Chapter 1

Introduction

United States military installations are home to America's fighting force. Training areas on these installations at home and abroad are subjected to heavy use by Soldiers, Marines, Sailors, Airmen, and their equipment as they prepare for combat operations. Add to that, the affects of weather and other natural processes and these areas become unsustainable for use by future warfighters, unless deliberate planning and implementation of control measures transpire.

Installation land managers are responsible for many decisions regarding the use and sustainment of military training areas. I explore TanGeoMS, a tangible geospatial modeling system, to facilitate the decision-making process. This unique technology is at the leading edge of three-dimensional geospatial modeling and simulation. TanGeoMS takes advantage of a physical, three-dimensional terrain model coupled with a laser scanner, projector, and a geospatial information system (GIS) to provide an interface for collaborative decision-making. Managers can examine their planned control measures in detail by modifying the physical model to represent their solution, capturing the results with a laser scanner and analyzing the results in a GIS interface. The resulting analysis is projected on the model, providing feedback on the impact of the terrain modifications and simulated processes. The feedback is used to improve existing designs and to develop subsequent scenarios.

Accelerated erosion of military training lands is one of the largest environmental challenges encountered by U.S. Army land managers. Preliminary results indicate that TanGeoMS can aid land managers by presenting them with a planning and evaluation environment to quantify erosion problems and to aid in the development of sustainable practices. Many military installations experience common erosion-related problems; however, only a handful of installations track erosion through quantified methods. Most installations track erosion through qualified methods (Miller & Linn, 2001). In these cases, descriptors are used and temporal comparisons made without scientific monitoring. Given the mission and the right tools, land managers could explicitly quantify the erosion effects on their installation. They would provide reputable advice to garrison commanders and their staff concerning best management practices to preserve these valuable training resources.

Soil erosion can be categorized into three stages: detachment, transport and deposition. The first two stages define the mechanics of soil erosion, while the third occurs only when sufficient energy is no longer generated to transport particles (Morgan, 2005). Two factors determine the magnitude of erosion: erosivity of natural events (i.e., rainfall, runoff, and wind) and erodibility of the soil. As stated by Toy, Foster and Renard, 2002: "Erosivity is a measure of the forces applied to the soil that cause erosion, and erodibility is a measure of the susceptibility of the soil to erosive forces." Detachment occurs when the erosive force(s) energy surpasses the erodibility threshold of the soil at which point particles become detached and are susceptible to transport. Transport occurs while the energy retained by the erosive force(s) is greater than the friction created by the surface over which the agent moves.

Controlling erosion is achieved in only two ways: reduce the erosive forces applied to the soil, or reduce the erodibility of the soil. When the problem is identified and quantified, the delicate balance between enacting conservation and training priorities ensues. Removing Soldier-induced erosive forces indefinitely from military training sites is counterproductive to their purpose, so land managers must consider alternative options to supplement management even when erosive forces may be reduced. Land managers will likely implement a combination of these principles using a variety of methods.

1.1 Objectives

The purpose of this project is to prolong the existence of useable U.S. Army training land by presenting land managers a planning and evaluation environment to quantify erosion problems and to aid in the development of sustainable practices.

I will explore current computer-aided modeling approaches and investigate innovative approaches to evaluate the environmental impact caused by various land-use scenarios. Current approaches to generating new land-use alternatives include using map algebra and digitizing. I will investigate the use of TanGeoMS as an environment that Army land managers can use to facilitate their decision-making process.

The endstate of this project is to disseminate the procedure to the Army land management team at Fort Bragg in the form of a paper, presentation and demonstration. The land management team at Fort Bragg displayed a great initial interest in the potential of TanGeoMS to become a widely used decision-making tool in the military land management community.

1.2 Significant Prior Research

Utilizing a three-dimensional tangible interface for landscape analysis is not a particularly new concept; however, remains in the development phase with regard to its ability to serve as a readily-available and widely-used decision-making tool for land managers. In his master's thesis, Ben Piper of MIT, outlines the evolution of computer-aided modeling to facilitate landscape design (Piper 2002). His thesis details the idea and functionality of *Illuminating Clay* that serves as the basis for the current hardware setup used in this project.

A North Carolina State University research team expanded the scope of the *Illuminated Design Environment* by integrating GIS. This configuration takes advantage of the powerful raster processing algorithms in GIS to aid in understanding topography and the impacts to landscape change (Mitasova, Mitas, et al. 2006). Integration of GIS enables the construction of accurate models based on real-world spatial data, projection of spatial data for visualization, and the ability to simulate natural processes in any landform-change scenario. Users can experiment with modifying the surface of the model by adding objects to represent real modifications to the landscape, such as buildings or dams. Then the GIS can perform sophisticated analysis to model how changes to the physical model affect environmental conditions, such as erosion and flooding. This combination of tangible and collaborative affordance, computational capability, and interactive feedback provide a powerful tool for exploring real terrain-modeling problems.

