A TOOL TO ANALYZE ENVIRONMENTAL IMPACTS OF ROADS ON FOREST WATERSHEDS

by

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ABSTRACT

A Tool to Analyze Environmental Impacts of Roads on Forest Watersheds

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Forest roads have impacts on geomorphic processes and erosion patterns in forested basins. To analyze these impacts the USDA Forest Service (USFS) has developed a detailed road inventory using Global Positioning System road surveys. This project has developed a set of GIS tools to derive environmental impact information from this inventory. A database schema was developed to represent the road inventory in a structured way. Filtering of the data during entry into the database serves as a quality control step. The first analysis function in the GIS tool set calculates the sediment production for each road segment from slope, length, road surface condition and flow path vegetation. Road segment sediment production is then accumulated at each drain point. Digital elevation model (DEM) derived overland flow directions are then used to accumulate the sediment input to each stream segment. The second function analyzes the impact of road drainage on terrain stability by calculating the specific discharge due to road drainage and using this, together with slope, as inputs to an infinite plane slope stability model. An erosion sensitivity index calculated using slope and contributing road length at each drain point is also calculated to predict gullying. The final function analyzes the fragmentation of stream network fish habitat due to potential blockage of fish passage at stream crossings. The new model was compared with present USFS roads analyses methods and found that the detailed information in the new road inventory allowed more specific association of road segments producing sediment with streams to which they were connected, providing for better calculations of stream sediment inputs. Comparison of indicators of the potential for gully formation from USFS roads analyses with surveyed drain points where gullies were observed found that terrain slope and an erosion sensitivity index that combines slope with the length of road draining to a drain point were good predictors of gully formation, with the erosion sensitivity index that relied on additional information from the road inventory survey having a greater capability for discriminating drain points with a high potential for gully formation.

(219 pages)

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CHAPTER 1

INTRODUCTION

Forest roads affect stream ecosystems in a variety of ways (Jones et al., 2000), and changes to sediment regimes and habitat fragmentation are two of the most direct. The construction and use of roads can be a significant source of sediment in forested basins (Swanson, and Dyrness, 1975; Reid, and Dunne, 1984; Wold, and Dubé, 1998; Luce, and Black, 1999). Road construction removes vegetation from the road cut slope, fill slope, ditch and tread, leaving these areas susceptible to surface erosion. Over time, the cut slope and fill slope re-vegetate, self armor and erosion from these areas is reduced, however, the road tread and ditch continue to be sediment sources as long as the road is in use (Megahan, 1974; Luce, and Black, 2001a). Runoff that drains from roads can initiate landslides or gullies (Montgomery, 1994; Borga, Tonelli, and Selleroni, 2004; Wemple, Jones, and Grant, 1996; Swanson, and Dyrness, 1975). Stream crossing culverts frequently become occluded at high flow and cause large road fill failures into the channel. Stream crossings commonly impair the passage of aquatic organisms moving both up and downstream or completely exclude some migratory species (Clarkin et al., 2003). Forest managers require information about the potential impacts of roads over large areas to conduct cumulative effects and watershed analyses for planning new road construction, maintenance, and decommissioning priorities. Road-Sediment yield estimates as well as information on broader aquatic impacts are needed for such work (Luce et al., 2001; Switalski et al., 2004; Bisson et al., 1999).

In assessing the cumulative impact of roads on forest ecosystems it is important to account for fine scale information such as linear and point data giving the erosion from road segments and sediment inputs at drain points. A detailed inventory of road segments and their linkages to drain points is required for this sort of analysis (Black, and Luce, 2002). Existing sediment yield models (e.g. Cline et al., 1984; Washington Forest Practices Board, 1995; Wold, and Dubé, 1998) do not use information about specific locations and characteristics of drains, impairing their ability to estimate delivery of sediment, not to mention the suite of geomorphic processes that are affected by point delivery of water. Black and Luce (2002) developed an inventory process to respond to this specific need. The inventory method uses Global Positioning Systems (GPS) and databases to record field derived information that can be used in a Geographic Information System (GIS) program to associate road characteristics with their spatial location within the landscape and thereby determine the environmental impacts and risks to aquatic ecosystems accounting for spatial effects.

The contribution of this Masters Thesis was to develop analysis methods based on detailed forest road inventory datasets, obtained from the United States Department of Agriculture, Forest Service (USFS) GPS surveys. These datasets were taken as inputs to quantify, predict and analyze geomorphologic impacts on forested watersheds due to the construction and use of forest roads. The methods developed are implemented as a set of GIS based analysis tools which quantify sediment production from forest roads, its delivery to the stream system, the effects of road drainage on terrain stability and erosion sensitivity, and the impact of road crossing barriers on aquatic habitat. I also developed, as a part of this thesis, a way to organize road lines, drain points, and erosion parameters inside a relational database model. The database schema was designed to ensure referential integrity between related attributes, and validate data obtained from USFS road surveys. The GIS model takes inputs from this relational database for its analyses. A preprocessing tool was developed to validate and store road inventory information in the relational database model.

Objectives

1. To develop a relational database model which enforces referential integrity between road and drain point attributes, and validates and stores the USFS inventory dataset. To develop a preprocessing tool to validate and import the inventory information into the database.
2. To develop a set of GIS tools that takes input from the forest road inventory and quantifies sediment production from forest roads and resulting stream sediment inputs, predicts the effect of road drainage on terrain stability and erosion sensitivity, and analyzes fish habitat segmentation due to road stream crossing blockage or failures. To implement these tools as a toolbar for the Environmental Systems Research Institute (ESRI®) ArcGIS™ GIS software.

CHAPTER 2

LITERATURE REVIEW

Expanding road networks have created many opportunities for new uses and activities in national forests, but they have also dramatically altered the character of the landscape, and the Forest Service must find an appropriate balance between the benefits of access to the national forests and the costs of road-associated effects to the ecosystem (Bisson et al., 1999). Bisson et al. (1999) suggested a roads analysis method, which is an integrated ecological, social, and economic approach to transportation planning that addresses both existing and future roads—including those planned in non-road areas. The objective of Bisson and others' (1999) road analysis is to provide Forest Service line officers with critical information to develop road systems that are safe and responsive to public needs and desires, are affordable and efficiently managed, have minimal negative ecological effects on the land, and are in balance with available funding for needed management actions. Bisson and others' (1999) road analysis consists of the following six steps:

1. Set up the analysis: Assign interdisciplinary team members, list information needs, and plan for the analysis designed to produce an overview of the road system. The interdisciplinary team will develop a process plan for conducting the analysis.
2. Describe the situation: Develop a map of the existing road system, descriptions of access needs, and information about physical, biological, social, cultural, economic, and political conditions associated with the road system.

3. Identify the issue: Develop a summary of key road-related issues, a list of screening questions to evaluate them, a description of the status of relevant available data, and a description of what additional data will be needed to conduct the analysis.
4. Assess the benefits, problems and risks: Synthesize the benefits, problems, and risks of the current road system and the risks and benefits of constructing roads into unroaded areas.
5. Describe opportunities and set priorities: Develop a map and descriptive ranking of management options and technical recommendations.
6. Report: Create a report and maps that portray management opportunities and supporting information important for making decisions about the future characteristics of the road system.

According to Bisson et al. (1999), a completed roads analysis will support the USDA Forest Service in making future management decisions by weighing the merits and risks of building new roads in previously unroaded areas; relocating, upgrading, or decommissioning existing roads; managing traffic; and enhancing, reducing, or discontinuing road maintenance. The USFS can also evaluate decommissioning priorities which includes thoroughly obliterating roads and restoring the environment, treatments to remove all hydrologic and erosion hazards, converting roads to trails, and simply closing roads without further action. Bisson et al. (1999) suggest that roads analysis can assist making future decisions based on the information at bioregional, provincial, subbasin, watershed, or project scales. Luce et al. (2001) discuss road decommissioning and highlight the need to include other resources in the prioritization scheme such as the value of aquatic habitat and presence of endangered species.

Information Systems and GIS Tools

Information systems help us to manage what we know, by making it easy to organize, store, access, retrieve, manipulate, synthesize, and apply data to the solution of problems (Longley et al., 2001). Relational Database Management Systems (RDBMS) are used to store and manage information in the form of records stored inside tables. MS Access, MS SQL Server, and Oracle are a few of the popular RDBMS. Relational databases use Structured Query Language (SQL) for specifying the organization of records (http://www.britannica.com/). SQL is used for creating, modifying, retrieving and manipulating data in a relational database.

The Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI) has a Hydrologic Information System project to improve infrastructure and services for hydrologic information. A hydrologic information system consists of a hydrologic information database coupled with tools for acquiring information to fill the database and tools for analyzing, visualizing and modeling the data contained within it (http://www.cuahsi.org/his.html). Part of this includes a data model for the storage and retrieval of hydrologic observations in a relational database (Horsburgh, Tarboton, and Maidment, 2005). A relational database format is used to provide querying capability that facilitates data retrieval in support of a diverse range of analyses.

Black and Luce (2002) describe the mechanics of collecting a road inventory dataset that can be used in a GIS to support scientifically sound watershed analyses for the USFS. Their paper explains the road sediment inventory procedure developed by the USFS to document the sources of sediment, how they interact with the road, and are ultimately routed to the hillslope and stream network. A portable Global Positioning System (GPS) unit is used to carry out the survey. The survey begins at a drainage point, moves through the road network draining to that point, and is completed when all of the segments leading to that drain are described. Data is stored in a road inventory data structure described by Black and Luce. This inventory is designed to quantify the rate of surface erosion due to overland flow from road surfaces. It can also be used to assess the risk of mass movement, gullying and stream capture. These analyses and their results can be useful for forest managers in planning new road construction, maintenance, evaluating best management practices, and setting decommissioning priorities (Black, and Luce, 2002).

A Geographic Information System (GIS) is used to provide a spatial framework to support decisions for the intelligent use of earth's resources and to manage the man-made environment (Zeiler, 1999). A GIS presents information in the form of maps and symbols. ESRI® ArcGIS™ (www.esri.com) is a popular GIS that has the capability of storing, accessing and manipulating information describing geospatial objects in a relational database referred to as a Geodatabase (Maidment, 2002). The ArcGIS framework allows users to customize the application with Microsoft's Component Object Model (COM) compliant languages like Visual Basic or Visual C++. ArcObjects are ArcGIS software components which expose the full range of ArcGIS functionalities to users (http://edndoc.esri.com/arcobjects/8.3/). Arc Hydro, TauDEM and SINMAP, described below, are a few GIS-based analysis tools that use the ArcGIS COM architecture and ArcObjects to develop custom toolbars which can be loaded in an ArcGIS ArcMap[TM] application.

Arc Hydro (http://www.crwr.utexas.edu/gis/archydrobook/ArcHydroTools/Tools.htm), is an ArcGIS data model with a set of GIS tools that allows users to build hydrologic information systems which synthesize geospatial and temporal water resources data for hydrologic analysis and modeling (Maidment, 2002). The Arc Hydro tools populate the attributes of the features in the data framework and interconnect features in different data layers. The data framework stores information about the river network, watersheds, water bodies, and monitoring points. All this is contained in a single ArcGIS geodatabase stored in the MS Access relational database format. Arc Hydro performs raster analysis of DEMs to produce Arc Hydro drainage features and build relationships between junctions and feature classes.

Tarboton (2003) describes Terrain Analysis Using Digital Elevation Models (TauDEM) (http://hydrology.neng.usu.edu/taudem) tool set as a set of functions for mapping stream networks and associated attributes from digital elevation models (DEM). TauDEM is implemented as an ArcGIS toolbar using Visual Basic, C++ and the ESRI ArcObjects library. The software accesses data in the ESRI grid data format directly using the GRIDIO application programmers' interface that is part of ArcView. TauDEM provides the capability to objectively select the channelization threshold based on geomorphology using a constant stream drop test (Tarboton, and Ames, 2001). TauDEM stream networks are output as shapefiles that contain an attribute table specifying network connectivity and other attributes. This shapefile attribute table provides a convenient data structure that can be extended to store sediment delivery and accumulation attributes for each stream segment.

Pack, Tarboton, and Goodwin (1998b) describe a terrain stability mapping tool called SINMAP (Stability Index MAPping) which uses a DEM in a GIS to compute and map slope stability. SINMAP was first developed for ArcView 3.0 in 1998, but with the appearance of ArcGIS, it was implemented by the author as an ArcGIS toolbar (http://hydrology.neng.usu.edu/sinmap2) programmed in ArcObjects, Visual Basic and Visual C++. The physical theory underlying SINMAP will be described below, because SINMAP output and modifications to SINMAP are useful for the analysis of road impacts.

Hydrologic Impacts of Roads

Wemple and Jones (2003) investigated how roads interact with hill slope flow in a steep forested landscape dominated by subsurface flow, and how road interactions with hill slope flow paths influence hydrologic response during storms. They suggested that road segments whose response increases the speed or magnitude of the overall hydrologic response of a catchment, should be identified and considered for decommissioning or road drainage improvement. Wemple and Jones examined the change in hydrologic response time of catchments with the construction of forest roads. They calculated the response times of the unsaturated and saturated zones using analytical solutions of Beven (1982a, 1982b) for kinematic subsurface storm flow on inclined slopes. These estimated response times were compared to observations of runoff behavior from road segments in Watershed 3 at the H. J. Andrews experimental forest in the Western Oregon Cascades.

Their findings show that runoff produced on some road segments may alter the timing and magnitude of hydrographs at the catchment scale.

The issue of hydrologic connectivity was addressed in Wemple, Jones, and Grant (1996). Using a field survey of roads and drainage features in the Oregon Cascades, 57 % of the road network was found to be hydrologically connected to stream channels. Wemple et al. identified two pathways that link roads to stream channels: ditches draining to streams (35% of culverts examined) and ditches draining to culverts with gullies incised below their outlets (23% of culverts). They noted that gully incision is significantly more likely below culverts on steep slopes with longer than average contributing ditch length. They found that in their study area these additional road related surface flow paths increased drainage density by 21 to 50% depending on which road segments are assumed to be connected to streams. Investigations of road hydrology in South Eastern Australia by Croke and Mockler (2001) found that between 11 % and 29 % of the road network was connected to streams resulting in a 6 % increase in the drainage density. Gullies were identified at 83 % of surveyed culverts.

Borga, Tonelli, and Selleroni (2004) developed a road interception algorithm to represent the formation of direct runoff from intercepted subsurface flow with its subsequent routing along the road drainage system. In their road interception algorithm, the amount of subsurface flow intercepted by the road is a linear function of the elevation of the water table relative to the base of the road cut, calculated as $h_i=h_w-d_{rc}$ where h_i is the intercepted subsurface flow elevation calculated from the water table elevation h_w, and the depth of the road cut base above the bedrock d_{rc}, both measured perpendicular to the slope (Figure 2-1). The relative road cut depth ($r_{rc}=d_{rc}/h$) is introduced to describe the interception potential for each grid element associated with a road.

Sediment Production from Road Surfaces

Sediment production from forest roads is a chronic problem due to their ability to generate excess runoff, fine sediment and their connection to the channel network. Reid and Dunne (1984) studied the amount of sediment mobilized by gravel road surface erosion in the central Clearwater basin, which lies between elevations of 50 and 1000 m on the western slope of Olympic Mountains of Washington State. They sampled rainfall, discharge, and sediment concentration in the catchments of road culverts. Reid and Dunne (1984) calculated rates of sediment production using relationships constructed from measurements of rainfall intensity, culvert discharge, and sediment concentration. Their study revealed that 81% of the total amount of sediment from the road surfaces was produced from roads subjected to heavy traffic which suggested that surfaces of gravel roads are extremely sensitive to the traffic intensity.

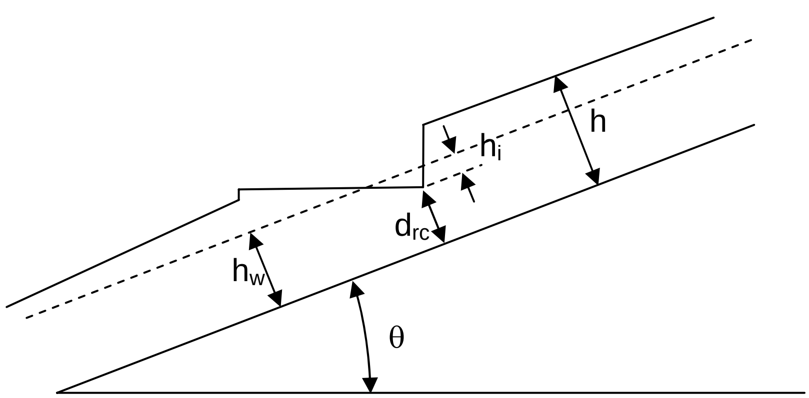


Figure 2-1. Schematic illustrating variables used in Borga's (2004) scheme for the interception of hillslope drainage by a road.

MacDonald, Sampson, and Anderson (2000) quantified the effect of unpaved roads on runoff and sediment production on St John in the US Virgin Islands and examined the key factors controlling runoff, erosion and sediment delivery. Their research involved measuring runoff and sediment production directly from vegetated plots and unpaved roads on St John and determining the controlling factors at both the plot and road segment scale. Their study showed that relatively undisturbed vegetated hillslopes on St John generate runoff only during largest storm events, and produce very little sediment, but that unpaved roads commonly generate runoff when rainfall exceeds 6 mm, and sediment yields from unpaved roads at the plot scale can be as high as 10-15 $kg/m^2/yr$. They also reported that unit area sediment yields from road segments that varied in length from 20 to 282 m were lower than the unit area sediment yields at the plot scale, although the one road segment with heavy traffic had an erosion rate of at least 7 $kg/m^2/yr$, more than twice that of comparable road segments with less traffic. They found that upslope contributing area was the best predictor of total sediment at the road segment scale because the cutslopes increase road runoff by intercepting subsurface flow, while road segment slope was the best predictor of unit area sediment yields.

Kahklen (2001) described a method developed in Southeast Alaska for measuring sediment production from forest roads and for determining possible impacts of road sediment on fisheries resources. Kahklen (2001) suggests a protocol to measure (1) sediment production from roads and (2) sediment transport from roads to small streams. In this protocol a road section with a uniform gradient and road surface that has a well-defined source area is selected for study. The road section should have cut slopes and a ditch with stable, erosion-resistant surface. The section should also have minimal interception of off-site surface and subsurface water by the ditch and should be located close to a stream if sediment delivery into streams is being studied. Two different sampling installations referred to as “road erosion sites” and “downstream transport sites” are used. Road erosion sites collect sediment in the ditch directly adjacent to the road, while downstream transport sites measure the sediment transported to small ephemeral or perennial streams. The method is designed to sample and compare sediment simultaneously at the road and downslope in small streams. According to Kahklen, this method can be used to determine the downstream transport of sediment originating from roads and can be used for developing regression models or validating existing sediment models.

The hydrologic and geomorphic effects of forest roads are closely linked to the linear nature of roads (Black, and Luce, 2002). Luce and Black (1999) examined the relationship between sediment production and road attributes such as distance between culverts, road slope, soil texture, and cut slope height in the Oregon Coast Range. From November 1995 to February 1996, varying amounts of sediment were collected in 74 sediment traps. Luce and Black hypothesized that sediment yield from road segments is related to length, L, and slope, S, according to a linear combination or product of L or $\sqrt{L}$ and S or S^2. Linear regression of measured erosion against these variables yielded the best relationship with sediment production proportional to the product of the road segment length and the square of the slope (LS^2) highlighting the importance of the road slope in the assessment of sediment budgets.

BOISED (Reignig et al., 1991) is the operational sediment yield model that is used by the Boise and Payette National Forests to evaluate alternative land management scenarios (http://www.epa.gov/OWOW/tmdl/cs2/cs2.htm). It is a local adaptation of the sediment yield model developed by the Northern and Intermountain Regions of the USFS (Cline et al., 1984) for application on forested watersheds of approximately 1 to 50 square miles. In BOISED, the total erosion from a uniform road segment within one landtype any year is calculated (Reignig et al., 1991) by:

$$Er = BER * DA * GEF * GF * MF * SDF \quad (2.1)$$

where Er is the total road sediment production (tons/year), BER is Base Road Erosion Rate which is erosion in tons per square mile of disturbed area per year from a standard road, assumed to be a maintained, 16 foot wide, native material road with a sustained grade of 5 to 7 percent, constructed on granitic material on a 50 percent side slope (Reignig et al., 1991). DA is Disturbed Area which is the total area disturbed by road construction expressed in square miles i.e. disturbed width times road length. Disturbed width is taken from default disturbed widths used for typical slope gradients (Reignig et al., 1991). GEF is Geological Erosion Factor which is a coefficient applied to management-induced surface erosion to account for the relative difference in erodability based on geologic parent material (Reignig et al., 1991). GF is Road Gradient Factor which is a coefficient used to correct for gradients other than the standard. MF is Mitigation Factor which is a coefficient used to express the percent reduction in erosion due to the application of erosion control practices. SDF is Sediment Delivery Factor which is a coefficient used to express the percent of onsite erosion which reaches streams.

Wold and Dubé (1998), discussed a road sediment model developed by Boise Cascade Corporation that identifies road segments with a high potential for delivering sediment to streams. The model divides the road network into three categories: segments that deliver sediment directly to streams (e.g. at stream crossings); segments that deliver sediment indirectly to streams (e.g. roads closely paralleling streams); and segments that do not deliver to streams (e.g. runoff directed onto the forest floor with an opportunity to infiltrate). The parameter inputs for the model to calculate sediment production from road segments are: geologic erosion factor, tread surfacing factor, road width and traffic factor, road slope factor, cutslope height, cutslope cover factor and precipitation factor. A sediment delivery factor was assigned to each road segment based on whether or not the segment drains directly or indirectly to a stream. Sediment production from the model was compared with field observations from six watersheds in Washington, Oregon, and Idaho, with a total area of about 500 square miles. Model sediment production estimates were 10 to 30 % more than field observations. According to Wold and Dubé model predictions will be more accurate with more information on road attributes.

Black and Luce's (2002), Wold and Dube's (1998), and BOISED (Reignig et al., 1991) models quantify sediment production from forest road segments, and identify the road segments with higher sediment yield. This is important information required for forest managers to plan maintenance operations.

Terrain Stability and Impacts of Roads on Terrain Stability

Predicting terrain instability due to the construction and use of forest roads is important for the management of forest ecosystems. The SHALSTAB (Montgomery, and Dietrich, 1994b; Dietrich et al., 1993; Montgomery, 1994) model is used in forest management to quantify potential instability and the risk of landslides. This model uses an assumed steady state recharge to calculate the saturation deficit at any point in the terrain. This is then combined with the infinite plane slope stability model to quantify terrain stability in terms of the critical steady state recharge required to trigger instability. Borga, Tonelli, and Selleroni (2004) applied the SHALSTAB model within a grid-based digital terrain model framework and model for interception of drainage by roads to quantify the effects of road geometry on quantification of landslide potential. The model for interception of drainage by roads was reviewed earlier (Figure 2-1).

SINMAP (Pack, Tarboton, and Goodwin, 1998a), uses an approach similar to SHALSTAB (Montgomery, and Dietrich, 1994b; Dietrich et al., 1993; Montgomery, 1994) to model the spatial potential for the initiation of shallow landslides. SINMAP combines a mechanistic infinite slope stability model with a steady-state hydrology model and is primarily governed by specific catchment area and slope. SINMAP (Pack, Tarboton, and Goodwin, 1998a) balances the destabilizing components of gravity and the restoring components of friction and cohesion on a failure plane parallel to the ground surface with edge effects neglected. In SINMAP the infinite slope stability model factor of safety is given by

$$FS = \frac{C + \cos\theta[1 - \min\left(\frac{R}{T}\frac{a}{\sin\theta}, 1\right) r]\tan\phi}{\sin\theta} \qquad (2.\ 2)$$

where r is the ratio of the density of water to the density of wet soil, C is a relative cohesion term defined as $(C_r + C_s)/(h\ \rho_s\ g)$ where C_r is root cohesion, C_s is soil cohesion, h is the thickness of the soil perpendicular to the slope, ρ_s is the density of soil, g is gravitational acceleration (9.81 m/s^2), θ is the slope angle, ϕ is the friction angle of the soil, *T* the soil transmissivity, *a* the specific catchment area and *R* the proportionality constant relating lateral discharge to contributing area, interpreted as a steady state recharge. The variables *a* and θ are obtained from the topography with *C*, $tan\phi$ and *R/T* taken as parameters The authors consider the density ratio *r* as constant and allow uncertainty in the parameters *C*, $tan\phi$ and *R/T* by specifying a lower and upper bound for each.

The SINMAP stability index (SI) is defined from the factor of safety (FS) as the probability that a location is stable (FS>1), assuming uniform distributions of the uncertain or variable parameters, *C*, $tan\phi$, *R/T*, over specified ranges.

$$SI = \text{Prob}(FS>1) \tag{2.3}$$

In the case where $FS > 1$ for all parameters, *SI* is set to the value of *FS* for the worst case scenario parameters, i.e. minimum *C* and $\tan\phi$ and maximum *R/T*.

SINMAP was implemented by Pack, Tarboton, and Goodwin (1998a) as a GIS tool that uses a digital elevation model as input to derive a stability index map.

Road related impacts on erosion and terrain stability generally result from concentration of both runoff generated on the road surfaces and intercepted subsurface discharge (Montgomery, 1994). Montgomery (1994) suggested that the geomorphic effects due to road drainage concentration may be sufficient to initiate or enlarge a channel due to increase in discharge, and concentrated discharge may contribute to slope instability below the drainage outfall. He compared models for erosion initiation by overland flow and shallow landsliding with data from field surveys of road drainage concentration in three study areas in the Western United States**.** Montgomery (1994) came to the conclusion that the concentration of road drainage is associated with both integration of the channel and road networks and landsliding in steep terrain.

<u>The Impacts of Roads on Erosion Sensitivity</u>

Forest roads have been shown to produce substantial volumes of runoff (Reid, and Dunne, 1984) and to discharge water at specific and often unstable points on the hillslope (Montgomery, 1994). Montgomery and Dietrich (1992), and Dietrich et al. (1993) showed that data from channel heads observed in their Tennessee valley, California field site have an inverse relationship between the specific catchment area a and local slope S of the form $aS^{\alpha} = C$, where C is a constant, a is the specific catchment area, S is the slope and α is an exponent that varies between 1 and 2. They found that with $\alpha = 2$, all channel heads observed are captured between two topographic threshold lines with C values of 25 m and 200 m.

Gully incision is significantly more likely below culverts on steep (> 40 percent) slopes with longer than average contributing ditch length (Wemple, Jones, and Grant, 1996). Wemple, Jones, and Grant (1996) assessed the hydrologic integration of an extensive logging-road network with stream network in two adjacent basins in the western cascades of Oregon. Their findings show that 57% of the road network in the basins studied was hydrologically connected to the stream network and enhanced routing efficiency due to connected road segments explained the changes in hydrograph following construction of roads. Their study outlined a general approach for assessing the magnitude of hydrologic effects of road in channel initiation.

The factors leading to gully initiation below roads has been examined as a function of contributing length of road (Croke, and Mockler, 2001) and length modified by hillslope slope (Montgomery, 1994). Montgomery (1994) compares models developed by Montgomery and Dietrich (1994a), and Dietrich et al. (1993) for erosion initiation by overland flow and shallow landsliding with data from field surveys of road drainage concentration in the Western United States: near Oiler Peak in the southern Sierra Nevada, California; on Mettman Ridge in the Oregon Coast Range, and along Huelsdonk Ridge on the Olympic Peninsula, Washington. The data from Mettman Ridge (Montgomery, and Dietrich, 1992) reveals that overland flow-initiated channel heads associated with road drainage plot at lower drainage areas than natural channel heads. Montgomery (1994) presumes this reflects the lower infiltration capacity for road surfaces than natural slopes. Montgomery (1994) approximates the empirical threshold road length required for channel initiation at the runoff discharge point (road drain point) in Huelsdonk Ridge to be:

$$L = 70\ m/\sin\theta \qquad (2.4)$$

For the Mettman Ridge data this threshold road length is:

$$L = 30\ m/\sin\theta \qquad (2.5)$$

According to Montgomery (1994) the difference in the contributing road length for channel initiation in these sites reflects the differences in climate and soil properties between these study areas.

Istanbulluoglu et al. (2001a) also studied the initiation of channels. In their paper they described how substantial amounts of sediment are transported from hillslopes to streams due to flow concentration and incision of channels. Istanbulluoglu viewed the channel initiation problem probabilistically with a spatially variable probability. They suggested that channel initiation depends on the slope, specific catchment area, and the probability distribution of median grain size, surface roughness, and excess rainfall rate. Istanbulluoglu et al. (2001a) tested this theory using field data collected from Trapper and Robert E. Lee Creeks in Idaho. The probabilistic model they developed was capable of producing a probability distribution of channel initiation threshold that matches the observed slope–area dependent channel initiation threshold. They conclude that channel initiation in different topographic locations depends on the model input values, such as variation of runoff rates and additional roughness due to vegetation cover, that characterize climate and land cover variability.

Road Stream Crossing Blockage and Habitat Segmentation

Road stream crossing and ditch relief culverts are common sites of ongoing or potential erosion (Flanagan et al., 1998). This can eventually result in blocking of culverts due to accumulation of sediment and organic debris. Identifying and locating these failure sites is an important step in planning road maintenance. Debris lodged at the culvert inlet reduces hydraulic capacity and promotes further plugging by organic debris and sediment. According to Flanagan et al. (1998), channel width influences the size of transported woody debris. From their study conducted in northwest California, 99 percent of transported wood greater than 300 mm long was less than the channel width. These findings led them to suggest that culverts sized equal to channel width will pass a significant portion of potentially pluggable wood. The configuration of inlet basin was also found to be a factor for wood plugging. These considerations led Flanagan et al.

(1998) to suggest the ratio of culvert diameter to channel width and the channel skew angle as factors related to plugging potential.

Dunne and Leopold (1978) describes the bankfull width of the river channel as a function of drainage area. They provide a relationship between observed channel width and drainage area for a number of locations. They suggest that a comparable graph could be constructed for any region by making field measurements of local channels. In particular, Dunne and Leopold (1978) report that the relationship between channel width and drainage area for the Upper Salmon River in Idaho is:

$$C = 7A^{0.404} \tag{2.6}$$

where C is the channel width in feet and A is the drainage area in square miles. This relationship can be used to calculate a probable channel width for road stream crossing based on the drainage area at that point. This is useful in screening for errors due to mislocation of stream crossing drain points that will be used in the analysis of fish habitat fragmentation.

Clarkin et al. (2003) describe the inventory procedure followed by the USFS to identify stream crossings that impede passage of aquatic organisms in or along streams. Clarkin et al's barrier inventory assessment process is summarized as follows:

1. Establish the watershed context. Build and overlay maps of streams, roads, land ownership, analysis species distribution, aquatic habitat types and habitat quality.
2. Collaboratively establish criteria for regional screens. Develop analysis species lists and criteria with the assistance of experts.

3. Conduct the field survey at stream crossings.
4. Determine barrier category as either resembling natural channel or analyzing, for specific species, whether crossing is passable.
5. Map barrier locations and overlay on habitat-quality maps to set priorities for restoring connectivity aimed at maximum biological benefit.

The ideas put forth by Flanagan et al. (1998) and Clarkin et al. (2003) can be used to identify stream crossings which are probable fish passage barriers and to locate habitat clusters. This information can be used by forest managers to prioritize and plan for stream crossing culvert restorations aimed at reconnecting fragmented habitat.

CHAPTER 3

STUDY AREA AND ROAD INVENTORY

Study Area

The relational database model and GIS tools developed in this project were tested using data from the South Fork of the Payette River in the Boise National Forest in Idaho where there is an existing road inventory on predominantly public land (Figure 3-1). This area is underlain by Idaho batholith granite, characterized by deeply incised fluvial valleys cutting broader uplands of moderate elevation (Meyer et al., 2001). From Meyer et al. (2001), annual precipitation varies strongly with elevation, from about 600 mm in the lower valleys to 1000 mm or more at higher elevations. The mean temperature in January at Lowman is -5 °C and about 60% of annual precipitation falls as snow with snowmelt dominating the runoff which occurs from March to May. The annual average precipitation at the lowest elevation station located in Lowman is 26 inches per year with the majority falling as snow in the winter months of November through March (Western Regional Climate Center). In the lower South Fork Payette River basin, sparse ponderosa pines (Pinus ponderosa), shrubs, grasses, and forbs cover dry low-elevation and south-facing slopes. Denser ponderosa pine and mixed pine–fir communities are found at middle elevations and on more shaded aspects, and thick forests of Douglas fir (Pseudotsuga menziesii) cover higher, north-facing slopes (Meyer et al., 2001). According to a USDA Forest Service website (http://www.fs.fed.us/r4/boise/) the forest contains large expanses of summer range for big game species like mule deer and Rocky

Mountain elk. Trout are native to most streams and lakes. Ocean going salmon and steelhead inhabit tributaries of the Salmon River.

The Digital Elevation Model (DEM) for the study area was obtained in ESRI grid format from the National Elevation Dataset server (seamless.usgs.gov) then projected and re-sampled to 30 m grid cell size using bi-cubic interpolation in ArcGIS. The area under investigation lies between 44.65 N to 43.81 N and 116.20 W to 114. 88 W and is approximately 5665 km^2.

A 303 km2 subset of the study area was used for analyzing fish habitat segmentation. A higher resolution 10 m grid cell size DEM was re-sampled from the National Elevation Dataset for this area. Table 3-1 gives more information about the full DEM and the subset used for fish habitat analysis.

Road Inventory

A road inventory was conducted in this area during the summer of 2004 in the months of June through August using three teams of two persons. They were Student Conservation Association volunteers working for the USDA Forest Service Boise National Forest. Much of the region that was surveyed is not accessible by wheeled vehicle before June due to snow and wet conditions. The inventory was conducted according to procedures developed by Black and Luce (2002).

A GPS device was used to collect the location information on drain points and road line features associated with the road network. The USFS road inventory data file was created using Trimble® GPS Pathfinder® Office software (http://www.trimble.com/pathfinderoffice.shtml). Appendix 1 gives the data dictionary

Table 3-1. Properties of the DEM for the study area and the subset study used for habitat segmentation analysis

Properties	Full DEM	Habitat Analysis Subset
Grid size	3465 x 3056 cells	1582 x 1918 cells
Cell size	30 x 30 m	10 x 10 m
Format	ESRI Grid	ESRI Grid
Pixel type (Grid type)	Floating point	Floating point
Minimum elevation	788 meters	1030 meters
Maximum elevation	3270 meters	2479 meters
Projection/Spatial Reference	GCS North American Datum 1927	GCS North American Datum 1927

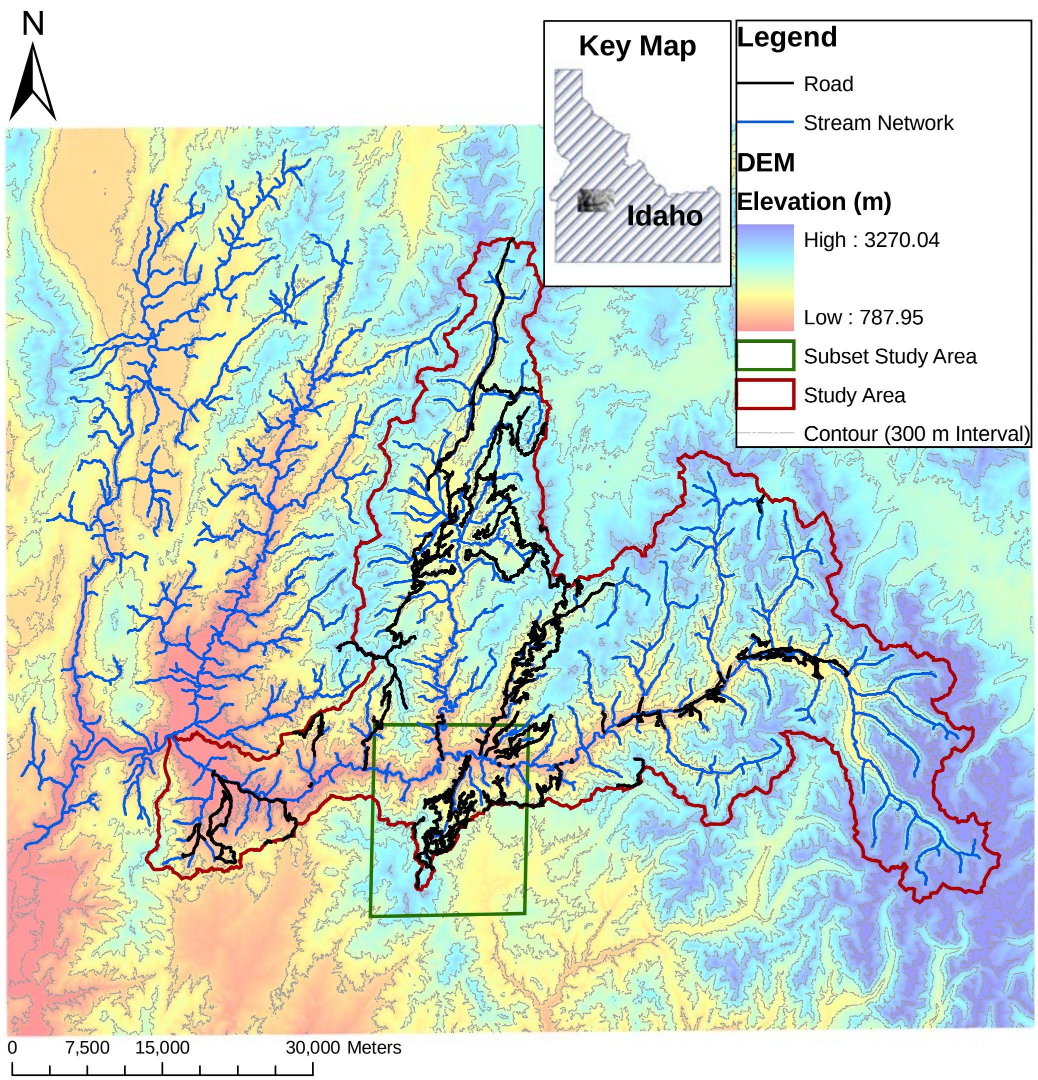


Figure 3-1. South Fork of Payette River in Boise National Forest, Idaho study area.

for the USFS road inventory survey data tables. The data file was loaded onto a laptop with Trimble® TerraSync™ (http://www.trimble.com/terrasync.shtml) software that, in conjunction with the Trimble® GPS Pathfinder Pro XRS Receiver (http://www.trimble.com/pathfinderproxrs.shtml), was used for the field surveys. TerraSync ™ provided a menu driven data collection interface for the GPS. Upon completion of the survey the GPS data was differentially corrected by the survey crew using the Pathfinder Office software. This process was used to improve the GPS precision. The dataset was then converted into ESRI's shapefile format.

Drain points

The road inventory assigned a tracking number and collected information on each road drain point. This information documents the disposition of the water as it flows downhill away from the road. The physical condition of drain points was also recorded and stored as drain point attributes.

A total of 7164 drain points were mapped during the survey of the study area. Table 3-2 lists eight different drain point types and the number of drain points in each type, for the complete dataset and for the subset used for habitat fragmentation analysis. Appendix 1 lists the attributes recorded for each drain point by type.

Road line segments

The road inventory gathered information on the road network at the scale of road line segments. Attributes for each road segment, such as surface type, cut slope height, etc. were recorded for each segment and stored in the inventory database. A road line segment was terminated and a new segment started when one of the attributes changed.

Table 3-2. Drain point summary information from USDA Forest Service road inventory

Drain point type	Shapefile name	Number of points in the full dataset	Number of points in habitat analysis subset
Broad Based Dip	BBdip.shp	346	12
Diffuse	DiffDrain.shp	402	62
Ditch Relief	Ditch_rel.shp	2524	264
Lead Off	Lead_off.shp	290	4
Non-Engineered	Ned.shp	1298	270
Stream Crossing	Str_Xing.shp	672	88
Sump	sump.shp	212	18
Waterbar	waterbar.shp	1420	213

The road line attributes describe three types of information: 1) the side of the road where concentrated flow occurs, 2) the drainage feature receiving flow from that segment, and 3) the physical condition of the road prism. The drain point receiving water from each road segment was identified using the drain point tracking number. Each side of the road segment can drain to different drain points. Consequently each road segment has two drain point tracking numbers associated with it designating the drain points to which each side drains.

The GPS survey was conducted for 8280 road line segments. The total length of the road network is 721 km. Out of 8280, 1484 road segments with a total length of 109 km were mapped as high clearance road type and rest as system road type. 1025 road line segments with a total length of 99 km were present in the subset area used for habitat segmentation analysis. Appendix 1 lists the road line shapefile attributes collected during the road survey.

CHAPTER 4

METHODS AND MODEL DESIGN

In order to analyze the USDA Forest Service road inventory data to determine the impact of roads on forest watersheds a set of GIS based analysis tools were developed. These tools are called the Geomorphologic Road Analysis and Inventory Package (GRAIP). The GRAIP model consists of:

1. The GRAIP database schema
2. The GRAIP database preprocessor to ingest and validate USFS road inventory data while loading it into the database.
3. A set of GIS procedures to delineate the stream network segmented at points where roads cross streams.
4. A set of GIS procedures to develop a slope stability index map.
5. The GRAIP road surface erosion module to quantify the sediment production from each road segment and sediment delivery to the stream system.
6. The GRAIP mass wasting potential module to quantify the potential for mass wasting due to the impacts of road drainage on both landslide and erosion risk.
7. The GRAIP stream blocking analysis module to quantify the plugging risk of road drains.
8. The GRAIP habitat contiguity module to identify road stream crossings that block fish passage and fragment habitat.

Each element will be described in detail in the sections that follow with additional detail in appendices. Appendix 2 gives details of the tables used in the GRAIP database.

Appendix 3 details the TauDEM stream network shapefile and its extensions to accommodate GRAIP outputs. Appendix 4 provides a step by step tutorial on using the GRAIP preprocessor and Appendix 5 provides a tutorial on using the GRAIP GIS tool.

GRAIP Database Schema

A relational database schema has been developed for a database to store the road inventory information in a systematic, organized fashion that preserves data integrity.

A relational database is a collection of data structured in accordance with a relational model. Here the relational database model was developed to organize the information obtained from the USDA Forest Service (USFS) road inventory survey. The USFS road inventory consists of a DEM and a set of drain points and road lines shapefiles with attributes of each feature stored in the file's attribute table as listed in Appendix 1.

To improve querying capabilities and ensure data integrity and consistency the GRAIP relational database model was designed as a Microsoft Access Database so as to validate and screen invalid records before the actual GIS analysis. The MS Access database provides efficient data storage, and retrieval as well as better data editing and updating capabilities than the tools that survey crews have been using.

The relational database model has the following groups of tables.

Master tables

The master tables comprise one table with attributes common to all eight drain point types, eight tables with additional attributes corresponding to each drain point type, and a road lines table. These tables are listed in Table 4-1. The inventory information about the drain points and road lines are imported and stored in these tables. Surveyed drain points attributes which are common to all eight drain point types (Table 3-2) are stored in the DrainPoints table while additional attributes corresponding to each drain point type are stored in the drain point attribute tables named according to the convention "<drain point type>Att" (BroadBaseDipAtt, LeadOffAtt, etc.). Figure 4-1 gives the part of the schema showing the relationships between the DrainPoints table, the eight drain point type attribute tables and the RoadLines table. Appendix 2 lists the fields in each of these tables. A key attribute GRAIPDID is used to establish the relationship between drain type specific attribute tables and the common DrainPoints table. This key attribute is also used in RoadLines to identify the drain point to which each side of each road segment drains. This key appears as GRAIPDID1 and GRAIPDID2 in RoadLines because each road segment has two sides. Each Road segment in RoadLines is also identified by a key field GRAIPRID.

Table 4-1. Tables in the master tables group

Table Name	Description
DrainPoints	Attributes common to all types of drain points
RoadLines	Attributes common to all types of road lines
BroadBaseDipAtt	Attributes of Broad Based Dip Drain Points
DiffuseDrainAtt	Attributes of Diffused Drain Points
DitchReliefAtt	Attributes of Ditch Relief Drain Points
LeadOffAtt	Attributes of Lead Off Drain Points
NonEngAtt	Attributes of Non-Engineered Drain Points
StrXingAtt	Attributes of Stream Crossing Drain Points
SumpAtt	Attributes of Sump Drain Points
WaterBarAtt	Attributes of Water Bar Drain Points

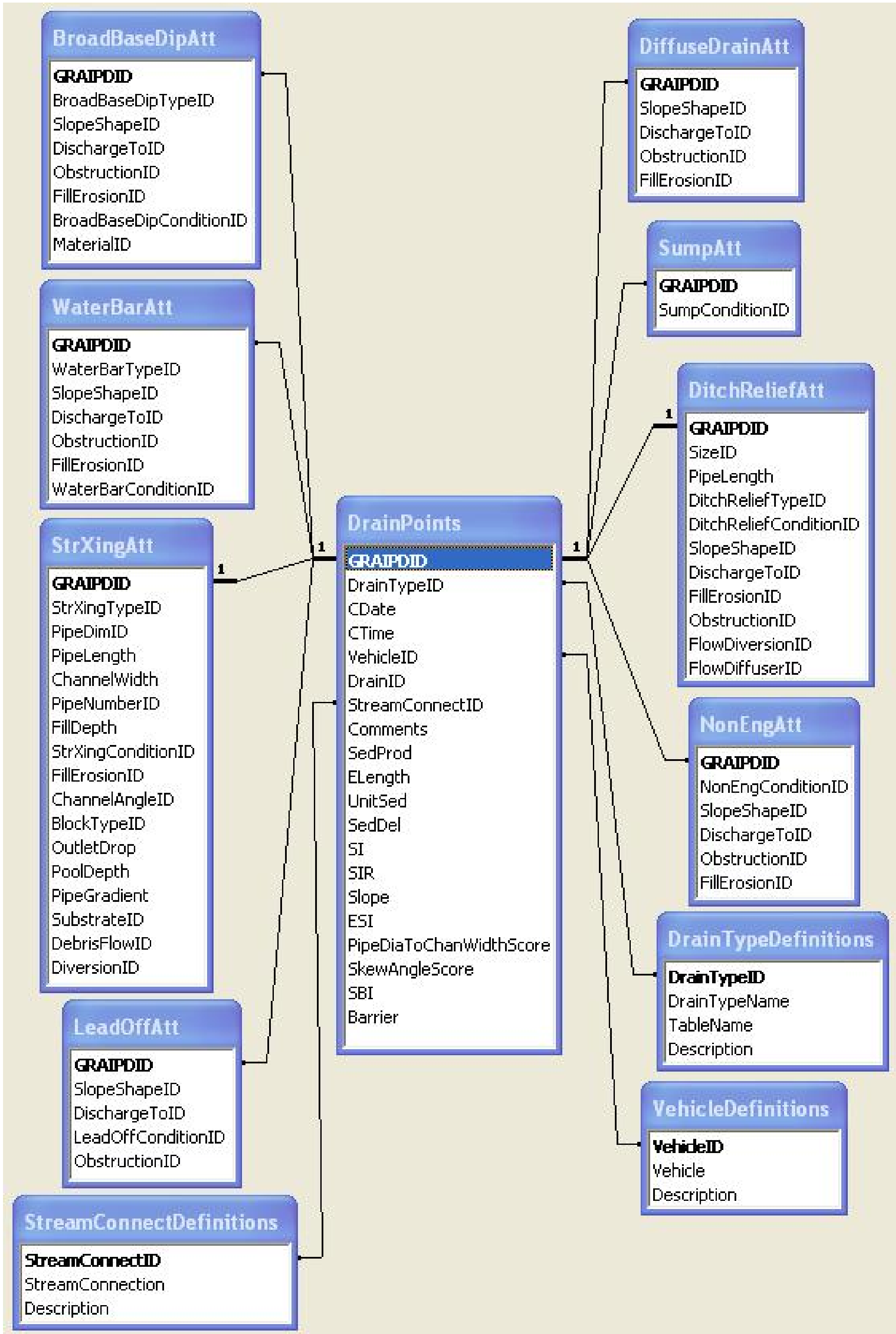


Figure 4-1. The GRAIP database schema showing the relationships between master tables.

<u>Preferred values tables</u>

The preferred values group of tables holds the valid or preferred values for each attribute of a drain point or road line. Each preferred value for each attribute is assigned a unique integer identifier and these tables list the physical quantity, class or condition associated with each identifier. Preferred values tables are listed in Tables 4-2, 4-3 and 4-4. These are categorized as applying to drain points, road lines, or common to both; the VehicleDefinitions table is common to both drain points and road lines. Appendix 2 gives the contents of these tables. Figure 4-2 gives the part of the schema depicting the relationship between a drain point attribute table (in this example, the DitchReliefAtt table) and its preferred values tables. Figure 4-3 gives the part of the schema depicting the relationship between RoadLines and the Road Line preferred values tables.

