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A GIS Tool to Analyze Forest Road Sediment Production and Stream Impacts

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Abstract: A set of GIS tools has been developed (Road Sediment Analysis Model, RSAM) to analyze and quantify the impacts of forest roads on forested watersheds. RSAM is organized into three modules. In the first module sediment production for each road segment is calculated from slope, length, road surface condition and road side drain vegetation. A GPS gathered road condition inventory provides surface and drain conditions, locations of drain points, information on connectivity between drain points and streams, and information on road stream crossings. Slope is obtained from the GIS by overlaying the road path on a Digital Elevation Model (DEM). Road sediment production is accumulated at each drain point by adding the sediment production draining to each drain point from different road segments. These drain point sediment loadings are then coupled with a DEM model for surface flow and used as inputs to a weighted flow accumulation function to calculate sediment load inputs to stream segments, also delineated based on the DEM. An option allows accumulation of all sediment produced or only sediment produced from drain points inventoried as connected to the stream. The second module analyzes the impact of forest roads on terrain stability. Terrain stability is assessed by calculating the specific discharge due to road drainage and using this, together with slope, as inputs to an infinite plane slope stability model. In the final module the inventory information on the fish passage status of stream crossings is used to demarcate contiguous clusters of stream habitat and assess the impact of fish passage barriers on the fragmentation of stream habitat. A map showing possible fish habitat clusters is obtained from the analysis. To ensure referential integrity between road segments, drain points and the stream network attributes, and to validate the road inventory dataset a relational database model framework is used. Preprocessing software has been developed to load the road inventory data into this framework and fulfill initial quality control and data validation functions. The sediment production, terrain stability and habitat cluster contiguity analyses then works off data from the relational database.

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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 revegetate 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, 2001). Runoff that drains from roads can initiate landslides or gullies (Montgomery, 1994; Wemple et al., 1996; Borga et al., 2004). Stream crossing culverts can impede passage of water downstream causing mass wasting (Flanagan et al., 1998) and fragment fish habitat by blocking fish passage (Clarkin et al., 2003). Forest managers need information about the potential impacts of roads over large areas to conduct cumulative effects analyses and watershed analyses for planning new road construction, maintenance, and decommissioning priorities. Information on aquatic impacts beyond just sediment yield estimates are needed for such work (Luce et al., 2001; Switalski et al., 2004).

An important characteristic of roads is that fine scale information such as linear and point data is important to impacts over large areas (Luce and Wemple, 2001) requiring a detailed inventory of roads and their relationships to their drainage points (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 depend on point delivery of water. Black and Luce (2002) developed a road and drainage inventory process to respond to this specific need. The method uses GPS and databases to capture field survey information that can be used in a GIS program to perform analyses that rely on the spatial coincidence of landscape and road characteristics to determine risks to aquatic ecosystems. The purpose of this paper is to describe GIS based analysis tools designed to calculate sediment production from forest roads, its delivery to the stream system, the effects of road drainage on terrain stability, and the impact of road crossing barriers on aquatic habitat.

2. Methods

2.1. Road Sediment Analysis Model

A road sediment analysis model (RSAM) has been developed to use forest road inventory information to analyze the impact of forest roads on forested watersheds. RSAM has the following three sets of functionalities:

1) Quantify sediment production from forest roads and stream sediment inputs.
2) Calculate terrain stability at road drain points and impacts of road drainage on terrain stability.
3) Analyze stream habitat segmentation due to road crossings that are barriers to fish passage.

2.1.1. Sediment Production and Stream Sediment inputs:

Figure 1 gives the flow of information and calculations performed to estimate sediment production and stream sediment inputs in RSAM.