Chapter 2

Study Location

2.1 Fort Bragg

Fort Bragg is located in the sandhills region just west of Fayetteville, North Carolina. Fort Bragg is the largest U.S. Army base by population, serving over 77,000 active duty Soldiers, Reserve Components, Temporary Duty Students, civilian employees and contractors (not including their families)(Figure 2.1).

The 30-year average (1971-2000) annual rainfall at Fort Bragg is 1202.44mm (47.34 inches) (Table 2.1). Rainfall is rather evenly distributed throughout the year. The wettest month is July, averaging 145.80mm (5.74 inches) (Figure 3.2) (NOAA). The hottest month is also July; however the calculated potential evapotranspiration is at its greatest in June (Table 2.2).

2.2 Falcon Airstrip

Falcon Airstrip (also known as Falcon Landing Zone) is a training area in the north-central portion of Fort Bragg, North Carolina with a high volume of military vehicle and aircraft use (Figure 2.2). The dirt air strip and dirt roads are highly susceptible to erosion, caused by rainfall runoff, by heavy vehicular traffic, and by the forceful downdraft from helicopter rotors displacing loose soil (Figure 2.3 a,b,c).

Concentrated rainfall runoff has exacerbated a particular problem area on the north end of Falcon Airstrip, contained within the 86-acre study site. As seen in Figures 2.4 and 2.5, a deep gully has been carved in the north-central portion of the landscape. This gully extends over 200 meters in length, is 33 meters wide at its widest and has depths up to four meters.

Chapter 3

Data

3.1 LIDAR Data

LIDAR point cloud data was used to create the digital elevation models (DEMs) in this project. The resulting surface models are inputs to several of the algorithms used to process subsequent analysis of the site.

3.1.1 Bare Earth LIDAR

Bare-earth LIDAR point data was retrieved from the North Carolina Floodplain Mapping Program website (http://www.ncfloodmaps.com/). The data was collected in 2001 during Phase 1B of the North Carolina and FEMA coordinated LIDAR-based floodplain mapping The data format is ASCII text in comma-delimited X,Y,Z coordinates. The projected coordinate system is North Carolina State Plane (FIPS 3200) feet , referenced to the North American Datum of 1983 (NAD83). Vertical datum is North American Vertical Datum of 1988 (NAVD88). The geodetic reference system is the GRS80 ellipsoid. One tile was required for the study site (be3710955100go20041018.txt).

3.1.2 Multiple Return LIDAR

Multiple-return LIDAR was obtained through the USGS Center for LIDAR Information Coordination and Knowledge (CLICK) website (http://lidar.cr.usgs.gov/). The data was collected using Light Detection and Ranging (LIDAR) technology during Phase1B of the North Carolina and FEMA coordinated LIDAR-based floodplain mapping. The data was collected in the spring of 2001, and processed by January 2002; however, additional processing of these data delayed publication until 2004. The data format is in common LIDAR data exchange format—.LAS. The projected coordinate system is HARN State Plane North Carolina (FIPS 3200) meters, referenced to horizontal datum: North American Datum of 1983 (NAD83). The vertical datum is North American Vertical Datum of 1988 (NAVD88) meters. The geodetic reference system is the GRS80 ellipsoid. Subsets from four separate tiles were required to comprise the study area (NC_Phase1b_35079b2a1, a2, a3, a4).

3.2 Scanner Data

The digital output of a scanned model is very similar to that of LIDAR. The scanner generates a point cloud in the scanner coordinate system in which the output file is a space-delimited ASCII text format file. Three columns of data represent *xyz* scanner coordinates, respectively. The scanner generates approximately 300,000 data points. Scanner coordinates have an origin (coordinate 0,0) in the center of the scanner working extent. The scanner produces positive *x* values in quadrants I and IV, negative *x* values in quadrants II and III, positive *y* values in quadrants I and II, and negative *y* values in quadrants III and IV. This scanner consistently produces only negative *z* values. An example of the first tuple in a scanner dataset is: -325.677 242.574 -1101.533. Scaling and georeferencing the scanner data is explained in Chapter 4, Section 2.2

