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

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Abstract

A set of GIS tools to analyze the impacts of forest roads on streams considering sediment production, mass wasting risk, and fish passage barriers, has been developed. Sediment production for each road segment is calculated from slope, length, road surface condition and road-side drain vegetation gathered by a GPS inventory and by overlaying the road path on a Digital Elevation Model (DEM). Sediment production is accumulated to drain points by adding the sediment production from contributing road segments. These drain point sediment loadings are then used in a DEM weighted flow accumulation function to calculate sediment load inputs to streams based on inventoried delivery. 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 extent of habitat.

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) . 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 loss of passage through culverts (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 the variety of aquatic impacts is needed for such work, not just sediment yield estimates (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 an inventory process to respond to this specific need. The method uses GPS and databases to input field derived information that can be used in a GIS program to produce information dependent on the spatial coincidence of landscape and road characteristics to determine risks to aquatic ecosystems. The purpose of this paper is to describe the 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.

Road Sediment Analysis Model

The Road Sediment Analysis Model developed has the following three sets of functionalities:

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

Sediment Production and Stream Sediment inputs

The conceptual framework of the GIS based approach for evaluating sediment production and stream sediment input is given in Figure 1

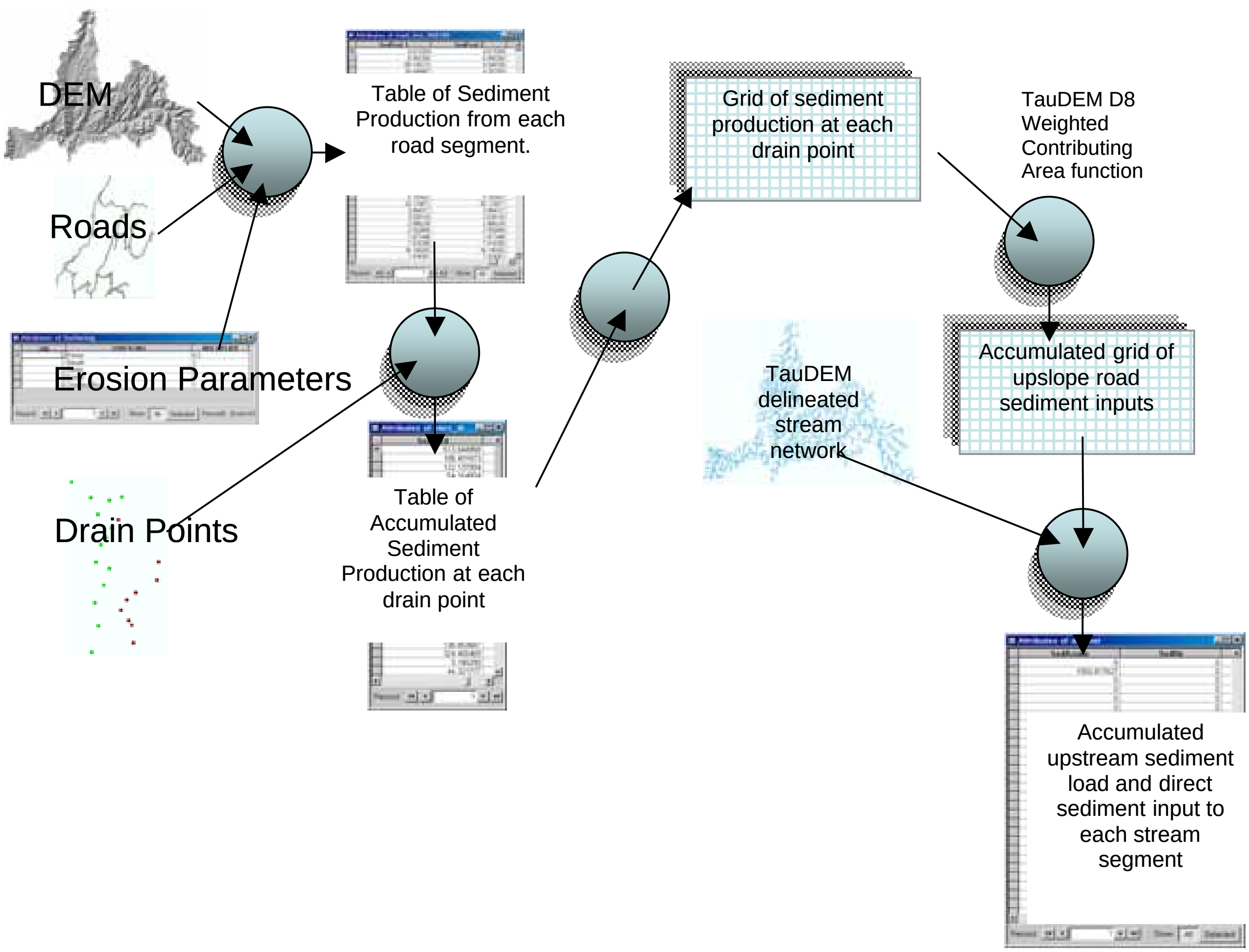

Figure 1: Illustration of GIS based approach to evaluate sediment production from forest roads and sediment input to stream system.

