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# Using Geographic Information Systems to Predict Changes in Water Quality Due to Erosional Processes

A. Pete Martinez

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# **Using Geographic Information Systems to Predict Changes in Water Quality Due to Erosional Processes**

**by**

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A Professional Project Report Submitted in Partial Fulfillment of the Requirements  
for the Degree of  
**Master of Water Resources**

Water Resources Program  
The University of New Mexico  
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## Committee Approval

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## **Abstract**

The primary objective of this project was to develop a spatial erosion model using Geographic Information Systems (GIS) that took into account various management issues including road construction, fire history, and grazing. The model was created in five steps: the erosion model, three individual management analyses (for roads, fire history, and grazing), and the combined analysis. Modeling was conducted at the 1:250,000 scale using USGS Hydrologic Unit Code (HUC) 5<sup>th</sup> code boundaries. The erosion model and individual analysis results were compared to expected results from applicable research in their respective fields of study. The project goal was for the combined analysis results, when compared to the New Mexico Environment Department's impaired waters dataset, to provide an indication of impaired waters.

Although the individual analyses produced accurate results, those of the combined analysis did not relate to the to the actual sample data. While several iterations of the model were run with various modified parameters, the results continually failed to yield a relationship. Although the model did not produce predictive results, several valuable conclusions could be drawn from which to base future modifications. The roads analysis required fine-tuning since many of the roads within the study area were located close to water bodies and could be expected to have significant impacts on erosion. In addition, weighting the combined analysis such that areas near watercourses and water bodies have a greater impact on water quality than those further away would have yielded more accurate results. Finally, using the entire watershed as a study area caused significant problems due to the large areas involved, and this could have been avoided by limiting analysis to the catchment of each impaired stream independently.

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## Introduction

### Background

The primary role of the USDA Forest Service is natural resource management. As such, decision makers within the Forest Service must often decide on how best to preserve the forest ecosystem despite the various pressures of multiple uses, such as logging, grazing, and recreation. In order to determine the impacts of certain uses on the environment, it is first necessary to conduct a road analysis, a watershed analysis or both. These analyses provide an interdisciplinary science-based approach to determine the effects on the environment from various activities. The research presented in this report is designed for use as part of either of these analyses.

The roads analysis is often incorporated into large planning operations within the Forest Service in order to

...identify and manage a minimum road system that is safe and responsive to public needs and desires; is affordable and efficient; *has minimal adverse effects on ecological processes, ecosystem health and diversity, and productivity of the land*; and is in balance with available funding for needed management actions (USDA, 2003. Emphasis added).

In addition, road analyses are always conducted as part of a watershed analysis to determine the impact of new or existing roads on a watershed. The research in this study is designed to work in conjunction with either the Forest Service road or watershed analyses when determining the effects of erosion on water quality. It uses standard federal and state datasets allowing for repetition of the process with little to no modification throughout Forest Service lands.

The primary objective of this project was to develop a spatial erosion model using Geographic Information Systems (GIS) that took into account various management issues including grazing, recreation, fire, and road construction. Output from the model was in the form of raster layers that showed erosion rates modified by the three management issues of concern. Such work would prove a useful tool while conducting either road or watershed analyses for several reasons. First, it would allow a resource manager to look at potential “at risk” areas within their spatial context. Second, it would allow a resource manager to determine risk to many small watercourses upon which field sampling is not practical. Finally, by changing certain management parameters within the model (building a new road, removing cattle from a grazing allotment, etc.), it would be possible to predict changes in the level of risk faced by given watercourses.

The secondary objective was to develop a standardized procedure for the creation of the model for planners and managers to follow during the course of roads and watershed analyses. Because the data involved are standard state and federal data, the procedure may be applied to any study area within any national forest with the same accuracy. The procedure could also be used as a guide to create a graphic user interface (GUI) for the model. While incorporating a graphic user interface is a long-term objective of this work as well, it was beyond the scope of this particular report.

Certain results were expected before starting this project. Most importantly, the model output was expected to follow the available literature on the subject matter. Much research has already been done on the effects of the individual management issues, roads, fire, and grazing, on erosion. This research served as a useful guide when calibrating the model results for the individual management analyses. In addition, the results of the

model would show increased average erosion rates in catchments where samples indicate high turbidity, conductivity and bottom deposits. The New Mexico Environment Department (NMED) samples for these contaminants in certain water bodies in the study area every three years. By determining the relationship between the model results and the NMED data, impaired waters could be predicted from the model results.

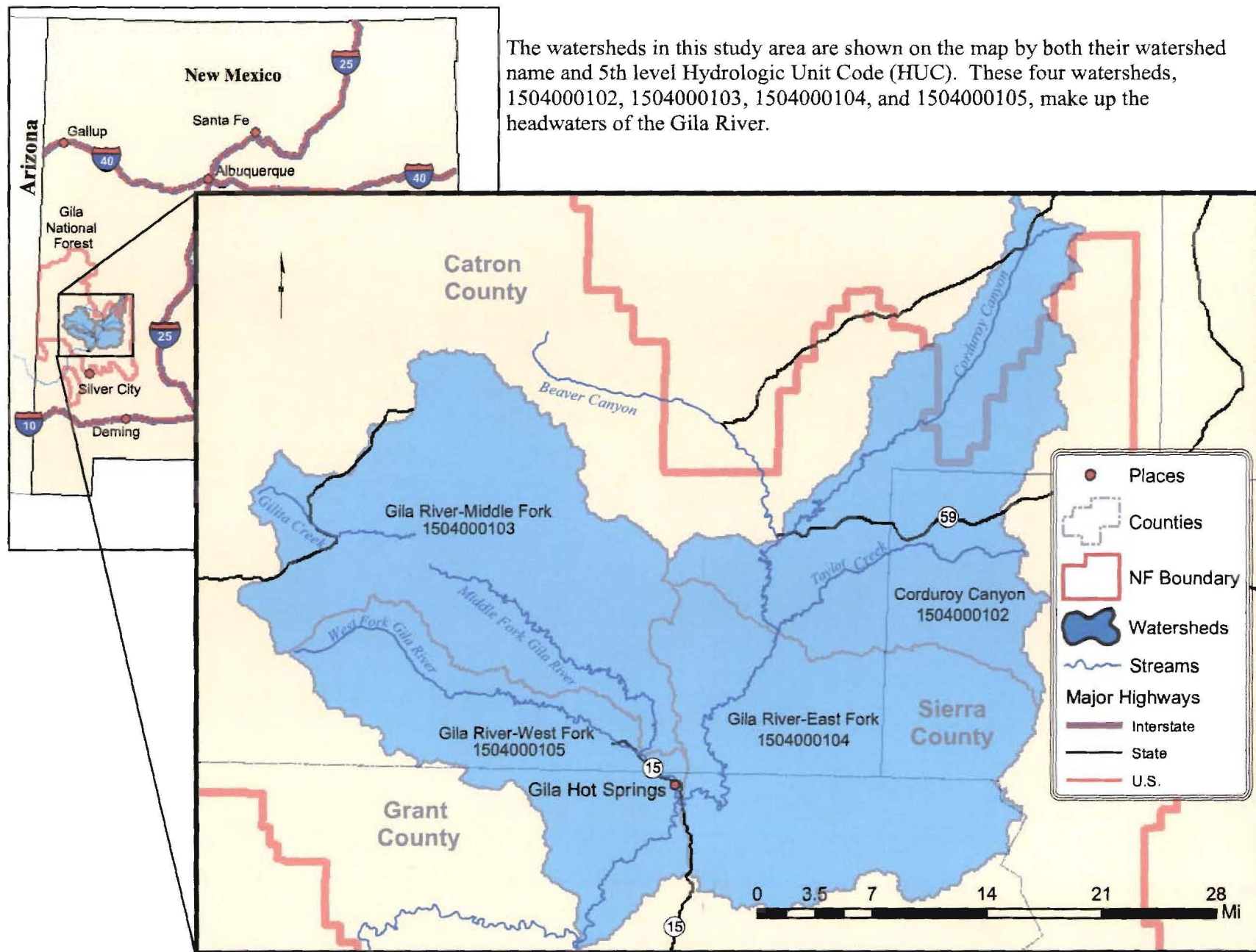
The model developed for this study was distinctly different from the Soil and Water Assessment Tool (SWAT), developed by Blackland Research Center, and the Water Erosion Prediction Project (WEPP) model currently used in various resource management applications within the Forest Service. Whereas WEPP estimates an actual amount of erosion and SWAT actually quantifies erosion, this new model will only predict relative changes in the quantities of contamination. The most important difference, however, was the ability of the new model to produce a spatial output.

#### Study Area

The study area consisted of four watersheds on the headwaters of the Gila River in New Mexico. These were Hydrologic Unit Code (HUC) Numbers 1504000102, 1504000103, 1504000104, and 1504000105, which correspond to the Corduroy Canyon, Middle Fork Gila River, East Fork Gila River and West Fork Gila River watersheds respectively (Figure 1). This area is almost entirely within the Gila National Forest and was chosen because of the variety of uses that occur there, in addition to the fire activity and presence of impaired streams.

The study area chosen for this project incorporated many of the management issues faced by Forest Service resource managers including the three relevant to this study. There are hundreds of miles of roads and trails within the study area. Most of this

Figure 1. Gila National Forest Study Area.



The watersheds in this study area are shown on the map by both their watershed name and 5th level Hydrologic Unit Code (HUC). These four watersheds, 1504000102, 1504000103, 1504000104, and 1504000105, make up the headwaters of the Gila River.



land is available for grazing, but sizable portions are designated wilderness and ungrazed. Within the study area, there are large tracts that have been burned within the last five years, most of which have been untouched by Burned Area Emergency Rehabilitation (BAER) actions. In addition, there are great contrasts not just in land use, but also in the land itself. The relief is approximately 1000 meters, and there are great variations in slope within the study area.

In terms of land ownership, there is little variation within the study area. Since this project was designed for use by Forest Service resource managers, most of the 306,250-hectare study area lies within National Forest boundaries. The Gila National Forest makes up about 94% of the total area. Approximately 5% is privately owned, while the remaining 1% is made up of state, BLM, and National Park Service land (Appendix I-1).

## Analyses

### Methodology

To meet the objectives of this research, a static model was constructed using GIS. Soil types, vegetation cover, and precipitation were used to develop the base erosion model. The three management issues, proximity to roads, fire history, and grazing, could then be directly incorporated into the model for three of the four watersheds in the study area. The finished model is not meant to quantify the levels of sediment contamination. It was developed to act simply as an indicator of change in the rate of erosion due to the above-mentioned factors. The output of the model is intended to present an accurate spatial representation of the potential to affect changes in surface water quality. To test this, each independent management issue analysis output was compared to existing

literature in order to be verified for accuracy. To validate the individual management analysis, the entire process was repeated on the remaining watershed. The combined analysis results were to be calibrated by comparing the model output to the NMED impaired waters dataset.

GIS work was conducted primarily from the ESRI ArcGIS 8.x platform with the Spatial Analyst and ArcHydro extensions. Vector analyses were conducted in the geodatabase environment to which ArcGIS8.x is especially well suited. The raster analyses outlined below were done through Spatial Analyst, specifically, the Raster Calculator and Reclassify tools.

The data chosen for use in this study are all standard state or federal data with their own governing standards for accuracy (Table 1). Scales and temporal resolution

Dataset: Source	Description
National Elevation Dataset (NED)-USGS: <a href="http://seamless.usgs.gov">http://seamless.usgs.gov</a>	10m Digital Elevation Models (DEMs)
National Hydrography Dataset (NHD)- EPA/USGS: <a href="http://seamless.usgs.gov">http://seamless.usgs.gov</a>	1:100,000 scale 4 <sup>th</sup> Code Hydrologic Units (HUCs). This dataset includes watersheds, water bodies and watercourses.
STATSGO-NRCS: <a href="http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html">http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html</a>	New Mexico Soils Dataset.
Impaired Surface Waters (303d)-NMED/EPA: <a href="http://www.nmenv.state.nm.us/swqb/index.html">http://www.nmenv.state.nm.us/swqb/index.html</a>	Impaired Water for the State of New Mexico.
Region 3 Core Data-USDAFS: <a href="http://fsweb.clearinghouse.fs.fed.us/regions/r3/r3.html">http://fsweb.clearinghouse.fs.fed.us/regions/r3/r3.html</a>	Roads/Trails, and Grazing Allotments at 1:24,000 scale. Core data also supplied boundaries used throughout the study.
Region 3 Fire Coverage-USDAFS: <a href="http://www.fs.fed.us/r3/gis/datasets.shtml">http://www.fs.fed.us/r3/gis/datasets.shtml</a>	Includes geometry and Burned Area Emergency Rehabilitation (BAER) Team involvement for 2000-2004.
General Ecosystem Survey (GES)-USDAFS: <a href="http://www.fs.fed.us/r3/gis/datasets.shtml">http://www.fs.fed.us/r3/gis/datasets.shtml</a>	This 1:250,000 scale dataset contains information on vegetation (type and percent cover), soil type (components, erosion potential), precipitation, and climate.
RUSLE R-Factors for NM-NRCS: <a href="http://www.nrcs.usda.gov/technical/efotg">http://www.nrcs.usda.gov/technical/efotg</a>	This contains isoerodents for the state of New Mexico.
*ACT_Grazing_Use-USDAFS INFRA Database	Contains up-to date information about times, numbers, and types of animals being grazed.

Table 1: Project Data List. All of the data listed above are available free on the Internet with the exception of the INFRA database.

\*The INFRA database is available directly from the Forest Service upon request.

therefore vary within the data. This being the case, the scale of relevancy for this project is set at the 1:250,000 scale for the year 2003. However, because the data are standard, all equations should be applicable for any year and any scale for which data are available with little to no modification.

All of the above spatial data were projected to the Albers Equal Area projection, native projection of the STATSGO dataset. The Albers Equal Area projection is useful for this analysis because it preserves area throughout the study area. The map document was also converted to this projection, but with standard parallels and the central meridian modified according to the size and shape of the study area: standard parallels of 33.1° N. and 33.5° N., with the central meridian at 108° W.

Model development was divided into two distinct phases: one for individual management analyses and one for combined analysis. The individual analysis phase occurred in four steps. First, the erosion model was developed and calibrated for an undisturbed forest scenario. Next, independent erosion analyses were conducted for each of the three management issues of concern; roads, fire, and grazing. Once each element in the individual analyses was verified for accuracy, the second phase of model development began. The calibrated results of the individual analyses were combined and compared to the NMED impaired waters data to check for accuracy.

#### Undisturbed Forest Analysis

The base erosion model was developed first, using the undisturbed forest scenario. This would allow direct comparison of the model results with what was expected based on the literature. In this analysis soil type was the key to understanding how erosion would affect water quality. A substantial amount of data collection and

preparation was therefore necessary for the soil computations. STATSGO soil, rainfall erosivity, GES Vegetation, and slope datasets were incorporated into the Revised Universal Soil Loss Equation (RUSLE).

The RUSLE is based on the original Universal Soil Loss Equation (USLE) outlined by Wischmeier *et al.* (1978). Various forms of the USLE are used in different erosion models around the world. SWAT uses the Modified Universal Soil Loss Equation (MUSLE), which allows for calculation of erosion rates after individual storm events (Williams 1975). Since single events are not considered in this project, the more simplified RUSLE can be used to calculate erosion. Five instances of the RUSLE were run for the creation of this model; one for undisturbed forest, one each for roads, fire, and grazing, and one for a combination of all of these factors. The RUSLE is:

$$A = R * K * L * S * C * P, \text{ where:}$$

A = Computed long term average soil loss from sheet and rill erosion

R = Rainfall and Runoff Factor

K = Soil Erodability Factor

L = Slope Length Factor

S = Slope Steepness Factor

C = Vegetation Cover Factor

P = Erosion Control Practices

The rainfall and runoff factor (R) in the RUSLE takes into account the effect on erosion due to the relationship between the kinetic energy of rainfall and rainfall intensity (Wischmeier *et al.* 1978). The R factor was collected from the NRCS RUSLE R Values for New Mexico map shown in Figure 2 below. For the study area, R-values were estimated at 30 for both watersheds 504000103 and 1504000105, 25 for watershed 1504000104, and 22 for watershed 1504000102 (Figure 2). This interpolated value was then inserted into the watershed layer and converted to raster format.

## RUSLE R - Factor Values for New Mexico

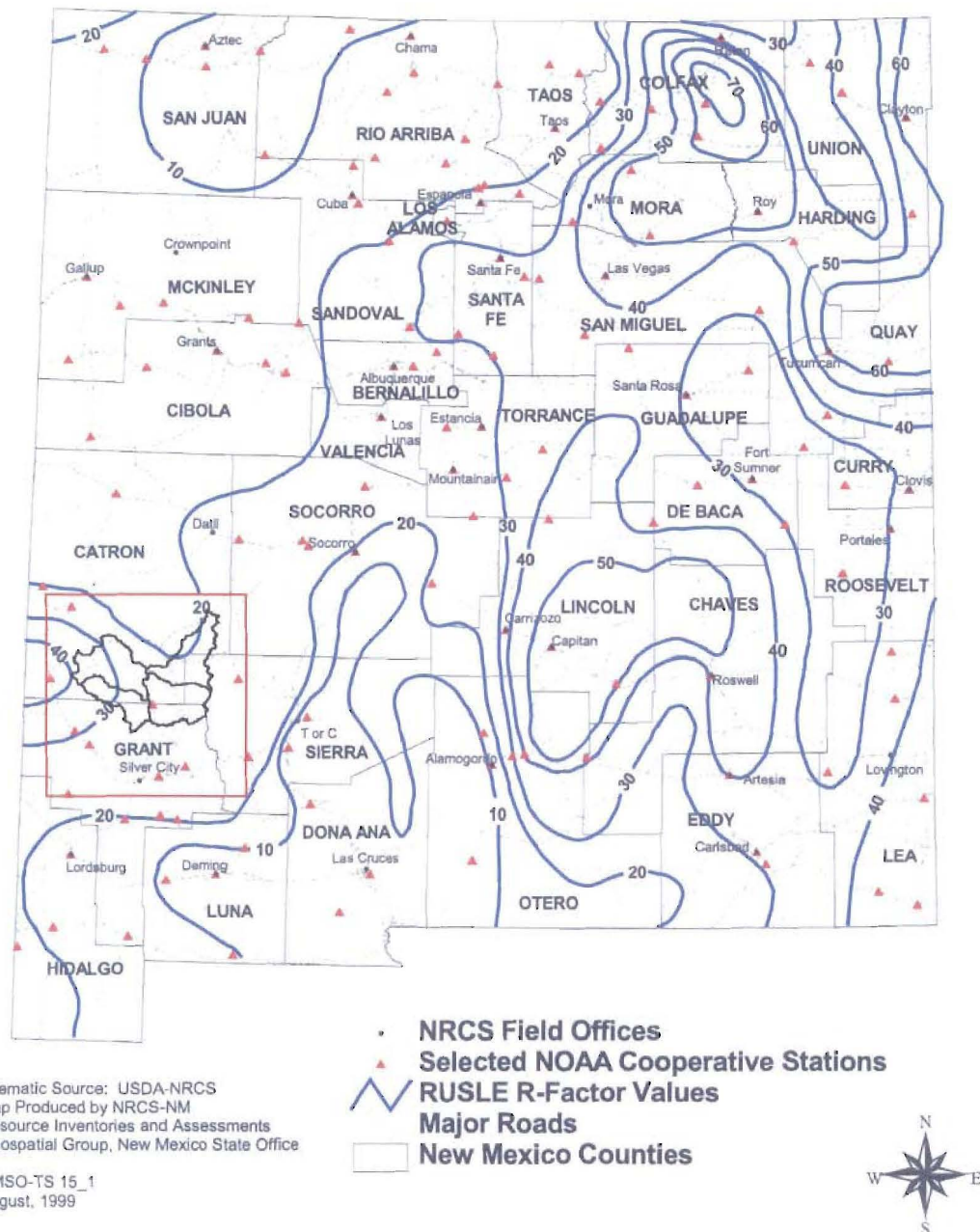


Fig. 2. RUSLE R-Factors Values New Mexico. From NRCS Electronic Field Office for the state of New Mexico. The study area for this project is shown above within the red box.