3.3 Soil Data

Digital soil data of the study area was downloaded from the Web Soil Survey (http://websoilsurvey.nrcs.usda.gov/). The Web Soil Survey is maintained by the Natural Resources Conservation Services (NRCS) of the U.S. Department of Agriculture (USDA). The data version is 11/2/2007. The spatial data is in Environmental Systems Research Institute, Inc. (ESRI) shapefile format. The coordinate system is UTM Zone 17N, referenced to horizontal datum NAD83 (Soil Survey Staff). The data obtained online was compared to the USDA Soil Survey of Cumberland and Hoke Counties, approved in 1981 (Service, 1984). Notably, the K-factor for soil CaB, Candor, is listed as 0.02 in the online data and 0.20 in the USDA soil book. The soil maps indicate that the heavily eroded gully is composed of soil type CaB. Despite the more recent online data, this area is extremely eroded, thus the higher K-factor, 0.20, was used in subsequent analysis.

3.4 Ancillary Data

Ancillary spatial data was obtained from the Fort Bragg GIS specialist at the Installation Management Office. The ESRI personal geodatabase includes most of the natural and man-made features on the installation. This information was useful in determining a study site and understanding the land use. Orthophotographs are in the proprietary MrSID format. A subset image was created and exported using ERDAS Imagine software. Orthophotographs are important to the visualization process presented with TanGeoMS.

Chapter 4

Methodology

4.1 Tangible Geospatial Modeling System Architecture

TanGeoMS consists of a flexible terrain model that can be modified by hand, while a 3D laser scanner scans the modified surface. The impact of the modification on a selected parameter, such as, soil erosion or water flow, is then projected as a color map on the otherwise white clay surface. In this way, the user can iteratively modify the surface, including adding structures, until the desired effect, such as the desired erosion or flow pattern, is achieved.

4.1.1 Graphics Hardware

The core graphics hardware components of TanGeoMS are a 3D laser scanner that captures the surface geometry of a physical model, coupled with a video projector that projects images onto the model. The scanning output represents the landscape as an *xyz* point cloud, which is imported into GIS and transformed into a digital elevation model (DEM) using a computer workstation that controls the scanner and generates images for the projector. Terrain analysis algorithms are applied to the DEM and results are projected back on the physical model. In addition to the parameters derived from the scanned model, linking with GIS allows us to project real-world GIS data, such as orthographic photographs, on the physical model to guide landscape model modifications. A prototype TanGeoMS was built at the Vision, Information and Statistical Signal Theories, and Applications Laboratory (VISSTA) in North Carolina State University's Department of Electrical and Computer Engineering, using a Minolta VIVID-910 3D laser scanner. Figure 4.1 shows the VISSTA lab hardware configuration.

4.1.2 Physical Setup

The scanner/projector pair is mounted facing the table on a coarse-mesh wire shelf 1.2 meters above the model. The scanner frustum is aligned with a grid on the table, so that when the model is placed on the grid, the model's relative position can be calculated. The system is designed for flexibility—terrain analysis can be conducted on the workstation linked to the scanner and projector devices or on any GIS-ready computing device. For example, users can bring a laptop, connect it to the system, and perform analysis on the laptop (Figure 4.2). An additional projector mounted above the table can be used to provide an optional large two-dimensional tabletop display to enable collaboration or for a secondary three-dimensional data display on physical models placed beneath it. A mobile visualization system was developed as an extension to TanGeoMS, which affords 3D visualization capability outside of the lab to facilitate presentations or class room instruction.

4.1.3 Software

TanGeoMS employs standard scanner software (e.g., Polygon Editing Tool) to control the scanner and acquire the data. Scanning is set to high resolution with low filtering parameters to preserve a high level of detail. The acquired point cloud is exported as ASCII *xyz* data and imported into a geospatial analysis system. This version of TanGeoMS uses Geographic Resources Analysis Support System (GRASS), a free, open-source GIS software. The GIS is used to transform the data scanned coordinates into a DEM with geospatial coordinates, interpolate the DEMs, perform topographic analysis, and process simulations.

4.2 Workflow

The TanGeoMS workflow consists of an interactive feedback loop in which the user can modify the physical model, scan it, perform analysis on the modified input, project the results back onto the physical model, and repeat the process as required:

4.2.1 Step 1: Scan

Scan the physical model, generating a point cloud in the scanner coordinate system (Figure 4.3).