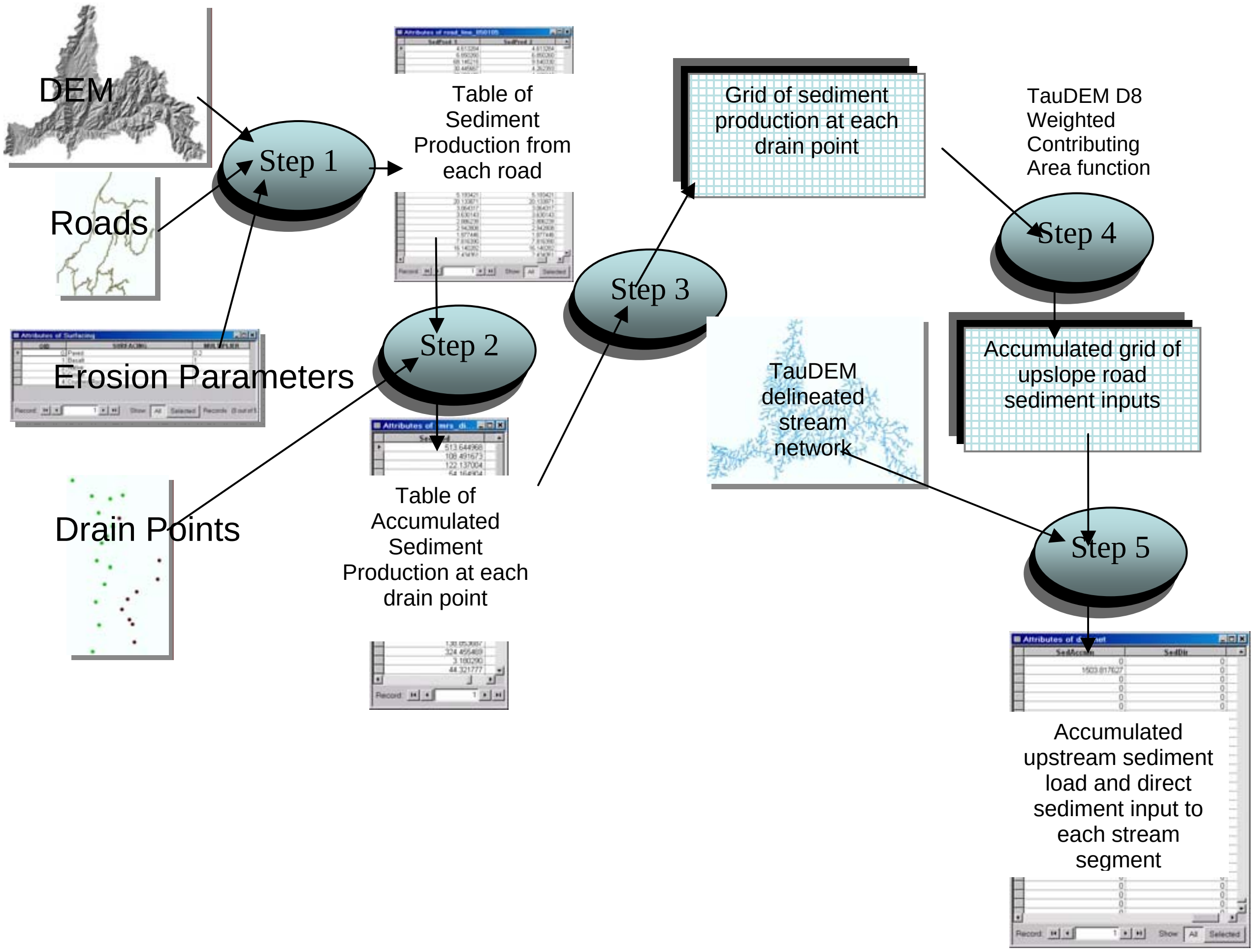

Figure 1: Flow of information in RSAM sediment calculation

Evaluating sediment production from each forest road segment is the first step in the model analysis (Step 1 in Figure 1). Road segment sediment production is calculated from a base road sediment production rate adjusted by factors to account for the condition of the road surface and ditch vegetation multiplied by the road segment length and slope (Luce and Black, 1999). 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 formula for calculating the annual erosion rate, following Luce and Black (1999) is

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

where L is the length, S is the slope, 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. Information for these multipliers is taken from Luce and Black (2001a and 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.

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 at each drain point is calculated by adding up sediment production values from all road segments draining to the drain point (Step 2 in Figure 1). The road attribute table in the road inventory contains the information about the drain points to which each road segment drains. Each drain point has a unique identifier, DrainID, and each road segment has two DrainID fields representing the drain point connected to each side of the road. The resulting accumulated sediment production is appended to the drain point attribute table.

Drain points divert water and sediment from the ditches and road surface to either directly to a stream or onto a hillslope, where it may continue to a stream. The drain point sediment loadings are used to obtain a grid giving the sediment production at each drain point (Step 3 in Figure 1). TauDEM (Tarboton and Ames, 2001) is then used to derive, from a digital elevation model (DEM), the D8 flow direction grid. This defines for each grid cell the flow direction to one of the eight adjacent or diagonal neighbors in the direction of steepest slope. This effectively parameterizes the surface flow field. A weighted flow accumulation function (Step 4 in Figure 1) is then used to sum the sediment inputs upstream from each grid cell. TauDEM also provides a DEM derived stream network and the last step (Step 5 in the figure) intersects the accumulated sediment grid with the stream network to calculate the sediment input accumulated at the downstream end of each stream segment. From this information, the model also calculates the sediment yield from roads per unit watershed area, allowing comparison to long term sediment yields from other processes. Direct sediment input to each stream segment is also calculated by subtracting the accumulated upstream sediment load from the accumulated sediment load at the downstream end of the stream segment. The results are appended as fields to the stream network attribute table.

2.1.2. Terrain Stability and Road Drainage

Because drain points accumulate storm water from the road side ditches and divert it to adjacent hillslopes, these hillslopes are locations of increased risk for erosion and pore water pressure induced landslides. The terrain slope at each drain point is needed to quantify the risk for erosion. 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 appended to the drain point table.

The SINMAP model (Pack et al., 1998) provides a quantification of terrain instability based on the infinite plane slope stability model and steady state hydrology (Montgomery and Dietrich, 1994) coupled with uncertainty in soil parameters. One measure of terrain stability at drain points is assessed by intersecting the stability index grid obtained from SINMAP with drain points to provide a table of stability index at each drain point. This is essentially a mapping of places where roads drain to inherently unstable slopes.

The SINMAP measure of stability index at each drain point does not quantify the impact of the quantity of road runoff from each drain point. To account for this the SINMAP approach has been modified to substitute road drainage for the steady state recharge used in SINMAP. The approach is illustrated in figure 2.