As its name suggests, the soil erodability factor (K) measures a soil's tendency towards erosion. It is derived from the texture, permeability, and organic content within

a soil (Roose 1996). The K factor is included with STATSGO soil data under the “Layer” Table. Each soil type in the STATSGO soil dataset is made up of various components in specified proportions, and each component contains soil layers in a stratigraphic order. For purposes of this study, only the K factors of the topmost layer were considered in analyses. Furthermore, rather than incorporating a K factor for each soil component (in some cases, there were as many as eight components to a soil type polygon), a weighted average of all K factors within a soil type was used to determine an average K value for each soil type. A raster dataset was then computed from the new  $K_{AVE}$  field.  $K_{AVE}$  was computed with the attribute field calculator using the following equation:

$$K_{AVE} = \sum_{i=1}^n \left( KFACT_i * \frac{COMPPCT_i}{100} \right), \text{ where}$$

$K_{AVE}$  = Weighted average of K Values for the topmost layers in each soil component

KFACT = K Value from STATSGO “Layer” Table

COMPPCT = Percentage of component that makes up a STATSGO soil type (From the “Comp” table in STATSGO)

$i$  = Component in a particular soil type (From the SEQNUM field in both the STATSGO “Comp “ and “Layer” tables

The slope length (L) and slope steepness (S) values of the RUSLE are determined by the length and gradient of the slope. They were considered together using the method outlined by Mitsova *et al.* (1999). In this method, specifically designed for use in GIS, L is derived from the upslope contributing area. This is accomplished by incorporating a flow accumulation grid into the topographic (LS) factor equation.

A flow accumulation grid is produced through a series of raster analyses in the GIS software. For this project, these raster analyses were performed using the ArcHydro extension. First, all sinks must be filled in the DEM. This function removes all inner

depressions from the DEM, such that all runoff will reach the edges (Maidment 2002). Unless there are large lakes in a DEM, this is generally a correct assumption. A flow direction grid is then generated using the filled DEM. The flow direction grid is a nearest-neighbor analysis that determines the direction of flow based on the assumption that water will flow in the direction of steepest descent (Maidment 2002). The flow accumulation grid then uses the flow direction grid to calculate the number of cells that drain into a given cell. The effect is values of 0 for relative topographic highs, and high values for stream channels (Figure 3). By multiplying this value by the spatial resolution (cell size), L in the RUSLE can be determined.

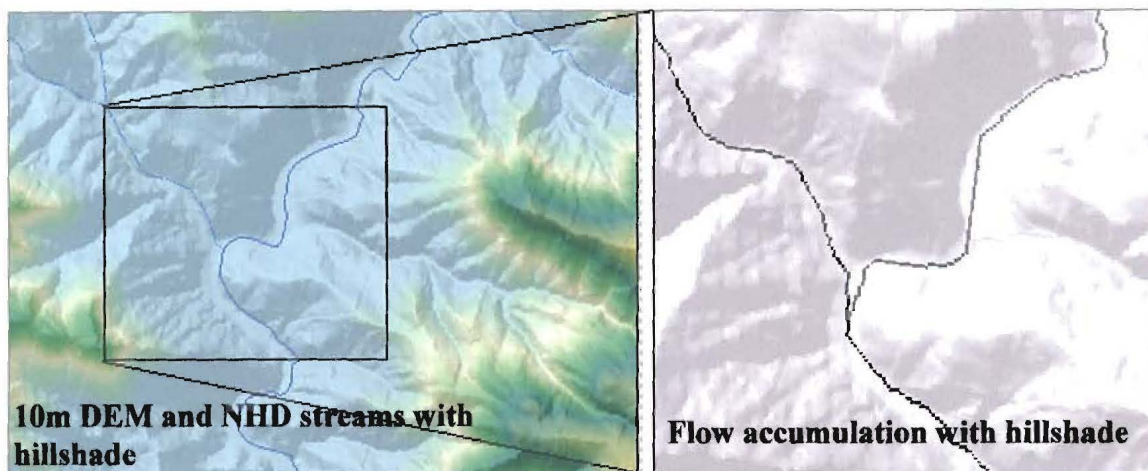


Figure 3. Flow Accumulation and Parent DEM. The flow accumulation grid at right was produced from the raw DEM at left. Notice the relationship between the NHD layer and the high value (dark) cells on the flow accumulation.

Mitasova *et al.* (1999) then divide the flow accumulation grid by the original parameters of the soil loss plots outlined by Wischmeier *et al.* (1978). Although the RUSLE is used for calculating sheet erosion, and not generally valid for gully erosion, this method of calculating the LS value simulates gully erosion in a useful manner. The output from the RUSLE using this method showed increased erosion in the stream channels due to the incorporation of the flow accumulation grid. The equation for the topographic factor as outlined by Mitasova *et al.* (1999) is:



$$LS_r = (m + 1) (A_r / a_0)^m (\sin [b_r / b_0])^n, \text{ where}$$

$LS_r$  = Topographic Factor at point (pixel) “r”

$A_r$  = Upslope Contributing Area at point “r” (flow accumulation \* resolution)

$b_r$  = Slope at point “r”

$a_0$  = Length of standard USLE plot (22.1 m)

$b_0$  = Slope of standard USLE plot (0.09)

$m$  = value determined by experiment (0.6 for slope length <100 m)

$n$  = value determined by experiment (1.3 for slope angles < 14°)

The vegetation cover factor (C) in the RUSLE is defined as a relationship between observed erosion on bare soil and erosion from vegetated plots. The values for the C Factor came from Roose (1996). He suggests values of 1/1000 for undisturbed forest, 1/100 for grasslands and 1 for bare soil. Using percent coverage of the vegetation types as given by the GES vegetation dataset, under normal conditions, the vegetation in the study area could be categorized as either undisturbed forest or grassland. Erosion control practices (P) remained equal to 1 for purposes of this model. This was because for the most part there were no implemented erosion control practices within the study area.

In order to calibrate the erosion model, the RUSLE was initially run to simulate natural undisturbed forest conditions. Roose (1996) estimated erosion in undisturbed forest or grassland to be somewhere between 0.01 and 1.5 tons per hectare per year (ton/ha/yr). Erosion values in the model ranged from 0 to 272 ton/ha/yr. Although these values seemed to fall well outside what was expected, careful examination suggested that this was not the case. The mean erosion within the study area was 0.14 ton/ha/yr. In addition, there were relatively few values above 5 ton/ha/yr, and all of these high values occur within channels, a product of using flow accumulation in the equation. The impact on average soil loss of these large erosion values is small due to the relatively low spatial



extent that they cover (Mitasova *et al.* 1999). Thus, unaffected by fires, roads, and grazing, the model results were close to those expected based upon the available literature (Appendix I-2).

The above analysis for undisturbed forest provided a base from which to expand the study. For simplicity, the study examines changes in erosion rate as a function of the RUSLE. The analyses for the three management issues of concern were constructed using the undisturbed forest scenario as a base. In addition, they were conducted individually and independently of each other. The results of their respective outputs were then compared to the results expected by the literature. In this way, the equations, and constants used in the individual analyses were judged to be appropriate and accurate.

The individual management analyses were initially run on three of the four watersheds within the study area, the Middle Fork Gila River, East Fork Gila River and West Fork Gila River watersheds (Figure 1). Upon achieving accurate results, the entire process was repeated on the fourth watershed, Corduroy Canyon, in order to validate the management analyses.

#### Road Analysis

Forest Service engineers divide roads within the National Forest System into four maintenance categories based on various characteristics. Class 1 denotes the least maintained roads, while class 4 denotes the most maintained. Class 4 roads are paved, generally well designed roads with structures that mitigate the effects of erosion in place. Class 3 roads are gravel roads with fewer drainage structures than in class 4 roads. Class 2 roads are native surface or gravel roads that are maintained. Class 1 roads are four-wheel drive roads or other roads that are not maintained by the Forest Service. These last

two road classes have few to no drainage structures in place, and are subject to road-wander after rains. For purposes of this study, trails were included in the least maintained (1) category.

The road analysis used the Forest Service Roads/Trails Layer. Using the available road data it is impossible to obtain the precision required for a detailed erosion analysis over such a broad area as the one used for this study. Surface type and maintenance category were the only variables used in this analysis. The primary assumption in this phase of the analysis was that all road classes would have the same impact on erosion, that of the “worst-case”, high traffic, native surface roads. However, the least maintained roads and trails would impact a larger area, while the more maintained roads are also better designed and, therefore, better drained, so their effects will be less widespread. Based on this assumption, the buffers around the different maintenance types had varying widths: 200 ft for types 1 and 2, 100 ft for type 3, and 50 ft for type 4.

<b>Road Maintenance Type</b>	<b>Impact Buffer Distance (ft)</b>	<b>Description</b>
1	200	Unmaintained roads or trails, few/no drainage structures in place
2	200	Native surface or gravel, infrequently maintained, few drainage structures in place
3	100	Paved or gravel, moderately well maintained, some drainage structures in place
4	50	Paved, well maintained, drainage structures in place, engineered to mitigate the effects of erosion

Table 2: Forest Service Road Maintenance Levels. Modified to include trails and impact buffer distance used in road analysis.

Upon converting these buffers into a raster format, a simple value scheme was applied. Areas outside the buffer were assigned a value of 1, and areas within the buffer, 1.25. These values were chosen to represent the effects of relative proximity to roads on

erosion. This simple system assumes that the erosion rate will increase by 25% within the buffer. This value was generated by running simulations on the Forest Service's WEPP: Road erosion prediction model (Figure 4), and comparing the results to the 5-year old (undisturbed) forest scenario in the WEPP: Disturbed model.

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### WEPP:Road WEPP Forest Road Erosion Predictor

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<b>Climate Station</b>		<b>Soil Texture</b>	
*BEAVERHEAD RS NM *FORT BAYARD NM *GLENWOOD NM *CLIFF 10 SE NM		clay loam silt loam sandy loam loam	
Custom Climate		Rock (%) 20	

<b>Road Design</b>		<b>Gradient (%)</b>	<b>Length (ft)</b>	<b>Width (ft)</b>
Insloped, bare ditch	<b>Road</b>	4	200	13
Insloped, vegetated or rock ditch	<b>Fill</b>	50	15	
Outsloped, rutted	<b>Buffer</b>	25	130	
Outsloped, unrutted				

Road surface: ☒ Native ☐ Graveled ☐ Paved  
 Traffic level: ☒ High ☐ Low ☐ None  
 Years to simulate: 5 (this may take several minutes)

Run WEPP

Figure. 4: WEPP: Road Model Interface. This model was used to determine a base erosion rate within the designated road buffers.

Four sets of five simulations were run on WEPP: Road, one for each soil texture. For each soil texture, road design, surface and traffic level were varied (Table 3). In the results for the worst-case scenario, that for rutted native surface (loam), erosion rates had increased to 0.58 ton/ha/yr, about 1.25 times that of undisturbed forest model results 0.15 ton/ha/yr. The factor of 1.25 was, therefore, entered into the RUSLE for all road buffers. Furthermore, a separate raster layer was created to show the impact of overlapping buffers. Where a single buffer occurred, a value of 1 was assigned. Where two or three

buffers overlapped, the values were changed to 2 and 3, respectively. The buffer value of 1.25 and the value of the new buffer coincidence layer were then multiplied by the undisturbed forest erosion rate.

Soil Type	Surface	Design	Traffic	Erosion Rate (lb/ac/yr)
Sandy Loam	Native	Insloped Veg/Rock Ditch	High	124
	Gravel			184
	Paved			234
	Native	Outsloped, Rutted	Low	165
				37
Loam	Native	Insloped Veg/Rock Ditch	High	367
	Gravel			233
	Paved			353
	Native	Outsloped, Rutted		520
		Outsloped, Unrutted	Low	53
Clay Loam	Native	Insloped Veg/Rock Ditch	High	324
	Gravel			169
	Paved			244
	Native	Outsloped, Rutted		439
		Outsloped, Unrutted	Low	35
Silt Loam	Native	Insloped Veg/Rock Ditch	High	349
	Gravel			277
	Paved			339
	Native	Outsloped, Rutted		458
		Outsloped, Unrutted	Low	51

Table 3: WEPP: Road Model Results. Highlighted iteration represents worst-case erosion scenario: High traffic rutted native surface road on loam soil.

Predictably, the results of the road analysis followed the results of the WEPP analysis. That is, within the road buffer, the mean erosion rate increased by nearly 27%. When viewing this change from the 1:250,000 scale on undisturbed forest, it seems insignificant. Indeed, mean erosion rate across the study area increased less than 0.01 ton/ha/yr from that of the undisturbed forest analysis. This was to be expected since the mean erosion rate in the undisturbed forest was 0.04 ton/ha/yr and the roads occupied a relatively small area. While this analysis showed only a marginal increase in average erosion rate across the study area, greater increases were expected for the combined analysis.

## Fire Analysis

The next management parameter to be considered was fire. The datasets used in this analysis are complete in terms of geometry. That is, geometry for almost all fires that occurred in the Southwest exists in this database whether or not the fire was fought. In nearly every other respect, the data are deficient. A field within the attribute tables denotes whether or not Burned Area Emergency Rehabilitation, (BAER), action took place, but not what those actions were. In addition, there is no mention of burn intensities or hydrophobicity. This made the fire analysis portion of the study fairly simplistic, but it met the needs for the overall goals of the study.

Analyses of fire data were conducted by year, since it was possible to burn one area in several different years. Each year from 1998 (the first year for which GIS data were available) to 2003 had its own set of two fire layers. One of these layers showed the geometry of the burned area, the other showed whether or not BAER action had taken place.

Before converting the fire data into a raster format, it was necessary to determine the effects of burned areas on erosion. As mentioned previously, burn intensities were not available in these data, so the base assumption was that each of the fires relevant to this study were moderate severity fires. From this information, it was possible to determine how fast erosion rates would return to their pre-fire levels. The year after a ponderosa pine wildfire, erosion rates have been observed to increase from near 0 ton/ha/yr before the fire to between 21 and 110 tons/ha/yr (Robichaud, 2000). In addition, for a moderate fire, Robichaud (2000) estimated a time frame of seven years until erosion rates return to normal.

After various trial and error attempts, on the first year after a fire, 2003, the erosion rate was increased by 64. This yielded erosion rates that averaged 28 – 35 ton/ha/yr per fire polygon. These figures tended to lie towards the low end of Robichaud's (2000) estimates, but were expected to increase during the combined analysis. Since erosion rates were expected to return to normal after seven years and observed recovery rates were logarithmic in nature, a base 2 scale was chosen for use as the model for erosion rate recovery after a fire (Table 4). For each year preceding 2003, the erosion rate went down by a factor of 2. The GIS data used in this study only went back to 1998, so the full seven year recovery period could not be shown.

Two rasters were created from the fire dataset: One for the year of the fire, and one for BAER action. The fire data were initially broken up by year. So starting from 2003, the year for which the study is valid, fire rasters were created for each of the five preceding years. These rasters were then reclassified based on their respective fire erosion factor listed in Table 4.

<b>Number of years after Fire</b>	<b>Fire Erosion Factor</b>
1	64
2	32
3	16
4	8
5	4
6	2
7	1 (Not Part of this Study)

Table 4: Fire Factor.

Since no detailed account of BAER action exists in the data, it was assumed that a BAER action would reduce the fire erosion factor by a factor of 2. This allowed BAER

to be considered in the model, despite the lack of detailed information. For BAER action, a simple value scheme was used: 1 for No BAER action and 2 for BAER action. All of the fire rasters were then divided by their respective BAER raster. The output was then reclassified and multiplied by the RUSLE.