Evaluating sediment production from each forest road segment is the first step in the model analysis. Road segment sediment production is calculated from a base road sediment production rate adjusted by multipliers to account for the condition of the road surface and ditch vegetation condition multiplied by the road segment length and slope (Luce and Black 1999). Although they suggest LS^2 as the best model, 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 used for this calculation, following Luce and Black (1999) is

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

where ‘L’ is the length, S is the slope, ‘a’ is the 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 through side ditches. Accumulated sediment load at each drain point is calculated by adding up sediment production values from all road segments draining to the drain point. The road attribute table 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 points’ attribute table.

Drain points divert water from the ditches and road surface to forest basin. This may result in transferring the sediment load from the forest roads to the stream system. To evaluate the sediment input to the streams, a TauDEM (Tarboton and Ames 2001) delineated stream network is used as input. A grid of accumulated sediment load evaluated using D8 contributing area is created with accumulated sediment load at each drain point used as weight grid. The accumulated sediment input to the stream system is calculated by overlaying stream network over the resulting D8 contributing area grid and finding the value of the grid cells lying under the downstream end of the stream segment. 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 of the stream network attribute table.

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 provides a quantification of the risk for erosion. Point slope estimates from a digital elevation model are uncertain due to 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). The 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.

The simple 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 conceptual approach is illustrated in figure 2.