4.2.2 Step 2: Scale and Georeference

Scale and georeference the point cloud, generating a point cloud in geographic coordinate system so that real-world data can be visualized and applied to analysis. Let N be the number of points in the point cloud, then the simplest method for this uses linear equations to scale the model and shift the data, converting each of $i \in 1, ..., N$ scanner tuples, $\mathbf{m}_i = [m_{ix}, m_{iy}, m_{iz}]$, to a geographic tuple $\mathbf{g}_i = [g_{ix}, g_{iy}, g_{iz}]$ as follows:

$$\mathbf{g}_i = \mathbf{a}\mathbf{m}^{\mathrm{T}}_i + \mathbf{b}$$

where the scaling vector, $\mathbf{a} = [a_x, a_y, a_z]$, is defined as

$$a_j = \frac{g_{jmax} - g_{jmin}}{m_{jmax} - m_{jmin}}$$

for j ϵ $\{x, y, z\}$ and the shifting parameter, **b** can be calculated as

$$\mathbf{b} = \mathbf{a}\mathbf{m}^{T}_{o} + \mathbf{g}_{0}$$

such that $\mathbf{m}_0$ are $\mathbf{g}_0$ are corresponding coordinates, such as the lower left corner of the model and the lower left corner of the geographic region, respectively, to anchor the relationship.

An Excel spreadsheet pre-formatted with formulas makes it easier to determine scaling and georeferencing factors. This method of calculation aids in repetition and stores the factors for record.

4.2.3 Step 3: Import into GIS

Import the georeferenced data into GIS, generating a vector point data layer. This also creates a record of the change history, storing the model state at each iteration, so that change analysis can be performed or a previous state can be restored.

4.2.4 Step 4: Create a DEM

Interpolate the vector points to create a digital surface model.

4.2.5 Step 5: Conduct Analysis

Compute derived parameters to be used in geospatial analysis, such as slope, aspect, curvatures, and flow path. Analysis can include any operation that a GIS can conduct on a real-world DEM. Processes that can be modeled include surface runoff, soil erosion and deposition, and solar irradiation.

4.2.6 Step 6: Produce Feedback

Project user selected results of the analysis over the physical model to provide feedback.

4.2.7 Step 7: Modify

Modify the physical model and repeat steps 1-7 as required. Modifications to the physical model can include adding objects to the surface or making modifications to the surface itself since the clay surface is malleable. For example, users can experiment by adding objects, such as pieces of bubble wrap or styrofoam to represent real modifications to the landscape like forest or buildings or they use clay tools to dig into or sculpt the landscape (Figure 4.4).

4.3 Model Construction

Building the physical model of the studied landscape can be automated with three-dimensional printers or three-dimensional cutters or a model can be built by hand by tracing and cutting foam board along contours projected onto the foam, then stacking pieces to build up the foam topology (Figures 4.5 and 4.6). Covering resulting models in a layer of Plasticine (non-drying modeling clay) creates a malleable surface (Figure 4.7). Automated approaches may lead to more accurate models, but hand-built models are an inexpensive alternative that provide sufficient accuracy for most real-world applications.

The model of Falcon Airstrip is 42cm x 59cm. The horizontal scale of the model is 1:1186, representing an area of 700 meters by 500 meters for a total of 86 acres. The z-scale is exaggerated by a factor of 2.4. This exaggeration is noticeable during visualization of the physical model; however the modeled processes are not affected, because the physical model DEM was scaled appropriately to match the LIDAR DEM values.

4.3.1 Current Method

The physical model of Falcon Airstrip used in this project was manually constructed. Several materials and cutting approaches were taken to determine the most cost-effective, efficient, and accurate manner in which to construct the model. Currently, the preferred method is to utilize firm 6mm insulating foam found at a typical home improvement store. Contours are projected onto the foam working surface, traced with a marker, then cut out with a razor knife. The layers are then stacked and secured in place with T-pins. Blocks of Plasticine are rolled out with a conventional rolling pin until a smooth surface of about 3mm is achieved. The clay is draped over the 3D contours and edges smoothed together. Final shaping is done with clay modeling tools to capture subtle, but apparent topographical features. This method of creating a three dimensional contour model is relatively fast and inexpensive. The model constructed in this project took approximately six hours to make at a cost of fifty dollars.

4.3.2 Alternative Method

An alternative approach to constructing the 3D contour model was to use foam board found at an art or office supply store. This material is significantly more rigid than the foam and therefore cumbersome to cut with a razor. A proto-type cutting station was developed by securing an inverted Dremel® tool with a jig-saw attachment in a bench top vise (Figure 4.8). The jig-saw was fitted with a very fine-tooth wood cutting blade. By guiding the foam material over the cutting tool, vice moving the tool over a stationary work surface, the operator maintained more control, resulting in smoother, more precise cuts.

