Spatial variability of sediment erosion processes using GIS analysis within watersheds in a historically mined region, Patagonia Mountains, Arizona

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Table 1: List Of Acronyms

ALRIS: Arizona Land Resource Information System

AML: Arc Macro Language CERCLA: Comprehensive Environmental Liability Act

DEM: Digital Elevation Model

DLG: Digital Line Graph

DOQQ: Digital Orthophoto Quarter Quad

DRG: Digital Raster Graphic

EPA: Environmental Protection Agenecy

ESRI: Environmental Systems Research Institute, Inc.

GCP: Ground Control Point

GIS: Geographical Information Systems

GUI: Graphical User Interface

MAS: (Bureau of Mines) Mineral Availability System

MUID: Map Unit Identifier

NAD27/83: North American Datum of 1927/ 1983

NBII: National Biological Information Infrastructure

NPS: Non-Point Source

NRCS: Natural Resource Conservation Service

SEDMOD: Spatially Explicit Delivery Model

SCS: Soil Conservation Service

SDR: Sediment Delivery Ratio

STATSGO: State Soil Geographic (Database)

UA/ART: The University of Arizona / Advanced Resource Technology Group

USDA: U.S. Department of Agriculture

USGS: United States Geological Survey

USLE: Universal Soil Loss Equation

UTM: Universal Transverse Mercator

Abstract

A hillslope-scale erosion prediction model (USLE) and a spatially derived sediment delivery model (SEDMOD) are applied within a raster geographic information system (GIS) to estimate erosion, sediment yield and sediment deposition for five adjacent sub-basins impacted by historical mining in the Patagonia Mountains of southern Arizona. Geospatial landscape data (elevation, soil type, vegetation, mine locations, and stream networks) were divided into $30m^2$ cell grids, allowing for consistent high-resolution analysis within each watershed. The automation of paper soils maps is described. The model results identify non-point sources and sinks of trace-metal bearing sediment.

Introduction

Mined and naturally mineralized systems are geologically highly variable, hence it is difficult to identify important processes and nonpoint sources of potentially toxic elements. A better understanding of regional-scale variation is needed to make informed land-use decisions. The Comprehensive Environmental Response Compensation and Liability Act of 1980 (CERCLA) has been implemented in efforts to provide cleanup to degraded areas in the Patagonia Mountains of southern Arizona. Erosion of historic waste rock, sub ore-grade waste rock, and tailings has been a primary factor in the mechanical breakup and distribution of detrital material deposited within the streambeds.

In this study, a geographic information system (GIS) is used to integrate and accurately map field studies, information from remotely sensed data, watershed models, and the dispersion of potentially toxic mine waste and tailings. The purpose of this study is to identify erosion rates and net sediment delivery of soil and mine waste/tailings to the drainage channel within several watershed regions to determine source areas of sediment delivery as a method of quantifying geo-environmental analysis of transport mechanisms in abandoned mine lands in arid climate conditions. Users of this study are the researchers interested in exploration of approaches to depicting historical activity in an area which has no baseline data records for environmental analysis of heavily mined terrain.

Patagonia and the southern Santa Rita Mountains area, located in southern Arizona (see fig. 1) was mined intermittently from the 1600's to the mid- 1960's for silver, lead, zinc, gold and copper. The movement of water through these mined areas and the factors that affect that flow determine the contribution the mines offer to the local water quality. Several of the mines have been identified as high priority environmental degradation sites by preliminary CERCLA-related examinations conducted by the U.S. Bureau of Mines (Chatman, 1994) and the U.S. Forest Service (Dean, 1982) within the Coronado National Forest.

Approach

Hydrological modeling was done using the spatial analysis tools available in a GIS in order to identify important hydrologic processes. To accurately simulate the erosion/ sediment yield response of a watershed, a computer model must be able to identify and treat the variability within a watershed. GIS has improved the efficiency and repeatability of hydrologic modeling (Guertin and others, 2000; Miller and others, 1996; Sasowsky and others, 1991), most notably in the representation of terrain, which depicts water flow (Maidment, 1993). The spatial analysis tools available within a GIS can be associated with hydrological modeling that will depict flow and transport patterns in a particular cell (Maidment, 1993). Watersheds differ tremendously in their variability; soil types, steepness of slope, and vegetation cover are not homogenous within a watershed boundary. Simplifications or generalizations must be made at some level to reduce real world situations to model capabilities. A raster GIS better represents the changes within these environmental landscape variables as well as defines a scale at which these changes occur to be analyzed by an individually selected cell.

The Universal Soil Loss Equation (USLE) is an empirical model that estimates net hillslope erosion worldwide. The USLE was developed on Midwestern US cropland to predict average annual soil loss caused by sheet and rill erosion from a hillslope element (Wischmeier, 1976; Wischmeier and Smith, 1978). It was not created to consider deposition or route sediment from a hillslope element. It is known as a lumped parameter model (Fraser, 1999); lumping spatial and temporal factors into an average number across a varying landscape (Lane and others, 1993). Using a GIS-platform has liberated the USLE from its spatial and technological limitations (Maidment, 1993; Brooks and others, 1997) by allowing cell-by-cell spatial analysis. The inputs to this model are geographically dependant and can be created as separate layers which can be processed within a raster GIS (Cowen, 1993; Eli and others, 1980, Eli, 1981; Eli and Paulin, 1983).

The Spatially Explicit Delivery Model (SEDMOD) is a GIS-based technique for deriving spatially unique sediment delivery ratios (SDR's) through a GRID-based suite of Arc Macro Language (AML) procedure in ARC/INFO. These ratios are then multiplied by the soil loss prediction from the USLE to approximate sediment yield on a cell-by-cell basis. This yield is then summed within SEDMOD to calculate riparian zone sediment deposition with only hillslope routing, not channel routing (Fraser, 1999). Nonpoint source pollution (NPS) in surface mined lands has also been investigated using a GIS methodology in prior studies. The USLE has been applied to predict potential soil erosion and combined with the kinematic wave equation to determine suspended sediment loads and these studies have determined a link between erosion prediction and water quality prediction (Eli, 1981; Eli and Paulin, 1983; Eli and others, 1980; DeVantier and Feldman, 1993).

In this study, the data derived from the hydrologic modeling procedures were queried and analyzed to derive the specific NPS sources and sinks within the watershed. This study focuses on locating areas that are contributing sediment and deriving estimates of rate and volume, in tons per acre per year, of material moving out of these identified source areas during an average erosion event.

GIS Definitions of Watershed Parameters

A watershed is defined as the total drainage basin or catchment area flowing into a given outlet (pour point). A digital elevation data set is used to delineate watersheds. A set of six 30-meter resolution Digital Elevation Model’s (DEM’s) (U. S. Geological Survey, 1999) were combined using the GIS software in ARC/INFO to form the surface model DEM that covered the study area. Digital elevation data sometimes come with inherent error due to the resolution of the data or spatial limitations due to rounding of elevations in creating the dataset (U. S. Geological Survey, 1999). In ARC/INFO, locations on a DEM can be generated that actually may not exist and these may create inaccurate surface flow conditions. These points are referred to as ‘sinks’ or ‘peaks’ depending on whether values are over- or under-estimated. These anomalies in the DEM data were adjusted to ensure proper representation of water flow and watershed systems. A total of 650 sinks were identified and filled while 1720 peaks were identified and leveled, using the ‘FILL’ command in ARC/INFO 7.2.1

Watershed delineation within a GIS requires a user-specified outlet to be defined as a starting point for analysis. An outlet is the mouth of the river or stream. When the user identifies this point, the computer calculates the total contributing surface area using a series of complex algorithms. A script was downloaded from the Environmental Systems Research Institute, Inc. (ESRI) ArcView Hydrological Modeling help pages to delineate the watersheds using elevation data. It requires the use of ESRI’s ArcView Spatial Analyst and Geoprocessing extensions, based on a point that is specified with a cursor in the view. The shape of the surface of the elevation change at any given point determines the direction of which water will flow. The hydrological analysis tools available in GRID, help portray this type of natural system. The outlets or pour points used in this study were identified based on prior studies in the area, as well as priority areas identified by CERCLA. Watershed boundaries are required for statistical analysis in hydrologic modeling. The study area referred to herein as the Patagonia Experimental Watershed is comprised of five sub-watersheds (fig. 1). The size of these sub-watersheds is given in table 2 and named according to their corresponding canyons (see fig. 1).

Table 2: Delineated sub-watershed size

Subwatershed	Acres	Hectares	Length of channel (m)
Alum_Flux	6,515	2,638	27,990
Cox_3R	3,757	1,521	10,441
Lower_Harshaw	5,027	2,035	16,680
Providencia	11,131	4,505	16,636
Upper_Harshaw	15,857.77	6,420.15	27,826.34

Digital thematic layers describe the environmental conditions within the watershed boundaries and can be integrated as input into models for predicting hillslope erosion, quantification of sediment amounts and location of deposits.

Stream networks were developed using commands in ARC/INFO's GRID module (FLOWDIRECTION and FLOWACCUMULATION). The tools within GRID allowed for the determination of down slope water flow. For quality assurance, the digital representation of likely channels was compared to known stream networks observed from a Digital Line Graph (DLG) created by the Arizona Land Resource Information System (ALRIS) within the Arizona State Land Department and downloaded from a digital library at the University of Arizona / Advanced Resource Technology (UA/ART) Group. The comparison indicated that the derived stream channels (fig. 2) were accurately defined. Stream channels and direction of overland flow were used in the applied hydrological models to describe watershed characteristics.

Universal Soil Loss Equation (USLE)

The USLE is an empirical formula used to predict average annual soil loss from hillslope elements in tons per acre per year (Wischmeier and Smith, 1978). In this study, the location of sites with high potential erosion allows for identification of important sources of pyrite-bearing metal-rich sediment to the channel system which may effect water quality. The amount of erosion calculated on a cell-by-cell basis, also acts as input to derive sediment delivery calculations in a second model. The USLE formula to calculate soil loss is as follows:

$$A = R * K * L * S * C * P$$

Where:

A = annual soil loss in tons per acre per year

R = rainfall erosivity factor

K = soil erodibility factor

L = slope length factor

S = slope gradient factor

C = cover management factor

P = erosion control practice factor

This formula is appropriately suited to be applied in a GRID based environment where map algebra can be performed. Acquisition of the necessary factors is described below.

The *R factor* as defined by the USDA, Soil Conservation Service (SCS) (1976) for areas of strong relief, was a constant value of 80. The Patagonia Experimental Watershed is small enough (only 42,307 acres) that it fell within a single designated region.

The *S factor* is very closely associated with the *L factor*. The *S* is the slope gradient factor and the *L* is the length of that slope. The slope was calculated from the 30 meter DEM discussed earlier. This was calculated in percent in order to fit into the equation properly. This percent (s) was then plugged into the formula:

S = (0.43 + 0.30s + 0.043s^2)/ 6.613

The USLE was created by Wischmeier (1976) to predict soil erosion delivered to the base of a 22-meter agricultural plot. As applied in this study, the cell's flow length was calculated as 30 meters and plugged into the following formula:

L = (30/ 22.1)^m, where m= 0.5

The *S* and *L factors* are then combined to form the *LS factors* using the following formula:

LS = L * S (10,000/ (10,000 + s^2))

The *C factor* is the cropping or vegetation management factor. This is a user-defined number assigned according to vegetation type. *C* values are derived from the SCS Technical Notes (table 6), for permanent pasture, rangeland, and idle land according to a vegetation coverage of the study area that was downloaded and clipped from the USGS GAP Analysis Vegetation and Land Cover geo-spatial data-set at the USGS National Biological Information Infrastructure (NBII) library. The watershed comprised 10 vegetation types which predominantly consisted of Encinal Mixed Oak and Semidesert Mixed Grass (see fig. 3).

The *C factor* to vegetation type is available in table 3. This factor ranges greatly, the lower the value, the greater the vegetative biomass. All known mine sites cells were assigned a value of 1, in recognition of the lack of vegetation at these sites.

Table 3: Assigned C Factor to vegetation type.

Vegetation TYPE	**C FACT**
Agriculture	0.3
Encinal Mixed Oak	0.013
Encinal Mixed Oak-Mesquite	0.01
Encinal Mixed Oak-Pinyon-Juniper	0.04
Int. Riparian/Mixed Riparian Scrub	0.07
Riparian/Flood-damaged 1993	0.1
Semidesert Mixed Grass-Mesquite	0.09
Semidesert Mixed Grass-Mixed Scrub	0.038
Semidesert Mixed Grass-Yucca-Agave	0.18

The *P factor*, or conservation practice factor was not relevant to the study area and therefore calculated as value = 1, which does not negatively or positively influence the output of the model.

