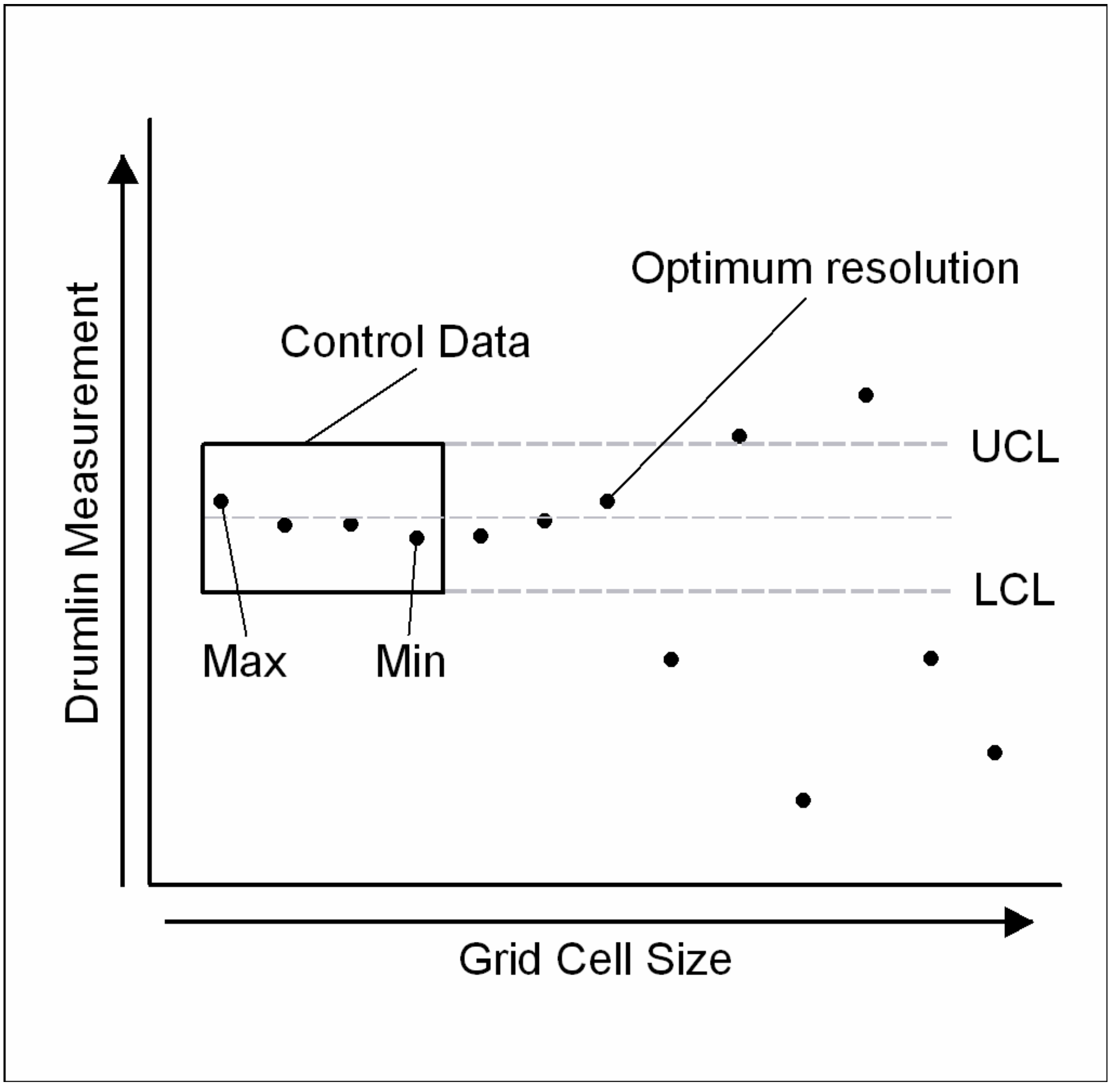


Figure 2.4. A conceptual diagram of a control chart used to determine optimum grid cell size for each drumlin. An upper and lower control limit (UCL and LCL) is calculated from minimum and maximum (range) values found within a control set of each drumlin. Last measurement (e.g. width, length) that falls within the UCL and LCL is considered optimum resolution.

Results

Basic Drumlin Morphometry

For this study, basic drumlin morphometry includes the basic dimensions of a drumlin, including length, width, and orientation. Drumlin morphometry was influenced by a coarsening of grid cell size, although the changes in size were generally negligible between 1 m and 10 m (Fig. 2.5). Drumlin width varied between 80 m and 300 m (as determined from a 1 m DEM). When the optimum resolution for each drumlin is plotted against drumlin width a slight correlation between drumlin width and the optimum resolution is found, as the smallest widths produced the smallest optimum resolutions. Drumlins 5, 10, and 12 had the three smallest widths and smallest optimum resolution (with the exception of drumlin 1). This wide range of widths was common for all drumlins throughout the study area. In particular, drumlin 12 exhibited little variability between resolutions 1-11 m; however, after 11 m, width calculations began to fluctuate between a high value of 186 m and a low calculation of 57 m (a range of 129 m for a drumlin that measures 84 m across) (Fig. 2.6).

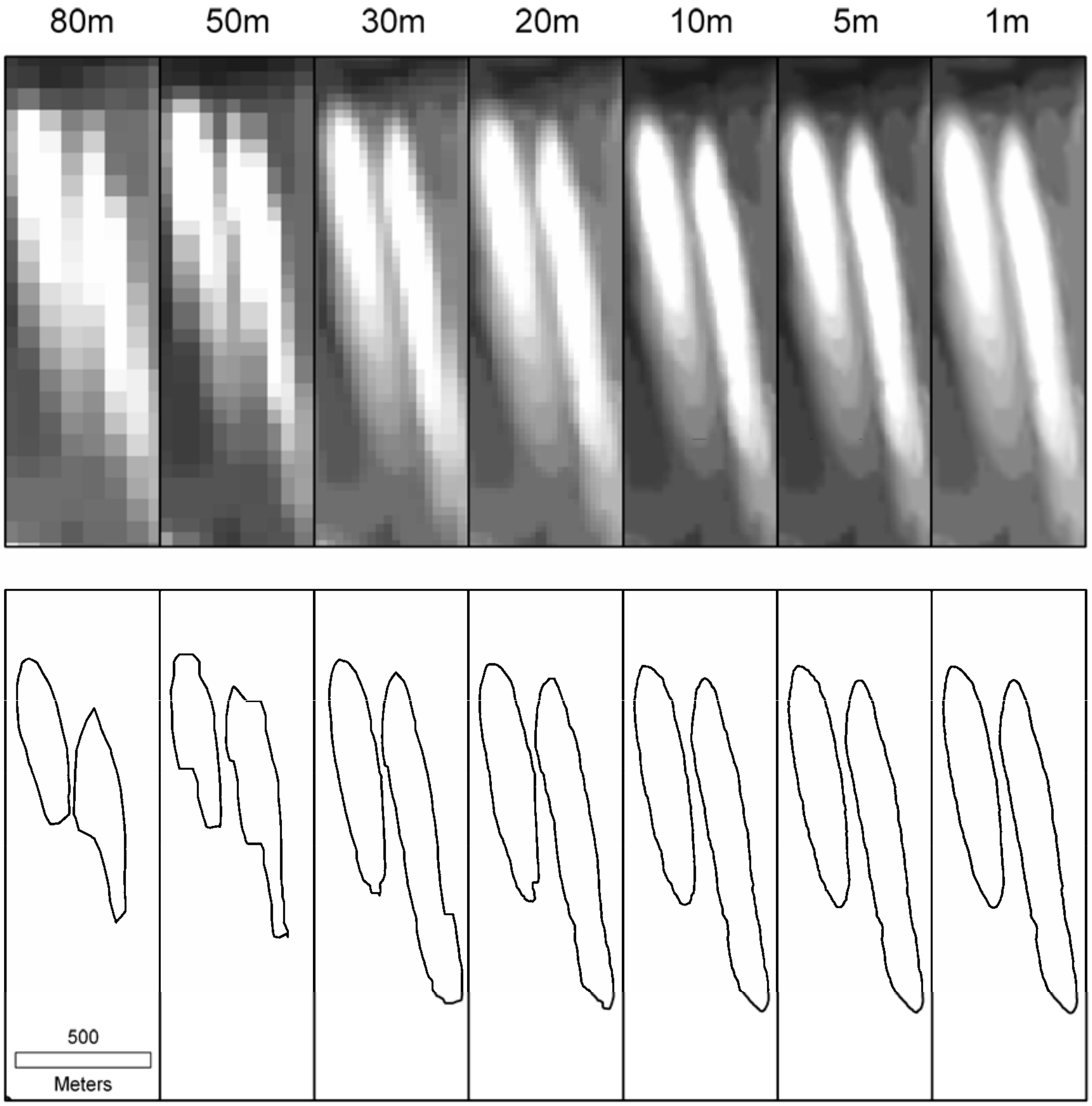


Figure 2.5. Variations of drumlin shape and size caused by changes in grid cell size. Note that subtle changes that occur between 1 and 20 m and that there more obvious alterations in size and shape at resolutions ≥30 m.