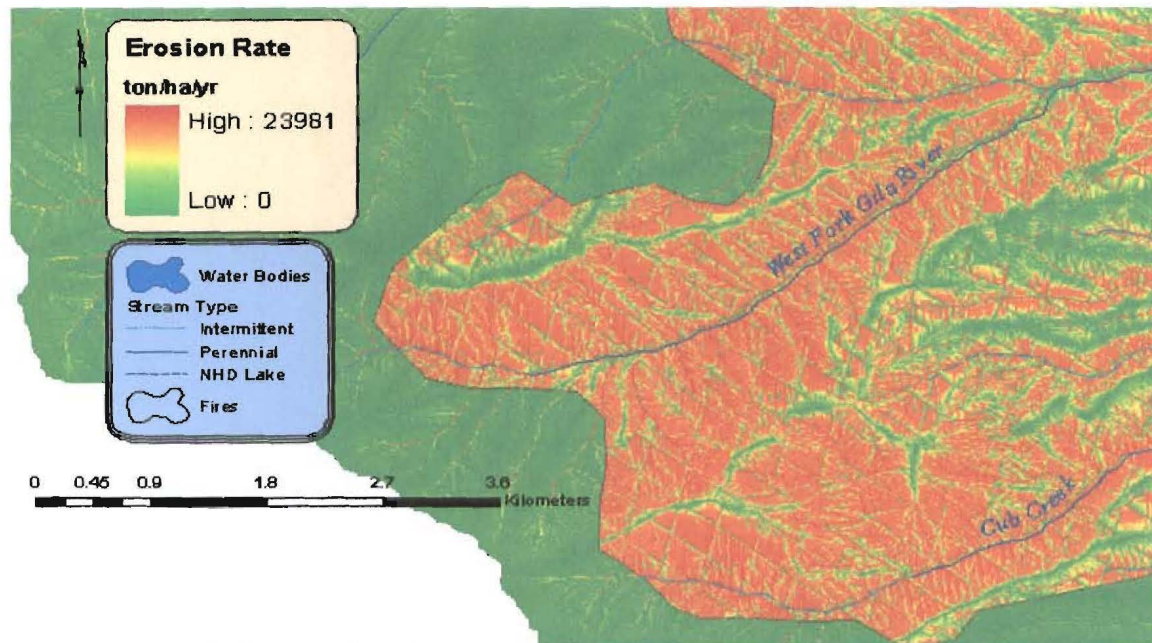


Figure 5: Sample of Fire Analysis. This area is located in the Gila Wilderness at the western edge of watershed 1504000105 at the headwaters of the West Fork Gila River (Figure1).

The results of the fire analysis showed a marked increase in erosion across the study area with erosion rates running from 0 to about 24,000 tons/ha/yr (Figure 5, Appendix I-4). The mean had increased significantly from the undisturbed forest scenario to 4.1 tons/ha/yr. Within the entire fire area the average erosion rate was 20 tons/ha/yr, which falls near the low end of Robichaud's (2000) estimates for post-fire erosion. As with the roads analysis, these values were expected to increase during the combined analysis.

#### Grazing Analysis

The Forest Service grazing allotment dataset was by far the most extensive and complete. Relating the spatial data to the INFRA data, provided a detailed spatial

accounting of numbers of animals and rotation schedules for forest service grazing allotments. In addition, by using the stream and slope layers, the model was able to generate a detailed picture of the most likely grazing areas.

The base assumption for the grazing analysis was that for a 50% reduction in the available forage, erosion rates will return to normal after a period of 3 years if left ungrazed. By means of this assumption, the available forage in an allotment increased by 1.26 every year. This is based on an over estimation of the Forest Service guidelines that specify only 30% - 40% of available forage should ever be removed in one year, and also assumes healthy grazing land on the allotments prior to the establishment of a grazing rotation. No data, other than geometry, for individual pastures within allotments was available, therefore, no smaller divisions were considered to exist within grazing allotments. This meant that the model did not account for grazing rotation patterns within an allotment; therefore, the grazing impacts on erosion were spread across the entire area. In addition, because the study area also contained state and private land, certain assumptions and statistics were made for the different ownership, which will be discussed later.

As with the fire data, the allotment analyses were broken up by year for vector analysis and combined in the raster analysis. Because of the base assumption, only four years were considered in this study: 2000 – 2003. For each year, the total number of Animal Unit Months (AUMs) was calculated for each allotment. For the purpose of this analysis, the Forest Service definition of an Animal Unit Month was used. Thus, 1000 lb of forage were required to sustain a 1000 lb cow for 1 month. This base AUM was then modified by the animal type as designated by the Forest Service using what is called an



AU- Factor (Table 5). This provided an accurate assessment of forage removed from an allotment based on number and type of animal and length of time grazed.

<b><u>Class</u></b>	<b><u>AU-Factor</u></b>
Mature Cow	1.00
Mature cow w/nursing calf	1.32
Yearling (9-18 months)	0.70
Weaner calf	0.50
Bull	1.50
Mature sheep or goat	0.20
Ewe w/lamb or nanny w/kid	0.30
Horse or mule	1.20
Swine	0.50
Bison	1.00
Burro, pony, or donkey	0.60

Table 5: List of AU-Factors. FSH 2209.15 – Range Management Annual Reports Handbook.

Furthermore, experiments using test plots and simulated rainfall in New Mexico have demonstrated standing biomass to be around 1550 kg/ha in an ungrazed pasture (Catlin, *et al.* 2003). Using this as a conversion factor for AUMs, the model can then approximate the amount of biomass removed by grazing. Since the removal of biomass relates directly to the removal of vegetation cover, the impact of grazing on erosion can be determined as a function of biomass removed.

To determine the amount of biomass removal per year, Catlin and others (2003) were again consulted. Using their assumptions for suitable grazing land, the model divides grazing allotments into areas most likely to be grazed based on slope and distance from surface water. By this method, areas within 300 ft of surface water and less than 60% slope were weighted higher for grazing potential. Catlin *et al.* (2003) assume a 100% reduction in grazing capacity for areas > 60% slope, and those further than 2 miles from water. The current model was more liberal when considering distance from water. Areas further than 1 mile from surface water and those with > 60% slope were considered to have negligible grazing potential.

When all of the above were combined, the process was as follows. The GIS grazing dataset was related to the INFRA tabular data. In this way, AUMs, AU- Factors, total areas of allotments, and dates of permitted grazing were incorporated into the spatial data. The spatial data were then divided into separate raster layers based on the year grazed. Each year contained two raster layers: one for total AUMs per allotment, and one for total area of the allotment in hectares. In a separate analysis, 300 ft buffers of streams were rasterized and combined to a reclassification of slope less than 60%. The resulting layer, was weighted 40 for areas < 60% slope within 1 mile of surface water, 60 for within 300 ft of watercourses, 100 for both and 0 for neither.

No grazing data were available for private and state land. Rather than excluding this fairly sizable area, approximately 5 - 6% of the total area, from the grazing analysis (Appendix I-1), assumptions were made to account for grazing in these areas. For state land it was assumed that no grazing took place. For private land, an assumption was made for total AUMs in these areas. By this assumption, for every year of the study half the maximum supportable AUMs per hectare were assumed to have grazed. To compute this value, the following equation was used:

$$\#AUMs = 0.5 * \left( \frac{Hectares * 637 kg/ha}{453.59 kg} \right), \text{ where:}$$

#AUMs = Maximum supportable Animal Unit Months

Hectares = Total area of parcel (from Attribute Table)

637 kg/ha = Average standing biomass in a grazed pasture (Catlin, *et al.* 2003)

453.59 kg = 1000 lbs of forage to sustain 1 AUM

These layers were then combined sequentially starting with the first year in the grazing analysis, in this case, 2000. In the first year, a raster layer of initial biomass was used to determine initial condition of the allotment. For BLM, state and private land,

50% biomass was assumed to be present. For grazing allotments on the national forest, 75% biomass and for ungrazed land on the national forest, 100% biomass. The initial biomass layer was only used in the first year calculation. The first calculation was used to determine the biomass remaining after one year of grazing. For each of the four years in the study, the following analyses were run.

$$BM_r = 100 * \frac{[(A_t * 1550 * BM_o / 100) - (AUMs * 453.59)]}{(A_t * 1550)}, \text{ where:}$$

$BM_r$  = % Biomass remaining after grazing for 1 year

$A_t$  = Total area (in hectares) of the grazing allotment

$BM_o$  = % Initial biomass described above. In the succeeding years, this value was replaced by the calculated biomass regeneration value (explained below).

$AUMs$  = Total number of Animal Unit Months in the grazing year

1550 kg/ha = Average standing biomass in an ungrazed pasture (Catlin, *et al.* 2003)

453.59 kg = 1000 lbs of forage to sustain 1 AUM

The output from this equation required some reclassification in order to be incorporated into the following analyses. It was also modified by the layer created earlier, which defined the likelihood of being grazed based on slope and proximity to water. Once this was accomplished,  $BM_r$  for each year could be used to calculate biomass regeneration each successive year. Using the base assumption that available forage will increase by 1.26 every year,  $BM_r$  was modified to include the percent biomass regenerated in the growing season. The regenerated biomass was modified to remove values greater than 100 %, and then incorporated into the Remaining Biomass equation for the next year. This process was repeated until the year of relevancy of the study, 2003, was reached. In this way the cumulative effects of grazing and biomass regeneration could be represented in the model results.  $BM_r$  for 2003 was then subtracted from 101 and the difference multiplied by the erosion rates grid for the undisturbed forest scenario.

The result generated by the grazing analysis followed erosion values seen in the literature (Figure 6, Appendix I-5). The mean erosion value across the study area was 0.45 ton/ha/yr. However, for the most heavily grazed allotment, excluding private land, the mean was about 1.3 ton/ha/yr, generally, with the highest erosion rates occurring in areas within 300 ft of watercourses and having less than 60 % slope. Even within these buffers, mean erosion rates only reached 5.6 ton/ha/yr, which was well below the 9 ton/ha/yr maximum allowed by the forest service on grazing allotments.

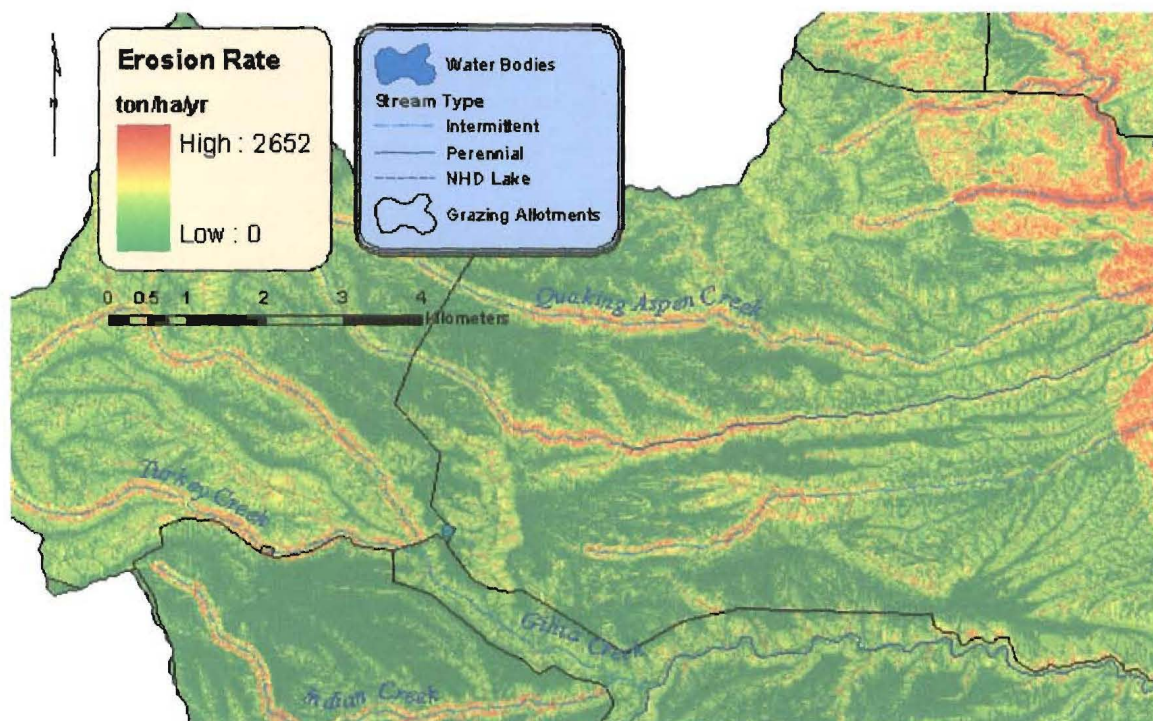


Figure 6: Sample of Grazing Analysis. This area is located at the western edge of watershed 1504000103 at the headwaters of Gilita Creek (Figure1).

### Combined Analysis

Once the independent management analyses were determined to be reasonably accurate when compared to the literature, they were combined. The resulting layer incorporated all three management issues into the undisturbed forest analysis. This new “combined” equation was:

$$\text{Erosion}_c = \text{Erosion}_u * [(\text{Fire} + (101 - \text{BM}_i)) * \text{Road Buffer} * \text{Road Coincidence}], \text{ where}$$



$Erosion_c$  = Erosion layer affected by all three relevant management issues  
 $Erosion_u$  = Erosion layer for undisturbed forest  
 Fire = Fire layer (Summed Fire Factor described above)  
 $BM_r$  = Biomass remaining after the forth consecutive grazing year (described above)  
 Road Buffer = 58 within buffer, 1 outside buffer  
 Road Coincidence = 1 for one or no buffer, 2 for two coincident buffers, 3 for three coincident buffers

Across the study area, values ranged from 0 to about 25,000 ton/ha/yr, with relatively few cells above 50 ton/ha/yr. The mean erosion rate for the combined analysis rose to 4.5 ton/ha/yr. Contrary to what was expected, roads appeared to have a marginal impact even when located within grazing and fire polygons (Figure 7, Appendix I-7). Grazing played a major role in increasing erosion along NHD watercourses, and this effect was predictably compounded within fire polygons.

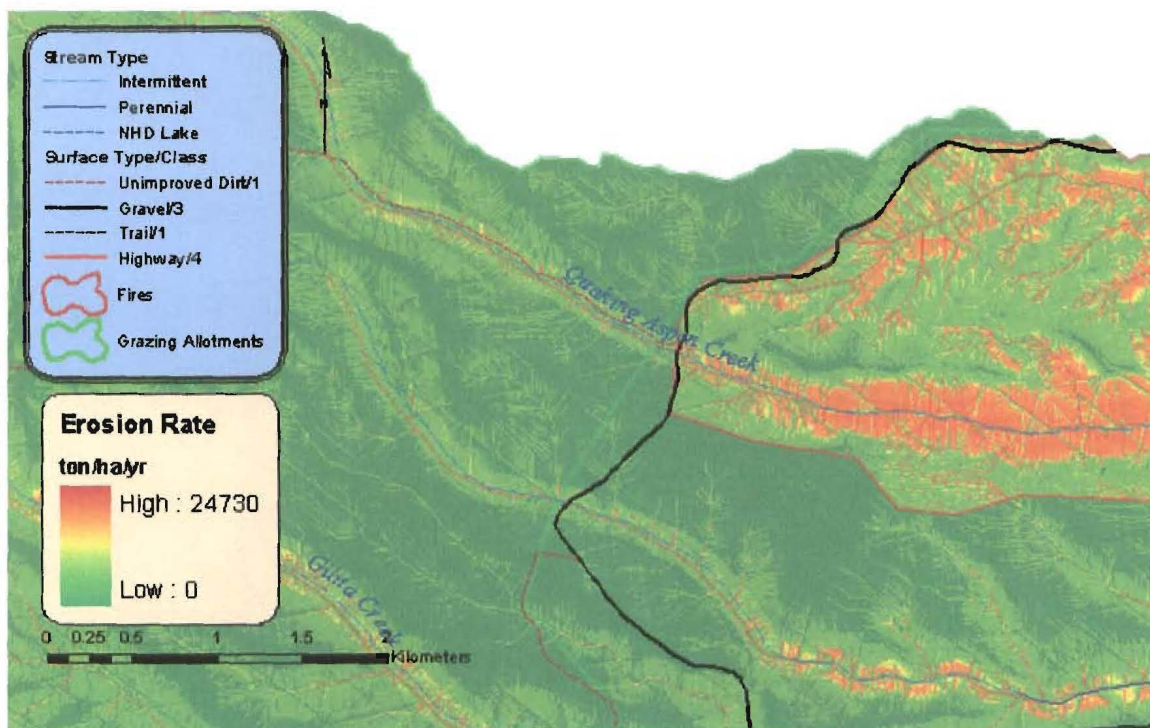


Figure 7: Sample of the Combined Analysis. This area is located on the T Bar allotment at the western edge of watershed 1504000103 near the headwaters of Gilita and Quaking Aspen Creeks (Figure 1).

To validate the model, the analyses detailed above were then repeated on the last watershed, HUC number 1504000102. The results of this analysis were comparable to

those achieved for the first three watersheds (Table 6). The only real disparities occurred with the fire history and grazing results. In the case of fire history, the burned areas were relatively small in HUC 1504000102, and the fires occurred in the years 2000 and 2001. Due to the method of determining burned area erosion recovery, these results were not unexpected. For grazing, the offset appears to come from private land, and the assumptions for determining total AUMs. This too was not unexpected. The model appeared to carry over to the last watershed well. The successful completion of this test demonstrated the validity of the model.

Management Analyses	Mean Erosion Rates for first three watersheds (ton/ha/yr)	Mean Erosion Rates for watershed: 1504000102 (ton/ha/yr)
Undisturbed Forest	0.14	0.11
Roads (within buffer)	0.14	0.11
Fire (within polygons)	20	8.9
Grazing (including private/state land)	0.45	2.45
Grazing (not including private/state lands)	0.45	0.33
Combined (including private/state lands)	4.51	3.33

Table 6: Validation. Comparison of mean erosion rates between watersheds 15040001 (03, 04, and 05) and watershed 1504000102.

At this point, it became necessary to compare the results of the model to the NMED impaired waters data. Turbidity, conductivity, and bottom deposits are the parameters of concern when looking at the New Mexico Impaired Waters Dataset for this part of the State. By using the streams within the study area that failed to meet these standards as guides, the combined analysis could be calibrated. Chapter 20.6.4 (Figures 8 and 9) of the New Mexico Administrative Code (NMAC), shows the water quality standards for various reaches within the Gila River Watershed.

<b>20.6.4.12</b>	<b>GENERAL STANDARDS:</b> General standards are established to sustain and protect existing or attainable uses of surface waters of the state. These general standards apply to all surface waters of the state at all times, unless a specified standard is provided elsewhere in this part. Surface waters of the state shall be free of any water contaminant in such quantity and of such duration as may with reasonable probability injure human health, animal or plant life or property, or unreasonably interfere with the public welfare or the use of property. When changes in dissolved oxygen, temperature, dissolved solids, sediment or turbidity in a water of the state is attributable to natural causes or the reasonable operation of irrigation and flood control facilities that are not subject to federal or state water pollution control permitting, numerical standards for temperature, dissolved solids content, dissolved oxygen, sediment or turbidity adopted under the Water Quality Act do not apply. The foregoing provision does not include major reconstruction of storage dams or diversion dams except for emergency actions necessary to protect health and safety of the public, or discharges from municipal separate storm sewers.
<b>A.</b>	<b>Bottom Deposits:</b> Surface waters of the state shall be free of contaminants from other than natural causes that will settle and damage or impair the normal growth, function, or reproduction of aquatic life or significantly alter the physical or chemical properties of the bottom.