The *K factor* requires acquisition of accurate geo-spatial soils data and the study required the automation of existing tabular data from the U.S. Department of Agriculture (USDA), Natural Resource Conservation Service (NRCS). A description and comparison of soils data was completed in the following procedure: the State Soil Geographic (STATSGO) Database, the only digital publication available for Santa Cruz County (U.S. Natural Resources Conservation Service, 1995), was downloaded as Arc Info coverages and unzipped and untarred from its compressed deliverable. The projection was converted from Albers, NAD27 to UTM, Zone 12, NAD83.

The study area was digitized with the use of a Digital Raster Graphic (DRG) of the Nogales, Ariz. Quadrangle. This was then used to clip the soils map to the watershed boundary map. The frequency command was then issued and eight known soil types emerged as the composition of this area (see fig.4). The soils types, known as MUID's (Map Unit Identifiers), were composed of multiple soils series (compnames) (see table 3). For example, MUID: AZ032, is composed of 55 percent Comoro, 25 percent Riveroad, and 20 percent Arizo type soil components. Each of these components in turn has many different soil descriptors assembled in a complex relational database. Of these were two *k factor* variants of interest to this study. The first is represented by the term '*kfact*', the soil erodibility factor, which includes rock fragments. The second descriptor, referred to as the '*kffact*' term, defines the soil erodibility factor that was fragment free for use in the USLE. Unfortunately, this number was often given as zero, which when multiplied into the USLE would predict a zero amount of erosion, which is highly unlikely.

Weighted averages for all MUID components were calculated for *kfact* and *kffact* for purposes of comparison. These values are given in table 4 (fig. 4).

Table 4: STATSGO derived K factors (U.S. Natural Resources Conservation Service (NRCS), 1995).

MUID	Map Unit Name	Weighted kffact	Weighted kfact
AZ032	*COMORO-RIVEROAD-ARIZO (AZ032)*	0.2815	0.2575
AZ060	*WHITE HOUSE-BERNARDINO-HATHAWAY (AZ060)*	0.3055	0.18
AZ066	*LAMPSHIRE-CHIRICAHUA-GRAHAM (AZ066)*	0.3365	0.11
AZ146	*TYPIC HAPLUSTALFS-LITHIC HAPLUSTALFS (AZ146)*	0	0.188
AZ251	*FLUVENTIC USTOCHREPTS-TYPIC USTIFLUVENTS (AZ251)*	0	0.256
AZ254	*TYPIC USTORTHENTS-ROCK OUTCROP-TYPIC USTOCHREPTS (AZ254)*	0	0.131
AZ272	*LITHIC USTOCHREPTS-ROCK OUTCROP (AZ272)*	0	0.178
AZ277	*QUINTANA-TIMHUS-FLUGLE (AZ277)*	0.284	0.167

The STATSGO soil map data were created by interpretation of other, more detailed soils maps in the area and reasonable estimates of descriptors were calculated by the NRCS. These were then digitized using USGS 1:250,000 scale, 1 by 2-degree quadrangle series maps for reference in their creation (U.S. Natural Resources Conservation Service, 1995). Because of the idiosyncrasy of having multiple values within the soils database and due to the poor resolution, better data are needed for this portion of the study.

Automation of Soils Maps

Preexisting high-resolution soils data were not available in digital form. The most accurate soil information for the study area was a product of the USDA, NRCS, formerly the Soil

Conservation Service, and the Forest Service in cooperation with the Arizona Agricultural Experiment Station (U.S. Soil Conservation Service, 1976). These data were created according to the site conditions in 1971, when soil scientists drew the boundaries of identifies soils types onto aerial photographs. The scale at which these paper maps were published is 1:20,000.

The task of automating these soil maps required several steps; the aerial photos had not been orthoganalized, and contained distortion. A total of 15 maps composed the study area. These maps were scanned using an 8-bit black and white drum scanner at 100 dpi into GeoTiff format. The images were imported into ERDAS IMAGINE software and the white borders were removed through subset decollaring processes. Digital Orthophoto Quarter Quads (DOQQ's) were used to register and rectify the scanned soils maps. Known points were identified on the aerial photo and matched to points on the DOQQ's, these were referred to as Ground Control Points (GCP's). This was the most time consuming portion of this project as the aerial photos were taken some 30 years prior to the DOQQ's and buildings, trees, and waterways had changed considerably. The easiest and most accurate objects to identify were roads and intersections of roads with other features. These appeared to have the same shape throughout time, although some forest roads were now out of use, or had been paved or widened.

A 3^{rd} order polynomial transformation requires a minimum of 10 GCP's to be identified. However, the level of accuracy increases as more points are entered and widely distributed. The GCP prediction tool within ERDAS IMAGINE uses the current transformation parameters to guess where the user will locate GCP's from the work in progress to source data, this enables the user to identify when enough points have been entered to ensure that the transformation is accurate (ERDAS Inc., 1997). An average of 80 GCP's were identified on each aerial photo and cross-referenced with the source data for this study (see fig. 5). The cubic convolution method of resampling was performed to effectively pierce the aerial photo with pinpoints to known real time coordinates and stretch or fold the picture to accurate proportions. This sampling method is suggested for aerial photos in which the cell size is dramatically changed (ERDAS Inc., 1997).

This process transformed the distorted photo originals into a substantially more accurate representation of real time and space with registered known coordinates. The cubic convolution method resamples using an algorithm which recognizes the data files of 16 pixels in a 4 by 4 window, and creating the most accurate output when ortho-rectifying aerial photos (ERDAS, 1997). Error still exists despite the high number of GCP's used to control the transformation. Error existed in the original DOQQ's and new error was introduced in the resampling process. However, the photos edge-matched positively and roads, rivers, trees and soil polygons merged together seamlessly when combined to create the composite image. The final .IMG format file was converted and compressed within ARC/INFO to GeoTiff format and displayed onscreen with known vector coverages of digitized roads and rivers overlaid to check for accuracy and error. The most useful was the road coverage downloaded the UA/ART library which identified error to be within 0-40 meters. This seemed to be acceptable error for the project. A small portion of this analysis is shown in figure 6.

The soils data that had been inscribed on the aerial photos was then automated through the process of on-screen digitizing in ARCEDIT. The distance command identified acceptable tolerances, node snap to closest 100 meters and weed and grain tolerances to 15 meters. The user-friendly graphical user interface (GUI) called ARCTOOLS was employed for the initial digitizing (see fig. 7). The coverage was then cleaned manually using command line editing and topology was built.

User defined items were added to the newly digitized soil coverage feature attribute table to define the map unit descriptions: soil series, slope angle and previous erosion. Labels were created and attribution of the new soils coverage was completed utilizing the ARCEDIT GUI called ‘forms’. This naming process allowed for regular segmentation of space and 443 polygons were attributed against the labeled polygons of the final aerial TIFF as a backdrop. The image was then clipped to the size of the study area, leaving 305 polygons which was displayed in ARCPLOT (see fig. 8) and is also available as a full color soils map (see fig. 9).

The *k factor* values derived from the SCS (1976) were added as an item to this coverage’s attribute table. Thirty-four different soil types are represented in this area; some have two *k factors* depending on multiple associations or complexes (SCS, 1976). These soil type k factors were averaged to calculate the total *k factor* per soil type. These are listed in table 5.

Table 5: SCS Technical Notes K Factor values.

Symbol	Name	K Factor
Ba	*Barkerville-Gaddes complex*	0.195
Bg	*Barkerville-Gaddes association*	0.195
Bh	*Bernadino-Hathaway association*	0.3
Ca	*Calciorthids-Haplargids association*	0
Cb	*Canelo gravelly sandy loam*	0.24
Cg	*Caralampi gravelly sandy loam*	0.17
Cm	*Casto very gravelly sandy loam*	0.28
Co	*Chiricahua cobbly sandy loam*	0.37

Symbol	Name	K Factor
Cr	*Chiricahua- Lampshire association*	0.345
Cs	*Comoro sandy loam*	0.2
Ct	*Comoro soils*	0.15
Fr	*Faraway- Rock outcrop complex*	0.32
Ga	*Gaddes very gravelly sandy loam*	0.24
Gb	*Grabe- Comoro complex*	0.195
Ge	*Grabe soils*	0.24
Gh	*Graham soils*	0.32
Gu	*Guest soils*	0.37
HO	*Water*	0
Ha	*Hathaway gravelly sandy loam*	0.32
Lc	*Lampshire-Chiricahua association*	0.345
Lg	*Lampshire- Graham- Rock outcrop association*	0.32
Lu	*Luzena gravelly loam, deep variant*	0.37
Mg	*Martinez gravelly loam*	0.43
NA	*Not Available*	0
Pm	*Pima soils*	0.32
Rn	*Rock outcrop- Lithic Haplustolls association*	0
So	*Sonoita gravelly sandy loam*	0.17
Th	*Torrifluvents and Haplustoils*	0
Tr	*Tortugas- Rock outcrop complex*	0.28
Wg	*White House gravelly loam*	0.37
Wh	*White House cobbly sandy loam*	0.32
Wn	*White House- Bonita complex*	0.325

Symbol	Name	K Factor
Wo	*White House- Caralampi complex*	0.27
Wt	*White House- Hathaway association*	0.295

The projection was defined according to its origin and the Patagonia Experimental Watershed boundary was used to clip the extents of the new soil map to the area of interest and converted to GRID format. A visual comparison of the three derived *k factor* values for the study area (fig. 10) indicates that resolution was substantially improved through the process of automating the SCS (1979) data. Consequently, only the data from this approach were selected for use in the USLE model.

The watershed contains 73 known mine sites according to a vector point coverage downloaded from the UA/ART library, created by the Bureau of Mines Mineral Availability System (MAS) dataset. Many of these mines are so small that they are not visible even on a 1- meter resolution DOQQ. These mines are often sites of preexisting mills, extensive waste dumps, and sub-ore piles that are very visible in the field and pose the potential to contribute substantial quantities of metals to the watershed, although due to gravity and time, many have already eroded substantially down from their maximum volumes. The mine coverage was converted to a raster grid and the mine location cells were assigned a *k factor* of 0.55. The k factor values range from 0- 0.99; the assignment of 0.55 indicates a high number in the range of k factors actually applied to agricultural plots to account for the tendency of previously excavated material to be quick to erode. This was laid over the higher resolution Soil Conservation Service (1976) grid of *k factors* to predict erosion potential of the soils due to mine, dump, and tailing pile presence. This was the final *k factor* grid used in the USLE equation.

Estimated Soil Loss Results

Once all of the factors were accounted for in GRID based environments, with any data outside the watershed equaling NODATA, the grids could be multiplied together to get a gross estimate (fig. 12). The average rate of annual potential soil loss in the Patagonia watersheds is 48.5 tons per acre per year. This simple erosion prediction technology was applied to a subwatershed on the nearby Walnut Gulch Experimental Watershed, near Tombstone, Arizona (Guertin and Miller, 2000) using a 30-meter resolution DEM and the mean was 43.8 tons per acre per year, slightly lower than the calculated average rate for the Patagonia Mountains study area. The total long-term average annual value of estimated soil erosion in Patagonia watersheds is 316,097.04 tons per year. A detailed list of total potential soil loss per watershed is described in table 6.

Table 6: The sum of total potential soil loss per watershed.

Watershed Name	Average of predicated soil loss in tons/acre/year in the 30-meter grid cells	Tons/ Year in Watershed
Alum Gulch –Flux Canyon	52.1	75,500
Cox Gulch -3R Canyon	105.5	35,700
Lower Harshaw Creek	21.2	23,700
Providencia Canyon	40.9	101,100
Upper Harshaw Creek	22.7	80,100

The results derived from the USLE are used for planning purposes to predict the impact of land use on soil erosion and to identify sensitive areas. The determination of areas with potentially low erosion rates is useful if the mitigation strategy is to physically move the potentially toxic materials to sites of safer repositories. It also identifies critical source areas of metals.

In relatively large watersheds, most sediment gets deposited within the watershed and only a fraction of soil that is eroded from hillslopes will reach the stream system or watershed outlet. This fraction or portion of sediment that is available for delivery is referred to as the Sediment Delivery Ratio (SDR). This ratio is then multiplied by the predicted erosion rate to estimate the percent of eroded material/ sediment/ pollutant to reach the watershed outlet (Fraser, 1999).