4.3.3 Preserving Scale

In order to maintain the correct spatial scale of the topography, each contour layer should be traced on the table-top surface level. It is worth noting that visual distortions are apparent in the higher elevations when the digital surface is projected over the physical model. Upon stacking four or more foam layers, this distortion is noticeable. If the layers are sequentially stacked, traced and cut, the digital image will look correct, but spatial distortion is introduced into the model.

4.4 Simulated Processes

Generally, the problems that can be solved are linked to design tasks such as sustainable land management that involves storm water and erosion control, optimizing solar energy potential for new developments, and coastal protection. The simulated processes significant to this case study are flow and erosion. The base input for these simulations is a LIDAR-derived digital elevation model (DEM). The methods used to generate the surface DEMs are discussed.

4.4.1 Digital Elevation Model

This study is primarily concerned with two distinct DEMs: last-return LIDAR, or bare-earth, and multiple-return LIDAR. The *v.surf.rst* method uses a regularized spline with tension algorithm to interpolate the vector data and was used to process each DEM. Both LIDAR data sets were interpolated at a resolution of one meter, with tension was set at 1000 and the smoothing parameter set at three.

4.4.1.1 Processing Bare Earth LIDAR

The text file containing point cloud data is imported into GRASS using the command *r.in.xyz*. The data is binned at 1-meter resolution using the command *v.in.ascii*. The resulting output file is a vector. The bare-earth data is in NC State Plane meters referenced to NAD83 and must be projected to match the UTM 17N location referenced to WGS84 using the command *v.proj*. The 3-dimensional surface is created by interpolating the vector points with the command *v.surf.rst*. It can optionally generate the elevation, slope, aspect, profile curvature, tangential curvature and mean curvature raster maps (Figure 4.9). The parameters for *v.surf.rst* were:

tension=1000
smoothing=3.0
dmin=1.0
zmult=0.3048 (to convert elevation in feet to meters)
segmax=35
npmin=180

Other parameters were set to default values.

4.4.1.2 Processing Multiple Return LIDAR

Multiple-return (MR) LIDAR is in LAS file format, representing “all return” points. The LAS file format is a binary file format used for the interchange of 3-dimensional point cloud data. It is an alternative to proprietary and common ASCII file interchange systems. The fact that it is not proprietary makes it a viable file format for wide public distribution of LIDAR data.

The current WinGRASS binary installer (http://josef.fsv.cvut.cz/wingrass/) does not install with LAS file support. LAS tools (executables) can be downloaded and added to the GRASS library to operate with the software, but it is not an effortless process. Two alternative methods were explored to convert the LAS files to ASCII files. The preferred method is to run the *las2txt.exe* executable from the windows command prompt. This executable, along with several additional LAS tools are open source and available online from: http://liblas.org/, or for a more comprehensive list with README files: http://www.cs.unc.edu/~isenburg/lastools/. The second method to convert the LAS file to text involves using ESRI's ArcGIS tool *LASToMultipoint_3d* followed by exporting with *FeatureClassZToASCII*.

Regardless of the method used to generate a text file containing point cloud data, it is imported into GRASS using the command *r.in.xyz*. Next, compute the binned elevation model at 1-meter resolution using the command *v.in.ascii*. The resulting output file is a vector. The MR data is in NC State Plane meters referenced to NAD83 and must be projected to match the UTM 17N location referenced to WGS84 using the command *v.proj*. The 3-dimensional surface is created by interpolating the vector points with the command *v.surf.rst*.

tension=1000
smoothing=3.0
dmin=1.0
segmax=35
npmin=180

Other parameters were set to default values. The *zmult* remained at the default 1.0, because the *z*-coordinate data unit is already meters.

The multiple return data included only the first return for those points where multiple returns were detected, so only points that represent the top of the canopy were given. There were no points in areas with no vegetation leading to artificial pattern in the resulting DEM that should be masked out (Figure 4.10), or the MR data should be combined with the bare earth data to get the complete surface coverage. For comparison 2,168,992 bare-earth points were returned in the region and only 193,032 multiple-return points were returned (Figure 4.11). The image was smoothed by increasing the resolution to three meters, using the command *v.to.rast*. The null values were set to zero, and the bare-earth raster subtracted to generate the vegetation height raster map.

4.4.2 Flow

Flow analysis is conducted to understand the affect topography has on flow routing. The result of the analysis is an input to the erosion model. There are two flow routing commands typically used in GRASS: *r.watershed* and *r.flow*.