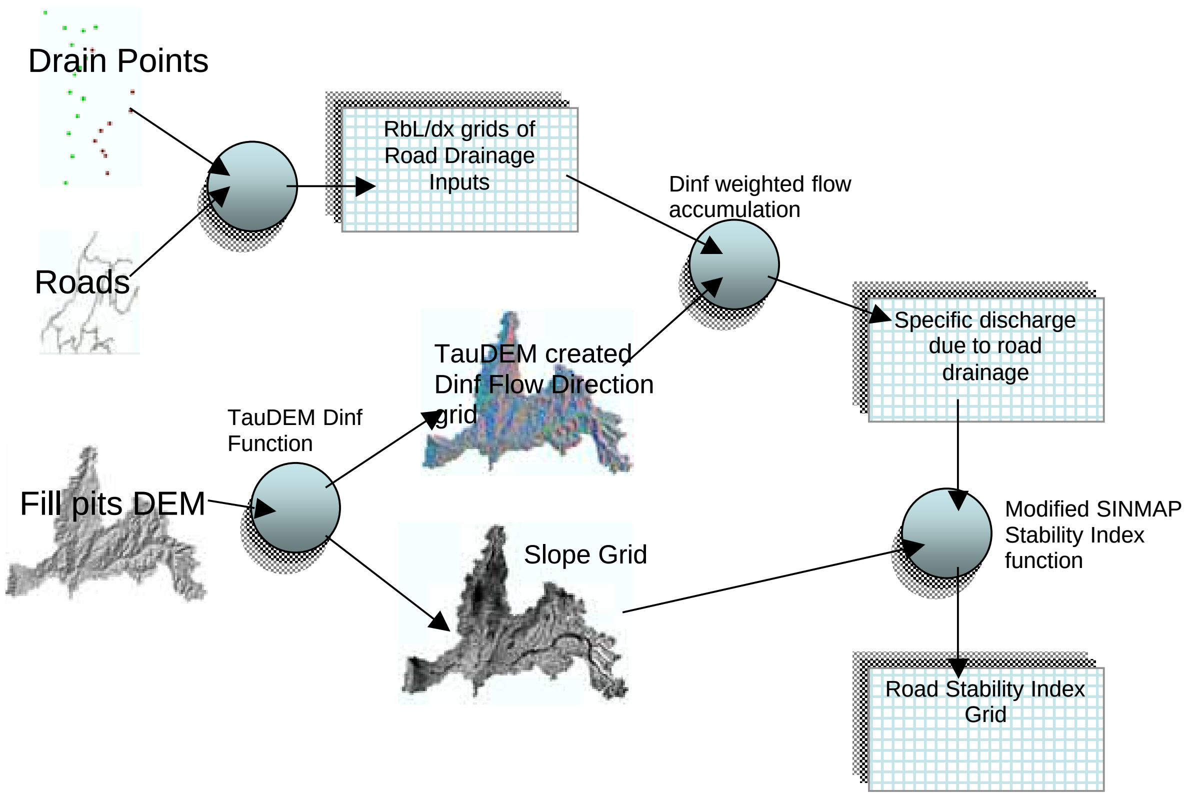

Figure 2: Illustration of GIS approach to evaluate Road Stability Index at each drain point using a modified SINMAP Stability Index function.

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.

Identify fish passage barriers

Stream crossing 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 the stream crossing resulting in possible barriers to fish passage. Identifying the stream crossing which is 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 the crossing is completely blocked, partially blocked or open based on information in the forest road inventory. This has not yet been implemented. 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.