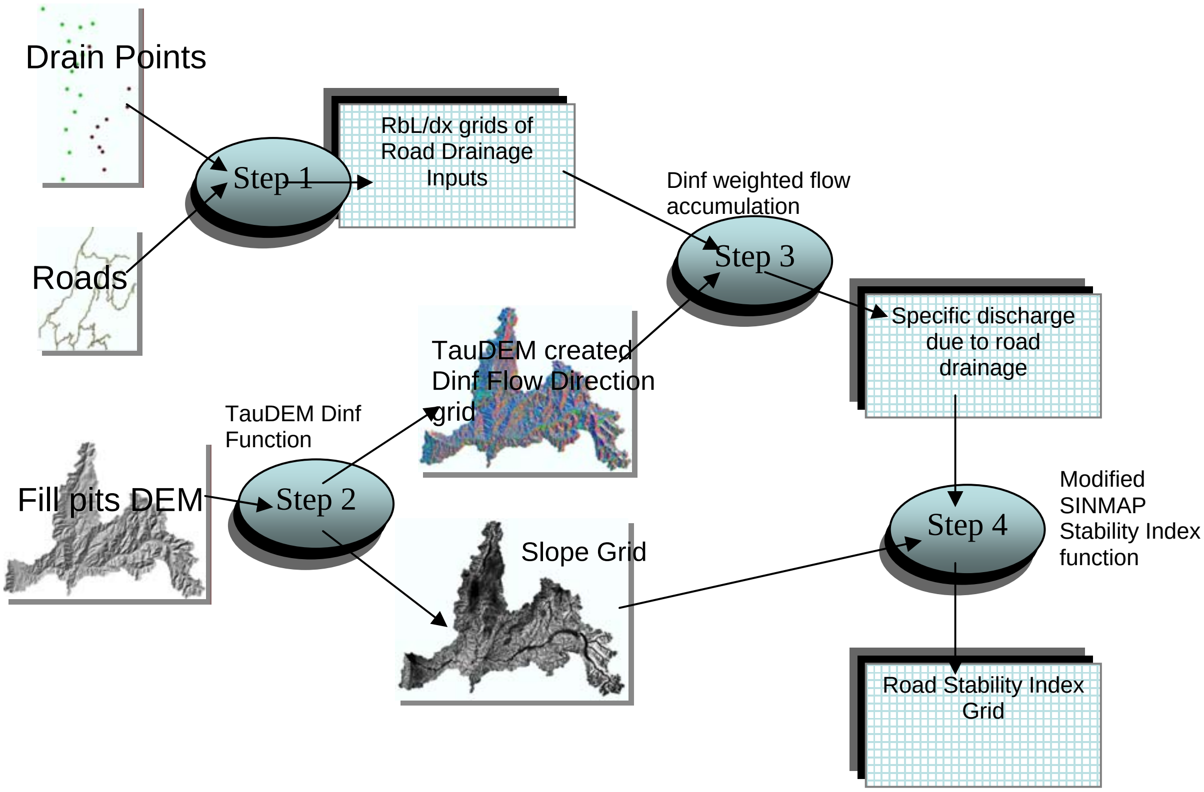

Figure 2: Evaluation of Road Stability Index at each drain point using a modified SINMAP Stability Index function.

SINMAP bases its calculations of terrain stability on a relative wetness evaluated from specific catchment area, slope, and other steady state hydrology parameters

$$w = Min(\frac{Ra}{TS}, 1)$$

where *R* is the per unit area steady state recharge that supplies soil moisture, *T* is the Transmissivity of the soil profile, *a* is the specific catchment area, and *S* is the slope. In modifying SINMAP to represent road drainage, the numerator *Ra* which represents the supply of water or the specific discharge is replaced by *RbL/dx*. This is the specific discharge, i.e. flow per unit width, due to road drainage. *R* is per unit area steady state runoff originating from roads, and *b* is the road width. The product *Rb* represents the per unit length runoff from the road. This is multiplied by the road length *L* and divided by grid cell size *dx* to arrive at a specific discharge. The relative wetness in the modified approach is therefore

$$w = Min(\frac{RbL/dx}{TS}, 1)$$

This is then used in the SINMAP equation for quantifying terrain stability. Grids of $R_{min}bL/dx$ and $R_{max}bL/dx$ values at each drain points are created and used as weight grids for calculating contributing area. The resulting minimum and maximum contributing area grid are used in a modified SINMAP stability index function to determine the Road Stability Index grid.

2.1.3. Stream habitat fragmentation due to road stream crossings

Stream crossings in the road network may be a barrier to many species of fish. Sediment produced from the road surface and other organic debris can end up blocking fish passage at stream crossings. Identifying stream crossings which are or can be blocked will help forest managers to plan for culvert maintenance. Barriers to fish passage are based on factors like

- Stream crossing substrate
- Blocked or crushed culvert
- Crossing channel gradient
- Outlet drop
- Pipe to channel width ratio

An algorithm flowcharted in Figure 3 was developed based on examples in Clarkin et al. (2003) to determine whether a stream crossing is completely blocked, partially blocked or open based on information in the forest road inventory. Once fish passage barriers are identified network operations on the stream network will be used to map and evaluate attributes of contiguous stream habitat clusters. The size and connectivity of these clusters is important in assessing the fragmentation of habitat due to road stream crossing fish passage barriers.