Table 4-2. Drain Point preferred values tables

Table Name	Description
BlockTypeDefinitions	Stream crossing blockage conditions (e.g. Organic Debris Pile)
BroadBaseDipCondDefinitions	Broad Base Dip conditions (e.g. Puddles on road)
BroadBaseDipTypeDefinitions	Broad Base Dip types (e.g. Flat Ditch)
ChannelAngleDefinitions	Channel Angle classes (e.g. <25 degrees)
DebrisFlowDefinitions	Indicator for presence of Debris Flow at stream crossing (e.g. Yes/No)
DischargeToDefinitions	Indicator of what drain point discharges to (e.g. Gully)
DitchReliefCondDefinitions	Gives the condition of Ditch Relief drain points (e.g. Partially Crushed)
DitchReliefTypeDefinitions	Gives the type of pipe used at Ditch Relief drain points (e.g. ALM (Aluminum)
DiversionDefinitions	Gives the number of directions in which flow is diverted at a stream crossing.
DrainPointTypeDefinitions	Gives the type of each drain point (e.g. Broad base dip) and name of type specific attribute table (e.g: BroadBaseDipAtt).
FillErosionDefinitions	Indicator of the presence or absence of erosion of road fill at a drain point (e.g. Yes/No)

Table 4-2 continued

FlowDiffuserDefinitions	Ditch relief drain point flow diffuser type. (e.g. Half Pipe Fabric)
FlowDiversionDefinitions	Indicator of the presence or absence of flow diversion at a ditch relief drain point. (e.g. Yes/No/Unknown)
LeadOffCondDefinitions	Condition of lead off drain point (e.g. Gullied)
MaterialDefinitions	Road surface material at a broad based dip. (e.g. Native Soil)
NonEngCondDefinitions	Condition of non-engineered drain point (e.g. Diverted wheel track)
ObstructionDefinitions	Indication of the degree of obstruction at a drain point (e.g. None/Moderate/Abundant)
PipeDimDefinitions	Stream crossing pipe size class (e,g: 12 for 12 inch round pipe or 13X17 for oval pipe 13 inches x 17 inches)
PipeNumberDefinitions	Number of pipes used at a stream crossing. (e.g. 1)
SizeDefinitions	Ditch relief drain point pipe size (e.g. > 24")
SlopeShapeDefinitions	Shape of the slope to which a drain point discharges. (e.g. Concave)
StreamConnectDefinitions	Indicator of whether drain point discharges directly to a stream. (e.g. Yes/No)
StrXingCondDefinitions	Condition of stream crossing culvert/pipe. (e.g. Totally crushed)
StrXingTypeDefinitions	Type of stream crossing. (e.g. Steel culvert round or Natural ford)
SubstrateDefinitions	Substrate material at a stream crossing. (e.g. Sand)
SumpCondDefinitions	Condition of sump drain point. (e.g. Fill saturation)
WaterBarCondDefinitions	Condition of a waterbar drain point. (e.g. Wheel track damage)
WaterBarTypeDefinitions	Material used for waterbar construction. (e.g. Road material or Fabricated material)

Table 4-3. Road Lines preferred values tables

Table Name	Description
EdgeConditionDefinitions	Condition of the road cut or fill slope, repeated for each side of the road. (e.g. Badly rilled)
EdgeVegetationDefinitions	Density classes for road side vegetation, repeated for each side of the road. (e.g. > 75%)

Table 4-3 continued

FillChannelDefinitions	Distance classes from fill slope toe to channel edge (ft). (e.g. 1-20,[20])
FlowPathCondDefinitions	Condition of road side flow path, repeated for each side of the road. (e.g. Rutted)
FlowPathDefinitions	Types of road side flow path, repeated for each side of the road. (e.g. Wheel tracks or Base of cut)
FlowPathVegDefinitions	Density classes for vegetation in road side flow path, repeated for each road side (e.g. > 75%). This table also holds the multiplier used to adjust road segment sediment production based on road side flow path vegetation. (e.g. 0.14 for >25% vegetation)
RoadEdgeDefinitions	Road edge cutslope height or fill feature categories, repeated for each road side. (e.g. 0' no ditch, fill or 6' to 18' cutslope height)
RoadNetworkDefinitions	Table containing the road network's base erosion rate parameter used to calculate sediment production. A default is provided but if a specific road network requires a different base rate, additional records should be added to this table.
RoadTypeDefinitions	The type of the road. (e.g. System road)
SurfaceConditionDefinitions	Road surface condition. (e.g. Rilled/eroded)
SurfaceCoverDefinitions	Categories for density of road surface vegetation cover. (e.g. >10%)
SurfaceTypeDefinitions	Road surface type. (e.g. Paved or Herbaceous Veg.) This table also holds the surface multiplier which is used in calculating sediment production (e.g. 0.2 for paved or 1 for Herbaceous Veg)

Table 4-4. Common preferred values tables

VehicleDefinitions	Vehicle used to conduct the road survey. (e.g. Survey Truck).

General information tables

Table 4-5 lists a group of utility tables used for database management and the recording of errors that occur during pre-processing. Appendix 2 lists the fields in each of these tables.

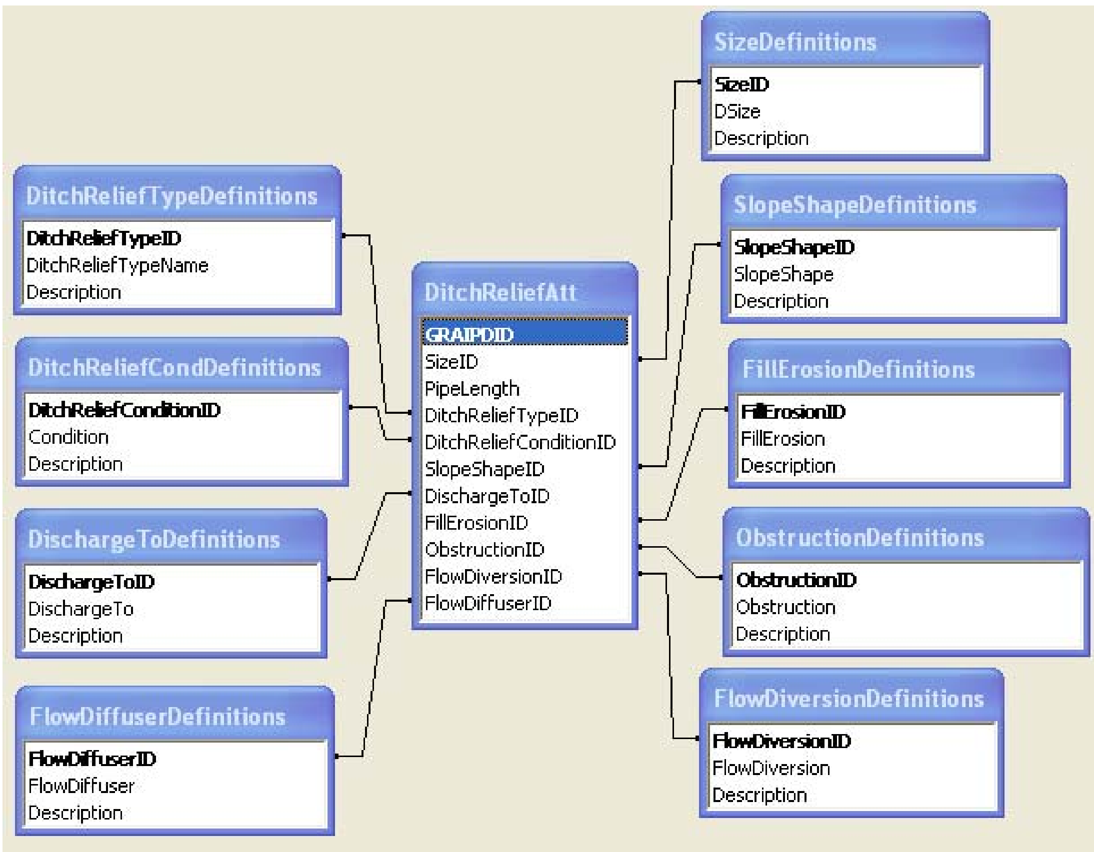


Figure 4-2. Schema representing the relationship between the Ditch Relief attributes table and its preferred values tables.

GRAIP Database Preprocessor

The database preprocessor tool was developed using Visual Basic 6.0, Visual C++ and Structure Query Language (SQL) that is used to query, edit and add records to the database. During preprocessing, unique identifiers are assigned to each drain point and road line to eliminate ambiguity in data retrieval.

The GRAIP Database Preprocessor Tool imports the existing shapefile attributes, created by the USFS from the road survey, into a MS Access database. The USFS road inventory dataset contains a set of drain point and road line shapefiles. These, together

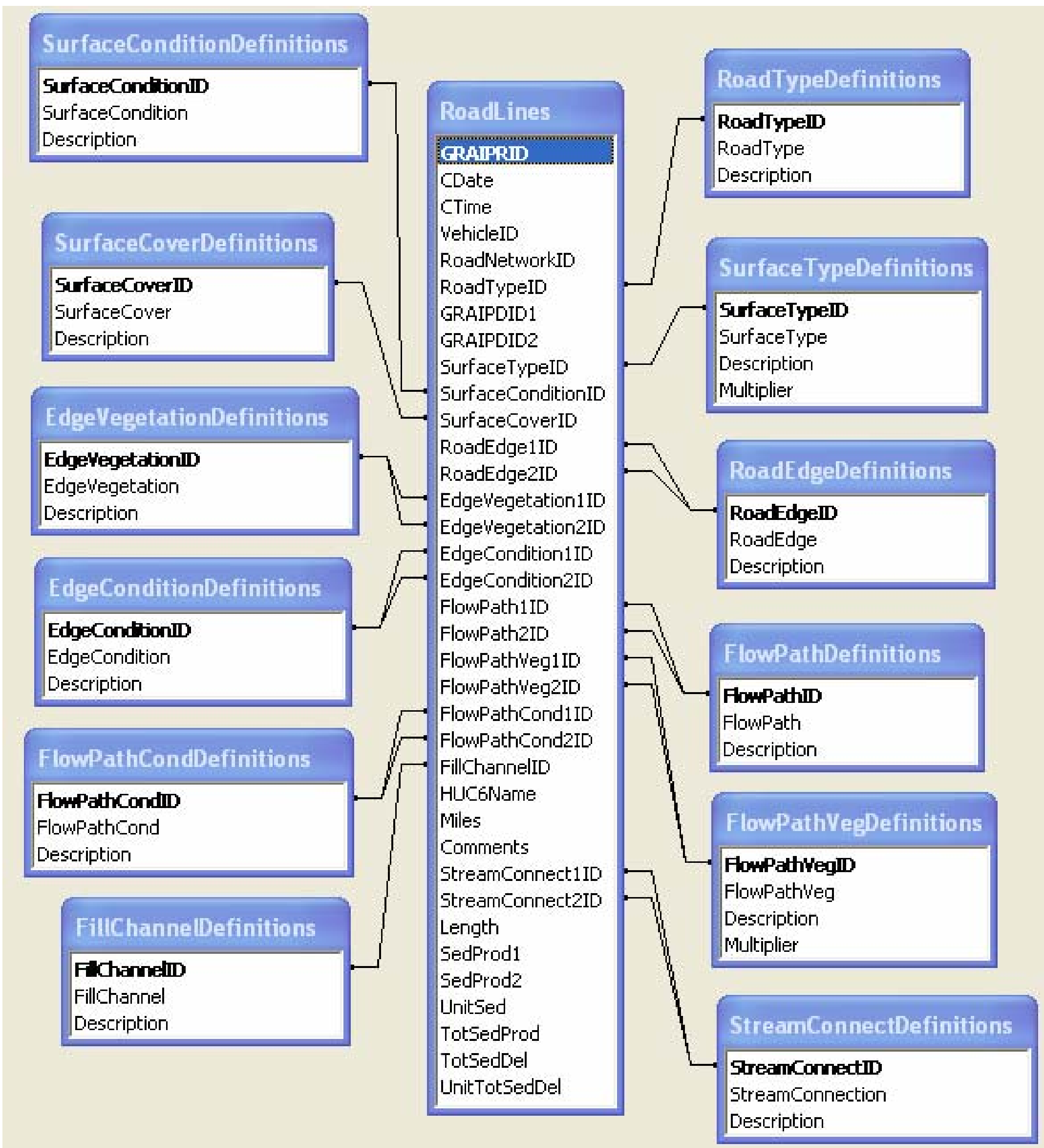


Figure 4-3. Schema of relationship between road lines and its preferred values definition tables.

Table 4-5. Utility tables

Table Name	Description
FieldMatches	Provides default matches between fields in the original road inventory with fields in the GRAIP database for use by the preprocessor.
ValueReassigns	Contains information about the unrecognized values in the road inventory reassigned to an existing preferred value in the associated GRAIP database preferred values table during data preprocessing
DPErrorLog	Information about the errors encountered by the preprocessing operation while importing Drain points attributes in to the GRAIP Database model
RDErrorLog	Information about the errors encountered by the preprocessing operation while importing Road lines attributes in to the GRAIP Database model
MetaData	Lists the preferred value definitions table associated with each identifier field in the GRAIP Database.

with a DEM of the area are provided as input to the GRAIP Database Preprocessor tool. The preprocessor operation is illustrated in Figure 4-4 and comprised of the following steps:

1. File name input. Create a project file with extension ".graip" which stores names of the input DEM grid file, drain point and road line shapefiles, GRAIP database file and consolidated drain point and road line shapefiles that are outputs.
2. Drain point shapefile processing. Enter field matching dialog and use field matches table to map between source USFS inventory shapefiles and target GRAIP database table field names.
3. Assign a unique identifier GRAIPDID for each drain point.
4. Assign the DrainPointTypeID field corresponding to the drain point type.
5. Validate each matched drain point attribute from the USFS inventory shapefile with preferred values from the GRAIP preferred value definitions tables and store the corresponding identifier in the associated field in the GRAIP database. The attribute

validation dialog is used to resolve attributes that do not match with definitions by either reassigning them to the default value, another existing value in the definitions table, or adding a new value to the definitions table.

6. Road shapefile preprocessing. Enter field matching dialog and use field match table to map between source USFS inventory shapefile and target GRAIP database table field names. This dialog also includes an interface to identify the Road Network and associated base road erosion rate.
7. Assign a unique identifier GRAIPRID for each road segment.
8. Assign the RoadNetworkID field corresponding to the Road Network to each road segment.
9. For each road segment match the input USFS inventory DRAINID1 and DRAINID2 fields that designate the drain point to which each side of the road drains with the DRAINID field in the database drain points table and assign GRAIPDID1 and GRAIPDID2 key fields to reference the corresponding drain point.
10. Validate each matched road segment attribute from the USFS inventory shapefile with preferred values from the GRAIP preferred value definitions tables and store the corresponding identifier in the associated field in the GRAIP database. The attribute validation dialog is used to resolve attributes that do not match with definitions by either reassigning them to the default value, another existing value in the definitions table, or adding a new entry to the definitions table.
11. Orphan drain points. Check for drain points without any roads draining to them and log in the DPErrorLog file and table in the GRAIP database.

12. Road-Stream connectivity and orphan roads. Check the drain point that each side of each road segment drains to and if it is stream connected assign the corresponding road stream connection attribute (StreamConnect1ID or StreamConnect2ID) to indicate that stream connectivity. If the road line segment does not drain to any drain point, log it as an orphan road segment in the RDErrorLog file and table in the GRAIP database.
13. Consolidate multiple drain point shapefiles to a single shapefile (DrainPoints.shp) with GRAIPDID field that references the drain points table in the GRAIP database.
14. Consolidate multiple road line shapefiles to a single shapefile (RoadLines.shp) with GRAIPRID field that references the road lines table in the GRAIP database.
15. Tables 4-6 and 4-7 give the data structure of the DrainPoints and RoadLines and shapefiles.

The GRAIP database is a Microsoft Access database file. The database preprocessor tool uses generic ADODB components to read and write the database and an open source shapelib library to read and write shapefiles. The database preprocessor does not depend upon ArcGIS components so that it can be used on any Windows computer. This allows the survey crew to screen and validate the inventory data being collected in the field, or without returning to base and entering the data into the GIS. Appendix 4 gives documentation on using the GRAIP Preprocessor tool.

Stream Crossings and Stream Network Delineation

The USFS Road inventory surveys conditions that can be used for the analysis of the fish passage status at stream crossings. This analysis requires that a stream network

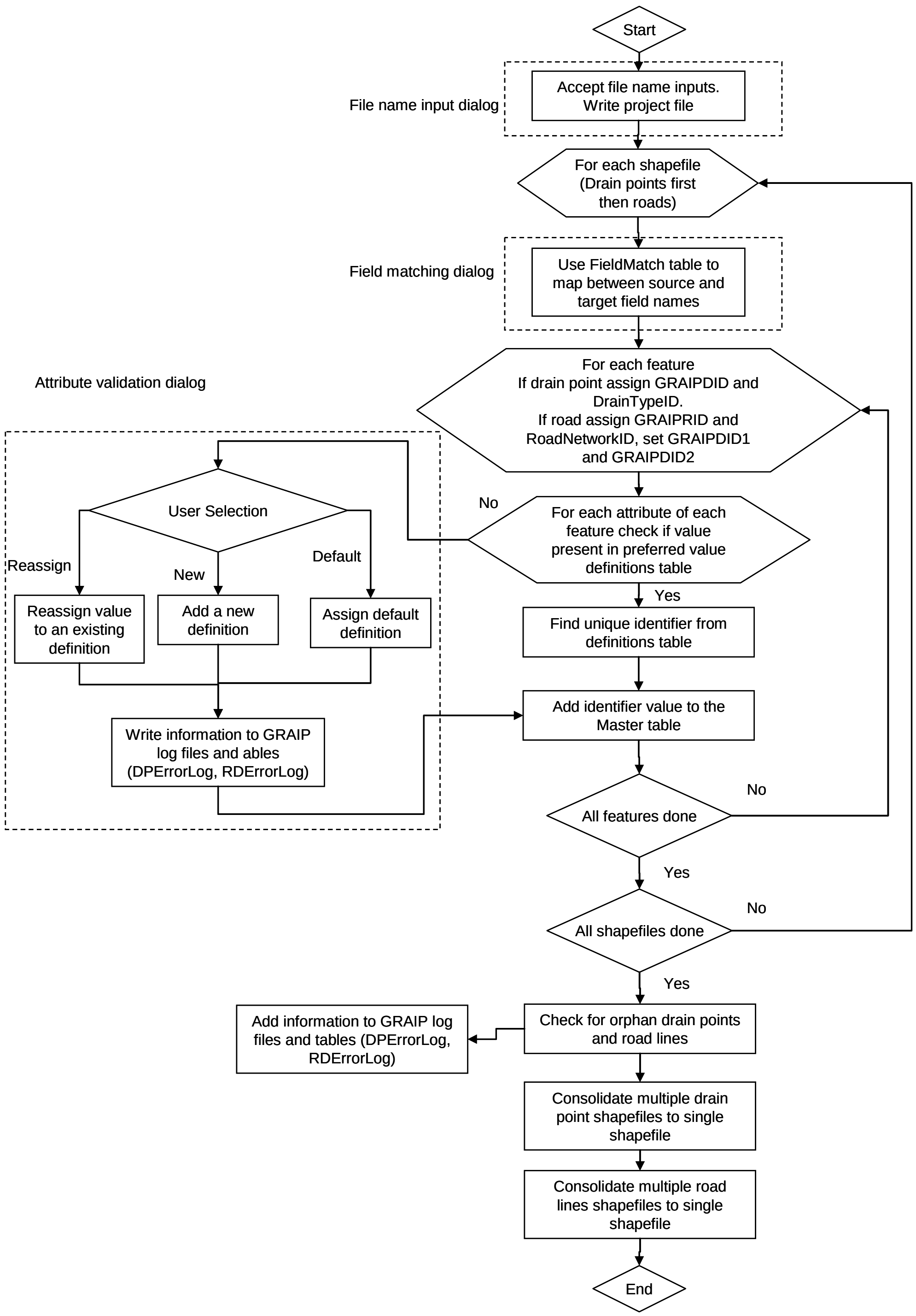


Figure 4-4. Preprocessing algorithm for validating and importing attributes to GRAIP Database.

Table 4-6. Data structure of DrainPoints shapefile

Field Name	Description
FID	Shapefile Feature identifier
Shape	Binary shape data
GRAIPDID	Identifier for each feature in the shapefile. Linked with the GRAIPDID field in the DrainPoints table in the GRAIP Database.

Table 4-7. Data structure of RoadLines shapefile

Field Name	Description
FID	Shapefile Feature identifier
Shape	Binary shape data
GRAIPRID	Identifier for each feature in the shapefile. Linked with the GRAIPRID field in the RoadLines table in the GRAIP Database.

be delineated and that stream crossings be located precisely on the correct stream within the stream network.

A digital elevation model is used to delineate the stream network. In order to identify clusters of the stream network that are contiguous or fragmented with respect to stream crossing barriers the stream network needs to be delineated with separate segments upstream and downstream of each stream crossing. This section describes the procedure that was developed for precisely locating surveyed stream crossings on the stream network and delineating the stream network to contain streams that are segmented at stream crossings. Surveyed stream crossings do not generally fall precisely on delineated streams. Furthermore stream crossings are sometimes mapped in the field where no stream has been delineated using the DEM. There are also errors in the positioning of roads and streams that result in them appearing to cross where there is not really a stream crossing. Figure 4-5 gives the procedure developed to resolve these problems. This procedure is comprised of the following steps identified numerically in Figure 4-5.

1. Run the GRAIP database preprocessor tool (explained in the previous section) to obtain the consolidated road lines and drain points shapefiles.
2. Extract stream crossing drain points (as indicated by the DrainTypeID) from the drain points file using the GRAIP extract stream crossings tool. Table 4-8 shows the fields included in the extracted stream crossings shapefile (StrXingEx.shp).
3. Use basic grid analysis functions of TauDEM (Tarboton, 2002) with the DEM as input; to produce the pit filled DEM, flow direction, contributing area, slope and initial stream raster grid files.
4. Create overall outlets shapefile. A shapefile is first created in ArcCatalog, then points are added to it in ArcMap using the initial stream raster as background to guide the proper positioning of the outlets.
5. Run the TauDEM functions for delineating the stream network and objectively identifying the appropriate threshold for channelization using the overall outlets specified. The TauDEM "Do all network delineation functions" is a simple way to achieve this, or alternatively a user may select from some of the other options TauDEM provides to map a stream network most consistent with the topographic setting of the study area. Output from this step is a shapefile with the TauDEM stream network that is designated as preliminary because it does not have stream segments split at road stream crossings.
6. Intersect road lines and the preliminary stream network. The “Intersect lines to get points” tool in Hawth’s Analysis tools (http://www.spatialecology.com/) is used

to intersect the preliminary TauDEM stream network and the consolidated Road Lines shapefiles to create a road-stream intersection shapefile (StrXingRi.shp). Hawth's Analysis tools are a free set of GIS tools available as an extension to ArcGIS ArcMap.

7. Snap stream crossings to the preliminary stream network. Hawth's "Snap points to lines tool" is used to snap the extracted stream crossings shapefile to the nearest position on the TauDEM stream network shapefile resulting a new point shapefile (StrXingSn.shp) with attributes from Table 4-9.

8. Run the filter stream crossings tool to associate the appropriate points on the stream network from the snapped stream crossings (StrXingSn.shp) and road stream intersections (StrXingRi.shp) with nearby surveyed stream crossings. The rules and logic used to program this tool are illustrated in figure 4-6 and described in the following steps.

    8.1 Use ArcObjects "Near" function to find the nearest stream crossing drain point (in StrXingEx.shp) to each road stream intersection (in StrXingRi.shp). Record the distance to the nearest stream crossing drain point and physical attributes surveyed at that drain point as attributes of the road stream intersection shapefile (Table 4-10).

    8.2 Merge the road stream intersection and snapped stream crossing shapefiles (StrXingRi.shp and StrXingSn.shp) recording in the PType field either "Road Stream Xing" or "Snapped", and in the Distance field the distance to the nearest surveyed stream crossing from SNAPDST or Near_Dist. The result is the shapefile MergedSX.shp consisting of on-stream points that are candidates for matching with stream crossing drain point (Table 4-11).

8.3 Find the contributing area at each candidate on-stream point by intersecting the shapefile with the contributing area grid. The contributing area values (after conversion from number of grid cells to m^2) are appended as the CArea field. A geomorphologic channel width is estimated from contributing area using the following hydraulic geometry relationship

$$GeoCW = 7 * (CArea * 3.86*10^{-7})^{0.404} \quad (4.1)$$

The 3.86×10^{-7} converts *CArea* from m^2 to square miles and this equation from Dunne and Leopold, (1978), reviewed in chapter 2 reports channel width in ft, for comparison with surveyed channel width. This equation, derived for the Upper Salmon River in Idaho is, without other data, deemed appropriate for this study area.

8.4 Flag on-stream points based on proximity to surveyed stream crossing drain points and channel width criteria. The on-stream points shapefile contains at least one point on a stream for each surveyed stream crossing drain point, but may contain multiple points due to the snapped location and nearest road stream intersection being different. These are parsed, examining the snapped point first (because it is always closest) followed by road stream intersections that were nearest to the stream crossing drain point. A point considered is accepted and flagged as an acceptable match if it meets the following criteria:

a) Distance (to stream crossing drain point) less than threshold (user specified, 100 m default)

b) Consistency between geomorphologic and surveyed channel widths according to

$$\frac{\left|\left(GeowCW - Chan\_Width\right)\right|}{\left(GeowCW + Chan\_Width\right)/2} < \text{Tol (user specified with default 0.5)} \quad (4.2)$$

For a point that passes these criteria the flag is set to 1 and the note field set to “Passes both criteria”. Once a match is found for a stream crossing drain point, any remaining points associated with that drain point are flagged as 0. This ensures only one matched on stream point per surveyed stream crossing. Points that fail either or both of these criteria are flagged as 0 with notes such as “Fails automated distance threshold”, or “Fails both criteria” entered in the notes field.

8.5 The final step is to save the matched on-stream points (that were flagged as 1) to a new shapefile (MatchSX.shp) and all the on-stream points for those surveyed stream crossing drain points which do not match any on stream points (were flagged as 0) to the shapefile of unmatched points (UMatchSX.shp).

9 Check matched and unmatched on-stream points, manually editing and resolving mismatches where possible or identifying situations requiring further examination in the field.

10 Combine matched on-stream points shapefile with overall outlets shapefile renumbering the Id field to avoid Id duplicates between the on-stream points and overall outlets.

11 The combined outlets + stream crossings shapefile is then specified as the outlets shapefile for running the TauDEM network delineation functions. With this file as input TauDEM creates a stream network shapefile with stream segments split at stream crossings. Appendix 3 gives the attributes of the TauDEM stream network shapefile.

The GRAIP tutorial in Appendix 5 gives additional details on following this procedure to create the TauDEM stream network.

Slope Stability Index Map

Road drainage is often implicated in the triggering of landslides. A terrain stability index map is used to identify drain points where the terrain is unstable with a greater risk of landslides being triggered, so that these can be put on a higher priority for maintenance or treatment. SINMAP (Pack, Tarboton, and Goodwin, 1998a) is a terrain stability index mapping tool implemented as an ArcView extension that produces a map of terrain stability calculated without regard for road drainage. I converted SINMAP from an ArcView 3.x extension written in Avenue to a COM plug-in for ArcGIS 9.x written in Visual Basic. This is distributed as SINMAP2 (Pack et al., 2005). SINMAP2 is used to

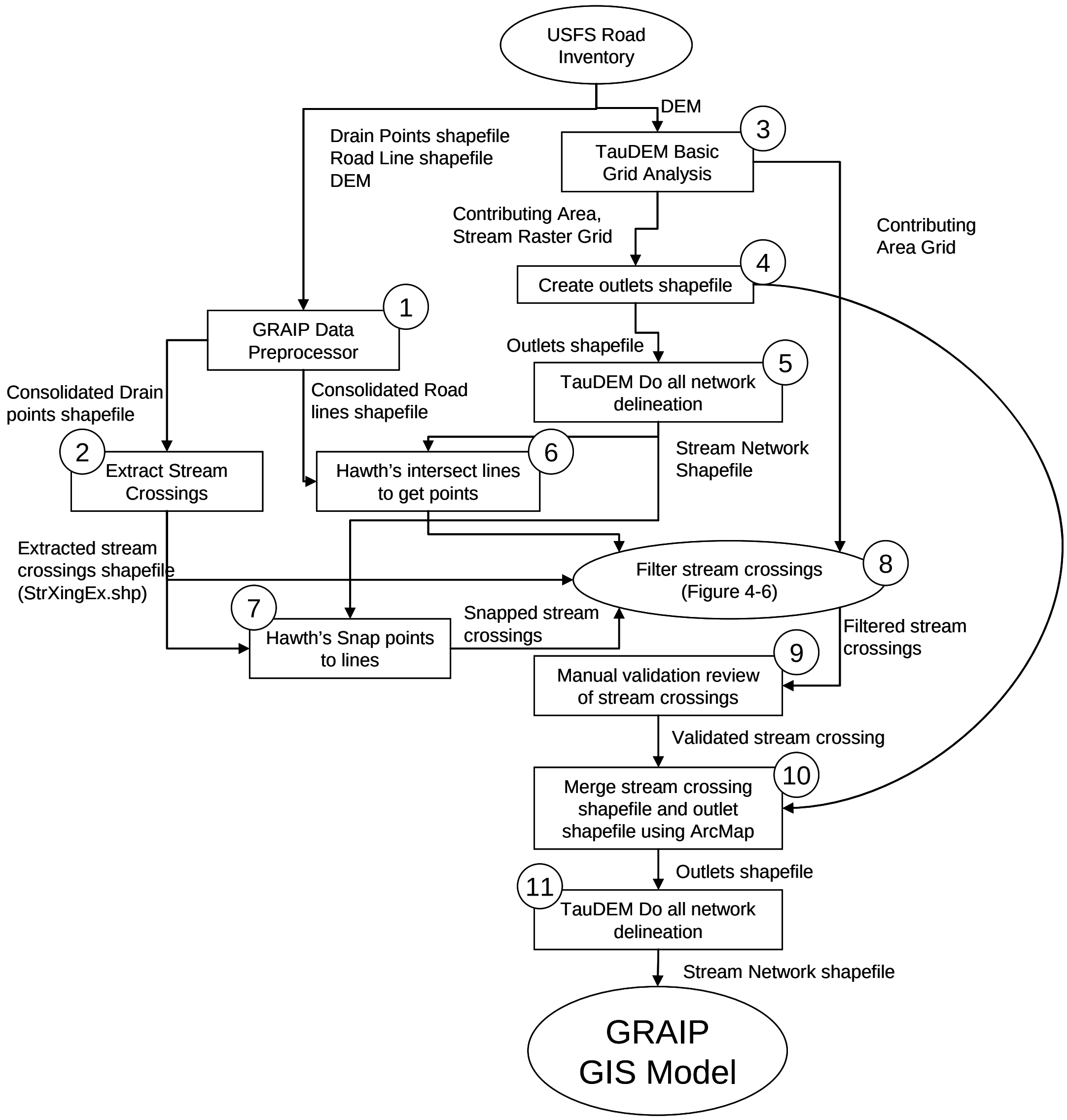


Figure 4-5. Stream network and stream crossings preprocessing algorithm.

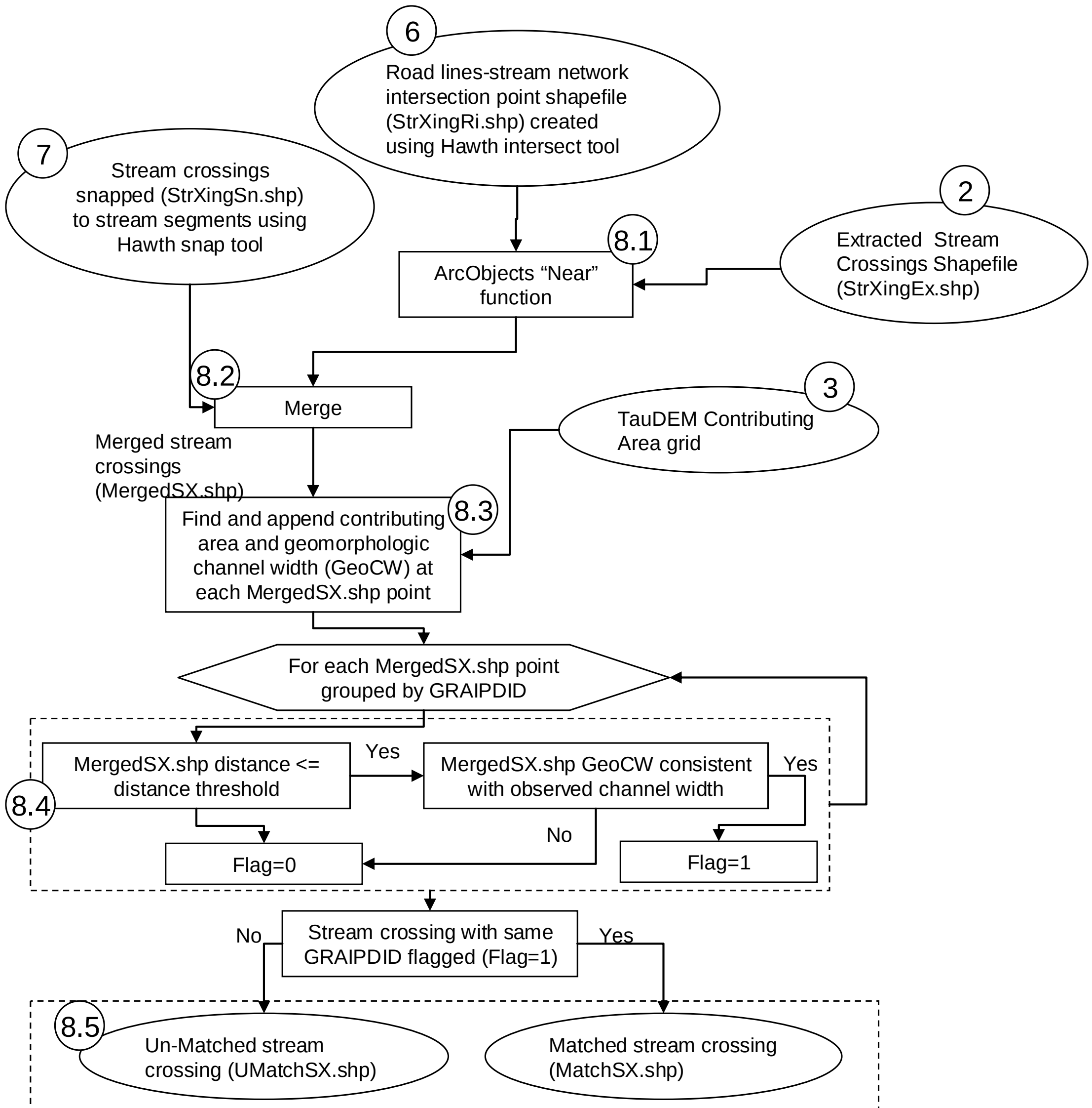


Figure 4-6. Filter stream crossing function algorithm for finding and filtering stream crossings.

Table 4-8. Extracted stream crossings attribute table structure (StrXingEx.shp)

Field Name	Description
FID	Shapefile internal feature identifier.
Shape	Binary shape feature.
GRAIPDID	Identifier for drain point.
DPType	Drain point type Id. In this case 6 to indicate stream crossing.
Chan_Wdth	Surveyed or observed channel width from USFS road inventory (feet).

Table 4-9. Snapped stream crossing shapefile attribute table structure (StrXingSn.shp)

Field Name	Description
FID	Shapefile internal feature identifier.
Shape	Binary shape feature.
GRAIPDID	Identifier for drain point that was snapped.
SNAPDST	Snapped distance (m)
PType	Preprocessing type. In this case “Snapped”.
Chan_Wdth	Surveyed or observed channel width from USFS road inventory (feet).

Table 4-10. Road-stream intersection shapefile attribute table structure (StXingRi.shp)

Field Name	Description
FID	Shapefile internal feature identifier.
Shape	Binary shape feature.
GRAIPDID	Identifier for nearest drain point.
PType	Preprocessing type. In this case “Road Stream Xing”.
Chan_Wdth	Surveyed or observed channel width from USFS road inventory (feet).
Near_FID	The Feature ID of the nearest stream crossing drain point.
Near_Dist	The distance to the nearest stream crossing drain point.

Table 4-11. Merged stream crossings shapefile attribute table structure (MergedSX.shp)

Field Name	Description
FID	Identifier representing each stream crossings
Shape	Binary shape feature
GRAIPDID	Identifier for each drain point
PType	Preprocessing type, either snapped (“Snapped”) or road stream crossing (“Road Stream Xing”)
Distance	Distance from the nearest USFS stream crossing drain point (m)
CArea	Contributing area at each point (sq. m)
Chan_Wdth	Surveyed or observed channel width from USFS road inventory (feet)
GeoCW	Channel width calculated from contributing area (feet)
Flag	An integer identifier. Matched =1 and Unmatched=0
Notes	Description of the result from the test and decision taken by the program

obtain the stability index grid used by the GRAIP GIS tool to assign the stability index values at each drain point. SINMAP2 takes the DEM and slope stability parameters over calibration regions as input and runs the following set of procedures to create the stability index (SI) grid.

1. Fill pits to remove depressions in the DEM
2. Calculate slope and flow direction
3. Calculate contributing area
4. Calculate terrain stability and wetness index grids

SINMAP 2 includes the same procedures as SINMAP for visual calibration using a slope-area plot and observed landslides.

GRAIP Road Surface Erosion Analysis

The GRAIP Road Surface Erosion Analysis quantifies sediment production from each road segment and sediment delivery to the stream system. This analysis consists of the following steps:

1. Road Segment Sediment Production - Calculates surface erosion from forest roads.
2. Drain Point Sediment Accumulation - Calculates sediment accumulation at each drain point.
3. Accumulated Upstream Sediment Load - Creates a grid of accumulated sediment load from road drain points upstream of each grid cell.
4. Accumulated Upstream Specific Sediment – Accumulated Upstream Sediment Load normalized by dividing by upstream contributing area.

5. Upstream Stream Sediment Input - Calculates accumulated upstream stream sediment inputs to each stream segment.
6. Direct Stream Sediment Input - Calculates direct stream sediment inputs to each stream segment.

Figure 4-7 gives the flow of information and calculations performed to estimate sediment production and stream sediment inputs in GRAIP.

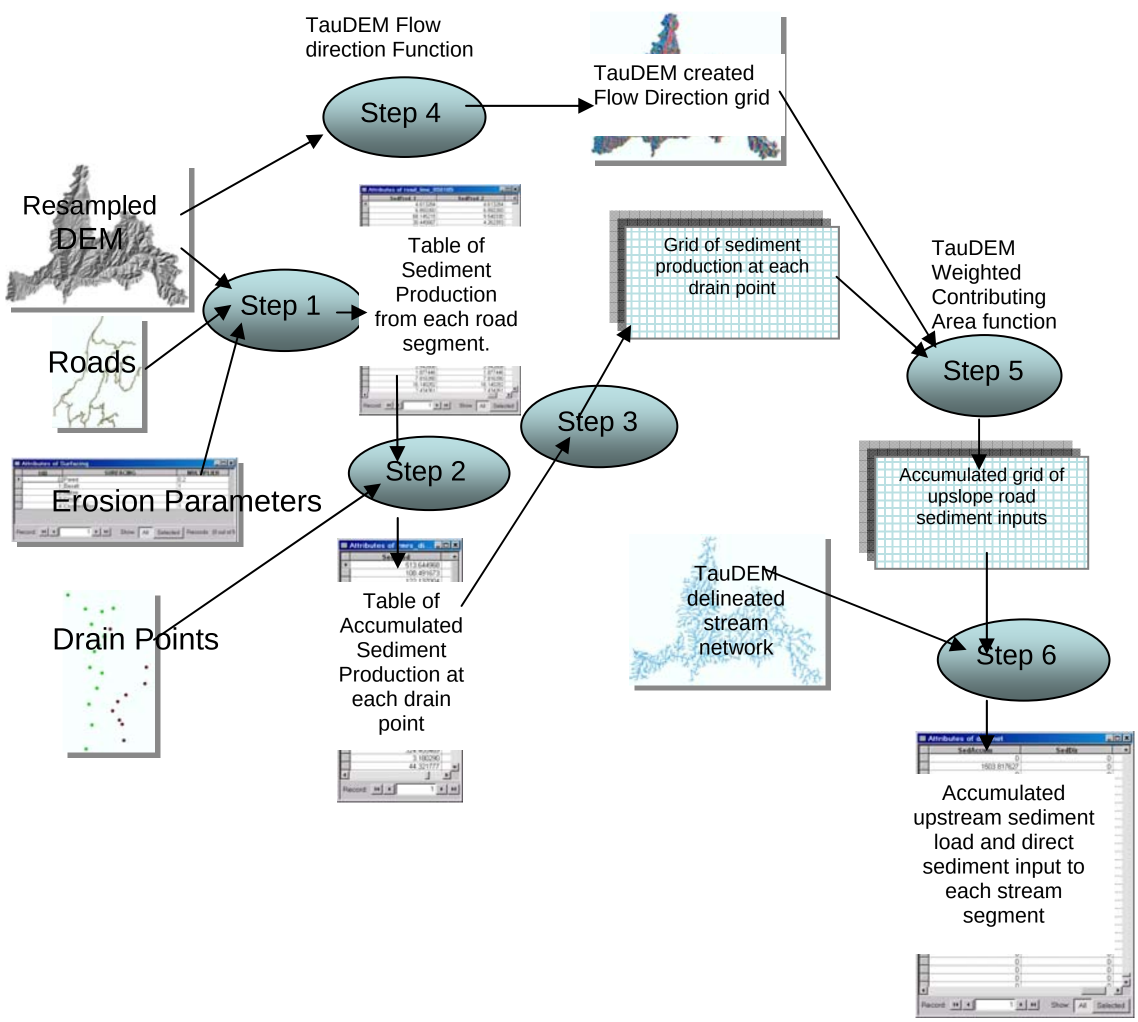


Figure 4-7. Flow of information in GRAIP sediment calculations.

The first step is to evaluate erosion from each forest road segment in *kg/yr* using Luce and Black (1999):

$$E_i = \frac{aLSrv}{2} \tag{4.1}$$

where L is the road segment length, S is the slope of the road segment, a is the annual base erosion rate (79 kg/m (elev) default), r is the road surface multiplier, v is the vegetation multiplier based on ditch vegetation and i indicates the side of the road. The multipliers v and r are determined based upon road surface type (Figure 4-8) and flow path vegetation (Figure 4-9). Information for these multipliers is taken from Luce and Black (2001a, 2001b) and the Washington Forest Practices Board (1995) which synthesizes work by several scientists. This formula is applied separately to each side of the road because road side ditches may drain to different drain points and have different attributes, hence the division by 2 in the above equation. Although Luce and Black suggest LS^2 as the best explanatory variable, for road segment sediment production a model using LS was nearly as good. Given the types of errors that can be generated from GPS inputs, the LS model is preferable because that is simply the elevation difference between the beginning and end of a road segment. The elevation difference was calculated from the DEM. A tool is provided in GRAIP to interpolate the DEM to a fine scale (e.g. 5m) for this calculation so as to reduce the occurrence of differencing errors for short road segments. The elevation difference values are appended as a field called "Range" to the RoadLines shapefile attribute table. The length of each road segment is also calculated and appended as field "Length" to the RoadLines shapefile attribute table.

SurfaceTypeDefinitions : Table

SurfaceTypeID	SurfaceType	Description	Multiplier
1	Default	Default	1
2	Crushed rock		1
3	Native		5
4	Paved		0.2
5	Herbaceous Veg		1
6	Brush		1
7	Trees > 4 in Dia		1
8	Cinder		1

Record: 1 of 8

Figure 4-8. SurfaceTypeDefinitions table in GRAIP Database model. The multiplier field in this table is the road surface multiplier, *r*.

FlowPathVegDefinitions : Table

FlowPathVegID	FlowPathVeg	Description	Multiplier
1	110%	Default	1
2	>75%		0.14
3	>50%		0.14
4	>25%		0.14
5	>10%		1
6	>0%		1
7	0%		1

Record: 1 of 7

Figure 4-9. FlowPathVegDefinitions table in GRAIP Database model. The multiplier field in this table is the vegetation multiplier, *v*.

The resulting sediment production values from each side of the road segment, and the total sediment production from both sides of the road, are stored in the SedProd1 (kg/yr), SedProd2 (kg/yr) and TotSedProd (kg/yr) fields, respectively, in the RoadLines table in the GRAIP database. The unit road sediment production is calculated by dividing total sediment production (TotSedProd) by the length of the road segment. This is stored in the UnitSed (kg/m/yr) field in the RoadLines table. The sediment delivered to the stream network from each road segment is calculated by using the stream connectivity information from StreamConnect1ID and StreamConnect2ID fields in the RoadLines table and stored in the TotSedDel (kg/yr) field (the total being from both sides of the road). Finally the stream connected unit sediment values are calculated by dividing TotSedDel by the road segment length and are stored in the UnitTotSedDel (kg/m/yr) field in the RoadLines table.

Sediment produced from the road surface is transported to drain points along side ditches, wheel tracks, berms or other surface flow paths. Accumulated sediment load (kg/yr) at each drain point is calculated by adding up sediment production values from road segments that drain to the drain point (Step 2 in Figure 4-7) using the database information about the drain points to which each side of each road segment drains. The resulting accumulated sediment production is saved in the SedProd (kg/yr) field in the DrainPoints table. The effective length of road draining to each drain point is also calculated and stored in the ELength (m) field. Each side of the road contributes half of its length to effective length. The effective length is then used to calculated unit sediment load at each drain point (SedProd/ELength, kg/m/yr) and these values are stored in UnitSedProd (kg/yr). The sediment loading at each drain point that will be delivered to streams is then assigned using the stream connection information (StreamConnectID) in the DrainPoints table and the results are stored in the SedDel (kg/yr) field.

The sediment loading at each drain point is then used at step 3 in Figure 4-7 to create a drain point sediment loading grid that represents the sediment input from the road drainage system to the natural drainage system. Optionally this grid may be created from the sediment loading to stream connected drain points, SedDel, or from all drain point, SedProd. Using stream connected drain points, SedDel, is the default.

At step 4 in Figure 4-7, TauDEM is used to derive the flow direction grid from the DEM. The choice of D8 or D-infinity flow direction approaches is left for selection as a user preference. This defines, for each grid cell, the flow direction to one or more of the eight adjacent or diagonal neighbors in the direction of the steepest slope and effectively parameterizes the surface flow field.

At step 5 in Figure 4-7 the flow direction grid is used with the sediment loading grid as input to the weighted contributing area function to obtain a grid of the accumulated sediment loading upslope of each DEM grid cell.

The stream network created by the TauDEM network delineation functions is then intersected with the accumulated sediment grid at step 6 to obtain the total sediment load (kg/yr) from road sediment erosion delivered to each stream segment. The accumulated sediment grid value at the downstream end of each stream segment is stored in the SedAccum field that is appended to the TauDEM stream network shapefile. Direct sediment input or the amount of the sediment load delivered directly to each stream segment is calculated by subtracting the accumulated upstream sediment load from the accumulated sediment load at the downstream end of the stream segment. These values are then appended to stream network attribute table as the SedDir (kg/yr) field. The quantity of sediment per unit contributing area drained to each stream segment, from both accumulated and direct sediment input, is then calculated by dividing sediment load in that stream segment by upstream contributing area at the downstream end of the segment and the contributing area which directly drains to the segment respectively. The results are appended as SpecSed (Mg/km^2/yr) and SpecSedDir (Mg/km^2/yr) fields in the stream network attribute table. These values allow comparison to long term sediment yields from other processes.

GRAIP Mass Wasting Potential Analyses

Mass wasting as considered here comprises both landslides and erosion due to road drainage being concentrated at drain points. Drain points accumulate storm water from the road side ditches and divert it to adjacent hillslopes, and so these hillslopes are locations of increased risk for erosion and pore water pressure induced landslides. The GRAIP mass wasting potential analysis quantifies the impacts of road drainage on both terrain stability and the potential for the formation of gullies due to erosion.

Terrain stability

The SINMAP model (Pack, Tarboton, and Goodwin, 1998a) provides a quantification of terrain instability based on the infinite plane slope stability model and steady state hydrology (Montgomery, and Dietrich, 1994b) coupled with uncertainty in soil and geologic parameters. SINMAP bases its calculations of terrain stability on a relative wetness evaluated from specific catchment area, slope, and other steady state hydrology parameters

$$w = Min(\frac{Ra}{T \sin\theta}, 1) \qquad (4.2)$$

where R (m/hr) is the per unit area steady state recharge that supplies soil moisture, T (m^2/hr) is the Transmissivity of the soil profile, a is the specific catchment area, and θ is the slope angle. In equation (4.2) the numerator Ra represents the specific discharge, i.e.

the drainage per unit width from the terrain surface. The Stability index *SI* is evaluated from the factor of safety (equation 2.2) assuming uniform distributions for three quantities *C*, *R/T* and $\tan\phi$ specified through their lower and upper bounds as

$$C \sim U(C_{min}, C_{max})$$

$$x \sim U(x_{min}, x_{max}) \qquad (4.3)$$

$$t \sim U(t_{min}, t_{max})$$

where C_{min} and C_{max} are minimum and maximum soil cohesion, x_{min} and x_{max} are minimum and maximum *R/T* ratio, denoted as *x*, and t_{min} and t_{max} are minimum and maximum $\tan\phi$. The density ratio *r* is assumed to be constant (with a default value of 0.5). The evaluation of *SI* (equation 2.3) results in a rather complex expression (Pack, Tarboton, and Goodwin, 1998a), not repeated here, but expressed in terms of the inputs as

$$SI = F_{SI}\,(\sin\theta, a, C_{min}, C_{max}, t_{min}, t_{max}, x_{min}, x_{max}, r) \qquad (4.4)$$

In the Slope Stability Index Map section above, the SINMAP terrain stability index at drain points was used to provide a measure of terrain instability at locations where there is impact from road drainage. This is essentially a mapping of places where roads drain to inherently unstable slopes and does not quantify the impact of the quantity of road runoff from each drain point. To account for the impact of the quantity of road runoff from each drain point the SINMAP approach was modified to take into consideration the combined effect of road and terrain drainage in the calculation of stability index. The approach is illustrated in Figure 4-10.

In modifying SINMAP to accommodate road drainage the terrain specific discharge, *Ra*, is combined with the specific discharge due to road drainage, evaluated as $R_r bL_c/dx$, resulting in equation (4.2) being modified to

$$w = Min\left(\frac{Ra + \left(R_r bL_c / dx\right)}{T \sin\theta}, 1\right) \quad (4.5)$$

where R_r (m/hr) is the additional per unit area increment of runoff from the road surface, and *b* (m) is the road width. The product $R_r b$ represents the per unit length runoff from the road. This is multiplied by the cumulative upslope road length L_c (m) draining to each drain point and divided by grid cell size *dx* (m) to obtain the specific discharge due to road drainage, $R_r bL_c/dx$, that appeared in equation (4.5) above. In this approach the additional runoff generated from the road surface is presumed to flow downslope similar to runoff generated over the terrain surface and contribute to relative wetness at points downslope from road drain points.