Spatially Explicit Delivery Model (SEDMOD)

The Spatially Explicit Delivery Model (SEDMOD) calculates a SDR that can be used to estimate the amount of eroded material that could be deposited in stream channels (Fraser, 1999). A SDR is not homogenous across a watershed; instead it varies with changes in watershed area and slope (Osterkamp and Toy, 1997). SEDMOD allows for the calculation of this spatial variation utilizing a GIS. The SDR is multiplied by the predicted amount of erodable soil to calculate NPS sources and sinks within a watershed.

The delivery ratio evaluates deposition that occurs in overland flow before reaching the stream channels (Haan and others, 1981). Many factors are addressed when calculating this ratio: water availability, texture of eroded material, ground cover, slope shape, gradient and length, surface roughness, and other on-site factors. SEDMOD incorporates these parameters in a cell-by-cell calculation of uniquely specific derivations for changes over space.

Sediment Delivery Ratio (SDR) Input

Input grids representing terrain, soil type, land classification, and soil loss were created at a 30-meter resolution for input into SEDMOD according to specifications (Fraser, 1999). These grids were DEM, SOIL_TEXTURE, ROUGHNESS, and SOIL_LOSS, respectively (see fig. 13). SEDMOD also calls for the optional input of SOIL_TRANS (saturated soil transmissitivity) and STREAM (stream network) grids, which were not included in this project. The input grids were clipped to each watershed area leaving the surrounding non-watershed cells with a value of NODATA.

The SOIL TEXTURE grid was created from the STATSGO soil database (U.S. Natural Resources Conservation Service, 1995) this database presents a calculated percent of clay content for each soil type. The newly created soils coverage was originally intended for this study, but the documentation of clay percentage was unavailable for parts of the study area. Within the STATSGO database, table names layer contained two related components: '*clayl*' and '*clayh*'. These are the minimum and maximum values for the range in clay content of the topsoil layer, expressed as a percentage of the material less than 2 mm. in size (U.S. Natural Resources Conservation Service, 1995). This was extrapolated in Microsoft Access, averaged in Microsoft Excel, and incorporated into the already existing STATSGO MUID ARC vector polygon coverage feature attribute table and rasterized to GRID format (table 7).

Table 7: Clay percent calculations (U.S. Natural Resources Conservation Service, 1995) per soil type.

Soil Layer	**Clay Content (in percent)**		
Map Unit Identifier (MUID)	**Minimum**	**Maximum**	**Average**
AZ032	8	15	12
AZ060	20	30	25
AZ066	10	20	15
AZ146	10	18	14
AZ251	8	20	14
AZ254	10	20	15
AZ272	15	27	21
AZ277	18	25	22

The ROUGHNESS grid (fig.13) was derived from the GAP Analysis vegetation and land use data mentioned previously. These vegetation descriptions were used to estimate Manning's Surface Roughness Coefficients for Overland Flow (Fraser, 1999).

These input grids were then shuttled through a series of AML scripts in SEDMOD that enable a friendly GUI for calculation, display, and analysis. Secondary grids were derived from the DEM, very similar to the hydrologic modeling described previously (flow accumulation, direction and channel networks). Finally the six grids plotted to calculate the SDR (fig. 14). These are a combination of DEM and site description grids.

Sediment Delivery Ratio (SDR) Output

The input data were used to calculate the SDR using SEDMOD (fig. 14). The SDR in Patagonia ranges from 0 –79% of eroded material to be transported by the process of overland flow. This ratio was then multiplied by the soil loss prediction equation to derive net sediment or nonpoint source pollution delivery to the watershed (fig. 15) and to calculate the net sediment delivered to the stream channels and the bordering riparian area (fig. 16).

SEDMOD was also used to calculate the total potential gross erosion (316,220.7 tons/ acre/ year), estimated sediment delivered to the streams (51,500.1 (tons/cell) /year) and finally, the estimated total delivery to the outlet (16,347 (tons/cell) /year) for the total study area.

Analysis of Watershed Components

The models maintain a lumped parameter of time; the assumption is made that the supply remains constant, yielding an average annual estimate of sediment yield. The name and commodity of the mines in the total study area were extracted using the sample command in GRID. Each mine location grid cell was queried to see the amount of contributing sediment it was supplying to the stream system (table 8). It is assumed in this study, that all sediment yielded by mines will reach stream channels due to the volume and history of mine activity, and by the obvious proximity to streams. The mine-contributed sediment was calculated to percentages of the sample points' total sediment. The authors would like to restate that the relative size of each mine was averaged to a 30- meter GRID cell in order to calculate within a GIS. This size approximation may be representative of a mine which is 2-3 times larger or smaller, yet predominantly depicts the disturbance size. Where no waste materials exist, the number represents the yield due to natural conditions of soil type and relief. An average sediment yield rate is 0.17-tons/ acre/year for mixed-use West coast watersheds (Brooks and others, 1997). .

Table 8: Contribution of sediment as calculated by SEDMOD from grid cells containing mines in [English] Tons per acre per year.

Mine ID #	**Name of Mine cell**	**Commodity**	**Net Sediment delivery rate (tons/acre/year)/ cell**
1	ALTA MINE	FLUORINE, LEAD, SILVER	53.4
2	AMERICAN MINE	SILVER, LEAD, ZINC, COPPER, GOLD	158.7
3	AUGUSTA MINE	SILVER, LEAD, ZINC, GOLD	166.9
4	AZTEC MINE GROUP	COPPER, SILVER, GOLD	153.7
5	BENDER PROPERTY	MANGANESE, ZINC, LEAD, COPPER	142.2
6	BENNETT MINE	COPPER, SILVER, GOLD	160.4
7	BIG LEAD MINE	LEAD, COPPER, SILVER, GOLD	7.56
8	BLACK EAGLE GROUP	MANGANESE	62.9
9	BLACK ROSE	MANGANESE	117
10	BLUE BIRD 1,2,3	IRON	20
11	BLUE EAGLE MINE	COPPER, SILVER, GOLD, LEAD, ZINC	43.2
12	BONNIE CARRIE	SILVER	192.9
13	BROWN	COPPER, LEAD, SILVER, GOLD	98.8
14	BUENA VISTA MINE	COPPER, SILVER, GOLD, LEAD, MOLYBDENUM	17.5
15	CHIEF	LEAD, SILVER, GOLD, COPPER	86.4

Mine ID #	**Name of Mine cell**	**Commodity**	**Net Sediment delivery rate (tons/acre/year)/ cell**
16	CHRISTMAS GIFT MINE	SILVER, LEAD, COPPER	30.3
17	COLLICELLO AND LURAY MINE GROUPS	COPPER, GOLD, SILVER, ARSENIC	112.5
18	COLOSSA	MANGANESE, SILICON, IRON	25.3
19	CONLEY KECK COPPER	COPPER, ZINC	17.3
20	COPPER LEDGE	COPPER, SILVER	128.5
21	CORONADO MINES INC	TUNGSTEN	94.9
22	DOMINO MINE GROUP	SILVER, LEAD, COPPER, GOLD, ZINC, MOLYBDENUM	48.6
23	ELAVATION MINE GROUP	COPPER, LEAD, SILVER	275
24	ENDLESS CHAIN	COPPER, SILVER	152.2
25	ESPERANZA	LEAD, SILVER	103.7
26	EUROPEAN MINE GROUP	COPPER, SILVER, GOLD, LEAD, ZINC	416.6
27	EXPOSED REEF	COPPER, SILVER, GOLD	61.3
28	FLUX MINE	ZINC, LEAD, COPPER, SILVER, GOLD	128.5
29	FOUR METALS	COPPER, SILVER, GOLD, LEAD, ZINC, MOLYBDENUM, TUNGSTEN	167.9
30	GARFIELD GROUP		66.8
31	GLADSTONE MINE GROUP	COPPER, SILVER, GOLD, LEAD, ZINC	40.7
32	GOLD STANDARD	LEAD, SILVER, GOLD	157.21

Mine ID #	Name of Mine cell	Commodity	Net Sediment delivery rate (tons/acre/year)/ cell
33	GOLDEN GATE	LEAD, SILVER, ZINC, COPPER, GOLD, MANGANESE	7.99
34	GOLDEN ROSE MINE	COPPER, GOLD, SILVER, LEAD	3.48
35	GUAJOLOTE	COPPER, SILVER, GOLD	9.88
36	HAMPSON	COPPER, IRON	67.9
37	HARDSHELL MINE	MANGANESE	207.8
38	HARSHAW DISTRICT MN-AG MANTO	MANGANESE, SILVER, LEAD, ZINC	127.7
39	INVINCIBLE PROSPECT	COPPER, GOLD	301.5
40	IRON CAP	LEAD, SILVER, ZINC, COPPER	146.88
41	JACKALO	COPPER, SILVER, GOLD	424.2
42	JANUARY AND NORTON MINE GROUP	ZINC, LEAD, SILVER, COPPER, GOLD, MANGANESE	97.5
43	JAVELINA	COPPER, SILVER	15.04
44	KING MINE	COPPER, GOLD, SILVER	0
45	LIBRADA	LEAD, SILVER, ZINC, COPPER, GOLD	79.8
46	MINNESOTA MINE	COPPER, SILVER	36.8
47	MONO	LEAD, SILVER, COPPER, ZINC, GOLD	148.5
48	MORNING GLORY	COPPER, SILVER, GOLD, ZINC, LEAD, BARIUM	204.5
49	NATIONAL MARBLE CORP	GOLD	117.6

Mine ID #	Name of Mine cell	Commodity	Net Sediment delivery rate (tons/acre/year)/ cell
50	NEW HOPE MINE GROUP	COPPER, SILVER, ZINC, LEAD, GOLD	21.7
51	OLD TIMER	GOLD, SILICON, SILVER, LEAD	396.2
52	PROSPERITY GROUP	COPPER, MAGNESIUM	274.5
53	PROTO GROUP	COPPER, SILVER, LEAD, GOLD	206.6
54	RED MOUNTAIN	COPPER, MOLYBDENUM	123.1
55	RED RACER	MOLYBDENUM	12.1
56	ROBERT G	GOLD, SILVER, COPPER, MOLYBDENUM	27.9
57	SALVADOR	MANGANESE, COPPER, LEAD, ZINC, IRON, SILICON, SILVER	62.8
58	SANSIMON MINE	SILVER, LEAD, ZINC	19.3
59	SANTA CRUZ MINE	COPPER,SILVER	3.3
60	SEMCO MILL	COPPER, SILVER, GOLD	18.9
61	SILVER EAGLE	COPPER, GOLD	0
62	SONOITA CREEK-ALUM CANYON PLACERS	SILVER, LEAD, COPPER, ZINC, GOLD	59.3
63	SPECULARITE PROSPECT	IRON	40.4
64	SUNNYSIDE	COPPER, SILVER, LEAD, ZINC	325.8
65	THREE R MINE GROUP	COPPER, SILVER, LEAD, ZINC, GOLD, ALUMINUM	216
66	TREASURE KING	GOLD, COPPER, SILVER	3.28

Mine ID #	Name of Mine cell	Commodity	Net Sediment delivery rate (tons/acre/year)/ cell
67	TRENCH MINE	LEAD, ZINC, SILVER, COPPER, GOLD, MANGANESE	178.3
68	VENTURA MINE GROUP	COPPER, SILVER, LEAD, ZINC, GOLD, MOLYBDENUM	137.2
69	VIRGINIA 1 AND 2	QUARTZ CRYSTAL	9.8
70	VOLCANO	COPPER, SILVER	123.8
71	WELLINGTON GROUP	COPPER	213.4
72	WEST SIDE	COPPER, SILVER, GOLD	151.2
73	WORLD'S FAIR MINE	SILVER, LEAD, COPPER, ZINC, GOLD	148

Results

The calculated effects of mine waste positioned near streams in steep canyons within the mountainous watersheds are dramatic. The average sediment delivered from a 30-meter grid cell is 0.06-tons/acre/year; the result of sediment delivered from a mine site grid cell is 113.408 tons/acre/year. Several sites, including the European Mine Group, Jackalo, Invincible Prospect, Old Timer, and Sunnyside mines have been identified as major sources of sediment delivery. The model results accurately depict expected sediment delivery from most mine sites, yet exaggerate some sites situated in areas of high erosion according to other model inputs (soil type, relief, etc.) Therefore, digital data model results need to be field checked and adjusted accordingly prior to management action. The EPA supports watershed approaches that aim to prevent pollution and cites nonpoint source pollution as one of their main focuses. EPA also identifies sediment as the number one pollutant in streams and water channels. The identification of these areas is useful to for purposes of rehabilitation of old mine sites and also helps to pinpoint major contributors of NPS pollutants (sediments) to the system.