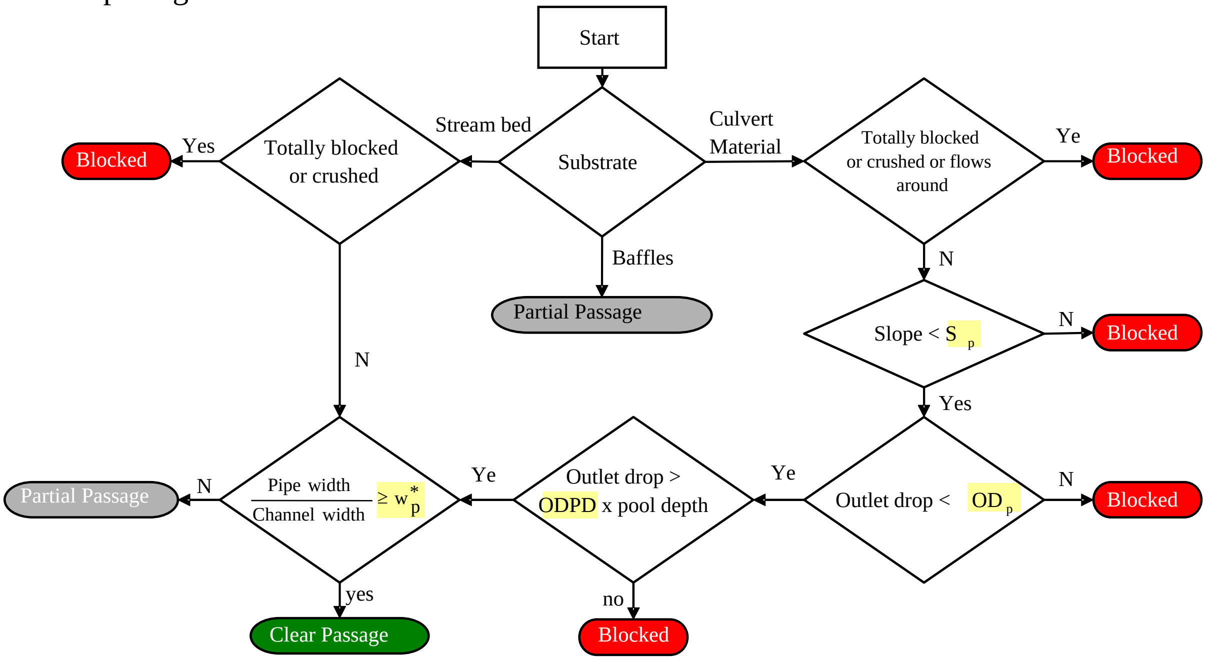

Figure 3: Fish passage barrier determination. Parameters for decisions may be user modified.

2.2. RSAM Database Model Schema

Figure 4 gives the relational database schema developed for RSAM. This has been designed to accommodate the eight drain point types into one drain points table with subsidiary tables that give attributes associated with each specific drain point type. There are attribute definition tables (not shown) that hold pre-defined allowable attribute values and serve to enforce referential integrity and validate records as they are imported into the database.

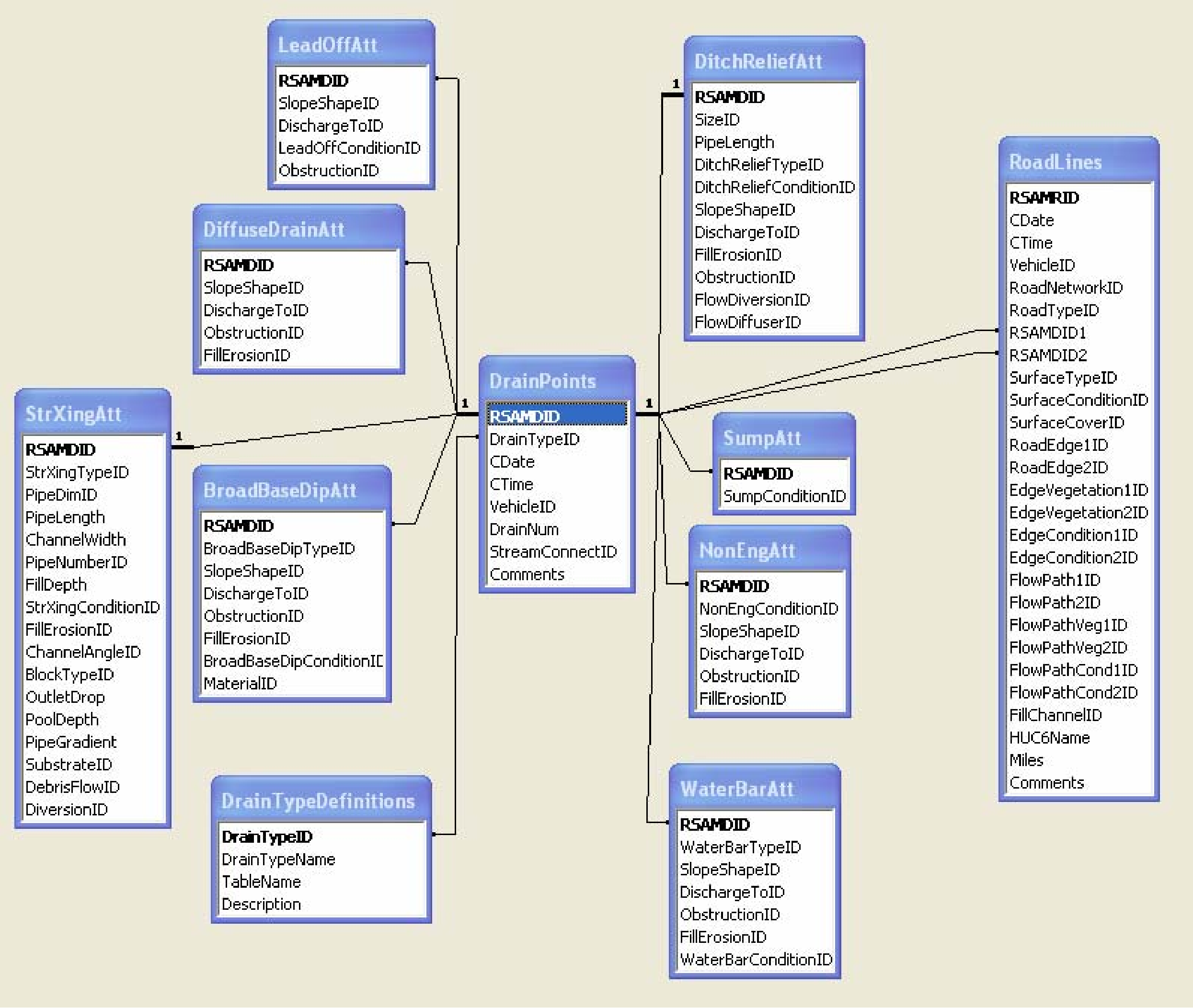

Figure 4: RSAM data model schema.