Evaluation of the Stability Index due to the effect of forest roads starts by creating the flow direction and slope grid (Step 1 of Figure 4-10) using the TauDEM D-infinity flow direction function (Tarboton, 1997). Using this flow direction grid as the input to the TauDEM flow accumulation function, the TauDEM terrain contributing area grid is created (Step 2 of Figure 4-10).

The stability index value for combined effect of road and terrain contributing area is obtained by replacing the term *Ra* in equation (2.2) with combined road and terrain relative wetness from equation (4.5) resulting in:

$$SI = prob\left(\left[\frac{C+\cos\theta[1-Min\left(\frac{Ra+\left(R_r bL_c / dx\right)}{T\sin\theta},1\right)r]\tan\phi}{\sin\theta}\right]>1\right) \qquad (4.6)$$

In equation 4-6, *R/T* does not appear together as a ratio as was the case in the original SINMAP, so *R/T* cannot be treated as one parameter. To evaluate this equation *R* and *T* are treated as separate parameters with uncertainty incorporated by specifying R_{min}, R_{max}, T_{min} and Tmax separately.

To account for the uncertainty in runoff from the road surface (equation 4.5), the bounds representing uncertainty in Rr are expressed as Rrmin and Rrmax. The parameters Rrmin and Rrmax are used to create two weight grids that quantify RrminbLc/dx and RrmaxbLc/dx at each drain point, respectively (Step 3 of Figure 4-10).

These two grids are then specified as weight grids in a D-infinity flow accumulation function to create two specific discharge grids representing flow accumulation at each drain point from the area of the road surface draining to it.

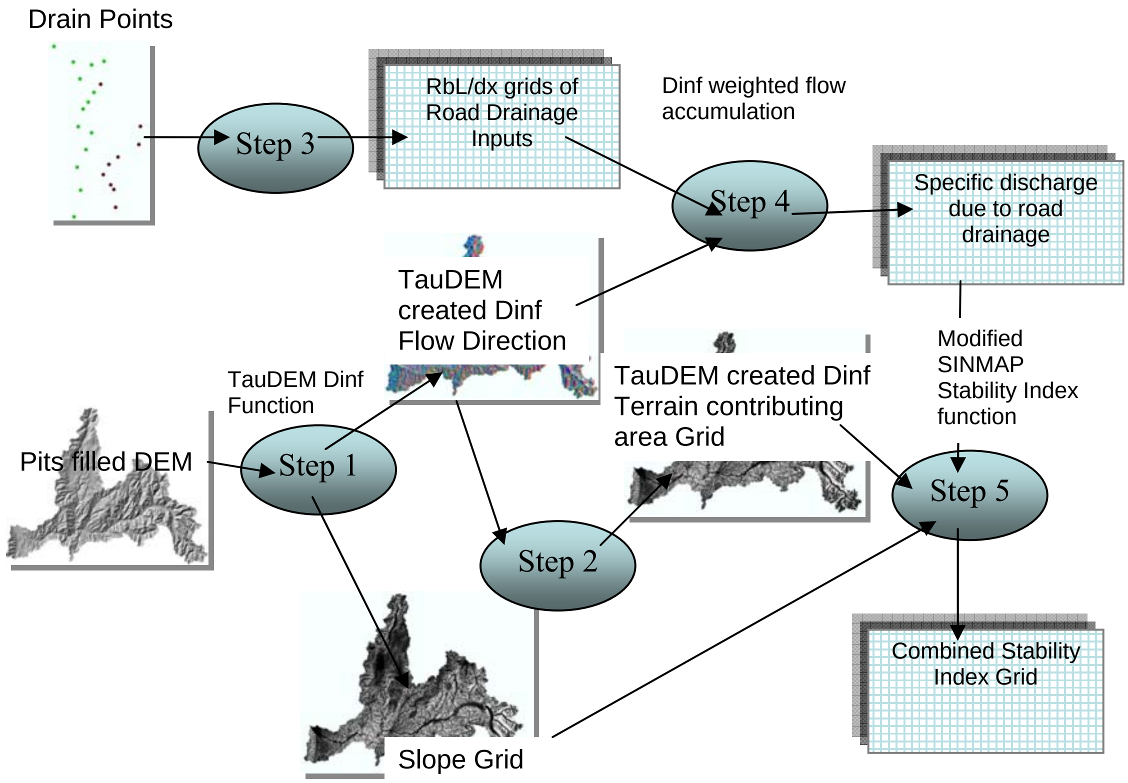


Figure 4-10. Evaluation of the combined effect of terrain and road drainage on Stability Index.

The resulting minimum and maximum specific discharge grids are R_{aminRD} and R_{amaxRD} from R_{rmin} and $R_{rmax,}$ respectively.

The minimum, R_{aminRD}, and maximum, R_{amaxRD}, specific discharge grids due to road drainage from Step 4 in Figure 4-10 along with D-inifinity specific catchment grid and slope are used in a modified SINMAP stability index function given by the following equation

$$SI = F_{SIR}(\sin\theta, C_{min}, C_{max}, t_{min}, t_{max}, X_{min}, X_{max}, r) \qquad (4.7)$$

where, $X_{min} = (R_{min}a+R_{aminRD})/T_{max}$ and

$X_{max} = (R_{max}a+R_{amaxRD})/T_{min}$

The slope angle, θ, and specific catchment area, a, are derived from the topography. The bounds on C and t are user specified inputs and X is the modified form of x that includes road contributions to specific discharge, assumed to be uniformly distributed between the bounds specified.

Pack et al. (1998a) suggested default values for the parameter R/T. With the splitting of this ratio into R and T, we require new default values for both R and T. Based upon Montgomery (1994) a default of 2.7 m^2/hr was selected for both T_{min} and T_{max}. These value of T_{min} and T_{max} were then used to specify defaults for R_{min} (0.0009 m/hr) and R_{max} (0.00135 m/hr) to be consistent with Pack's (1998a) original R/T defaults. Default values of R_{rmin} (0.001 m/hr) and R_{rmax} (0.002 m/hr) were chosen to parameterize the additional runoff from the road surface.

The combined *SI* function also uses a calibration regions grid which defines areas within which the soil density ρ_s is constant and Transmissivity T, cohesion C, friction angle ϕ and terrain recharge R, can be represented by distinct lower and upper parameter bounds. Lower and upper bounds of R_r are specified as properties of each road segment. Stability index values are calculated using equation (4.7) to create a combined stability index grid and then intersected with the drain points shapefile to determine the combined stability index values at each drain point. These values are stored in the SIR field in the DrainPoints table.

Gully formation

The potential for gully development at a drain point depends on slope and drain point discharge. Point slope estimates from a digital elevation model are uncertain due to slope calculations amplifying uncertainty in the DEM. Therefore we provide a function for calculating slope over a specified down gradient distance to ameliorate these effects. The slope at each drain point is stored in Slope field in the DrainPoints table.

Flow concentration due to channelization is an important mechanism in erosion and sediment transport. Here road drain points are a source of concentrated water flow and sediment transport. Montgomery (1994) and Istanbulluoglu et al. (2001b) have related erosion potential to aS^{α}, where a is the specific catchment area, S is slope and α is an exponent that varies from 1 to 2. The contributing area a is used as a surrogate geomorphologic measure for discharge. To evaluate the effect of road drainage on erosion potential, an analogous erosion sensitivity index, *ESI*, is developed from the cumulative upslope road length L_c draining to each drain point and the slope at the drain point.

$$ESI = L_c S^{\alpha} \tag{4.8}$$

Here L_c is used as a surrogate measure for the quantity of road drainage and is obtained from the effective length (ELength) field in the DrainPoints table. The *ESI* values are stored in the ESI field in the DrainPoints table.

To compare *ESI* to observed gullies, a graph is developed with Length L_c on the vertical axis and Slope S on the horizontal axis with capability to display lines which represent low, medium and high *ESI* areas in the plot area. Information derived from the discharge to (DischargeToID) field which contains information on whether the drain point is discharging to a gully is used to symbolize drain points on the plot. *ESI* partitioning lines are drawn to separate the domain into regions that hold approximately equal numbers of drain points. A statistics table (Table 4-12) is also provided to display the distribution of drain points in each *ESI* class. The table also shows the number of drain points with observed gullies in each category. This analysis is used to define *ESI* ranges where the potential for gully development is high or low, and to identify for mitigation or treatment drain points with high gully development potential.

Stream Blocking Analysis

The plugging of culverts by organic debris and sediment can result in blocking of drain points. Flanagan et al. (1998) discuss procedures for assessing the erosional hazards and risks to aquatic and riparian ecosystems of road stream crossings, ditch relief culverts, and other road drainage features. Scores representing the probable hazard level are determined using the culvert diameter to channel width ratio (w^*) and the channel skew angle. Tables 4-13 and 4-14 list hazard scores for each of these from Flanagan et al. (1998). Calculated hazard scores for w^* and channel skew angle are stored respectively in PipeDiaToChanWidthScore and SkewAngleScore fields in the DrainPoints table. These scores are added to obtain an index for stream blocking which estimates the plugging susceptibility of the culvert and the resulting scores are stored in SBI field in the DrainPoints table.

Table 4-12. Structure of the ESI statistics table

DischargeTo	$ESI >= ESI_{high}$	$ESI_{med} <= ESI < ESI_{high}$	$ESI_{low} <= ESI < ESI_{med}$
Gullies #			
Elsewhere #			

Table 4-13. Hazard score for ratio of culvert diameter to channel width (w*)

Culvert diameter/width of channel	Hazard score
$w^* < 0.5$	3

0.5 < w* < 1	2
w* > 1	1

Table 4-14. Hazard score for channel skew angle values

Skew angle	Hazard score
> 45 degree	1
< 45 degree or no definable channel	0

Habitat Segmentation Analysis

Stream crossings in the road network may be a barrier to many species of fish. Identifying stream crossings which are or can be blocked will help forest managers to plan for culvert maintenance. Fish passage barriers are identified based on factors like

1. Stream crossing substrate
2. Blocked or crushed culvert
3. Crossing channel gradient
4. Outlet drop
5. Pipe to channel width ratio
6. Sediment and organic debris from roads

The GRAIP habitat segmentation analysis identifies road stream crossings that block fish passage and causes habitat segmentation. This analysis consists of following steps:

1. Locate fish passage barriers − Identifies fish passage barriers.
2. Demarcate fish habitat clusters − Identifies contiguous stream habitat clusters and assigns each a unique identifier.

The algorithm shown in Figure 4-11 was developed, based on examples in Clarkin et al. (2003), to determine the status of each stream crossing by analyzing the attributes of the stream crossing drain point. Here S_p is the crossing slope threshold (2% default), OD_P is the outlet drop threshold (0.8 ft default), w^*_p is the pipe width, PW, to channel width, CW, ratio threshold (0.75 default) and *ODPD* is the outlet drop to pool depth barrier ratio threshold (1.125 default). The resulting stream barrier status is stored in Barrier field in DrainPoints table. Table 4-15 lists the identifiers used for representing the status of each stream crossing.

Table 4-15. Barrier information for stream crossing drain points

Barrier Status	Value
Completely Blocked	0
Partial Passage	1
Clear Passage	2

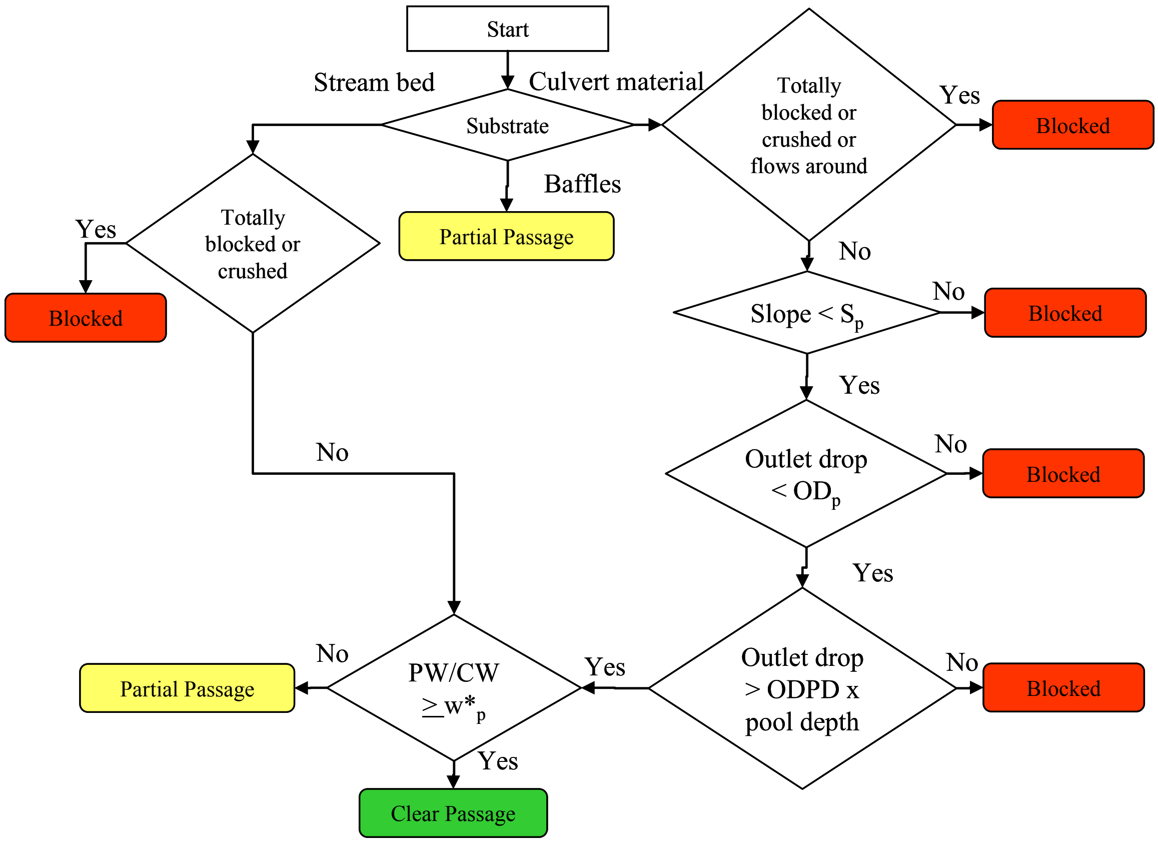


Figure 4-11. Fish passage barrier determination.

Once the stream crossings which are fish passage barriers are identified and assigned a barrier status, stream habitat fragmentation is analyzed. The size and connectivity of stream habitat clusters is important in assessing the fragmentation of habitat due to road stream crossing fish passage barriers. Figure 4-12 shows the flow chart for demarcating habitat clusters in the stream network. The function takes the TauDEM stream network shapefile segmented at drain points as described earlier (see section Stream Crossings and Stream Network Delineation), the filtered stream crossings shapefile (MatchSX.shp) from GRAIP drain points, and the GRAIP drain points shapefile

(DrainPoints.shp) (see section GRAIP Database Preprocessor) as input. The habitat segmentation analysis is comprised of following steps:

1. Create habitat patch identifier field (HabPatchID) in the TauDEM stream network shapefile
2. Find each downstream segment in the stream network. There may be multiple downstream segments due to multiple distinct outlets. The TauDEM stream network shapefile is scanned to locate a stream segment where the downstream link number (in DSLINKNO field) is -1. Assign habitat patch identifier as the ID of the stream segment. These represent the downstream ends or outflows of the drainage network and are is taken as the starting point for the stream network tracing operation.
3. Trace upstream: The upstream link is identified from the information in the stream network attribute table (see Appendix 3).
4. Get downstream node identifier: The downstream node id (DSNODEID) is identified from the stream network attribute table.
5. Find stream crossing with ID corresponding to DSNODEID in the matched stream crossings shapefile (MatchSX.shp).
6. For the stream crossing identified in MatchSX find the GRAIPDID.
7. Check stream crossing status: The GRAIPDID is used to identify the drain point in the GRAIP drain points shapefile (DrainPoints.shp) and the stream crossing barrier status is checked.
8. Assign habitat patch identifer in the stream network: If the stream crossing is blocked a new habitat cluster is created upstream. The stream segment habitat patch identifier (HabPatchID) is assigned with the ID of the upstream stream segment. If the stream

crossing is not blocked the HabPatchID for the downstream segment is assigned to the upstream segment HabPatchID field. This procedure is continued until all the upstream links have been traced and assigned with HabPatchIDs.

The result from this procedure is a set of contiguous habitat clusters identified by the ID of the most downstream stream segment. The tool also provides the user with an option to treat partially blocked stream crossings as completely blocked.

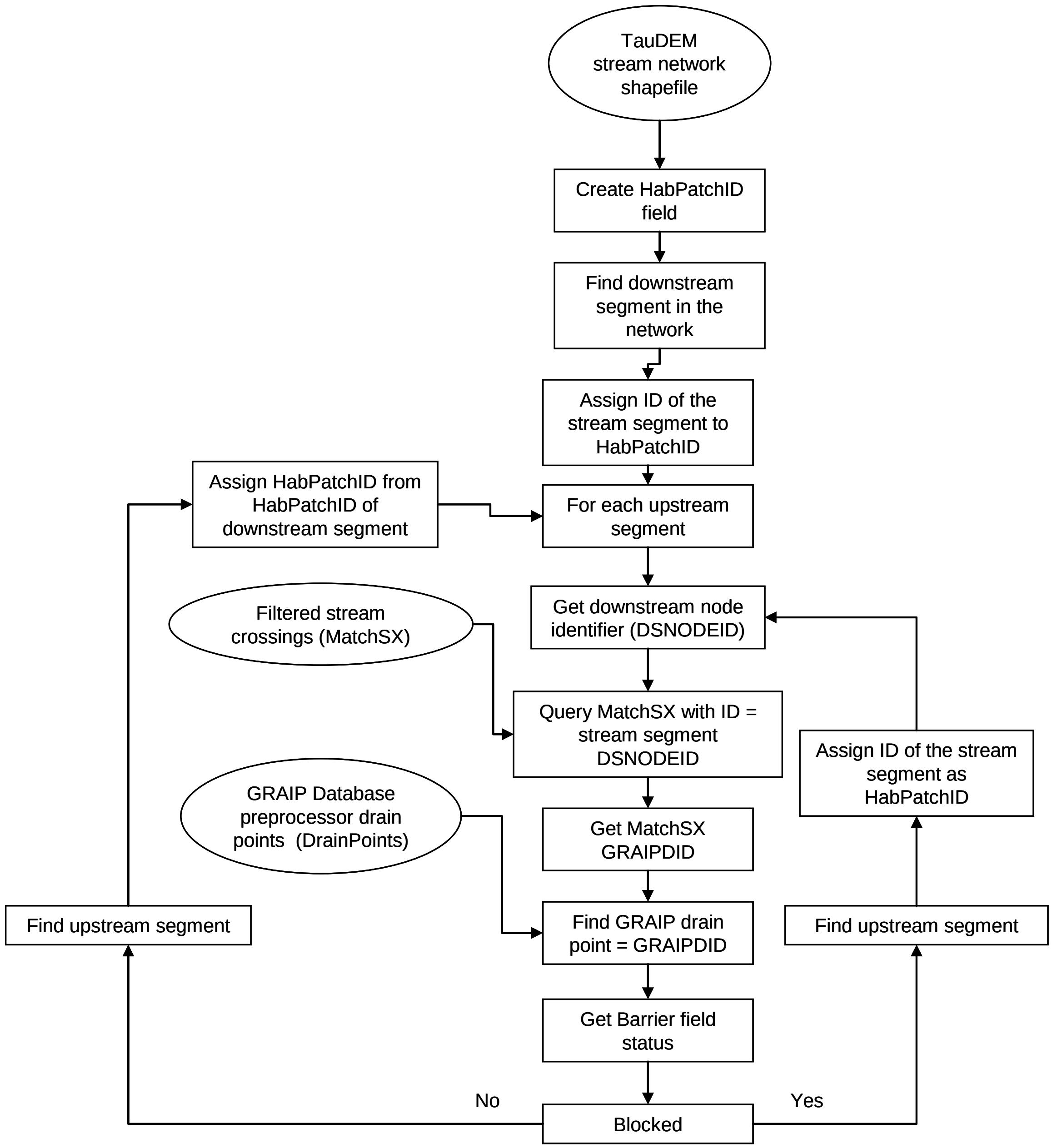


Figure 4-12. Algorithm for assigning habitat cluster identifier.

CHAPTER 5

CASE STUDY

This project contributes to both information science and process science as related to the cumulative impact of roads on forest ecosystems. In terms of information science I have addressed the question as to how to formally organize and structure the data that represents the interaction between roads, drain points, hillslopes and stream networks to enable and facilitate road impact assessments. These assessments are cumulative across a number of processes (erosion, landsliding, stream habitat fragmentation) as well as integrating spatially the local effects at points. In terms of process science I have implemented a number of process models and packaged them as a set of user friendly GIS tools. Verifying all these process models against data would be beyond the scope of what I am able to do with the data available. Some of the methods have been separately published and tested by others, so the contribution here is the integration into a single tool set. The validity of the model relies on the validity of the methods developed and published by others that have been integrated.

GRAIP Database Preprocessing

The GRAIP Database stores information about road lines, drain points, pre-defined valid values (preferred values) and relationships between tables. The GRAIP Database Preprocessor tool (explained in Chapter 4 Section 2) was used to validate and store the USFS road inventory dataset into the GRAIP Database model. The GRAIP Database Preprocessor tool was used to take the USFS road inventory data described in

Chapter 3 as input to create a validated inventory in the form of a GRAIP Database. The output files listed in Table 5-1 were created for both the full study area and the subset study area that was used for the habitat segmentation analysis.

Tables DPErrorLog and RDErrorLog store information about the issues found and actions taken to rectify the issues while importing to the GRAIP Database. For the full study area, the entries in these tables identified 479 issues related to the drain point shapefiles and 96 issues related to the road lines shapefile. These issues are categorized in Tables 5-2 and 5-3. Table 5-4 lists the attributes that were reassigned as recorded in ValueReassigns table during data preprocessing.

Table 5-1. Output files for GRAIP project called “run1”

File Name	Type	Description
run1.graip	Binary file	GRAIP Project File with information about file paths for DEM, Input and output Shapefiles, GRAIP Database file and log files. This file is used as input to GRAIP GIS Model (Explained in next section)
run1.mdb	GRAIP MS Access Database file	GRAIP Database which holds attributes of Drain points and road lines
run1DP.log	Text file	Contains error logs and action taken for Drain points file. This file has the similar structure and contains the same information in DPErrorLog table (see appendix 2)
run1RD.log	Text file	Contains error logs and action taken for Road lines file. This file has the similar structure and contains the same information in RDErrorLog table (see appendix 2)
DrainPoints.shp	Shapefile	Consolidated drain points file with a unique identifier field called GRAIPDID which has one to one relationship with GRAIPDID inside GRAIP Database
RoadLines.shp	Shapefile	Consolidated drain points file with a unique identifier field called GRAIPRID which has one to one relationship with GRAIPRID inside GRAIP Database

Table 5-2. Drain point issues identified during the preprocessing operation for the full study area

Issue Type	Number of Issues
New value added to preferred value table	2
Reassign attribute to an existing value in preferred values table	9
Orphan Drain Points (Drain points without any roads draining to it)	321
Duplicate DRAIN_ID (refer to Appendix 1 drain points structure)	147

Table 5-3. Road line issues identified during preprocessing operation for the full study area

Issue Type	Number of Issue
New value added to preferred value table	1
Reassign attribute to an existing value in preferred values table	6
Orphan Road line (Road line not draining to any drain point)	89
Duplicate Road Identifiers	0

Table 5-4. Reassigned attributes recorded in the ValueReassigns table for the full study area

ID	FromField	ToField	DefinitionID	DefinitionTable
2	Abundent	Abundant	3	ObstructionDefinitions
3	Puddles on road	Puddles on road	2	BroadBaseDipCondDefinitions
4	Gulley	Gully	2	DischargeToDefinitions
5	Previous	Unknown	0	FlowDiversionDefinitions
6	Outsloped	Out sloped	6	NonEngCondDefinitions
7	Gully Crosses Road	Gully	4	NonEngCondDefinitions
8	Blocked Ditch	Blocked	1	NonEngCondDefinitions
9	2 directions	2 Direction	3	DiversionDefinitions
10	Steel arch bottomles	Steel arch bottomless	3	StrXingTypeDefinitions
11	21-50	21-50,[50]	3	FillChannelDefinitions
12	0-20	1-20,[20]	2	FillChannelDefinitions
13	Rd hits channel	0,[1]	1	FillChannelDefinitions
14	> 110 %	110%	1	FlowPathVegDefinitions
15	100 %	>75%	2	FlowPathVegDefinitions
16	>50"	Above 50,[100]	4	FillChannelDefinitions

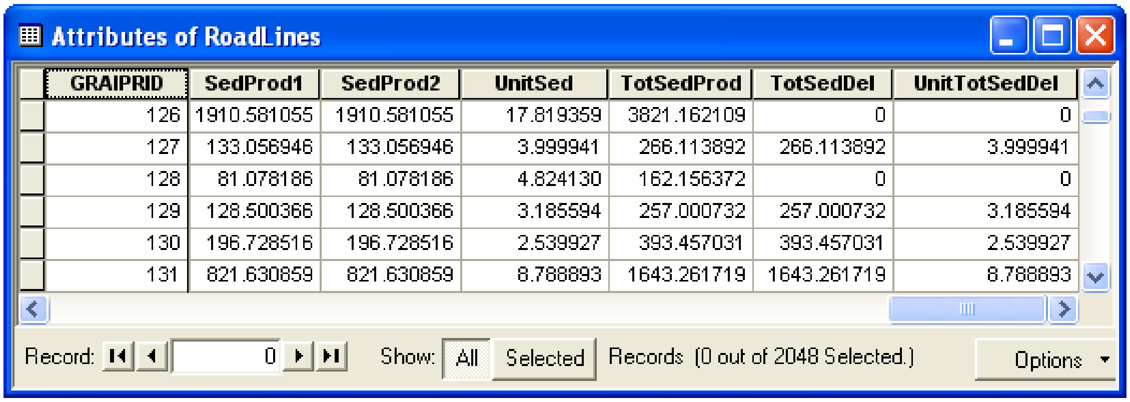
These comprise problems such as typographical spelling errors and inconsistencies in the recording of attributes that were rectified. The issues identified can also be manually examined and flagged for re-examination in the field if not resolvable given information at hand.

The GRAIP database preprocessor tool has made it a lot easier than was previously possible to identify and correct data discrepancies that may have an impact on the results.

Road Surface Erosion Analysis

The road surface erosion analysis was carried out for the full study area and sediment production from road segments, drain point sediment accumulation and stream sediment inputs were calculated. The resulting sediment values for road segments and drain points were appended to the RoadLines and DrainPoints table in the GRAIP database (run1.mdb). The stream sediment inputs were appended to the stream network shapefile attribute table.

The road segment elevation range and length was calculated and appended to the RoadLines shapefile attribute table. Using this information, sediment produced from each side of the road segment, unit sediment produced, total sediment produced, total sediment delivered to the stream network and unit sediment delivered, were calculated and appended to the RoadLines table. Figure 5-1 shows an excerpt from the RoadLines table with stored sediment production values



Attributes of RoadLines

GRAIPRID	SedProd1	SedProd2	UnitSed	TotSedProd	TotSedDel	UnitTotSedDel
126	1910.581055	1910.581055	17.819359	3821.162109	0	0
127	133.056946	133.056946	3.999941	266.113892	266.113892	3.999941
128	81.078186	81.078186	4.824130	162.156372	0	0
129	128.500366	128.500366	3.185594	257.000732	257.000732	3.185594
130	196.728516	196.728516	2.539927	393.457031	393.457031	2.539927
131	821.630859	821.630859	8.788893	1643.261719	1643.261719	8.788893

Record: 0 Show: All Selected Records (0 out of 2048 Selected.) Options

Figure 5-1. RoadLines table inside GRAIP Database model populated with sediment production.

A total of 21.7 x 10^6 kg/yr was calculated to be produced from the 8280 road segments with total length of 721 km. One thousand nine hundred and sixty six road segments are calculated to deliver a total sediment load of 4.7 x 10^6 kg/yr to the stream system. Figure 5-2 shows the distribution of unit sediment production and unit sediment delivered.

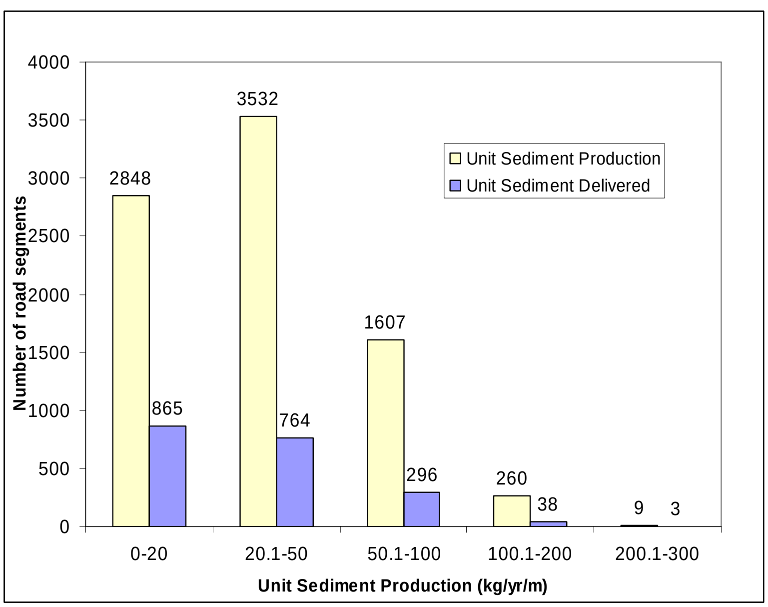


Figure 5-2. Number of road segments within each unit sediment production class.

From the sediment production values calculated for each side of each road segment and information about the drain points to which each side drains, the accumulated sediment load, effective length of road, sediment delivered to the stream network and unit sediment load were calculated at each drain point and appended to the DrainPoints table. Figure 5-3 shows an excerpt from the DrainPoints table with corresponding accumulated sediment load values, and Figure 5-4 shows the distribution of sediment load at drain points.

The accumulated sediment load at each drain point was then used to create a grid of drain point sediment load values. This grid was used as a weight grid in the TauDEM D8 contributing area function to create a grid of accumulated upslope road sediment inputs. Figure 5-5 illustrates the drain point sediment production and accumulated sediment load grid.

Attributes of DrainPoints

GRAIPDID*	SedProd	ELength	UnitSed	SedDel
2775	5106.720276	113.791112	44.878024	5106.720276
2776	498.844208	75.569889	6.601098	0
2777	4225.757446	92.362208	45.752018	0
2778	3839.195557	42.361821	90.628671	3839.195557
2779	1337.609253	28.836628	46.385772	0
2780	2659.969153	43.221811	61.542289	2659.969153
2781	2040.037097	60.899101	33.498640	0

Record: 0 Show: All Selected Records (0 out

Figure 5-3. DrainPoints table in GRAIP database with sediment load values.

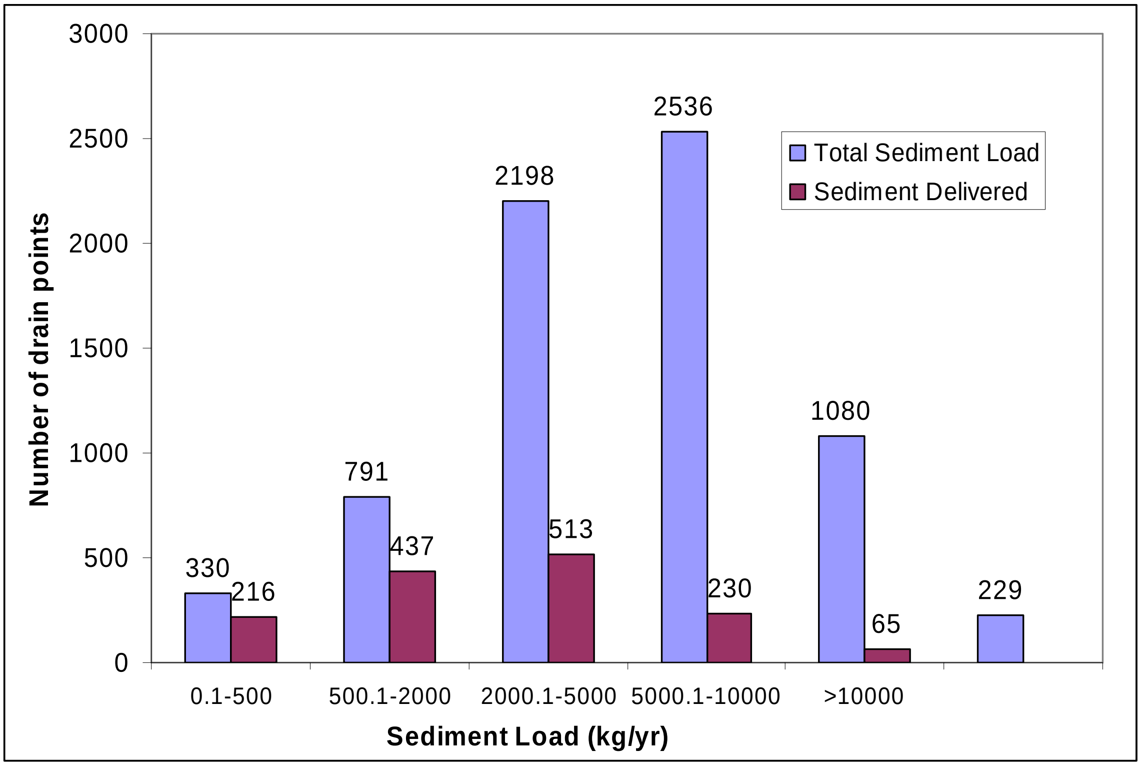


Figure 5-4. Number of drain points within each unit sediment production value class.

The accumulated and direct sediment inputs to each stream segment were calculated by intersecting the accumulated sediment load grid and stream network shapefile and values were appended to the stream network attribute table. Accumulated and direct specific sediment values were then calculated by dividing the accumulated and direct sediment values at each stream segment by upstream and direct area draining to each segment. Figure 5-6 shows an excerpt of the stream network shapefile attribute table that has appended sediment input values. The total accumulated sediment load to the stream network calculated for the study area was 20.7 x 107 kg/yr and the direct sediment input was 5.3 x 107 kg/yr.

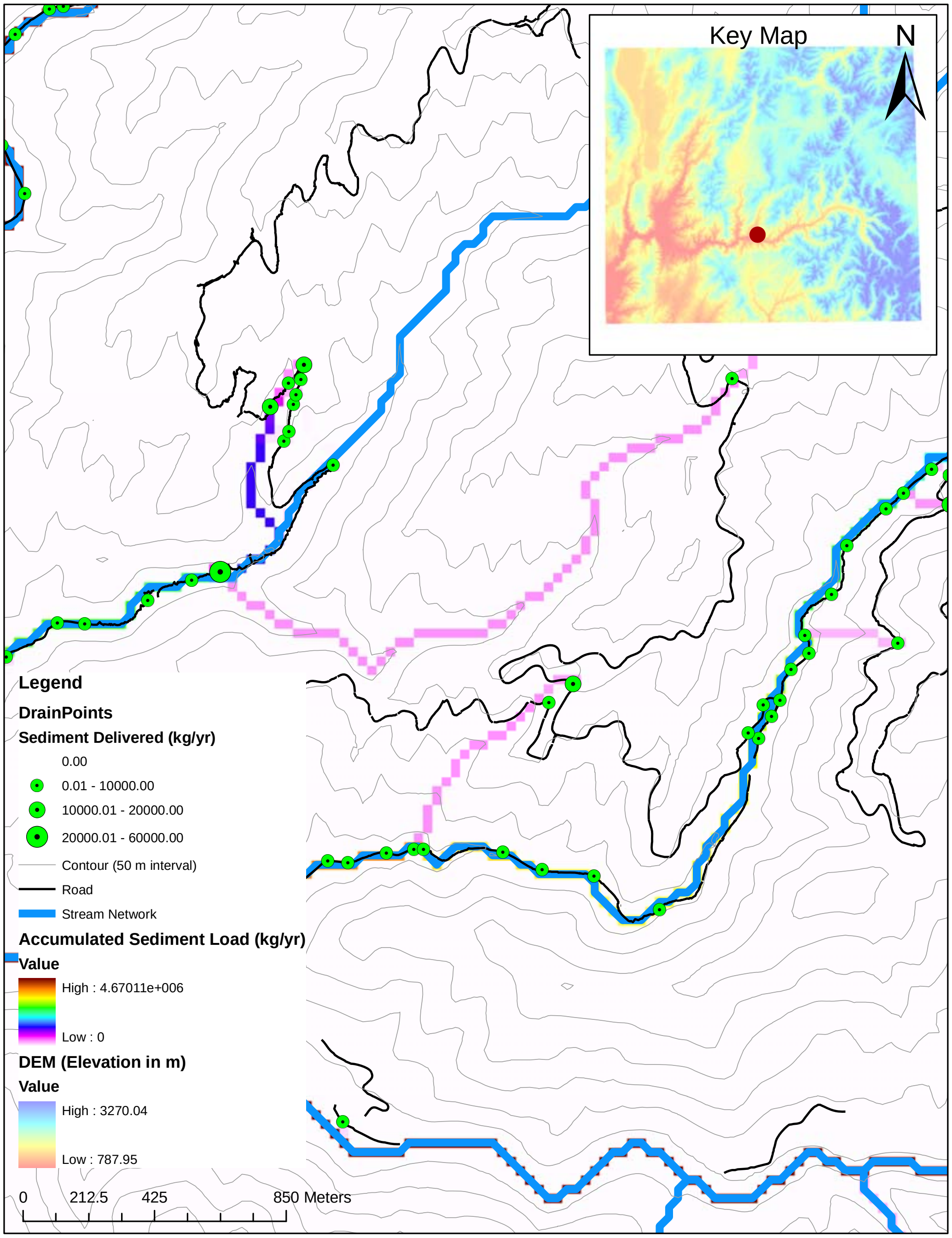
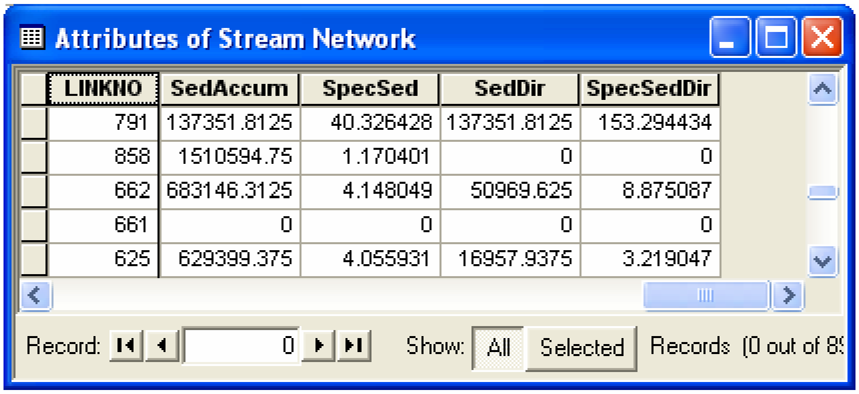


Figure 5-5. Drain point sediment production and accumulated sediment load grid.



LINKNO	SedAccum	SpecSed	SedDir	SpecSedDir
791	137351.8125	40.326428	137351.8125	153.294434
858	1510594.75	1.170401	0	0
662	683146.3125	4.148049	50969.625	8.875087
661	0	0	0	0
625	629399.375	4.055931	16957.9375	3.219047

Figure 5-6. Stream network shapefile attribute table with sediment input values.

Mass Wasting Potential Analysis

The impact of road drainage on initiation of landslides and gully formation were analyzed using SINMAP with and without road drainage modifications, and using the Erosion Sensitivity Index, ESI.

Terrain stability

SINMAP 2.0 was first run for the study area to get the stability index (SI) grid without the impact of road drainage. A single calibration region was used with default parameter settings (Table 5-5 first 9 rows) to develop the SI grid. Using the stability index grid the SI value at each drain point was found and appended to DrainPoints table in GRAIP database.

The combined stability index function, accounting for road drainage, was then run to obtain a grid of SIR values. The default parameters, including the last two rows pertaining to road drainage, from table 5-8 were used. The combined SI value at each drain point was appended as the SIR field in the DrainPoints table in the GRAIP database. Figure 5-7 illustrates the combined SI values.

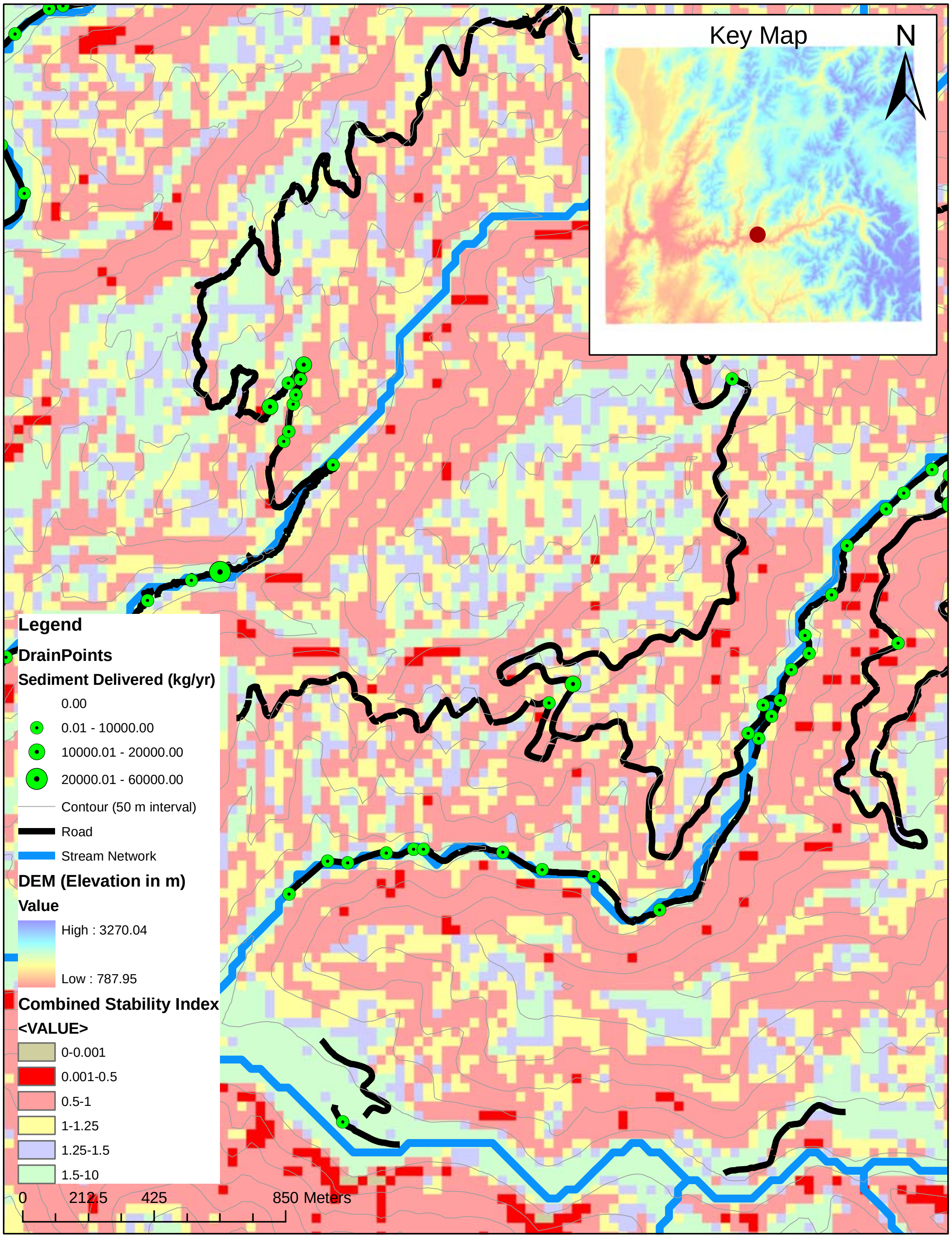


Figure 5-7. Combined Stability Index grid.

Table 5-5. Default SINMAP calibration parameters

Minimum transmissivity	2.708 (m^2/hr)
Maximum transmissivity	2.708 (m^2/hr)
Minimum cohesion	0 (N/m^2)
Maximum cohesion	0.25 (N/m^2)
Minimum friction angle (ϕ_{min})	30^o
Maximum friction angle (ϕ_{max})	45^o
Soil Density	2000 (kg/m^3)
Minimum terrain recharge	0.0009 (m/hr)
Maximum terrain recharge	0.00135 (m/hr)
Minimum additional road runoff	0.001 (m/hr)
Maximum additional road runoff	0.002 (m/hr)

Erosion sensitivity index

ESI values were calculated for all drain points in the study area. I carried out a GPS survey to identify road drain points over a 33.5 km stretch of road that had led to the development of erosion gullies. This stretch of road contained 263 drain points of which 39 were mapped as gullied. The stretch of road surveyed for gullies is shown in Figure 5-8 and the drain points along this stretch of road were used to examine the relationship between ESI and gully occurrence.

In evaluating ESI, first the slope at each drain point was calculated. For that a grid of slope values was created using downslope averaging over a distance of 60 meters in the direction of D8 flow. The drain points were then intersected with the slope grid and slope values at each drain point were determined and appended to the Slope field in the drain points table in the GRAIP database. The ESI values were then calculated using the slope and the effective length (ELength) of the road draining to each drain point. A value of 2 was used for α. The drain point slope and the effective length of the road draining to each drain point were plotted (Figure 5-9). Observed gullies were identified and symbolized in the plot. ESI class thresholds were chosen to define regions that hold approximately an equal number of drain points in each class. The threshold values of ESI obtained in this manner were 1.25, 8 and 25 for low, medium and high values respectively.

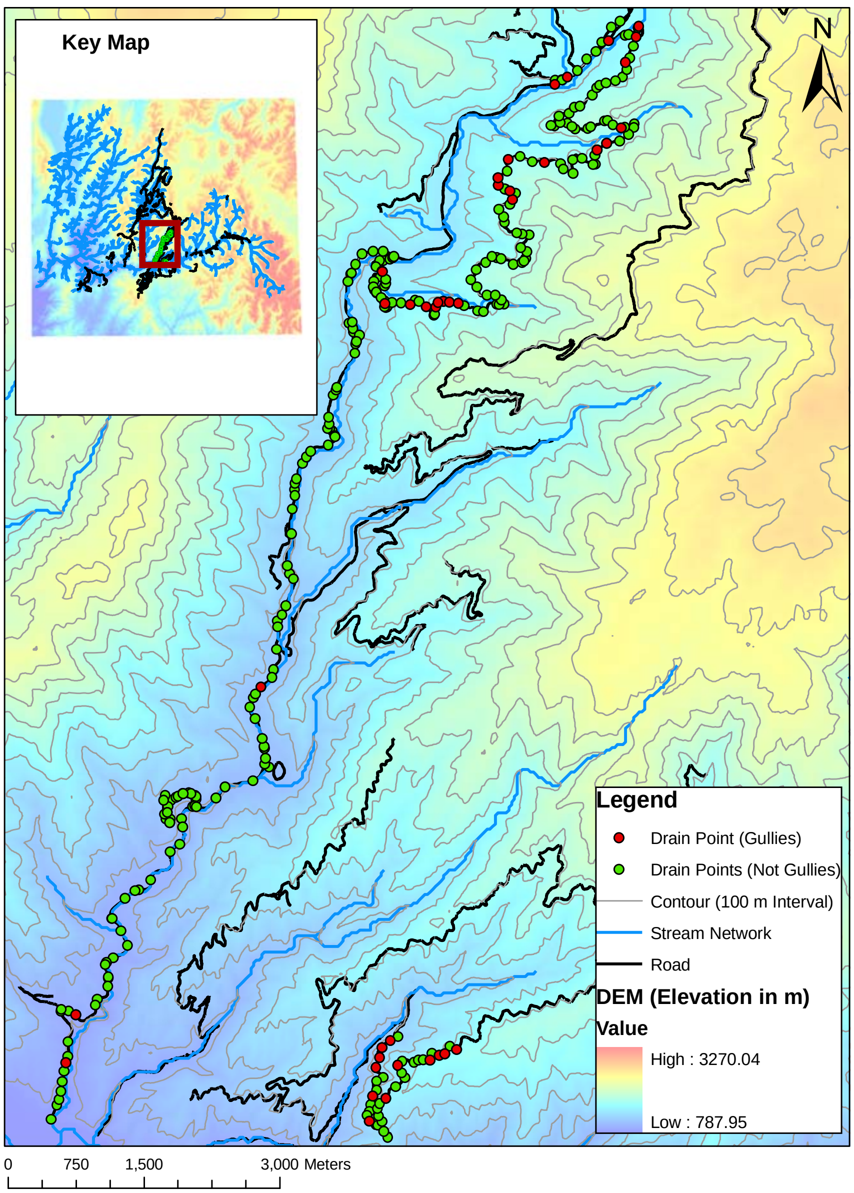


Figure 5-8. Subset of drain points used for *ESI* analyses along road specifically surveyed for gullies.

Table 5-6 shows the classification of ESI values inside each class. The observed percentage of gullies is seen to be higher in higher ESI classes indicating a direct relationship between ESI and gullying. These curves discriminate the drain points according to the potential for gully formation.