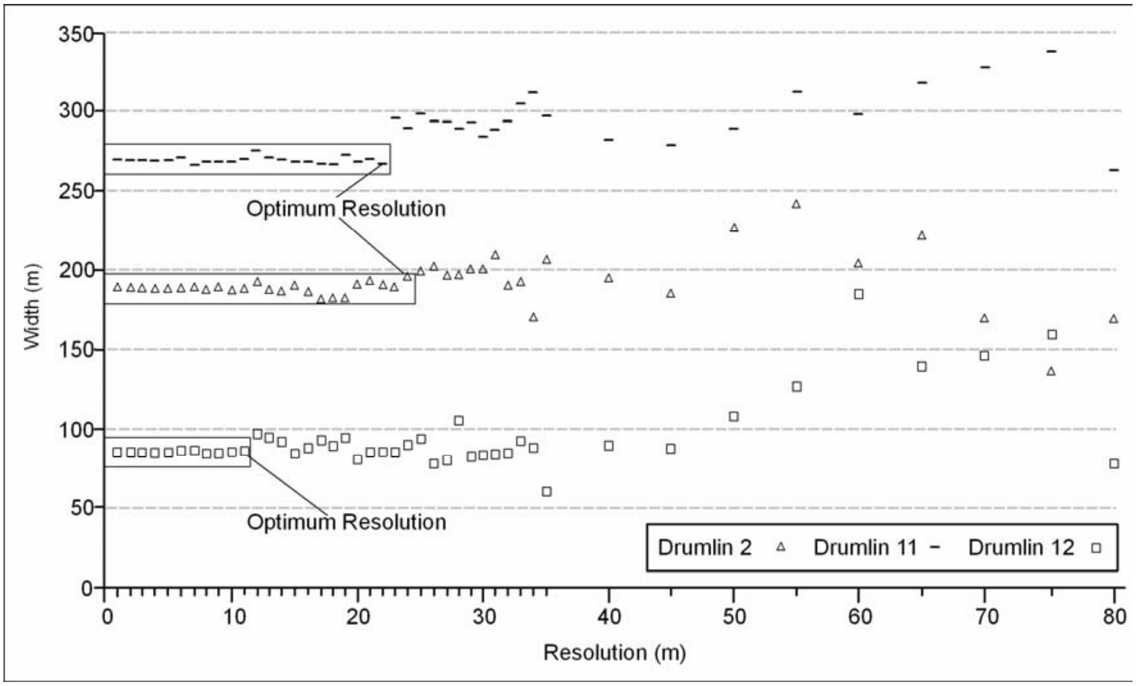


Figure 2.6. A control chart used to evaluate variations in width of drumlins 2, 11, and 12. UCL and LCL are included in each dataset. Optimum resolution for drumlins 2, 11, and 12 is 24, 22, and 11 (see Table 1). Note variability in width calculations with resolutions larger than optimum resolution.

Drumlin length within the study area ranged between 244 – 1279 m (as determined from a 1 m DEM). Surprisingly, calculations of drumlin length were more sensitive to resolution than width or orientation. Initially, we believed that drumlin width was the “limiting variable” because it is the smallest dimension, at times less than 100 m. However, the length of drumlins was frequently affected by substantial portions of the drumlin being removed, which also tended to influence the drift of the drumlin centroid (see below for drumlin location). In most cases, the changes in length caused by increases in grid cell size behaved similarly to width, having little variability between 1-10 m and significant variability with coarser resolutions (equal to or larger than the optimum resolution).

Orientation exhibited the most variability with regards to optimum resolution, possibly owing to the methodology. Bounding containers were used to measure the width and length of drumlins, while the orientation of the boxes correlated to drumlin orientation. However, it is possible that the orientation of the boxes was not parallel to the drumlin spine since a drumlin can change characteristics in a manner in which the containers do not rotate. For example, drumlin 9 had an optimum orientation resolution of 60 m but an optimum width and length resolution of 18 m. Therefore, as resolution increased beyond 18 m, the drumlin size changed without rotating.

Overall, the average optimum resolution for the sixteen drumlins was 17 m (width), 13 m (length), and 29 m (orientation). For most drumlins, the measurements of each variable remained constant as resolution increased from 1 m to 10 m, indicating that a 10 m DEM would be as effective as any sub-10 m DEM when analyzing drumlin characteristics.

Drumlin Shape

Elongation, area, and the rose curve were more sensitive to changes in grid cell size than the basic variables (see Fig. 2.7). Because each of these indices relied on at least two of the basic variables, the sensitivity to changes in resolution was exacerbated. As a result, two important trends differentiated shape indices from the basic variables. First, the range used to calculate the UCL and LCL for elongation, rose curve, and area were smaller than the range values for width, length, and orientation, which causes tighter control limits. Second, tight control limits results in finer optimum resolutions and as a result, most drumlins had an optimum resolution of less than 10 m for the three indices. Exceptions to this trend include drumlins 10, 11, and 16, which also have low elongation values, indicative of relatively wide drumlins.

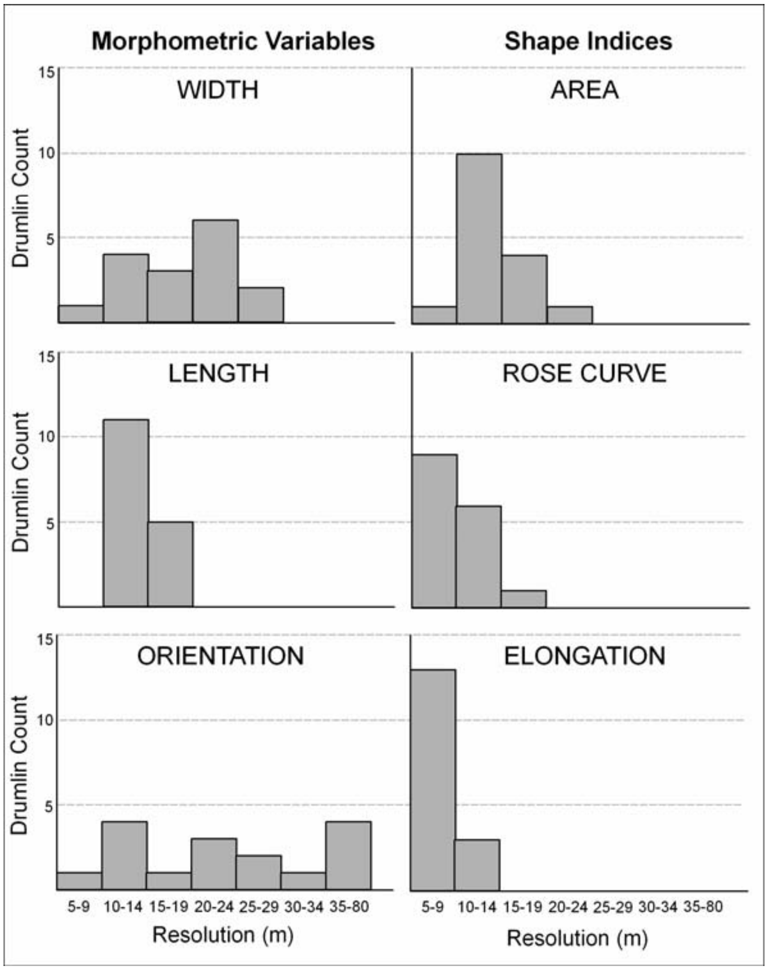


Figure 2.7. A summary of optimum resolutions used in this study. This type of summation can be useful when determining optimum resolution with assemblages of drumlins (drumlin fields). Shape indices are more sensitive to changes in resolution than basic variables, but as a general rule, conducting a drumlin study at resolutions of 30 m or greater will not produce more reliable results.

Drumlin Location

Drumlin centroid drifting was minimal between 2 m and 15 m and increased as grid cell size increased (≥30 m). Documented causes of centroid drift include changes in drumlin size (e.g. drumlin 6 in Fig. 2.8), “movement” of drumlin while maintaining constant size (e.g. drumlins 2 and 8 in Fig. 2.8), or a combination of the two. Most of the drifting increased substantially after 20 m, with maximum drift distances of over 170 m. Furthermore, most of the drumlin centroids drifted northward, a likely result of the landscape’s gentle northward slope. In general, with an increase in grid cell size and the generalization of bounding contours, the lowest enclosed contour appear at a lower elevation, typically north of the original drumlin location.

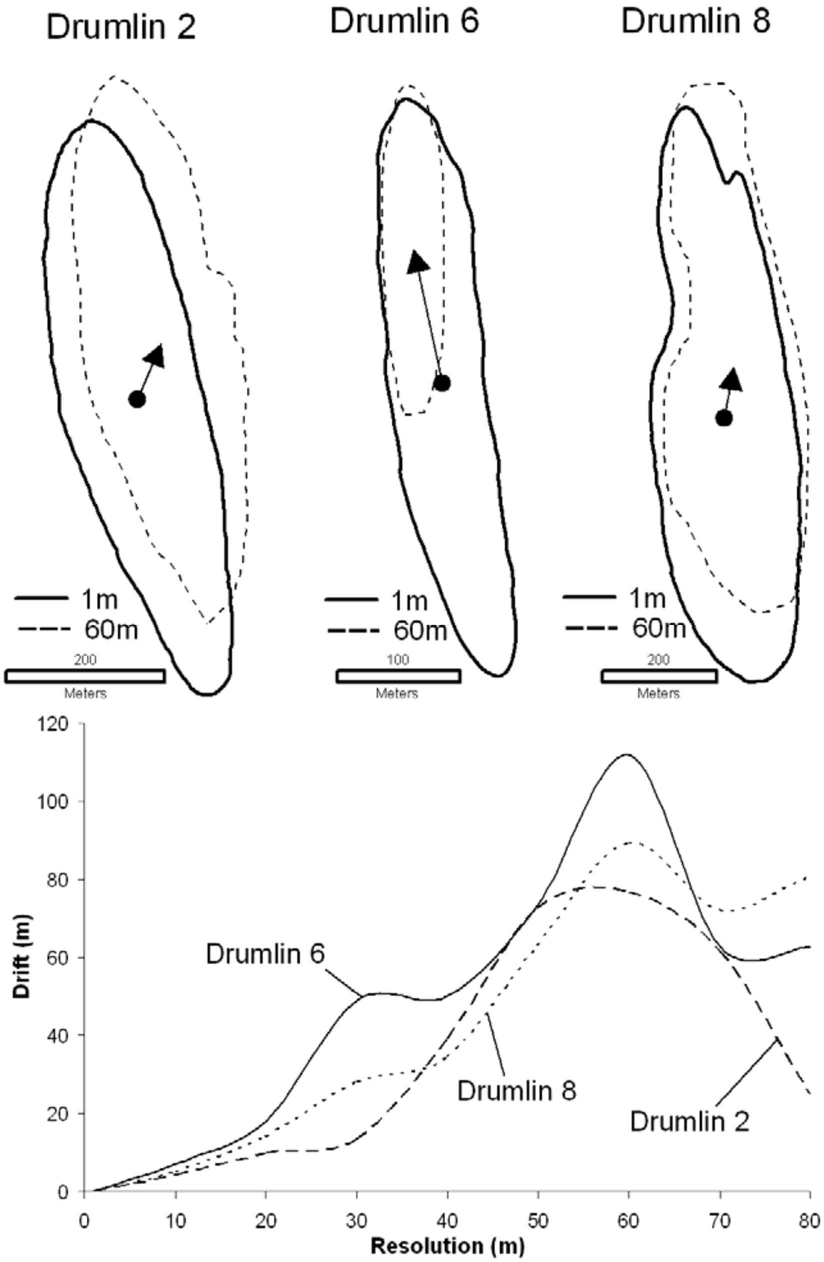


Figure 2.8. As grid cell size increases, a drumlins centroid shifts position, which can be attributed to a drumlin changing size (drumlin 6), a drumlin physically shifting (drumlins 2 and 8), or a combination of both. Drumlins in this study area tended to shift northward as resolution increased (perhaps attributed to a gentle northward dip of topography).