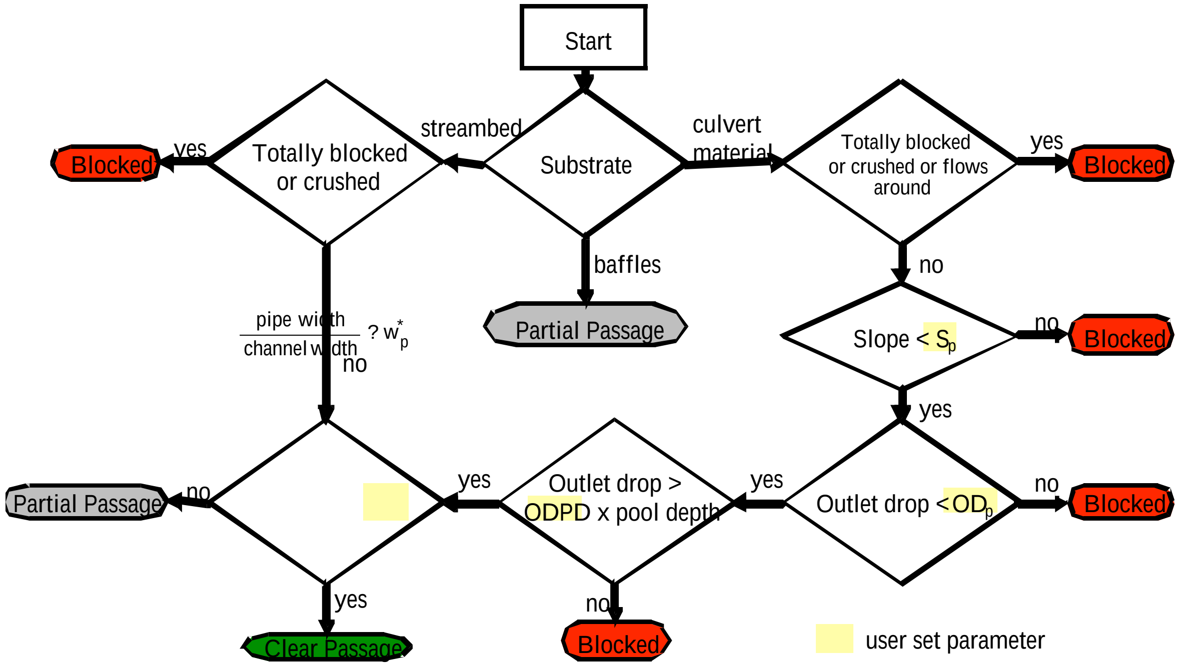

Figure 3: Fish passage barrier determination

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.

Presently input to the Road Sediment Analysis Model is in the form of ESRI grids, pre-defined parameter files (Common Parameters.dbf, Vegetation.dbf, Surfacing.dbf), 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). We hope to convert this over to the use of geodatabase data formats to improve data integrity.

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 4 to 5.

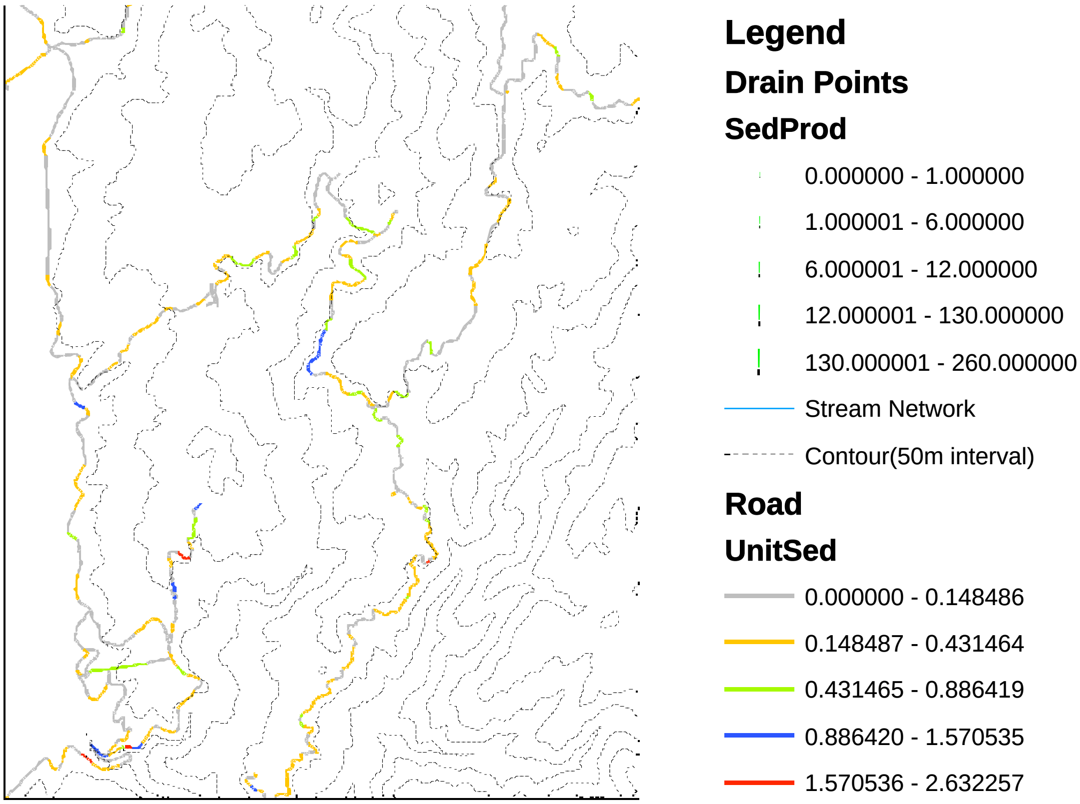

Figure 4: Road segment unit sediment production (kg/m/yr) and drain point sediment load over the Upper Deadwood area. Unit Sediment production is the sediment load from both sides of the road segment divided by road length.