Figure 8: General Standards for Surface Water Quality in New Mexico. NMAC 20.6.4.12.

<b>20.6.4.503</b>	<b>GILA RIVER BASIN – The main stem of the Gila river from Gila hot springs upstream to the headwaters and all perennial tributaries to the Gila river at or above the town of Cliff.</b>
<b>A.</b>	<b>Designated Uses:</b> domestic water supply, high quality coldwater fishery, irrigation, livestock watering, wildlife habitat, and secondary contact.
<b>B.</b>	<b>Standards:</b>
<b>(1)</b>	In any single sample: conductivity shall not exceed 300 µmhos for the main stem of the Gila river above Gila hot springs and 400 µmhos for other reaches, pH shall be within the range of 6.6 to 8.8, temperature shall not exceed 20°C (68°F) except in the east fork of the Gila river and Sapillo creek below Lake Roberts where the temperature shall not exceed 32.2°C (90°F), and turbidity shall not exceed 10 NTU. The use-specific numeric standards set forth in 20.6.4.900 NMAC are applicable to the designated uses listed above in Subsection A of this section.
	The monthly geometric mean of fecal coliform bacteria shall not exceed 100/100 mL; no single sample shall exceed 200/100 mL (see Subsection B of 20.6.4.13 NMAC). [20.6.4.503 NMAC – Rp 20 NMAC 6.1.2503, 10-12-00]
<b>20.6.4.504</b>	<b>GILA RIVER BASIN – Wall lake, Lake Roberts, Bear Canyon lake and Snow lake.</b>
<b>A.</b>	<b>Designated Uses:</b> coldwater fishery, irrigation, livestock watering, wildlife habitat, and secondary contact.
<b>B.</b>	<b>Standards:</b>
<b>(1)</b>	In any single sample: conductivity shall not exceed 300 µmhos, pH shall be within the range of 6.6 to 8.8, temperature shall not exceed 22°C (72°F). The use-specific numeric standards set forth in 20.6.4.900 NMAC are applicable to the designated uses listed above in Subsection A of this section.
<b>(2)</b>	The monthly geometric mean of fecal coliform bacteria shall not exceed 200/100 mL; no single sample shall exceed 400/100 mL (see Subsection B of 20.6.4.13 NMAC). [20.6.4.504 NMAC – Rp 20 NMAC 6.1.2504, 10-12-00]

Figure 9: Use Designation and Standards for Basins in New Mexico. NMAC 20.6.4.500.

The impaired waters data contained information about the year sampled and parameters that were found to be outside the standards set forth above. For the study area as a whole, there were nine impaired water bodies (Figure 10). Seven of these failed to



meet the standards for turbidity, conductivity or bottom deposits set by the NMAC. In order to discover how the model compared to these sampling data, two different approaches were taken.

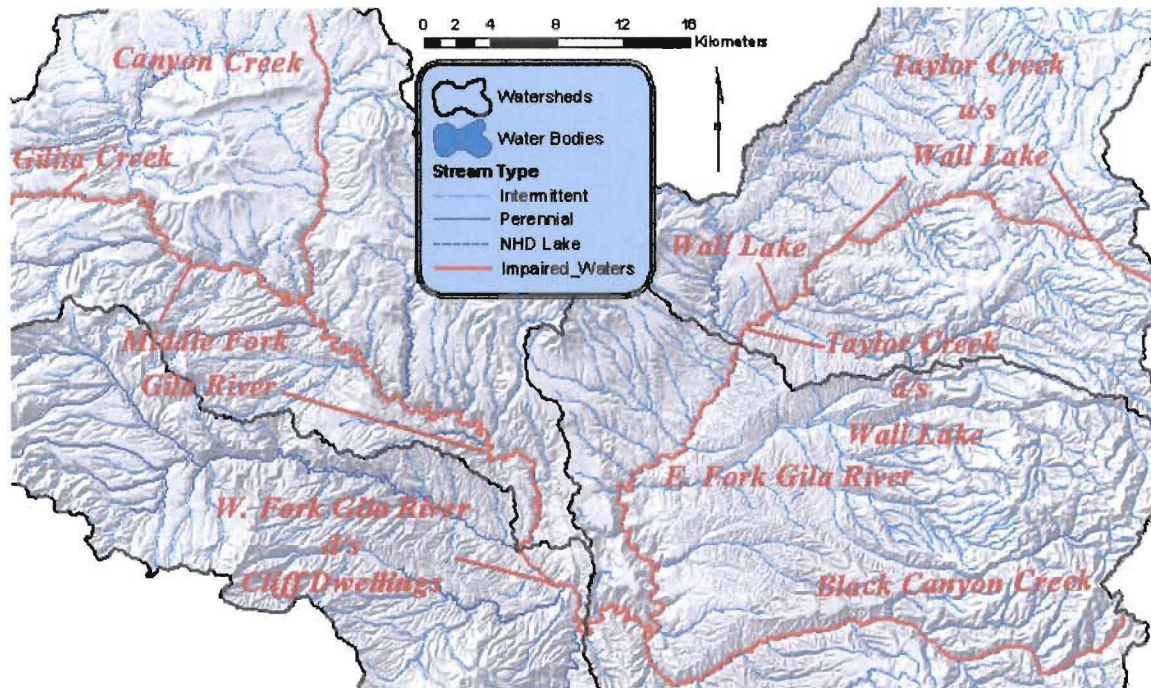


Figure 10: Distribution of Impaired Waters Within Study Area. Only the West and Middle Forks of the Gila River are not impaired by sediment.

In the first method, catchments were derived from the NED datasets using ArcHydro. By clipping both the undisturbed forest erosion and the combined erosion results to the catchments for the impaired streams, the effects of modeled erosion could be compared to actual samples. This was done for each impaired stream, even those where turbidity, conductivity, and bottom deposits were within the state standards. The potential problem with this method was that within each catchment, there are areas where the erosion rate did not significantly change. These values, if they occur in a large enough area, could affect the average erosion rate within a catchment.

Across each clipped catchment, the comparison yielded no apparent relationship between model results and impaired waters. All catchments showed an increase in



average erosion rate of at least 100%. Among those catchments that showed the highest increases according to the model results was the Middle Fork Gila River, which is not impaired by sediment. In this catchment, erosion rates went from 0.06 ton/ha/yr in the undisturbed forest to 0.71 ton/ha/yr in the combined analysis, an increase of over 1000%, yet still not above the high value expected for an undisturbed forest, 1.5 ton/ha/yr (Roose 1996). This information stands in stark contrast to the Black Canyon Creek, Wall Lake, and the reach of Taylor Creek upstream of Wall Lake, which are impaired by sediment. In each of these cases, the mean erosion rate showed a negligible increase.

These results did not provide enough information upon which to base a relationship between the model results and the impaired waters dataset. It therefore became necessary to approach the problem a different way. Visual inspection of the individual catchments showed that much of the area is not impacted by the combined analysis. The management issues considered in this model impacted areas immediately surrounding watercourses the most. The reasons for watercourse impact are two-fold. The LS factor of the RUSLE used in the model incorporates flow accumulation and a 300-foot buffer denoting the most suitable grazing land was applied to all watercourses as part of the grazing analysis.

The above process was repeated using the model results for the undisturbed forest and the combined analysis clipped to the same 300 foot buffer used in the grazing analysis. Table 7 contains the results of this new iteration compared to the results from the catchments analysis. In almost all instances of sediment impaired watercourses, erosion rate increased by at least 100% from the undisturbed forest scenario. Unfortunately, the same is true of the Middle Fork Gila River, one of the two

watercourses unimpaired by sediment, which maintained an increase of about 1000%. Also, as before, Wall Lake and the reach of Taylor Creek downstream of Wall Lake, showed negligible increases. Also, only on Canyon Creek in either analysis did the mean erosion rate rise above 1.5 ton/ha/yr, the maximum estimate for an undisturbed forest. While a clearer picture emerged from this step, there was still not enough information to formulate a relationship between the model results and the NMED impaired waters data.

Impaired Stream	Mean Erosion Rate in tons/ha/yr			
	<i>Catchments</i>		<i>300ft Buffer</i>	
	Undisturbed Forest	Combined Analysis (% increase in erosion)	Undisturbed Forest	Combined Analysis (% increase in erosion)
West Fork Gila River (NS)	0.081	0.081 (0)	0.09	0.10 (10)
Canyon Creek (S)	0.20	14.00 (6900)	0.64	43.03 (7070)
Black Canyon (S)	0.05	0.05 (0)	0.11	0.21 (100)
Gilita Creek (S)	0.07	0.10 (40)	0.21	0.41 (100)
East Fork Gila River (S)	0.06	0.08 (30)	0.23	0.43 (100)
Middle Fork Gila River (NS)	0.06	0.71 (1070)	0.10	1.10 (1000)
Wall Lake (S)	0.02	0.02 (0)	0.02	0.03 (50)
Taylor Creek D/S Wall Lake (S)	0.02	0.02 (0)	0.04	0.08 (100)
Taylor Creek U/S Wall Lake (S)	0.02	0.04 (100)	0.07	0.08 (10)

Table 7: Results of Catchment and Buffer Analysis. S = Impaired by sediment, NS = Not impaired by sediment.

The second failure to produce a relationship between impaired waters and the model results prompted a rethinking of some of the analyses. In both cases outlined above, the Middle Fork Gila River and Wall Lake proved problematic. Each was examined in turn to determine and correct the probable causes for the mismatch.

Figure 11 shows the test catchments and buffers for the Middle Fork Gila River overlaying the combined analysis grid. Visual analysis suggested that fires in the upper portion of the catchment are affecting the average erosion rate in both the catchment and buffer analyses. Clipping the buffer based on a buffer some distance from impaired streams could conceivably reduce the effects of high value cells far from the channel.

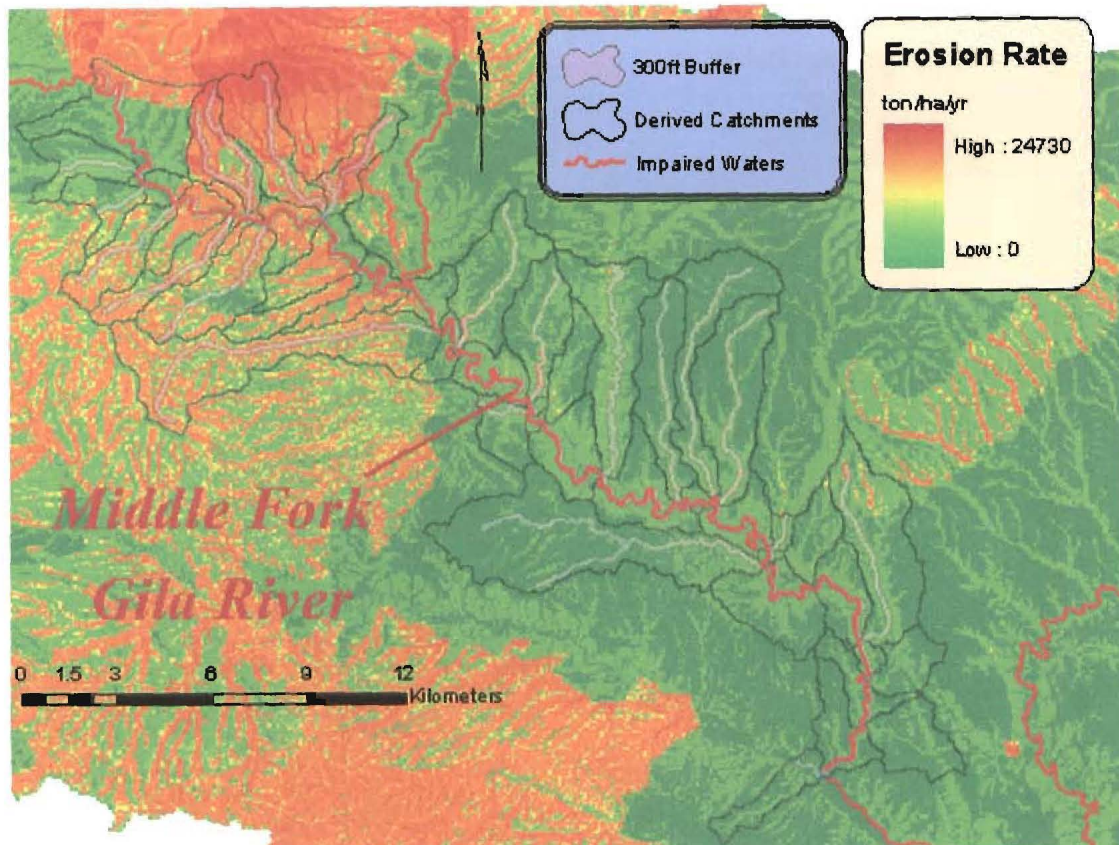


Figure 11: Analysis of Middle Fork Gila River.

A similar analysis of Wall Lake revealed a different set of conclusions, which can be seen in Figure 12. Most notably, the road analysis obviously should have impacted the lake more than it did. Gravel roads and trails flank the lake and its associated buffer. Also, the catchments around Wall Lake lie almost entirely within a grazing allotment. In order to see any impairment in Wall Lake, changes in both the road and grazing analyses were required.

In an attempt to produce a relationship between the NMED samples and the model results, both the road and grazing analysis were repeated, with some modification, and then reincorporated into the combined analysis. The object of these modifications was to produce a greater impact from roads and grazing. Once the new combined analysis produced results, a modified buffer analysis was run.

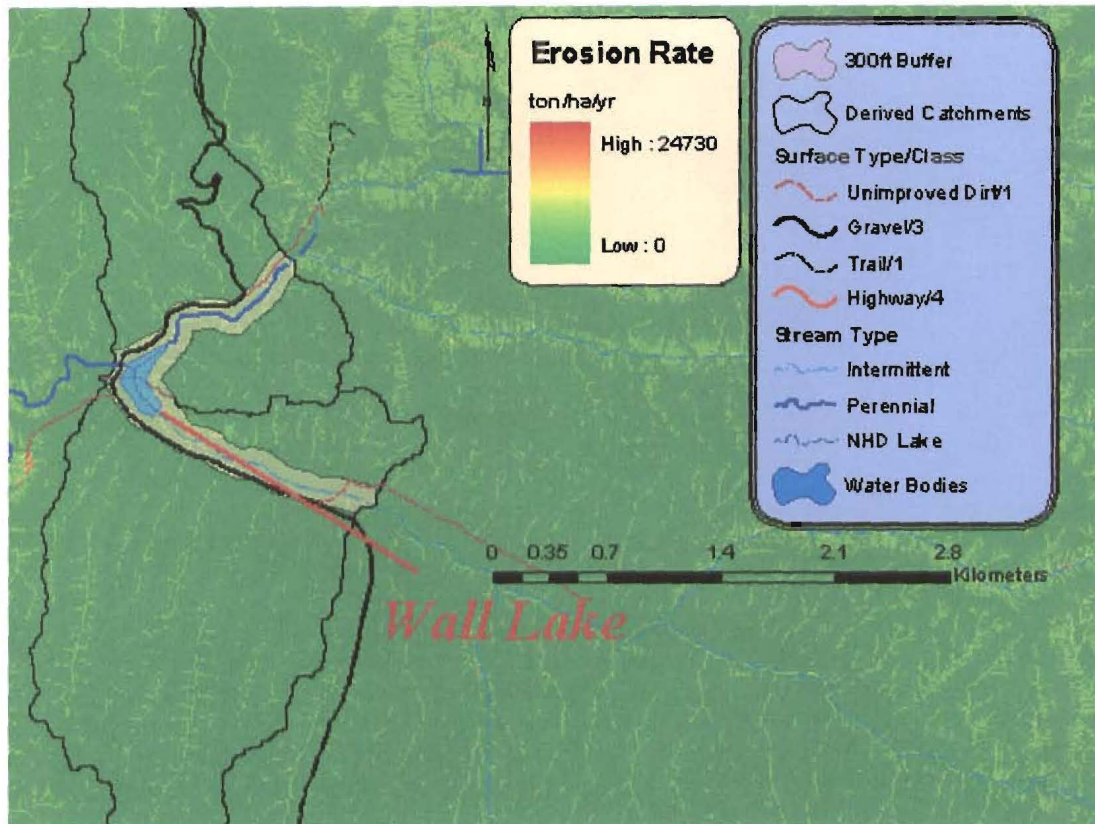


Figure 12: Analysis of Wall Lake.

To increase the impact from the roads analysis, the 1.25 value within the road buffer was assigned a value of 58. This new value was based on the worst-case scenario generated previously on the WEPP: Road erosion prediction model (Table 3). This value was then compared to the results to the low end of Roose's (1996) estimates of erosion rates in an undisturbed forest, 0.01 ton/ha/yr. This set the WEPP: Road results in the context of the lowest possible undisturbed forest erosion rates. This system assumed that the erosion rate would increase 58 times within the buffer.

The results of the new road analysis showed a significant impact on erosion (Figure 13). The mean erosion rate across the study area increased to 0.41 ton/ha/yr while the maximum increased to 5723 ton/ha/yr. This was a considerable change from the original road analysis where both of these values were virtually equal for the road analysis and undisturbed forest analysis. Also, within the road buffer, the mean erosion



rate had increased to 4.9 ton/ha/yr. This amounted to approximately 50 times the value for the same area in the undisturbed forest scenario.