RSAMDID is the primary key in the DrainPoints table and acts as foreign key in all other special attributes table. The DrainTypeDefinitions table contains Drain point type names and corresponding unique identifiers. DrainTypeID is the primary key in the DrainTypeDefintions table and is a foreign key in DrainPoints table.

A pre-processing module has been developed to import information from USDA Forest Service road inventory into this database. This is illustrated in figure 5. The pre-processing tool is used to prepare the RSAM dataset that is then used as input to the RSAM GIS model (Figure 6).

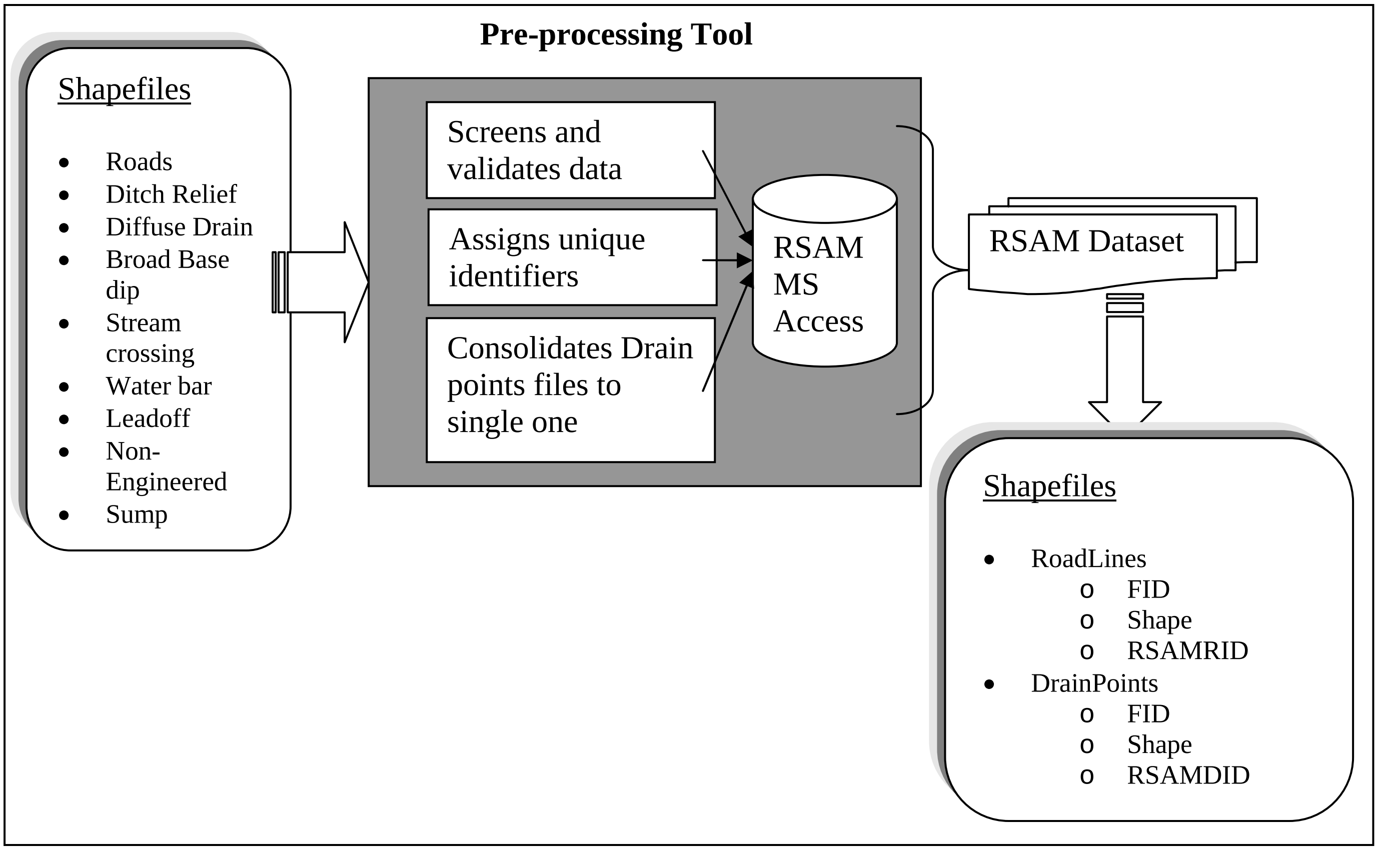

Figure 5: RSAM pre-processing tool

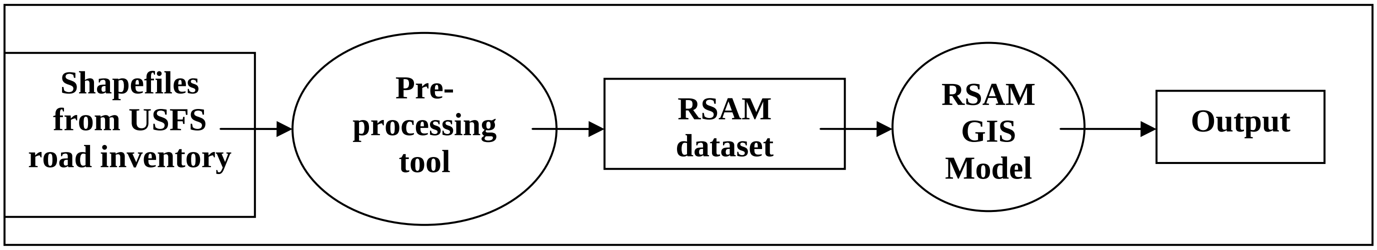

Figure 6: Work flow of RSAM model

3. Model Implementation in ArcGIS

The procedures presented have been programmed partially in C++ and partially in Visual Basic 6.0 as library functions compiled into a component object model dynamic link library. The model 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. An ArcMap toolbar extension has been developed using Visual Basic to provide graphical user interface access to the functionality presented from within ArcMap.