Discussion

General observation and trends

Results from this case study indicate that grid cell size clearly influences the measurements and descriptions of drumlin characteristics. The amount of influence occurs at different grid cell sizes for each drumlin and there is no visible trend that indicates which resolution generates unreliable measurements of drumlin characteristics. However, as a general rule, the optimum resolution for calculating drumlin width, length, and orientation ranged between 10-30 m. Although the optimum resolution for one drumlin may not be the same for another, the 10 m DEM consistently registered as an acceptable resolution for reliable morphometric studies of drumlin fields. Drumlin fields that contain unusually small drumlinized features, such as in the Tweed basin, Scotland, may require customizing by spatially analyzing subsections of the drumlin field with a high number of small features or using a finer resolution. Furthermore, 10 m elevation datasets are becoming readily available (e.g. NED) and can be used in regional studies without requiring significant processing capabilities. Based on the results of this study, it is not recommended to use a DEM resolution of 30 m, since almost all drumlins exhibit drastic change in size with resolutions coarser than 30 m.

A coarse optimum resolution could be caused by: 1) substantial variability within the control data (unusually large offset between the minimum and maximum data values within the control group, see Fig. 2.4), or 2) very little change in drumlin size and shape, such that the measurements barely deviate from the fine resolutions. However, in this case study, the control data for each drumlin tended to show little variability between 1 m and 5 m, indicating that (2) is the most likely scenario. The only exception is orientation, when it is possible that the bounding container position remains static while the drumlin spine shifts. This would cause the range of "optimum resolutions" to vary more than as a result of the other variables. In addition, there seemed to be little correlation ($<0.2\ R^2$) between optimum resolution and drumlin size or shape (e.g. large drumlins having larger optimum resolutions), which indicates that a sensitivity analysis of this type should be practiced before conducting a rigorous study on drumlin morphometry.

While contour interval is not discussed at length in this paper, the interval used to extract drumlins is important. Figure 2.2 illustrates the method of delineating and extracting a drumlin based on a 5 m contour interval. The vertical profile of the drumlin shows where the lowest enclosed contour line exists (185 m). Based on the vertical profile, however, one could argue the base of the drumlin is located near the trough between the two drumlins (181 m), which is actually concealed by a 5 m contour interval. Thus, the next lowest contour line (180 m) is shared by both drumlins and, for the purpose of this study, is removed. This will undoubtedly influence the size and shape of a drumlin. Certainly, the base height that drumlins are derived from can be altered to address this issue but in most drumlinized landscapes, there is a general dip (here, towards the north) that is difficult to account for with most GIS contouring toolboxes.

While 1 m contour intervals were consistently used in this study to provide the most detail and isolate grid cell size as the variable of interest, most DEMs will have at least a few meters of uncertainty, whether derived from satellite imagery, topographic maps, or aerial photogrammetry. Dunlop and Clark (2006) reported vertical accuracies of ±10 m for ASTER derived DEMs and ±2.5-5.0 m for DEMs derived from aerial photogrammetry. In addition, the horizontal accuracy of contour lines (if derived from a DEM) is a function of the vertical and linear error of the DEM and should be considered when using control charts to determine optimum resolution. In many landform studies, field observations can be used to determine the base elevation of a particular landform, thus minimizing dependence on digital data to derive landform boundaries.

Technique: Boxes

The use of bounding containers to measure drumlin characteristics is an efficient, automated method for studying multiple drumlins or a drumlin field (see Fig. 2.3). The bounding container script allows the user to select convex hull, minimum area rectangle, and minimum area circle or extent rectangle. Before this script can be used, the user must contour the DEM and remove all of the contour lines except for the closed contour lines, which is the boundary of each drumlin. At this point, there is flexibility in the classification or demarcation of a drumlin, since the user selects the contour line that marks the boundary of each drumlin. However, a set of rules can be used to provide consistency in this process throughout the drumlin identification and extraction process.

Technique: Statistics

While there are many variations of SPCC, we used upper and lower control limits to indicate when the measurement of a drumlin variable began to vary statistically and, as a result, decrease in reliability. We used the first five resolutions of every drumlin to calculate the standard deviation because the values were generally consistent within this range for all drumlins; these measurements were used to provide the limits for acceptability for calculations of each drumlin variable. Rather than statistically analyzing each drumlin as a discrete object, the mean standard deviation of the drumlin field (here, 16 drumlins) was used to generate the UCL and LCL for each drumlin. This was done to allow some flexibility in the analyses, as some drumlins showed no measurement variability within the first five resolutions, while other showed subtle variations. The end product of this difference is that some drumlins would have tighter UCL and LCL than others, even though the drumlin sizes and shapes varied equally. However, drumlin fields with enormous variations in drumlin dimensions may be influenced by the use of a mean standard deviation and, as a result, we recommend conducting a sensitive analysis beforehand to determine if the mean or individual standard deviation is favorable for determining optimum resolution.

Future work

Applying this technique to a larger study area would yield more insight into the effectiveness of the bounding container method and the reliability of the statistical analysis used to describe drumlin form. However, the data management obstacle associated with the large amount of digital data required for building 1 m DEMs covering extensive regions would remain, although results from this study suggest that using a DEM less than 10 m (i.e. NED) would be unproductive and time consuming.

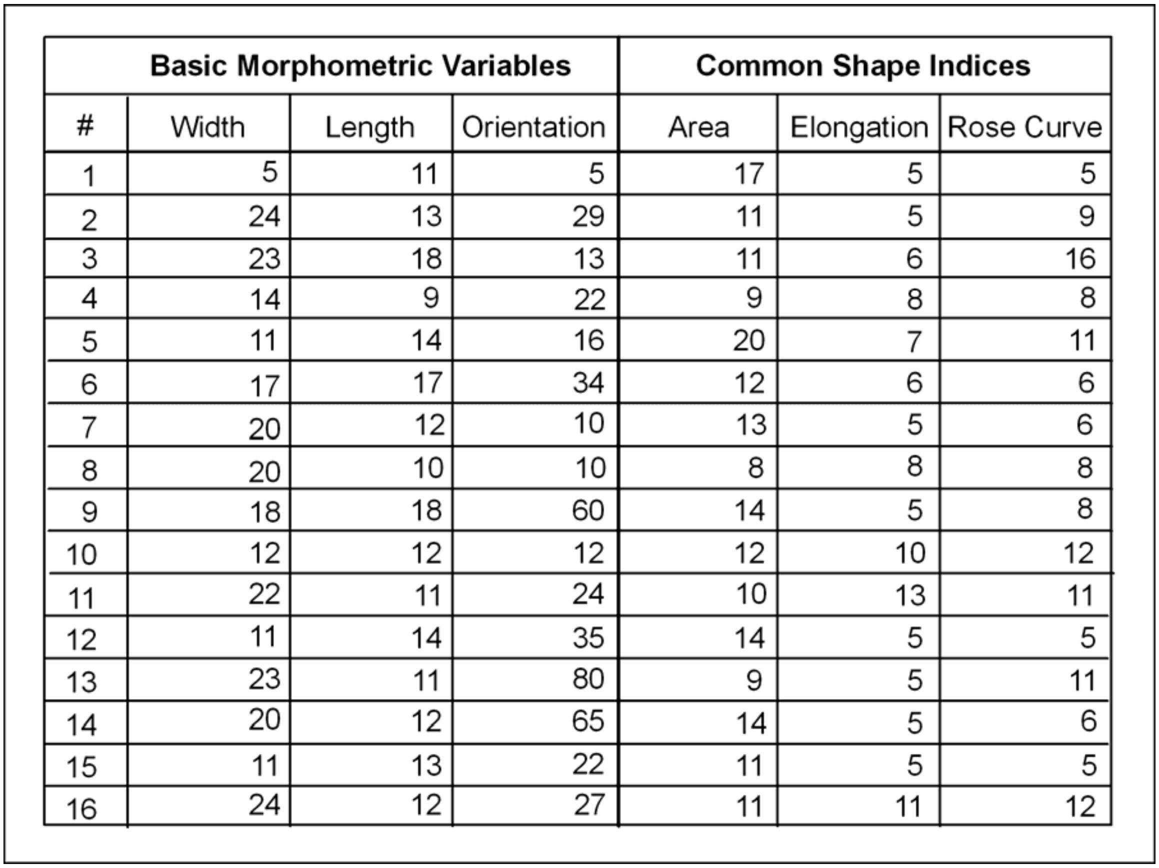
Other variables and indices should also be tested to evaluate the influence of resolution. For example, the slope angle of drumlins, a common attribute used to characterize drumlins, may be influenced by changes in grid cell size. Other shape indices may prove to be more robust or sensitive to changes in resolution, including forms of circularity and comparison measurements (Chan and So, 2006; Maceahren, 1985; Miller and Wentz, 2003; Taylor, 1971). Several of these indices have recently been used as surrogates for elongation (MacLachlan and Eyles, 2007; Nalepa and Napieralski, 2007) and a good correlation between elongation and circularity when measuring drumlin shape has been found (Nalepa and Napieralski, 2007). As different indicators of shape are merged into drumlin studies, it is recommended that the influence grid cell size has on each of these indices is taken into consideration.

Since many studies have utilized contrasting techniques for identifying and measuring drumlins, it may be worthwhile to re-evaluate these results by utilizing the optimum resolution to conduct comprehensive studies of drumlin form and patterns. Additionally, recent studies have focused on the impact of grid cell size variation on hydrologic models, such as the United States Department of Agriculture's Soil and Water Assessment Tool (SWAT), watershed delineations, and slope form definition (Alarcon et al., 2006; Chaubey et al., 2005; Gao, 1997; Hutchinson and Gallant, 2000; Marcus et al., 2004; Martz and Garbrecht, 1992; Thieken et al., 1999; Yin and Wang, 1999; Zhang and Montgomery, 1994), creating applications of this technique beyond drumlins.