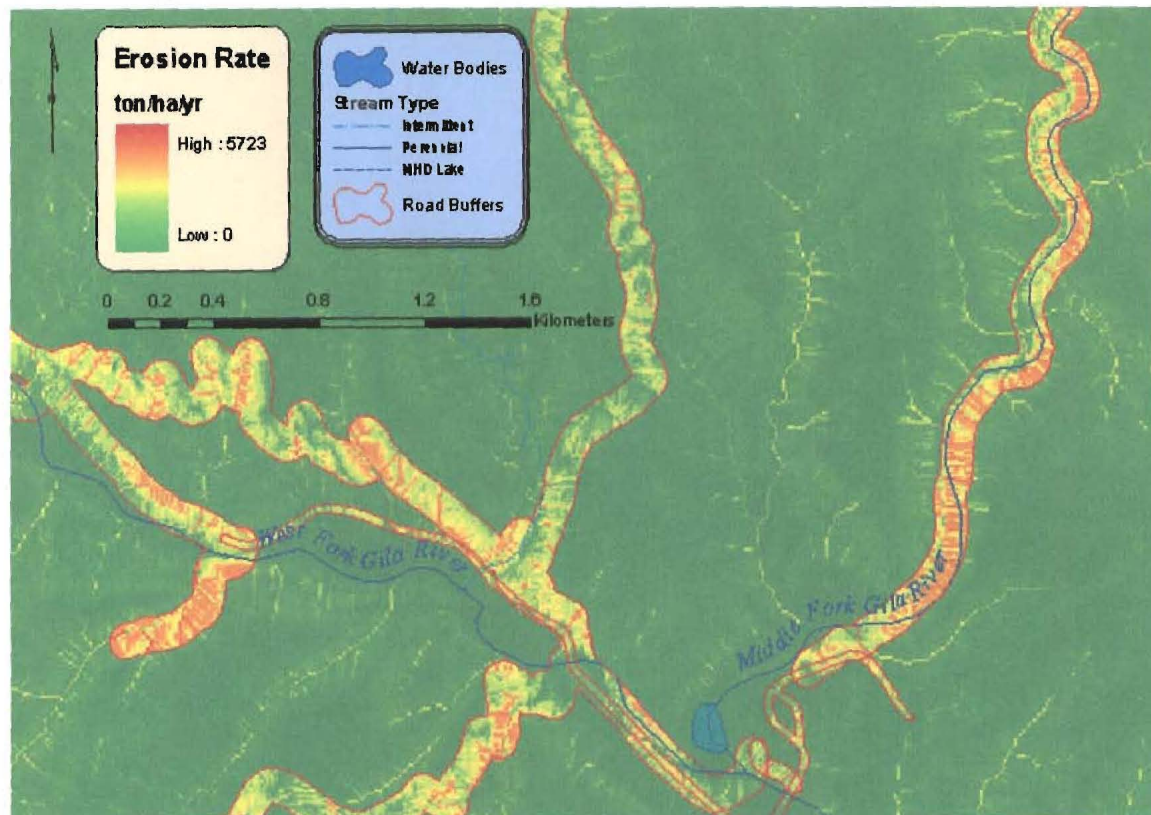


Figure 13: Sample of 2<sup>nd</sup> Road Analysis. This area is located at the northeast edge of watershed 1504000105 at the confluence of the West Fork and Middle Fork Gila Rivers (Figure1).

The most obvious factor contributing to a reduced grazing impact was allotment area. The areas used in computing the biomass remaining after the grazing year were too large to allow for accurate determination of grazing impact. To mitigate this, the allotments were sub-divided into buffers based loosely on the criteria for grazing capacity set forth by Catlin and others (2003). A 1-mile buffer was created around perennial streams and lakes and unioned with the existing 300 ft buffer. The total area of this buffer within grazing allotments became the basis for which animal impact was determined. In some allotments, this procedure reduced the total grazing area by as much as 95 %. The grazing analysis was then repeated with only one change: The new

area value was substituted for total area of the allotment ( $A_t$ ) in the  $BM_r$  equation presented above:

$$BM_r = 100 * \frac{[(A_t * 1550 * BM_o / 100) - (AUMs * 453.59)]}{(A_t * 1550)}, \text{ where:}$$

$BM_r$  = % Biomass remaining after grazing for 1 year

$A_t$  = Total area within buffers (in hectares) for each grazing allotment

$BM_o$  = % Initial biomass described above. In the succeeding years, this value was replaced by the calculated biomass regeneration value (explained below).

AUMs = Total number of Animal Unit Months in the grazing year

1550 kg/ha = Average standing biomass in an ungrazed pasture (Catlin, *et al.* 2003)

453.59 kg = 1000 lbs of forage to sustain 1 AUM

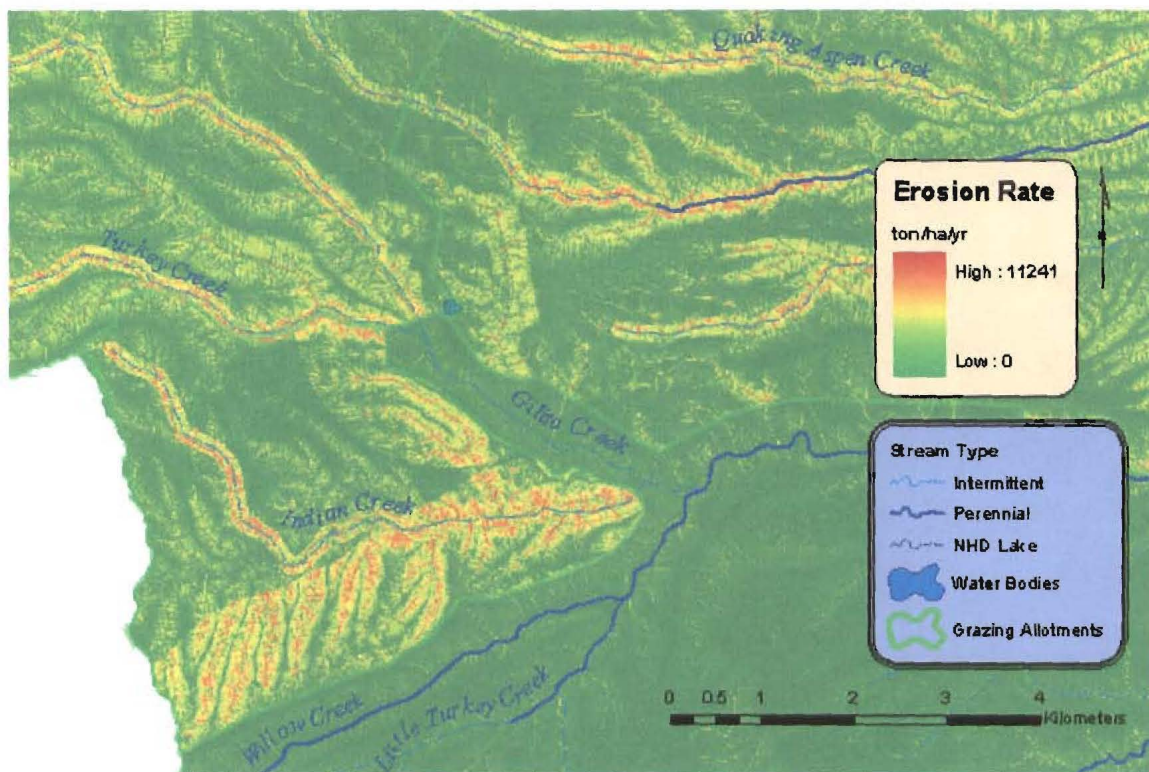


Figure 14: Sample of 2<sup>nd</sup> Grazing Analysis. This area is located at the western edge of watershed 1504000103 near the headwaters of Gilita Creek (Figures 1 and 6).

A visual comparison of Figures 14 and 6 revealed much about this new grazing analysis. The allotment line above Willow and Gilita Creeks marked the boundary between grazed and ungrazed forest land. This boundary was difficult to determine with the old grazing analysis, but became clearly visible in the new iteration. A look at the



data itself was even more telling. As expected, The mean erosion rate across the study area increased to 1.3 ton/ha/yr, up almost a full order of magnitude from the first grazing analysis.

The combined analysis was then recomputed using these new grids. A major weakness in the combined equation was exposed during this second run. Especially high values were produced due to the nature of the road buffer and how it was applied. Every cell value within the buffer was increased at least 58 times. To mitigate this, a theoretical cap was placed on the combined analysis. The total value of  $[(\text{Fire} + (101 - \text{BM}_i)) * \text{Road Buffer} * \text{Road Coincidence}]$  could not exceed 100. This value was derived using Roose's (1996) high estimate for erosion in an undisturbed forest. If this model were applied to an area with 1.5 ton/ha/yr, the Roose's (1996) high estimate, the maximum erosion rate resulting would be 150 ton/ha/yr.

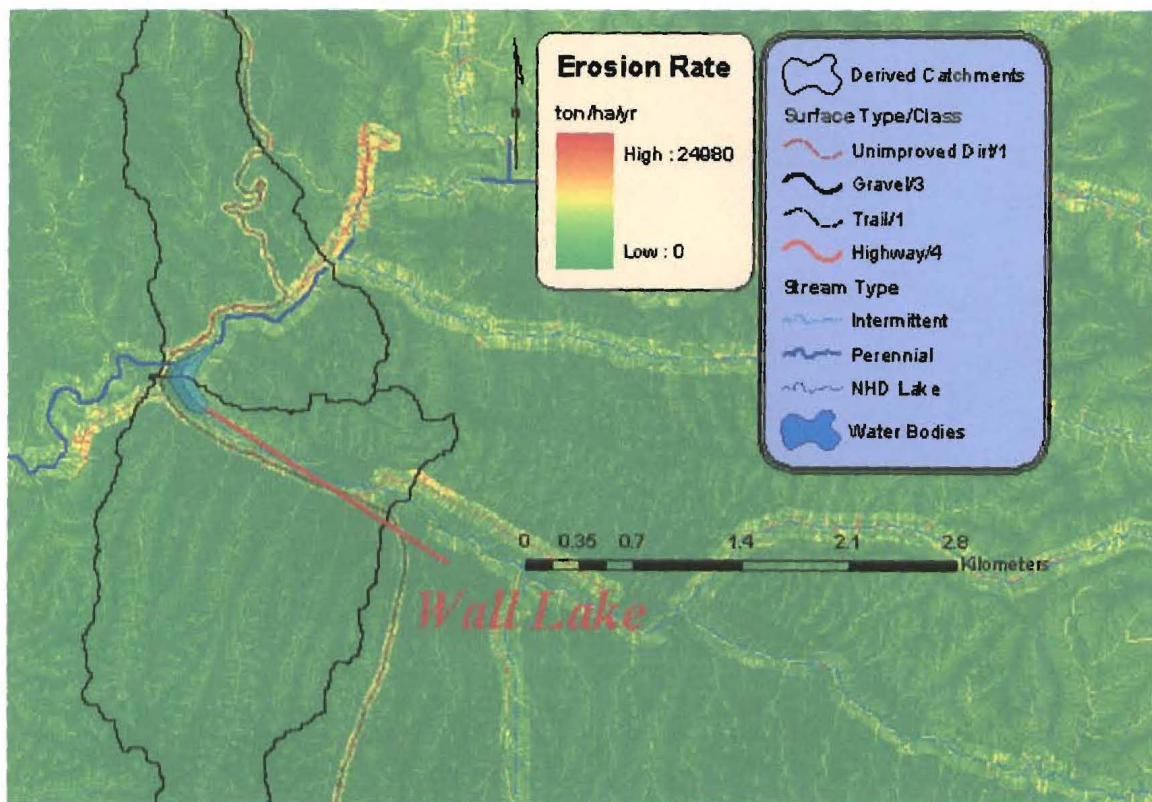


Figure 15: Sample of 2<sup>nd</sup> Combined Analysis.

Visual comparison of Figures 15 and 12 revealed a marked increase in the impact of roads on erosion. The same cannot be said of the grazing analysis. While there was some visible increase in erosion rate around the NHD stream layer, there was little noticeable impact anywhere else. This could have been a product of the biomass recovery rate incorporated into the model. The grazing allotment pictured in Figures 15 and 12 was heavily grazed in 2000. This meant that the erosion impacts of this grazing could have recovered by 2003 according to the model. Despite this, the results of the new combined analysis showed a marked increase in erosion rates across the study area. While the range showed an increase of a little less than 200, the mean erosion rate had increased to 5.2 ton/ha/yr.

In order to compare the new model results with the impaired streams dataset, the 300 ft buffers used in the grazing analysis were clipped to a 1 km buffer. Unfortunately, the pattern that seemed to be emerging in the first model results, no longer held true (Table 8). The new road and grazing analyses brought up the mean erosion rate values for Wall Lake, but also served to increase the erosion rates for the two streams that were

Impaired Stream	Mean Erosion Rate in tons/ha/yr			
	<i>300 ft Buffer (Unweighted)</i>		<i>300ft Buffer (Weighted)</i>	
	Undisturbed Forest	Combined Analysis (Factor of increase in erosion)	Undisturbed Forest	Combined Analysis (Factor of increase in erosion)
West Fork Gila River (NS)	0.11	2.10 (18)	0.07	1.61 (22)
Canyon Creek (S)	0.94	76.69 (80.5)	0.66	58.27 (87.5)
Black Canyon (S)	0.16	3.92 (23.5)	0.13	3.59 (26.5)
Gilita Creek (S)	0.22	8.29 (36.5)	0.21	7.66 (35.5)
East Fork Gila River (S)	0.10	1.79 (17)	0.09	1.59 (16.5)
Middle Fork Gila River (NS)	0.23	5.53 (23)	0.18	4.79 (25.5)
Wall Lake (S)	0.22	5.38 (23.5)	0.17	4.66 (26.5)
Taylor Creek D/S Wall Lake (S)	0.04	0.51 (12)	0.04	0.51 (12)
Taylor Creek U/S Wall Lake (S)	0.12	2.46 (19.5)	0.09	1.32 (14)

Table 8: Weighted vs. Unweighted Buffer Analyses. These analyses were performed on the 2<sup>nd</sup> iteration of the model.



not impaired by sediment, the West and Middle forks of the Gila River. Furthermore, the incorporation of the 1 km buffer did not appear to have the desired effect of reducing the average erosion rate in the Middle Fork Gila River.

In an attempt to remedy this, the analyses were repeated with a weighting system built into the 1 km buffer. Areas within a quarter kilometer of impaired streams were weighted 1, those between a quarter and half were weighted 0.75, those within a half and three-quarters of a kilometer were weighted 0.5, and the rest were set to 0.25. This analysis revealed nothing new. While it did serve to bring down erosion rates, it did not reveal any new patterns between the NMED impaired waters dataset and the model results.

## **Results**

As noted previously, two important results were expected. Model output would follow the results from the available literature, and the results of the model would show increased erosion rates in catchments where samples indicate high turbidity, conductivity and bottom deposits. As expected, the model output for the individual management analyses followed what was found in the literature, although due to some data issues, these analyses were overly simplistic in some cases. In the case of following the impaired waters dataset, the results were even less agreeable. No apparent relationship existed from which to predict impaired waters based from the model results.

In addition, comparing the model results to the actual sample data found within the NMED impaired waters data revealed further issues with the model results. The comparison did not yield enough information to predict impairment by sediment. Whether this was due to deficiencies in the model itself or failure to account for other

factors that contribute to erosion remains to be seen, but the most likely reasons are outlined below.

A critical analysis of the project should focus on why the model results failed to correspond with the NMED impaired waters data, and should be broken down into two distinct categories, data issues and procedural issues. Each of these factors contributed, either directly or indirectly, to the methodology or assumptions used in this model, and therefore, have a direct connection to the model's accuracy and validity.

#### Data Issues

Table 2 provides a list of the data used in this model. Due to the nature of this project, standard state and federal data were used. The long-range goal of this project was to be used as an agency-wide management tool. This necessitated the use of standard data. This proved to be useful in terms of data collection and organization but a handicap in the analysis phase of the project.

The use of standard datasets made data collection easy. Little to none of the burden of data creation was left to the analyst. In addition, some of these data are interrelated and created to work together. In some cases, one dataset is directly created from another. The USGS NHD dataset, for instance, was used as the base for the NMED Impaired Waters Dataset. This made the use of buffers made for the extensive NHD dataset usable with the impaired waters data with little geographic error. In addition, joining and relating in ArcGIS were initially very easy, due to the preexisting relationships of the data.

Although scales and projections varied widely, the scales and projections themselves were often fairly standard. Metadata was generally present and detailed, so

the particulars of the data could be found and dealt with easily. In addition, complete metadata made it possible to dictate the temporal and spatial scale at which the model was relevant.

When it came to the individual management analyses however, much of the data was lacking some information that would have been useful. Each management parameter evaluated in this model brought out some new deficiency in the available data. Each dataset used in the management analysis, roads, fire and grazing, will be looked at individually.

The Forest Service road dataset contained three pertinent attributes for this model: Surface type, maintenance category, and length. Surface type and maintenance category provided a good sense of the general effect of a road segment on erosion. The biggest problem with the road data was the lack of associated erosion affecting data, such as culvert locations and other drainage features. Information such as culvert and gabion location could have allowed for the creation of high or low erosion zones that could then be incorporated into the road buffers described above. While this did not hamper the actual road analysis, the results could have been more accurate with this information provided.

The Forest Service has such files at their disposal, but not in spatial format. In time such a layer could be included into this model. Incorporation of such data could not only improve the accuracy of the model, it would also prove useful in other environmental analyses.

The Forest Service fire datasets were separated by year. Spatially, the fire datasets were complete, but the associated tabular data were not. The only useful

information in the tabular data was whether or not a BAER action had taken place, although not the specifics of such action. Absent also were local burn intensities and fire severity. This made the fire analysis rather simplistic. Burn intensities are necessary for determining hydrophobicity of soils after a fire, and fire severity is vital to determining the post-fire recovery period. These data are collected via satellite or aircraft during a fire, and are not likely to be improved due to the danger and/or cost involved in collection. These data also lacked details on the season in which the fire occurred. This information is also important when determining the recovery rate after a fire, and such data could be added to forest service databases without the costs or risks inherent in most other fire data collection. Specifics on the season in which the fire occurred would also be useful in various environmental analyses.

By far the most complete datasets available for this project were the Forest Service grazing data. Even these data, however, were deficient in one area that had a major impact on the results of the study. Allotments were the smallest division available in the data. This meant that the data did not take into account individual pastures or exclusions within the allotments. This fact made it impossible to factor in grazing rotation within the individual allotments. It also skewed the grazing modified erosion results towards the low end in the initial version of the model. This is because for a given AUM value, all things being equal, there will be less impact from grazing over a larger area. While the pasture data exists within the spatial data, the tables do not specify which pastures are grazed and which are not. Above all other data issues, this fact most affected the model outcome in the initial version since so much of the study area was grazed. Both the spatial data and the INFRA databases should account for individual pastures

within the separate grazing allotments. This information is essential to any evaluation of grazing rotations and environmental assessments of grazing practices.