Input to the Road Sediment Analysis Model is in the form of ESRI grids, the RSAM database in MS Access format, and roads and drain point shapefiles. The shapefiles are accessed using 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).

4. Illustrative Results

Some illustrative results from the RSAM model applied to the Upper Deadwood study area in Idaho using example data from the U.S. Forest Service are shown in figures 7 and 8.

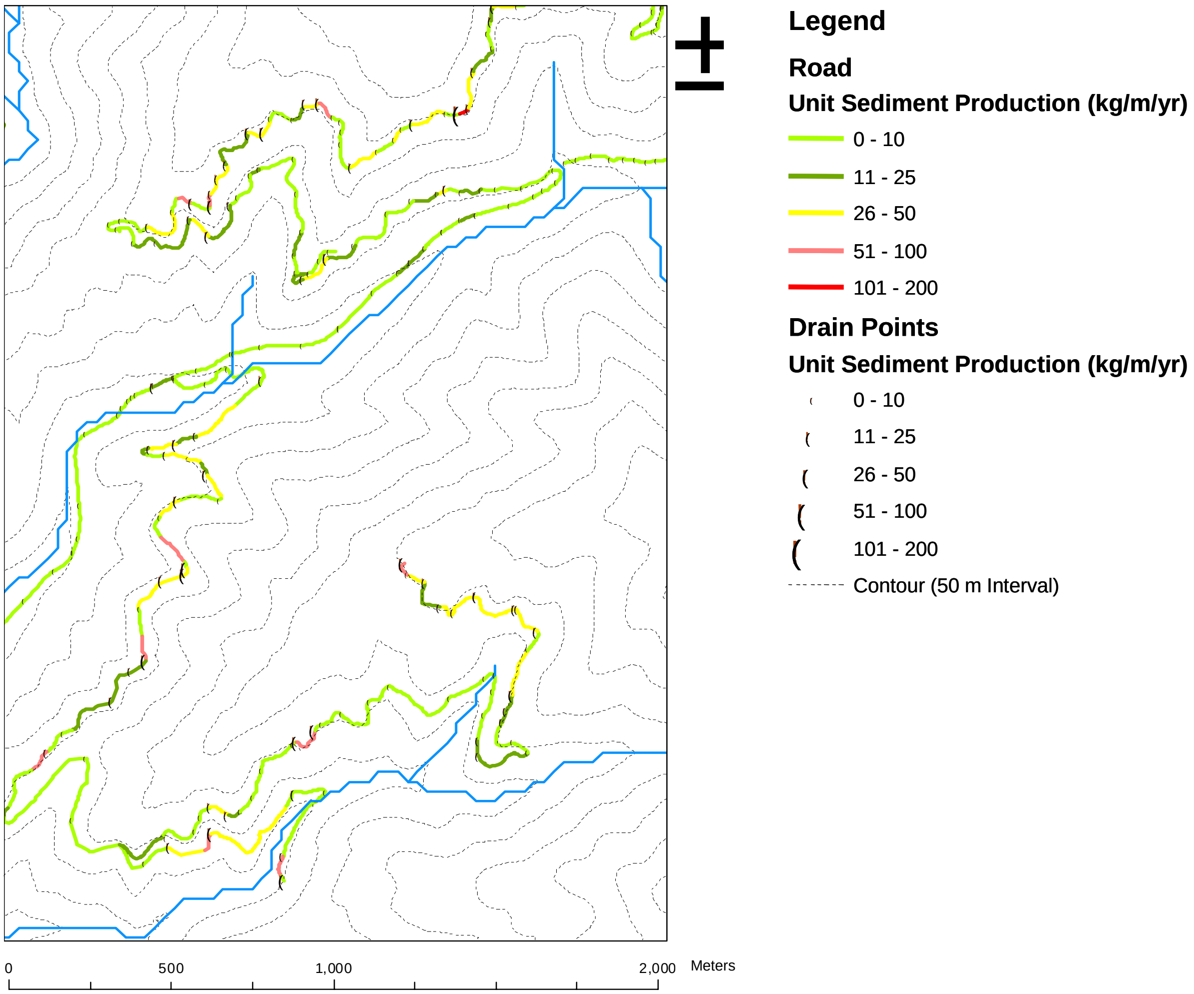

Figure 7: Road segment unit sediment production (kg/m/yr) and drain point sediment load over the Upper Deadwood area. Unit Sediment production is the sediment load from both sides of the road segment divided by road length.