Conclusion

We developed a semi-automated technique for the identification, extraction, and measurement of drumlins using GIS. Bounding containers quickly and effectively measured the dimensions of drumlins, reducing the subjectivity of drumlin analyses and also increasing the efficiency of what was traditionally a laborious task. In addition, this technique was used to determine the influence DEM grid cell size has on calculations of drumlin variables. The measurements of sixteen drumlins using a range of DEM resolutions demonstrated that grid cell size plays an important role in characterizing drumlin form and, with the use of Statistical Process Control Charts, determined the optimum resolutions that best characterize drumlin form without the use of excessively fine DEM resolutions (increased processing time and storage). The results from this study indicated that a 10 m DEM (e.g. NED) produced calculations of length, width, and orientation that were relatively similar to those of a 1 m DEM (or any other sub 10 m DEM).

While scores of published research have reported on drumlin shape, size, and location, there is no widely-accepted, standardized technique for the extraction of drumlins. It is imperative that there is an optimization of resolution and contour interval when conducting a detailed analysis of a drumlin or a drumlin field. As the field of geomorphology continues to integrate digital data into morphometric analyses of landforms, it is crucial to understand how grid cell characteristics influence landform variables. Although this has been stressed in other disciplines that rely on the use of DEMs, very little attention has been paid in the field of glacial geomorphology.



	Basic Morphometric Variables			Common Shape Indices		
#	Width	Length	Orientation	Area	Elongation	Rose Curve
1	5	11	5	17	5	5
2	24	13	29	11	5	9
3	23	18	13	11	6	16
4	14	9	22	9	8	8
5	11	14	16	20	7	11
6	17	17	34	12	6	6
7	20	12	10	13	5	6
8	20	10	10	8	8	8
9	18	18	60	14	5	8
10	12	12	12	12	10	12
11	22	11	24	10	13	11
12	11	14	35	14	5	5
13	23	11	80	9	5	11
14	20	12	65	14	5	6
15	11	13	22	11	5	5
16	24	12	27	11	11	12

Table 2.1. Optimum resolutions for each drumlin for each variable.

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Chapter 3: Optimizing Geomorphology Using Statistical Process Control Methods

Abstract

Although process control techniques typically support manufacturing and industrial applications, the fundamental concepts behind statistical process control charts (SPCC) can contribute to the analysis of digital elevation models (DEM) for remote sensing and geologic applications. The quality and potential of a DEM is limited, in part, by grid cell size: excessively large cell sizes increase ambiguity, whereas small cell sizes increase processing time and storage. Since DEM availability, use, and quality continue to increase, it is necessary to define and isolate an optimum resolution to study topographic form. This paper introduces the customization of process control methods to isolate an optimum resolution for the analysis of topographic features (i.e. streamlined glacial landforms) from DEMs. The same feature is extracted from successive DEM resolutions (all derived from 1 m), measured in a geographic information system (GIS), and statistically analyzed using a control chart. While control charts normally determine stability, or signify when a process is "out of control", we consider out of control synonymous with significant variability, which signifies the resolution(s) at which the cell size influences the outcome of a dimensional analyses of geographic form.

There are several observations derived from this work: (1) The impact cell size has on landform measurement is predictable. The size of a feature derived from a 1 m DEM is virtually identical to the same feature extracted from a 3 m DEM. However, as resolution increases, so then does the variability (e.g. a feature measurement may vary by a magnitude between DEMs). (2) The size and extent of a landform or landscape influences optimum resolution. A relatively large landform tends to have a larger optimum resolution than relatively smaller landforms. (3) The design and implantation of an SPCC in geomorphometric analysis requires exploration, since the user ultimately defines the extent of acceptable data variability. (4) Optimum resolution can be

determined for clusters of features, which is a necessity for geomorphometric analyses of landscapes (e.g. extensive drumlin fields). The results suggest that an optimum resolution does exist for most topographic features and that, when analyzing landforms derived from DEMs, process control methods can elicit resolutions that will exhibit minimal effect from cell size. In turn, this improves spatial analyses of landscapes, including pattern analyses and correlations, landform evolution, and process dynamics.

Introduction

Geomorphometry (i.e. terrain analysis) combines mathematical, statistical, and image processing techniques to quantify bare-Earth topography from digital data, and this generally involves either the analysis of continuous elevation data or the delineation and measurement of discrete landforms (Pike, 1995, 2000a; Rasemann et al., 2004; Pike et al. 2009). Surface metrology, used in industry to measure surface roughness or texture, is analogous to geomorphometry (see Thomas, 1999; Pike 2000b; Stout and Blunt, 2000). Similar to the way geomorphometrists use digital elevation data to measure variations in Earth's topography, surface metrologists use profilometers to ensure surface roughness measurements are within acceptable thresholds for many products and systems (e.g. automotive, electronic, textile).

Most of the topographic quantification and analysis of Earth's surface is derived from digital elevation models (DEM), which are gridded sets of points in Cartesian space ascribed values of elevation that represent Earth's surface. Each grid cell has a spatial location, size, and attribute (in this case, elevation above some datum, such as sea level). A continuous set of grid cells representing Earth's terrain can be used to elicit topographic trends (e.g. slope, aspect), indicate landscape change over time, extract discrete or patterns of landforms (e.g. glacial, fluvial, coastal), or construct and operate complex predictive models of environmental scenarios (Evans et al. 2009).

The study of topography using digital data has broad application, including environmental and Earth science (Bishop and Minasny, 2005; Mitá□ová et al., 1995; Moore et al., 1991; Chorowicz et al., 1995; Jordan et al., 2005), engineering and military (Li et al. 2005; Petrie and Kennie, 1987; Griffin, 1990; Franklin and Ray, 1994), bathymetric studies of oceans and large lakes (Burrows et al., 2003; Giannoulaki et al., 2006; Lundblad et al., 2006), planetary surface exploration (Smith et al., 1999; Dorninger et al., 2004; Stepinski, 2006; Williams and Zuber, 1998; Cook et al., 2000), and entertainment (i.e. virtual reality) (e.g. Blow, 2000). For example, the characteristics of glacial landforms can confirm or reject theories of ice-land interactions or glacial processes, as more streamlined features may indicate more efficient ice sculpting process. Additionally, watershed slopes established off DEMs, will influence hydrologic model outcomes based on grid cell-to-cell connectivity, which then influences the derivation of stream network density and thus predictions of the route and timing of surface waters within the watershed. Many of these applications in geomorphology and hydrology utilize automated tools within a geographic information system (GIS) that efficiently expedite multifaceted techniques on sophisticated spatial problems.

However, the grid cell size of a DEM will clearly influence geomorphometric analyses, much like the number of pixels in a digital camera limits the capability to resolve features. Although this seems intuitive, extensive work has attempted to quantify the role of grid cell size in the description, classification, and analysis of terrestrial and extra-terrestrial landforms and landscapes. Too coarse resolutions smooth the landscape (i.e. filter surface roughness), thus reducing accuracy of terrain attributes), alters derivations of slope by shortening length and decreasing angle, and reduces landform “capture” capability (e.g. landform count, shape, size) (Gao, 1995; 1997; Guth, 2003; Ziadat, 2007; Smith and Wise, 2007). Grid cell size compromises watershed delineation (Chochrane and Flanagan, 2005), hydrologic model predictions (Vieux and Needham, 1993; Perlitsh, 1994; Wolock and Price, 1994; Zhang and Montgomery, 1994; Band and Moore, 1995; Quinn et al., 1995; Chaplot, 2005; Chaubey et al., 2005; Wechsler, 2006), topographic and wetness index (Wolock and McCabe, 2000; Sorensen and Seibert, 2007; Wu et al., 2007), channel networks, stream order, and channel flow (Wang and Yin, 1998; Cho and Lee, 2001; Lin and Oguchi, 2004; Rolim da Paz et al., 2008; Dixon and Earls, 2009; Dutta and Nakayama, 2009), soil attributes (Claessons et al., 2005; Smith et al., 2006), and estimates of erosion and sedimentation (Hessel, 2005).

Studies that aimed to quantify the effects of resolution on geomorphometric and hydrologic analyses also have a veiled assumption about the relationship between the landform size or landscape area and the range of grid cell sizes (Quinn et al., 1991). Small area studies that focused on runoff processes (soil-hillslope relationship) were generally tested using grid cell sizes of 1 m to 30 m. Streamflow and watershed processes were analyzed using ranges between 10 m to 1000 m, while the impact of resolution on several continental-scale hydrologic models were tested using grid cell sizes of 1 km to 100 km. There is an intrinsic connection between scale of study and grid cell size: relatively small topographic features are studied using small grid cell sizes, while it would be appropriate to study larger features using relatively larger grid cell sizes (Fig. 3.1). However, excessively fine resolutions will not necessarily reveal more detail; rather an increase in grid cell resolution also increases processing time and storage without producing more detail (Napieralski and Nalepa, 2010).