Conclusions

This study integrates digital geospatial data (elevation, vegetation, stream networks, soils, and mine locations) with advanced GIS applications in erosion prediction (USLE) and sediment delivery (SEDMOD). The division of the study area into a grid of small cells (30 m^2) allows for distributed spatial analyses of higher resolution of data. The USLE (Wischmeier, 1976) can then be more accurately applied at the scale for which it was originally intended (22 m long agricultural plot), allowing high-resolution predictions of sediment delivery. The models used for this study are fairly simple to manipulate once all of the necessary input layers are automated and/or acquired. This integration facilitates a more predictive and quantitative approach to watershed management.

Recommendations

Although the cost of high-resolution aerial photos was prohibitive for this study, photos would greatly improve this study by facilitating the identification of vegetative conditions (at an Association level), a variable which presently carries a high degree of uncertainty. Future research plans are to route chemical constituents through the watershed system from point of origin to point of deposition to evaluate the quantity of sediment contributed from mine sites. A comparison could be made between the amounts of sediment eroded from upstream mine sites to potentially toxic concentrations of elements, such as arsenic, found downstream near sites of sediment deposition from water and sediment analyses.

Appendix A: Figures

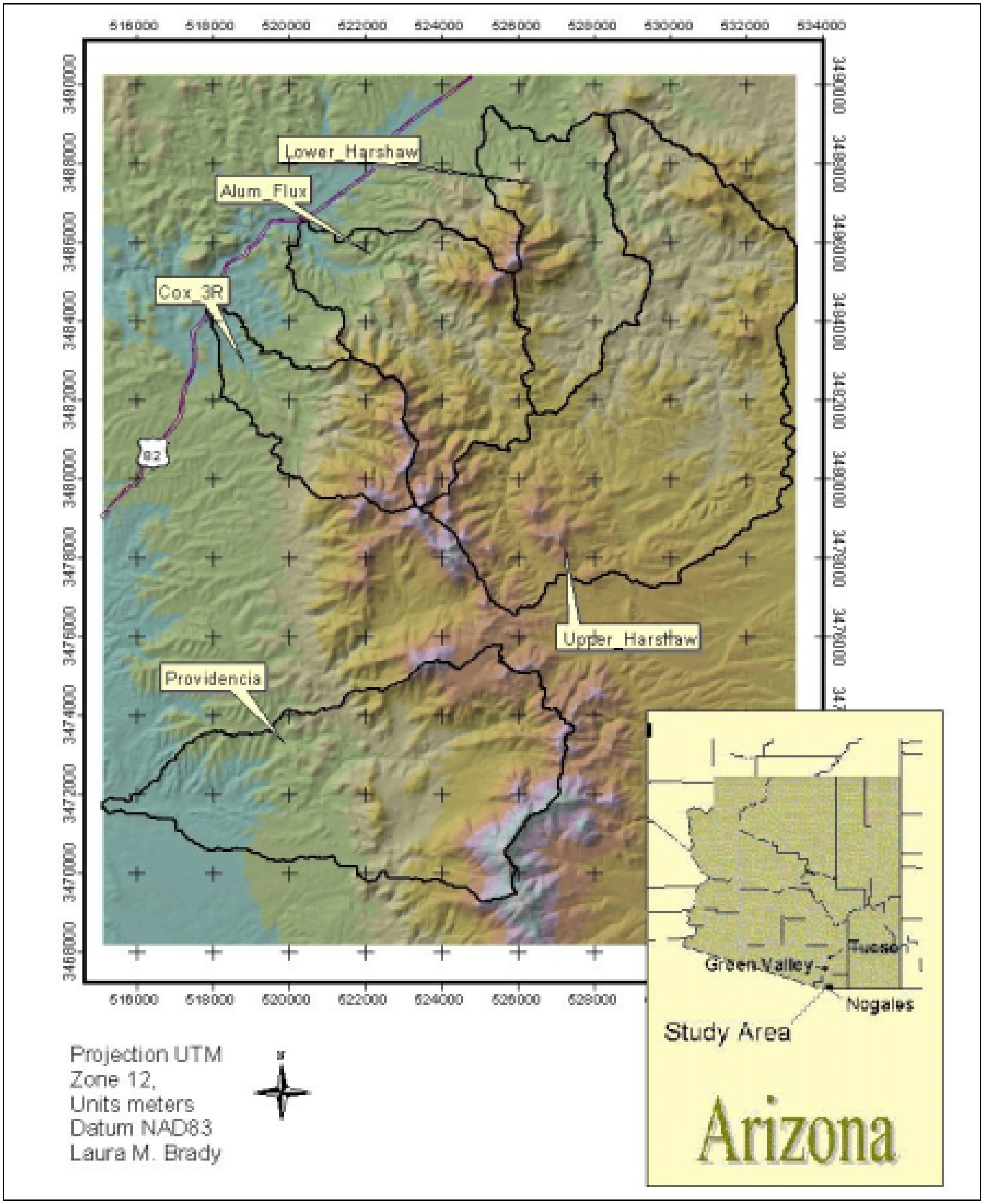

Figure 1: Five selected watersheds as delineated in the Patagonia Mountains, southern Arizona.

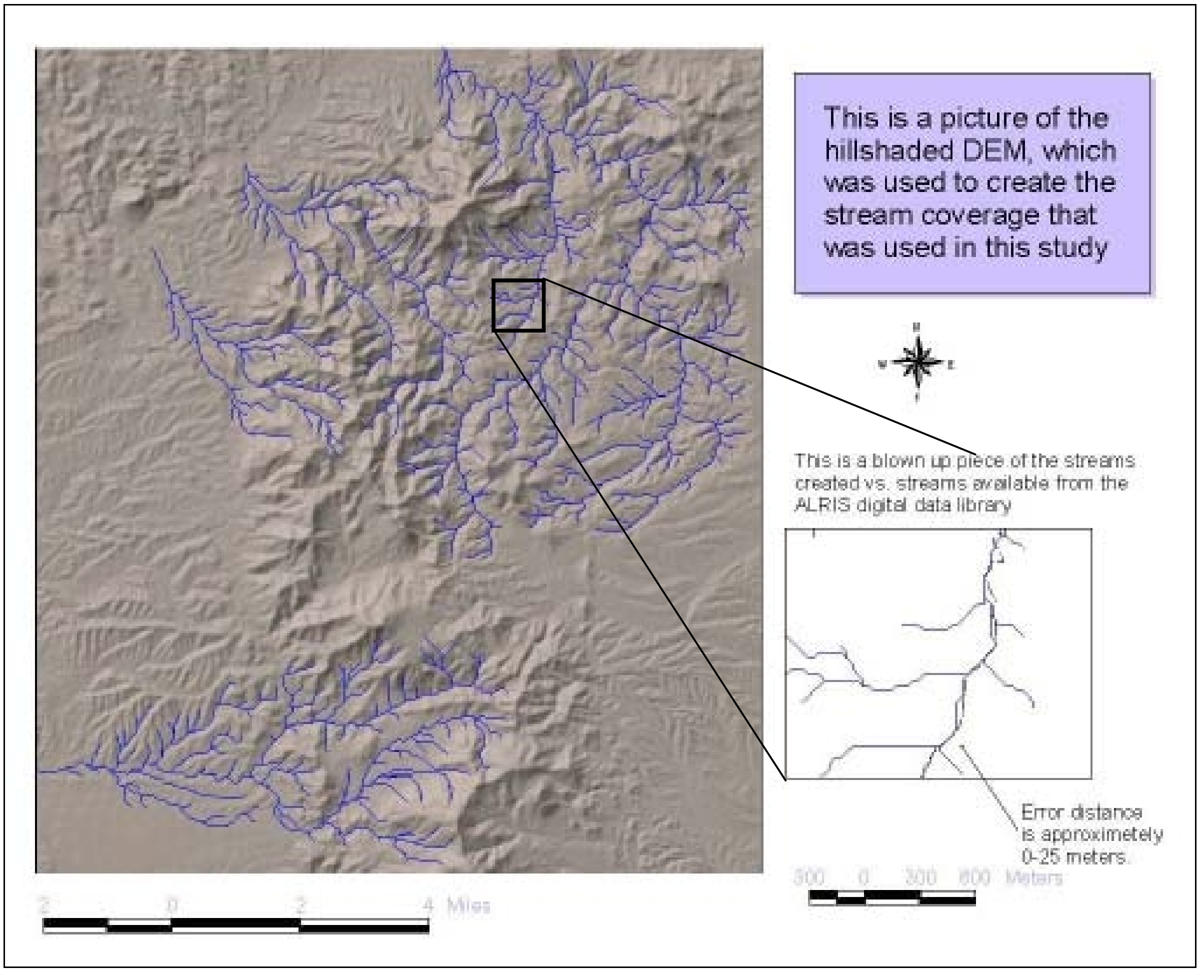

Figure 2: Derived digital representation of likely channels shown in comparison to known stream networks observed from a Digital Line Graph (DLG) created by the Arizona Land Resource Information System (ALRIS) within the Arizona State Land Department.

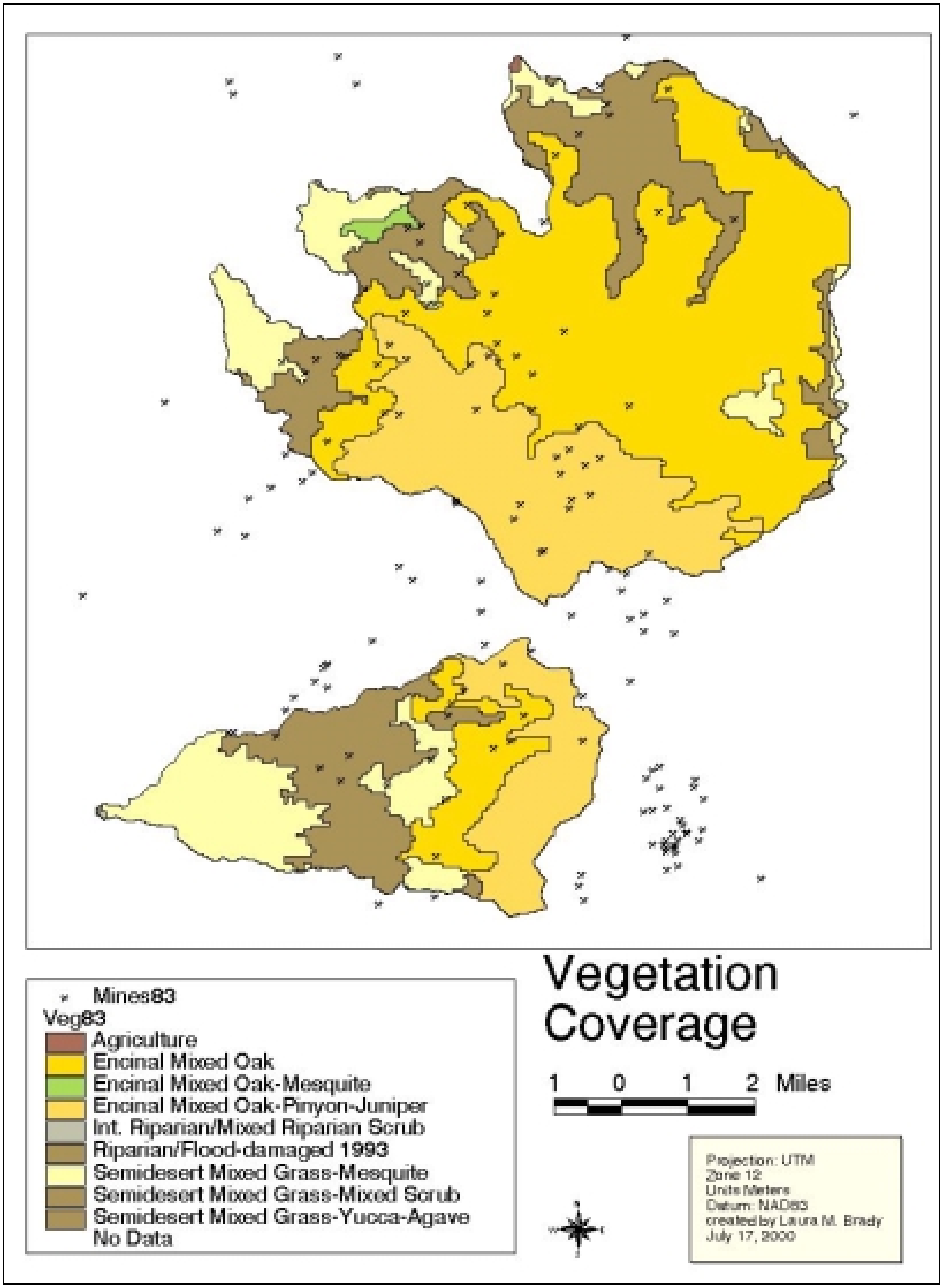

Figure 3: A vegetation coverage of the study are that was downloaded and clipped from the USGS GAP Analysis Vegetation and Land Cover geo-spatial data-set at the USGS NBII library.