The last, and potentially most damaging, data issue dealt with the impaired waters dataset. NMED samples these reaches once every three years, but not all of the reaches in the study area were sampled in the same year. Consequently, for the impaired waters within the study area, sample years ranged from 2001 – 2003. The year for which this research was relevant was 2003, which means different conditions existed when four of the nine impaired waters were originally sampled. In order to account for this, rather than using the USGS 5<sup>th</sup> code HUC to delineate the basic study area, future iterations of the model should be run independently for each sub-watershed of each impaired stream for the year in which the actual samples were taken.

#### Procedural Issues

Apart from data issues influencing the model results, the comparisons to the NMED data exposed potential problems with the model itself. The base erosion model using the RUSLE was shown to be accurate based on the available literature (Roose 1996). A closer look at the data however, shows some potential trouble spots. Most of the values in the RUSLE are taken directly from primary sources. It is unlikely that these values are generating errors in the equation.

The same cannot be said of the Slope-Length (LS) Factor. To calculate the LS factor according to the Mitasova method, slope and flow accumulation must be derived from a digital elevation model (DEM). NED 10 meter DEMs exhibit a peculiar phenomenon when used in spatial analysis. Stippling occurs when slopes, hillshades, or any of the ArcHydro analyses are run, giving the entire layer a "waffle-iron" look. More

importantly, the actual pixel values are affected. As yet, there is no adequate algorithm to correct the stippling problem that does not significantly alter the data.

The roads analysis also proved problematic. In the first version of the model, an extremely low value for road impact was used in the model with negligible results. In the second version, a high value was used with results that drove erosion rates along unimpaired waters to high values as well. Both road impact values were derived by comparing the WEPP: Road model erosion rates with different erosion rates for undisturbed forests. Further comparison would yield a more suitable impact value.

In the case of the fire analysis, there was one main area for concern with regards to errors, erosion rate recovery. Robichaud (2000) estimated a seven-year erosion rate recovery period after a moderate severity fire in Ponderosa pine forest. Since the data lacked this information, moderate severity was assumed. Had the fires been high severity in reality, the first year post-fire erosion rates would have been significantly higher, and the recovery period would have extended as long as fourteen years. Furthermore, the logarithmic scale used to simulate the rate of recovery was based on observed post-fire erosion rates in the American Northwest. Because of soil and climatic differences, this may not translate well to the desert Southwest.

The grazing analysis was similar in some ways to that of fire, but much more complex due to the availability of data. In addition, because so much of the study area was grazed, this analysis potentially had the most effect on the model results. The most problematic parameter in the grazing analysis was allotment area. The effects of reducing the grazing area could be seen in the comparison of the two versions of the grazing analysis. In addition to this, the analysis of Wall Lake also suggested that the

estimates of biomass recovery might be too liberal. This would mean that of the four years evaluated in the grazing analysis, the first years are being seriously underestimated.

The last potential problem was purposely built into the procedure in order to calibrate the individual management analyses. The management analyses were conducted independently of one another. At a minimum, this also skewed the grazing results towards the low end. Fires would have reduced the amount of available forage, which was used to calculate biomass in the grazing analysis. This would have resulted in much higher erosion rates in grazing allotments where fires had occurred.

## **Conclusions**

### **Recommendations**

The overall improvement of existing digital data should be made a priority. Several examples have already been listed above concerning the improvement of data, but there is one more worth noting. The Forest Service's General Ecosystem Survey (GES) data exists as digital spatial data. It is, however, unattributed except for a legend code referring a user to a very thick binder that has a fairly complete listing of vegetation type, soil type, precipitation, slope, and percent cover. Alone, the spatial data is useless. For this project, the attribute tables had to be populated. It can only be presumed that this has been done before by another user on another project, and will in fact be done again. These data should be converted to digital once and made available to all users as soon as possible.

Another issue that is still surprisingly common at the state and federal level is lack of digital data. The Forest Service has an extensive detailed soils layer at a scale of 1:24000. These data are at a much finer scale than the STATSGO soil layer used in the

model, attributed with much of the same information, but it is 100 % analog. The same can be said of the NRCS' Soil Survey Geographic (SSURGO) dataset. Unless the analyst spends countless hours at a digitizing table or scanner, the data are all but useless for GIS analysis. This should also be done once and be made available to all users.

In addition, government agencies should move to a multiple use data model. This means digital datasets that are useful for many different applications. As it stands now, many agencies and departments create their own specific dataset to fit their own specialized needs. Essentially each of these groups funds their own data, so by combining efforts, they could also combine funds. NHD stands as a good example of the multi-use data model already in effect. Moving to the multi-use model would not only provide more useful data, it would also increase funding for data creation and ground truthing. Multi-use data would be beneficial not only to this project, but many others in progress.

Finally, more water quality samples are necessary to ground truth the model results. The NMED data used in this project was good in the sense that it was dated and listed the various impairments of the streams. However, it was not nearly extensive enough. Of nine impaired streams in the study area, only two were not impacted by sediment. There was no way of knowing which streams were sampled and found to be unimpaired. Incorporating these changes into the NMED data would no doubt improve the accuracy of the model.

### Conclusion

The model itself was completed as part of the primary objective of this project. However, closer examination reveals that more work is necessary to predict impairment



from sediment from the model results. The results, while matching fairly well with results expected from the literature, did not translate to the comparison with the impaired waters dataset. There are many possible explanations for this mismatch, the most likely of which have been outlined previously.

The undisturbed forest scenario model is sound, but significant problems still exist with the model. As part of future work, the model will be run again with NED 30 meter DEMs, which do not exhibit stippling. This will provide a means of comparing results across the two elevation datasets, as well as, providing an output that is free of stippling. Also, the spatial and temporal scale of the model should be reduced to that of the sub-watershed of each of the nine impaired water bodies. The data scale would remain at 1:250,000 until better finer resolution data are produced, but the sub-watershed seems more manageable and, indeed, more appropriate.

In addition, more experimentation with road impact and grazing area is definitely necessary to produce a relationship between the NMED data and the model results. Also, the model should be modified such that the individual analyses are able to interact in a limited capacity at the very least. Finally, more experimentation is required to determine the method of combining the management analyses.

Despite these faults, this project was a good first step towards developing a working spatial erosion model. Some work remains in order to provide results that can be translated to the impaired waters dataset, but it was built on a solid base, the RUSLE, which provided results that were close to what was expected by the literature. The few modifications and additions mentioned above should do much to reduce the mismatch between the model results and the actual samples.

Once the model output can be related to the impaired waters data, the model could truly be called predictive. Running the model could generate an accurate spatial representation of potential for contamination from sediment. With the incorporation of a GUI, such a tool would prove invaluable as a decision support system for resource managers within the Forest Service. Because the data and software used to produce the model are standard, it could be run on any agency with ArcGIS capabilities. All of these are long range goals of this project.

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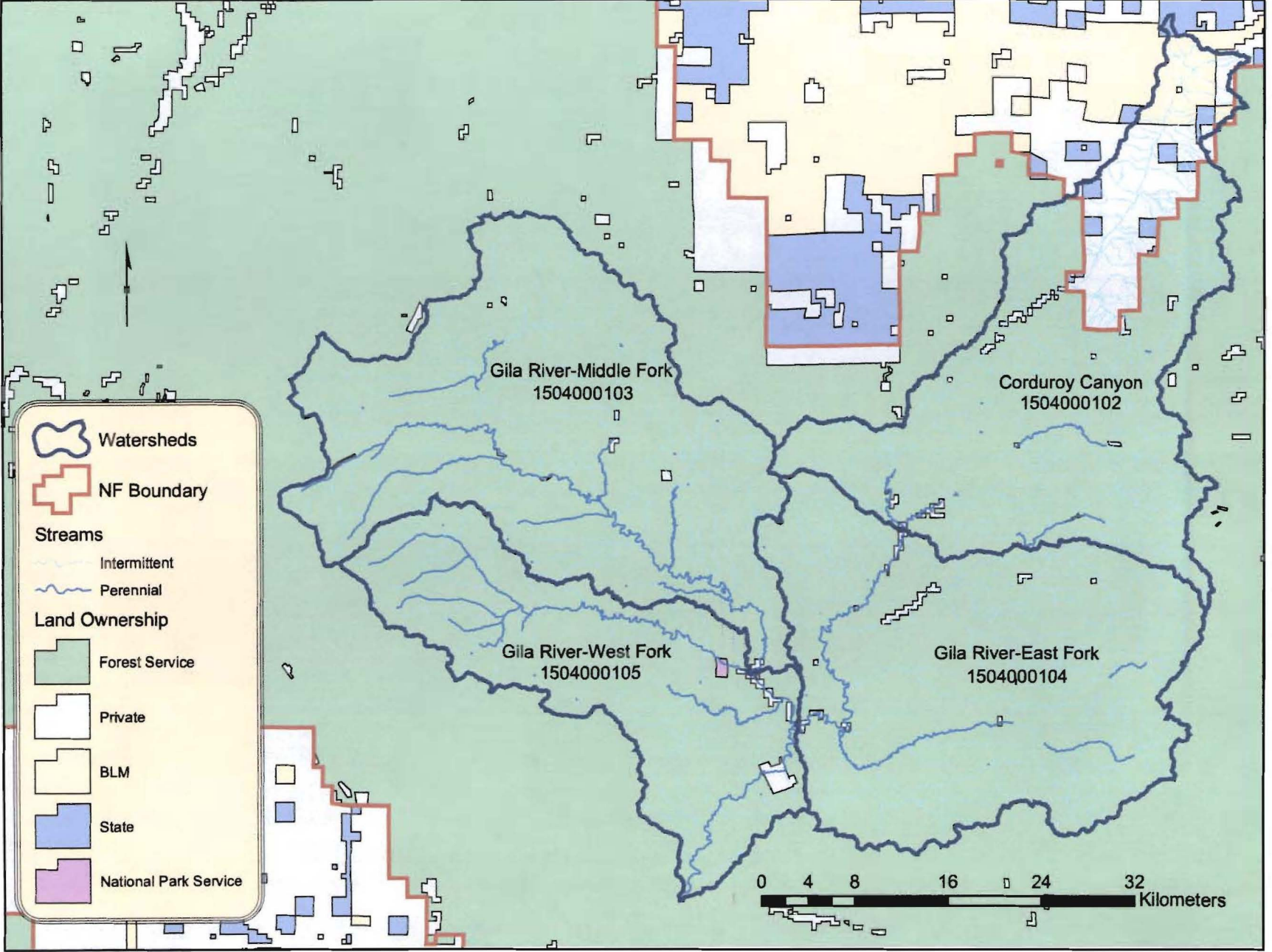
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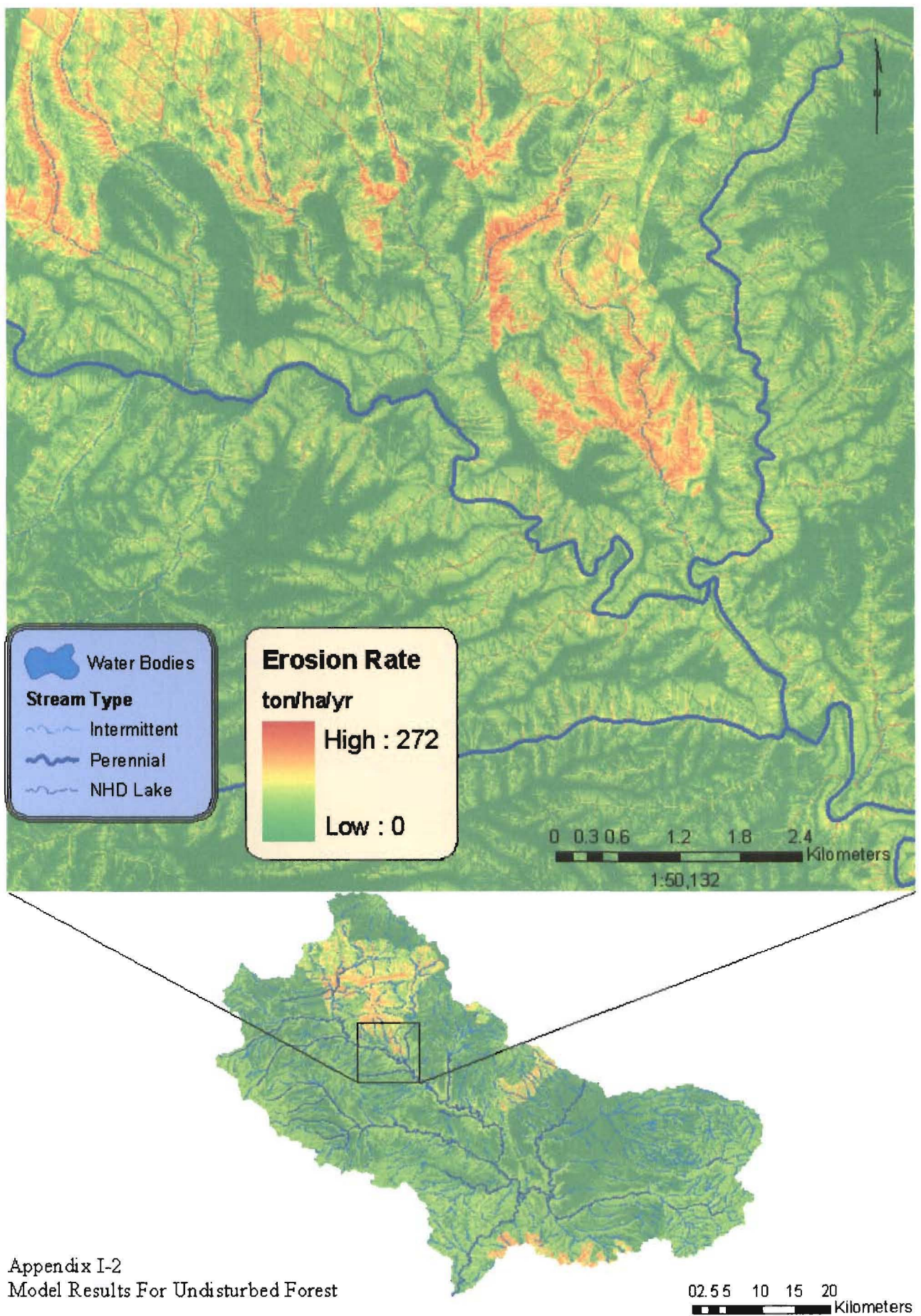
## **Appendix I: Additional Maps**

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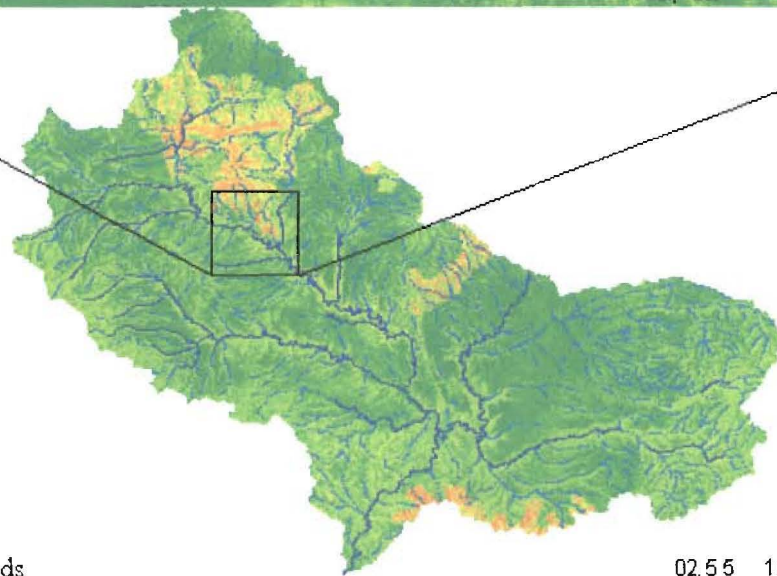
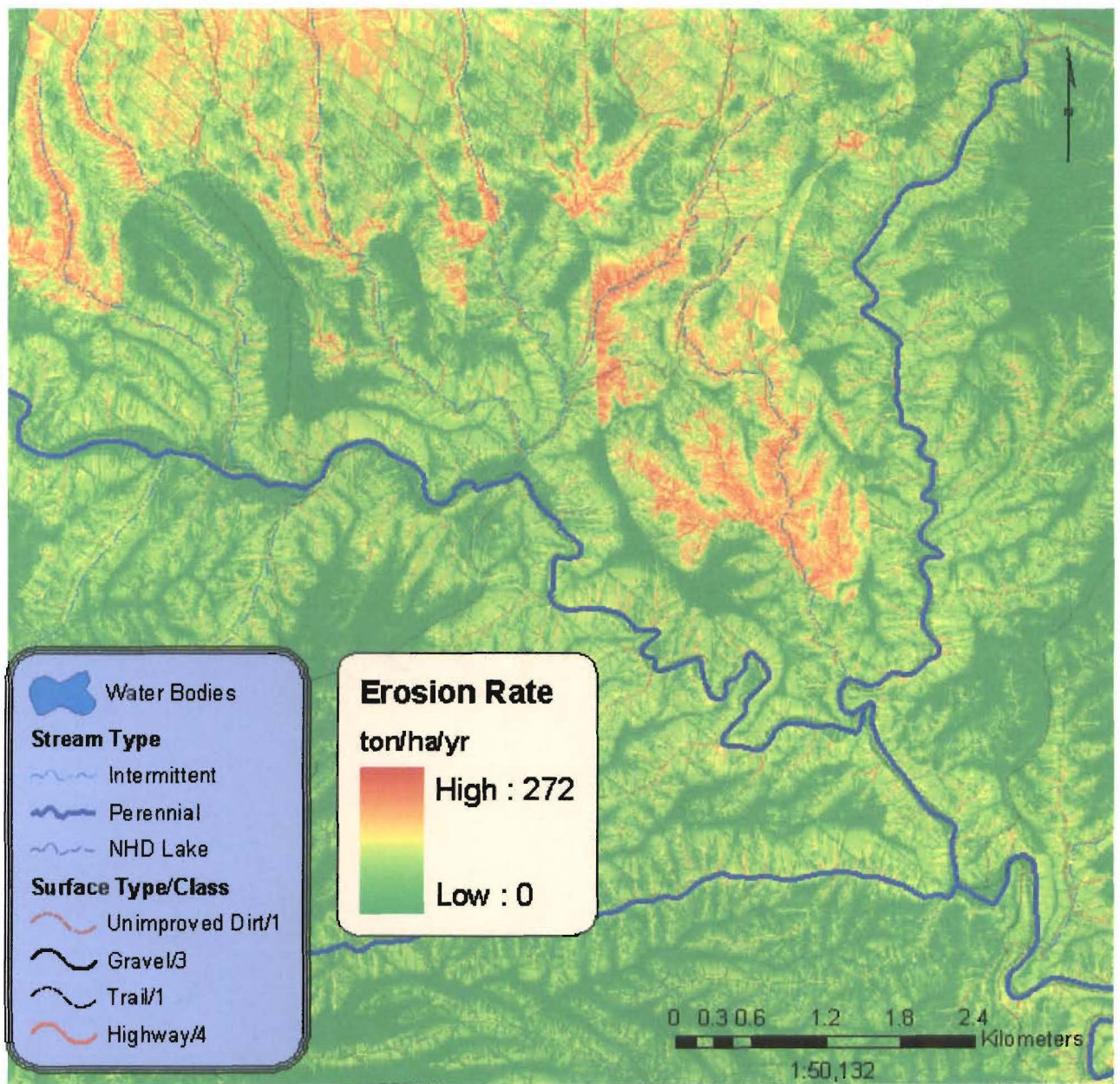
Appendix I-1: Land Ownership within the Study Area