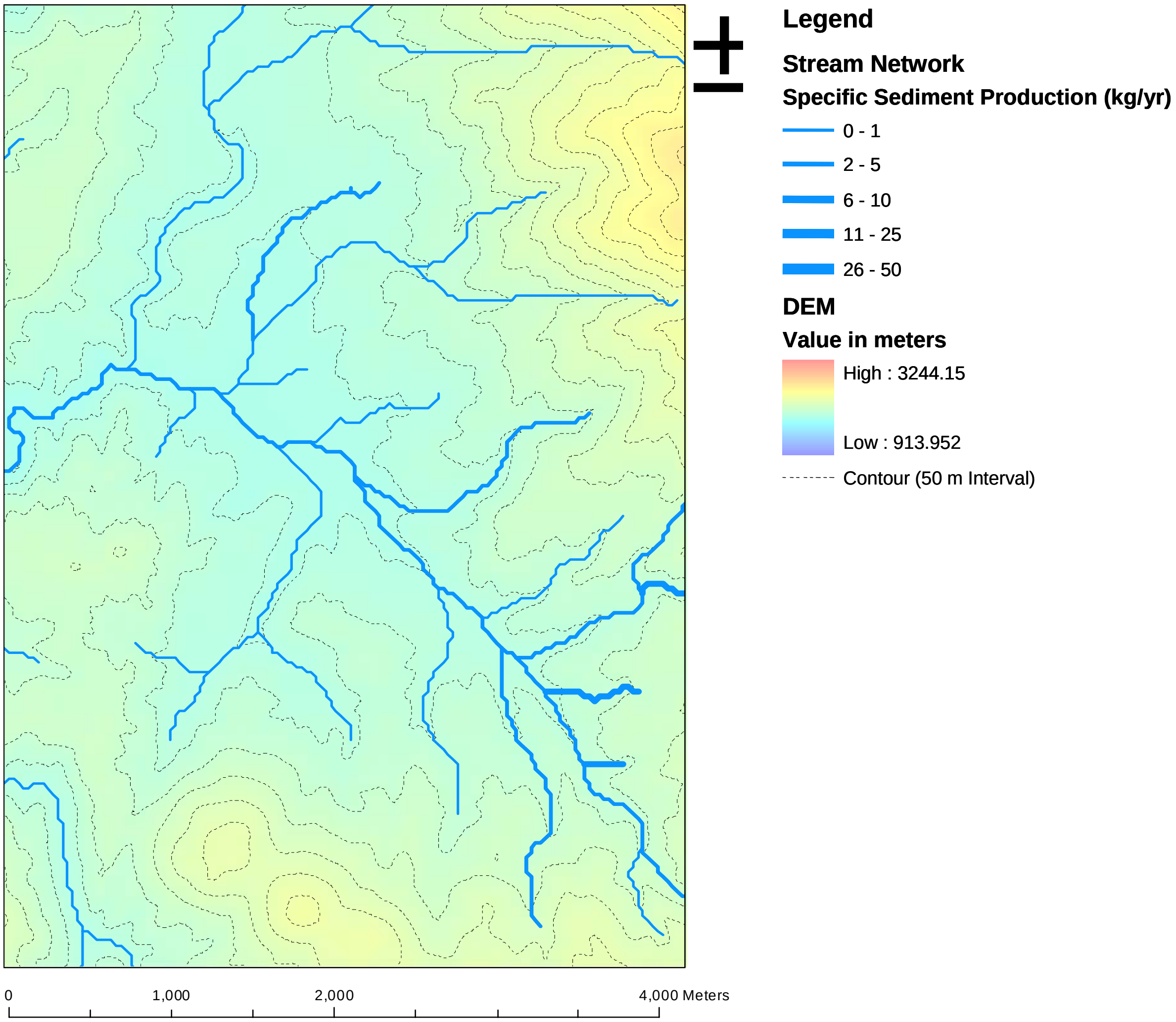

Figure 8: Total accumulated sediment load in kg/year to each stream segment.

Figure 9 illustrates the Road Lines and Drain points overlaid on Stability Index (SI) grid created from SINMAP model. The Stability Index at each drain point is calculated by intersecting the drain points with the SI grid.