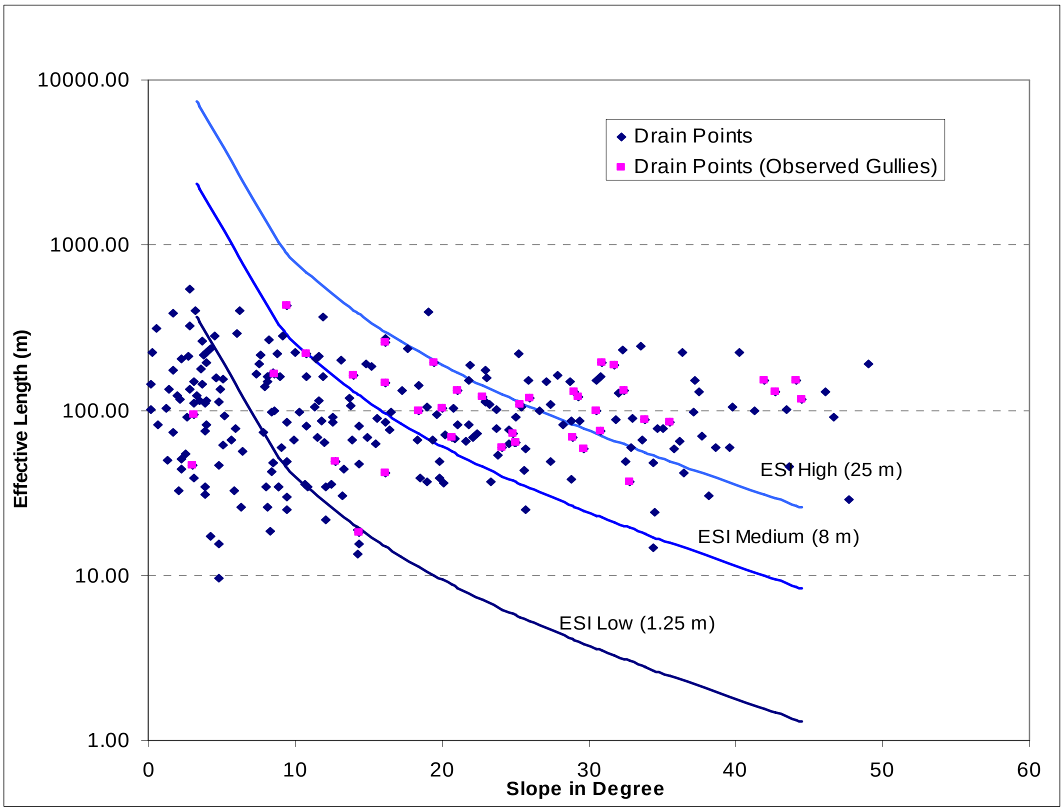


Figure 5-9. Length-Slope graph with ESI threshold lines plotted.

Table 5-6. Classification of gullies inside each ESI class

Index	ESI Value Class	Number of Drain Points	Number of Gullies	Percentage of % Gullies
1	< 1.25	81	4	4.94
2	1.25 - 8	64	3	4.69
3	8 - 25	63	18	28.57
4	25 <	55	14	25.45
	Total	263	39	14.83

Stream blocking index

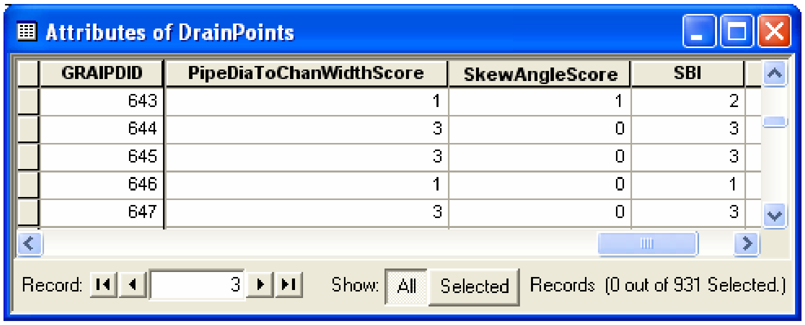
The next step is to estimate the stream blocking index (SBI) as the additive hazard score for culvert plugging susceptibility. This was calculated by dividing the culvert diameter by channel width. Culvert dimension and channel width information was obtained from the drain point attribute tables and the resulting hazard score (Table 4-11) values were appended to the drain points attribute table in the field PipeDiaToChanWidthScore. The channel skew angle was also examined and corresponding hazard scores were appended in SkewAngleScore field in the drain points table. The SBI is the sum of PipeDiaToChanWidthScore and SkewAngleScore. The SBI values were then added to the SBI field in the drain points table. Figure 5-10 displays a partial listing of the calculated hazard scores in the drain points table.

Habitat Segmentation Analysis

Habitat segmentation analysis was carried out for the 303 km^2 subset of the study area described in Chapter 3. To prepare for this analysis the stream crossing drain points were preprocessed and stream crossings which were beyond the distance threshold (100 m) or had channel width inconsistent with the contributing area at that point were filtered out using the methods described in Chapter 4. The tool automatically matched 33 stream crossings which passed both distance threshold criteria of 100 meters and channel width criteria as shown in equation 4.2. Figure 5-11 presents an example of this filtering process that derived matched stream crossings (MatchSX.shp) from surveyed stream crossings (StrXingEx.shp). The stream crossing with GRAIPDID 674 was eliminated because there was no stream near to the drain point. Even if there is a stream crossing at

GRAIPDID 674 as surveyed, this is unlikely to be a factor in the fish habitat fragmentation analysis. This should be further verified by field crew if necessary. The surveyed stream crossing with GRAIPDID 675 has a stream near to it and two candidates on stream locations that it matches, one each from snapping and the road stream intersections. Both of these pass the criteria of being closer than the distance threshold (100 m) and having geomorphologically estimated channel width consistent with the surveyed channel width. The snapped point, which is nearer, was flagged as the on stream location for GRAIPDID 675 and written to the MatchSX.shp file while the road stream intersection with GRAIPDID 675 in StrXingRi.shp was eliminated. Table 5-7 lists the stream crossings which passed both criteria. The filtered stream crossings were appended to the outlets file to create a new stream crossings + outlets shapefile which was used to delineate a new TauDEM stream network that was segmented at each stream crossing.

The first step in Habitat Segmentation Analysis was identification of drain points that are barriers to fish passage. The DrainPoints shapefile was taken as input to find and assign each drain point its fish passage status, (fully blocked, 0, partially blocked, 1 or clear passage, 2). This information was stored in the DrainPoints table Barrier field. Default parameters listed in Table 5-8 were used to calculate the fish passage barriers following the algorithm in Figure 4-11.



Attributes of DrainPoints

GRAIPDID	PipeDiaToChanWidthScore	SkewAngleScore	SBI
643	1	1	2
644	3	0	3
645	3	0	3
646	1	0	1
647	3	0	3

Record: 3 Show: All Selected Records (0 out of 931 Selected.)

Figure 5-10. Stream Blocking Index values stored in DrainPoints table.

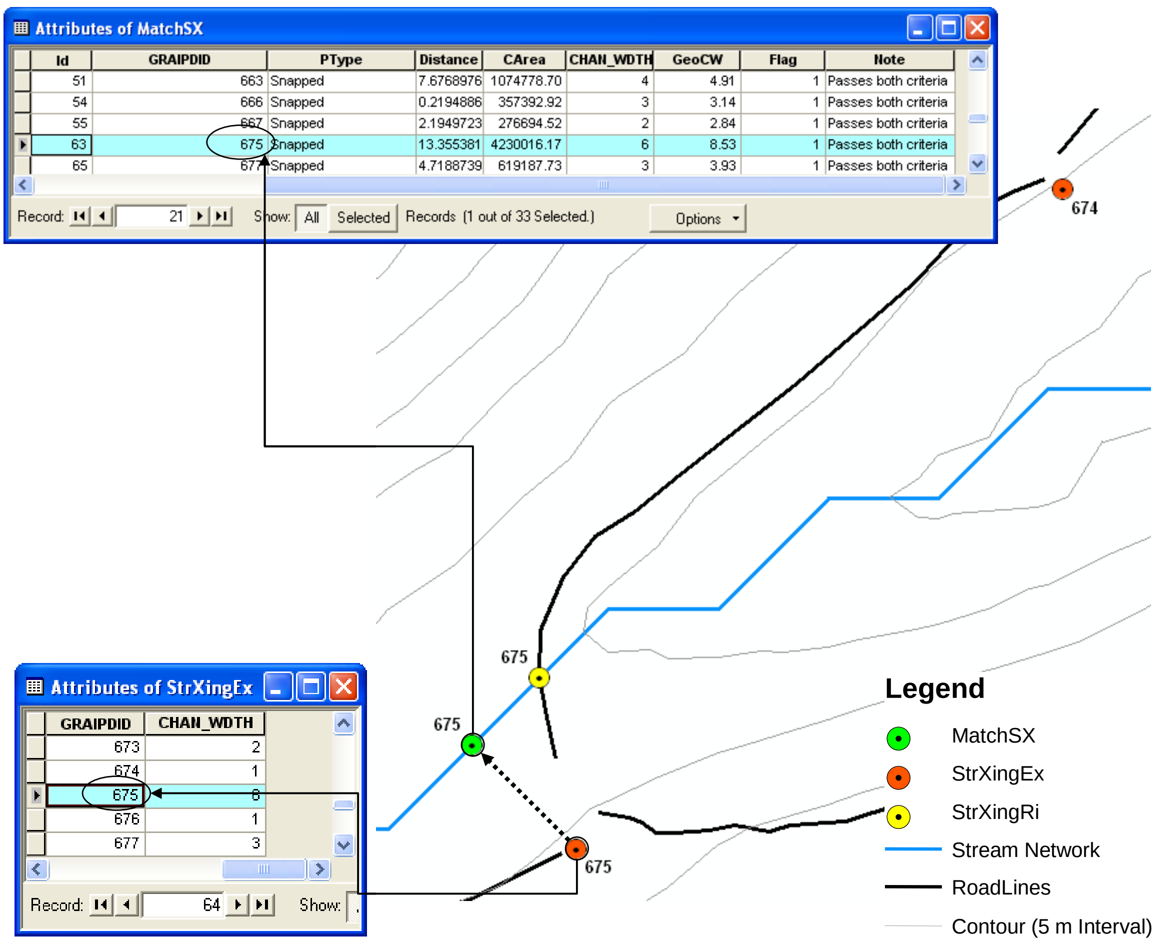


Figure 5-11. Filter stream crossings illustrated for selected surveyed stream crossings.

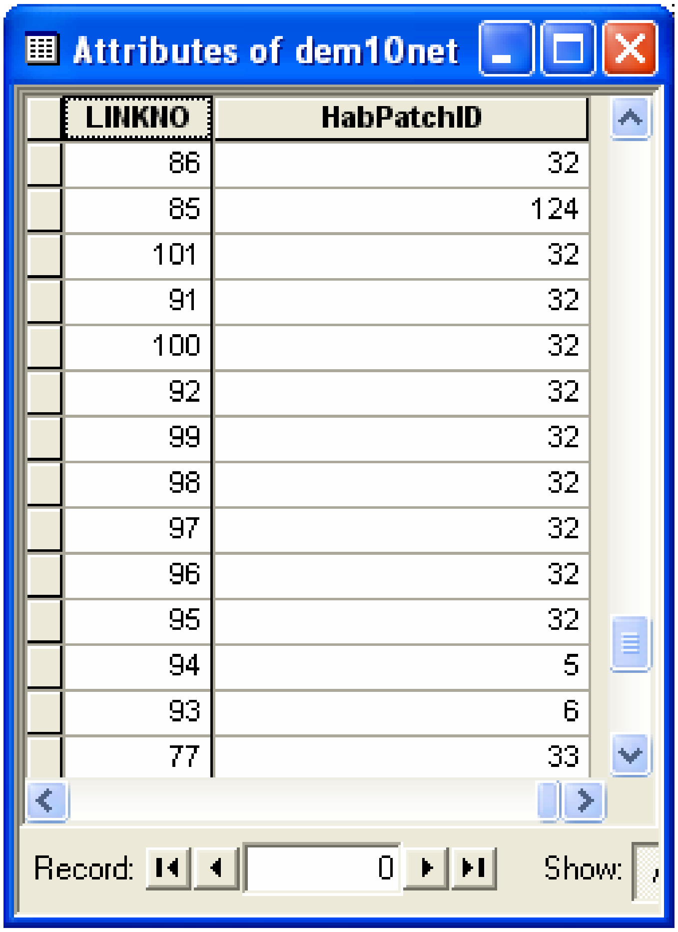
Table 5-7. Matching stream crossings attribute table

ID	RSAMDID	CHAN_WDTH	PType	Distance	CArea	GeoCW
4	616	5	Snapped	4.89	3.3×10^5	3.04
5	617	5	Snapped	12.02	8.7×10^5	4.51
6	618	6	Snapped	25.68	8.7×10^5	4.5
13	625	2	Snapped	1.62	3.8×10^5	3.24
14	626	3	Snapped	18.55	1.1×10^6	4.87
15	627	2	Snapped	18.85	2.2×10^5	2.6
16	628	10	Snapped	10.13	1.4×10^7	13.86
17	629	3	Snapped	0.03	5.6×10^5	3.78
18	630	2	Snapped	4.31	3.5×10^5	3.11
26	638	2	Snapped	8.1	2.3×10^5	2.61
32	644	12	Snapped	13.5	6.0×10^6	9.82
33	645	8	Snapped	4.33	6.9×10^6	10.41
39	651	2	Snapped	48.02	2.8×10^5	2.85
42	654	5	Snapped	21.49	9.0×10^5	4.57
43	655	8	Snapped	10.47	1.7×10^6	5.84
44	656	12	Snapped	0.1	1.8×10^7	15.23
45	657	3	Snapped	6.93	2.7×10^5	2.79
51	663	4	Snapped	7.68	1.1×10^6	4.91
54	666	3	Snapped	0.22	3.6×10^5	3.14
55	667	2	Snapped	2.19	2.8×10^5	2.84
63	675	6	Snapped	13.36	4.2×10^6	8.53
65	677	3	Snapped	4.72	6.2×10^5	3.93
68	680	5	Snapped	2.62	4.9×10^5	3.58
69	681	5	Snapped	13.13	4.6×10^5	3.48
70	682	4	Snapped	74.48	2.2×10^5	2.59
73	685	3	Snapped	2.99	3.2×10^5	2.99
76	688	2	Snapped	11.54	3.8×10^5	3.22
80	692	2	Snapped	6.81	4.0×10^5	3.3
81	693	4	Snapped	1.01	7.3×10^5	4.21
86	698	8	Snapped	5.9	8.1×10^6	11.1
87	699	12	Snapped	12.74	3.5×10^7	19.96
118	640	6	Road Stream Xing	29.24	1.9×10^6	6.19
124	648	4	Road Stream Xing	20.47	3.0×10^5	2.91

Table 5-8. Default parameters for fish passage barrier determination.

Parameter Name	Value
Crossing Slope - S_p	2%
Outlet Drop - OD_p	0.8 feet
Pipe to Channel Width ratio – w^*_p	0.75
Outlet Drop to Pool Depth ratio- ODPD	1.125

Three out of 88 stream crossings were classified as completely blocked and 13 stream crossings were classified as partially blocked. Out of the 33 stream crossings identified during the filtering process and matched with on stream points, two stream crossings, with GRAIPDID 628 and 651 were completely blocked and five stream crossings, with GRAIPDID 617, 618, 644, 645 and 648 were partially blocked. Fish habitat clusters were then identified by using the fish barrier information and tracing through the stream network to demarcate the clusters. Inputs to this function were the TauDEM created stream network file, the stream crossing drain point file used as outlets shapefile in the TauDEM network delineation function, and the GRAIP Drain Points file. Habitat clusters were identified using both partially blocked and completely blocked stream crossings as barriers. The resulting habitat cluster or patch identifiers were appended to the shapefile attribute table as shown in Figure 5-12. Figure 5-13 illustrates contiguous habitat clusters due to blocked stream crossings.



LINKNO	HabPatchID
86	32
85	124
101	32
91	32
100	32
92	32
99	32
98	32
97	32
96	32
95	32
94	5
93	6
77	33

Figure 5-12. Habitat patch identifiers appended to stream network attribute table.

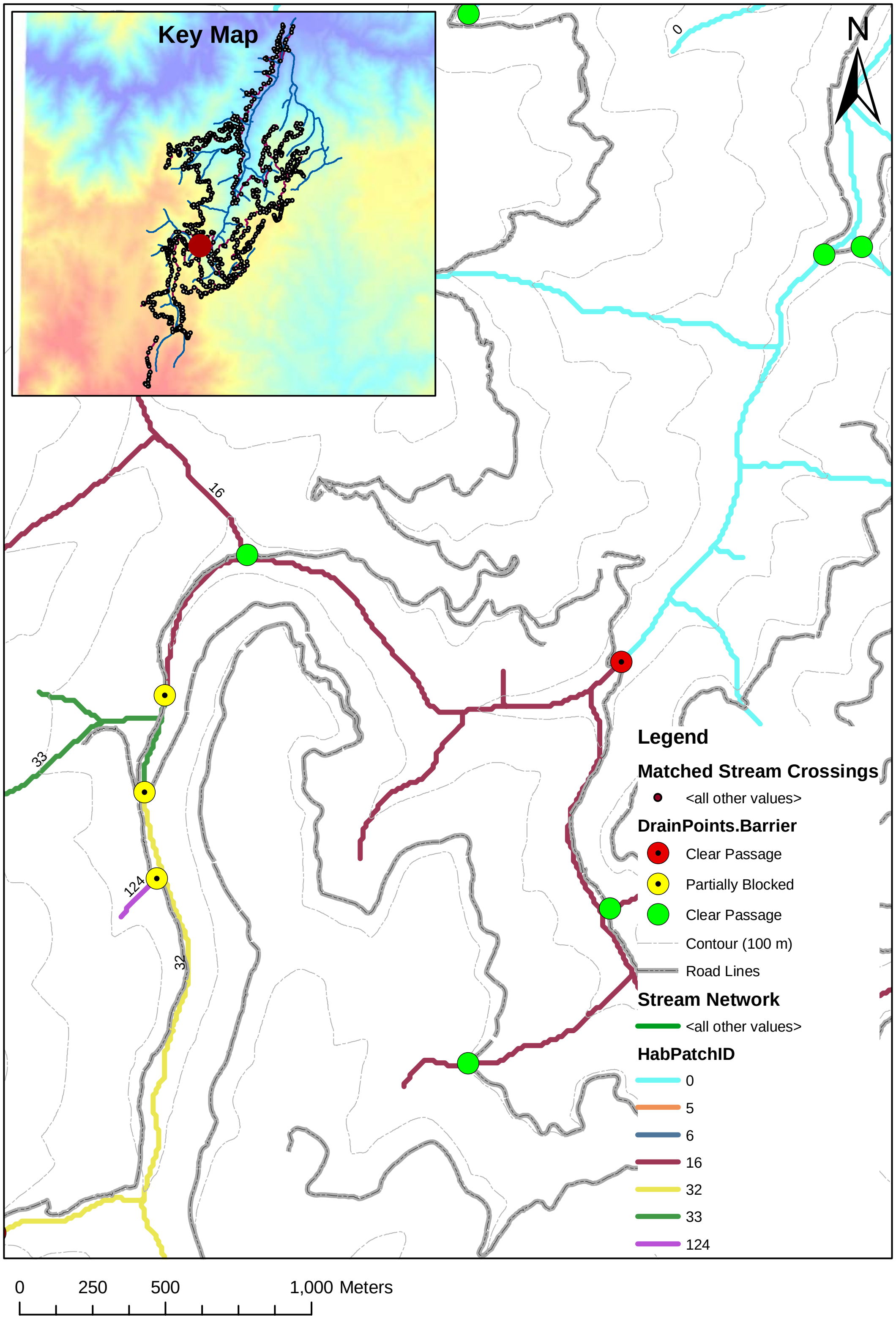


Figure 5-13. Subset study area with habitat patches (HabPatchID) located.

CHAPTER 6

MODEL COMPARISON

Introduction

An important question, in the context of the inventory and analysis procedures discussed in earlier chapters, is how much more information is gained from inventorying and analyzing both the road lines and the drain points over simply knowing where the road lines are. The USFS Roads Analysis methodology (Bisson et al., 1999) combines the roads line coverage obtained from land management agencies and the DEM to estimate the impacts of forest roads on watersheds. Wold and Dubé (1998) and Luce and Wemple (2001) explain the potential importance of knowing more information about road attributes for better evaluating sediment production and delivery from road segments. Black and Luce (2002) describe the benefits of making a comprehensive inventory of forest roads and analysis of that inventory as part of watershed analysis. Their inventory focuses on questions like, "Where are runoff and sediment generated or intercepted by roads, and where do the water and sediment travel?" The inventory comprises a detailed GPS survey of road and drain point attributes such as the location of culverts and presence of mass wasting sites like gullies or land slides. The GRAIP model is based on Black and Luce (2002) and takes input from the inventory.

The objective of this section is to quantify the incremental value of road analysis based on a GPS road survey as proposed by Black and Luce (2002) that includes detailed attributes of roads and drain points (such as road ditch vegetation type, culvert pipe dimensions, drain point discharge location) for estimating road sediment production and impacts of road drainage on erosion and mass wasting. This section first compares the road sediment production and delivery to streams as calculated by the BOISED Model (Reignig et al., 1991) which uses just the road lines shapefile with a GRAIP road inventory and analysis for the South Fork of Payette River in the Boise National Forest. This section then evaluates the GRAIP erosion sensitivity index and indicators from the USFS Roads Analysis (Bisson et al., 1999) that are intended to be predictors of gullying by comparing them to observed gully locations. The comparison also shows how each analysis method can better inform forest road management decision making.

Study Area

Figure 6-1 shows the road network used in the sediment production and stream sediment delivery comparison of BOISED with GRAIP. Figure 6-2 shows the six-digit Hydrologic Unit Code (HUC) Watersheds within the study area that were used to aggregate the sediment production values used in some of the model comparisons. Figure 6.3 shows the subset of the study area used to evaluate the effectiveness of gullying indicators. Along this stretch of road 263 drain points were inspected for the occurrence of gullying and 39 were found to have gullies.

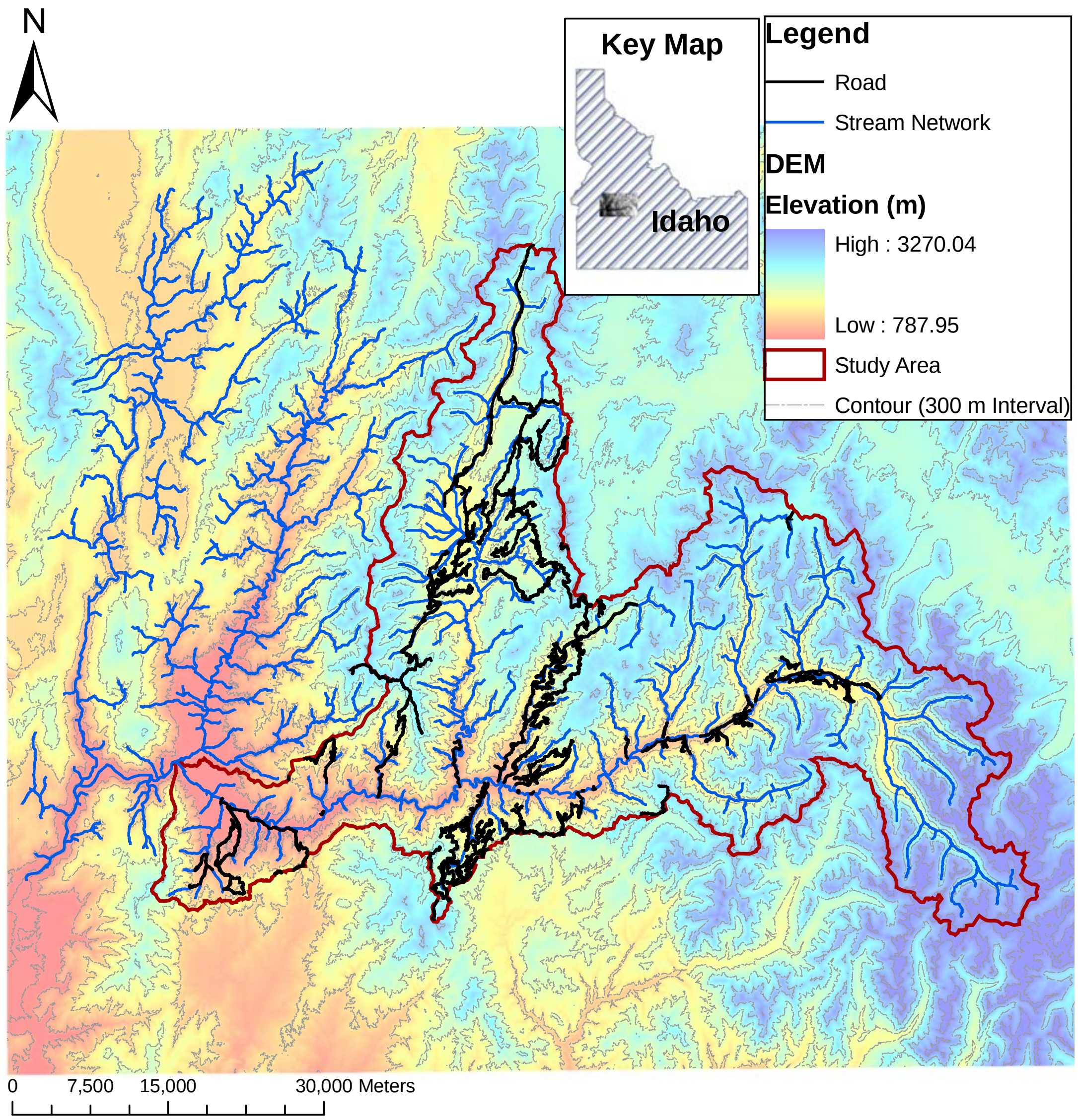


Figure 6-1. South Fork of Payette River in the Boise National Forest, Idaho study area.

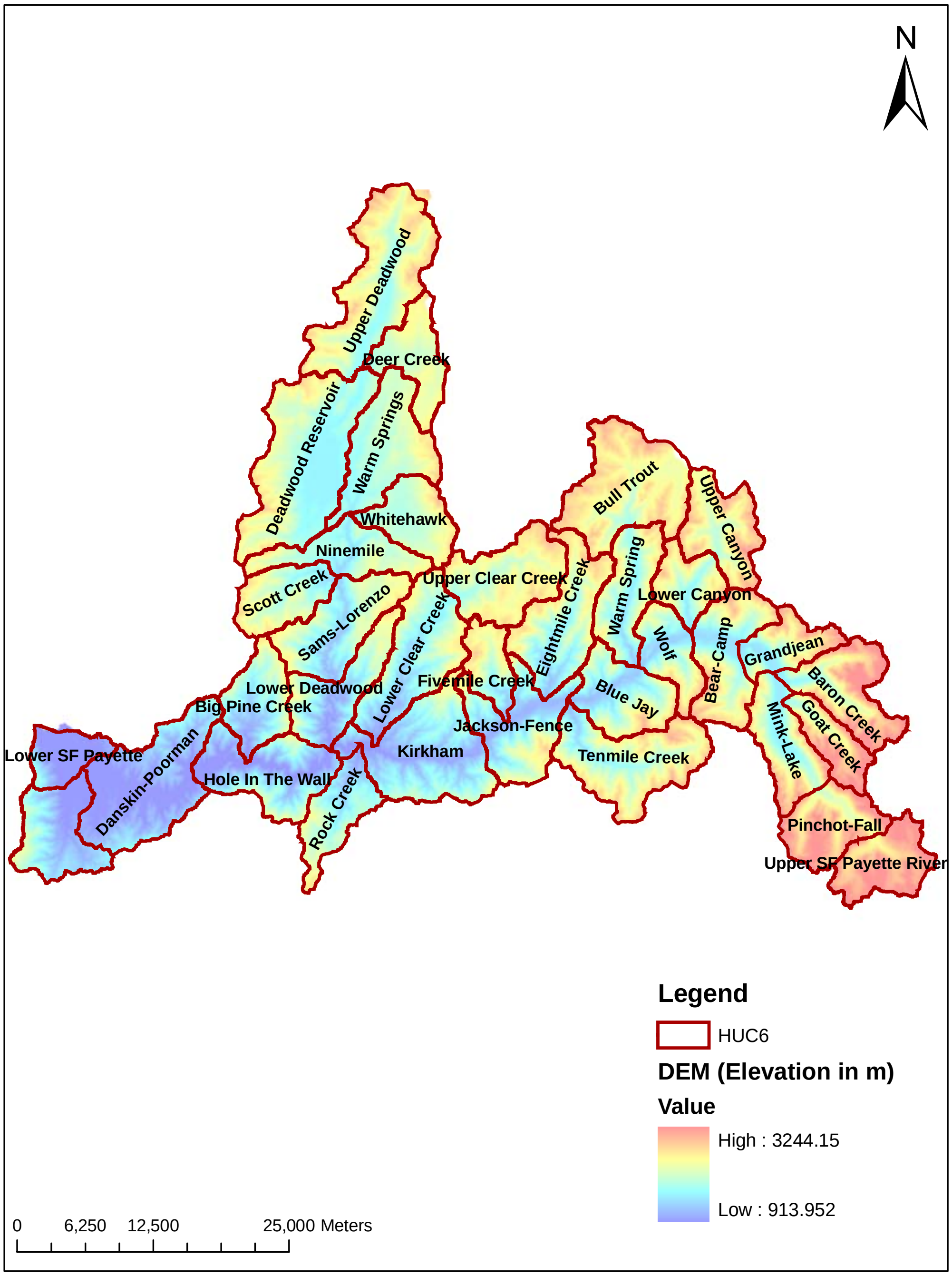


Figure 6-2. Six-digit Hydrologic Unit Code (HUC) watersheds for the South Fork of the Payette River, Boise National Forest, Idaho.

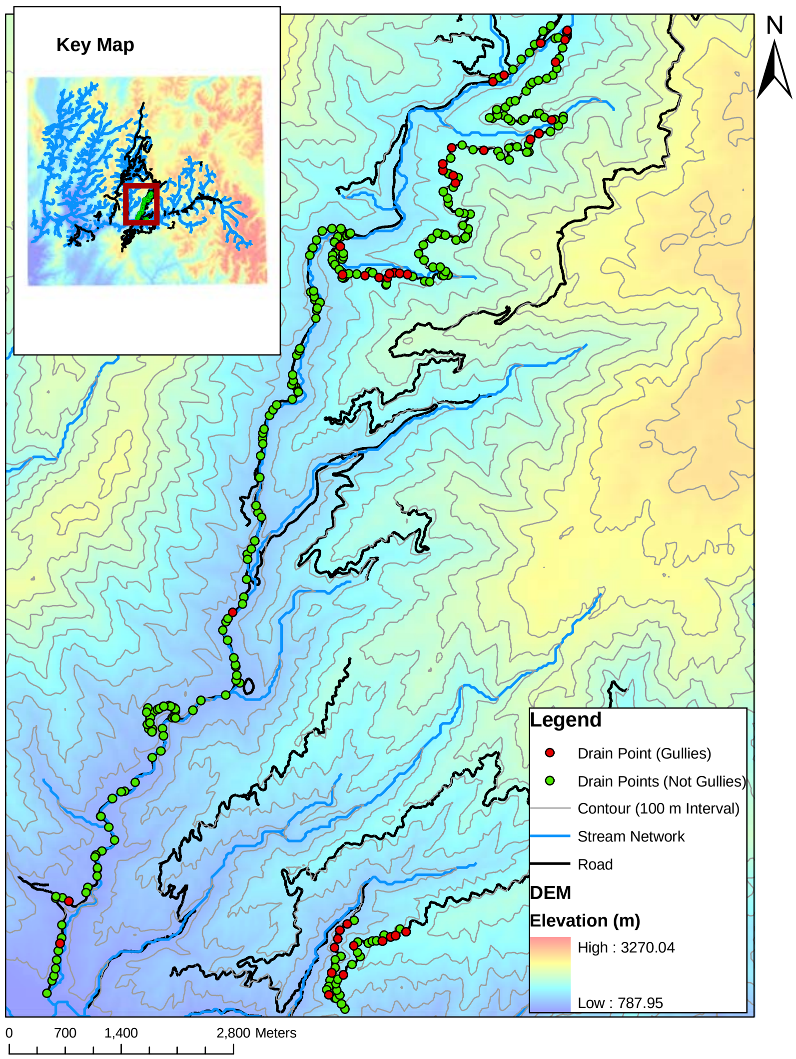


Figure 6-3. The subset area, used in gully initiation risk, illustrates the road segments, drain points and stream network.

Methods

Sediment production

This section explains the calculations involved in estimating the road sediment production and stream sediment delivery using BOISED (Reignig et al., 1991) and GRAIP models.

BOISED road surface erosion analysis. BOISED is one of several models used for estimating sediment production and delivery from land management operations that were derived from the R1/R4 Guide for Predicting Sediment Yield from Forested Watersheds (Cline et al, 1984). The model estimates the sediment production based on road age, gradient, mitigation techniques, and the "landtype" the segment crosses. Landtypes are derived from geomorphic and geologic classification of terrain (Arnold, Arnold and Associates, and Dames and Moore, 1975). For example canyon breaklands would be one classification with a distinct difference from periglacial uplands or alluvial stream bottoms. Each landtype is assigned characteristic quantitative features, such as slope and drainage distance, which are then used to estimate critical parameters of the BOISED model, e.g. side slope, geologic erosion factor, and sediment delivery ratio (see Appendix 6 for example values). Values for typical landtype characteristics are assigned somewhat subjectively by a group of experienced watershed specialists (Arnold, Arnold and Associates, and Dames and Moore, 1975).

The BOISED model calculates the total erosion from a uniform road segment within one land type as:

$$Er = BER_{AF} * DA * GEF * GF * MF \tag{6.1}$$

$$BER_{AF} = BER * AF \tag{6.2}$$

$$SD = SDR*Er \tag{6.3}$$

where Er is the sediment production, BER_{AF} is the base erosion rate adjusted for vegetation age factor, BER is the base erosion rate per year (Reignig et al., 1991), AF is the BOISED age factor calculated from decay of the base erosion rate (Reignig et al., 1991) with age, DA is the disturbed area, GEF is the geologic erosion factor, GF is the road gradient factor, *MF* is the mitigation factor, *SDR* is the sediment delivery ratio and *SD* is the sediment delivery to streams. Following are the steps in the sediment production calculation for the BOISED model.

1. Calculate Base Erosion Rate with age factor (BER_{AF}) for BOISED: The base erosion rate (*BER*) was assumed as 67500 tons/mi^2/yr (Reignig et al., 1991) or 23.7 kg/m^2/yr for an average 6% sustained grade, 50% side slope and native road surface type. Table 6-1 lists the age factors calculated based on the decay of base erosion rate with years since road was open to traffic (Reignig et al., 1991). The age factor for each age of the road is the ratio of the base erosion rate for that age and the base erosion rate for year one i.e. 67500 tons/mi^2/yr. In the current application the years since the road was open to traffic is not known but we do have information on the percentage of vegetation coverage in flow paths on each side of the road. The 4th column of Table 6-1 gives the mapping between flow path vegetation and age factor that was assumed, with AF being taken as the average of the two AF values from column 3 corresponding to the flow path vegetation in column 4.
2. Calculate the disturbed area: Road widths were adjusted based on the average side slope of the landtype on which the road was constructed. Appendix 6 gives the list of side slope values for each landtype obtained from Reignig et al. (1991). The default road tread width used in this model was taken as 4 meters (Reignig et al., 1991). Equation 6.4 shows the formula for default disturbed width derived from the relation between disturbed road width and side slope gradient (Reignig et al., 1991).

$$dw = b + b * 0.0006 * (Side\ Slope\ Gradient)^2 \quad (6.4)$$

Here *dw* is the disturbed width and *b* is the default road tread width. Appendix 6 lists the default disturbed width for each side slope gradient calculated from this formula, where the side slope gradient is assigned by landtype.

3. Calculate road length: The Road Surface Erosion Analysis tool in GRAIP was used to calculate the road segment length.
4. Get geologic erosion factor (*GEF*): Information from Reignig et al. (1991) about *GEF* for each land type (Appendix 6) was used.
5. Estimate road surface mitigation factor (*MF*): The *MF* for each road segment was calculated using surface type information in the road lines shapefile. Table 6-2 lists the mitigation factor for each surface condition type. The SURF_TYPE field in road lines table contains the condition of the road surface obtained from the USFS GPS road survey (Black, and Luce, 2002). Based on the surface type information, *MF* for each road segment was calculated and appended to the road lines shapefile as the "MitiFactor" field.
6. Calculate road gradient factor (*GF*): The *GF* is a function of the slope of each road segment calculated as the elevation range divided by road length. Elevation range and road length for each road segment were calculated using the GRAIP Road Surface Erosion Analysis function. *GF* for each road segment was then obtained from Table 6-3 (Reignig et al., 1991).
7. The sediment delivery ratio (*SDR*) was obtained based on land type class (Appendix 6) and was multiplied with *Er* to calculate sediment delivery from each road segment to streams.

Table 6-1. Relationship of base road erosion rate and age factor with year since activity (Reignig et al., 1991)

Years since open to traffic	BER_{AF}	Age Factor (AF)	Road Flow Path Vegetation
1	67500	1	0%
2	18000	0.26	>10%
3	5000	0.07	>25%
4	5000	0.07	>50%
5	5000	0.07	>75%
6+	5000	0.07	>75%

Table 6-2. BOISED mitigation factor

Surface Type	Mitigation Factor
Crushed rock	0.2
Native	1
Paved	0.05
Herbaceous Vegetation	0.2
Trees > 4 inch diameter	0.2

Table 6-3. BOISED road gradient factor

Gradient (%)	Road Gradient Factor
< 5	0.5
5 - 9.9	1.0
> 10	1.5

GRAIP road surface erosion analysis. The GRAIP Road Surface Erosion Analysis function calculates the road sediment production and sediment delivery at each drain point. The sediment produced from each road segment was calculated following Luce and Black (1999)

$$E_i = \frac{aLSrv}{2} \tag{6.5}$$

where L is the road segment length, S is the slope of the road segment, a is the annual base erosion rate, r is the road surface multiplier (Table 6-4), v is the vegetation multiplier (Table 6-5) based on ditch vegetation and i indicates the side of the road. Information for these multipliers were taken from Luce and Black (2001a, 2001b) and the Washington Forest Practices Board (1995) which synthesizes the work of several scientists.

The formula for sediment production (equation 6.5) was applied separately to each side of the road because flow paths on opposite sides of the road may drain to different drain points and have different attributes, hence the division by 2. The base erosion rate, *a*, was calculated to make the results consistent with the BOISED erosion calculations. The BOISED base erosion rate *BER* of 67,500 tons/m^2/yr converts to 23.7 kg/m^2/yr for a road with 6% slope, 50% side slope and native surface material (Reignig et al., 1991). The base erosion rate in GRAIP is per unit of vertical elevation change on a gravel surface road. This requires some manipulation to estimate an equivalent base rate so that the “standard” road segment for BOISED (the empirical basis) would produce the same amount of sediment in either model. Assuming a default road tread width of 4 m, equation 6.4 gives a disturbed width of 10 m ($4 + 4 * 0.0006 * (50)^2$). The GRAIP base erosion rate parameter is then calculated as

$$a = BER * dw/(S * r) = 23.7 * 10 / (0.06 * 5) = 790 \text{ kg/m/yr}$$

The multiplication by *dw* = 10 m accounts for the road tread width. The division by slope, *S*, adjusts to per unit elevation change and the division by road surface multiplier, *r*=5, adjusts the BER rate which is for a native surface to the GRAIP rate which is for gravel (Table 6-4).

This base erosion rate of 790 kg/m/yr was used along with the vegetation and road surface multiplier and length and slope (elevation range) of the road segment to estimate the sediment production from forest roads in the GRAIP Road Surface Erosion Analysis. Before performing the Road Surface Erosion Analysis, the GRAIP database preprocessor tool was run to validate the USFS road inventory and store it in the GRAIP database. The preprocessor creates consolidated drain points (DrainPoints.shp) and road lines (RoadLines.shp) shapefiles. These files and the DEM for the study area were then taken as inputs to the Road Surface Erosion Analysis. Using the drain point identifier information (GRAIPDID1 and GRAIPDID2 representing each side of the road and explained in Chapter 4) the accumulated sediment load at each drain point was calculated. Stream connection information for each drain point was then used to estimate the sediment delivery to streams.

Table 6-4. SurfaceTypeDefinitions table with surface types and multipliers, based on Washington Forest Practices Board, 1995

Surface Type	Multiplier
Default (gravel)	1
Crushed rock	1
Native	5
Paved	0.2
Herbaceous Veg	1
Brush	1
Trees > 4 in Dia	1
Cinder	1

Table 6-5. Factor or multiplier for each class of flow path vegetation, based on Luce and Black, 2001

Road Flow Path Vegetation	Vegetation Factor
0%	1
>10%	1
>25%	0.14
>50%	0.14
>75%	0.14

Indicators of gully initiation risk

Gullies below road drainage features are potentially major sediment contributors from road systems. No tools currently estimate sediment production from gullies, or even specify the probability of occurrence; however, several techniques are available as indicators of relative risk of gully erosion. When only road line information is available, there are several indicators based on the road location. These are discussed in the USFS Roads Analysis methodology (Bisson et al., 1999). GRAIP incorporates additional information about road drainage distances to predict gully formation at drain points.

USFS roads analysis indicators

USFS Roads Analysis (Bisson et al., 1999) uses stream channel proximity, slope position and hillslope gradient as indicators of the possibility of gully formation. The calculation used to obtain each indicator is explained below.

Stream channel proximity. The TauDEM distance to streams function was used to evaluate the distance from each drain point to the stream. These distances were classified into

a. Less than or equal to 100 meters
b. Greater than 100 and less than or equal to 200 meters

c. Greater than 200 and less than or equal to 300 meters

d. Greater than 300 meters

Slope position. Slope position is the division into categories of a hillslope from the ridge top, often the driest and most stable position, to the valley bottom, usually wetter and subject to mass wasting, saturation overland flow, and increased groundwater interception by roads. In this analysis, slope was divided into four classes based on the position along the flow path from ridge top to stream. These classes were

a. Valley bottom – Distance to stream is between 0 and 25% of hillslope flow path length.

b. Lower quarter – Distance to stream is between 25% and 50% of hillslope flow path length.

c. Upper quarter – Distance to stream is 50% and 75% of hillslope flow path length.

d. Ridge tops – Distance to stream is between 75% and 100% of hillslope flow path length.

Slope position for the study area was evaluated by from the DEM using TauDEM functions. The TauDEM grid network flow path length function calculates the longest upslope flow path terminating at each grid cell. This is denoted as “plen”. The distance to stream function calculates the distance from each grid cell to the stream network defined by the stream raster grid. This is denoted as “dist”. The grid slope position was calculated at each grid cell as dist divided by (dist+plen). This quantifies the fraction that distance to the stream is of the complete hillslope flow path length. The classes a to d above are then determined from this fraction.

Hillslope gradient. Steeper hillslope gradients yield an increase in the bed shear stress and stream power of water flowing out of road drains. Additionally, steem hillslopes are commonly associated with an increase in the frequency of road failures. Slope at each drain point was evaluated from the DEM using the GRAIP tool that averaged down gradient a distance of 50 meters. Slope was then classified into 4 classes with each class containing an approximately equal number of drain points.

GRAIP Indicator

GRAIP uses Erosion Sensitive Index (*ESI*) to asses the gully initiation risk at each drain point. GRAIP ESI analysis is explained below.

Erosion sensitivity index. Montgomery (1994) and Istanbulluoglu et al. (2001a) have related erosion potential to aS^{α}, where a is the contributing area, S is the slope and α an exponent varying from 1 to 2. In the case of road drainage an erosion sensitivity index (*ESI*) which uses the cumulative upslope road length draining to each drain point and the slope at the drain point is defined. The cumulative length was used as a surrogate measure for the quantity of road drainage and was obtained from the effective length (ELength) calculated using GRAIP.

$$ESI = L_c S^{\alpha} \quad (6.5)$$

where L_c is the total length of discharging road segments, S is the slope at the drain point and α is taken as 2. GRAIP was used to calculate the slope at each drain point averaged over a down gradient distance of 50 m. Effective road length at each drain point is the contribution from each side of each road segment as different sides of the road segment may drain to different drain points.

Results

Sediment production

The sediment production values were calculated for the all the road segments in the study area shown in Figure 6-1 using both the BOISED and GRAIP methods. Figure 6-4 illustrates the sediment production values from GRAIP and BOISED for each road segment. GRAIP sediment production values were found to be approximately twice those calculated by BOISED. To evaluate the differences in the sediment production values, the parameters used for each of the models were examined. BOISED uses a categorical slope factor (Table 6-3) whereas GRAIP uses slope directly in the evaluation of sediment production. The standard road slope in BOISED is 6%. Figure 6-5 shows the GRAIP slopes divided by 0.06 (6%) so that these factors are comparable. For slopes less than 3% and between 5% and 6%, the BOISED slope factor is higher; otherwise, the BOISED slope factor is lower. On average, the GRAIP slope factor is 1.65 times that of the BOISED slope factor.

BOISED uses an age factor (AF) that was assigned based on flow path vegetation according to Table 6-1. There are three discrete AF values in Table 6-1, which when averaged for each side of the road result in a total of five possible average age factors in BOISED. In GRAIP vegetation factor was assigned based on flow path vegetation according to Table 6-5. There are two discrete vegetation factor values in Table 6-5, which when averaged for each side of the road results in three possible average GRAIP vegetation factors. Figure 6-6 plots the road segment average BOISED age factor versus GRAIP vegetation factor. The six points that result comprise all the possible combinations from flow path vegetation on different sides of the road. The GRAIP vegetation factors were generally estimated to be higher compared to BOISED age factors.

Figure 6-7 illustrates the distribution of disturbed widths in the BOISED analysis. GRAIP uses a constant disturbed width of 10 meters while the BOISED disturbed width ranges from 4 meters to approximately 19 meters (Figure 6-7) depending on landtypes (Appendix 6), with an average of 9.2.

Figure 6-8, compares the GRAIP and BOISED surface type mitigation factors which are linearly related and differ by a factor of 4 for paved roads and 5 for gravel and native roads. This does not play a role in differences between the models due to the factor of 5 difference being factored in to the calculation of the base erosion rate parameter a and the fraction of roads that are paved being very small.

Finally the distribution of Geologic Erosion Factor (GEF) for BOISED was compared to the implicit uniform GRAIP GEF (Figure 6-9) that has a value of 1 because geologic effects in GRAIP are controlled by the base erosion rate. The average GEF from BOISED (1.05) is a little bigger than the GRAIP value of 1.

Table 6-6 lists the average values of multipliers calculated for the study area. The product of the ratios between GRAIP and BOISED multipliers (from Table 6-6, 1.06/1.65 * 0.8/0.9 * 9.2/10 * 1.05/1) gives a value of 0.55 representing the average difference in the sediment production values calculated from each model. In Figure 6-4, some of the difference is absorbed in the non-zero positive intercept.

Table 6-6. Comparison of multipliers for GRAIP and BOISED

Multiplier type (Average)	GRAIP	BOISED
Slope factor	1.65	1.06
Vegetation factor	0.9	0.8
Road width	10	9.2
GEF	1	1.05

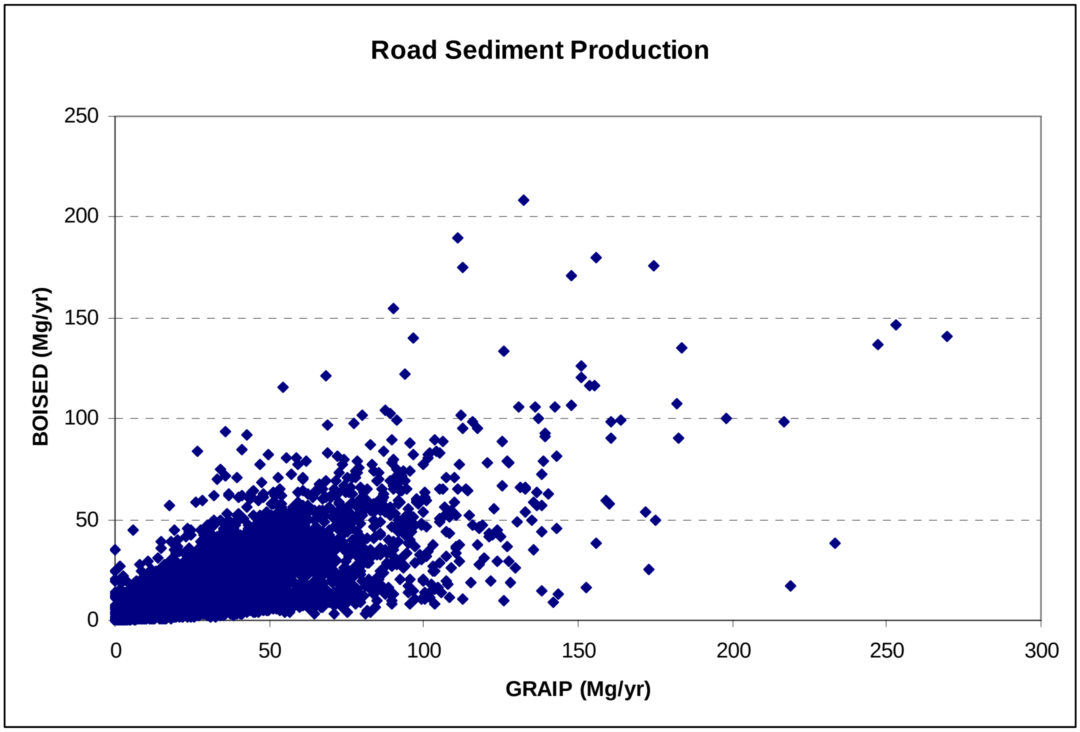


Figure 6-4. GRAIP vs BOISED road segment sediment production values.