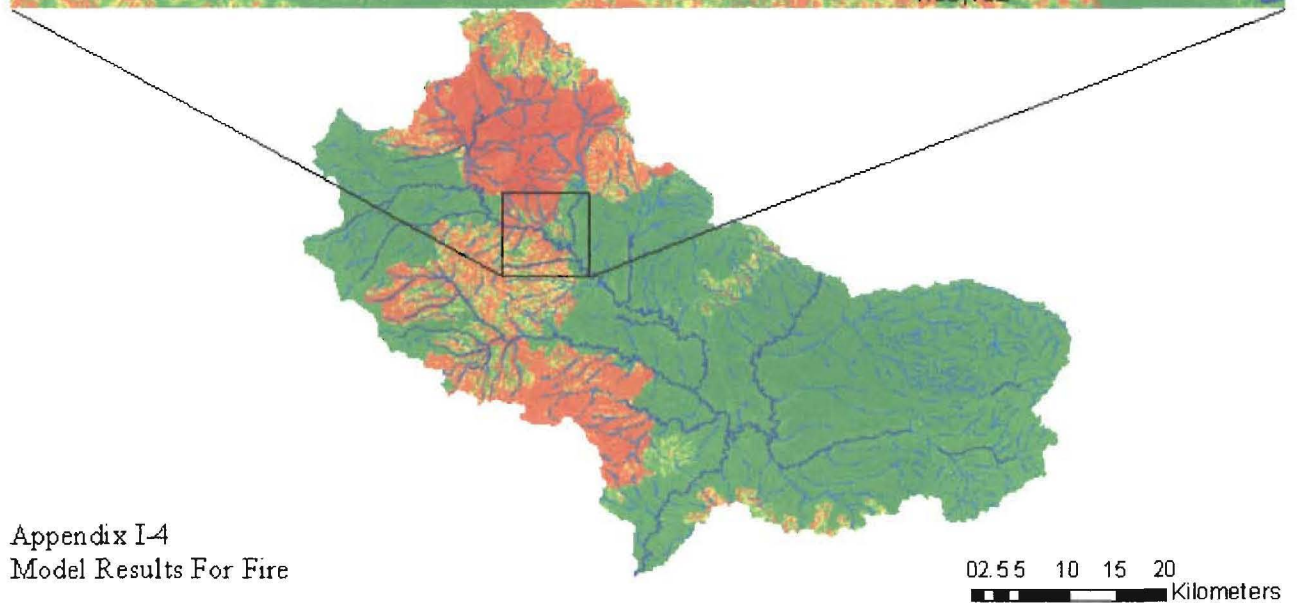
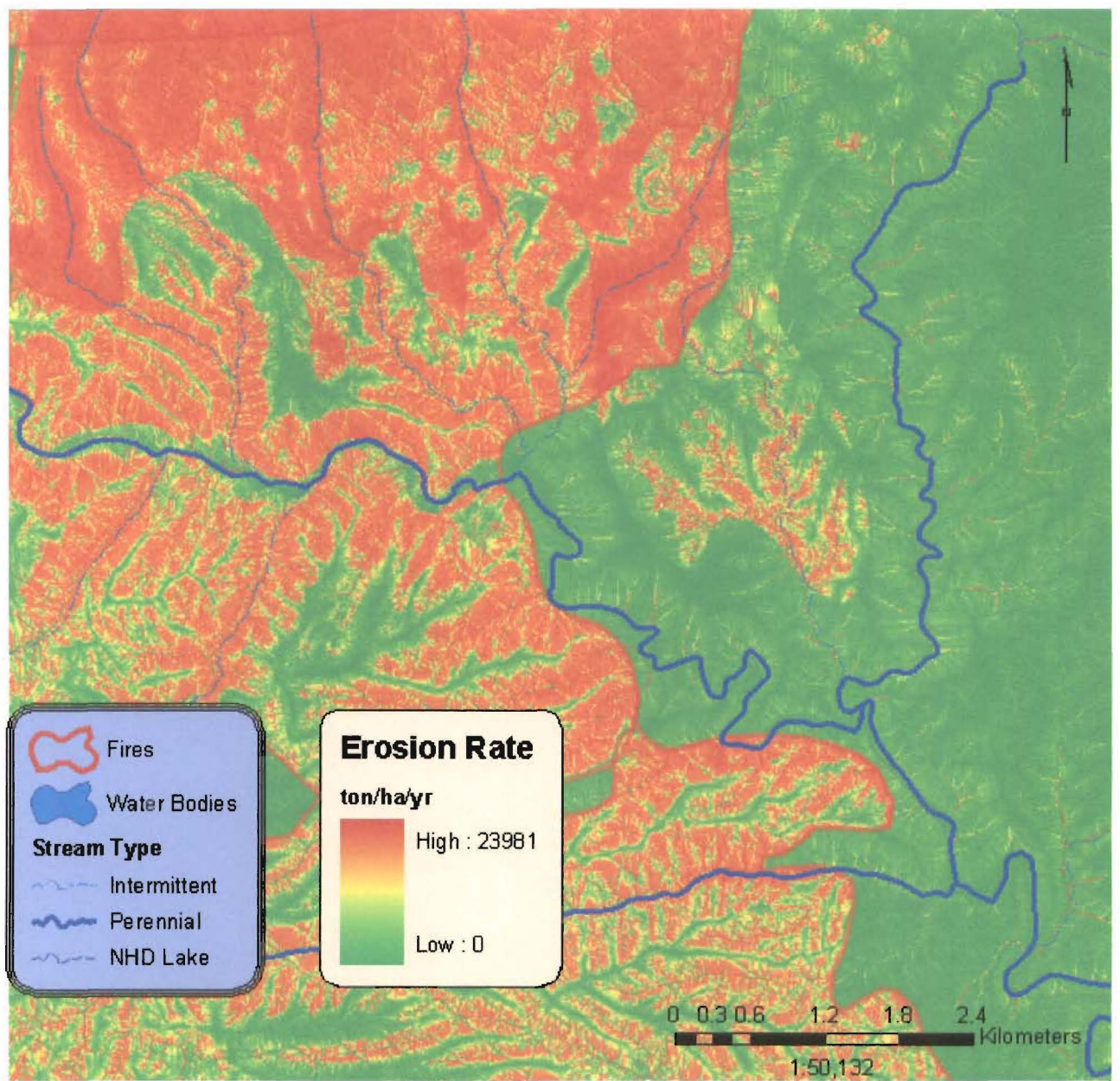
Appendix I-2  
Model Results For Undisturbed Forest





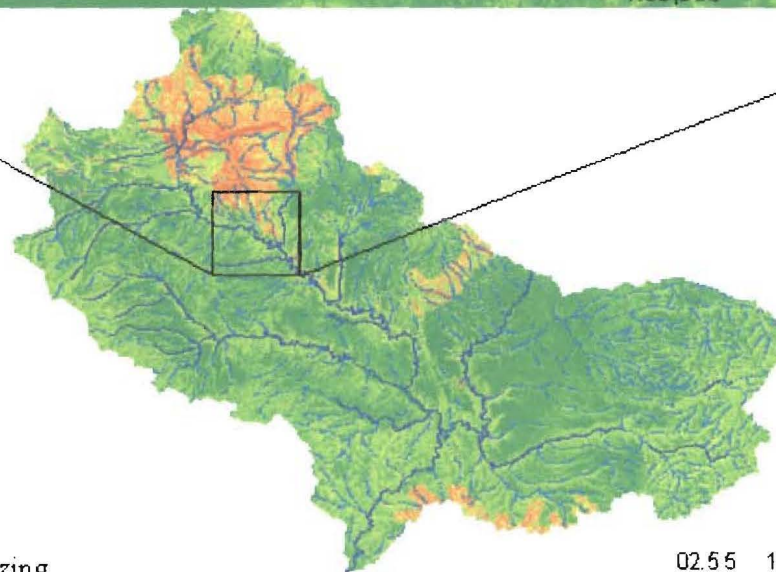
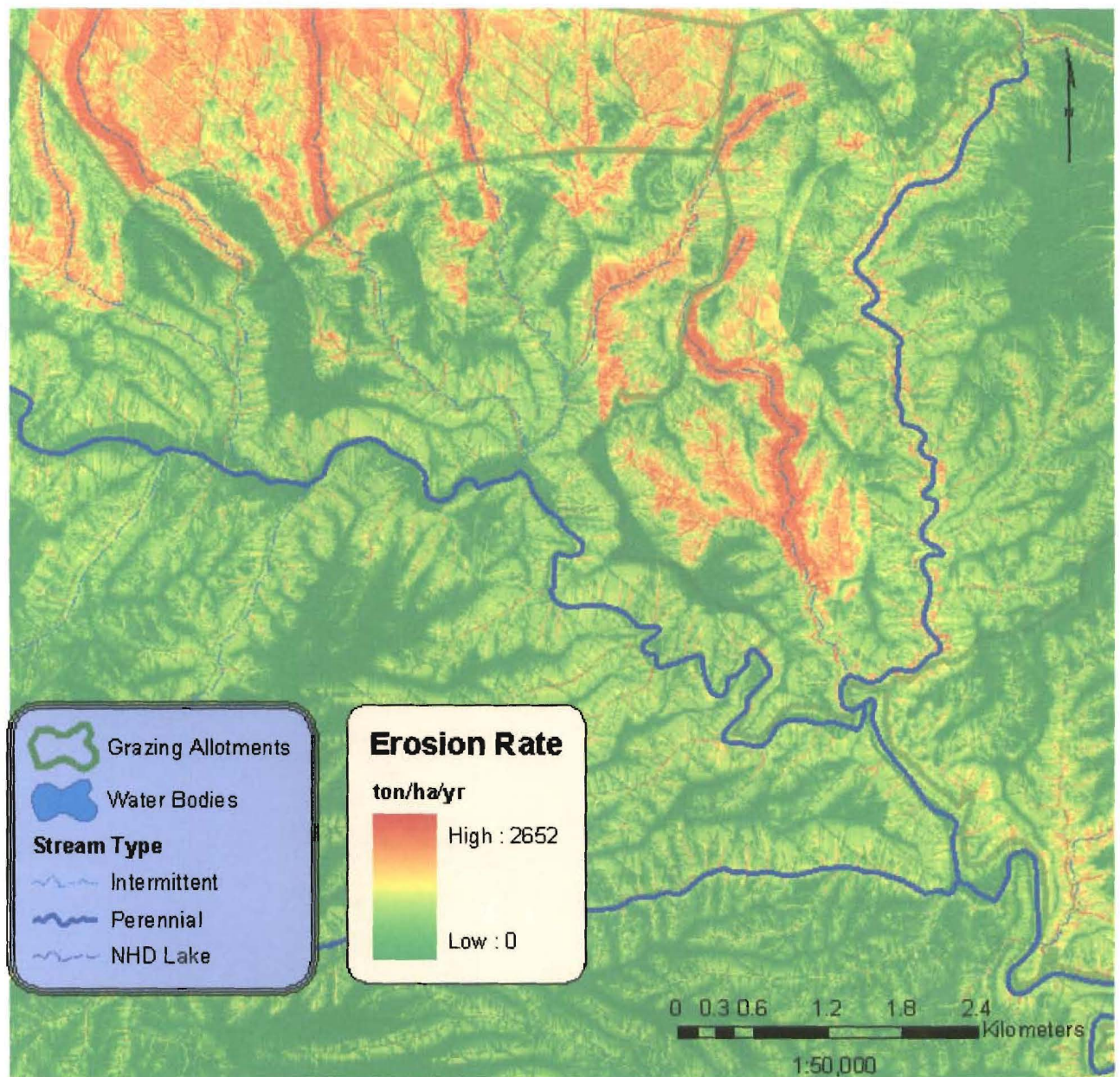
Appendix I-3  
Model Results For Roads





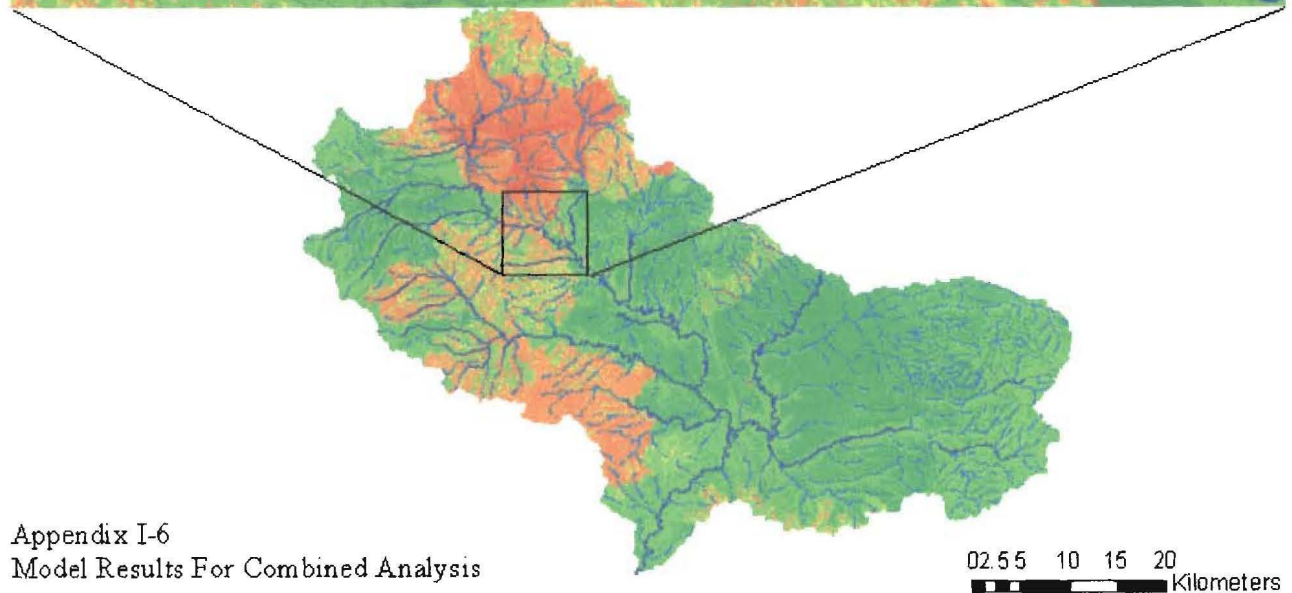
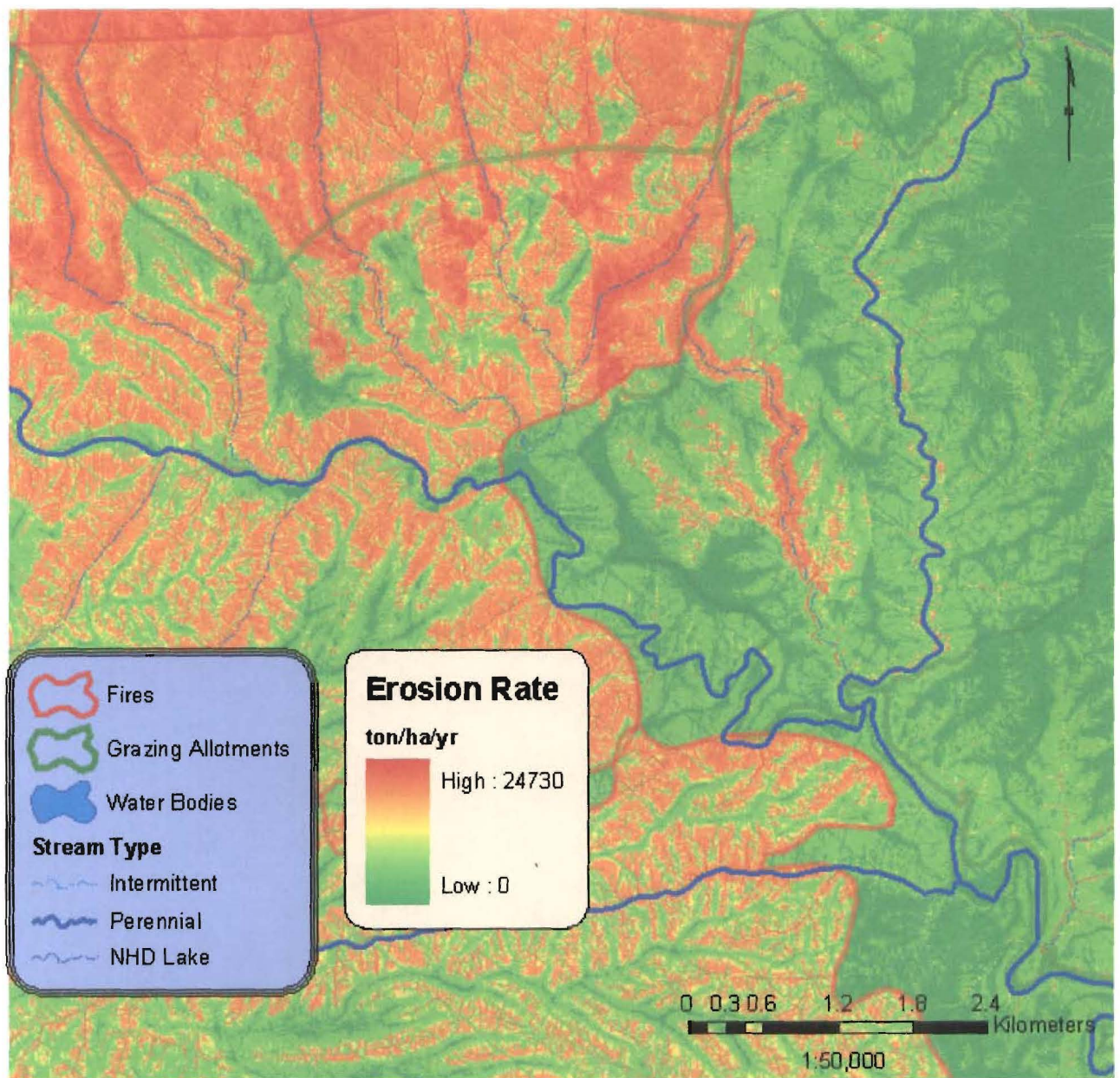
Appendix I-4  
 Model Results For Fire