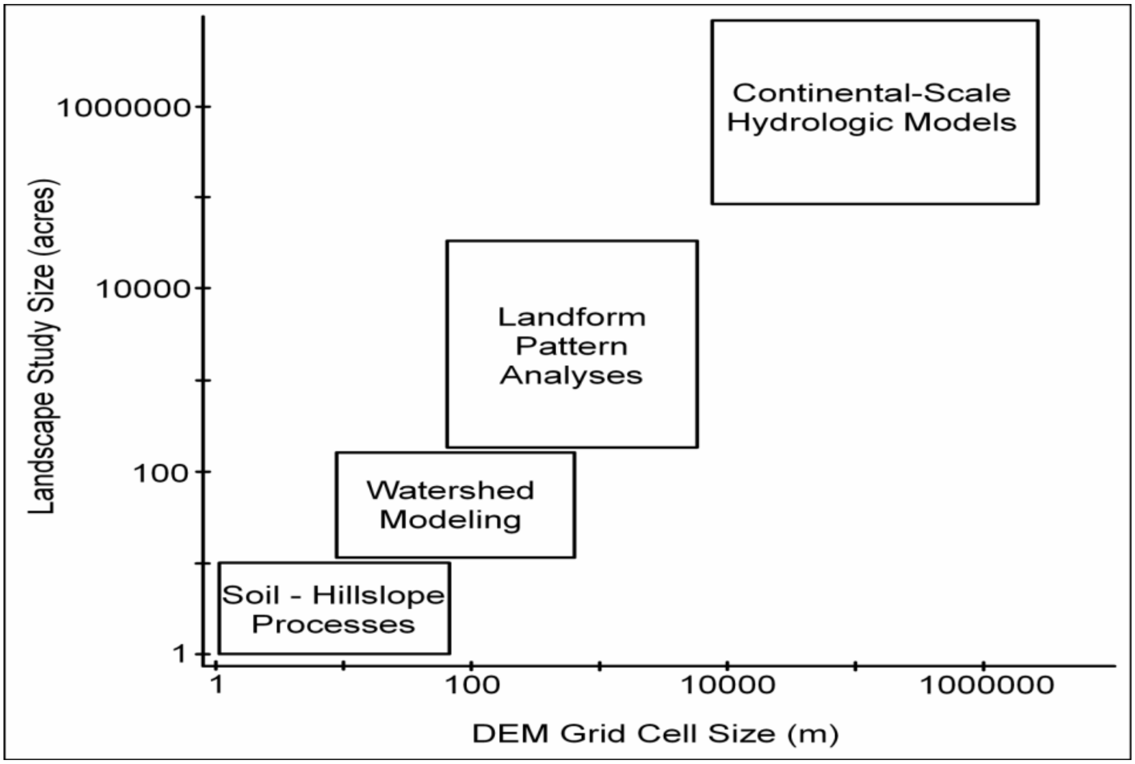

Figure 3.1. An extensive summary of previous studies that have analyzed the impact of resolution fall within predictable ranges for grid cell sizes examined and the size of the study area or landform. Relatively large study areas tested the impact of relatively large grid cell sizes, indicating the intuitive linkage between resolution and study area size.

Despite this intuitive relationship, little has been done to suggest an optimum resolution to analyze and describe various landforms and to correlate optimum resolution with landform size (Napieralski and Nalepa, 2010). For the purpose of this paper, optimum resolution is identified by the largest grid cell size in which there is no sacrifice in representative accuracy. Thus far, there have been two basic approaches to evaluating optimum grid cell size for geomorphometry or hydrologic modeling: graphical inflection and relative error. Horritt and Bates (2001) conducted flood predictions using various grid cell sizes (20 m to 1000 m) and graphically illustrated the relationship between model performance and grid cell size. The model performed at relatively the same accuracy using the three smallest grid cell sizes. However, as grid cell size increased, the model performance decreased significantly, leading to an inflection in a graphical illustration of model performance and resolution. In contrast, relative error, which assumes the smallest resolution is the most accurate representation of reality, compares model output or morphometric measurements for any resolution against the smallest resolution to evaluate the disparity (Garbrecht and Martz, 1994; Cotter et al., 2003). Frequently, a threshold of ±10% is used to indicate when resolution is influencing the outcome of the analysis, and thus implies an optimum resolution (Garbrecht and Martz, 1994). Both methods rely on relatively arbitrary thresholds or observations to gauge the impact of resolution on outcomes of landform descriptions or process models.

Therefore, the purpose of this paper is to (1) present statistical process control charts as a tool to determine optimum resolution for studies of topographic form derived from digital elevation models (DEMs), (2) conduct a sensitivity analysis of input variables for SPCC and report the impact this has on estimates of optimum resolution, and (3) attempt to relate optimum grid cell size with landform size, if any such relationship exists. A swarm of streamlined glacial landforms (i.e. drumlins) were delineated from varied-resolution DEMs covering approximately 6 km^2 in area.

Methodological Design

Drumlin Extraction

This study area includes 16 drumlins located within a 3 km x 2 km rectangle, south of Palmyra, NY (Fig. 3.2). A USGS Digital Raster Graph (DRG) (i.e. a scanned image of a standard series topographic map), provided vertical benchmarks and contour lines, which was used to derive a 1 m DEM using spatial interpolation. The 1 m DEM was sub-sampled to produce successive DEMs in 1 m increments (to 30 m) and then 5 m increments from 35 m to 80 m (producing a total of 40 different DEMs). Each DEM was contoured using 1 m intervals, so that changes in drumlin form could be measured as grid cell size coarsened. Several GIS tools were customized (Napieralski and Nalepa, 2010) to automate the process of extraction and measurement of a wide range of drumlin variables, including width, length, height, slope, centroid (i.e. geographic center), shape (e.g. elongation, rose curve), and orientation for each drumlin within all DEMs (Fig. 3.3). Hence, each of the 16 drumlins had dimensions for 40 different resolutions.

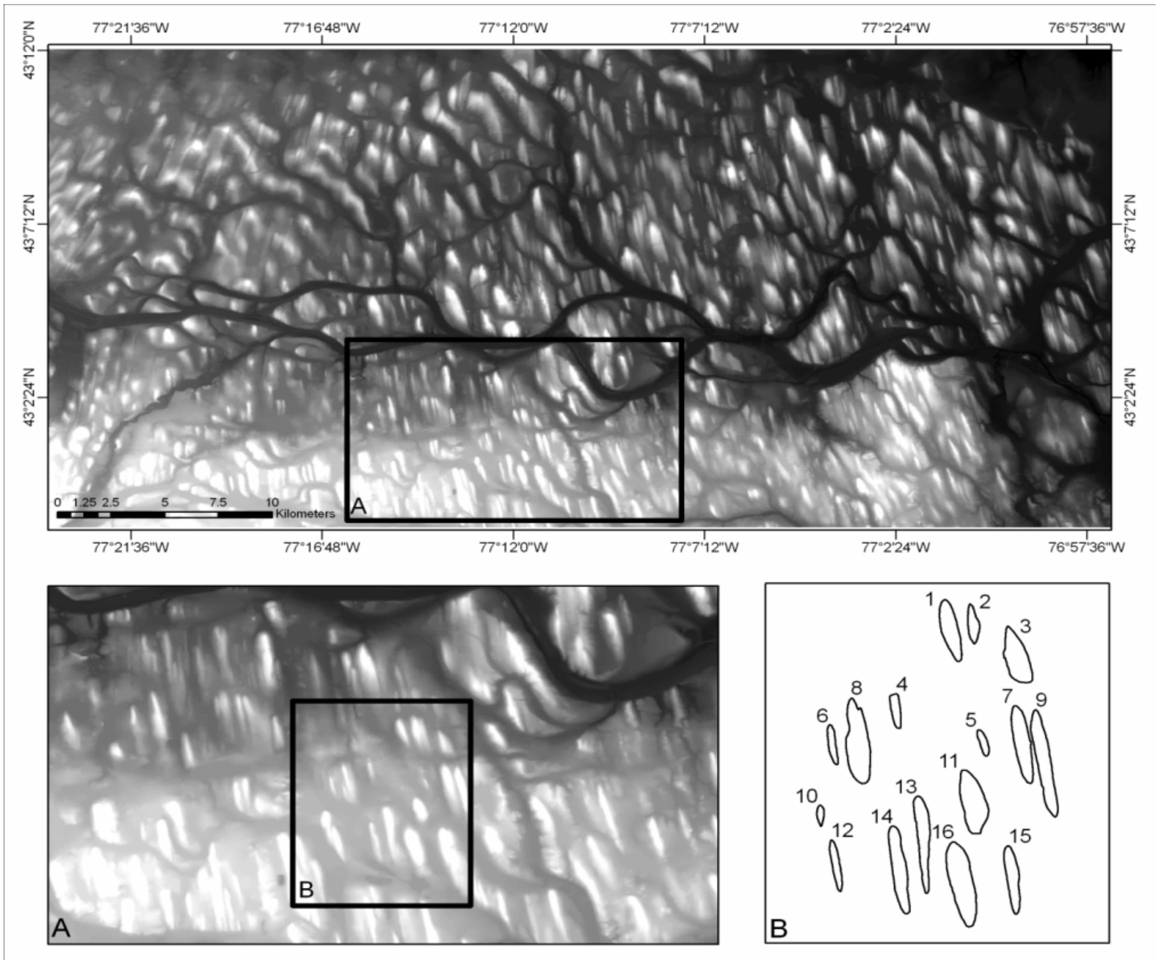

Figure 3.2. Regional map illustrating prevalence of drumlins in north-central New York, USA (top). Map A presents the drumlins used within this study, including an illustration of individual boundaries for each drumlin and drumlin identification numbers (Map B).