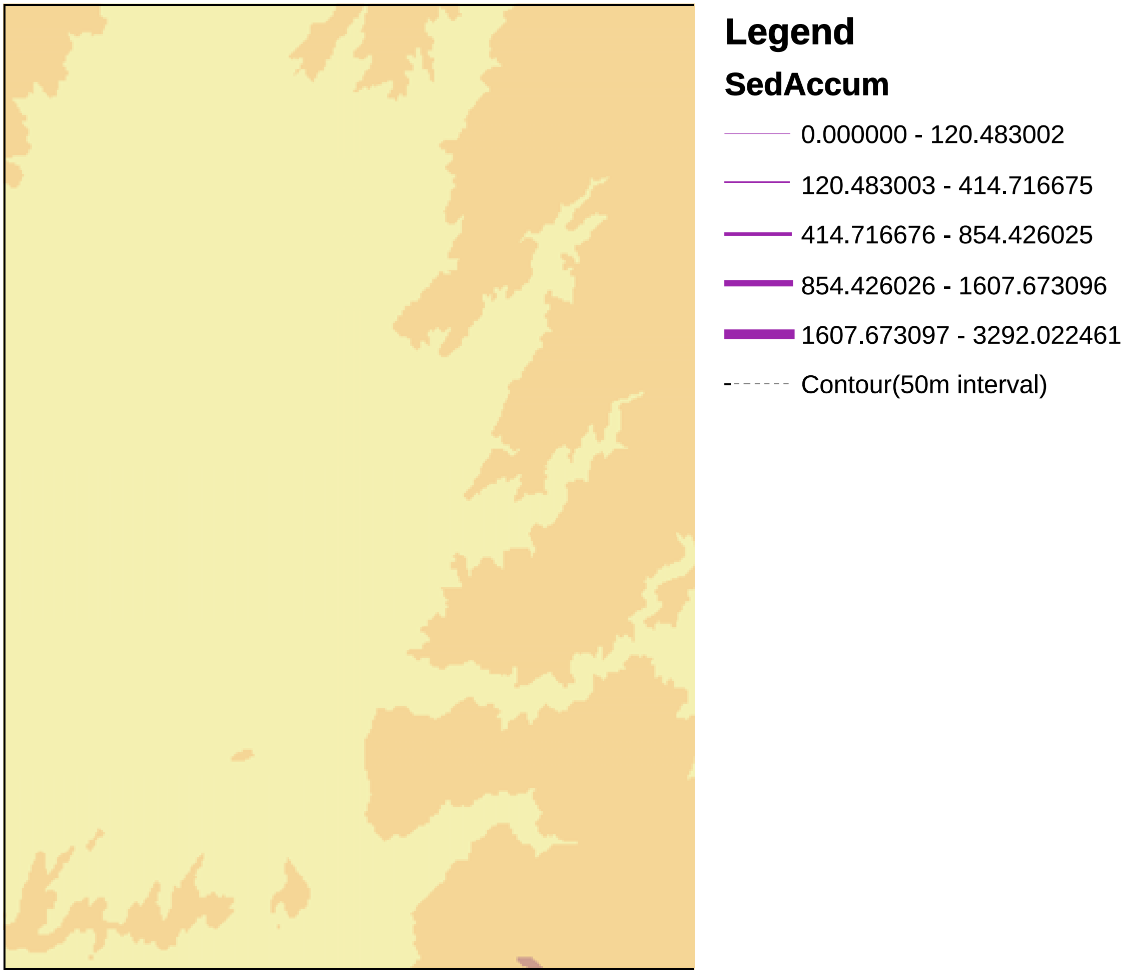

Figure 5: Total accumulated sediment load in kg/year to each stream segment.

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 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. Work is in progress to identify road crossing that are barriers to fish passage and to use GIS network analysis methods to analyze the segmentation of habitat due to road crossing fish passage barriers.

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