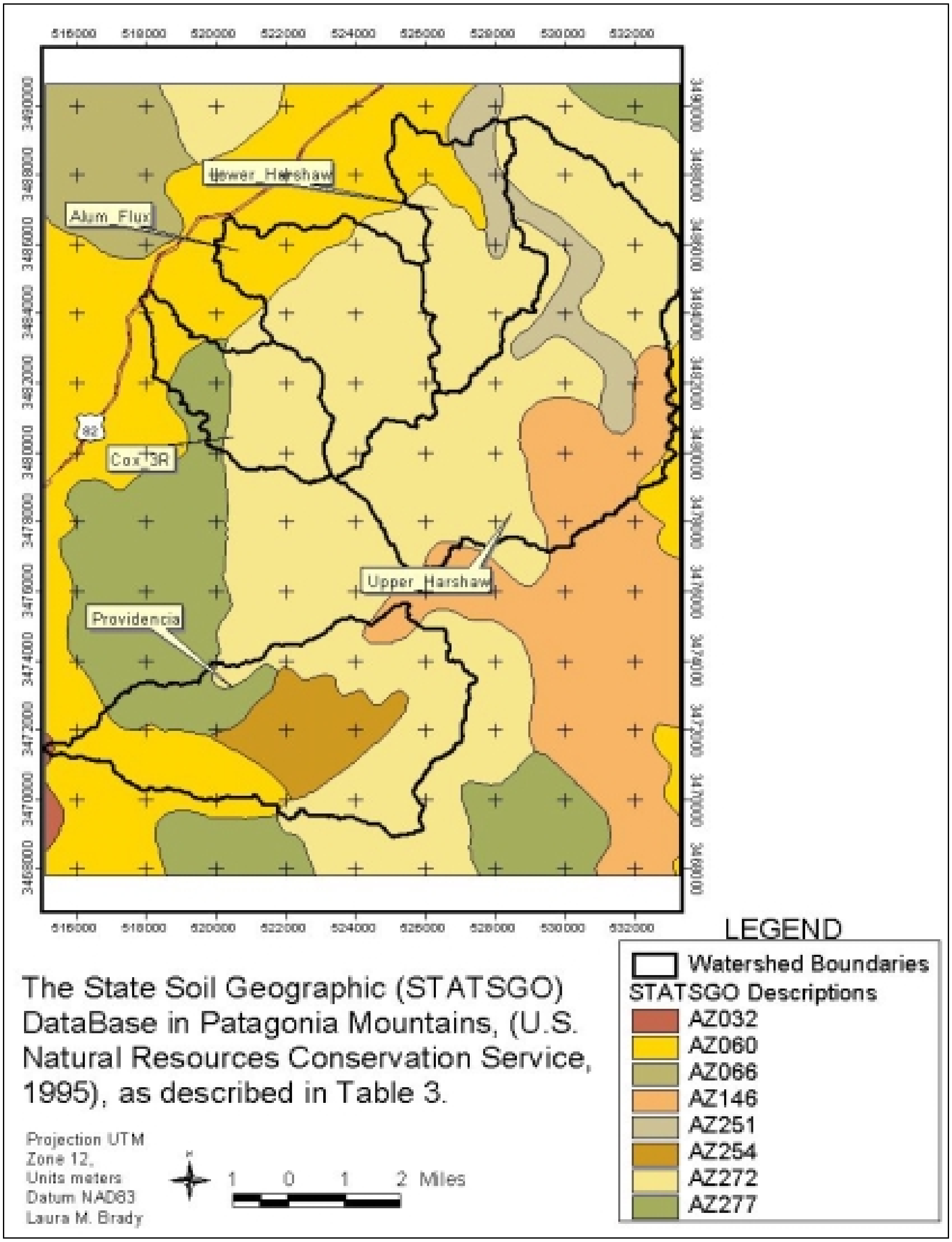

Figure 4: The State Soil Geographic (STATSGO) DataBase for Santa Cruz County (U.S. Natural Resources Conservation Service, 1995).

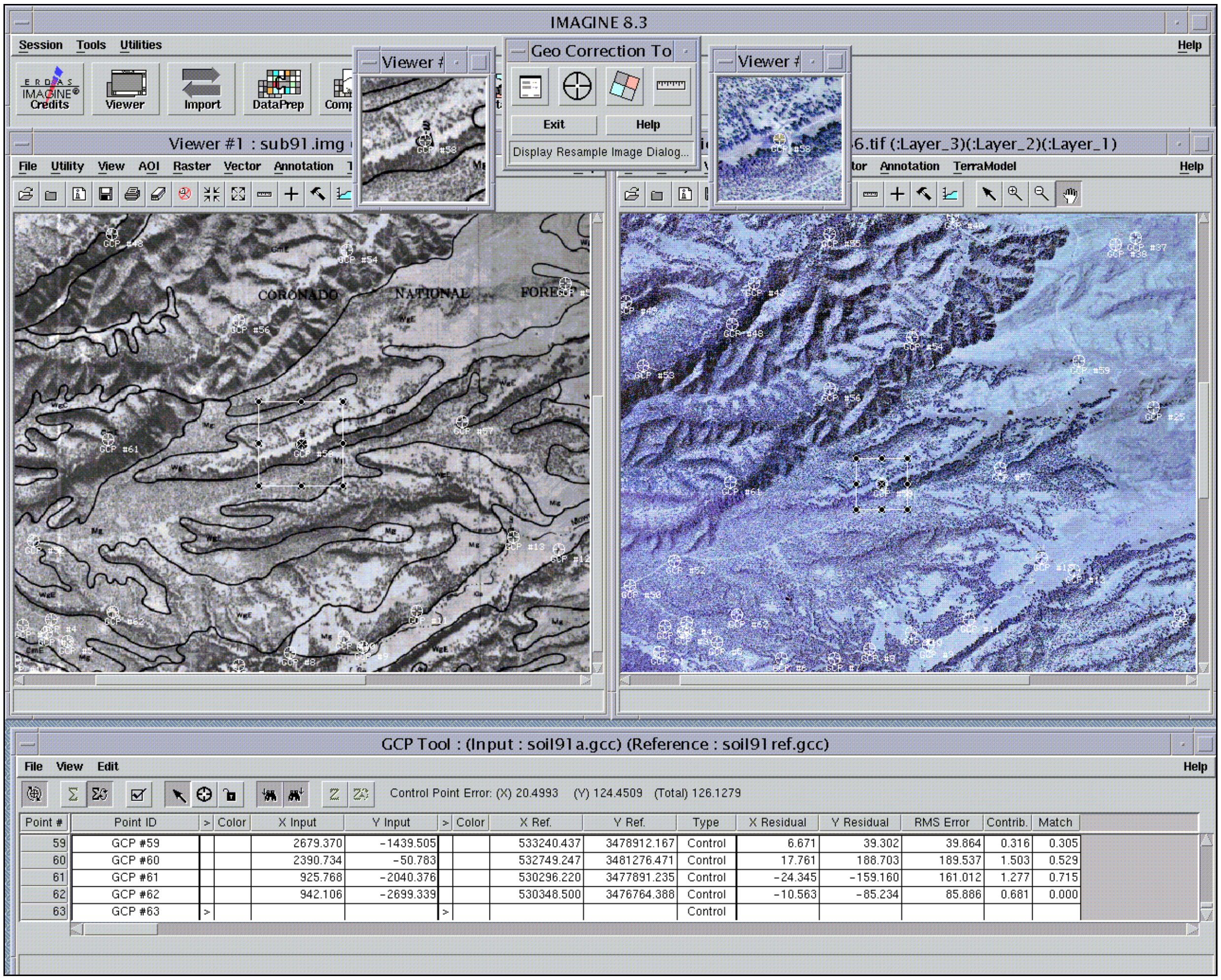

Figure 5: A picture of the geo-rectification process in ERDAS IMAGINE.

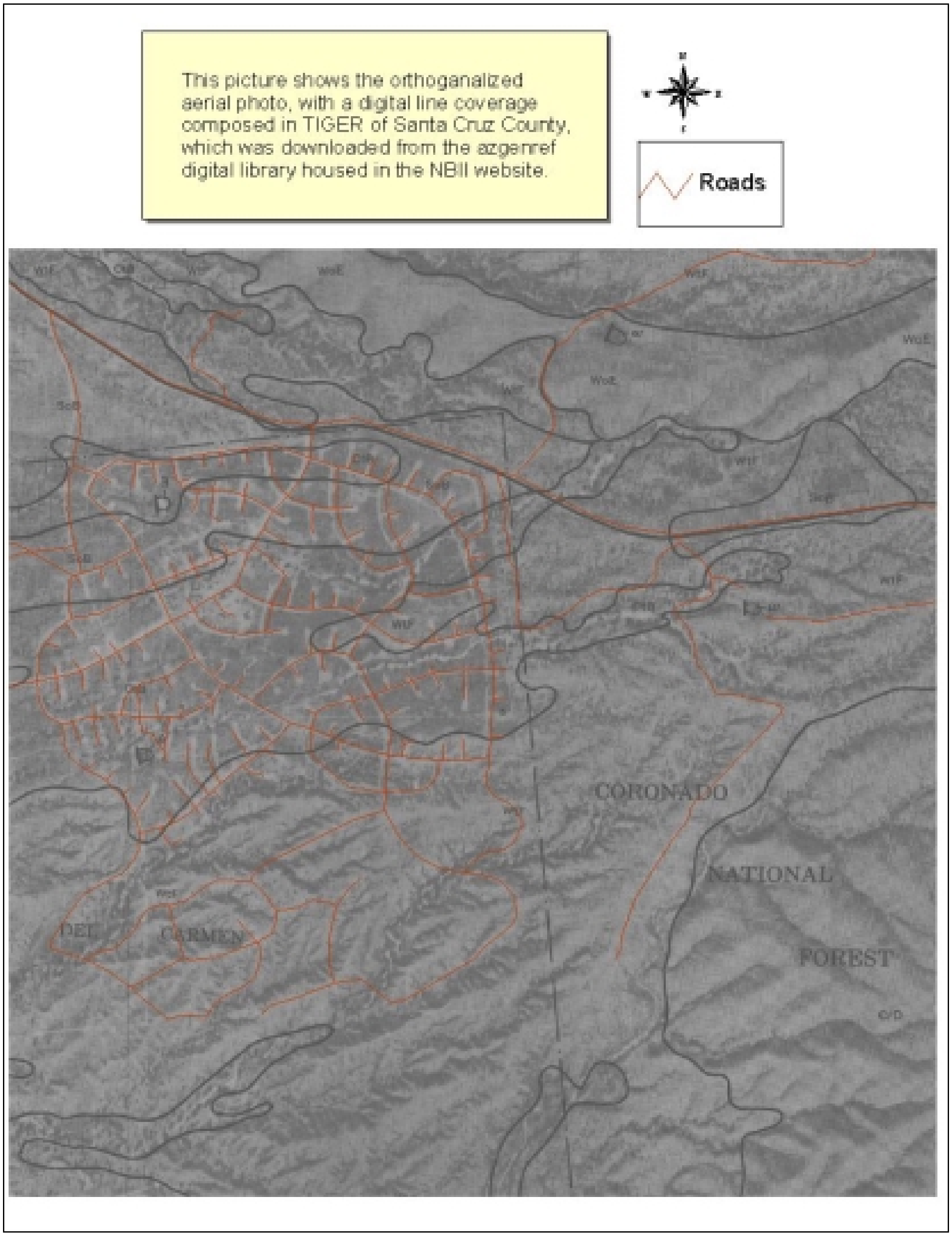

Figure 6: Orthoganalized aerial photograph with a Digital Line Graph (DLG) overlain depicting acceptable error for this project.