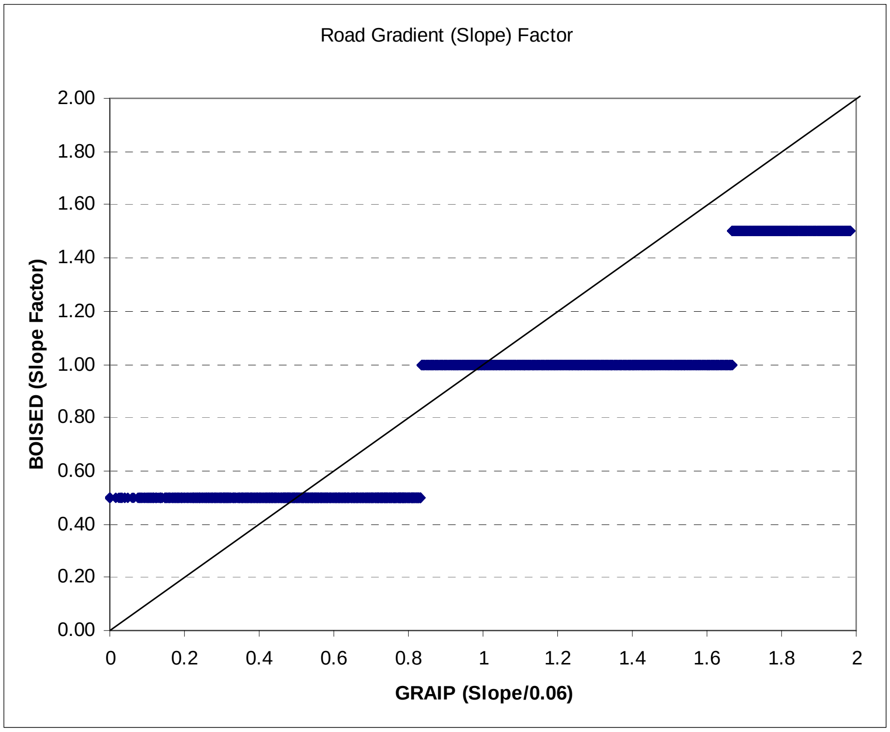


Figure 6-5. Gradient or slope factor for road segment (GRAIP vs BOISED).

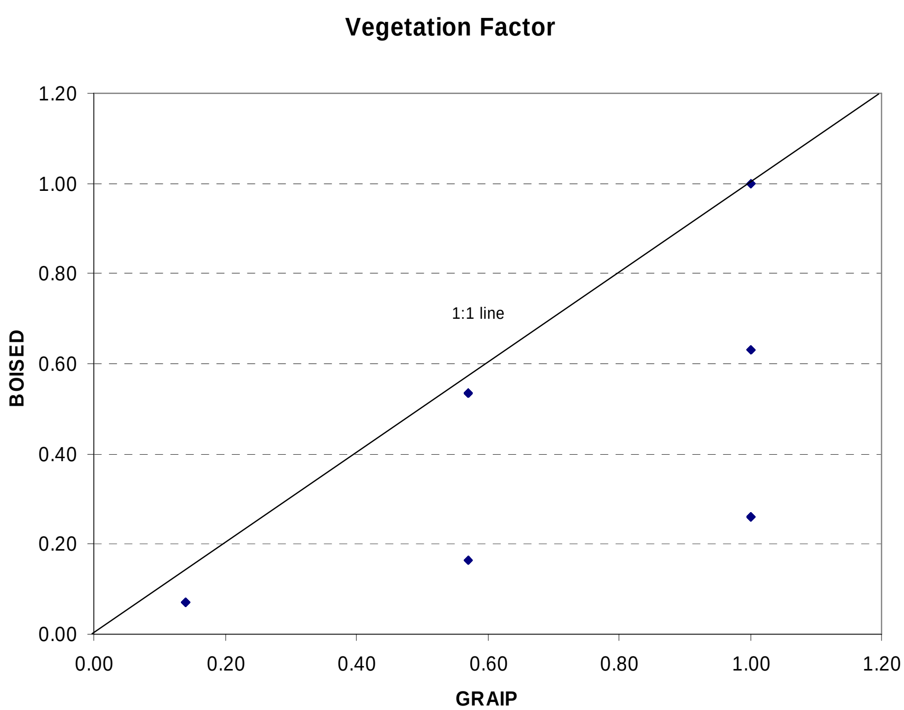


Figure 6-6. Vegetation factor used for each road segment (GRAIP vs BOISED).

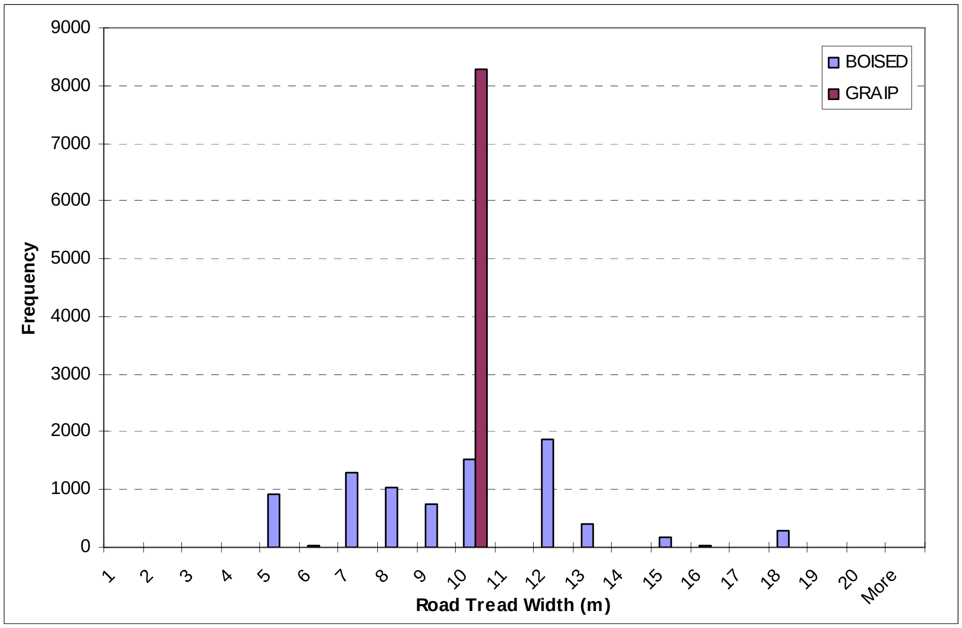


Figure 6-7. Frequency of road tread width for each road segment used in GRAIP and BOISED.

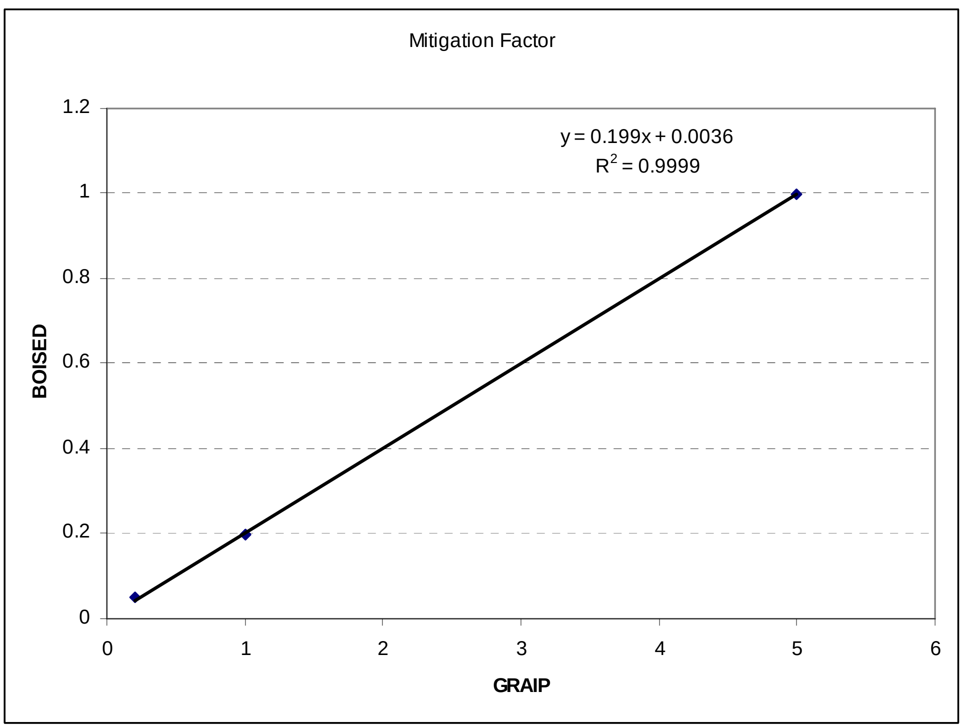


Figure 6-8. Surface mitigation factor for each road segment (GRAIP vs BOISED).

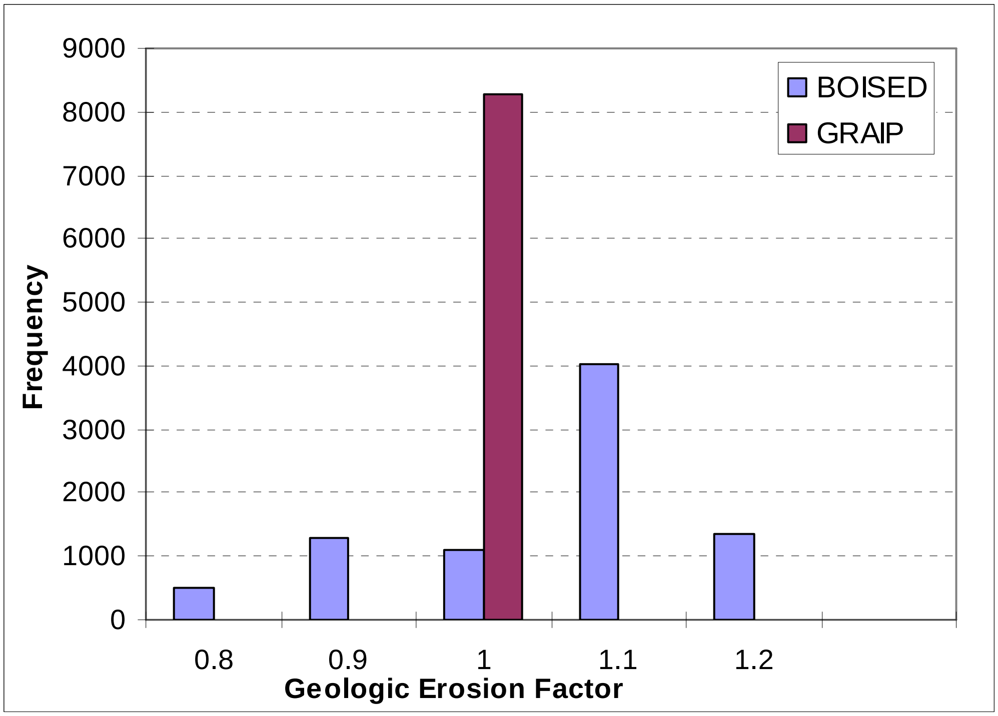


Figure 6-9. Frequency of geologic erosion factor for each road segment (GRAIP vs BOISED).

The calculated sediment production and delivery values (for both GRAIP and BOISED) were then summarized for each six digit HUC sub-watershed (Figure 6-2). The resulting aggregate sediment production and delivery values in each HUC region were plotted to examine the relationship between GRAIP and BOISED. Figure 6-10 shows the graph for HUC summarized by sediment production in each HUC. GRAIP has higher estimates of sediment production values compared to BOISED as expected from the earlier examination of the effects of multiplication factors for sediment estimation.

Because of the similarity of the formulation of the two models for sediment production, some similarity is expected in sediment production values. There are substantial differences in how the models work with respect to the delivery of sediment to the streams. BOISED assumes some delivery from each road segment based on the landtype attributes while GRAIP uses delivery points identified in the field as connected to streams. Although Figure 6-4 shows a relationship between sediment production for each segment, Figure 6-11 shows nearly no relationship between sediment delivery from the two models, with a distinct tendency for BOISED to under-predict delivery. This difference is due to GRAIP having used stream connectedness information from the road inventory that was not available to BOISED. In principle GRAIP should give a better estimate of sediment delivery values. When aggregated over a six digit HUC sub-watershed there is a reasonably strong relationship between the two models, with an R^2 of 0.87 (Figure 6-12). The strong relationships in Figures 6-10 and 6-12 are primarily due to the variation of the length of road in each sub-watershed. Comparing Figures 6-10 and 6-12, although the GRAIP calculated sediment production values in Figure 6-10 were approximately twice as high as BOISED, the amount of sediment estimated to be delivered to the streams in Figure 6-12 was approximately 6 times more than BOISED, reflecting the underestimated delivery using landtype information.

Figure 6-13 compares the sediment delivery ratio (*SDR*), for GRAIP and BOISED, calculated by dividing the sediment delivery for each HUC region with the total sediment produced. The graph shows, similar to Figure 6-11, no relationship between *SDR* for GRAIP and BOISED. The regression between *SDR* values for GRAIP and BOISED has a p-value of 0.22, which is not significant.

Figures 6-14 and 6-15 compare the sediment production to the sediment delivery for GRAIP and BOISED models, respectively. Approximately 5% of the sediment production calculated using BOISED is delivered compared to 18% in GRAIP. The

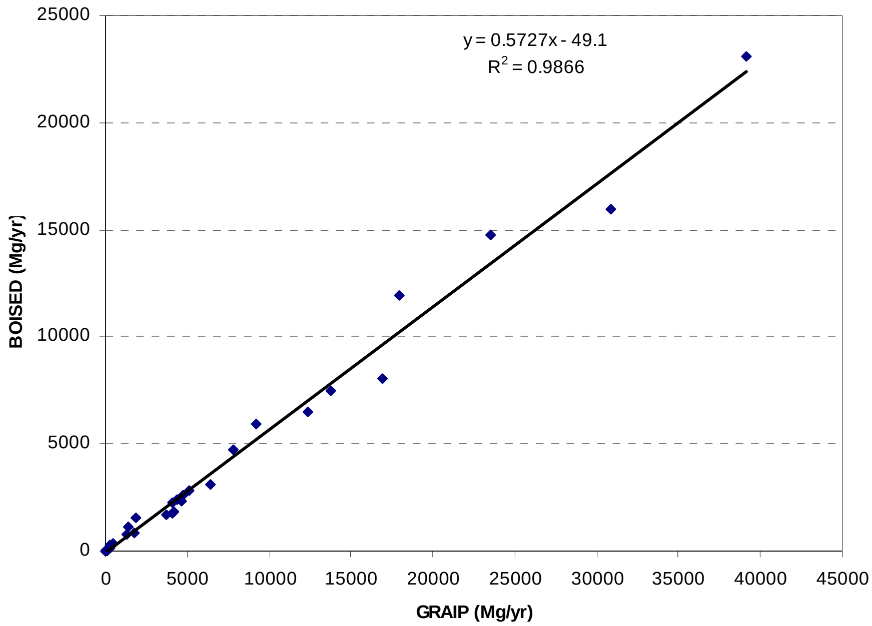


Figure 6-10. Sediment production values in Mg/yr summarized by HUC (GRAIP vs BOISED).

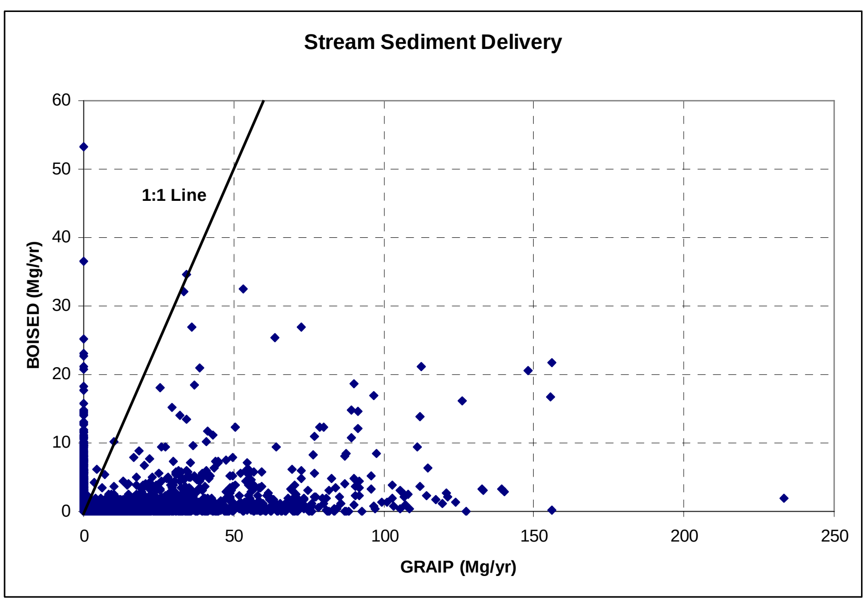


Figure 6-11. GRAIP vs BOISED road segment scale comparison of stream sediment delivery.

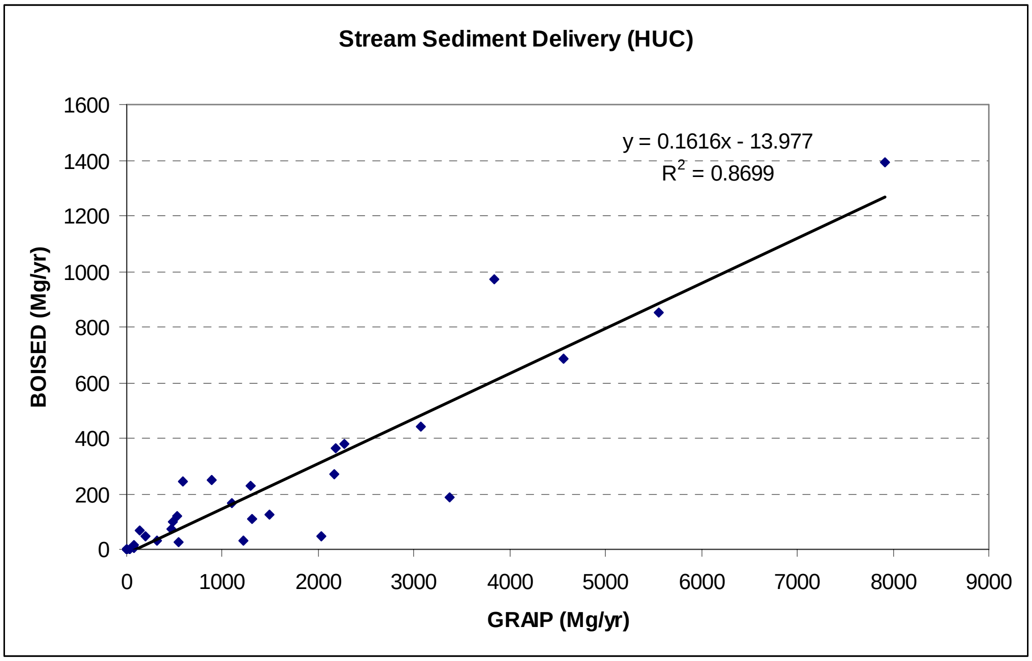


Figure 6-12. GRAIP vs BOISED stream sediment delivery in Mg/yr.

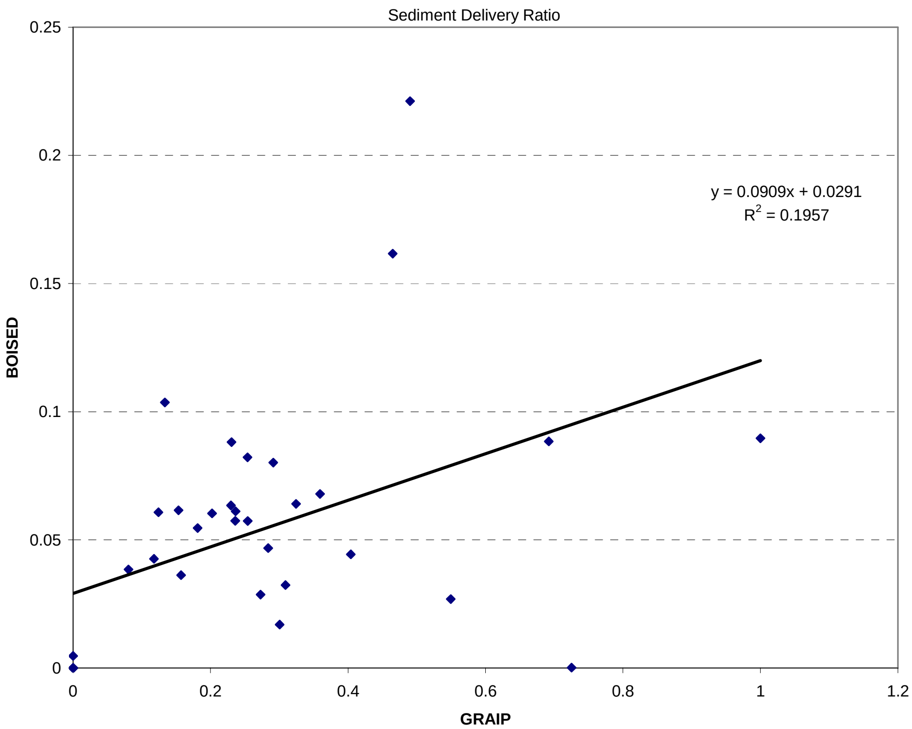


Figure 6-13. GRAIP vs BOISED sediment delivery ratio.

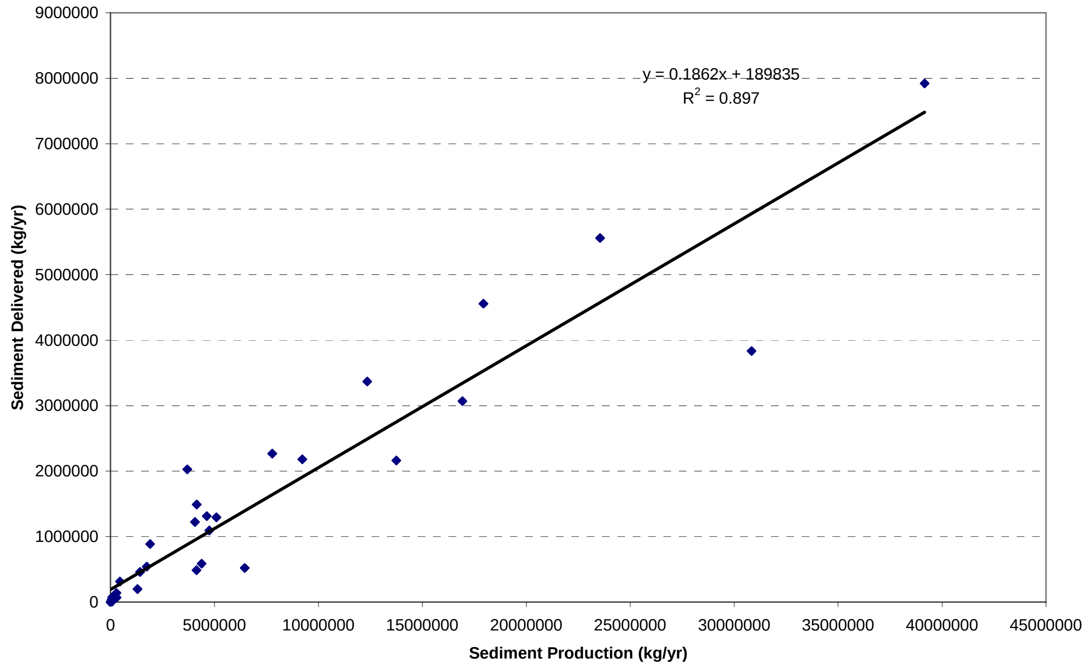


Figure 6-14. GRAIP Sediment production vs Sediment delivery.

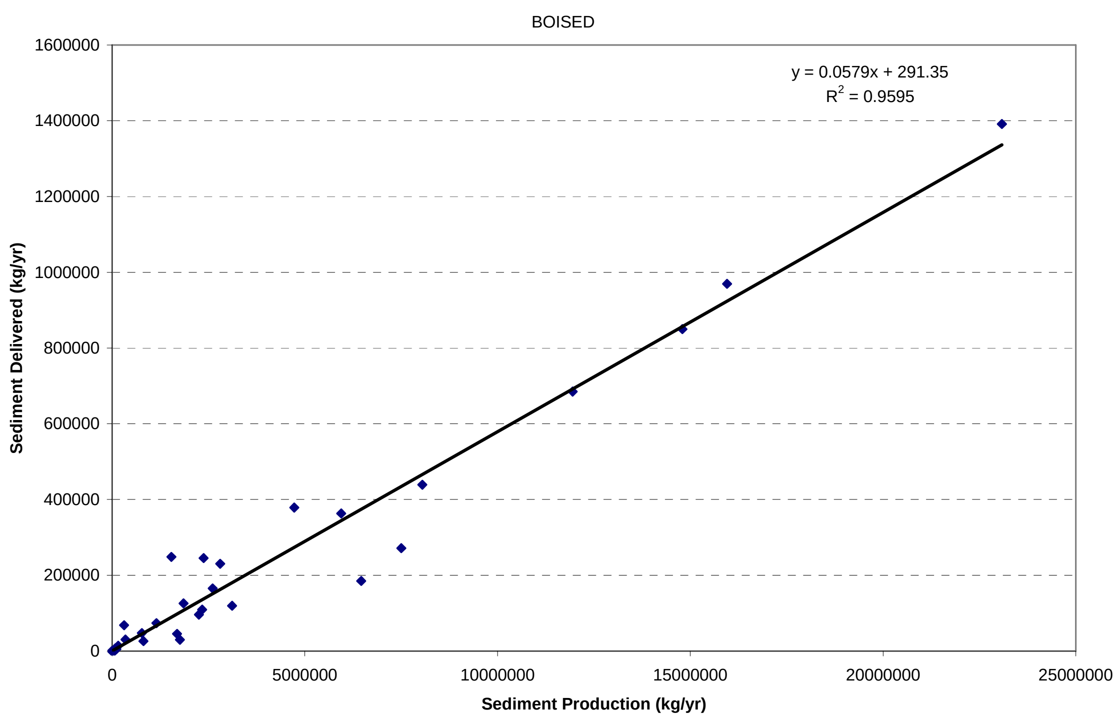


Figure 6-15. BOISED Sediment production vs Sediment delivery.

GRAIP calculations are believed to be more accurate because they use observed information about the sediment delivery to streams from the USFS inventory.

Indicators of gully initiation risk

The USFS Roads Analysis indicators of gully formation (Slope Position, Stream Channel Proximity and Slope or Hillslope) were compared with the GRAIP indicator of gully formation (ESI Class).

Stream channel proximity. The terrain nearer to stream channels is generally considered to be wetter due to higher upstream contributing area when compared to other parts of the hillslope and hence more susceptible to gully formation. The USFS Roads Analysis (Bisson et al., 1999) consequently uses stream channel proximity as an indicator of the potential for gully formation. Table 6-7 lists the number of drain points and observed gullies in each flow path distance class and Figure 6-15 shows the distribution of gullies in each distance to stream channel class. We find that only 8.4% of drain points less than 100 meters to the stream channel have gullies compared to 30.3% of gullies observed between 100 and 200 meters. There is not a monotonic trend to the percentage of drain points with gullies as a function of distance from the stream and the average percentage of drain points with gullies is close to the percentage for all three of the larger distance classes. The class of stream distances closest to the stream has the lowest percentage of drain points with gullying, in contradiction to the hypothesis that the potential for gullying is higher close to streams. One cause for the failure of this hypothesis might be a different geomorphology for our study area compared to where this hypothesis was developed. In some setting slopes are steep adjacent to streams, but in

Table 6-7. Shows the classification of gullies with respect to distance from streams

Index	Distance from streams (meters)	Number of drain points	Number of gullies	Percentage of drain points with gullies
0	< 100	143	12	8.39
1	100 - 200	33	10	30.30
2	200 - 300	27	5	18.52
3	300 <	60	12	20
	Total	263	39	14.83

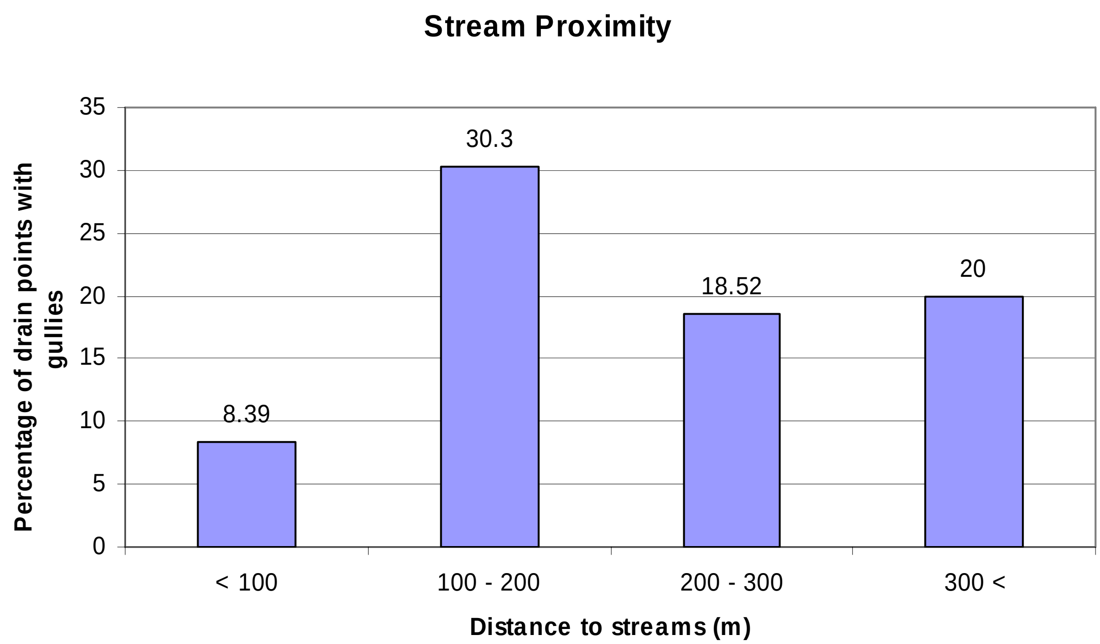


Figure 6-16. Distribution of gullies and distance from stream channels.

our study area the slopes were generally less steep resulting in less gully formation adjacent to streams. Based on these findings we conclude that for this data the distance from the stream appears to be uninformative for predicting gullies.

Slope position. Figure 6-16 illustrates the slope position grid evaluated from the TauDEM flow distance to streams and longest upslope flow path grids. The TauDEM derived stream network, road segments and drain points classified as to whether gullies were or were not observed are also shown.

Table 6-8 gives drain points within each slope position class. According to the Roads Analysis (Bisson et al., 1999), lower slope position is an indicator of gully formation potential because it is associated with larger contributing area. We found that the percent of drain points with gullies in the slope position class (Figure 6-17) 50% to 75% was approximately 27%. 12% of the drain points nearer to the ridge top (slope were gullied while only 4.8% of drain points close to streams were gullied. This is in contrast to the findings of Bisson et al (1999) for the Bluff Creek watershed in California. There, slope position was divided into three classes, 20% for the upper slope positins and 40% for mid and lower slope positions. Within the uppers slope position class 23 % of the area was steeper than 50 % slope. Within the middle and lower slope position classes about 35 % of the area was steeper than 50 % slope. The Bluff creek watershed had road failures 30 times higher in the lower slope position class compared to the upper position. From the fact that we do not find a monotonic relationship between slope position class and percentage of drain points with gullies and from the fact that our data displays a different relationship in comparison to Bisson et al.'s work we conclude that the classification of the slope position does not appear to provide information on the potential for gully formation. As for stream proximity, the differences may be due to differences in regional geomorphology. In areas with high uplift rates (e.g. coastal areas) the "inner gorge" with steep slopes near the streams may dominate gully formation, whereas in areas with glacial pasts or very old mountains with wider flatter valley bottoms the relationship with slope position is likely to be different.

Table 6-8. Shows the classification of gullies inside each slope position class

Index	Slope Position Class	Number of Drain Points	Number of Gullies	Percentage of drain points with gullies
0	< 25%	83	4	4.82
1	25 – 50%	53	5	9.43
2	50 – 75%	102	27	26.47
3	75 – 100%	25	3	12
	Total	263	39	14.83

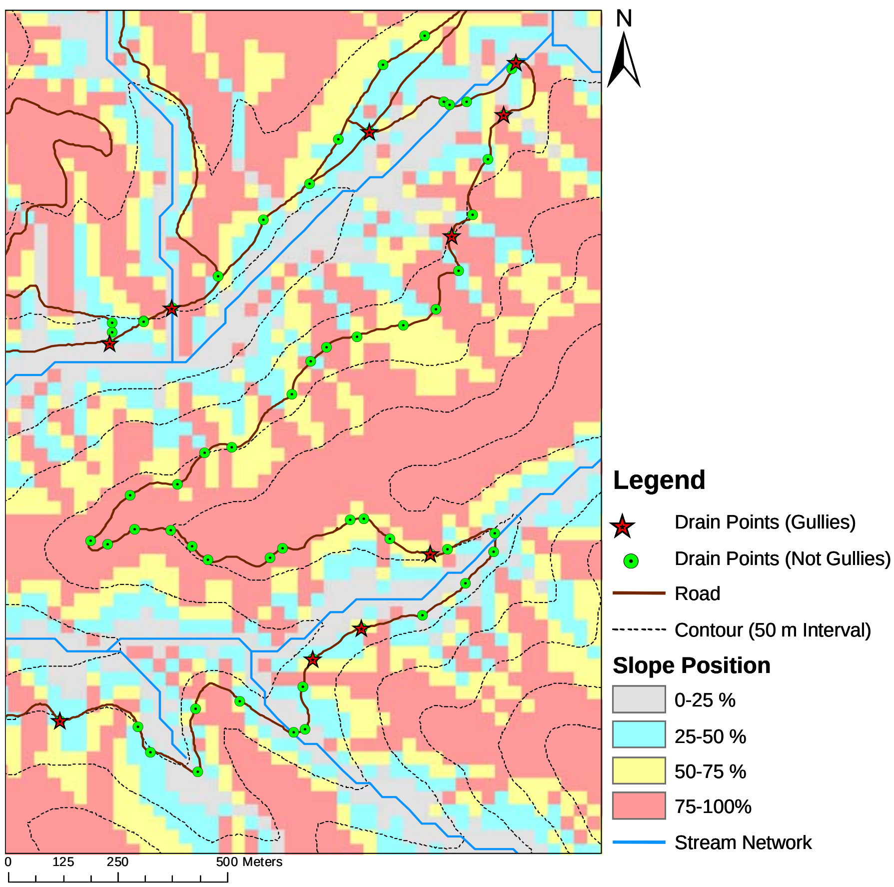


Figure 6-17. Grid of slope position classes.

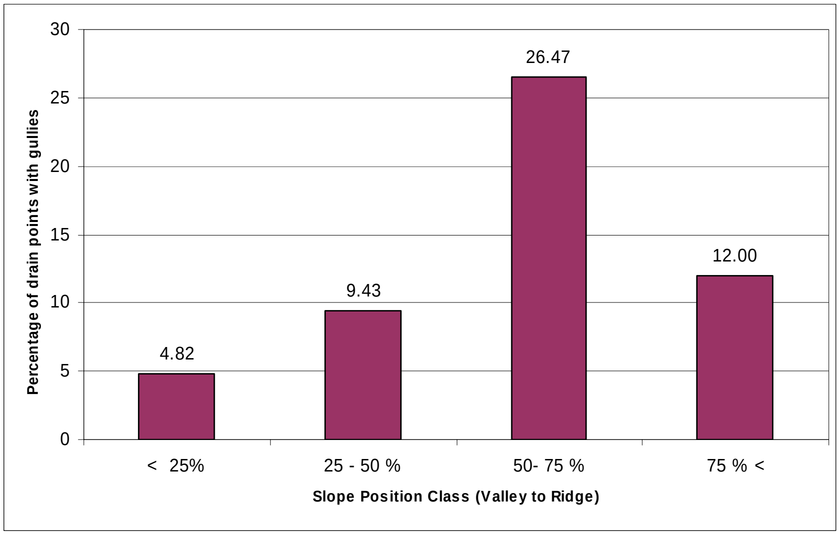


Figure 6-18. Distribution of gullies in each slope position class.

Slope at each drain point. Slope at each drain point was determined by intersecting the drain point with the slope grid created from the DEM of the subset study area shown in Figure 6-3, averaging over a 50 m down gradient distance. Figure 6-18 illustrates the slope classes that were derived so that each class contained approximately the same number of drain points. The TauDEM derived stream network, road segments and drain points classified as to whether gullies were or were not observed are also shown. Table 6-9 shows the slope classes with number of drain points in each class and the number of drain points having observed gullies in that class. Almost 29 % of drain points with slope of more than 28.8 degrees have observed gullies. But the threshold used for this indicator is a decisive factor in grouping the gullies. From Figure 6-19 we find that more than 95% of the drain points with observed gullies have slope more than 8.5 degrees. But only 30% of the gullies have more than 28 degrees slope and almost 60% of

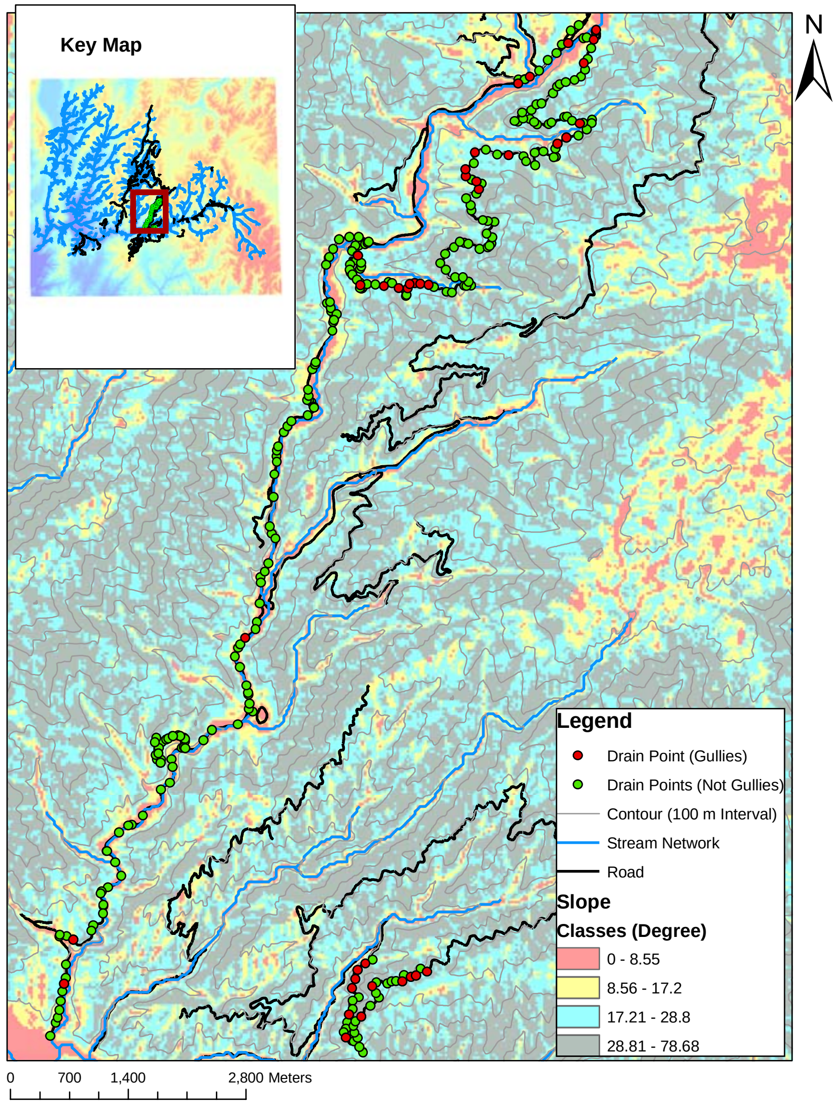


Figure 6-19. Part of the road network with gullies mapped. The raster grid shows the slope classification.

Table 6-9. Shows the classification of gullies inside each slope class

Index	Slope Class (Degrees)	Number of Drain Points	Number of Gullies	Percentage of drain points with gullies
1	Slope <= 8.55	82	2	2.4
2	8.55< Slope <= 17.2	64	10	15.6
3	17.2 < Slope <=28.8	62	11	17.7
4	Slope >28.8	55	16	29.1
	Total	263	39	14.83

them have lower slope. For slopes less than 8.5 degrees there is 2% chance of having a gully and for slopes greater than 29 degrees there is a 29% chance of gullies. These two classes clearly discriminates the gully initiation risk. But for the intermediate classes (2 and 3) chances of gullying are little above the mean percentage of gullies. Because of the bin selection which holds approximately equal number of drain points roughly 50% of the drain points fall into these two intermediate classes where the discrimination of gully formation potential is limited.

Erosion sensitivity index. Calculation of GRAIP ESI used knowledge of effective length, L, of the road draining to each drain point from the USFS road survey. This is additional information over slope only, and requires field survey information. ESI was evaluated as LS^{α}. The α was taken as 2 (Montgomery, 1994; Istanbulluoglu et al., 2001a). Table 6-10 shows the number of drain points and observed gullies for each class. Figure 6-20 shows the distribution of gullies in each ESI class. The drain point slope – length graph in Figure 6-21 shows the ESI lines that discriminate the slope and effective length space into the four classes with varying percentage of drain points with gullies given in Table 6-10. Table 6-10 and Figure 6-21 indicate that 85% of the observed gullies are found at drain points with ESI values greater than 8. The middle ESI class (Index 3 in Table 6-10) shows that after a threshold ESI value (8 in this case) the chances of gullying are high. Here the first two classes containing approximately 50% of drain points with ESI values less than 8, hold 5 % of the drain points having gullies and the other two classes with ESI values more than 8 have 28% chance of gullying. This categorization into ESI classes has provided a good discrimination of the potential for gully formation at drain points.

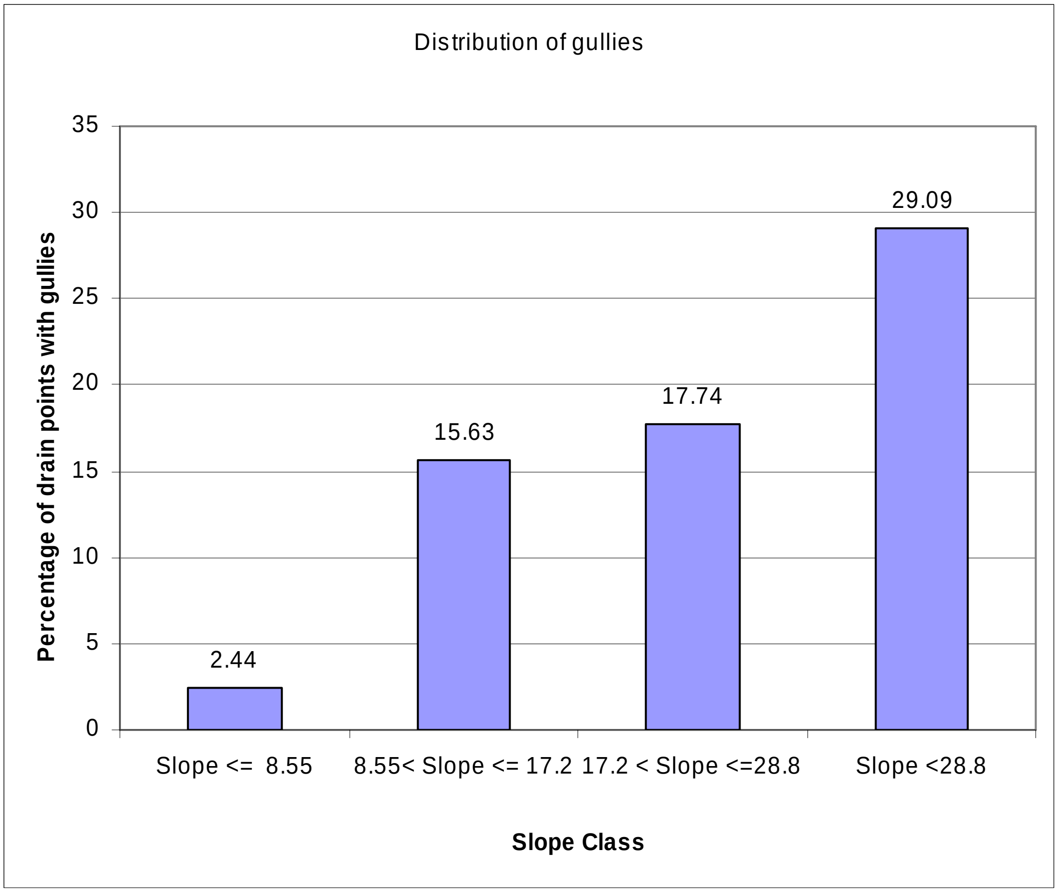


Figure 6-20. Percentage of gullies in each slope class.

Table 6-10. Classification of gullies inside each ESI class

Index	ESI Value Class	Number of drain points	Number of gullies	Percentage of drain points with gullies
1	< 1.25	81	4	4.94
2	1.25 - 8	64	3	4.69
3	8.01 - 25	63	18	28.57
4	> 25	55	14	25.45
	Total	263	39	14.83

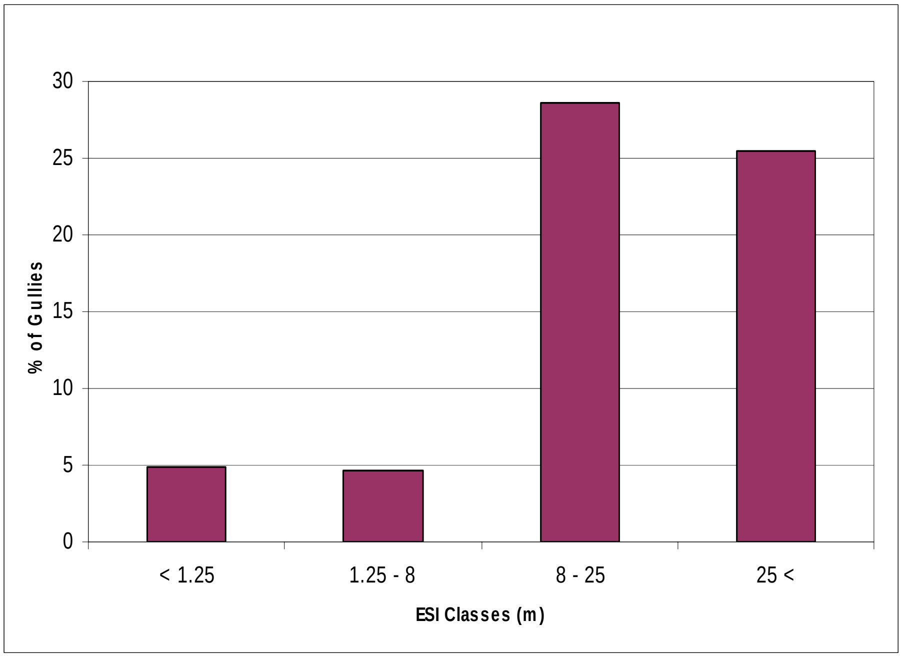


Figure 6-21. Distribution of gullies in each ESI class.

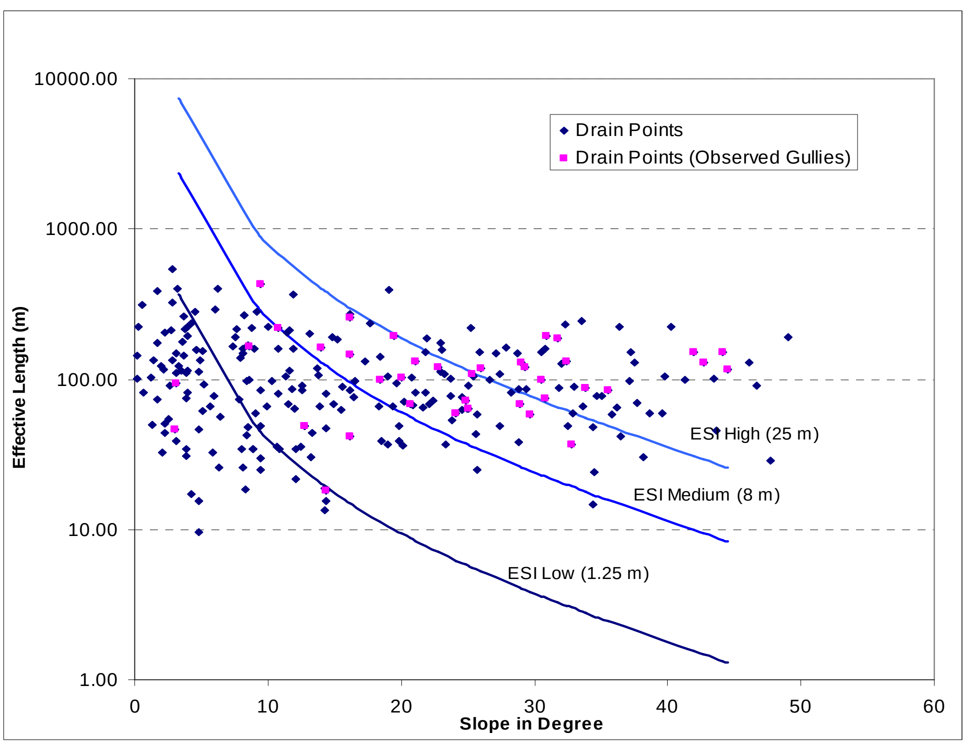


Figure 6-22. Length-Slope graph with ESI threshold lines plotted.

Conclusion

This chapter compared the USFS Roads Analysis methods to analyze the impact of forest roads on watersheds, with the GRAIP model. The comparison started with the calculation of sediment production values using the BOISED model used by the USFS, and the GRAIP road surface erosion analysis. Sediment production values from GRAIP were found to be twice as high as BOISED both at the road segment scale and HUC scale. The sediment delivery values for GRAIP were approximately 6 times higher than BOISED. Because GRAIP calculates sediment delivery from the observed road-stream connectivity information, we believe the GRAIP values to be a better estimate of stream sediment inputs. These results indicate that while BOISED may provide a rough estimate of sediment delivery at the sub-watershed scale (six-digit HUC); segment scale estimates require information about the drainage and delivery patterns. Segment scale information can be valuable in targeting treatments to roads to meet regulatory requirements. Furthermore, corrections for basin-scale delivery can be provided from a field based inventory of delivery to improve estimates from a model like BOISED.