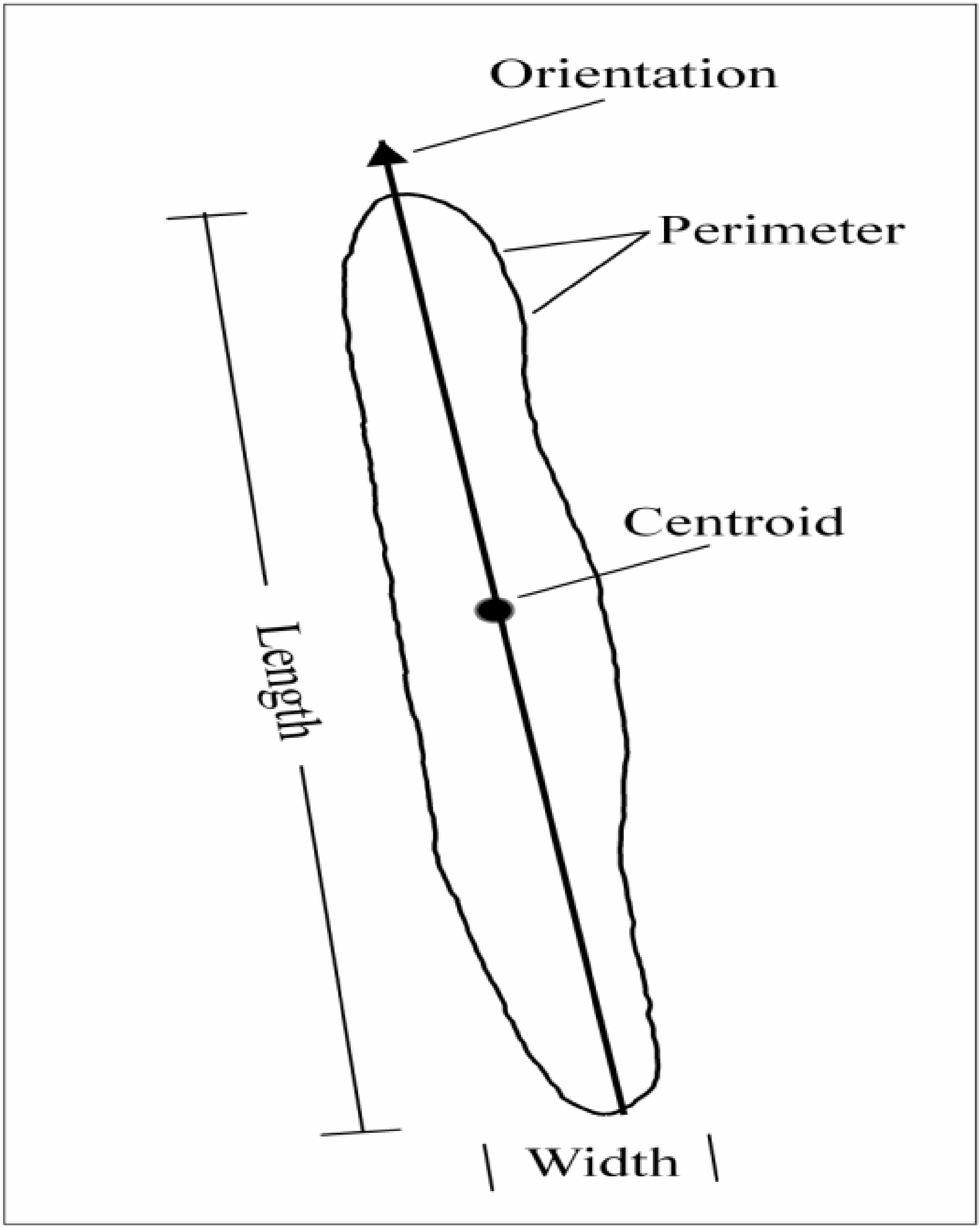

Figure 3.3. The basic dimensions of a drumlin analyzed in this study. As grid cell size changed, each dimension was re-measured and basic measurements were combined to characterize drumlin form and shape using shape indices (e.g. elongation, rose curve).

Statistical Process Control Analysis

While control charts normally determine stability in manufacturing or industry, or signify when a process is “out of control”, we consider out of control synonymous with significant variability, which signifies the resolution(s) at which the cell size influences the outcome of a dimensional analyses of form or shape. Control charts statistically analyze performance so that future deviations can be detected (and possibly rejected) (Augustin and Brice Minvielle, 2008; Bissel, 1994; Kolesar, 1993). In this particular application of statistical process control charts, the dimension of the object is unknown due to vertical and horizontal uncertainty associated with the construction of DEMs and the lack of corroboration on the location of the true landform boundary. Therefore, the control charts must assume the finest DEM best represents topographic reality and this value is used, in part, to establish acceptable limits by which to evaluate the impact of increasing resolution. The upper and lower control limits are established on the variability (i.e. the Range or R) exhibited by the finest grid cell sizes (i.e. control set). For this study, the control set included measurements taken from the 1 – 5 m DEMs. The first measurement that falls outside the limits is considered "unreliable" data (Bissel, 1994). The mean range values for the 16 drumlins established the upper and lower control limit based on a standard deviation (σ):

$$\sigma = \bar{U}/1.023$$

Optimum resolution was determined two ways: testing each drumlin as a discrete landform (i.e. optimum resolution for that particular drumlin) and grouping all the drumlins to test for optimum resolution of the group of drumlins (i.e. drumlin field). The impact of selecting various control set sizes and standard deviations in the control charts was evaluated by determining the optimum resolution for each variation of control set and number of standard deviations. Additionally, the optimum resolution for each drumlin was correlated to the drumlin size. Finally, a matrix was used to analyze and report the influence control set size and area between upper and lower limits (i.e. number of standard deviations) have on the optimum resolution. The optimum resolution for several drumlins was calculated using a control set ranging from 3 to 9 and varying the number of standard deviations from 1.5 to 4.5. Assembling the results in a matrix revealed patterns in the data directly related to the extent of the upper and lower limits, which can then guide future geomorphometric analyses of resolution using an SPCC.

Results

Drumlin morphometry was influenced by grid cell size, although most measurements remained comparable within the first 10 cell sizes (Fig. 3.4). Fluctuations in width, length and area were substantial for several drumlins. Drumlin 12, as an example, showed insignificant variability in width and length as grid cell size increased from 1 m to 12 m. Although the original width (at 1 m) was approximately 84 m, width ranged from 57 m to 186 m. This variability was also observed with length. This trend was detected for most drumlins (i.e. substantial disparity between minimum and maximum measurements for width, length, and area). As grid cell size changed, drumlin shape frequently changed in a drastic manner, thus influencing measurements. Several drumlins disappeared, amalgamated, or altered size as grid cell size increased to beyond 30 and 40 m.

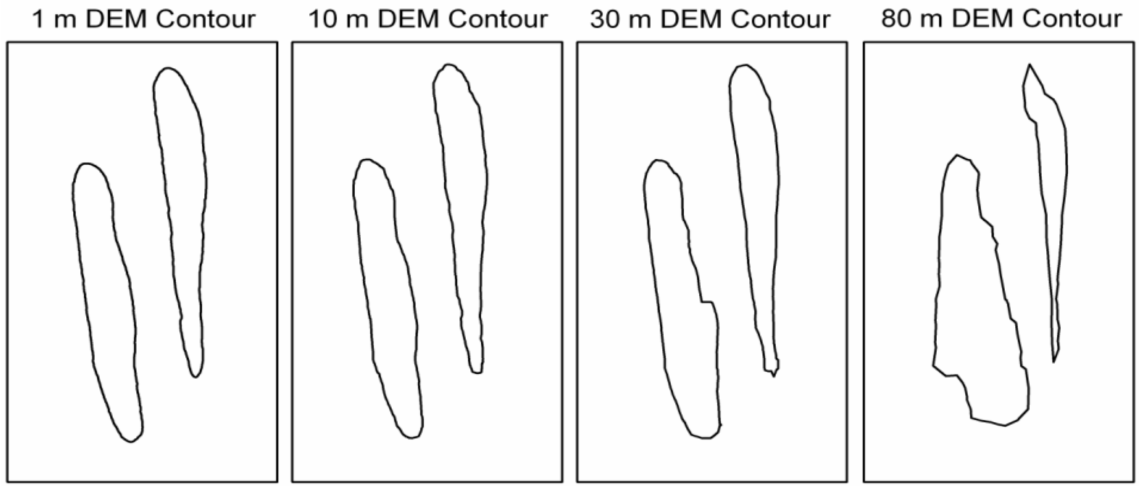

Figure 3.4. Illustration of drumlins 14 (left) and 13 (right) delineated from resolutions commonly used in previous and present-day landform studies, including Landsat 1-3 (80 m), Landsat 5-7 (30 m), National Elevation Dataset (10 m), and using Light Detection and Ranging (1 m). Note barely discernible differences between 1 m and 10 m, in contrast to obvious changes to shape and size at 30 and 80 m.

The optimum resolution for individual drumlin width, length, and area ranged between 10 – 20 m, 9 – 20 m, and 8 – 20 m, respectively (Table 3.1). Relatively narrow drumlins (e.g. 5, 10, 12) produced low optimum resolutions, while the same trend with length and optimum resolution was unconvincing (i.e. long drumlins exhibited both relatively high and low optimum resolutions). Optimum resolution for the entire study area was 17 (width), 14 (length), and 12 (area), although it is also worth reporting the minimum value (10, 9, and 8 m, respectively), rather than mean, since the optimum resolution selected for an entire suite of drumlins must ensure that grid cell size has no influence on any drumlin characteristics.

Discussion

Optimum resolution is controlled by several variables. More variability within the control set increases the extent of the limits, which generates coarser optimum resolution. Although several drumlins have relatively narrow widths (78 – 100 m) compared to length, drumlin width exhibited coarser optimum resolutions than length. The relatively higher optimum resolutions were caused by larger variability within the control set, thus increasing the upper and lower limits and producing coarser optimum grid cell sizes. Width is a limiting factor (i.e. smallest dimension), especially when measuring elongated features; it is critical that the design of the process control chart centers on this limiting dimension, as this will most likely influence estimates of optimum resolution.

The control chart design and implementation influences estimates of optimum resolution. Increasing control set size had a similar impact on optimum resolution as increasing variability within a control set. As control set size increased from 3 to 9, optimum resolution doubled, or even tripled, regardless of drumlin number, size, shape, or relief. Similarly, if the control set size remained the same, but the number of standard deviations changed, an equivalent pattern was detected. As the number of standard deviations increased, the optimum resolution likewise increased, although not at the same magnitude as detected with changes in control set size. As expected, large control sets (e.g. 8 or 9) with large standard deviations (e.g. ±4.0 or 4.5) amplifies the extent of the limits and produces larger optimum resolutions (Table 3.2). Consequently, selecting large control set sizes with large standard deviations will extend the optimum resolution. When studying streamlined landforms that have a “limiting dimension”, such as width, it is advisable to use a large control set size and/ or standard deviation to offset the variability that exists within the control set. In contrast, variability is relatively minimal within the control set for measurements of length and “tightening” the upper and lower control limits would increase the optimum resolution.

Optimum resolution is also controlled by factors that influence the landform delineation process, including the local relief and overall complexity of the study area (Moore et al., 1991). Drumlins that share boundaries or are proximal to another landform, tend to be more difficult to delineate and therefore exhibit more variability as grid cell size increased. For example, in this study, several drumlins are near-tangential to each other and as grid cell size increased, either one drumlin absorbed the other (thus decreasing overall count but also substantially increasing the area of the other drumlin) or both drumlins changed significantly in length or width. The SPCC detects these deviations and denotes them “out of control” or unreliable. Depending on the dimensional characteristics of the feature, this will influence the optimum resolution. Furthermore, features that exhibit high relief (especially those with steep, well-defined slopes) generally demarcate easier than low relief features and, as a result, produce larger optimum resolutions. While most drumlins in a drumlin field (including those in this study) have comparable relief, other landforms (e.g. mountain features, watersheds) vary significantly in relief and complexity, so that the optimum resolution is affected by topographic characteristics.