4.4.2.1 *r.watershed*

The advantages afforded by *r.watershed* prompted the use of this flow routing method in the simulations generated for this study. *r.watershed* uses a raster elevation map as input to generate maps indicating: flow accumulation, drainage direction, the location of streams and watershed basins. The command can calculate surface flow using single flow direction or multiple flow direction (MFD). An advantage to using the MFD flow routing algorithm is that water flow is distributed to all neighboring cells with lower elevation, using slope towards neighboring cells as a weighting factor for proportional distribution. This method results in graceful flow convergence even when traversing depressions and obstacles (Figure 4.12). The command can optionally compute the length slope factor (LS) for the Revised Universal Soil Loss Equation (RUSLE), explained in the next section; however, the factor calculated in this manner is typically used only in coarse resolution DEMs and must be multiplied by 100 (Neteler & Mitasova, 2008).

4.4.2.2 *r.flow*

The command *r.flow* generates flowlines using a combined raster-vector approach. The outputs from the algorithm are: a vector map of flowlines, a raster map of flowpath lengths and a raster map of flowline densities (equating to upslope contributing areas per unit width when multiplied by resolution.) This algorithm is very sensitive to depressions, pits and flat areas. It is best suited for modeling erosion on hillslopes and best results are achieved when using input elevation maps with high precision units (e.g., centimeters.)

4.4.3 Erosion

Several erosion modeling techniques have been developed to quantify the effects of erosion. While no particular method maintains fame as the perfect model, the original Universal Soil Loss Equation (USLE) developed in 1954 by the Science and Education Administration in cooperation with Purdue University (USDA Ag Handbook 537) and the new Revised Universal Soil Loss Equation (RUSLE) is a launch point for detachment capacity limited erosion modeling. The RUSLE computes the average annual erosion expected on field slopes as

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P$$

where A is the computed soil loss per unit of area, R is rainfall and runoff erosivity factor, K is the soil-erodibility factor, L is slope-length factor, S is slope-steepness factor, C is the cover and management factor and P is the erosion-control practice factor (Wischmeier & Smith, 1978).

4.4.3.1 Runoff Erosivity Factor *R*

The rainfall and runoff erosivity factor *R* represents a measure of the erosive force and intensity of rain in a normal year. The *R-factor* used in this study was visually interpolated from an isoerodent map of the United States (Figure 4.13). *R-factor* can be adjusted to account for the intensity of different storms and storms occurring at different times of the year. An aim of this study is to gain a general understanding of the erosion patterns at Falcon Airstrip, rather than patterns for specific storm events; therefore, a constant *R-factor* of 300 was used in each model.

4.4.3.2 Soil Erodibility Factor *K*

Soil erodibility factor *K* is a measure of a soil's susceptibility to erosion. A spatially-variable *K-factor* raster map was created to more accurately assess soil loss potential in the area of interest (Figure 4.14). The map was generated by adding a *Kf* column to the tabular data contained within the digital (vector) soil dataset, updating the soil categories with their respective *Kf* values, and converting the vector to a raster.

Some locations require the use of a temporal variable *K* value (*Kav*) to account for the effect of freeze-thaw processes and changes in soil moisture content of the surface soil layer throughout the year (Soil Survey Staff, Agronomy Technical Note 28: Revised Universal Soil Loss Equation, 1999). Soils on Fort Bragg do not experience a freeze-thaw cycle; therefore, *K-factor* values were not adjusted to *Kav*.

4.4.3.3 Length/slope Steepness Factor *LS*

The length/slope steepness factor *LS* represents the combined effect of slope length and slope steepness on erosion. The erosion models in this study use a modification of RUSLE, referred to as RUSLE3D, in which the slope length and slope steepness are combined into an *LS-factor* that replaces slope length with upslope area

$$LS = (m + 1)\left(\frac{U}{22.1}\right)^{m}\left(\frac{\sin\beta}{0.09}\right)^{n}$$

where U is the upslope area per unit width (measure of water flow, m^2/m), β is the slope angle in degrees, 22.1m is the length of the standard USLE plot, 0.09=9% is the slope of the standard USLE plot, m and n are empirical constants. Exponential constants have range m = 0.2 – 0.6 and n = 1.0 – 1.3 (Neteler and Mitasova, 2008). The exponents indicate the interaction between different types of flow and soil detachment and transport (Mitasova, W.M, & Johnston, 2001). The exponent m used in this study is explained below.

Sheet flow is typical for areas with good vegetation where detachment and sediment transport increases relatively with the amount of flow passing through. In this situation, topography has more of an impact on the evolving pattern of soil detachment and deposition than does water flow. A lower value of exponent m is used in this case to represent a smaller upslope contributing area. An exponent $m=0.4$ yields an averaged result, balancing the impact of turbulent and sheet overland flow (Mitasova, W.M, & Johnston, 2001). In this study an exponent m=0.6 is used to represent the prevailing rill and gully erosion typical of airstrip conditions. The disturbed land has soils vulnerable to rilling and gully formation, hence the impact of flow is much greater.