The next comparison dealt with the indicators used in the USFS Roads Analysis and GRAIP to analyze the risk of gully initiation at drain points. The stream channel proximity and slope position indicators in the USFS Roads Analysis could be used only in the context of a regional calibration to provide expectations about the pattern of gully occurrence with location. The slope (hillslope) class indicator in the USFS Roads Analysis showed clearer influence in predicting gullies compared to former two. In the case of the GRAIP ESI gully initiation risk indicator, above a particular threshold the chances of gullying were consistently high, while below that threshold, they were consistently low. For roads with intermediate sideslopes (between 8.5 and 28 degrees), representing about ½ of the drainpoints, the ESI model is more informative than slope alone.

Overall, this chapter has compared erosion, sediment delivery, and gullying indicators calculated from detailed attributes of road drainage, with more generalized calculations. The results demonstrates that, as suggested by Wold and Dubé (1998), and Luce and Wemple (2001), a detailed road inventory can provide the basis for a more informative analysis of road impacts on forest watersheds.

CHAPTER 7

CONCLUSION

This thesis presents a new way to integrate different terrain analysis models and GIS analysis tools and techniques to evaluate the impact of forest roads on watersheds. The model was implemented as a set of GIS tools and functions and as GIS procedures using terrain analysis (TauDEM), and slope stability analysis (SINMAP). Several GIS techniques were also developed to process the data for the analysis.

This thesis also presents a new relational database design, based on the USFS road inventory, to formally organize and structure the data that represents the interaction between roads, drain points, hillslopes and stream networks to enable and facilitate road impact assessments. A database preprocessor tool was developed to validate and import the USFS road inventory into the new relational database.

The procedures were programmed using a combination of C++ and Visual Basic 6.0 as library functions compiled into a Microsoft Component Object Model (COM) Dynamic link library. The GIS toolbar was implemented as an ArcGIS ArcMap toolbar that uses ArcObjects software components inside Visual Basic 6.0 to access spatial analysis and other ArcGIS functionalities used in the model. The software accesses data in the ESRI grid format using the RasterIO application programmer's interface. The database preprocessor tool was developed as a standalone tool using Visual Basic and C++. Both the GIS toolbar and the database preprocessor tool communicate with the Microsoft Access Database using the MS ActiveX Data Object and SQL. The database preprocessor tool and the GIS model uses the Shapefile C Library (http://shapelib.maptools.org/), which provides the ability to write simple C programs for reading, writing and updating shapefiles, and the associated attribute file (.dbf).

The complete model developed during the course of this work is called the Geomorphologic Road Analysis and Inventory Package (GRAIP) and includes the following components

1. Database schema,
2. Database preprocessor,
3. GIS methods for properly locating road stream crossings on streams so that a stream network segmented at these points can be delineated,
4. GIS procedures to develop a slope stability index map using SINMAP,
5. Road surface erosion and stream sediment delivery module,
6. Mass wasting potential module for the impacts of road drainage on both landslide and erosion risk,
7. Stream blocking analysis module,
8. Stream habitat contiguity module.

The GRAIP tool was used to quantify the impacts of forest roads in a case study within the South Fork of the Payette River within the Boise National Forest. The sediment production from forest roads, accumulated sediment load at each drain point, and sediment delivery to each stream segment was calculated and recorded in the database. Maps for the part of the study area were presented to illustrate how the results are useful for forest road analysis. These maps can be used by forest managers and decision makers to identify road segments and drain points with high erosion and high potential for delivery of sediment to streams, for use in the planning of future maintenance or decommissioning priorities.

The GRAIP terrain stability analysis calculated the SINMAP stability index values at each drain point. The GRAIP modified SINMAP approach considered both terrain and road effects on the slope stability and produced a map of stability index values accounting for road drainage effects. This map shows the effect of additional discharge on slope stability downslope from drain points and is useful for analysis of the effect of road drainage on terrain stability.

The gully initiation risk for each drain point was analyzed by calculating erosion sensitivity index (ESI) values. A graph was developed to group the display of drain points into classes with low, medium and high risk for gullying. The ESI lines bounding classes were specified so as to obtain classes holding an approximately equal number of drain points. Observed gullies were also displayed on the graph to better understand the relationship between ESI and gully formation at each drain point. More than 80 percent of the observed gullies were found to be located in medium and high ESI regions. The ESI can be used to determine a threshold value above which the chances of gullying are high.

A stream blocking susceptibility analysis was carried out for each drain point based on attributes of drain points recorded in the road inventory. Streams can be blocked by organic debris or sediments and this analysis helps to identify the drain points which are at risk.

The final module in GRAIP is the habitat segmentation module. Road-stream crossings may be barriers to fish passage. This module filtered GPS surveyed stream crossings in an effort to properly locate them on streams. A stream network with streams segmented at stream crossings was then derived from the DEM. The stream crossings were then analyzed for fish passage barrier status based on culvert and other stream crossing attributes from the road inventory. Using this information stream habitat clusters within the stream network were identified. The map of the habitat clusters identifies the stream blockages and contiguous fish habitats and is a tool for prioritization of stream crossing maintenance and barrier correction.

A model comparison study was performed to compare the existing USFS Roads analysis methods and GRAIP. For sediment production, the BOISED model was compared with GRAIP. This comparison found that GRAIP estimates were twice as high as the sediment production values from the BOISED model. This difference was explained in terms of the contribution of the various multipliers in each model to the overall difference. The amount of sediment estimated, by GRAIP, to be delivered to the streams was approximately 6 times higher than BOISED. This is believed to be a more reliable estimate because it is based on direct survey of the drain points connected to streams.

Existing geomorphologic indicators for the risk of gully initiation were also compared to the GRAIP ESI. We found that the slope position and stream channel proximity indicators in the USFS Roads Analysis do not predict the potential for gully formation very well. Both the terrain slope, which is a USFS gully initiation indicator, and GRAIP ESI showed good relationships with observed gullying. The fraction of drain points with observed gullies increased as the slope got steeper or the ESI increased. In the case of the GRAIP ESI indicator, more than 80 percent of the drain points where gullies were observed had ESI greater than threshold value of 8. ESI, that makes use of information on the length of road draining to each drain point, was found to be a better discriminator of the potential for gully formation than slope alone.

Overall this study has shown that a detailed road inventory containing information about the road and drain points helps in predicting the impacts of forest roads on the watershed. The inventory proposed by Luce and Black (2002) comprises a detailed GPS survey of the road system. The GRAIP model is based on this surveyed inventory information. The model comparison showed that with more information on road and drain point attributes, the analyses can better predict sediment production, sediment delivery, terrain instability due to road drainage, gully initiation risks and habitat segmentation. The GRAIP relational database also improves data integrity and consistency resulting in a better quality dataset for more accurate GIS road analysis.

One of the problems that is faced in performing a GRAIP analysis is the correct positioning of drain point and stream crossing on DEM delineated streams, due to imprecision in both the GPS positions and the delineated stream network. Additional information like the presence of streams and estimated distance to the stream in the road inventory would be helpful to locate the stream crossings more precisely. It is recommended to that field crews refer to the stream network delineated from the digital elevation model using TauDEM while conducting the GPS survey to facilitate the collection of this information. The surveyor should, at the time of mapping a stream crossing, identify stream segment that is crossed and provide a description of the position of the stream relative the road segment. This information would be helpful for verifying the consistency of the TauDEM stream network with observed streams while locating road-stream crossings properly. Images or photos of drain points which have resulted in the formation of gullies and landslides along the road would be helpful for further evaluation of model predictions where it is useful to be able to visually check the appearance of the site.

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APPENDICES

APPENDIX 1

USFS Road Inventory Tables Data Dictionary

Roads Shapefile Attribute Table

Field Name	Description
1DRAINNUM	Main road drainage feature
2DRAINNUM	Secondary road drainage feature
SURF_TYPE	Road surface type
SURF_COV	Road surface cover
SURF_COND	Road surface condition
RD_EDGE_1	Cut slope height or road edge feature
RD_EDGE_2	Cut slope height 2 or road edge feature
EDGE_VEG_1	Road side vegetation density
EDGE_VEG_2	Secondary road side vegetation density
EDGE_CND_1	Primary cut or fill slope condition
EDGE_CND_2	Secondary cut or fill slope condition
FLOW_PATH1	Location of flowing water
FLOW_PATH2	Location of flowing water
FLWPTH_VG1	Vegetation on flow path 1
FLWPTH_VG2	Vegetation on flow path 2
FLWPTHCND1	Condition of flow path 1
FLWPTHCND2	Condition of flow path 2
FILL_CHAN	Distance. Fill slope toe to channel edge in feet
Date	Collection date
Vehicle	Vehicle number used for survey

Ditch Relief Drain Point Shapefile Attribute Table

Field Name	Description
DRAINNUM	Main road drainage feature number
Size	Pipe diameter in inches
Pipe Len. (ft.)	Pipe length
Type	Pipe material
Condit	Percent sediment occlusion
Slope Shap	Shape of the slope. Eg: concave
Dischrg to	Destination of discharge
Stream Con	Stream connection
Fill_Eros	Is fill slope eroded below pipe
Flow Diver	Flow diversion present or not
Obstruct	Debris in flow path of drain
Flow diffuser	Flow diffuser type
Date	Collection date
Vehicle	Collection vehicle identifier
Comment	Additional comments

Stream Crossing Drain Point Shapefile Attribute Table

Field Name	Description
DRAINNUM	Main road drainage feature identifier
Type	Culvert type
R Pipe Dia.	Round pipe diameter
Oval Pipe	Oval pipe dimension
Pipe Len.	Pipe length
Chan. wdth	Channel width
Pipe Num	Number of pipe present
Fill Depth	Units of feet
Condit	Culvert condition
Chan Angl	Angle between pipe and channel
Block Typ	Evidence of blockage
Outlet drp	Measured below pipe in feet and tenths
Pl depth	Depth below outfall in feet and tenths
Pipe grade	Measured in %
Substrate	Crossing substrate
Debris Flw	Debris flow present or not
Fill Erosn	Flow present erosion present or not
Diversion	Diversion potential
Date	Collection date
Vehicle	Collection vehicle identifier
Comment	Additional comments

Lead-off Drain Point Shapefile Attribute Table

Field Name	Description
DRAINNUM	Main road drainage feature identifier
Slope Shap	Slope shape
Dischrg to	Destination of discharge
Stream Con	Stream connection present or not
Condit	Condition
Obstruct	Debris in flow path of drain
Date	Collection date
Vehicle	Collection vehicle identifier
Comment	

Water Bar Drain Point Shapefile Attribute Table

Field Name	Description
DRAINNUM	Main road drainage feature identifier
Slope Shap	Slope shape
Dischrg to	Destination of discharge
Stream Con	Stream Connection present or not
Obstruct	Debris in flow path of drain
Fill Eros	Fill erosion present or not
Type	Drain point material
Condit	Condition
Date	Collection date
Vehicle	Collection vehicle identifier
Comment	

Broad Based Dip Drain Point Shapefile Attribute Table

Field Name	Description
DRAINNUM	Main road drainage feature identifier
Slope Shap	Shape of the slope
Dischrg to	Destination of discharge
Stream Con	Stream connection
Obstruct	Debris in flow path of drain
Fill Eros	Fill erosion present or not
Type	
Condit	Condition of the drain point
Material	
Date	Collection date
Vehicle	Collection vehicle identifier
Comment	

Non-Engineered Drain Point Shapefile Attribute Table

Field Name	Description
DRAINNUM	Main road drainage feature identifier
Slope Shap	Slope shape
Dischrg to	Destination of discharge
Stream Con	Stream connection present or not
Obstruct	Debris in flow path of drain
Fill Eros	Fill erosion present or not
Condit	Condition
Date	Collection date

Vehicle	Collection vehicle identifier
Comment	

Sump Drain Point Shapefile Attribute Table

Field Name	Description
DRAINNUM	Main road drainage feature identifier
Condit	Condition
Date	Collection date
Vehicle	Collection vehicle identifier
Comment	

Diffuse Drain Point Shapefile Attribute Table

Field Name	Description
DRAINNUM	Main road drainage feature identifier
Slope Shap	Slope shape
Dischrg To	Destination of discharge
Stream Con	Stream connection present or not
Obstruct	Debris in flow path of drain
Fill eros	Fill erosion present or not
Date	Collection date
Vehicle	Collection Vehicle identifier
Comment	

APPENDIX 2

GRAIP Database Tables

Master tables

DrainPoints Table

Field Name	Description
GRAIPDID	Unique Drain Point identifier
DrainTypeID	Unique Drain Point type identifier
CDate	Survey date
CTime	Survey time
VehicleID	Survey vehicle Identifier
DrainID	Drain ID from Road inventory Drain points file
StreamConnectID	Attribute representing stream connection present or not
Comments	Description or comments about the Drain Point feature
SedProd	Accumulated Road Sediment load to each drain point (kg/yr)
ELength	Effective length of the road draining to each drain point (m)
UnitSed	Drain point unit sediment load (kg/m/yr)
SedDel	Sediment load delivered to streams
SI	SINMAP Stability Index values at each drain point
Slope	Slope at each drain point
ESI	Erosion Sensitivity Index (m) values at each drain point
PipeDiaToChanWidthScore	Hazard Score calculated from Ratio of Culvert pipe diameter to channel width
SkewAngleScore	Hazard Score calculated from Channel Skew angle
SBI	Stream blocking index indicating culvert plugging susceptibility
Barrier	Flag representing the drain point is a fish passage barrier or not

RoadLines Table

Field Name	Description
GRAIPRID	Unique Road line segment Identifier
CDate	Survey date
CTime	Survey time
VehicleID	Survey vehicle identifier
RoadNetworkID	Identifier for a road network. Base erosion rate depends on

	road network ID
RoadTypeID	Identifier for type of the road (eg: system road, trail)
GRAIPDID1	Identifier of drain point that drains side one of the road
GRAIPDID2	Identifier of drain point that drains side two of the road
SurfaceTypeID	Identifier representing road surface type.
SurfaceConditionID	Identifier representing road surface condition
SurfaceCoverID	Identifier representing the road surface cover
RoadEdge1ID	Identifier for road side one edge information
RoadEdge2ID	Identifier for road side two edge information
EdgeVegetation1ID	Identifier for road side one edge vegetation
EdgeVegetation2ID	Identifier for road side two edge vegetation
FlowPath1ID	Identifier for road side one flow path information
FlowPath2ID	Identifier for road side two flow path information
FlowPathVeg1ID	Identifier for road side one flow path vegetation
FlowPathVeg2ID	Identifier for road side two flow path vegetation
FlowPathCond1ID	Identifier for road side one flow path condition
FlowPathCond2ID	Identifier for road side two flow path condition
FillChannelID	Identifier giving road fill channel information
Comments	Additional Comments about the road segment
StreamConnect1ID	Identifier for road side one stream connectivity status
StreanConnect2ID	Identifier for road side two stream connectivity status
Length	Length of the road segment (m)
SedProd1	Sediment production from side one of the road (kg/yr)
SedProd2	Sediment production from side two of the road (kg/yr)
UnitSed	Unit sediment production from both sides of the road segment (kg/m/yr)
TotSedProd	Total sediment production from both sides of the road (kg/yr)
TotSedDel	Total sediment delivered to streams (kg/yr)
UnitTotSedDel	Total unit sediment delivered to streams (kg/m/yr)

BroadBaseDipAtt Table

Field Name	Description
GRAIPDID	Drain Point identifier. Foreign key to GRAIPDID in DrainPoints Table
BroadBaseDipTypeID	Identifier representing Broad Base Dip type
SlopeShapeID	Identifier for drain point discharge slope shape
DischargeID	Identifier for drain point discharge feature (e.g. gully, forest floor)
ObstructionID	Identifier for the presence of an obstruction

FillErosionID	Identifier for presence of fill erosion
BroadBaseDipConditionID	Identifier for broad base dip drain point condition
MaterialID	Identifier for material found in the drain point

DiffuseDrainAtt Table

Field Name	Description
GRAIPDID	Drain Point identifier. Foreign key to GRAIPDID in DrainPoints Table
SlopeShapeID	Identifier for drain point discharge slope shape
DischargeToID	Identifier for drain point discharge feature (e.g. gully, forest floor)
ObstructionID	Identifier for the presence of an obstruction
FillErosionID	Identifier for presence of fill erosion

DitchReliefAtt Table

Field Name	Description
GRAIPDID	Drain Point identifier. Foreign key to GRAIPDID in DrainPoints Table
SizeID	Identifier for the size of the drain point
PipeLength	Length of the culvert pipe used
DitchReliefTypeID	Identifier for ditch relief type
SlopeShapeID	Identifier for drain point discharge slope shape
DischargeToID	Identifier for drain point discharge feature (e.g. gully, forest floor)
FillErosionID	Identifier for presence of fill erosion
ObstructionID	Identifier for the presence of an obstruction
FlowDiversionID	Identifier for the presence of flow diversion
FlowDiffuserID	Identifier for flow diffuser type

LeadOffAtt Table

Field Name	Description
GRAIPDID	Drain Point identifier. Foreign key to GRAIPDID in DrainPoints Table
SlopeShapeID	Identifier for drain point discharge slope shape

DischargeToID	Identifier for drain point discharge feature (e.g. gully, forest floor)
LeadOffConditionID	Identifier for condition of lead off drain point
ObstructionID	Identifier for the presence of an obstruction

NonEngAtt Table

Field Name	Description
GRAIPDID	Drain Point identifier. Foreign key to GRAIPDID in DrainPoints Table
NonEngConditionID	Identifier for condition of Non-Engineered drain point
SlopeShapeID	Identifier for drain point discharge slope shape
DischargeToID	Identifier for drain point discharge feature (e.g. gully, forest floor)
ObstructionID	Identifier for the presence of an obstruction
FillErosionID	Identifier for presence of fill erosion

StrXingAtt Table

Field Name	Description
GRAIPDID	Drain Point identifier. Foreign key to GRAIPDID in DrainPoints Table
StrXingTypeID	Identifier for stream crossing type
PipeDimID	Identifier for culvert pipe dimension
PipeLength	Culvert pipe length (feet)
ChannelWidth	Channel width (feet)
PipeNumberID	Identifier for number of pipes used
FillDepth	Fill depth (feet)
StrXingConditionID	Identifier for condition of stream crossing drain point
FillErosionID	Identifier for presence of fill erosion
ChannelAngleID	Identifier for angle between stream and stream crossing
BlockTypeID	Identifier for the presence and type of stream crossing blockage
OutletDrop	Outlet channel drop (feet)
PoolDepth	Channel pool depth (feet)
PipeGradient	Stream crossing pipe gradient in percentage
SubstrateID	Identifier for substrate material
DebrisFlowID	Identifier for the presence of a debris flow
DiversionID	Identifier for the presence and direction of channel

	diversion

SumpAtt Table

Field Name	Description
GRAIPDID	Drain Point identifier. Foreign key to GRAIPDID in DrainPoints Table
SumpConditionID	Identifier for condition of sump drain point

WaterBarAtt Table

Field Name	Description
GRAIPDID	Drain Point identifier. Foreign key to GRAIPDID in DrainPoints Table
WaterBarTypeID	Identifier for water bar type
SlopeShapeID	Identifier for drain point discharge slope shape
DischargeToID	Identifier for drain point discharge feature (e.g. gully, forest floor)
ObstructionID	Identifier for presence of obstruction
FillErosionID	Identifier for presence of fill erosion
WaterBarConditionID	Identifier for condition of water bar crossing drain point

Preferred value tables

BlockTypeDefinitions

BlockTypeID	BlockType	Description
1	No	Stream crossing not blocked (default)
2	Sediment Plume	Stream crossing blocked by sediment plume
3	Scoured road	Stream crossing blocked due to scoured road
4	Washed out road	Stream crossing blocked due to washed out road
5	Organic debris pile	Stream crossing blocked by organic debris pile

BroadBaseDipCondDefinitions

BroadBaseDipConditionID	Condition	Description
1	No Problem	Default
2	Puddles on road	
3	Wetland in ditch	
4	Saturated fill	

BroadBaseDipTypeDefinitions

BroadBaseDipTypeID	BroadBaseDipTypeName	Description
1	Grade Reversal	Default
2	Flat Ditch	
3	Constructed	

ChannelAngleDefinitions

ChannelAngleID	ChannelAngle	Description
1	<25 degrees	The flow changes direction by less than 25 degrees when entering stream crossing (Default)
2	<45 degrees	The flow changes direction by less than 45 degrees when entering stream crossing
3	45-75 degrees	The flow changes direction by between than 45 and 75 degrees when entering stream crossing

DebrisFlowDefinitions

DebrisFlowID	DebrisFlow	Description
1	No	Default
2	Yes	

DischargeToDefinitions

DischargeToID	DischargeTo	Description
1	Forest Floor	Default
2	Gully	
3	Ditch	
4	Landslide	
5	Wetland	
6	Stream	

DitchReliefCondDefinitions

DitchReliefConditionID	Condition	Description
1	0	Ditch relief drain in good condition
2	1-20%	Ditch relief drain 1-20% blocked
3	20-80%	Ditch relief drain 20-80% blocked
4	80-100%	Ditch relief drain 80-100% blocked
5	Partially Crushed	Ditch relief drain partially crushed
6	Totally Crushed	Ditch relief drain totally crushed
7	Rusted Significantly	Ditch relief drain significantly rusted
8	Flows around pipe	Ditch relief drain flows around the pipe

DitchReliefTypeDefinitions

DitchReliefTypeID	DitchReliefTypeName	Description
1	CMP (Steel)	Default
2	CON (Concrete)	
3	ALM (Aluminum)	
4	ABS (Plastic)	
5	WDN (LOG)	

DiversionDefinitions

DiversionID	Diversion	Description
1	None	Default
2	1 Direction	
3	2 Direction	

DrainTypeDefinitions

DrainTypeID	DrainTypeName	TableName	Description
1	Broad base dip	BroadBaseDipAtt	Attribute table name for Broad Base Dip type drain point
2	Diffuse drain	DiffuseDrainAtt	Attribute table name for Diffused type drain point
3	Ditch relief	DitchReliefAtt	Attribute table name for Ditch Relief type drain point
4	Lead off	LeadOffAtt	Attribute table name for Lead Off type drain point
5	Non-engineered	NonEngAtt	Attribute table name for Non-Engineered type drain point
6	Stream Crossing	StrXingAtt	Attribute table name for Stream Crossings type drain point
7	Sump	SumpAtt	Attribute table name for Sump type drain point
8	Water bar	WaterBarAtt	Attribute table name for Waterbar type drain point

FillErosionDefinitions

FillErosionID	FillErosion	Description
1	No	Default
2	Yes	

FlowDiffuserDefinitions

FlowDiffuserID	FlowDiffuser	Description
1	None	Default
2	Half pipe fabric	
3	Fabric hose	
4	Rip rap	

FlowDiversionDefinitions

FlowDiversionID	FlowDiversion	Description
0	Unknown	
1	No	
2	Yes	

LeadOffCondDefinitions

LeadOffConditionID	Condition	Description
1	No problem	Default
2	Gullied	
3	Not functional	
4	Excess deposition	

MaterialDefinitions

MaterialID	MaterialName	Description
1	Crushed	
2	Native soil	Default
3	Vegetated	
4	Paved	
5	Cinder	

NonEngCondDefinitions

NonEngConditionID	Condition	Description
1	Blocked	Default
2	Diverted wheel track	
3	Broken berm	
4	Gully	
5	Crosses road	
6	Out sloped	

ObstructionDefinitions

ObstructionID	Obstruction	Description
1	None	Drain point not obstructed
2	Moderate	Drain point has moderate obstruction (Default)
3	Abundant	Drain point has considerable obstruction

PipeDimDefinitions

PipeDimID	Dimension	Description
0	N/A	Default
1	12	Round 12 inch pipe
2	15	Round 15 inch pipe

3	18	Round 18 inch pipe
4	24	Round 24 inch pipe
5	36	Round 36 inch pipe
6	48	Round 48 inch pipe
7	60	Round 60 inch pipe
8	>60	Pipe greater than 60 inches diameter
9	13X17	Oval pipe 13 inches x 17 inches
10	15X21	Oval pipe 15 inches x 21 inches
11	20X28	Oval pipe 20 inches x 28 inches
12	24X35	Oval pipe 24 inches x 35 inches
13	29X42	Oval pipe 29 inches x 42 inches
14	33X49	Oval pipe 33 inches x 49 inches
15	38X57	Oval pipe 38 inches x 57 inches

PipeNumberDefinitions

PipeNumberID	PipeNumber	Description
0	N/A	Default
1	1	
2	2	
3	3	
4	>3	

SizeDefinitions

SizeID	DSize	Description
1	<12"	Pipe size less than 12 inches
2	12"	12 inch pipe
3	15"	15 inch pipe
4	18"	18 inch pipe (Default)
5	24"	24 inch pipe
6	>24"	Pipe size greater than 24 inches

SlopeShapeDefinitions

SlopeShapeID	SlopeShape	Description
1	Concave	
2	Planar	
3	Convex	

StreamConnectDefinitions

StreamConnectID	StreamConnection	Description
0	Unknown	
1	No	Drain point discharge does not enter stream directly. (Default)
2	Yes	Drain point discharge enters stream directly

StrXingCondDefinitions

StrXingConditionID	Condition	Description
1	Open and Sound	Default
2	Partially blocked	
3	Totally blocked	
4	Partially crushed	
5	Totally crushed	
6	Rusted significantly	
7	Flows around pipe	
8	Scoured under bridge	

StrXingTypeDefinitions

StrXingTypeID	StrXingTypeName	Description
1	Steel culvert round	Default
2	Steel culvert oval	
3	Steel arch bottomless	
4	Plastic culvert	
5	Baffled culvert	
6	Concrete culvert	
7	Log culvert	
8	Concrete ford	
9	Natural ford	
10	Aluminum culvert	
11	Bridge	

SubstrateDefinitions

SubstrateID	Substrate	Description
1	Culvert Material	Default
2	Sand	
3	Gravel	

4	Boulders	
5	Bedrock	
6	Baffled	
7	Concrete	

SumpCondDefinitions

SumpConditionID	Condition	Description
1	No problem	Default
2	Fill saturation	
3	Puddles on road	

WaterBarCondDefinitions

WaterBarConditionID	Condition	Description
1	No problem	Default
2	Damaged	
3	Too small	
4	Drains inboard ditch	
5	Wheel track damage	

WaterBarTypeDefinitions

WaterBarTypeID	WaterBarTypeName	Description
1	Road material	Default
2	Fabricated material	

EdgeConditionDefinitions

EdgeConditionID	EdgeCondition	Description
1	No problem	Default
2	Badly rilled	
3	Badly ravelling	
4	Badly slumping	
5	Bedrock	

EdgeVegetationDefinitions

EdgeVegetationID	EdgeVegetation	Description
1	Default	Road side vegetation density is unknown or not specified
2	>75%	Road side vegetation density is greater than 75%

3	>50%	Road side vegetation density is greater than 50%
4	>25%	Road side vegetation density is greater than 25%
5	>10%	Road side vegetation density is greater than 10%
6	0%	Road side vegetation density is less than 10%

FillChannelDefinitions

FillChannelID	FillChannel	Description
1	0,[1]	Fill slope ends right at channel
2	1-20,[20]	Distance from fill slope toe to channel is between 1 and 20 feet
3	21-50,[50]	Distance from fill slope toe to channel is between 21 and 50 feet
4	Above 50,[100]	Distance from fill slope toe to channel is greater than 50 feet (Default)

FlowPathCondDefinitions

FlowPathCondID	FlowPathCond	Description
1	No problem	Default
2	Gullied	
3	Buried	
4	Rutted	
5	Blocked	
6	Stream course	
7	Woody veg (%)	

FlowPathDefinitions

FlowPathID	FlowPath	Description
1	Ditch	Default
2	Wheel tracks	
3	Base of cut	
4	Berm	
5	Diffuse	

FlowPathVegDefinitions

FlowPathVegID	FlowPathVeg	Description	Multiplier
1	110%	Unknown or unspecified road side flow	1

		path vegetation density (Default)	
2	>75%	Road side flow path vegetated more than 75%	0.14
3	>50%	Road side flow path vegetated 50% to 75%	0.14
4	>25%	Road side flow path vegetated 25% to 50%	0.14
5	>10%	Road side flow path vegetated 10% to 25%	1
6	>0%	Road side flow path vegetated 0 to 10%	1
7	0%	No road side flow path vegetation	1

RoadEdgeDefinitions

RoadEdgeID	RoadEdge	Description
1	Fill	Road side feature is fill
2	0' no ditch	Road side level with terrain, no ditch
3	0-6'	Road side cut between 0 and 6 ft high (Default)
4	6-18'	Road side cut 6 to 18 ft high
5	>18', 0%	Road side cut higher than 18 ft

RoadNetworkDefinitions

RoadNetworkID	RoadNetwork	Description	BaseRate
1	Default	Default Base rate from Luce and Black, 1999	79
2	Custom	Custom base rate for a specific study area	79

RoadTypeDefinitions

RoadTypeID	RoadType	Description
1	Default	Default
2	System road	
3	High clearance road	

SurfaceConditionDefinitions

SurfaceConditionID	SurfaceCondition	Description
1	Good	

2	Rilled/eroded	
3	Washboard	
4	Rutted	
5	Rocky	

SurfaceCoverDefinitions

SurfaceCoverID	SurfaceCover	Description
1	>75%	Road surface is vegetated more than 75% (Default)
2	>50%	Road surface is vegetated between 50 and 75%
3	>25%	Road surface is vegetated between 25 and 50%
4	>10%	Road surface is vegetated between 10 and 25%
5	0%	Road surface is vegetated between 0 and 10%

SurfaceTypeDefinitions

SurfaceTypeID	SurfaceType	Description	Multiplier
1	Default	Default	1
2	Crushed rock		1
3	Native		5
4	Paved		0.2
5	Herbaceous Veg		1
6	Brush		1
7	Trees > 4 in Dia		1
8	Cinder		1

VehicleDefinitions

VehicleID	Vehicle	Description
1	Survey Truck	

<u>Utility tables</u>

FieldMatches

ID	AttTableID	DBField	DBFField
1	1	Cdate	Date
2	1	Ctime	Time
3	1	VehicleID	Vehicle
4	1	DrainID	DRAIN_ID

5	1	StreamConnectID	STREAM_CON
6	1	Comments	COMMENT
7	1	BroadBaseDipTypeID	TYPE
8	1	SlopeShapeID	SLOPE_SHAP
9	1	DischargeToID	DISCHRG__T
10	1	ObstructionID	OBSTRUCT
11	1	FillErosionID	FILL_EROS
12	1	BroadBaseDipConditionID	CONDIT
13	1	MaterialID	MATERIAL
14	2	Cdate	Date
15	2	Ctime	Time
16	2	VehicleID	Vehicle
17	2	DrainID	DRAIN_ID
18	2	StreamConnectID	STREAM_CON
19	2	Comments	COMMENT
20	2	SlopeShapeID	SLOPE_SHAP
21	2	DischargeToID	DISCHRG_TO
22	2	ObstructionID	OBSTRUCT
23	2	FillErosionID	FILL_EROS
32	3	Cdate	Date
33	3	Ctime	Time
34	3	VehicleID	Vehicle
35	3	DrainID	DRAIN_ID
36	3	StreamConnectID	STREAM_CON
37	3	Comments	COMMENT
38	3	SizeID	SIZE
39	3	PipeLength	PIPE_LEN__
40	3	DitchReliefTypeID	TYPE
41	3	DitchReliefConditionID	CONDIT_
42	3	SlopeShapeID	SLOPE_SHAP
43	3	DischargeToID	DISCHRG_TO
44	3	FillErosionID	FILL_EROS
45	3	ObstructionID	OBSTRUCT
46	3	FlowDiversionID	FLOW_DIVER
47	3	FlowDiffuserID	FLOW_DIFFU
49	4	Cdate	Date
50	4	Ctime	Time
51	4	VehicleID	Vehicle
52	4	DrainID	DRAIN_ID
53	4	StreamConnectID	STREAM_CON
54	4	Comments	COMMENT
55	4	SlopeShapeID	SLOPE_SHAP
56	4	DischargeToID	DISCHRG_TO
57	4	LeadOffConditionID	CONDIT

58	4	ObstructionID	OBSTRUCT
60	5	Cdate	Date
61	5	Ctime	Time
62	5	VehicleID	Vehicle
63	5	DrainID	DRAIN_ID
64	5	StreamConnectID	STREAM_CON
65	5	Comments	COMMENT
66	5	NonEngConditionID	CONDIT
67	5	SlopeShapeID	SLOPE_SHAP
68	5	DischargeToID	DISCHRG_TO
69	5	ObstructionID	OBSTRUCT
70	5	FillErosionID	FILL_EROS
71	6	Cdate	Date
72	6	Ctime	Time
73	6	VehicleID	Vehicle
74	6	DrainID	DRAIN_ID
75	6	StreamConnectID	
76	6	Comments	COMMENT
77	6	StrXingTypeID	TYPE
78	6	PipeDimID	R_PIPE_DIA
79	6	PipeDimID(Oval)	OVAL_PIPE_
80	6	PipeLength	PIPE_LEN_
81	6	FillDepth	FILL_DEPTH
82	6	StrXingConditionID	CONDIT
83	6	FillErosionID	FILL_EROSN
84	6	ChannelAngleID	CHAN_ANGL
85	6	BlockTypeID	BLOCK_TYP
86	6	OutletDrop	OUTLET_DRP
87	6	PoolDepth	PL_DEPTH
88	6	PipeGradient	PIPE_GRADE
89	6	SubstrateID	SUBSTRATE
90	6	DebrisFlowID	DEBRIS_FLW
91	6	DiversionID	DIVERSION
93	7	Cdate	Date
94	7	Ctime	Time
95	7	VehicleID	Vehicle
96	7	DrainID	DRAIN_ID
97	7	StreamConnectID	STREAM_CON
98	7	Comments	COMMENT
99	7	SumpConditionID	CONDIT
100	8	Cdate	Date
101	8	Ctime	Time
102	8	VehicleID	Vehicle
103	8	DrainID	DRAIN_ID

104	8	StreamConnectID	STREAM_CON
105	8	Comments	COMMENT
106	8	WaterBarTypeID	TYPE
107	8	SlopeShapeID	SLOPE_SHAP
108	8	DischargeToID	DISCHRG_TO
109	8	ObstructionID	OBSTRUCT
110	8	FillErosionID	FILL_EROS
111	8	WaterBarConditionID	CONDIT
112	6	PipeNumberID	PIPE_NUM
114	0	Cdate	Date
115	0	Ctime	Time
116	0	VehicleID	Vehicle
117	0	RoadTypeID	ROAD_TYPE
118	0	RSAMDID1	1_Drain_ID
119	0	RSAMDID2	2_Drain_ID
120	0	SurfaceTypeID	SURF_TYPE
121	0	SurfaceConditionID	SURF_COND
122	0	RoadEdge1ID	RD_EDGE_1
123	0	RoadEdge2ID	RD_EDGE_2
124	0	EdgeVegetation1ID	EDGE_VEG_1
125	0	EdgeVegetation2ID	EDGE_VEG_2
126	0	EdgeCondition1ID	EDG_CND_1
127	0	EdgeCondition2ID	EDG_CND_2
128	0	FlowPath1ID	FLOW_PATH1
129	0	FlowPath2ID	FLOW_PATH2
130	0	FlowPathVeg1ID	FLWPTH_VG1
131	0	FlowPathVeg2ID	FLWPTH_VG2
132	0	FlowPathCond1ID	FLWPTHCND1
133	0	FlowPathCond2ID	FLWPTHCND2
134	0	FillChannelID	FILL_CHAN
135	0	HUC6Name	HUC6NAME
136	0	Miles	MILES
137	0	Comments	COMMENT
138	0	SurfaceCoverID	SURF_COV
139	0	OrigSourceCode	FID_1

DPErrorLog Table Structure

Field Name	Description
Index	Unique identifier (Auto number in MS Access)
GRAIPDID	Identifier from DrainPoints table
DrainID	Identifier from USFS road inventory
DrainType	Type of the drain point (Eg: Broad Base Dip)

ErrorMessage	Validation error message
ActionTaken	Action taken to correct error

RDErrorLog Table Structure

Field Name	Description
Index	Unique identifier (Auto number in MS Access)
GRAIPRID	Identifier from RoadLines table
RoadID	Identifier from USFS road inventory
RoadType	Type of road line (Eg: System road)
ErrorMessage	Validation error message
ActionTaken	Action taken to correct error

MetaData

ID	IDFieldName	DefinitionTable
1	DrainTypeID	DrainTypeDefinitions
2	VehicleID	VehicleDefinitions
3	StreamConnectID	StreamConnectDefinitions
4	BroadBaseDipTypeID	BroadBaseDipTypeDefinitions
5	SlopeShapeID	SlopeShapeDefinitions
6	DischargeToID	DischargeToDefinitions
7	ObstructionID	ObstructionDefinitions
8	FillErosionID	FillErosionDefinitions
9	BroadBaseDipConditionID	BroadBaseDipCondDefinitions
10	MaterialID	MaterialDefinitions
11	DitchReliefTypeID	DitchReliefTypeDefinitions
12	DitchReliefConditionID	DitchReliefCondDefinitions
13	FlowDiversionID	FlowDiversionDefinitions
14	FlowDiffuserID	FlowDiffuseDefinitions
15	LeadOffConditionID	LeadOffCondDefinitions
16	NonEngConditionID	NonEngCondDefinitions
17	StrXingTypeID	StrXingTypeDefinitions
18	PipeDimID	PipeDimDefinitions
19	PipeNumberID	PipeNumberDefinitions
20	StrXingConditionID	StrXingCondDefinitions
21	ChannelAngleID	ChannelAngleDefinitions
22	BlockTypeID	BlockTypeDefinitions
23	SubstrateID	SubstrateDefinitions
24	DebrisFlowID	DebrisFlowDefinitions
25	DiversionID	DiversionDefinitions

26	SumpConditionID	SumpCondDefinitions
27	WaterBarTypeID	WaterBarTypeDefinitions
28	WaterBarConditionID	WaterBarCondDefinitions
29	RoadNetworkID	RoadNetworkDefinitions
30	RoadTypeID	RoadTypeDefinitions
31	SurfaceTypeID	SurfaceTypeDefinitions
32	SurfaceConditionID	SurfaceConditionDefinitions
33	SurfaceCoverID	SurfaceCoverDefinitions
34	RoadEdge1ID	RoadEdgeDefinitions
35	RoadEdge2ID	RoadEdgeDefinitions
36	EdgeVegetation1ID	EdgeVegetationDefinitions
37	EdgeVegetation2ID	EdgeVegetationDefinitions
38	EdgeCondition1ID	EdgeConditionDefinitions
39	EdgeCondition2ID	EdgeConditionDefinitions
40	FlowPathVeg1ID	FlowPathVegDefinitions
41	FlowPathVeg2ID	FlowPathVegDefinitions
42	FlowPath1ID	FlowPathDefinitions
43	FlowPath2ID	FlowPathDefinitions
44	FlowPathCond1ID	FlowPathCondDefinitions
45	FlowPathCond2ID	FlowPathCondDefinitions
46	FillChannelID	FillChannelDefinitions

APPENDIX 3

TauDEM Stream Network Shapefile Attribute table

The TauDEM stream network delineation function produces a stream network shapefile with the following attribute table.

Field	Description
LINKNO	Link Number. A unique number associated with each link (segment of channel between junctions)
DSLINKNO	Link Number of the downstream link. -1 indicates that this does not exist.
USLINKNO1	Link Number of first upstream link
USLINKNO2	Link Number of second upstream link.
DSNODEID	Node identifier for node at downstream end of stream reach. This identifier corresponds to the "id" attribute from the Outlets shapefile used to designate nodes.
Order	Strahler Stream Order
Length	Length of the link
Magnitude	Shreve Magnitude of the link. This is the total number of sources upstream
DS_Cont_Ar	Drainage area at the downstream end of the link. Generally this is one grid cell upstream of the downstream end because the drainage area at the downstream end grid cell includes the area of the stream being joined.
Drop	Drop in elevation from the start to the end of the link
Slope	Average slope of the link (computed as drop/length)
Straight_L	Straight line distance from the start to the end of the link
US_Cont_Ar	Drainage area at the upstream end of the link
WSNO	Watershed number. Cross reference to the *w.shp and *w grid files giving the identification number of the watershed draining directly to the link.
DOUT_END	Distance to the outlet from the downstream end of the link
DOUT_START	Distance to the outlet from the upstream end of the link
DOUT_MID	Distance to the outlet from the midpoint of the link

The following fields that record sediment inputs to the stream network and habitat patch clusters are added to the TauDEM stream network shapefile by the GRAIP model.

Field	Description
SedAccum	Accumulated upstream sediment load from road surface at the

	downstream end of each stream segment (kg/yr)
SedDir	Direct sediment input from road surface to each stream segment (kg/yr)
SpecSed	Specific sediment accumulation to each stream segment defined as accumulated upstream sediment production divided by upstream contributing area at the downstream end of each stream segment (Mg/km^2/yr)
SpecSedDir	Direct specific sediment input to each stream segment divided by the direct area draining to each stream segment (Mg/km^2/yr)
HabPatchID	A unique identifier for each contiguous habitat cluster as demarcated by fish passage barrier

APPENDIX 4

GRAIP preprocessor tool tutorial

Introduction

The GRAIP Data Preprocessor Tool is a software utility developed to validate and import USFS inventory shapefile attributes into a relational database structure created in MS Access file format. The purpose of this database (the GRAIP Database) is to enforce referential integrity and ensure consistency between related attributes. The tool helps to screen out invalid or corrupt data and provides the user with a better dataset to continue with forest road impact analysis. It also consolidates multiple drain point and road line shapefiles and creates a single shapefile for each. This appendix presents a tutorial example to illustrate the working of the GRAIP Database Preprocessor tool

Getting started

The setup file required for running the tool can be downloaded from www.engineering.usu.edu/dtarb/graip. The GRAIP tool setup is called "GRAIPSetup.exe" and it includes a sample dataset in a zipped file (*.zip) format named "demo.zip". This zip file contains a tutorial folder which contains the "dem" (ESRI Raster Grid) file and a shapefiles folder containing eight types of drain points shapefiles (BBdip.shp, Diffuse.shp, Ditchrel.shp, Lead_off.shp, ned.shp, Str_Xing.shp, sump.shp, waterbar.shp) and one road lines shapefile (road.shp).

Download GRAIPSetup.exe and save it to your working folder. Double click to run the setup. This will install GRAIP in the designated folder (by default C:\Program Files\GRAIP)

The GRAIP installation includes

1) GRAIPPreprocessor.exe, consolidateShp.dll, agGRAIP.dll and graipCOMDLL.dll: An executable and binary libraries.
2) GRAIP.mdb: Template database in folder "graip db".
3) A tutorial folder that contains tutorial documentation and zipped demonstration data.
4) A shortcut to the GRAIP Database Preprocessing tool will be created on the in the Start-> Programs menu

GRAIP database preprocessor

Start the GRAIP Database Preprocessor Tool by clicking the windows “Start” button and going to the All Programs -> GRAIP menu and clicking GRAIP Database Preprocessor icon. The File Definition screen will be displayed as shown in Figure 1.

Define Files

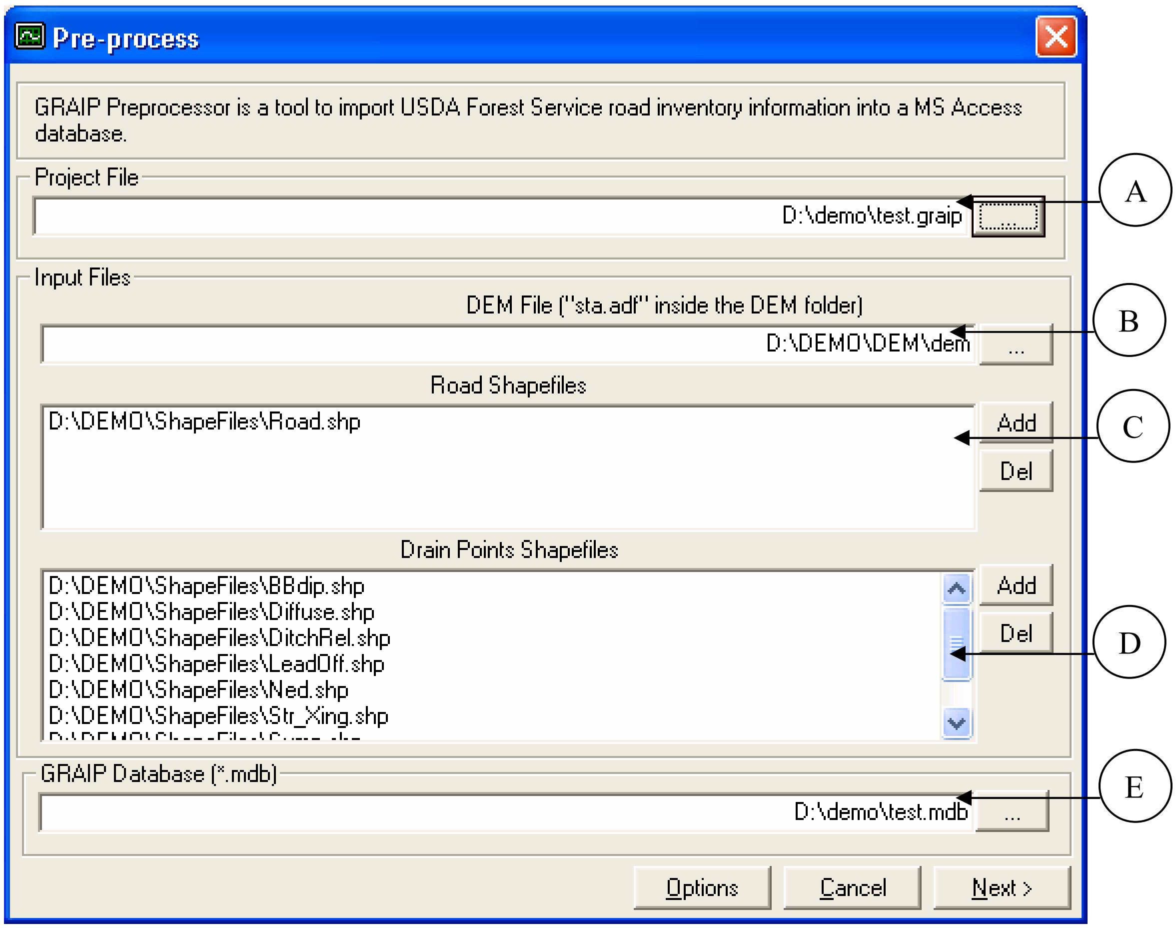


Figure 1: File Definition Screen.

1. Start by unzipping demo.zip file to working folder (eg:- C:\demo).
2. Click on the More Button (…) next to the Project File field of test.graip. In the Save Project dialog select a folder and enter a file name for the new GRAIP Project file to be created
3. An initial path and file name for GRAIP Database file (E) will be generated based on the path and file name selected in step 1.

4. Click on the More button (…) next to DEM file field (B). Browse to the working folder and select the dem\sta.adf file and click “OK”. Figure 2 shows the location of the DEM sta.adf file used in this example.

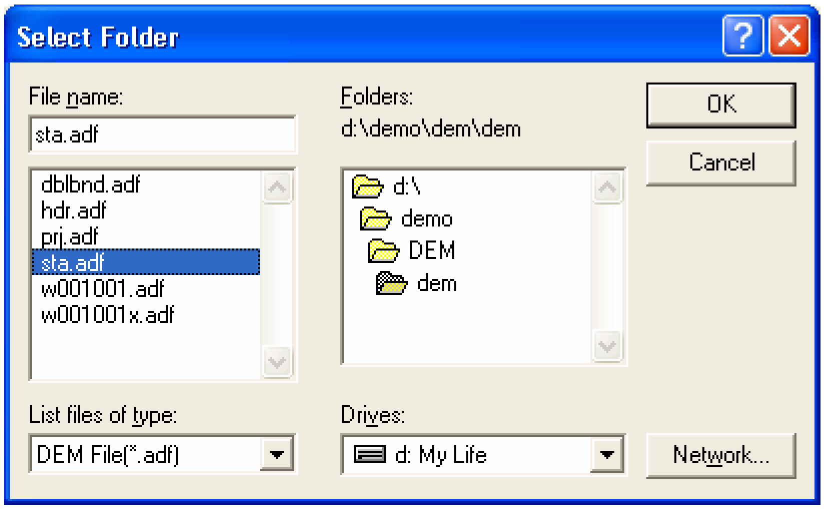


Figure 2: The “Select Folder” dialog shown when the More (…) button next to the “DEM File” field is clicked

5. Click on the “Add button adjacent to Road Shapefiles field (C). Select the \Program Files\GRAIP\tutorial\Demo\Shapefiles\Road.shp file and click “OK”.
6. Click on the “Add” button adjacent to Drain Points Shapefiles field (D). Select the \Program Files\GRAIP\tutorial\Demo\Shapefiles\ directory. Select the following files from that directory by holding down the “Ctrl” key and clicking on each filename in the File name list: BBdip.shp, Diffuse.shp. DitchRel.shp, LeadOff.shp, Ned.shp, Str_Xing.shp, Sump.shp, WaterBar.shp. Release the “Ctrl” key and click on “OK”.
7. Click the “Options” button to change Message options. (See Figure 3). If you choose to override the error messages the program will run to the end accepting

the default choices for field matches and resolving undefined values. This is useful if a user knows the defaults are satisfactory.

8. Click “Next”.

9. You should see that a new GRAIP project file (TBtest.graip) has been created which holds the information about the file paths. A new MS Access database file (TBtest.mdb) should also have been created at the specified GRAIP Database path. All the shapefile attributes will be validated and stored inside this database file.