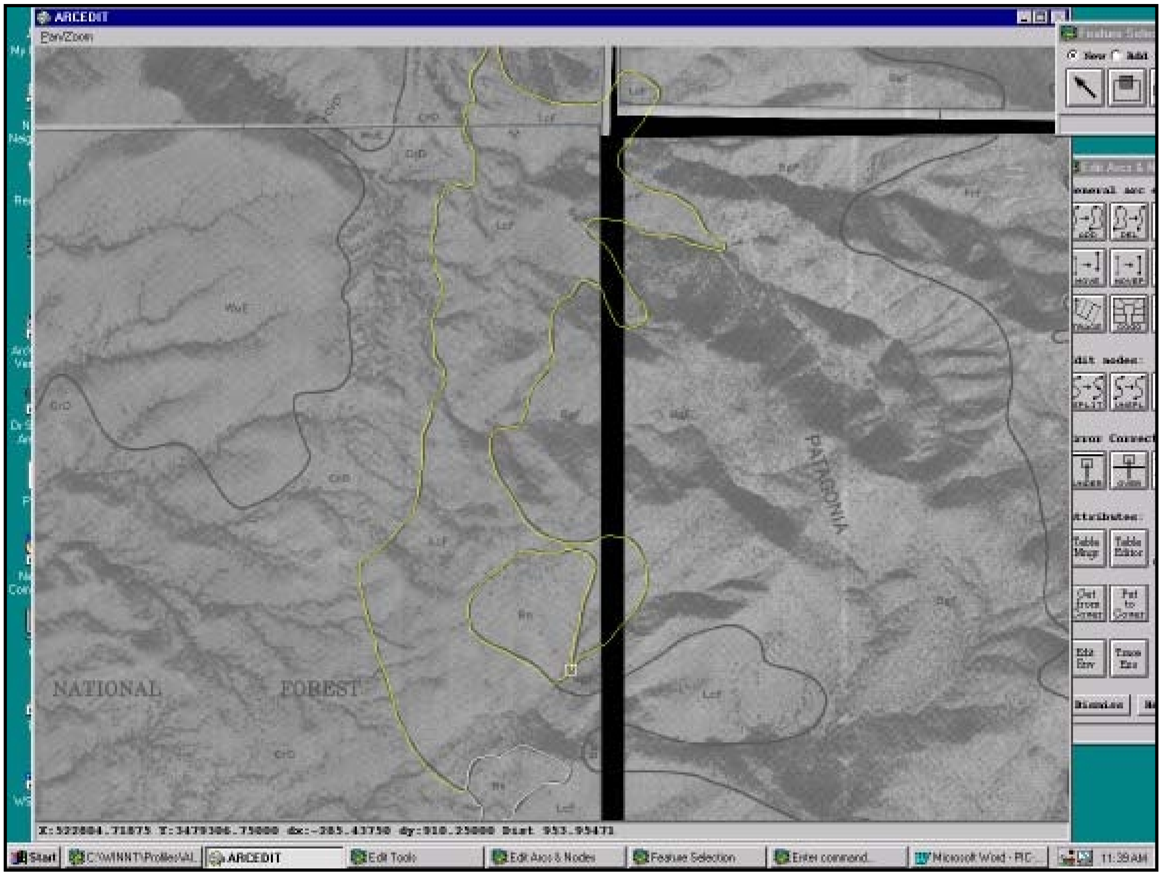

Figure 7: ArcEdit ARCTOOLS Graphical User Interface (GUI) used to digitize soils data from legacy aerial photography.

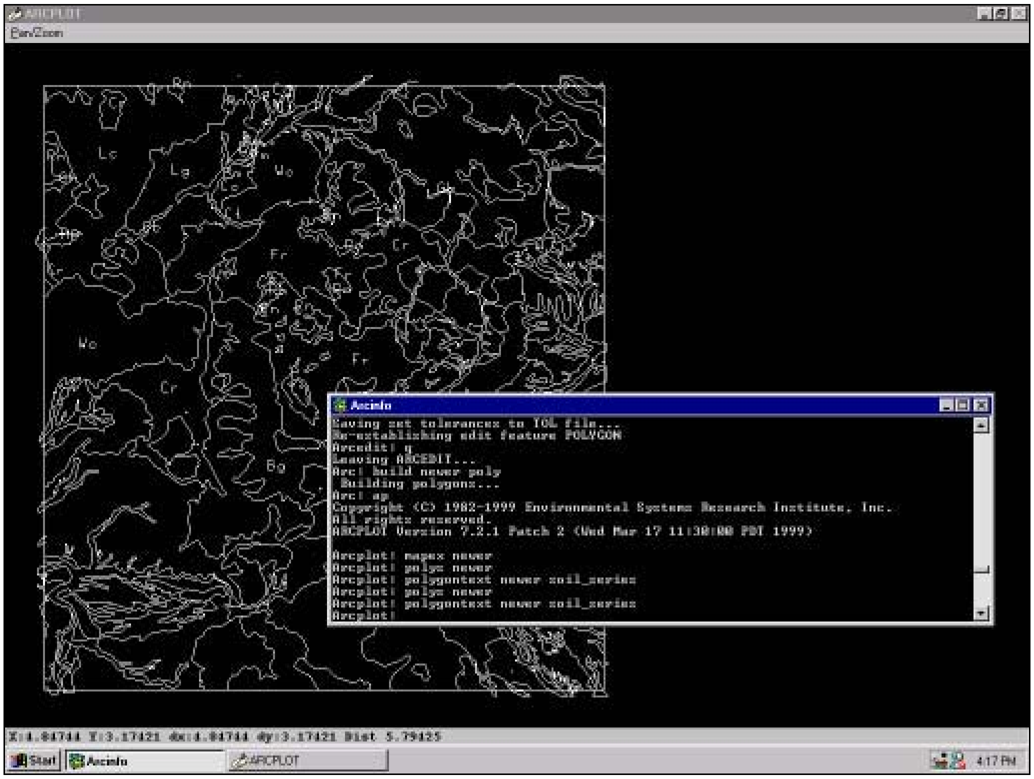

Figure 8: ArcPlot diagram of soils data being attributed.

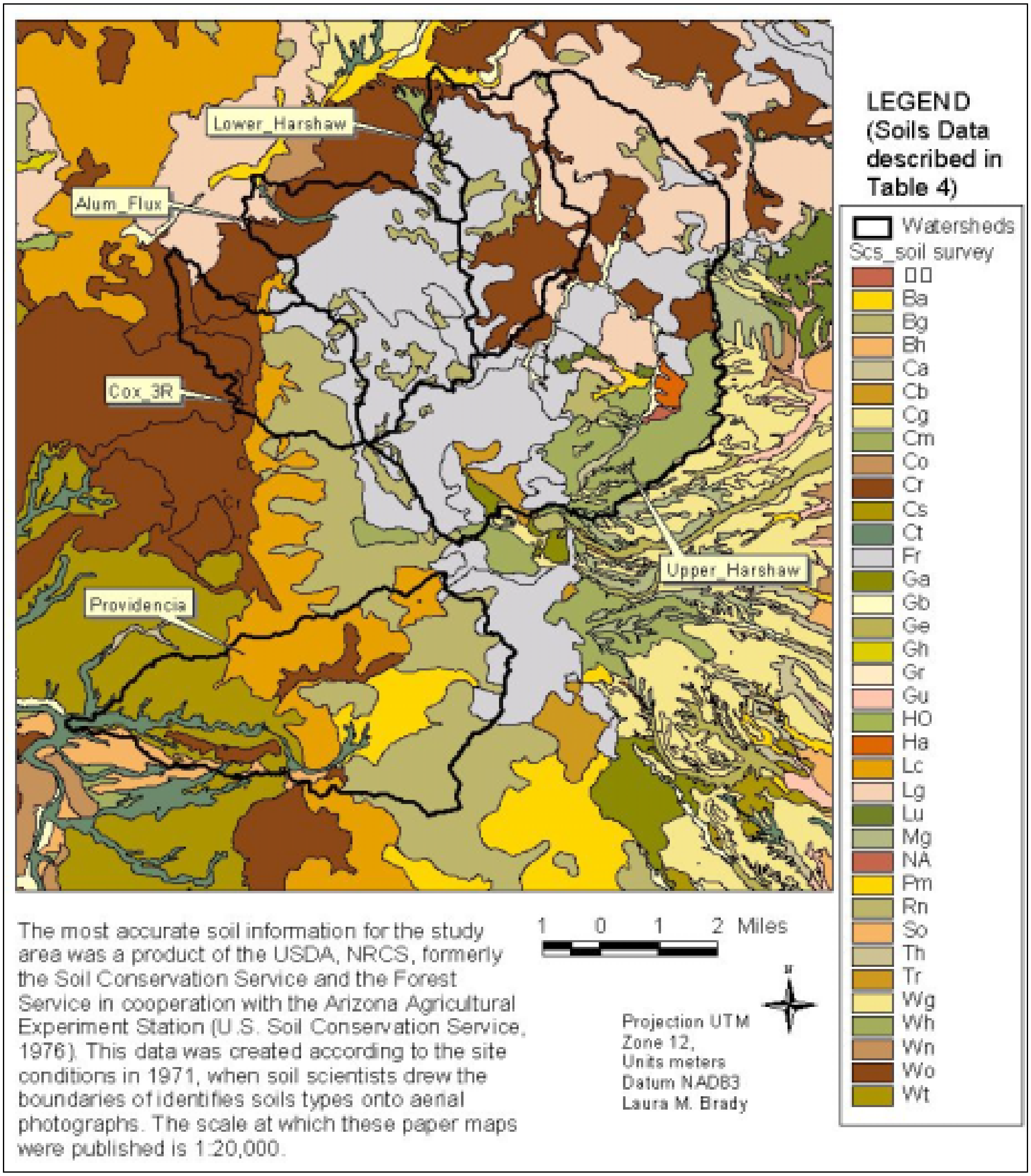

Figure 9: Automated soils data, a product of the USDA, NRCS, formerly the Soil Conservation Service and the Forest Service in cooperation with the Arizona Agricultural Experiment Station (U.S. Soil Conservation Service, 1976). (See Table 4 for soil unit names.)

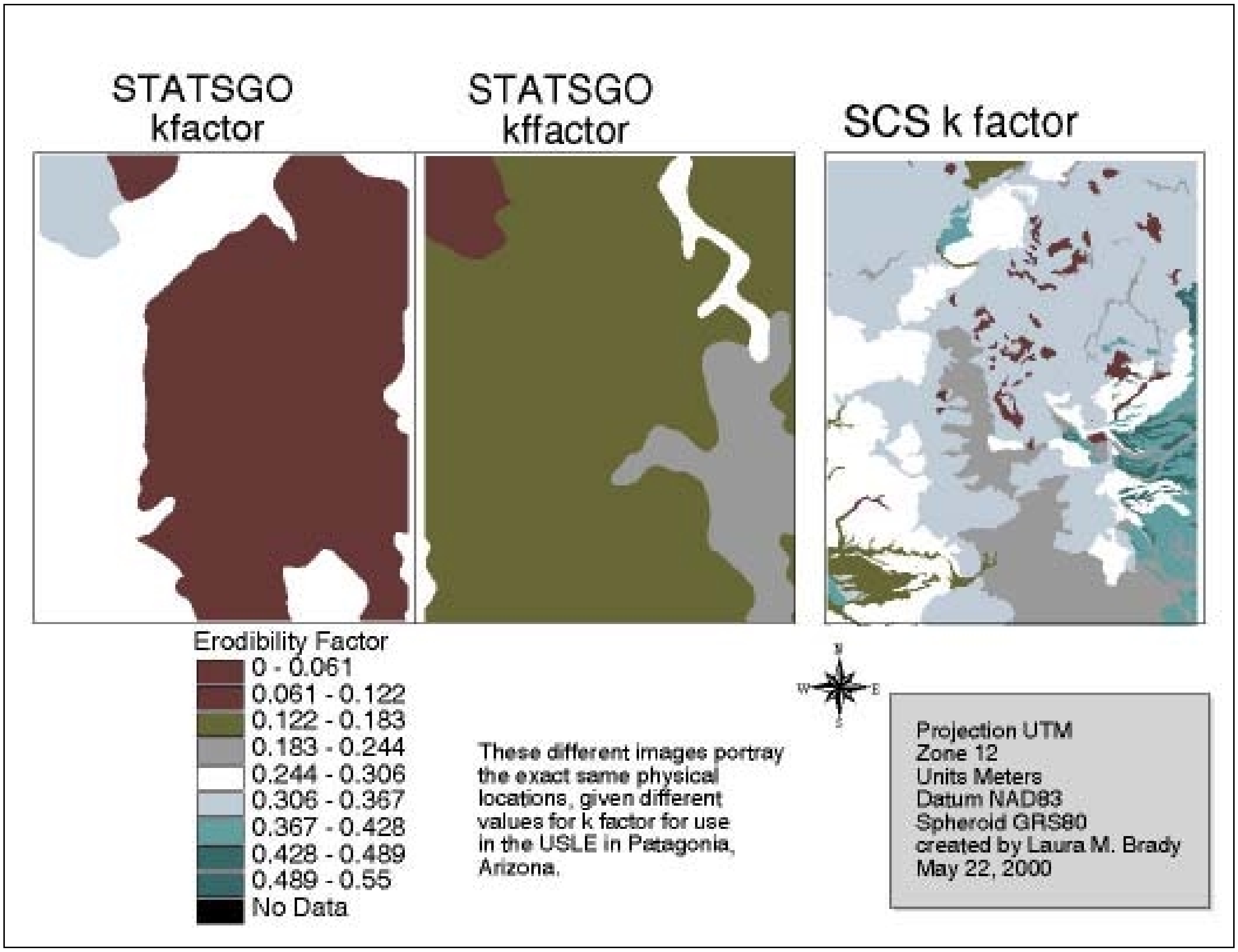

Figure 10: The State Soil Geographic (STATSGO) (U.S. Natural Resources Conservation Service, 1995) and the U.S. Soil Conservation Service (U.S. Soil Conservation Service, 1976) comparison of three acquired *K factors*.