It is intuitive to relate landform size to optimum resolution (see Fig. 3.1); larger landforms typically obtain larger optimum resolutions, while relatively small features are “out of control” at a smaller resolution because of the ratio between grid cell size and feature dimensions. For example, drumlins with a width of 84 m will be impacted by changes in grid cell size quicker than larger drumlins (e.g. 250 m). As grid cell size increases from 1 m to 10 m to 20 m, the number of grid cells characterizing a drumlin 84 m in width would decrease from 84 to 8 to 4. Smaller features thus diminish in size, alter in shape as it becomes more pixilated, and sometimes disappear altogether as grid cell size increases. Drumlins in this study were analyzed for this relationship, although it was expected to be a weak connection due to the complexity of this drumlin field and the relatively comparable sizes of drumlins. The optimum resolution for drumlin width exhibited good correlation to drumlin width ($R^2 = 0.647$), while the optimum resolution for length ($R^2 = 0.395$) and area ($R^2 = 0.195$) is less dependent on drumlin size than width (Fig. 3.5).

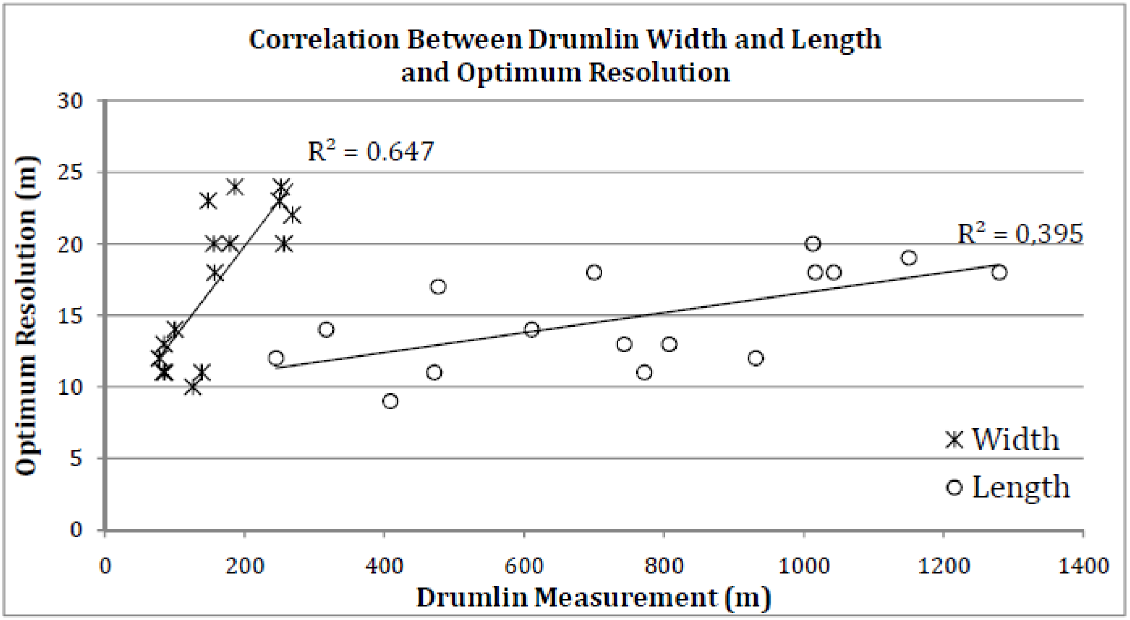

Figure 3.5. Correlation between optimum resolution and drumlin width and length. Wide drumlins generally had higher optimum resolutions; the same trend exists for length and area, although not as strong ($R^2 = 0.195$ for area).

In practice, geomorphologists are typically more interested in suites of landforms and therefore must determine an optimum resolution for use on a landscape. In this study, the optimum resolution was determined for each individual drumlin. This information can be statistically analyzed to estimate an acceptable resolution to measure all landforms within a study area, such as mean or minimum value- which ensures all drumlins can be described with no influence from DEM resolution. In contrast, it is more efficient to combine landform measurements first, before implementing an SPCC. Regardless of the order in which an SPCC is used, the results are comparable (Table 3.3), although combining measurements first produced smaller optimum resolutions. In addition, the ranges can be combined within the control set for each drumlin, rather than treating each drumlin separate and this will influence the extent of the upper and lower limits in the SPCC.

There is also some interpretation involved when considering a particular measurement as "out of control" and unreliable. Depending on the nature of the feature, as grid cell size increases, the changes in a measurement may be more drastic, such that it is easier to distinguish when a measurement is considered out of control. A number of drumlins exhibited this trend; once the measurement falls outside the limits, subsequent values continue to demonstrate high variability and few fall within the limits. Thus, there is little debate as to the optimum resolution. However, in some instances, the optimum resolution may be followed by a sequence of larger grid cells size that fall within the control limits. Although the last measurement before being labeled “out of control” is considered optimum, it is possible that the next measurement returns to within the control limits for extended group of resolutions. The user must consistently interpret the SPCC throughout that analysis, including how to manage data that leaves, then returns inside, the limits. It is expected that continuous, digital data (e.g. DEMs) representing bare-Earth elevation will have inherent errors and varying levels of uncertainty caused by the source or derivation method. Consequently, as data variability increases and grid cell size increases, local variability should be considered. Subtle changes in a particular measurement may be a reflection of DEM uncertainty.

Finally, the DEMs used in this study were constructed from a 1 m DEM to provide consistency, so that data variability would primarily be a reflection of changes in grid cell size. In reality, there is a wide range of sources for DEMs and, when determining optimum resolution to conduct a geomorphometric analysis of a landform or landscape, this will influence the outcome of an SPCC. Anytime a DEM is derived from a topographic map, errors and uncertainty are propagated from the source map and are derived from variations in interpolation algorithms, input data density, and grid resolution (Weng, 2002). Other DEMs, especially those derived from satellites (e.g. U.S. Landsat Thematic Mapper: TM, Shuttle Radar Topography Mission: SRTM) or light detection and ranging (LIDAR), have different standards for horizontal and vertical uncertainty and error. Comparing optimum resolution between DEMs from varying sources is therefore problematic, since variability in measurements may come from changing grid cell size, or as a result of source errors.

Conclusion

Geomorphometrists seek to recognize, delineate and quantify Earth’s terrain with an overall goal of evaluating spatial patterns, developing automated, statistical and extraction methods, and contributing to geomorphic process models. Due to an abundance of digital data, geomorphometry is predominantly conducted on gridded data (DEM). The quality and potential of a DEM is limited, in part, by grid cell size: excessively large cell sizes increase ambiguity, masking or altering features, whereas small cell sizes increase processing time and storage. Since DEM availability, use, and quality continue to increase, it is necessary to define and isolate an optimum resolution to study topographic form. This study aimed to determine if an optimum resolution exists for particular landforms and, if it does, how it can be obtained in a statistically rigorous manner. The location, shape, size, relief, and orientation of landforms, such as drumlins, are frequently used as "building blocks" in landform evolution models. Therefore, results from a geomorphometric analysis are critical, enhancing process- models and reconstructions of paleo-environments (Napieralski and Nalepa, 2010).

Statistical process control methods are typically designed to support manufacturing and industrial applications inquiries of quality, with the objective of signifying when a process is "out of control" by measuring the mean and variance of a particular process. Control charts can be customized to address specific behaviors or to indicate a special-cause variation. In this study, a basic SPCC was constructed to indicate changes in dimension, rather than in process. We considered out of control synonymous with significant variability, signifying the resolutions at which the cell size influences the outcome of a dimensional analysis of geographic form or size (i.e. special-cause variation). While there is some flexibility in the design and implementation of the chart and some debate in the interpretation of data that falls outside the control limits, the general theory behind SPCC provide a more statistically sound approach to determining optimum resolution than observing graphical inflections or with relative error.

Despite a few exceptions, optimum resolution was less than 30 m but fining grid cell size beyond 10 m would not yield more accurate results with the drumlins used in this study. One key conclusion to this study is the inference that previous geomorphometric analyses of drumlins (and perhaps other landforms) derived from older satellite data (e.g. 80 m and 30 m) are probably more influenced by grid cell size than previously thought. As geomorphometry progresses due to improved computing capability, advanced analytical techniques, and increased sources of elevation datasets, the importance of precision and certainty are amplified. As a result, there is an emergent necessity to quantify the impact digital data has on geomorphometric analyses of landform characteristics, and an SPCC affords a statistically-sound process to elicit an optimum resolution for studies of bare-Earth terrain.

Number	Drumlin Dimensions			Optimum Resolution		
	Width	Length	Area (m^2)	Width	Length	Area
1	126	471	39,281	10	11	17
2	186	743	101,056	24	13	11
3	250	700	126,503	23	18	11
4	100	408	34,301	14	9	9
5	86	317	21,850	11	14	20
6	85	477	31,484	13	17	12
7	179	931	125,272	20	12	13
8	256	1013	187,825	20	20	8
9	157	1280	159,366	18	18	14
10	78	245	13,450	12	12	12
11	268	772	153,577	22	11	10
12	84	611	41,387	11	14	14
13	148	1150	115,552	23	19	9
14	156	1043	129,906	20	18	14
15	138	807	84,387	11	13	11
16	252	1016	201,443	24	18	11

Table 3.1. Summary of drumlin size and optimum DEM resolution for 16 drumlins (in meters).

	3	4	5	6	7	8	9		3	4	5	6	7	8	9
1.5	5	10	10	14	14	14	14	1.5	5	6	7	7	8	9	10
2	5	11	12	17	18	19	19	2	5	7	9	9	9	10	10
2.5	5	17	18	20	20	20	20	2.5	5	9	9	10	10	11	11
3	5	17	20	24	22	22	22	3	5	10	11	11	11	11	11
3.5	5	17	21	24	24	22	22	3.5	5	11	12	12	11	12	12
4	5	22	21	26	28	29	29	4	5	12	12	12	12	12	12
4.5	5	22	26	26	27	29	30	4.5	5	12	12	12	12	12	14

Table 3.2. Evaluation of the impact control set size and number of standard deviation has on optimum resolution for width (left) and length (right).