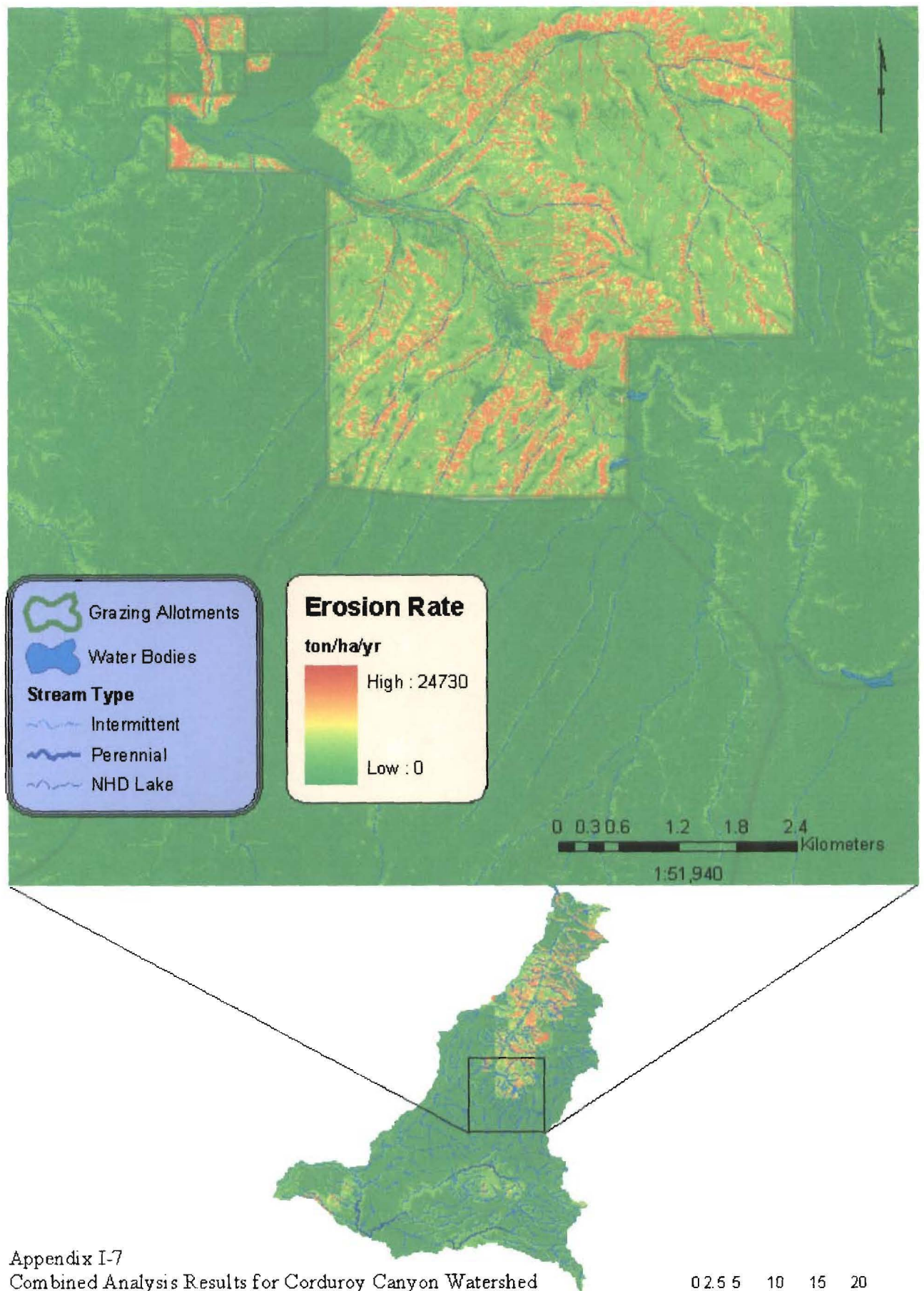
Appendix I-5  
Model Results For Grazing





Appendix I-6  
Model Results For Combined Analysis





## Appendix II: Model Procedure

Create a Geodatabase

Create a Feature Dataset-Import coordinate system from STATSGO

Clip all vector data to study area *except grazing* - Save output to new Feature Dataset

Data preparation:

WATERSHEDS – Add RUSLE R Value

Add [R\_Value] Field: Long Int - (RUSLE R Value Map)

VEGETATION – Add RUSLE C Value

Add [C\_Value] Field: Long Int - (GES C Value \* 100)

SOIL – Extrapolate average K value

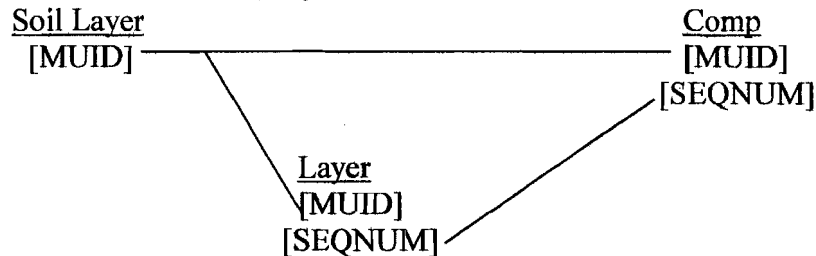
Load Soil Data: Clipped STATSGO Soil Layer, Comp Table, and Layer Table

Relate soil tables to soil layer using [Muid]

Select all: View each related table-Export each table

**In Microsoft Access:**

Construct Query based on this relation:



[MUID] | [SEQNUM] | [COMPPCT] | [LAYERNUM] | [KFACT]

Save as ***Soil\_Query***

Add [PCT\_K] Field: Double – {[KFACT] \* [COMPPCT] / 100}

**In ArcGIS:**

Add ***Soil\_Query***

Summarize ***Soil\_Query*** based on [MUID]

Sum – [PCT\_K]

Save as ***Query\_Summarize***

Join ***Query\_Summarize*** to soils

Add [K\_FACT] Field: Long Int – {[PCT\_K] \* 100}

ROADS – Create buffers based on Maintenance Class

Extrapolate Maintenance Classes from CFF data using Select by Attributes (Use provided expressions):

Road\_Buffer\_Class\_1.exp ( Selects CFF 107 - Trails)

Create 200 ft Buffer around selected (Trails) Roads – ***Class\_1\_Buffer***

Road\_Buffer\_Class\_2.exp ( Selects CFF 89, 106, 117 – 4WD/

Unimproved//Dirt Roads)

Create 200 ft Buffer around selected (Dirt) Roads – ***Class\_2\_Buffer***  
 Road\_Buffer\_Class\_3.exp ( Selects CFF 118 – Gravel Roads)  
 Create 100 ft Buffer around selected (Gravel) Roads – ***Class\_3\_Buffer***  
 Road\_Buffer\_Class\_4.exp ( Selects CFF 105 – Paved Roads)  
 Create 50 ft Buffer around selected (Paved) Roads – ***Class\_4\_Buffer***  
 Union ***Class\_(#)\_Buffers – Road\_Buffer***  
 Add [Buffer] Field: - Long Int – (125)  
     For Version 2 – substitute 58 for 125 above  
 Add [Coincidence] Field: - Long Int – ({1, 2, 3, 4})

FIRE – To each fire layer, Add [BAER] Field: Text – {Yes, No}

GRAZING – Combine spatial data with INFRA Data

Export Grazing layer to Feature Class in Geodatabase –

***Grazing\_Allotments***

For Version 2 –

From NHD ***Drains*** and ***Water Bodies*** layer-

Select by Attributes [Fcode] = “46004” (Perennial)

Create 1 mile buffer around selected ***Drains*** and  
***Water Bodies - Buffer\_(dr/wb)\_1mi*** as  
 appropriate

Merge ***Buffer\_dr\_1mi*** and ***Buffer\_wb\_1mi*** –  
***Merge\_Buffer\_1mi***

Dissolve ***Merge\_Buffer\_1mi - Buffer\_1mi***

Create 300 ft Buffers around NHD ***Drains*** and  
***Water Bodies - Buffer\_(dr/wb)\_300ft*** as  
 appropriate

Merge ***Buffer\_dr\_300ft*** and ***Buffer\_wb\_300ft*** –  
***Buffer\_300ft***

Union ***Buffer\_1mi*** and ***Buffer\_300ft*** – ***Hydro***  
***Buffer***

Add Field [PCT] Field: Short Int –

For [Buf Dist] 300 = 60

For [Buff Dist] 1 = 40

Union ***Hydro Buffer*** and ***Grazing\_Allotments*** –  
***Allot\_Buff\_Union***

For ***Allot\_Buff\_Union*** Select by Attributes:

[PCT] <> 60 or [PCT] <> 60

Export to Geodatabase – ***Export\_Allot\_Buff***

Summarize ***Export\_Allot\_Buff*** based on [Allot\_Num]

Sum – [Shape\_Area] – ***Grazed\_Area***

Summarize grazing layer based on [Name]

Sum – [Shape\_Area]

Save as ***Grazing\_Areas***

Join ***Grazing\_Areas*** to ***Grazing\_Allotments***

For Version 2 –

Substitute **Grazed\_Area** for **Grazing\_Areas** above  
 Add [Hectares] Field: Long Int - {[Sum\_Shape\_Area] \* 0.001}  
 Clip **Grazing\_Allotments** to study area – Save output as  
**Grazing\_Complete** in project feature dataset  
 To **Grazing\_Complete** –  
 Add [Year] Field: Long Int –  
     For private land [Year] = 9999  
     For forest land [Year] = [Act\_Year]  
 Import INFRA Actual\_Grazing\_Allotment data – Save as **Grazing\_Info**  
 Relate **Grazing\_Info** to **Grazing\_Complete** based on [Name]  
 Select all: View related table - Export table – Save as **Graze\_Table**  
 From **Graze\_Table**:  
     Select [Act\_Year] = 2000 – 2003 one year at a time  
     Export each selection - **Graze\_(Year)**  
 For each **Graze\_(Year)** - Summarize based on [Name]  
     Sum – [Actual Head Months]  
     Save as **Sum\_AUMs\_(Year)**  
     Join **Sum\_AUMs\_(Year)** to its respective **Graze\_(Year)**  
     Add [AUMs] Field: Long Int - ([Sum\_Actual\_Head\_Months])  
     Join **Graze\_(Year)** to **Grazing\_Complete**  
     Add [AUMs] Field: Long Int - ([AUMs])

$$[AUMs] \text{ for private land} = \frac{1}{2} * \frac{[Hectares] * 637}{453.59}$$

$$\#AUMs = (([Hectares] * 637 \text{ kg/ha}) / 453.59 \text{ kg}) / 2$$

#AUMs = Maximum supportable Animal Unit Months  
 [Hectares] = Total area of parcel (from Attribute Table)  
 637 kg/ha = Average standing biomass in a grazed pasture (Catlin, *et al.* 2003)  
 453.59 kg = 1000 lbs of forage to sustain 1 AUM

Select by Attributes [Year] = 9999 or [Year] = (year)  
 Export selection to Feature Class in Geodatabase –  
**Grazing\_(Year)**  
 To **Grazing\_(Year)**, Add [BM0] Field: - Long Int – (BLM, State, Private = 50, Grazing Allotments = 75, Ungrazed Forest = 100)

Raster Analysis:

#### UNDISTURBED FOREST

Convert Watersheds to Raster based on [R\_Value] – **R\_Value**  
 Convert Vegetation to Raster based on [C\_Value] – **C\_Value**  
 Convert Soils to Raster based on [K\_FACT] – **K\_Factor**

For LS Factor –

Using ArcHydro – Terrain Preprocessing

Recondition NED data using NHD Watercourses - **Recond**

Fill Sinks - **Filled**

Flow Direction – **Flowdir**

Flow Accumulation - **Flowacc**

Create slope in degrees from **Filled** – **Slope**

Calculate – **LS\_Factor**

$$1.6 * ((\text{Flowacc} * 10 / 22.1)^{0.6} * (\sin(\text{Slope}) / 0.09)^{1.3})$$

$$LS(r) = (m + 1) (A(r) / a_0)^m (\sin b(r) / b_0)^n$$

LS(r) = Slope Length Factor at point (pixel) “r”

A(r) = Upslope Contributing Area at point “r” (flow accumulation \* resolution)

b(r) = Slope at point “r”

a<sub>0</sub> = Length of standard USLE plot (22.1 m)

b<sub>0</sub> = Slope of standard USLE plot (0.09)

m = value determined by experiment (0.6 for slope length <100)

n = value determined by experiment (1.3 for slope angles < 14°)

Calculate RUSLE - **Erosion**

$$R\_Value * (K\_Factor / 100) * LS\_Factor / C\_Value$$

## ROADS

Convert **Road\_Buffer** to Raster based on [Buffer] – **Buffer\_Grid**

Reclassify **Buffer\_Grid** – (No Data = 100) – **Road\_Buffer**

For Version 2 – No Data = 1

Convert **Road\_Buffer** to Raster based on [Coincidence] – **Coincidence**

Reclassify **Coincidence** – (No Data = 1) – **Coincident**

## FIRE

Repeat for every year that fire occurred

Convert Fire Layers to Raster based on [Fire\_Year] –

**Fire\_(Year)\_Temp**

Reclassify **Fire\_(Year)\_Temp** – (No Data = 1, See Table) –

**Fire\_(Year)**

Year of Fire (Study Occurred-)	Fire Erosion Factor
-1 year after fire	64
-2 years after fire	32



-3 years after fire	16
-4 years after fire	8
-5 years after fire	4
-6 years after fire	2
-7 years after fire	1

Convert Fire Layers to Raster based on [BAER] --

***BAER\_(Year)\_Temp***

Reclassify ***BAER\_(Year)\_Temp*** -- (1 = No Data, No BAER, 2 = BAER) -- ***BAER\_(Year)***

Calculate -- ***BAER\_Effect***

***Fire\_(Year)***

***BAER\_(Year)***

Reclassify ***BAER\_Effect*** -- (0 = No Data) - (Overwrite)

***Fire\_(Year)\_Temp***

SUM All ***Fire\_(Year)\_Temp*** - ***FIRE***

## GRAZING

Create ***PCT\_Grazed*** Layer

Reclassify ***Slope*** -- (> 27° = 0, < 27° = 40) -- ***Reclass\_Slope***

From NHD ***Drains*** and ***Water Bodies*** layer-

Select by Attributes [Fcode] = "46004" (Perennial)

Create 1 mile buffer around selected ***Drains*** and ***Water***

***Bodies - Buffer\_(dr/wb)\_1mi*** as appropriate

Merge ***Buffer\_dr\_1mi*** and ***Buffer\_wb\_1mi*** --

***Merge\_Buffer\_1mi***

Dissolve ***Merge\_Buffer\_1mi - Buffer\_1mi***

Create 300 ft Buffers around NHD ***Drains*** and ***Water***

***Bodies - Buffer\_(dr/wb)\_300ft*** as appropriate

Merge ***Buffer\_dr\_300ft*** and ***Buffer\_wb\_300ft*** --

***Buffer\_300ft***

Union ***Buffer\_1mi*** and ***Buffer\_300ft*** -- ***Hydro\_Buffer***

Add Field [PCT] Field: Short Int --

For [Buf Dist] 300 = 60

For [Buf Dist] 1 = 40

Convert ***Hydro\_Buffer*** to Raster based on [PCT] -- ***Hydro\_Buffer***

Reclassify ***Hydro\_ft*** -- (No Data = 0) -- ***Hydro\_Buffer***

Calculate: SUM ***Hydro\_Buffer*** and ***Reclass\_Slope*** - ***PCT\_Grazed***

Repeat for every grazing year starting from the latest to the current year

Convert ***Grazing\_(Year)*** to Raster based on [BM0] -- ***BM0***

Convert ***Grazing\_(Year)*** to Raster based on [AUMs] --

***AUMs\_Year)***  
 Convert ***Grazing\_Year)*** to Raster based on [Hectares] –  
***Hectares\_Year)***  
 Calculate in sequence for each year:

$$CALC = 100 * (((Hectares * 1550 * BM0) - (AUMs * 453.59)) / (Hectares * 1550))$$

Reclassify ***CALC*** – (1 = No Data) – ***bm\_pct\_Year)***

$$CALC \text{ (Overwrite)} = (bm\_pct\_Year) < 1 * bm\_pct\_Year + (bm\_pct\_Year = 1) * BM0$$

$$CALC2 = 100 - (.5 * (100 - CALC) + ((100 - CALC) * ((PCT\_Grazed = 0) + PCT\_Grazed + ((CALC <= 33) * 10)) / 100))$$

$$bm\_pct\_Year) \text{ (Overwrite)} = (CALC2 > 10) * CALC2 + ((CALC2 < 10) * 10$$

$$CALC \text{ (Overwrite)} = bm\_pct\_Year) + (.26 * bm\_pct\_Year) * (bm\_pct\_Year < 100))$$

$$Regen\_Year) = ((CALC >= 100) * 100) + ((CALC < 100) * CALC)$$

Replace ***BM0*** with ***Regen\_Year)*** in all iterations after the first year

COMBINED ANALYSIS

Calculate – ***Erosion\_Comb***

$$(Fire + (101 - bm\_pct\_Year)) * Erosion * Coincident * Road\_Buffer / 100$$