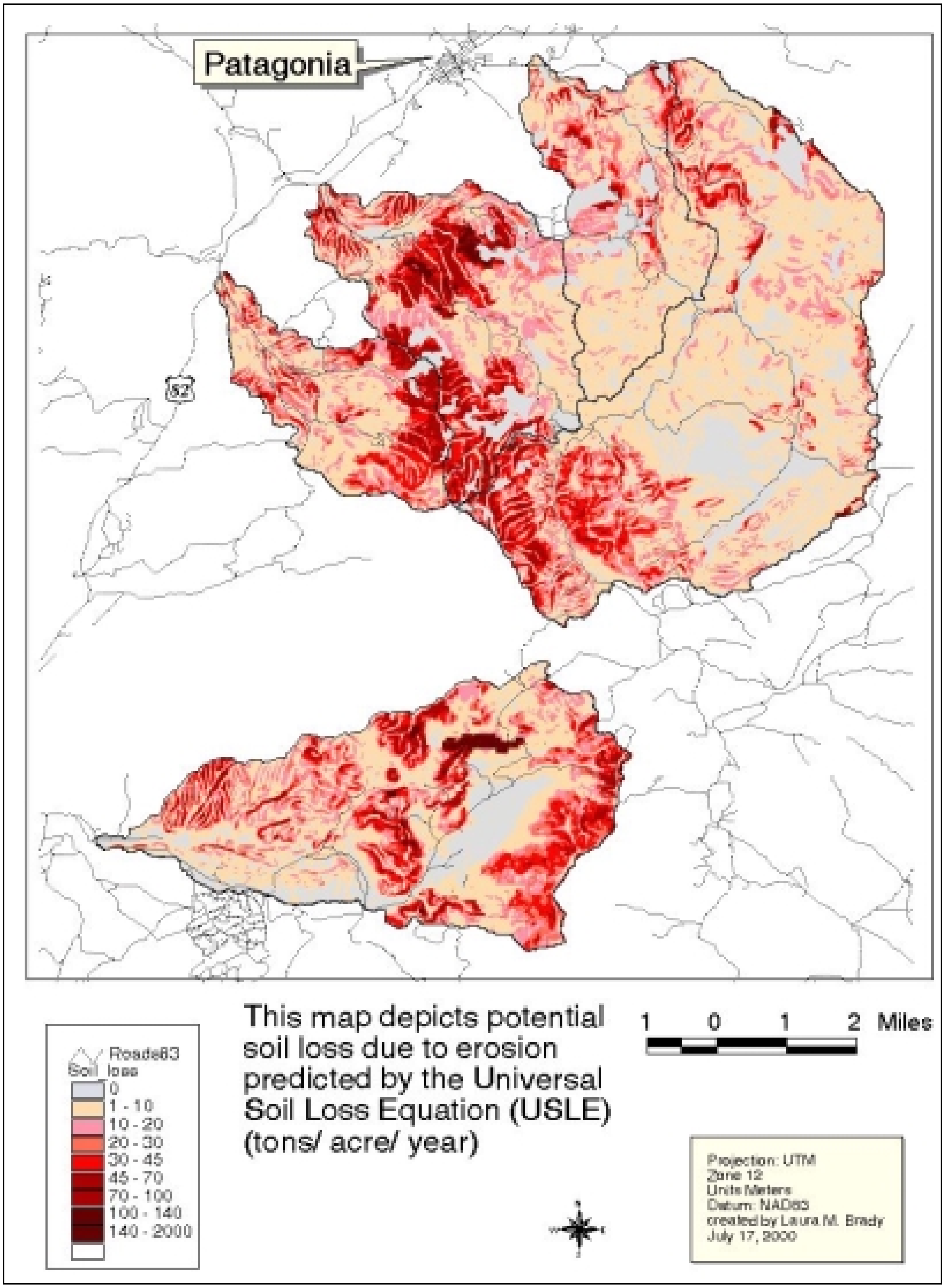

Figure 11: The results from calculating the USLE (Wischmeier, 1976) to predict soil erosion in the watersheds of the Patagonia Mountains, southern Arizona.

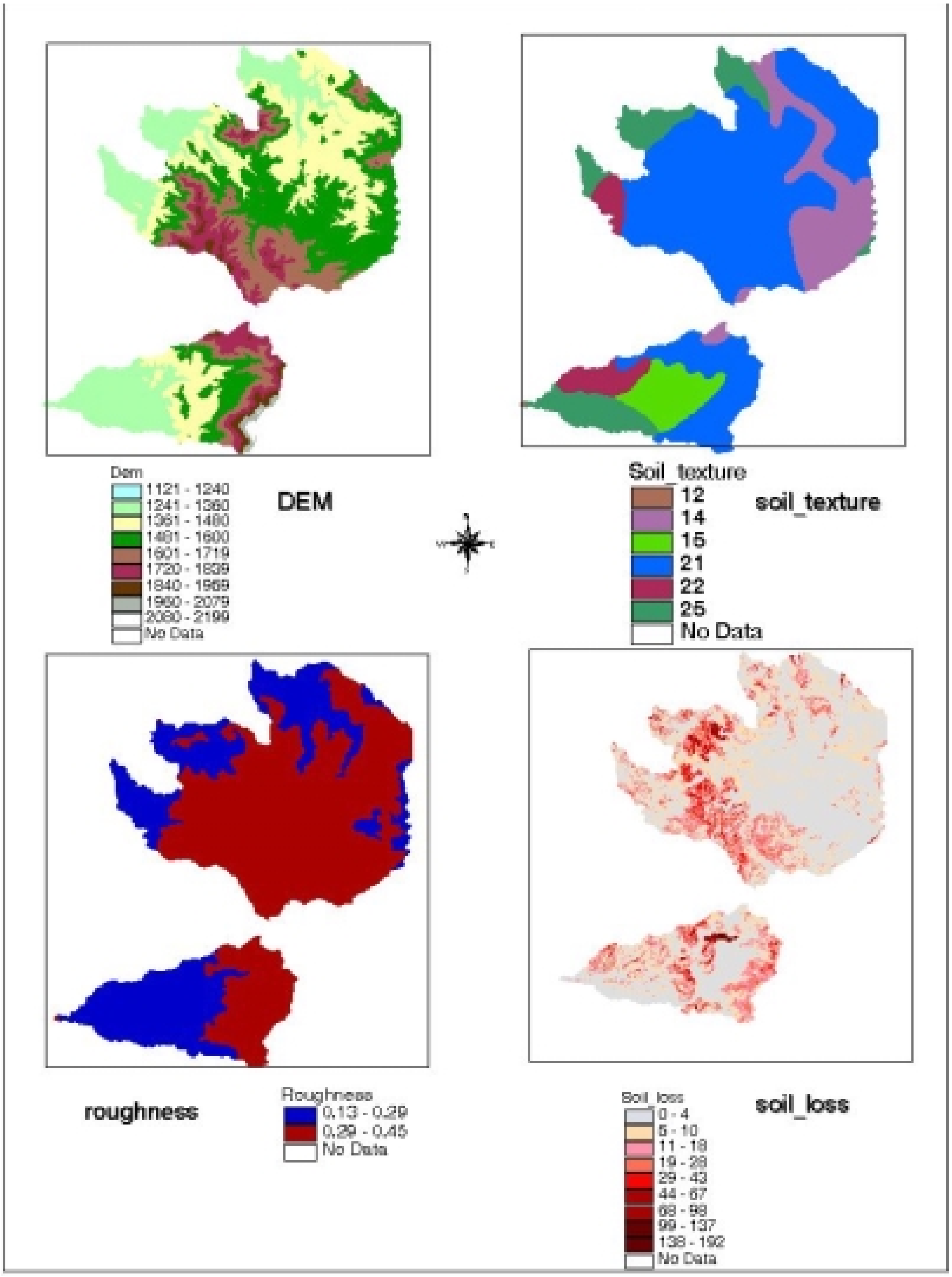

Figure 12: SEDMOD Input includes a DEM (meters), a Soil Texture Grid (percent clay), a Roughness Grid (Manning's Coefficient Ratio), and the predicted soil loss results (tons/acre/year) derived from the USLE (Wischmeier, 1976).

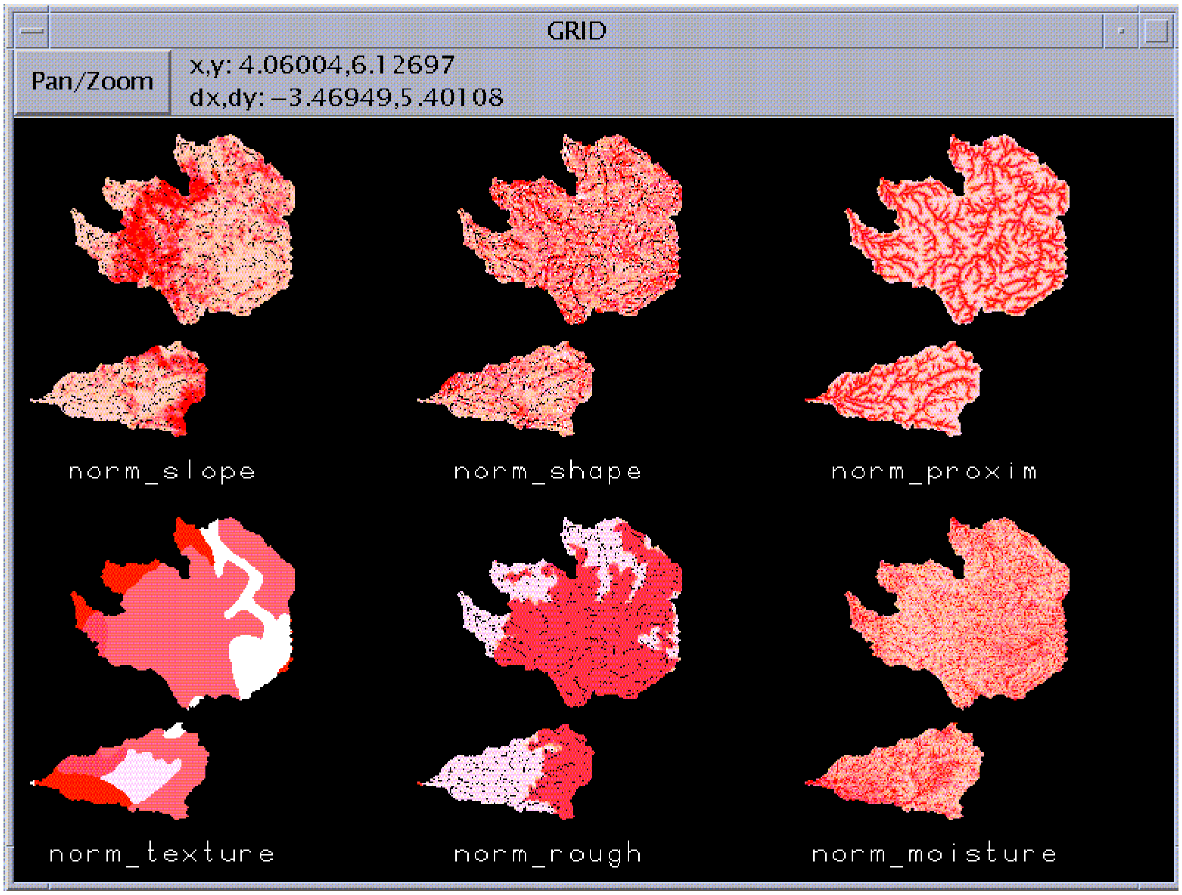

Figure 13: SEDMOD created analysis grids.