	3	4	5	6	7	8	9		3	4	5	6	7	8	9
1.5	3	5	5	5	6	7	8	1.5	4	5	5	6	7	8	9
2	4	5	6	6	6	7	8	2	4	5	6	7	7	9	9
2.5	4	5	6	6	7	8	11	2.5	4	6	8	9	10	11	11
3	4	5	6	6	7	8	11	3	4	7	9	12	12	13	11
3.5	4	5	6	6	7	8	11	3.5	4	8	11	13	13	14	14
4	4	5	6	6	7	11	11	4	4	8	12	14	13	14	15
4.5	4	6	6	6	7	11	12	4.5	4	8	12	14	13	14	15

Table 3.3. Attaining optimum resolution for drumlin area through use of SPCC for each individual feature before summarizing (right) compared to calculating mean drumlin area before conducting an SPCC (left**).**

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Chapter 4: Conclusion

Introduction

Grid cell resolution can impact landform and landscape studies in multiple ways (e.g., landform morphometry, runoff models, watershed delineation). These impacts can lead to over or under estimation of the size/shape of landforms, lead to wrong estimates from watershed models, and to the omission of subtle features missed by coarser resolutions (Dixon and Earls, 2012; Tan et al., 2015; Yu et al., 2015; Ely et al., 2016). Most geomorphic analyses are conducted using grid data (e.g., DEMs). Therefore, the reliability of such an analysis is limited by the resolution of the DEM. As a result, it is important to determine an "optimum resolution" that is appropriate for a given study: fine enough to capture detail but coarse enough to minimize processing time. The objective of this thesis was to develop and test a statistical technique that would allow for assessing the impact of grid cell resolution on landform morphometry, with the overall goal of identifying the optimum resolution for drumlin analyses.

The increased availability of post-processed LiDAR data and high-resolution laser scanning makes it even more important that an optimum resolution be defined for topographic studies because of the very large file sizes. Having too fine a resolution can exponentially increase processing time while yielding negligible gains. This can be problematic because drumlins fields can be expansive (e.g., 1,300 km^2)(Trenhaile, 1975), making finer resolutions (sub 1 m) exacerbate this vast amount of data increasing processing time. As well-mapped landforms (e.g., drumlins) are used for input in, or verification of, landform evolution models, results from improved geomorphometric analysis can enhance our understanding of geomorphic processes and reconstructions of paleo-environments (e.g., Yu et al., 2015; Ely et al., 2016).

Previous studies focused on quantifying the amount of error associated with digital elevation models (Garbrecht and Martz, 1994), although most were simple descriptions, such as visual graph interpretation (Horritt and Bates, 2001) and relative error (Garbrecht and Martz, 1994). Rapid development and proliferation of high-resolution DEMs (e.g., LiDAR), necessitated a more rigorous technique to determine the optimum resolution for studies of landforms and landscapes. A technique used frequently in manufacturing was modified for this study to detect variations in a data set and to flag data values that exceeded statistical thresholds.

Statistical Process Control Charts (SPCC)

Statistical Process Control Charts (SPCC) is a valuable statistical analysis tool used in manufacturing, but its use is expanding into other business applications such as time management, resource allocation, and logistics (Bissel, 1994; Wise & Fair, 1998). SPCC has proved to be an invaluable statistical tool for the semi-automated analysis of the drumlin field study because flexibility within the user controlled variables allows the technique to be adapted for a wide range of applications. The flexibility lies in the analyst's ability to manipulate the control set size as well as the amount of standard deviations used in defining the control limits. The initial set up for the data lent itself almost specifically to SPCC because it mirrored an actual process in need of monitoring. SPCC lent itself to this study because defining the optimum resolution of a DEM mirrored an actual process in need of monitoring.

SPCCs typically support quality assessment of manufacturing and industrial applications by indicating when a mechanical process is "out of control". The control chart method can be modified to evaluate specific processes or parameters or to indicate a special-cause variation. SPCC were constructed here to indicate changes in landform dimension, rather than in a particular process. Thus, "out of control" was synonymous with statistically significant variability in dimensions, which then indicated the optimum DEM resolution. SPCC more generally could determine optimum resolution by statistical assessment, which is an improvement over previous efforts that determined optimum resolution by graphical inflections or calculated relative error.

Results

The Impact of Grid Resolution on Geomorphometric Analyses of Drumlins

Optimum Resolution

The optimum resolution for drumlin measurements was less than 30 m, and sometimes near 10 m, but it was clear that using a grid cell size below 10 m did not result in more accurate drumlin measurements. Based on these findings, it can be assumed that the results of drumlin studies that used Landsat MSS-derived elevation datasets (Maclachon and Eyles, 2013; Yu et al., 2015) are dependent on grid cell size and may require a reassessment using finer resolution DEM. On the other hand, several drumlins disappeared, amalgamated, or altered size, as cell size was increased beyond 30 and 40 m, which implies that these resolutions would not be optimum for measuring landforms of the same order as drumlins. One resolution cannot be definitively classified as optimum for all drumlins, as the majority of research indicates a range of optimum resolutions between 10 and 30 m, depending on variable and individual drumlin. The 10 m resolution was consistently deemed as an acceptable candidate for optimum resolution and is readily available for most of the US. As geomorphometry progresses due to improved computing capability, advanced analytical techniques, and increased sources of elevation datasets, the importance of precision and certainty are amplified. As a result, there is a necessity to quantify the impact the resolution of digital data has on geomorphometric analyses of landform characteristics, and SPCC affords a statistically-sound process to elicit an optimum resolution for studies of bare-Earth terrain.

Measurements

Varying resolutions of DEMs impact drumlin measurements in a number of ways. While measurements for the first series of cell sizes (i.e., 1 m, 2 m, etc…) remained similar, drumlin width, length, and area varied substantially. Among these variables, some are more sensitive to changes in resolution than others. Length exhibited finer optimum resolutions than width, which was an unanticipated result. It was expected that width would result in the finest optimum resolution because it was the smallest variable, but it appears that the amount of variation in a given variable has more influence than overall size. Variables with large variability (like length) have a finer optimum resolution than variables with smaller variability (like width).

Drumlin measurements that relied on shape indices (i.e. area, perimeter, elongation) responded differently than size variables (length, width, orientation). Size variables generally resulted in smaller ranges within the control set, which translated to tighter controls in the upper and lower control limits meaning the optimum resolution was much lower for shape indices than size variables (length and width).

Limitations to the Use of SPCC

While SPCC has been used successfully in this study to determine optimum resolution, there are several limitations that may hamper a more widespread adoption of this method. The first limitation is a lack of high resolution DEM data in drumlinized areas. High resolution data (most commonly Light Detection and Ranging, LiDAR) is limited to specific areas due to the high cost associated with gathering the data. At the beginning of this project, there were no 1 m DEMs available in drumlinized areas, especially in the Palmyra area of New York. The only way to proceed was by generating an artificial DEM surface based on a 7.5 minute USGS topographic quadrangle. This allowed for the subsequent creation of courser DEMs, which gave continuous DEM coverage at resolutions of 2 m – 80 m. While this study does not utilize remotely-sensed data, it still allowed studying the effect grid cell size has on morphometric measurements as resolution is coarsened.

The second limitation is the subjective nature of SPCC. When using SPCC, the analyst has to decide which parameters to change. These changes were assessed using a matrix to analyze and report the influence control set size and area between upper and lower limits (i.e. # of standard deviations) have on the optimum resolution. The optimum resolution for several drumlins was calculated using a control set consisting of the first 3 to 9 DEM resolutions' values and varying the number of standard deviations from 1.5 to 4.5. The results were assembled in a matrix that revealed patterns in the data directly related to the extent of the number of standard deviations. This technique highlighted how optimum resolution can vary depending on control set size and standard deviation.

Applying this method to other types of landforms is hampered by the difficulty in objectively delineating said features. Instead of relying on a single contour line, the Soil and Water Assessment Tool (SWAT) program was used in conjunction with ArcGIS 9.8 in the delineation of watersheds. SWAT used an algorithm that had unanticipated results. The coarsening resolution would change the location of the point of delineation, making a comparison practically impossible. This introduced another variable that was outside of our ability to control.

Further analysis of the sensitivity of SPCC should be tested by expanding the controllable variables refined to further narrow the UCL and LCL of what is acceptable variation. This is one of the benefits of using SPCC; it has the capacity to continually distill a process until it maximizes output. More data would allow for an enhanced ability to refine the results.

Impact of this Study

The first paper published within this study, (Napieralski and Nalepa, 2010) has already contributed to furthering the study of resolution. At the time of the submission of this thesis, "The Application of Control Charts to Determine the Effect of Grid Cell Size on Landform Morphometry," has been cited in 19 different peer reviewed papers in scholarly journals (according to Google Scholar). One paper conducted a geomorphologic analysis of a drumlin field in Canada used Napieralski and Nalepa (2010) to justify why a 10 m DEM was sufficient for their study and the results were similar to using a 1 m DEM (Maclachlan and Eyles, 2013). A separate study on subglacial bedforms used resolution that was finer than 30 m in their extensive analysis because of conclusions drawn from this thesis work that implied much could be overlooked using coarser data than 30 m (Ely et al., 2016). Lastly, an automated drumlin analysis of shape and volume estimation using LiDAR imagery in Minnesota cited this thesis work and revealed higher resolution images resulted in wider array of shapes that were not reported in previous drumlin studies and high resolution data could aide in understanding the origin of drumlins (Yu et al., 2015).

Suggestions for Further Research

The successful application of SPCC to drumlin studies suggests that it could also be applied to other landforms, such as cirques, glacial landforms, wetlands, coasts, dunes, and watershed delineations. SPCC so far has focused on landforms that have a base consisting of a single contour line, but other studies could focus on landforms with more intricate shapes. This study could also be expanded using LiDAR data of the study area. LiDAR data has increased in availability in recent years, and it would seem prudent to recreate this work to assess if LiDAR derived data yield similar results. High resolution data is allowing the opportunity for studies to assess the impact urbanization and development have on watershed boundaries.

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