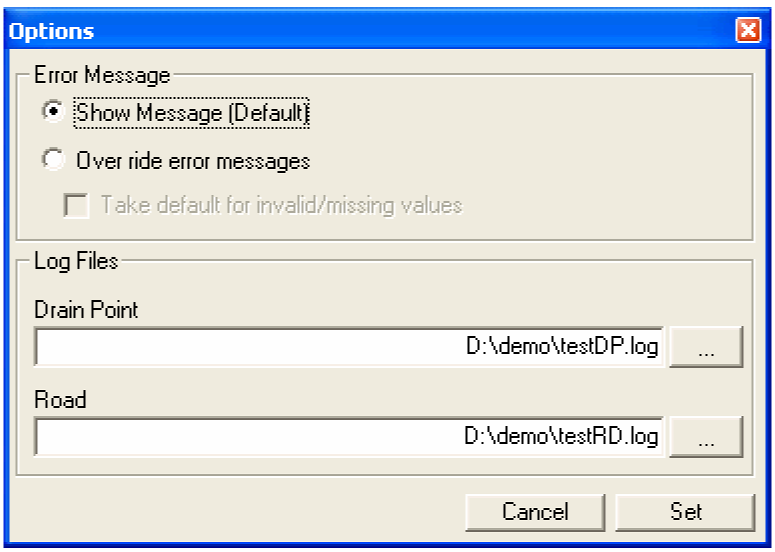


Figure 3: Options dialog to over ride error message and change the paths and/or file names of the log files

Import Drain Points Attributes

The Drain Points Import Screen is shown in Figure 4. (A) displays the path of the drain point shapefile to be imported from the shapefiles selected earlier. (B) shows the Drain point type which is automatically selected by the program based on the name. This can be changed if necessary. (C) displays the table with Target Fields that will be populated in TBTest.mdb and Matching Source fields from the shapefile.

The tool will match the fields by default.

1. Click on the row in the Matching Source Field column to change any default fields that are not correctly matched automatically (See Figure 5). If a matching field is not found "<No Match Use Default>" is selected by the tool.
2. Once you are satisfied with the matches click "Next".

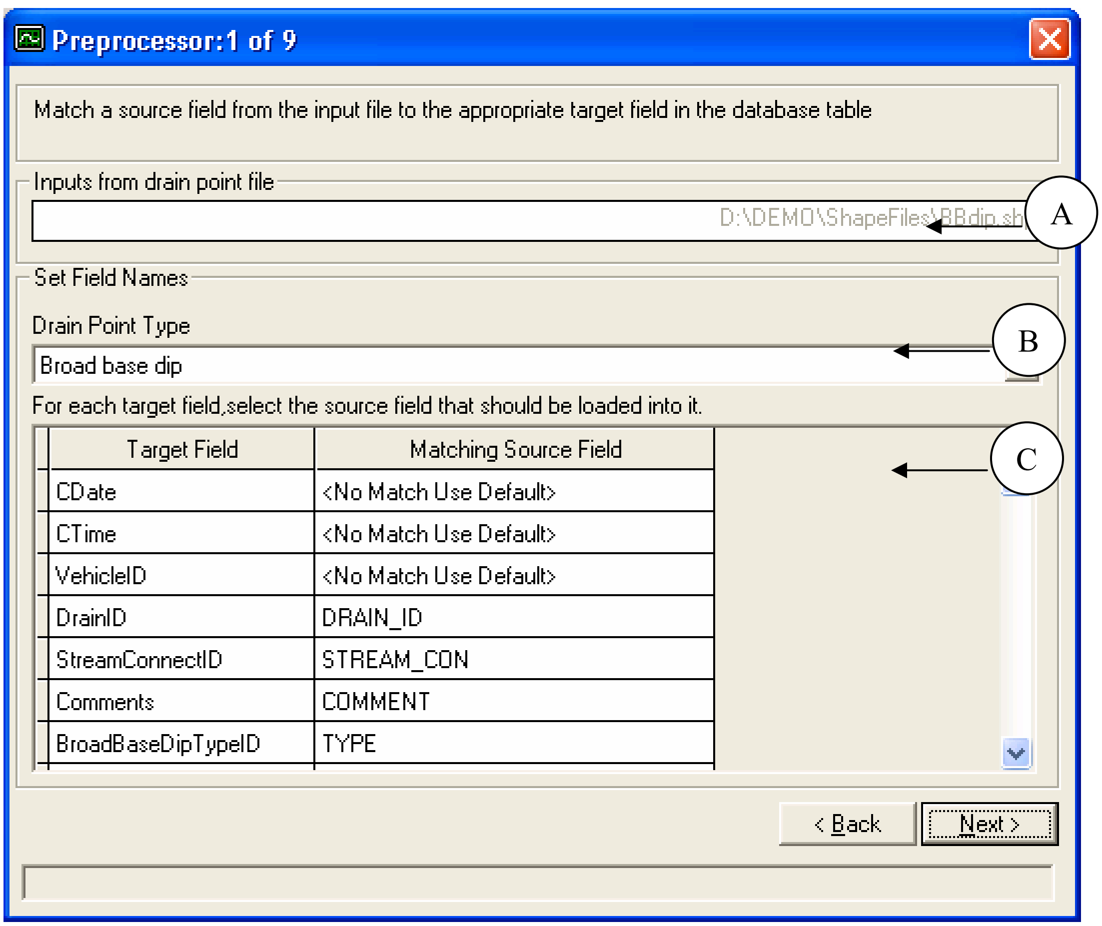


Figure 4: Drain Points Validate and Import dialog.

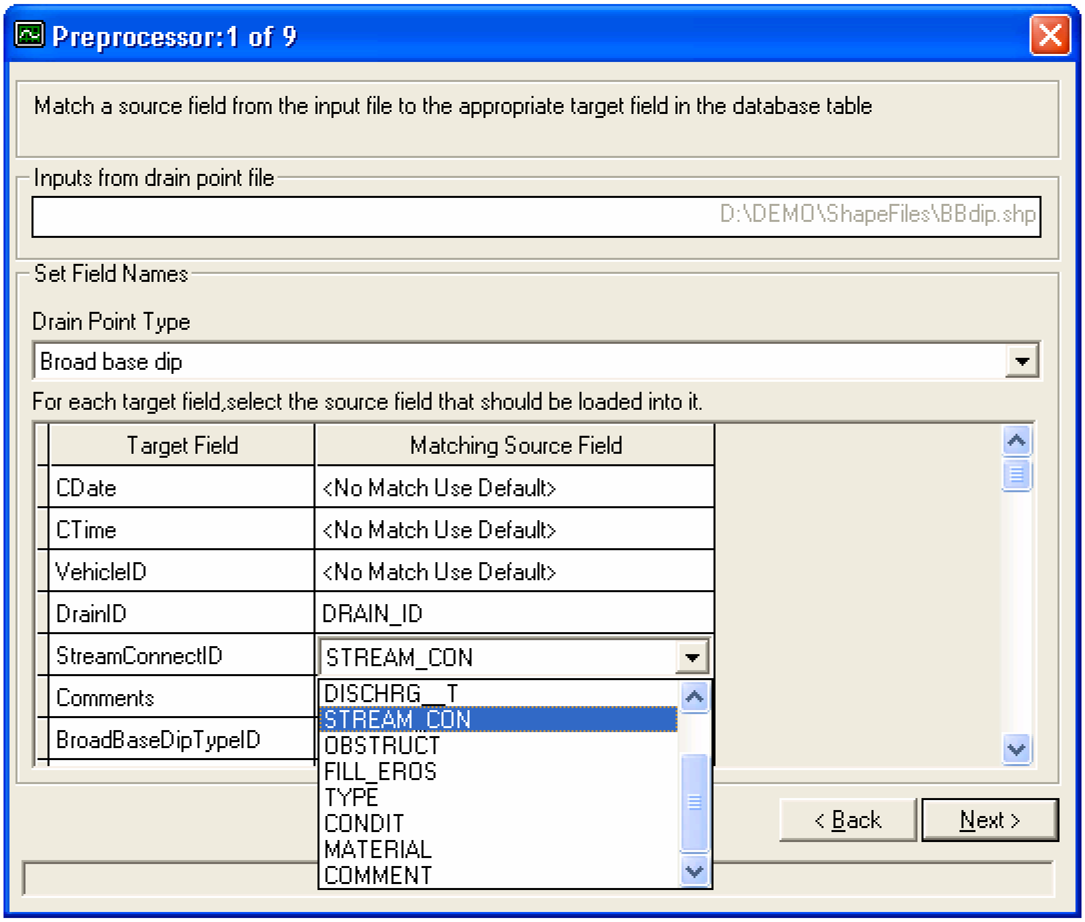


Figure 5: Selecting the Matching Source Field.

3. If an attribute value is found which is invalid or misspelled, an Attribute Validate dialog is displayed (See Figure 6). In that case either "reassign the value to an existing preferred value in definitions table" or "Add new entry to preferred value definitions table" or "Use default" and click "OK". ". This information is added to the DPErrorLog table to verify later.

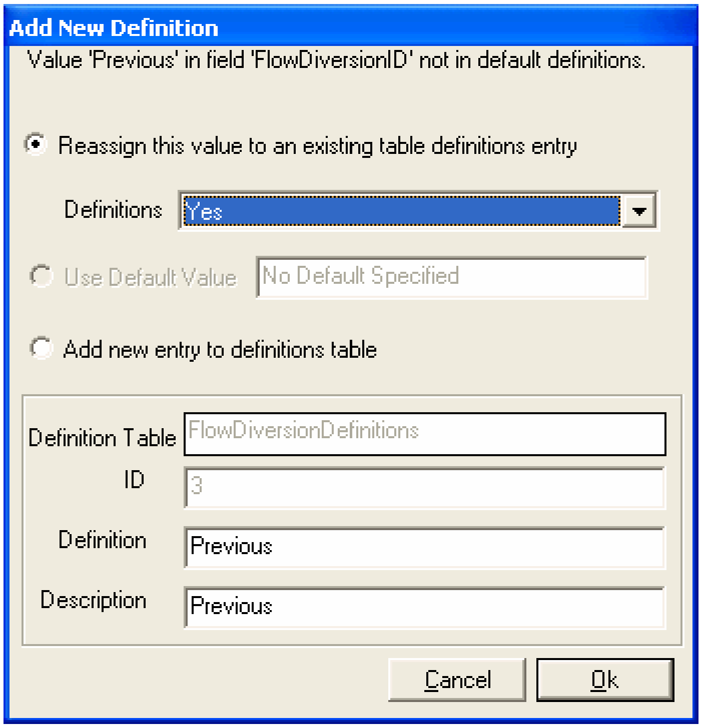


Figure 6: Attribute Validate dialog.

4. Once all of the invalid values in that drain point table are processed, the next drain points validate and import screen is displayed. Continue these steps until all the drain points are imported to the database.
5. Once all the drain points shapefiles are validated and imported, the Road Lines import screen is displayed.

Import Road Lines Attributes

The Road Lines Import screen will be displayed as shown in Figure 7. (A) displays the path of the road lines shapefile to be imported as selected earlier. (B) shows the Road Network Type. This can be changed if necessary. (C) shows the Base Rate associated with the road network type. (D) shows the Description for the base rate used. (E) shows the “+” button to add a new type of road network, associated base rate and the description for the base erosion rate. The “-“ button is to remove a road network type record and its associated base erosion rate. The user does not have the permission to remove the “Default” road network type record. (F) displays the table with Target Fields that will be populated in TBTest.mdb and Matching Source Fields from the shapefile. The tool will match the fields by default.

1. Click on the row in the Matching Source Field column to change the default fields matched (Figure 8).
2. If a matching field is not found, “<No Match Use Default>” is selected by the tool.
3. Once you are satisfied with the matches click “Next”.

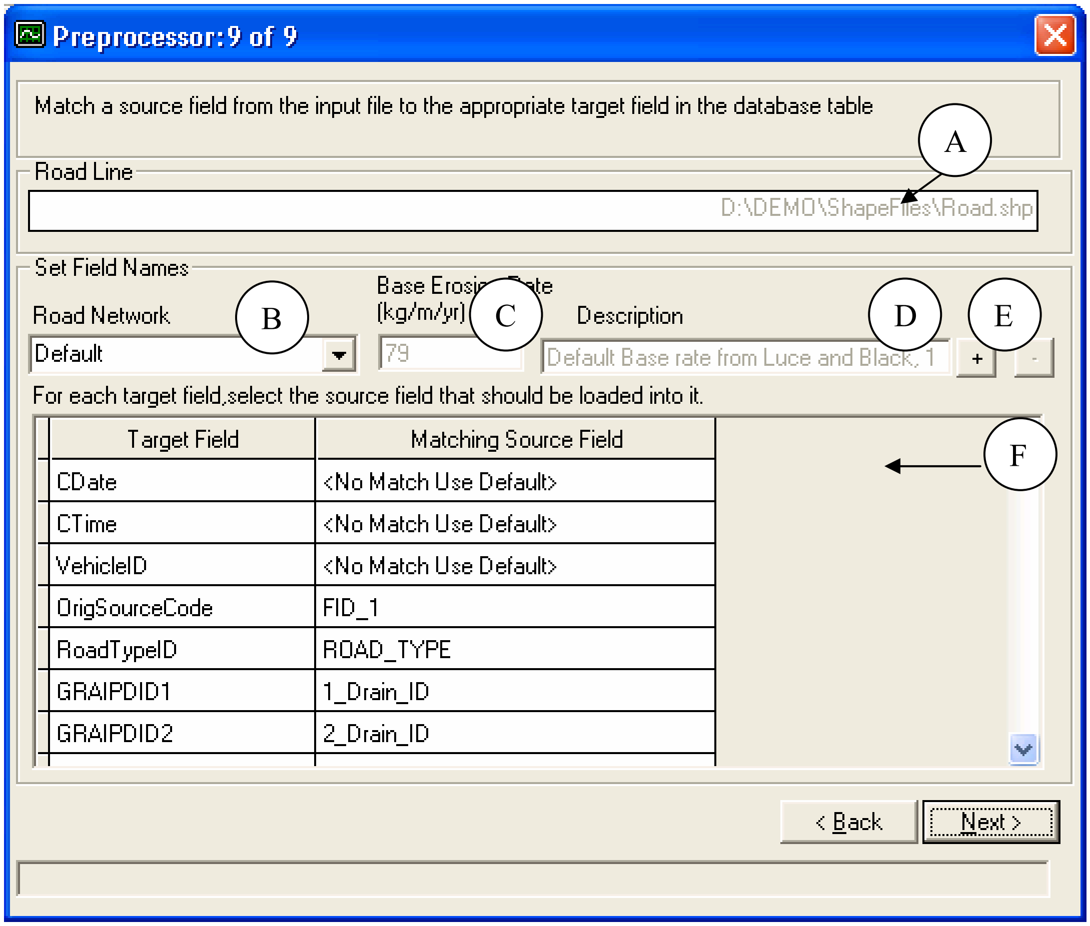


Figure 7: Road Lines Import dialog

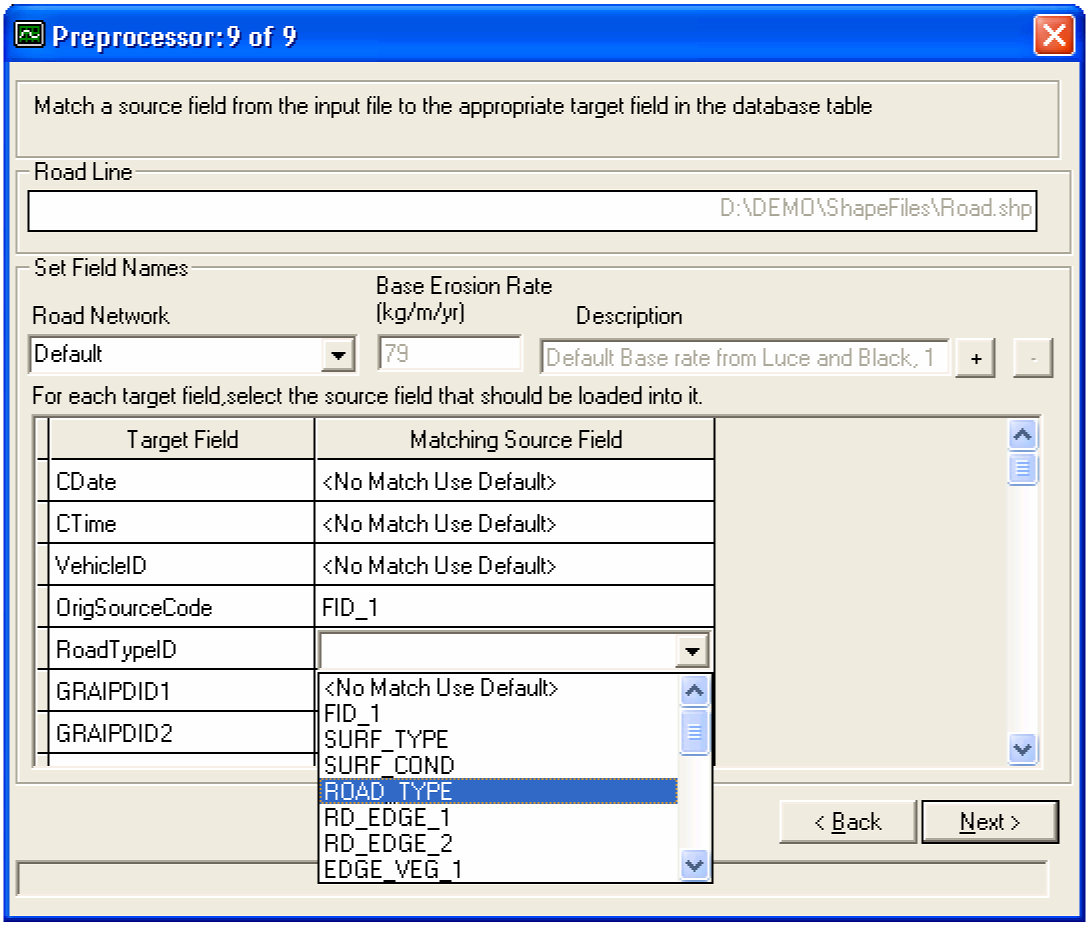


Figure 8: Selecting the Matching Source field.

4. If a Value is found which is invalid or misspelled an Attribute Validate dialog is displayed (See Figure 9)
5. In that case either “reassign the value to an existing value in preferred value definitions table” or “Add a new entry to definitions table” or select “Use Default Value” and click “OK”. This information is added to the RDErrorLog table to verify later.

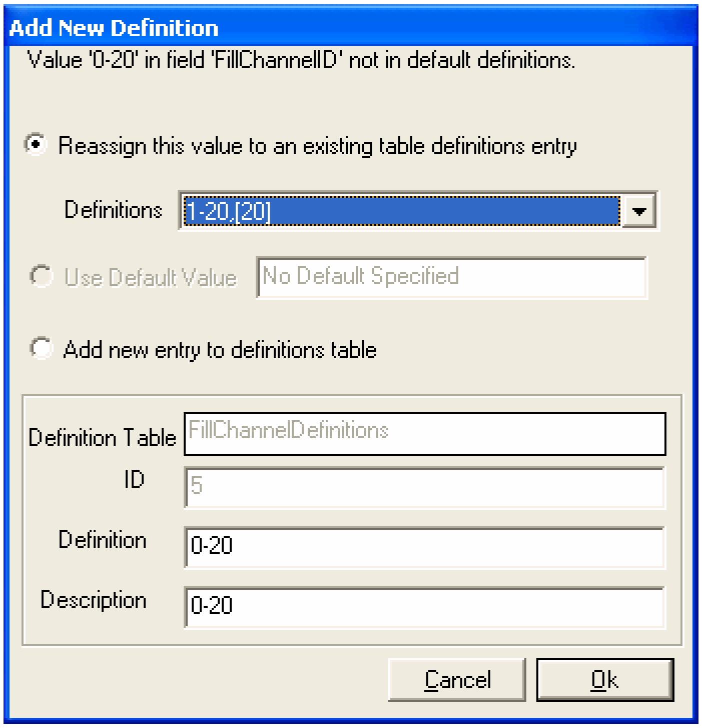


Figure 9: Attribute Validate dialog

6. Once all the Road Line attributes are imported to the database, the tool checks for drain points without any road segments draining to it and road segments that do not drain to any drain point. These are referred to as orphans Identifiers of drain points and road segments are stored in the error log tables and text files. DPErrorLog, RDErrorLog for drain points and road segments respectively.

7. The consolidate shapefiles progress bar will appear while the shapefiles are consolidated.

GRAIP Database Preprocessor Tool Output Files

Figure 10 gives a list of the output files created by the GRAIP Database Preprocessor tool.

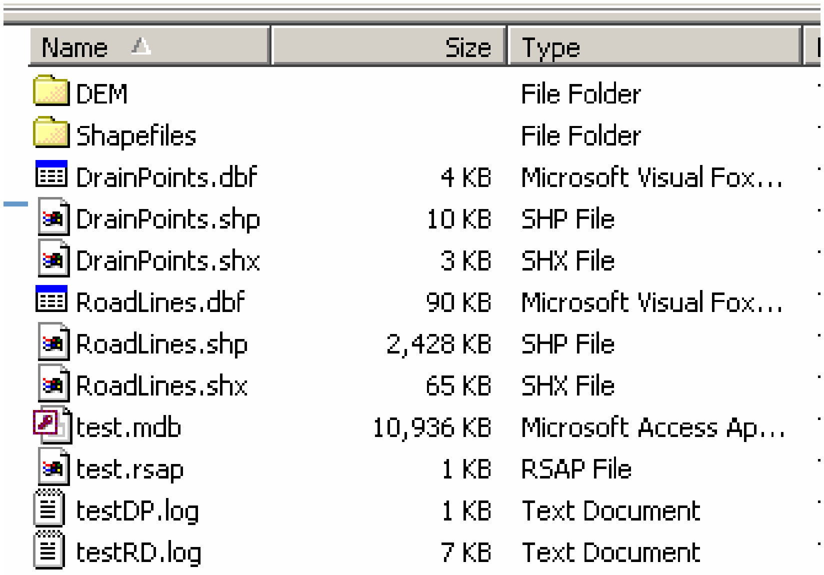


Figure 10: GRAIP Database Preprocessor Tool output files

APPENDIX 5

GRAIP GIS Tool Tutorial

GRAIP GIS model is an ArcGIS 9.1 toolbar developed to analyze the impact of forest roads on forest watersheds. This tutorial describes how to install and use the set of tools needed to perform a GRAIP analysis. These tools consist of the GRAIP Preprocessor, GRAIP GIS Tool, SINMAP2.0, TauDEM and Hawth's tools.

Installation

1. TauDEM: The website http://hydrology.neng.usu.edu/taudem/ explains how to install and use the TauDEM toolbar.
2. SINMAP2.0: The website http://hydrology.neng.usu.edu/sinmap2 explains how to install and use the SINMAP toolbar.
3. Hawth's Tools: The website http://www.spatialecology.com describes how to install and use Hawth's analysis tools.
4. GRAIP and GRAIP Preprocessor: The website http://www.engineering.usu.edu/dtarb/graip provides a link to the GRAIP tool setup file: “GRAIPSetup.exe”. Download GRAIPSetup.exe and save it to your working folder. Double click to run the setup. This will install GRAIP in the designated folder (by default C:\Program Files\GRAIP). This includes both the preprocessor and ArcMap toolbar. Use of the preprocessor is described in a separate preprocessor tutorial.

Getting started

To activate the GRAIP toolbar open ArcMap, go to the "Tool" menu and click "Customize" dialog, Figure 1, should open.

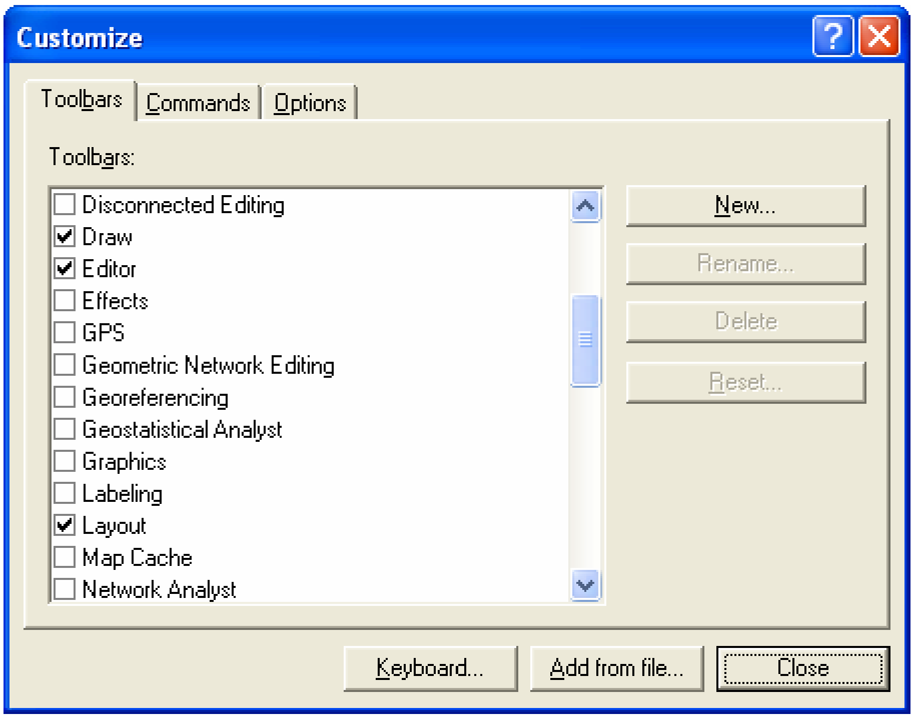


Figure 1: ArcMap Tool Customize dialog.

Click "Add from file…" and browse to \Program Files\GRAIP and select the agGRAIP.dll file. Check the "Geomorphologic Road Analysis and Inventory Package" box (Figure 2) to make the toolbar (Figure 3) visible.

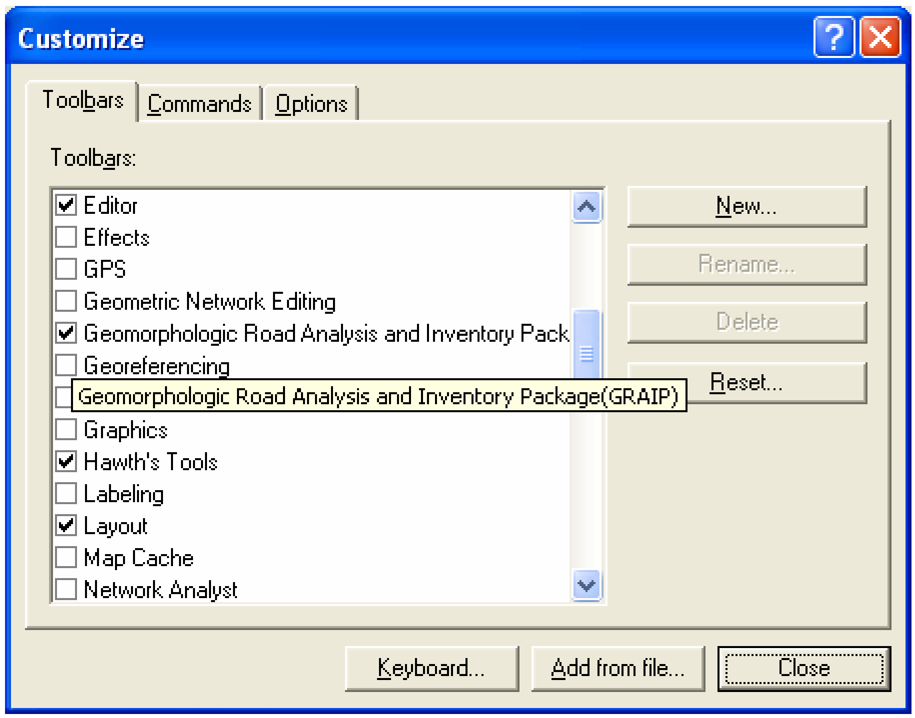


Figure 2: Check box to display GRAIP toolbar.

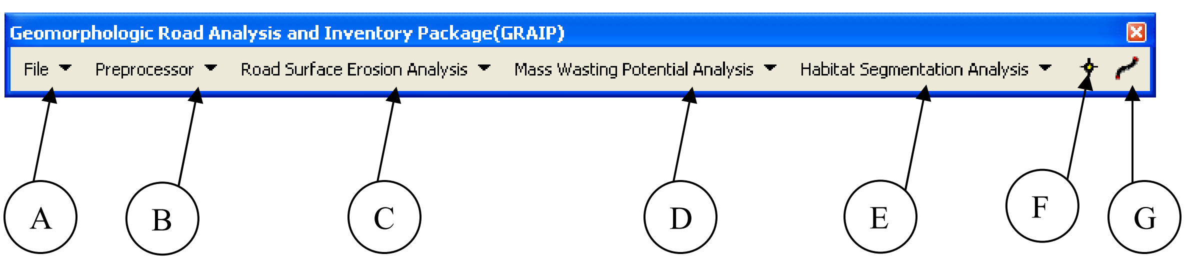


Figure 3: GRAIP ArcMap Toolbar.

<u>Toolbar overview</u>

The GRAIP toolbar functionality is divided into following parts (Figure 3)

1) Project settings file management (A).
2) Database preprocessor (B).
3) Road surface erosion analysis to quantify sediment production from forest roads and its delivery to streams (C).

4) Mass wasting potential analysis to quantify the impact of forest roads on terrain stability and gullying potential (D).
5) Habitat segmentation analysis to analyze and demarcate fish habitat segmentation due to failed or blocked culverts (E)

In addition to above features there are two extra tools to trace the road segments draining to a particular drain point (F) (Drain Rex, Rex being the faithful dog to sniff out where road segments drain) and to find drain points where a particular road segment is draining to (G) (Road Rex).

The following sections in this tutorial describe the steps taken in a typical GRAIP analysis.

Data preparation

1) Run the GRAIP Database Preprocessor tool
2) Run TauDEM Basic Grid Analysis and Network Delineation functions to delineate a TauDEM stream network.

Running the GRAIP GIS tool

The *.graip file created by the GRAIP database preprocessor contains information about input file paths for GRAIP GIS model.

1) From within ArcMap open the *.graip file by going to “File” -> “Open” in the GRAIP Toolbar (Figure 4). Browse to and select the *.graip file. The DEM,

DrainPoints.shp, RoadLines.shp and demnet.shp files required for the analyses will then be displayed in ArcMap (Figure 5).

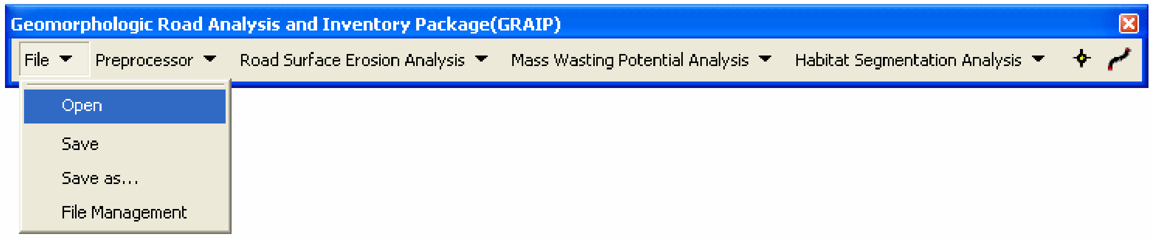


Figure 4: File Open Menu to open the Project settings file.

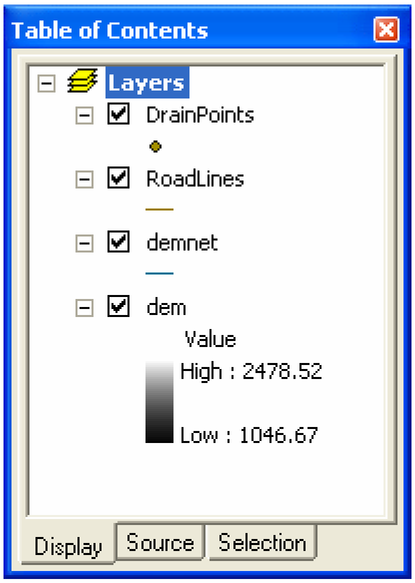
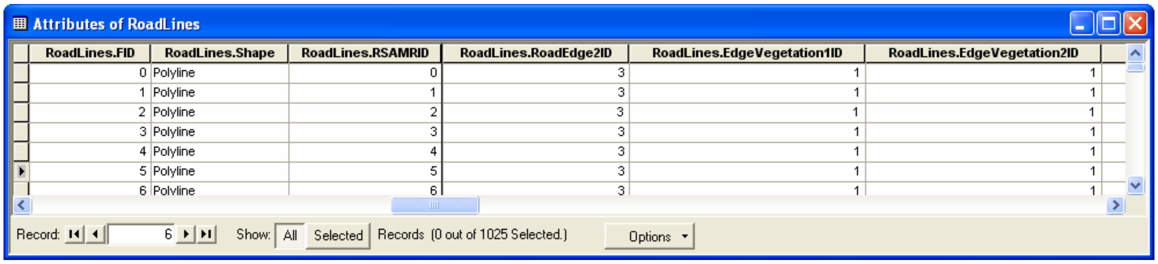


Figure 5: ArcMap Table of contents showing GRAIP analyses input files loaded.

When the *.graip files is used to load files the RoadLines and DrainPoints shapefiles are joined to the corresponding in the GRAIP Database (*.mdb) so that attributes are accessible (Figure 6).


Attributes of RoadLines

RoadLines.FID	RoadLines.Shape	RoadLines.RSAMRID	RoadLines.RoadEdge2ID	RoadLines.EdgeVegetation1ID	RoadLines.EdgeVegetation2ID
0	Polyline	0	3	1	1
1	Polyline	1	3	1	1
2	Polyline	2	3	1	1
3	Polyline	3	3	1	1
4	Polyline	4	3	1	1
5	Polyline	5	3	1	1
6	Polyline	6	3	1	1

Record: 6 Show: All Selected Records (0 out of 1025 Selected.) Options

Figure 6: RoadLines shapefile attribute table joined to MS Access RoadLines table.

2) To manage the file paths for input, intermediate and output files, go to File -> File Management menu to open the File Management Dialog (Figure 7)

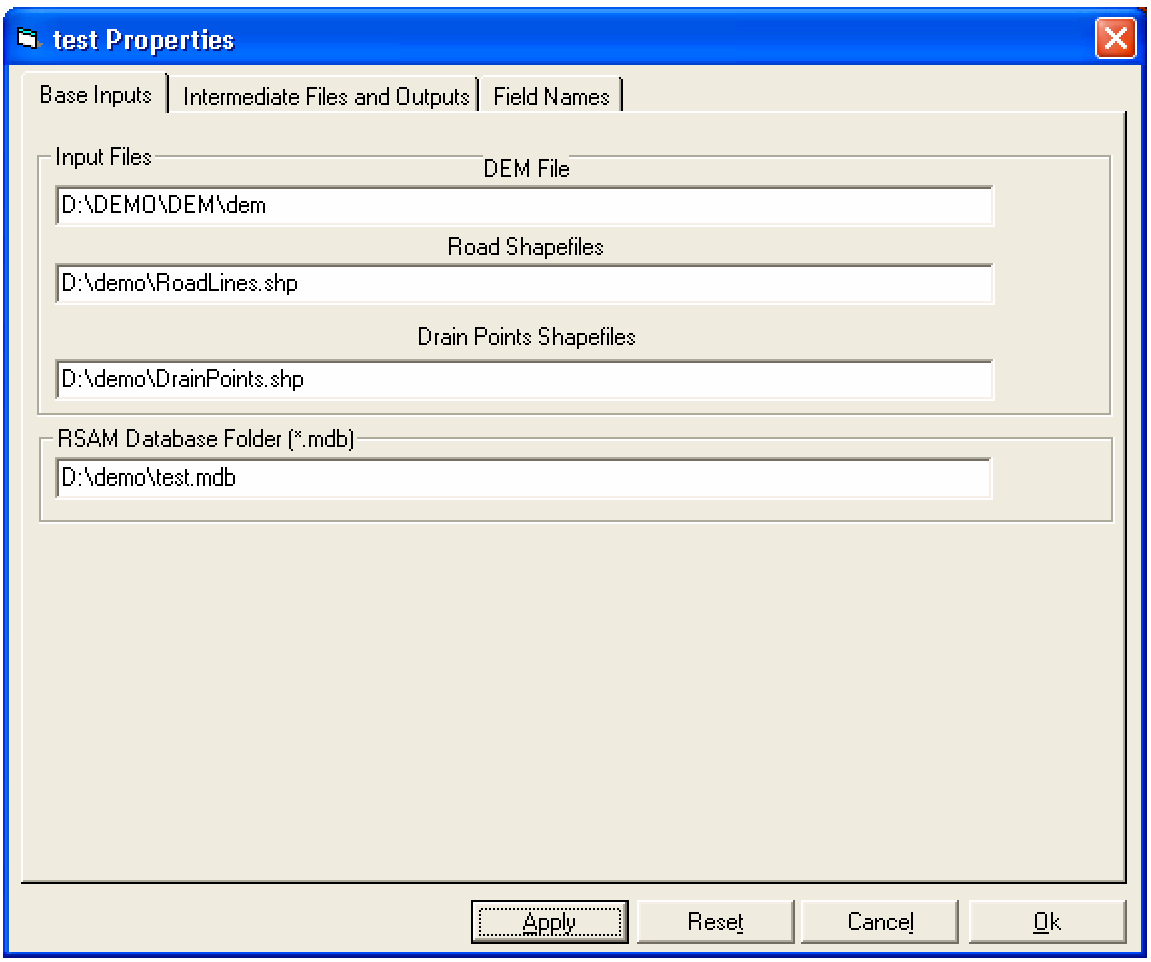


Figure 7: Base Inputs file information in File Management Dialog.

3) Select the Resample DEM function from the GRAIP Preprocessor menu. This function (Figure 8) resamples a DEM to a finer scale using the cubic convolution method from the ArcGIS Toolbox.

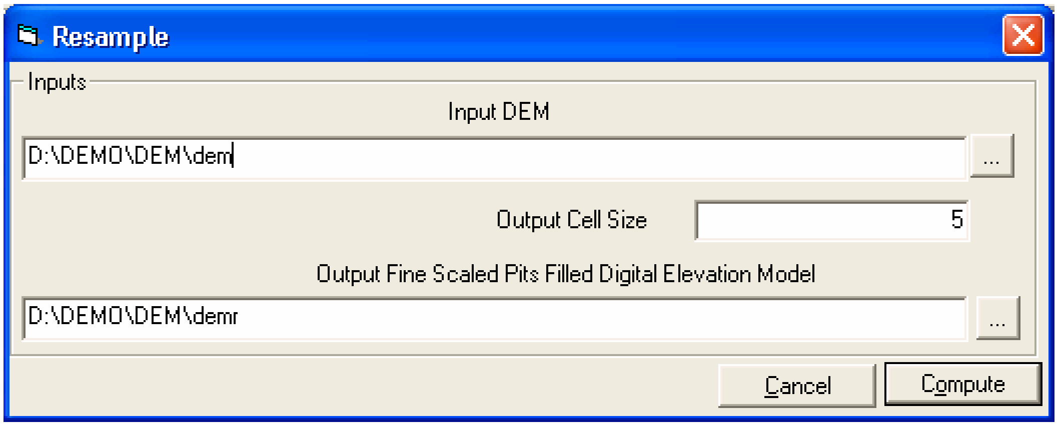


Figure 8: DEM Resample Function Dialog.

4) Select the Extract Stream Crossings function from the GRAIP Preprocessor menu. This function extracts the stream crossing drain points from the consolidated DrainPoints shapefile created by the Database Preprocessor tool.

5) Use the Hawth's Tools -> Vector Editing -> Intersect lines (make points) function to intersect the Road lines with the preliminary stream network. Name the output StrXingRi.shp (Figure 9).

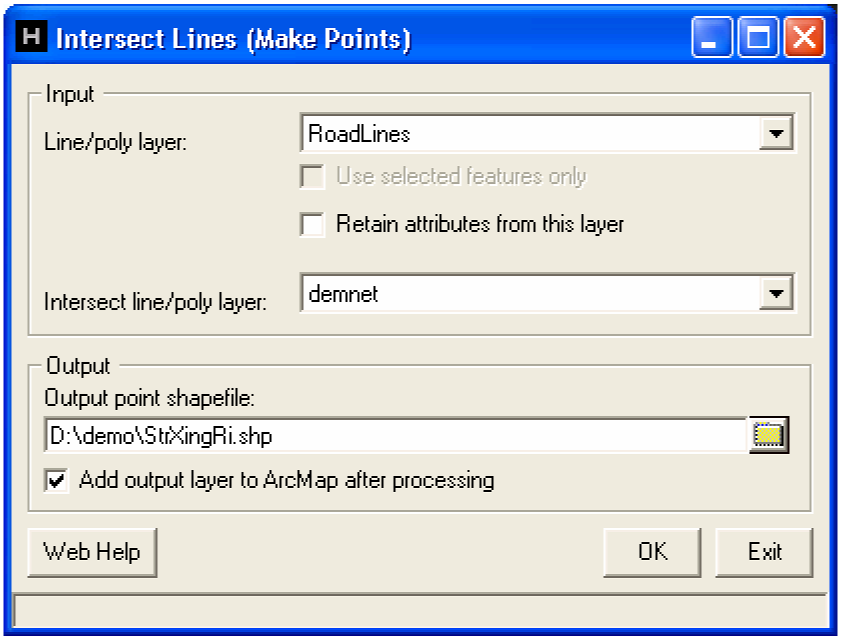


Figure 9: Hawth's Intersect Lines Tool Dialog.

6) Snap stream crossings to the preliminary stream network. Use Hawth's Tools -> Vector Editing -> Snap points to lines tool to snap the extracted stream crossings shapefile to the nearest position on the TauDEM stream network shapefile resulting in a new point shapefile (StrXingSn.shp) (Figure 10).

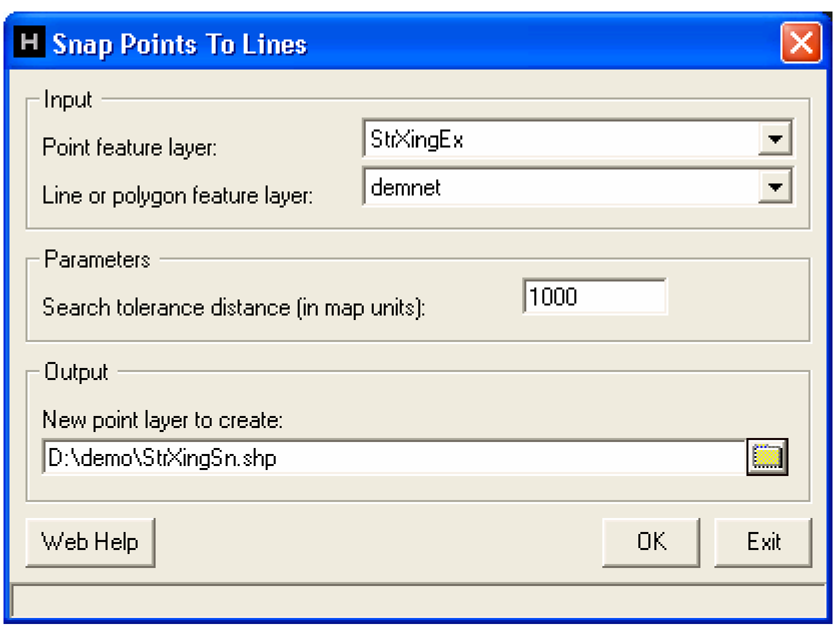


Figure 10: Hawth's Snap Points to Lines Tool Dialog.

7) Filter Stream Crossings. Use GRAIP -> Preprocessor -> Filter Stream Crossings function to automatically associate the appropriate points on the stream network from the snapped stream crossings (StrXingSn.shp) and road stream intersections (StrXingRi.shp) with nearby surveyed stream crossings screened according to nearness and a geomorphologically derived channel width criterion (Figure 11). The output is three shape files containing all merged stream crossings (MergedSX.shp), matched stream crossings (MatchSX.shp) and unmatched stream crossings (UMatchSX.shp).

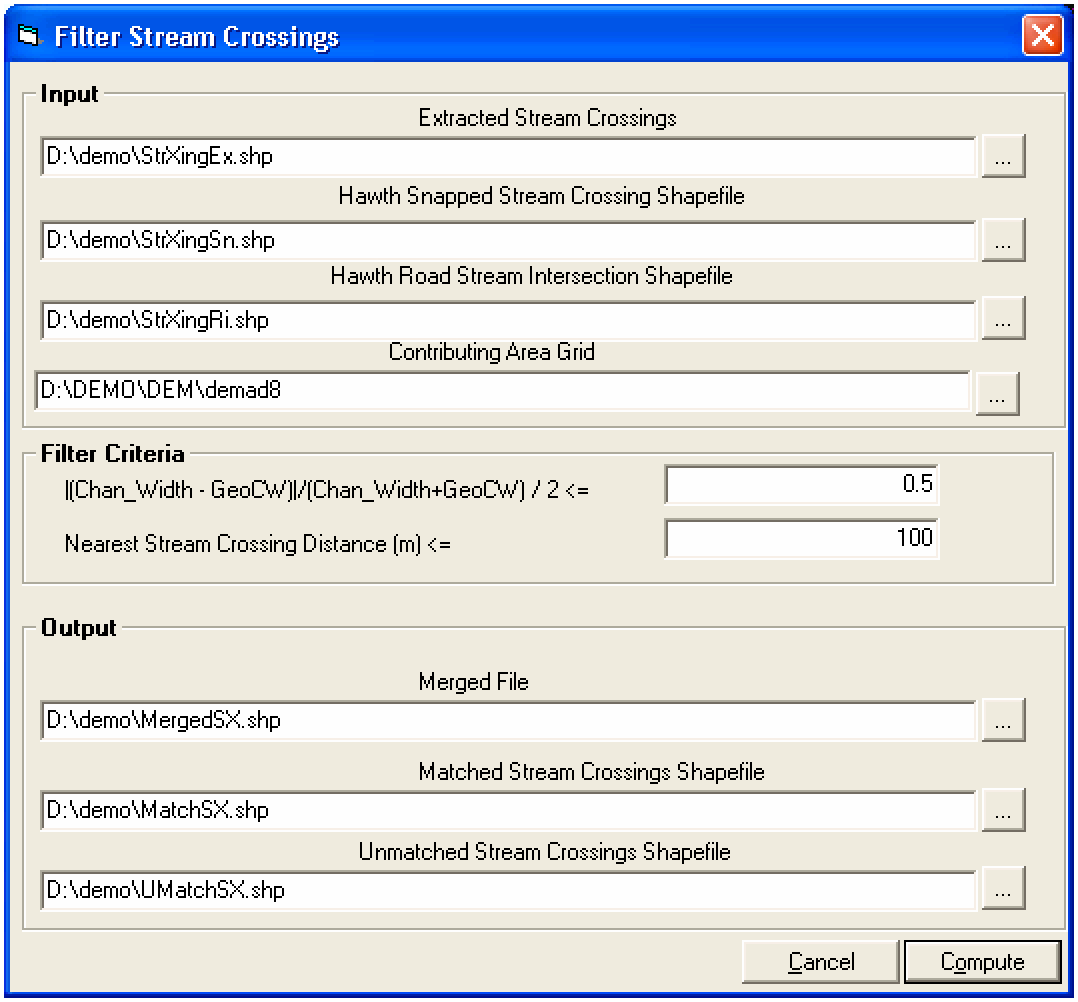


Figure 11: Filter Stream Crossings function.

8) Check matched and unmatched on-stream points, manually editing and resolving mismatches where possible or identifying situations requiring further examination in the field. The goal of the filter at the step above was to position each surveyed stream crossing from StrXingEx.shp on the stream network. This was attempted by examining both the nearest position on the stream to which the stream crossing can be snapped (StrXingSn.shp) and the nearest road stream intersection (StrXingRi.shp). Points where one of these passed the matching criteria are in MatchSX.shp. The user should in most cases be able to accept these without further analysis. The surveyed

stream crossings for which there was no match found are placed in UMatchSX.shp. The user should examine each of these to verify why they are not able to be placed on a stream and make the appropriate edits.

9) Combine the matched on-stream points shapefile with the overall outlets shapefile renumbering the Id field to avoid Id duplicates between the on-stream points and overall outlets. A simple way to combine shapefiles is to start editing the outlets shapefile, then select all the points in the MatchSX.shp shapefile and copy, then paste them into outlets.shp. A simple way to renumber the Id field is to use calculate values to set Id equal to Fid.

10) The combined outlets + stream crossings shapefile is then specified as the outlets shapefile for running the TauDEM network delineation functions. Use Preprocessor -> Create TauDEM Stream Network function to run the TauDEM network delineation function. With the new outlets shapefile as input TauDEM creates a stream network shapefile with stream segments split at stream crossings.

Road Surface Erosion Analyses

The functions on the GRAIP toolbar menu “Road Surface Erosion Analysis” (Figure 12) should be run in sequence from top to bottom.