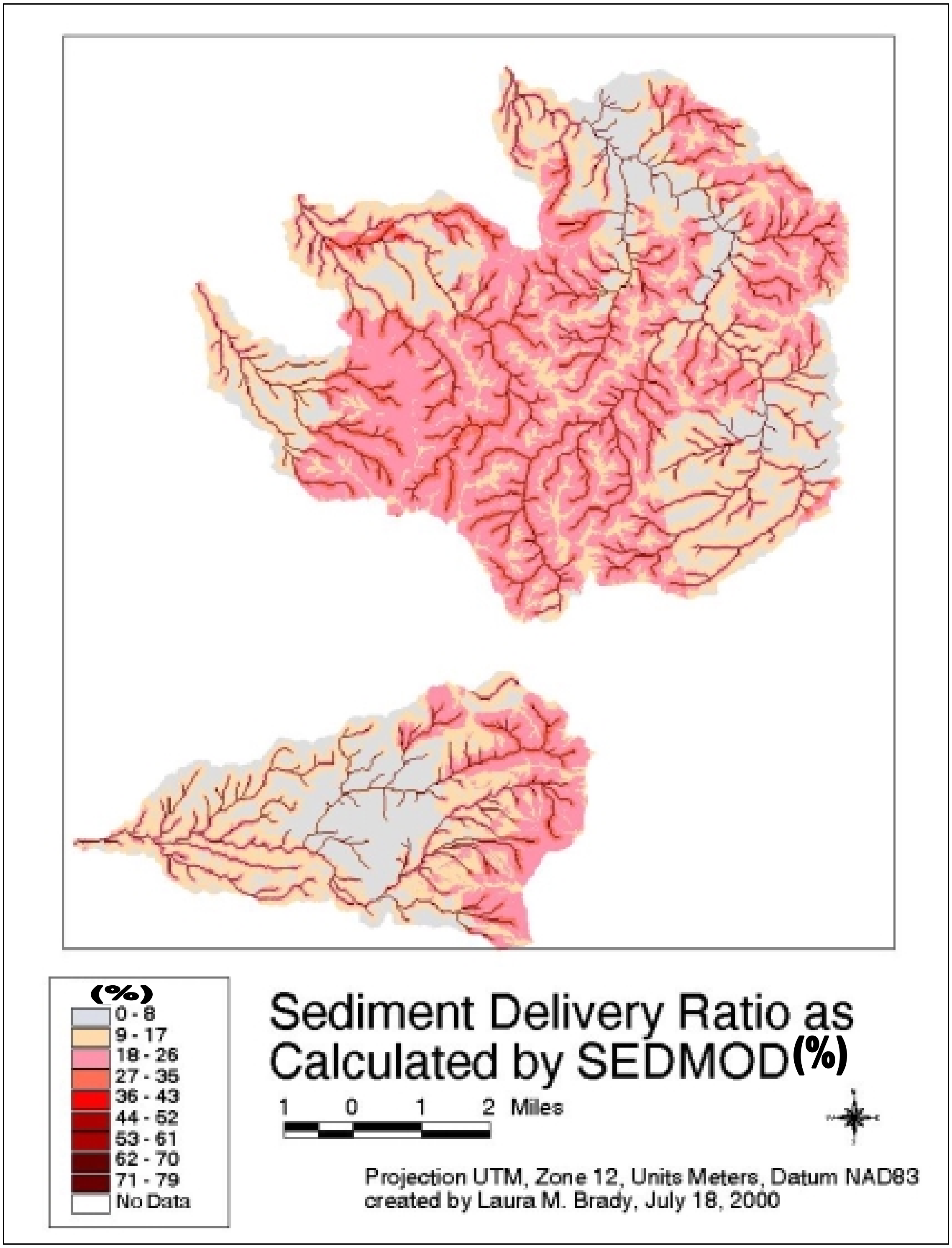

Figure 14: Sediment Delivery Ratio (SDR) (%) in the watersheds of the Patagonia Mountains, southern Arizona, as calculated by SEDMOD (Fraser, 1999).

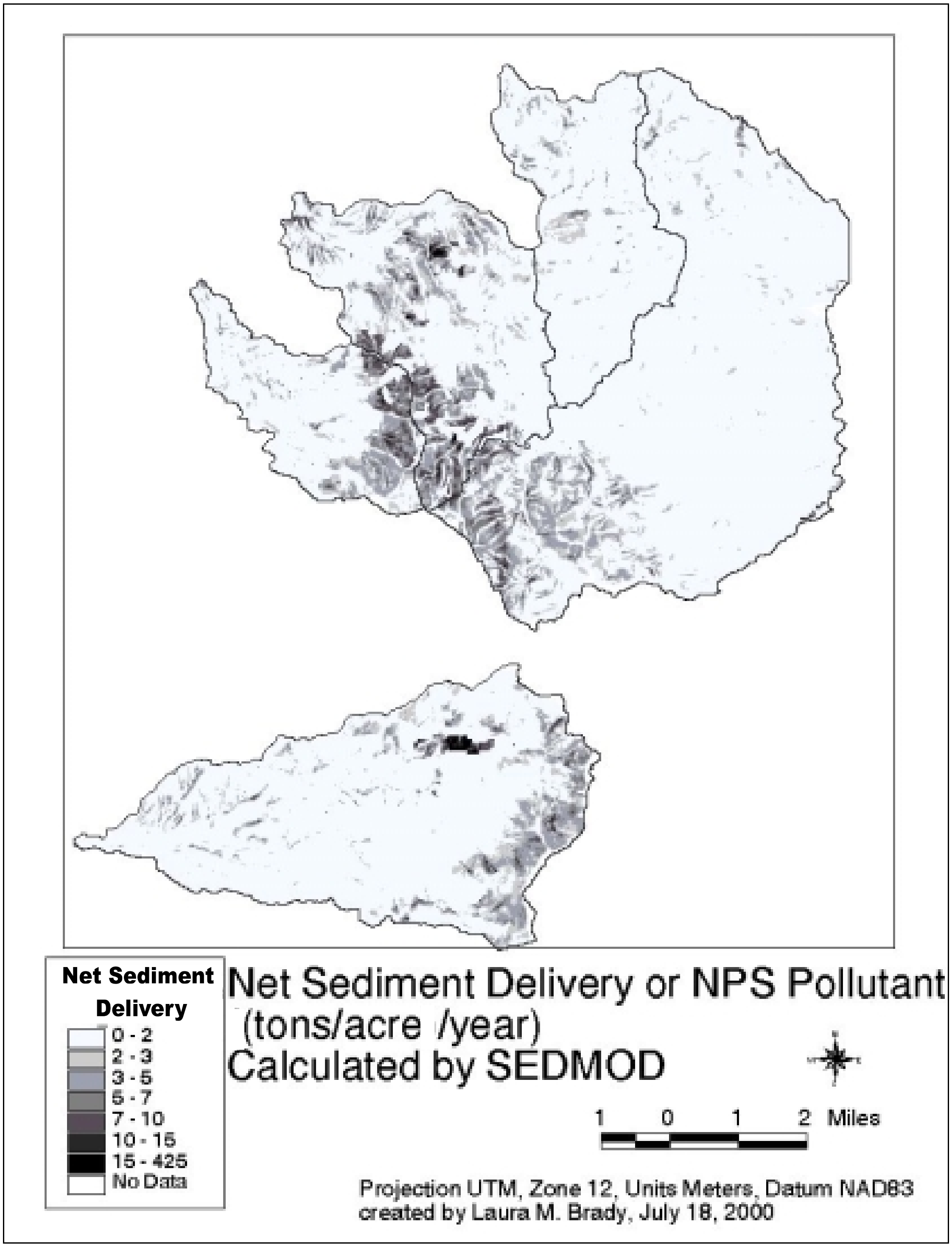

Figure 15: Net Sediment Delivery (tons/acre/year) in the watersheds of the Patagonia Mountains, southern Arizona, as calculated by SEDMOD (Fraser, 1999).

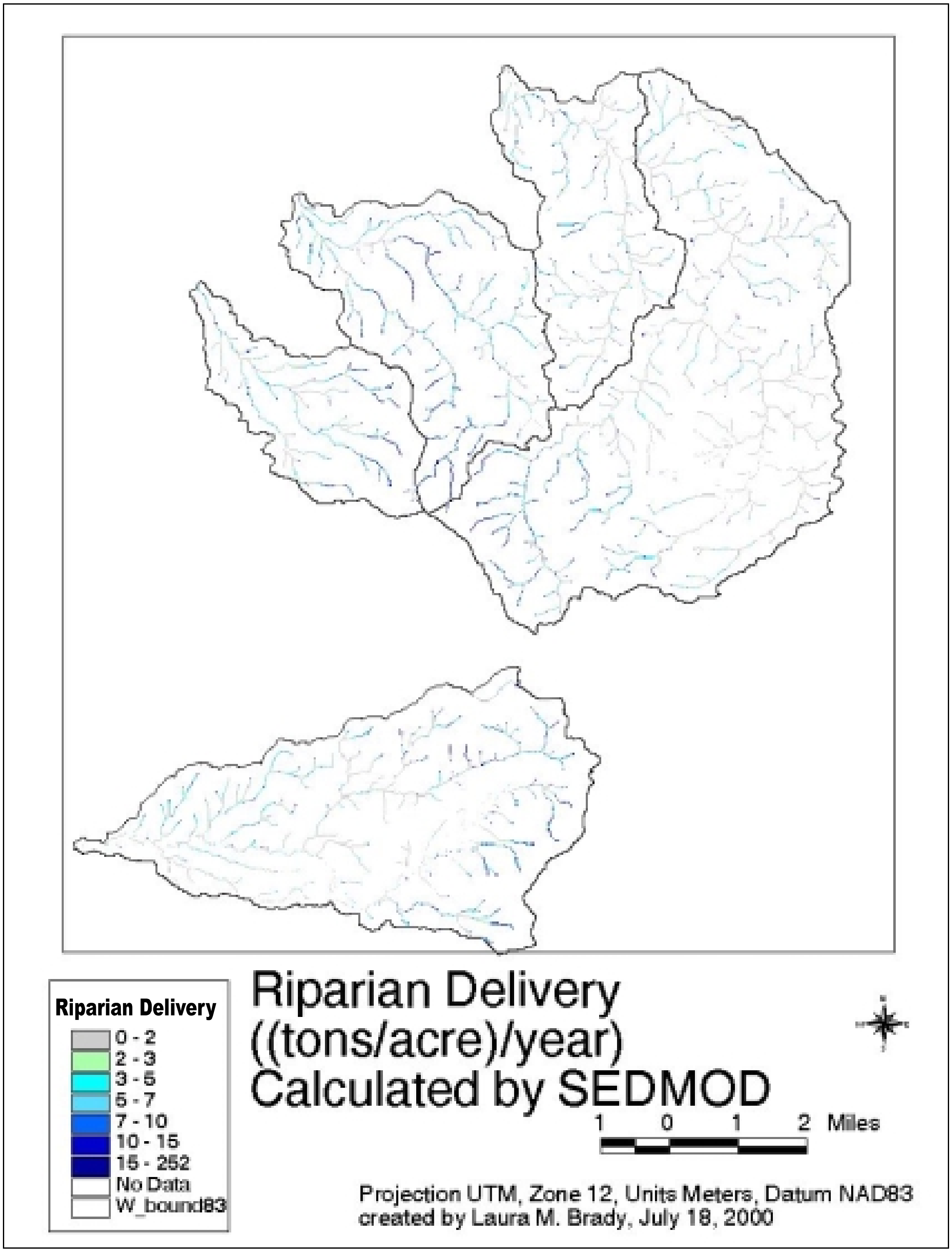

Figure 16: Riparian Sediment Delivery (tons/acre/year) in the watersheds of the Patagonia Mountains, southern Arizona, as calculated by SEDMOD (Fraser, 1999).

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