A weighted flow accumulation (U) raster map was calculated as a function of cover factor C (Figure 4.15) and applied to the erosion models to account for the different manner in which water flows through cover. The vegetation height map was recoded to reflect 80 percent rainfall excess through areas with bare soil and to reflect twenty percent rainfall excess in vegetated areas (Table 4.1).

4.4.3.4 Cover Factor *C*

Cover factor *C* accounts for the effects of ground cover on soil erosion. The effects can be categorized by: above-ground effects, surface effects, and below-surface effects (Haan, Barfield, & Hayes, 1994). A spatially-variable C-factor was applied to the erosion model for each scenario (Figure 4.16). The LIDAR data obtained for this study was used to parameterize above-ground effects using vegetation height. A vegetation height raster map was created by calculating the difference between first and last LIDAR returns (Figure 4.17). Upon evaluation of the vegetation height, orthophotographs, and first-hand knowledge of the study area, vegetation height values were recoded (replaced) with cover factor values published by Haan, Barfield, & Hayes, (1994). The result of this recode operation was a spatially-variable *C-factor* raster map.

The nature of the study site warranted the use of two USLE *C-factor* tables published by Haan, Barfield, & Hayes, (1994). The graded and heavily trafficked dirt strip and dirt roads most closely fit the description for construction sites. The table for "Construction Sites and Disturbed Lands" was used for bare soil, which describes 61.7 percent of the study area, or 53.39 acres. A *C-factor* commensurate with "Condition: 1. Bare soil conditions: Loose to 12 in. smooth" was used for these bare areas. *C-factors* for idle land were used for the remainder of the study area. (Table 4.2)

4.4.3.5 Conservation Support Practice Factor *P*

Conservation support practice, or erosion control practice, factor *P*, is the ratio of soil loss with a given surface condition to soil loss with upslope and downslope tillage. *P-factor* values correlate to landscape treatments that retain particles near the source and prevent further transport. *P-factor* accounts for erosion control effectiveness of landscape treatments such as contouring, terracing, and establishing sediment basins. This factor is typically used only when calculating erosion for agricultural lands and rangelands (Haan, Barfield, & Hayes, 1994). While it could be used cautiously for disturbed lands, such as found on Falcon

Airstrip, calculations in this study maintain a *P-factor* of one (i.e., there is no effective conservation support practice adjustment for the erosion rates.)

Chapter 5

Results

5.1 Model Construction Accuracy

The resultant raster map after subtracting the real-world DEM from the model DEM shows the elevation difference in meters between the two DEMs (Figure 5.1). Positive values indicate areas on the model that are too high (too much clay). Negative values indicate areas on the model that are too low (clay must be added). White indicates areas on the model where the elevation is within +/- 1.0 meters of the real-world DEM values. 76.9 percent of the area in the model is within +/- 1.0 meter of the real world DEM and 98.2 percent of the area is within +/- 2.0 meters of the real world DEM. This map provides important information that can be used to further refine the model if required. Previous model scans and simulations in which the spatial patterns were not as accurate indicate that for the purposes of flow routing and erosion modeling, the level of accuracy attained in the model is sufficient to simulate the results of landform change.

5.2 Evaluating the Models

Erosion models were conducted on seven scenarios based on interpolated digital elevation models. Figures 5.2 through 5.8 are modeled scenarios. One scenario is the real world DEM, one is the initial model state, and the five additional scenarios represent exploratory landform change created on the tangible model. Each scenario was modeled six times under varying parameters. Scenarios were modeled with weighted and non-weighted flow accumulation. Weighting the flow to account for the higher transport capacity in the high flow areas reduced the overall soil loss estimate for the study area (Tables 5.1 and 5.3). A comparison of the LIDAR-derived erosion estimates against the initial model state conclude the model underestimated erosion potential by eight percent, on average across the spectrum of the model parameters. The exception is in the case of modeling soil loss potential in concentrated areas with a spatially variable *C-factor*, where the tangible model more closely predicts erosion than in areas where flow is more dispersed (Table 5.2).

5.3 Parameterization

This modeling technique is not unlike several other computer modeling and simulation processes in that determining the “right” parameter set to yield satisfactory results is challenging and resource intensive. Perhaps the two most difficult parameters to characterize in the Revised Universal Soil Loss Equation are flow accumulation and cover factor. The fact that none of the landscape change scenarios did not decrease soil loss potential does not mean they are ineffective control measures, but that perhaps other erosion control measures are required (e.g., cover).