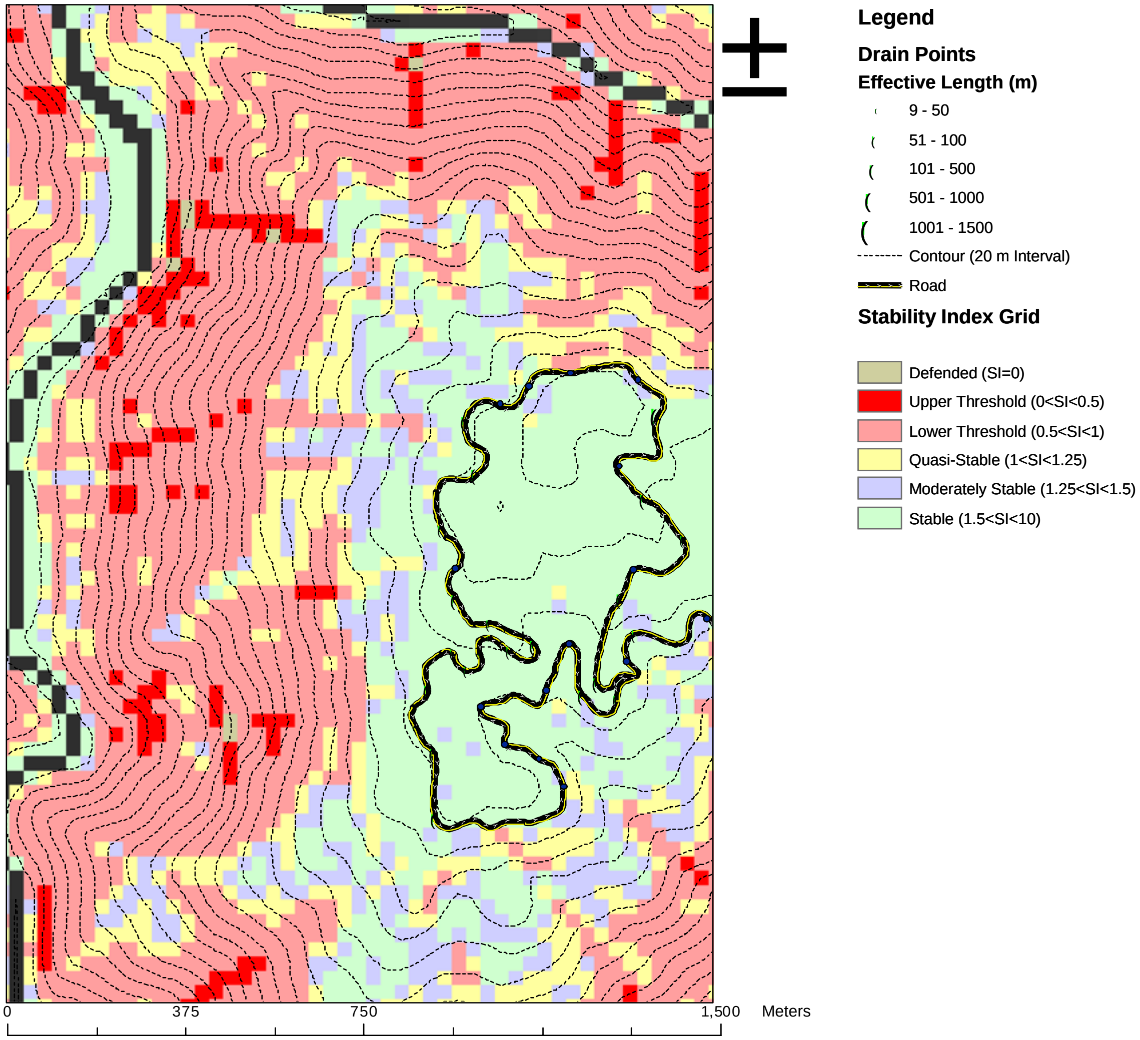

Figure 9: Map of Stability Index Grid created from SINMAP function

Using criteria represented in the flow chart shown in Figure 3 stream crossings that are fish passage barriers are flagged as completely blocked or partial passage or clear passage. Figure 10 shows the map of fish passage status at each stream crossing.

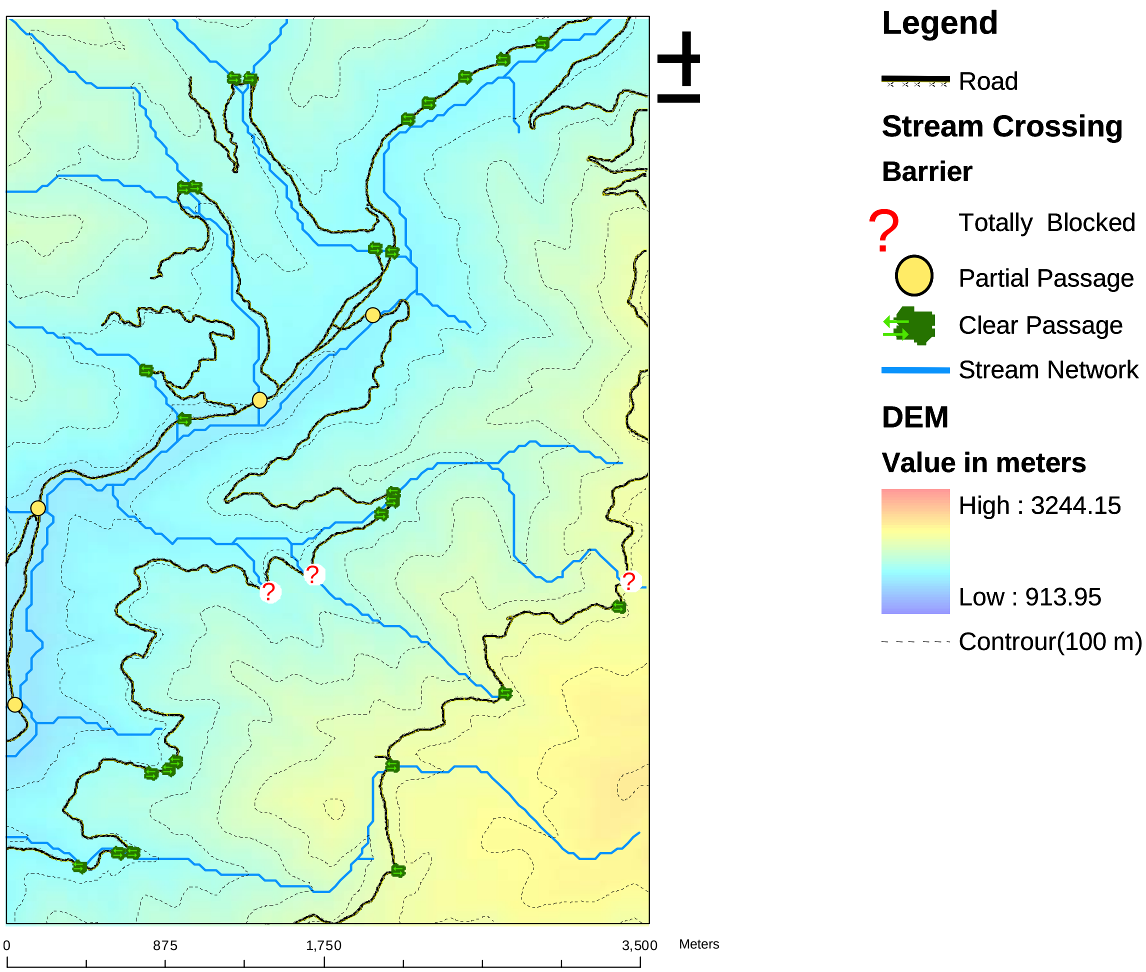

Figure 10: Fish passage determination

5 Conclusion

The paper has described a set of tools to assist with managing forest roads and planning for the maintenance of road segments based on data from the USFS road inventory. Sediment production from each road segment is calculated. Sediment accumulation at each drain point is then calculated and superimposed on the DEM derived flow direction field to quantify stream sediment inputs from forest roads. A modification of the SINMAP model provides an estimate of landslide potential due to road drainage. Finally road crossings that are barriers to fish passage are identified. GIS network analysis methods are used to analyze the segmentation of habitat due to road crossing fish passage barriers. To ensure referential integrity between attributes, and validate the records a relational database model was developed. A pre-processing tool is used to validate the records before storing inside the new database model.

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