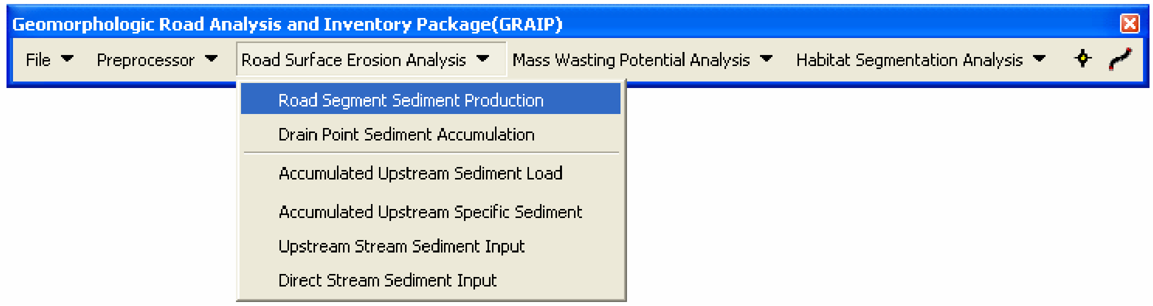


Figure 12: Road Segment Sediment Production Menu

1) Road Segment Sediment Production: Use Road Surface Erosion Analysis -> Road Segment Sediment Production function to calculate the sediment production values at each stream segment. Road Segment Sediment Production Analyses tool dialog is opened (Figure 13)

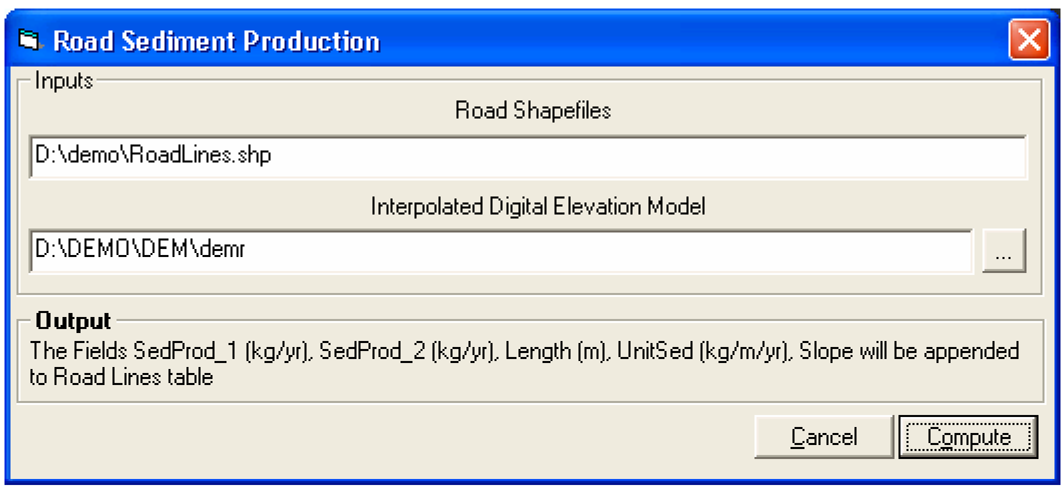


Figure 13: Road Sediment Production tool dialog.

Click compute to calculate sediment production values. The following fields are populated in the RoadLines table in the GRAIP database (*.mdb file)

a) Length : Road length (meters)

b) SedProd1: Sediment production from one side of road (kg/yr)

c) SedProd2: Sediment production from other side of road (kg/yr)

d) UnitSed: Unit sediment production from the road segment (kg/m/yr)

e) TotSedProd: SedProd1+SedProd2 (kg/yr)

f) TotSedDel: Sediment delivered to streams (calculated using stream connection information for each road) (kg/yr)

g) UnitTotSedDel: TotSedDel/Length (kg/m/yr)

2) Drain Point Sediment Accumulation: Use Road Surface Erosion Analysis ->Drain Point Sediment Accumulation function to open the tool dialog (Figure 14)

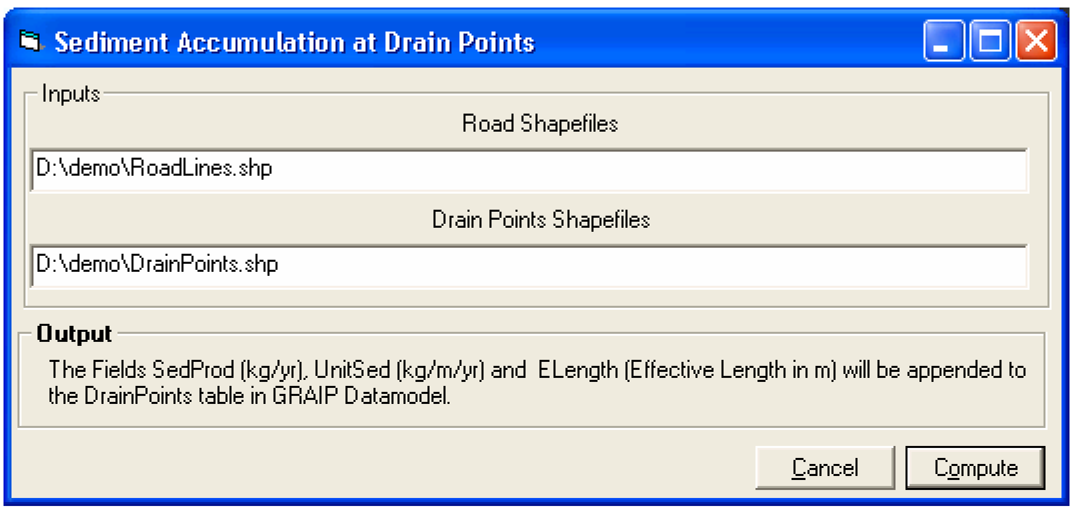


Figure 14: Drain point sediment accumulation tool dialog.

Click the compute button to calculate and store sediment accumulation values at each drain point in the DrainPoints Table in the GRAIP database.

The following drain point fields are populated

a) SedProd: Total accumulated sediment load at each drain point due to road surface erosion (kg/yr)

b) ELength: Effective length of road draining to each drain point (meters)

c) UnitSed: SedProd/Elength (kg/m/yr)

d) SedDel: Sediment delivery depending on stream connection (kg/yr)

4) Accumulated Upstream Sediment Load: Use Road Surface Erosion Analysis-> Accumulated Upstream Sediment Load function in the GRAIP toolbar to open the tool dialog (Figure 15)

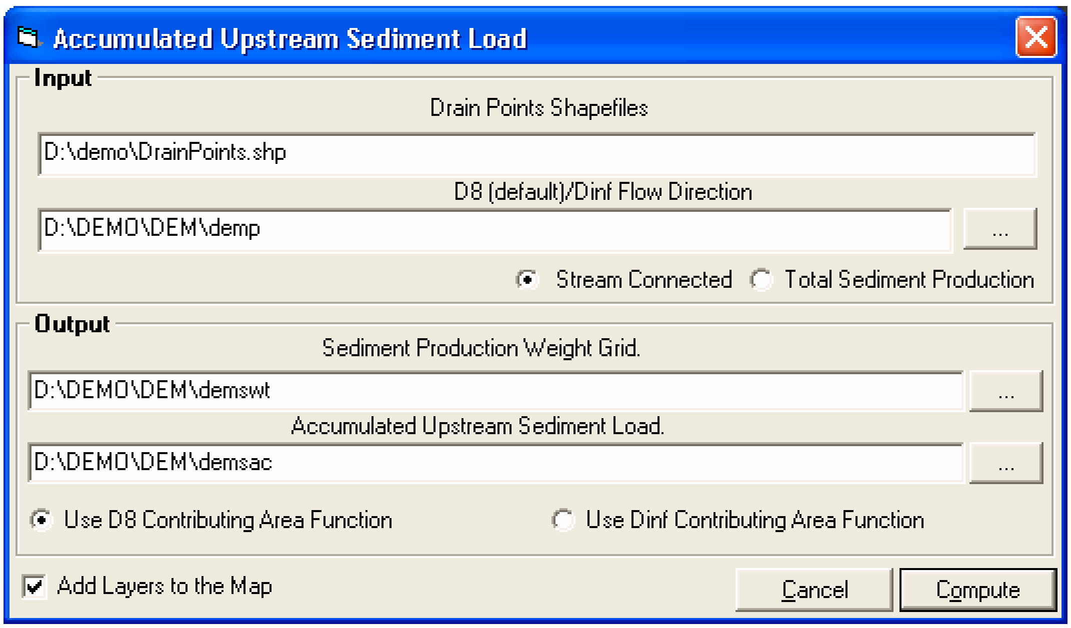


Figure 15: Accumulated Upstream Sediment Load dialog with default file names and options.

Click the compute button and following output grids are created.

a) Weight grid with Drain Point accumulated sediment load (swt suffix)

b) Weighted Sediment Accumulation grid (sac suffix). The user can select between D8 and Dinf Contributing area functions.

5) Accumulated Upstream Specific Sediment: Use Road Surface Erosion Analysis-> Accumulated Upstream Specific Sediment function to open the tool dialog (Figure 16)

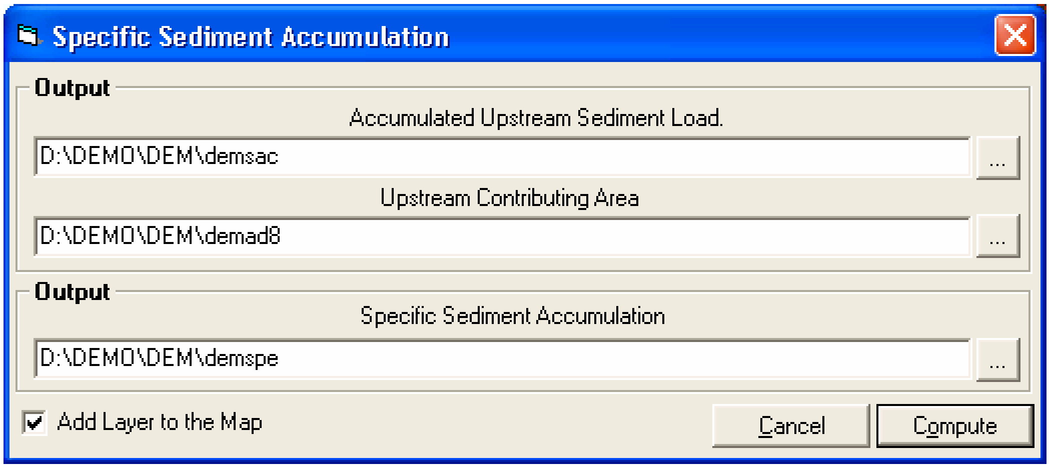


Figure 16: Specific Sediment Accumulation Dialog with default file names. User has the option to change input and output file names.

Click compute to create upstream specific sediment accumulation grid (Suffix spe)

6) Upstream Stream Sediment Input: Use Road Surface Erosion Analysis->

Upstream Stream Sediment Input function to open the tool dialog (Figure 17)

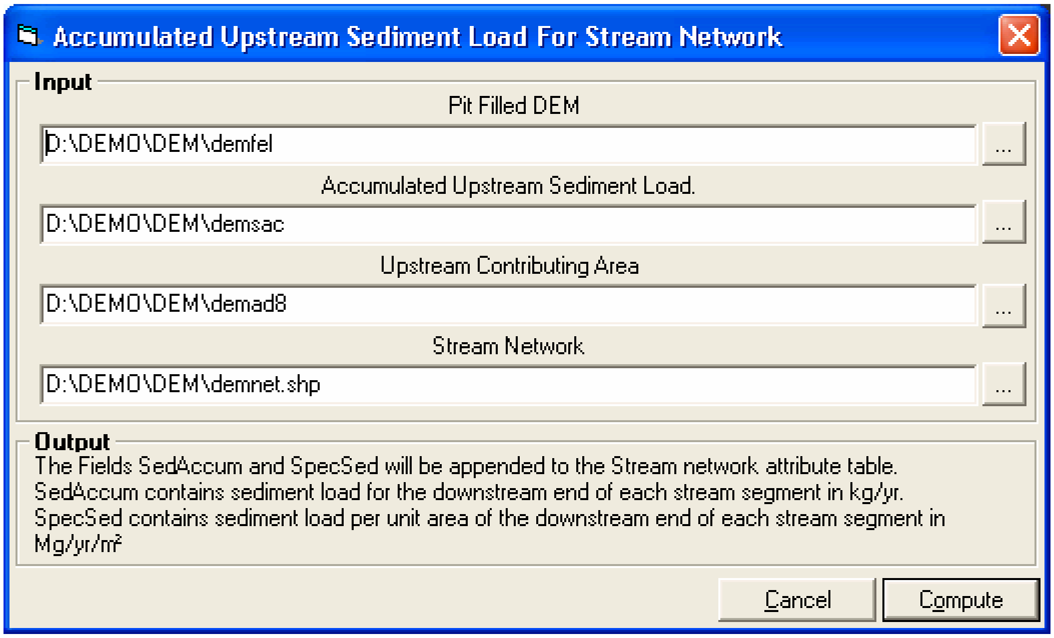


Figure 17: Accumulated Upstream Sediment Load for Stream Network with default file names and paths.

Click the compute button to calculate the upstream sediment inputs and specific upstream sediment inputs to each stream segment. Outputs from this function are

a) SedAccum: Accumulated Sediment Inputs to each stream segment (kg/yr)

b) SpecSed: Accumulated Specific Sediment load in each stream segment ($Mg/km^2/yr$)

These are appended to the stream network shapefile (*net.shp)

7) Direct Stream Sediment Input: Use Road Surface Erosion Analysis->Direct Stream Sediment Input to open the tool dialog (Figure 18)

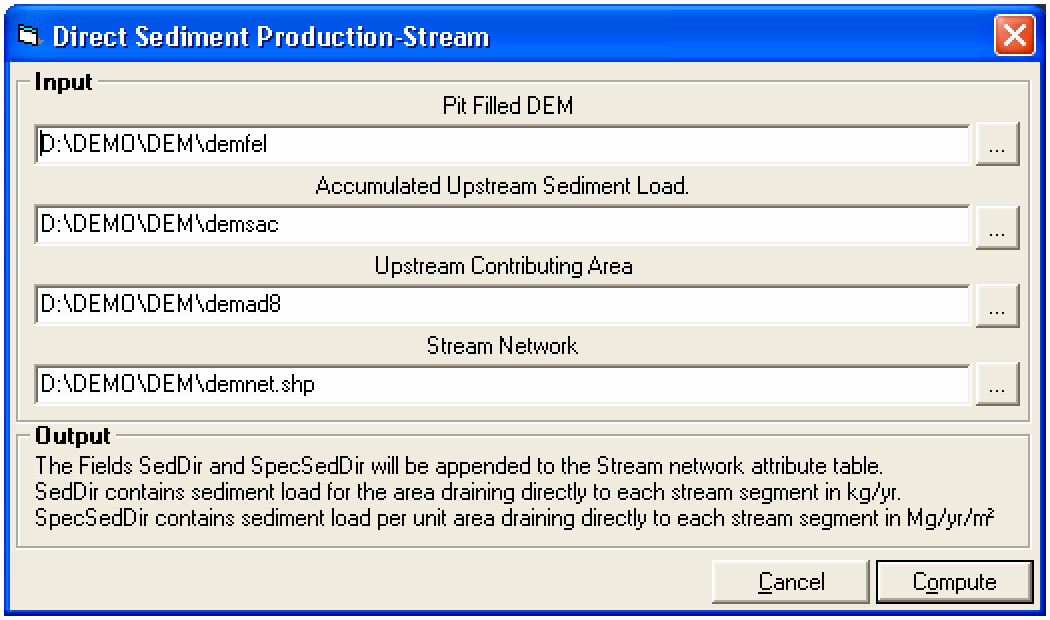


Figure 18: Direct Stream Sediment Input dialog with default file path.

Click the compute button to calculate the direct upstream sediment inputs and direct specific upstream sediment inputs to each stream segment. Outputs from this function are

a) SedDir: Direct Sediment Inputs to each stream segment (kg/yr).

b) SpecSedDir: Direct Specific Sediment load in each stream segment ($Mg/km^2/yr$).

These are appended to the stream network shapefile (*net.shp).

Mass Wasting Potential Analysis

The functions on the Mass Wasting Potential Analysis Menu (Figure 19) should be run in a sequence from top to bottom

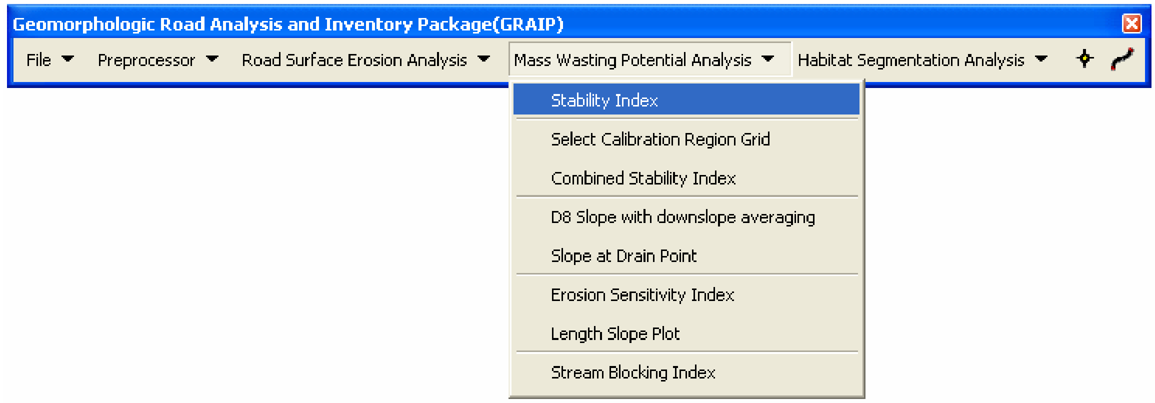


Figure 19: Mass wasting potential Analysis menu.

1) Stability Index: Use Mass Wasting Potential Analysis -> Stability Index function to open the tool dialog (Figure 20). Before doing this function you have to run SINMAP 2.0 to create the Stability Index (SI) grid. This SI grid is used as input in this function. For more information and tool documentation on SINMAP 2.0 please visit http://hydrology.neng.usu.edu/sinmap2/

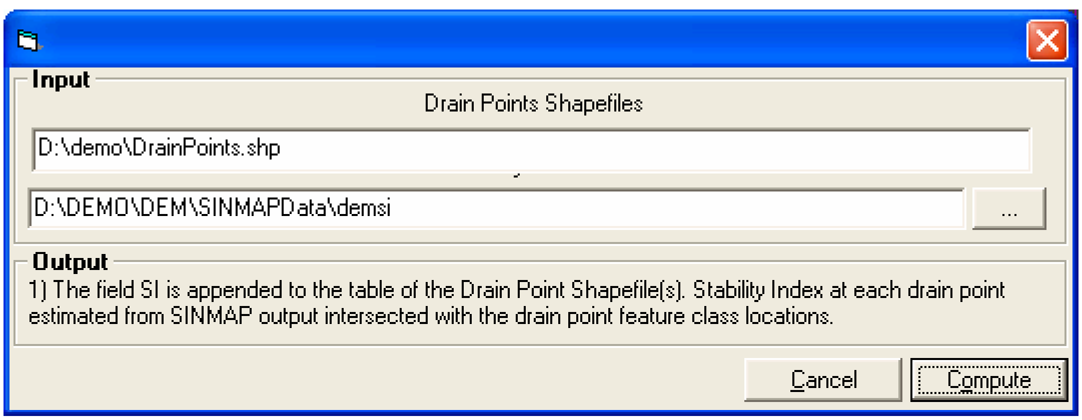


Figure 20: Stability Index at each drain point.

Click compute to identify Stability Index grid values at each drain point and store them in the DrainPoints table. The SI field is populated with values

2) Combined Stability Index: This function requires a calibration grid to run. Calibration regions are areas within which single lower bound and upper bound calibration parameters values can represent T/R, dimensionless cohesion, friction angle (ϕ) and soil density (ρ). SINMAP 2.0 tool documentation at

   http://hydrology.neng.usu.edu/sinmap2/ gives more information on creating the calibration region grid. To load the Calibration grid, click use Mass Wasting Potential -> Select Calibration Grid function and browse to the calibration grid. The grid is added to ArcMap when you select the grid. Now you can run Combined Stability Index using Mass Wasting Potential -> Combined Stability Index function. A tool dialog with default parameters and input and output file names will open (Figure 21)

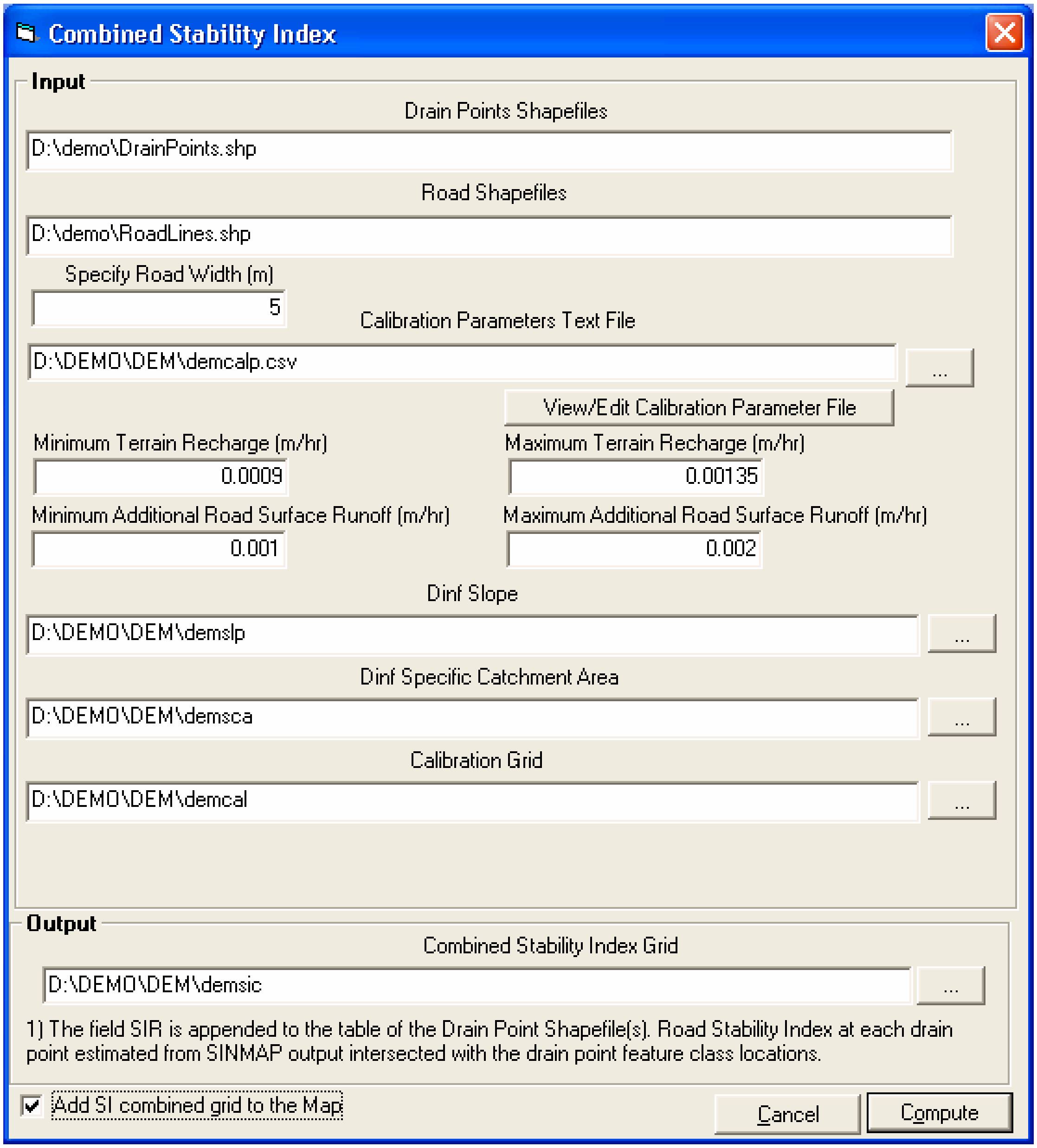


Figure 21: Combined Stability Index function.

Minimum and Maximum Terrain and Road recharges are user adjustable. Click View/Edit Calibration Parameter file button to open the table with modified SINMAP parameter values (Figure 22). These parameters are user adjustable.

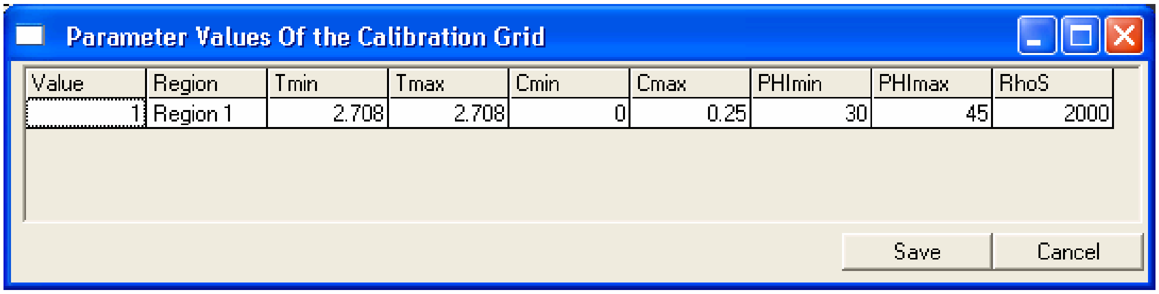


Figure 22: Calibration Parameter Table for single calibration grid selected.

The output and intermediate files created are

a) Minimum and maximum depth of terrain runoff generated (Suffix rmin and rmax).

b) Specific discharge due to road drainage for Minimum runoff and Maximum runoff (Suffix rdmin and rdmax).

c) Combined Stability Index Grid (Suffix sic).

The intermediate outputs (a) and (b) are not added to the ArcMap

In this function stability index (SI) due to terrain contributing area can be calculated by setting the road surface runoff to be 0 and SI due to road runoff only can be computed setting terrain recharge to be 0. The SI values from the grid are used to identify SI values to store in the SIR Field in for each drain point in the GRAIP database.

2) D8 Slope Grid with Downslope averaging: Use Mass Wasting Potential -> D8 Slope Grid with Downslope averaging function to open the tool dialog (Figure 23). Here the D8 flow directions are used to trace downslope and find the average slope for each grid cell over the specified averaging distance.

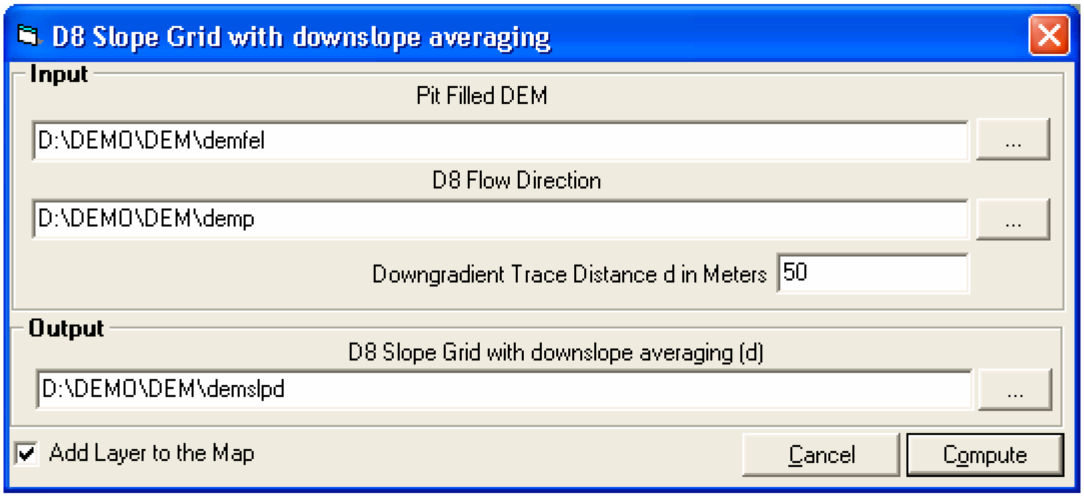


Figure 23: Slope Grid with downslope averaging function dialog.

The output from this function is the slope grid with downslope averaging (Suffix slpd)

3) Slope at Drain points: Use Mass Wasting Potential Analysis -> Slope at Drain Points function to open the tool dialog. Click compute to calculate the slope at each drain point (Figure 24). Slope field in the DrainPoints table in GRAIP database is updated with values.

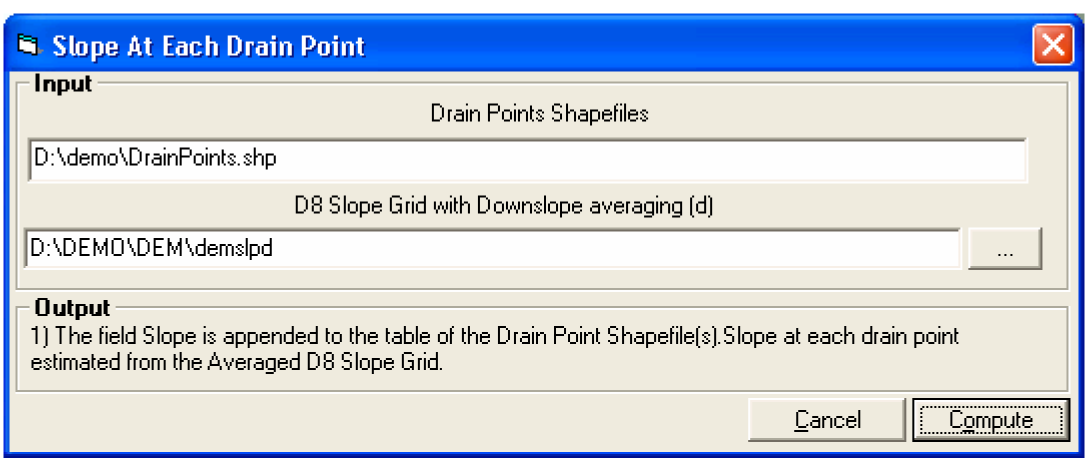


Figure 24: Slope at each drain point.

4) Erosion Sensitivity Index: Use Mass Wasting Potential Analysis -> Erosion Sensitivity Index function to open the tool dialog (Figure 25).

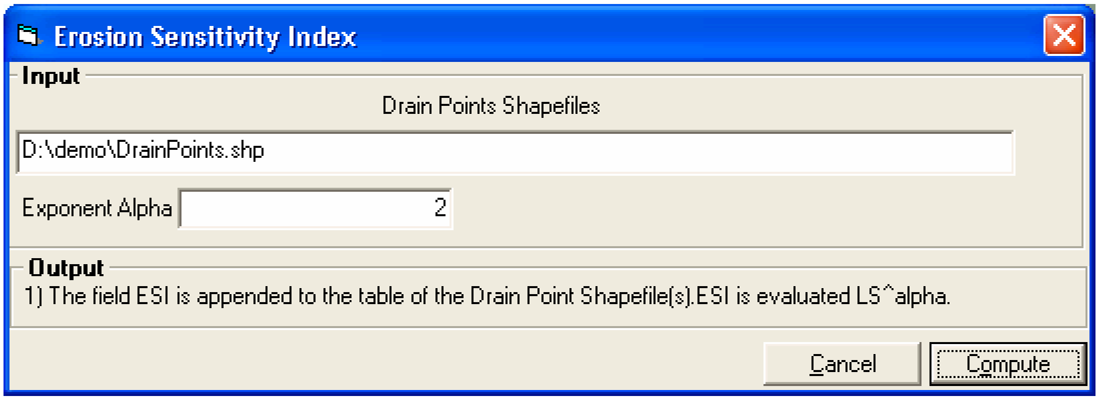


Figure 25: Erosion Sensitivity Index at each drain point.

This function outputs the ESI values at each drain point: LS^{α} where S is the slope and L is the Effective length of the road draining to each drain point.

5) Length Slope Plot: Use Mass Wasting Potential Analysis -> Length Slope Plot function to open the graph dialog with Length on the Y-axis and Slope on the X-axis (Figure 26)

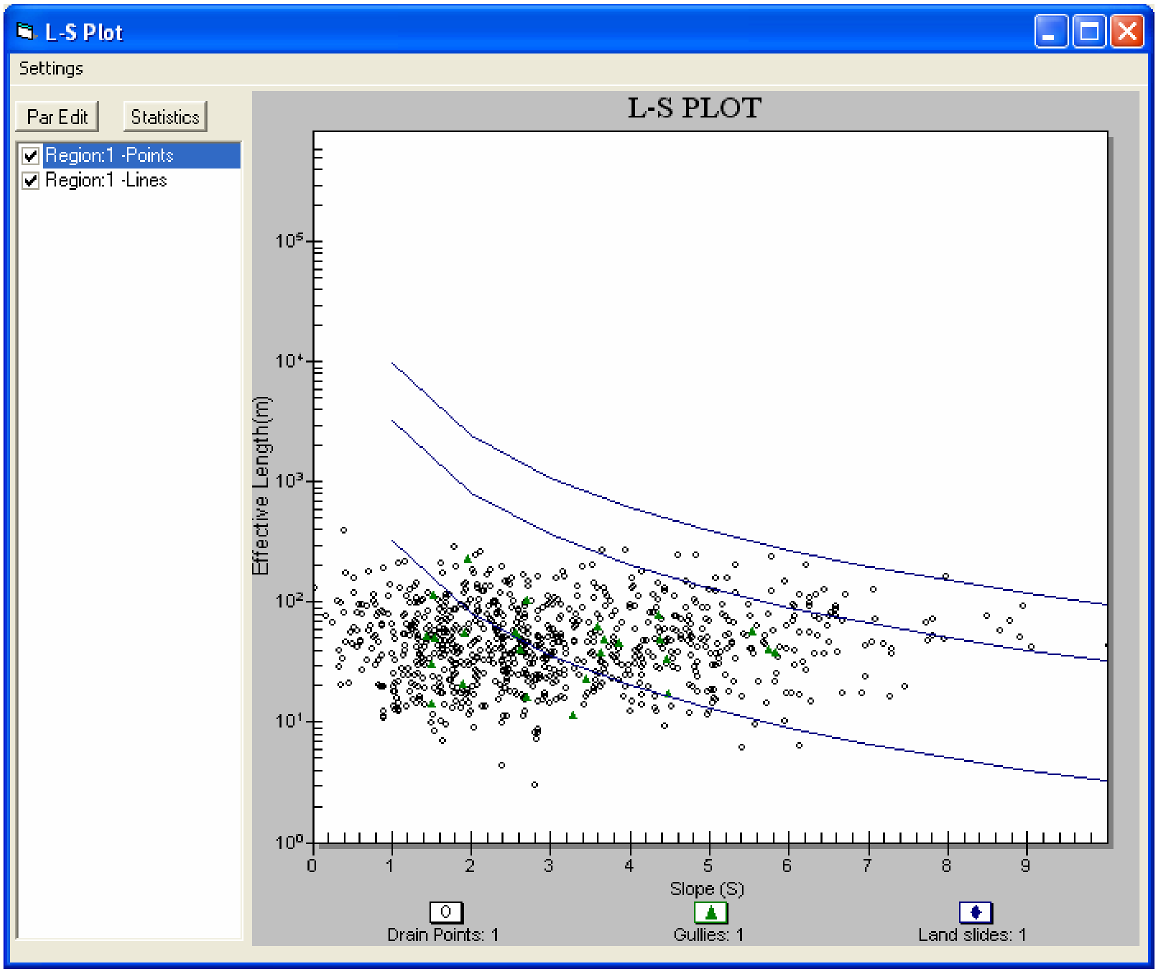


Figure 26: Length Slope Plot.

6) Stream Blocking Index: Use Mass Wasting Potential -> Stream Blocking Index function to open the tool dialog (Figure 27).

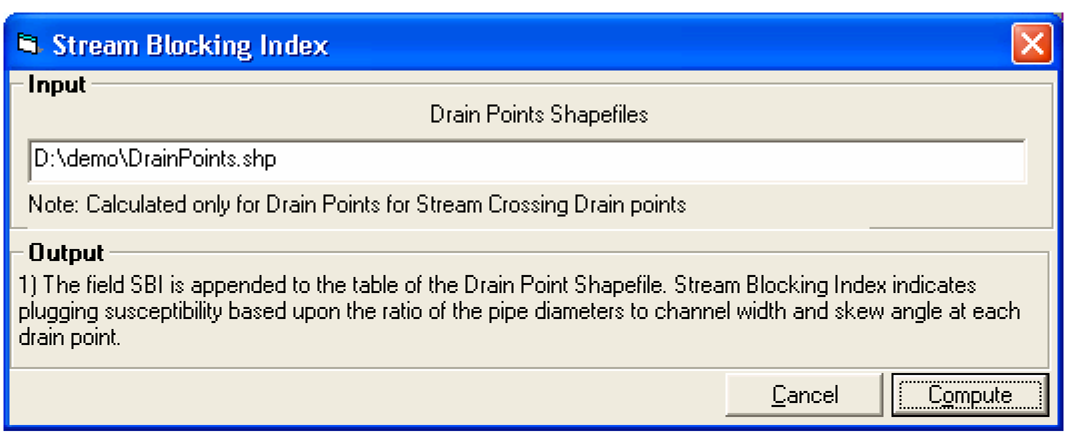


Figure 27: Stream Blocking Index function calculated at each drain point.

Outputs from this function listed below are populated in the DrainPoints table in the GRAIP database.

a) SBI: Stream blocking Index indicating plugging susceptibility based upon ratio of pipe diameters to channel width and skew angle.

b) PipeDiaToChannelWidth: Ratio for pipe diameter divided by channel width ratio class.

c) SkewAngle: skew angle.

Habitat Segmentation Analysis

1) Fish Passage Barrier: Use Habitat Segmentation Analysis -> Fish Passage Barrier function in the GRAIP GIS Toolbar to open the tool dialog (Figure 28).

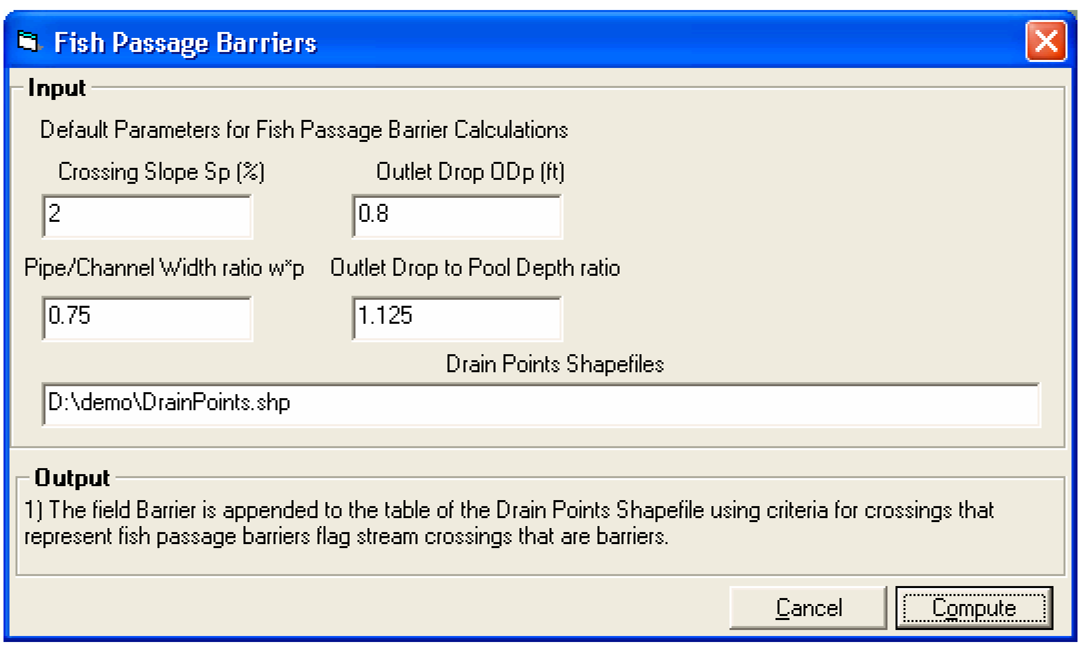


Figure 28: Fish Passage barrier function.

Click compute to find the fish passage barriers and assign identifier representing the status of the stream crossing. 0- Clear passage, 1- Partial passage and 2- Blocked.

2) Fish Habitat Segmentation: Use Habitat Segmentation Analysis -> Fish Habitat Segmentation function to open the tool dialog for demarcating habitat clusters. Figure 29 shows the dialog for fish habitat segmentation determination.

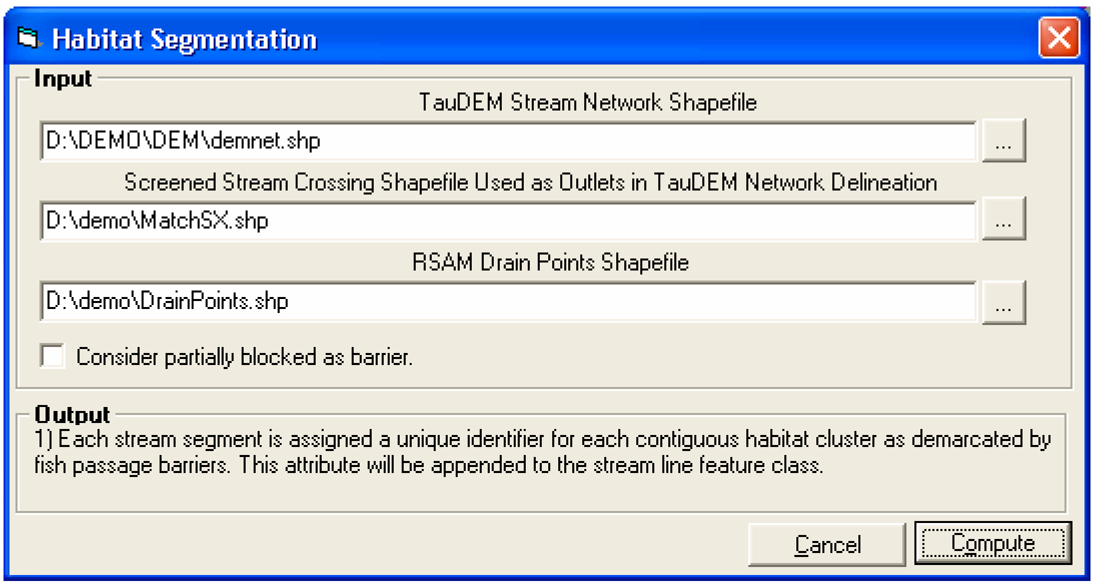


Figure 29: Habitat Segmentation Function Dialog.

Click Compute to assign each stream segment a unique identifier indicating which habitat cluster it belongs to. The habitat cluster identifier is appended to the TauDEM stream network shapefiles attribute table.

APPENDIX 6

USFS land type classes

Table 1: USFS land type classes used to determine BOISED parameters obtained from USFS Rocky Mountain Research station, Boise, ID.

Landtype	GEF	Side Slope gradient	SDR	Disturbed Width
ABCD	0.80	5	0.000326	4.06
101	0.80	5	0.000326	4.06
1012	0.80	5	0.000326	4.06
1013	0.80	5	0.000163	4.06
101A	0.80	5	0.000163	4.06
102	0.80	5	0.000163	4.06
103	0.80	10	0.000456	4.24
1031	0.80	5	8.14E-05	4.06
104	0.80	15	0.002568	4.54
1042	0.80	10	0.000761	4.24
105	0.80	15	0.002568	4.54
1054	0.80	20	0.017392	4.96
1055	0.80	15	0.007337	4.54
106	0.90	10	0.000364	4.24
1062	0.90	25	0.007119	5.5
106B	0.90	20	0.003645	4.96
107	1.00	40	0.048697	7.84
1071	1.00	20	0.008696	4.96
1072	1.00	25	0.016984	5.5
108	0.80	45	0.033215	8.86
109	0.90	35	0.019535	6.94
1092	0.90	35	0.027907	6.94
1095	0.90	35	0.027907	6.94
1099	0.90	30	0.012302	6.16
109A	0.90	35	0.055814	6.94
109A1	0.90	50	0.081361	10
109B	0.90	40	0.029131	7.84
109B1	0.90	40	0.029131	7.84
109C	0.90	45	0.031108	8.86
109D1	0.90	60	0.147769	12.64
109D2	0.90	20	0.003193	4.96
109E	0.90	45	0.06234	8.86
109G	0.90	50	0.051206	10
109G1	0.90	60	0.073737	12.64
109N1	0.90	40	0.02554	7.84
110	0.80	15	0.002568	4.54

110X	0.80	20	0.006087	4.96
111A	0.80	55	0.075804	11.26
111A1	0.80	55	0.108291	11.26
111A2	0.80	45	0.059312	8.86
111A3	0.80	40	0.02916	7.84
111B	0.80	55	0.075728	11.26
111B1	0.80	55	0.075728	11.26
111B2	0.80	50	0.056896	10
111C	0.80	55	0.056796	11.26
111C3	0.80	45	0.031108	8.86
111D	0.80	70	0.046837	15.76
111D2	0.80	60	0.036868	12.64
111D3	0.80	45	0.012443	8.86
111G	0.80	55	0.090874	11.26
111X	0.80	75	0.144017	17.5
111X1	0.80	50	0.042672	10
112	0.80	55	0.151759	11.26
1121	0.80	35	0.046604	6.94
113	0.80	75	0.115329	17.5
1131	0.80	55	0.037902	11.26
114	0.80	45	0.029656	8.86
1142	0.80	40	0.020828	7.84
115	0.80	55	0.060643	11.26
120A	1.00	50	0.068343	10
120A1	1.00	45	0.049822	8.86
120A2	1.00	45	0.041518	8.86
120A8	1.00	50	0.195266	10
120B	1.10	55	0.063612	11.26
120B1	1.20	45	0.049772	8.86
120B2	1.10	50	0.047792	10
120B3	1.10	55	0.181748	11.26
120B4	1.10	45	0.034841	8.86
120B5	0.60	50	0.056896	10
120B6	1.10	40	0.02447	7.84
120B10	0.42	45	0.049772	8.86
120B13	1.10	50	0.039827	10
120B14	0.42	60	0.098316	12.64
120C	1.10	55	0.047709	11.26
120C1	1.10	60	0.061939	12.64
120C2	1.10	55	0.136311	11.26
120C3	1.10	65	0.1125	14.14
120C8	1.10	60	0.176969	12.64
120C11	1.10	50	0.035844	10
120C12	1.10	50	0.035844	10

120D	1.10	70	0.14051	15.76
120D2	1.10	75	0.120975	17.5
120D3	1.10	65	0.1125	14.14
120D4	1.10	65	0.225	14.14
120E	1.20	30	0.014366	6.16
120E1	1.20	45	0.029034	8.86
120E2	1.20	40	0.029131	7.84
120E3	1.20	40	0.020391	7.84
120E4	1.20	30	0.024579	6.16
120E5	1.20	40	0.069914	7.84
120E6	1.20	40	0.058261	7.84
121	1.20	30	0.014366	6.16
121E	1.20	35	0.022813	6.94
121E1	1.20	20	0.004257	4.96
122	1.10	75	0.460856	17.5
1221	1.10	75	0.172821	17.5
1222	1.10	75	0.120975	17.5
1224	1.10	75	0.120975	17.5
1225	1.10	80	0.146818	19.36
1228	1.10	70	0.374693	15.76
123	1.10	40	0.02447	7.84
1231	1.10	15	0.001845	4.54
1232	1.10	55	0.075728	11.26
1233	1.10	40	0.02916	7.84
123B	1.10	25	0.008314	5.5
123B1	1.10	40	0.029131	7.84
123C	1.10	55	0.047709	11.26
125	0.30	50	0.045562	10
1312	0.42	40	0.020391	7.84
1313	0.42	40	0.058261	7.84
133A3	0.42	55	0.108291	11.26
133B	0.42	55	0.075728	11.26
133C1	0.42	55	0.056796	11.26
1343	0.42	40	0.023328	7.84
1351	0.42	70	0.133953	15.76
1352	0.42	40	0.049988	7.84
1353	0.42	45	0.033215	8.86
1361	0.42	10	0.000781	4.24
1362	0.42	15	0.002636	4.54
1363	0.42	15	0.001845	4.54
1365	0.42	45	0.041518	8.86
1366	0.42	25	0.008492	5.5
1367	0.42	5	4.07E-05	4.06
1368	0.42	35	0.055814	6.94

140B2	0.75	45	0.049772	8.86
140B3	0.75	55	0.181748	11.26
140C1	0.75	50	0.035844	10
140C2	0.75	55	0.068155	11.26
140C3	0.75	60	0.176969	12.64
140E1	0.75	40	0.029131	7.84
140E2	0.75	50	0.039827	10
141	0.75	45	0.048487	8.86
143	0.75	50	0.068343	10
143C	0.75	55	0.068155	11.26
D011	1.00	10	0.004686	4.24
D0111	1.00	10	0.002609	4.24
D0112	1.00	25	0.016984	5.5
D013	1.00	5	0.000163	4.06
D021	1.00	15	0.001834	4.54
D031	1.00	5	0.000163	4.06
D032	1.00	5	0.000163	4.06
D081	1.00	10	0.002609	4.24
D082	1.00	35	0.200929	6.94
D1010	1.00	15	0.003669	4.54
D102	1.00	50	0.108698	10
D131	1.00	5	0.000163	4.06
G061	1.00	15	0.002568	4.54
G062	1.00	25	0.011889	5.5
G131	1.00	15	0.003082	4.54
G161	1.00	15	0.002054	4.54
G162	1.00	35	0.046883	6.94
S052	1.00	50	0.135873	10
S081	1.00	45	0.087102	8.86
S091	1.00	60	0.154848	12.64
S0911	1.00	60	0.154848	12.64
S0912	1.00	70	0.421529	15.76
S0914	1.00	55	0.088526	11.26
S092	1.00	70	0.295071	15.76
S093	1.00	55	0.143126	11.26
S181	1.00	20	0.007811	4.96
S1811	1.00	60	0.253065	12.64
S1812	1.00	70	0.393427	15.76
S182	1.00	70	0.393427	15.76
S201	1.00	50	0.089611	10
S211	1.00	55	0.170389	11.26
S2810	1.00	50	0.170687	10
S301	1.00	40	0.045881	7.84
S3012	1.00	45	0.065326	8.86

V0N	0.42	10	0.003905	4.24
V111	0.42	10	0.004686	4.24
CZ1	0.42	15	0.002197	4.54
CZ2	1.00	60	0.073737	12.64
CZ3	1.00	55	0.056796	11.26
CZ4	0.70	55	0.075728	11.26
CZ5	1.00	55	0.039757	11.26
CZ6	1.00	55	0.075728	11.26
CZ7	1.00	65	0.09375	14.14
CZ8	1.00	35	0.014636	6.94
CZ9	0.70	45	0.041477	8.86
CZ10	1.00	60	0.073737	12.64
CZ11	1.00	60	0.073737	12.64
CZ12	1.00	50	0.042672	10
CZ13	0.42	45	0.059312	8.86
CZ14	1.00	55	0.075728	11.26
CZ15	0.70	50	0.056896	10
CZ16	0.70	45	0.041477	8.86
CZ17	0.70	15	0.001536	4.54