5.3.1 Flow Parameters

The RUSLE3D equation is relatively sensitive to flow accumulation because it can generate high values which are increased exponentially in the calculation of the length-slope factor. Determining the volume of rainfall runoff generated and the exact manner in which it flows through the study site would require a separate hydrological examination. It is relatively easy to determine reasonable parameters for the GIS flow tools used in this study, but only experience delivers consistently good results.

5.3.2 Cover Factor Parameters

Cover factor has a significant impact on the soil loss estimates. Determining a spatially variable cover factor is challenging because it requires an accurate land classification analysis and a trained individual to correlate the empirical data to published *C factor* rates. Models with spatially variable *C* had a *C-factor* as high as 0.9 for areas classified as bare ground and as low as 0.011 for areas classified as canopy with 95-100 percent cover (Table 4.2). As a result, the soil loss estimate was extremely high (Table 5.1). When a uniform *C-factor* = 0.1 was applied to the model, more reasonable erosion estimates were achieved (Table 5.3). In order to make the best use of a variable cover factor, a more detailed and accurate land classification of the study area needs to be conducted. Application of advanced multispectral and/or hyperspectral remote sensing data during the classification process may yield more accurate cover factors and more precise boundaries between classes. Use of LIDAR intensity return data may also be useful to quantify the biomass density which could be correlated to appropriate cover factors.

5.3.3 Exponents *m* and *n*

Other parameters to consider are the *m* and *n* exponents in LS factor. The fact that they are exponential operators makes the soil loss equation sensitive to their values. The exponents can be individually "tuned" to return a reasonable output. This tuning method is routinely done by fellow modelers in the VISSTA, but it takes experience and a thorough knowledge of the study area topography. The next step is to calculate and employ spatially variable *m* and *n* exponents. Spatially defining the exponents gives the modeler more control over the types of modeled erosion that may be occurring on a landscape (e.g.; rill and gully).

Chapter 6

Implications to Future Research

6.1 Multi-scale Computations

Advancements to the TanGeoMS include exploration into the functionality of using a multi-scale digital model, a technique not currently used in this modeling approach. A one-meter resolution LIDAR dataset covering the entire $13km^2$ watershed equates to nearly one gigabyte of data to process for each simulation. Processing such a large dataset requires significant computing memory, disk storage space and time. The concept is to comprise the watershed model of a high-resolution DEM (1-meter) for the immediate study area and a lower-resolution DEM (i.e., 10-meter) for the remainder of the watershed. Essentially, TanGeoMS will scan and compute data from the physical model, concurrently accounting for data from a "virtual landscape" in its calculations. This method has potential to generate a more accurate flow accumulation in the target site, because the model accounts for the rainfall in the entire watershed. A multi-scale model accomplishes two main objectives: 1) accounts for flow accumulation for the entire watershed; and 2) facilitates faster computation of flow accumulation.

6.2 Military Operational Application

This technology has great potential to be applied to military operational planning. The real-time feedback and collaborative nature of the method compliments the Military Decision-Making Process (MDMP). A similar process applied to mission planning and rehearsals would allow for better synchronicity amongst the MDMP staff and facilitate the planning process.

6.3 Instructional Environments

The learning potential resulting from the visualization capabilities of TanGeoMS is significant. In their analysis of spatial cognition, Linn and Petersen (1985) outline three spatial ability categories as: spatial perception (determining spatial relationships in spite of distracting information), mental rotation (the ability to mentally rotate a two or three dimensional figure rapidly and accurately), and spatial visualization (the ability to understand complex spatial information when it involves multistep manipulation of spatially presented information.) Lei et al (2009) reviewed these abilities in their study of geographical knowledge supported by GIS. Their study suggests that students can benefit greatly from direct exposure to actual or virtual environments and that presenting distributional relationships among spatial phenomena in an active and vivid manner can enhance student interest in learning geography. TanGeoMS can enhance "spatial thinking" through its hands-on virtual environment in which students have the opportunity to gain a better understanding of relationships within spatial configurations. This added level of perception (information) applied in a conventional classroom learning environment may promote students from having mere knowledge of spatial relationships to understanding them.

INFORMATION >> KNOWLEDGE >> UNDERSTANDING

Chapter 7

Conclusion

The design environment created by TanGeoMS greatly facilitates a collaborative effort amongst staffs with similar goals and objectives. The real-time feedback provided by the system in a collaborative setting may equate to greater efficiency in the planning phase, equating to a faster response, or execution of the plan. With further development, TanGeoMS can be launched from its research environment into the world to augment any team confronted with three-dimensional geospatial problems.

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