## Abstract

Forest managers need to estimate the environmental impacts of alternate road and harvest options. Existing landslide models however do not provide estimates of sediment volumes delivered to streams, or even numbers of landslides. A regression approach is proposed which estimates landslide sediment volume delivered to streams using exiting GIS functions and existing GIS coverages. The complicated modeling process is made tractable by dividing the problem into landslide initiation, delivery to streams, and volume of sediment delivered. GIS macros will be produced which will allow field staff to create hazard maps, and estimate delivered landslide sediment volumes resulting from individual operations or entire landscape plans.

## Introduction

Forest management operations can have a number of environmental impacts including increased runoff, coarse and fine sediment delivery, stream temperature, etc (WFPB 1997). Forest managers should consider these impacts when comparing alternate management plans, such as shifting from a near-stream road alignment to a ridge-based road alignment. For each option, the forest manager can use existing software (Wold & Dubé 1998) to estimate the volume of fine sediment eroded from the road network and delivered to the stream network.

There is no comparable model that allows forest managers to estimate landslide sediment volume delivered to the stream network. Landslide models can predict the steady state rainfall needed to initiate landsliding (Montgomery & Dietrich 1994), or the probability that a hillslope will slide (Hammond et al. 1992), or the factor of safety under alternate management options (Wu & Sidle 1995), or a map of landslide hazard (Shaw & Johnson 1995). None of these models however estimates landslide numbers or the resulting volume of sediment delivered to the stream network.

## Approach

Landslides may run for hundreds of meters and deliver thousands of cubic meters of sediment to the stream network (Figure 1), but they begin at a single small area. (Riestenberg & Sovonick-Dunford 1983). Managing that initiation point correctly, should reduce the probability that that point will initiate a slide and thus prevent the delivery of the resulting sediment. For each point on the landscape, we might ask:

1. Will a landslide initiate here?
2. Will it deliver to the stream?
3. How much sediment will it deliver? (if it does deliver)

The answer to each question will depend on a number of factors. Initiation at any give point will be a function of local properties such as slope, curvature, harvesting, and road proximity (Sidle et al. 1985). Delivery will be a function of distance and slope to the stream. The volume of sediment delivered by a slide will be a function of the distance to the stream, and the depth of the soil. Each of these properties can be found on, or derived from existing GIS coverages and forest management plans.

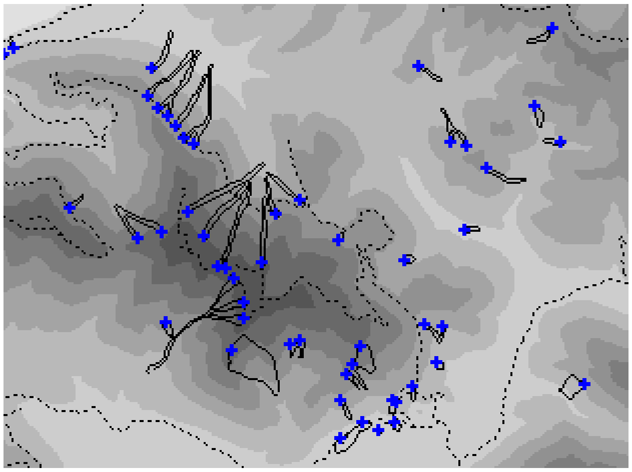

Figure 1. Landslides (outlined above) may grow to be spatially extensive, but they begin in a small initiation area (plusses), which if managed correctly will reduce the probability of initiating the entire landslide.

In order to turn these maps into predictions of delivered sediment, we need a model. A general framework of a landslide model (Figure 2) is to input the topography and management, and predict the resulting landsliding. The inputs and outputs are related through model parameters that can be estimated by turning the model around and using past landslides (and their related inputs) to infer the parameter values that best explain the observed landslides. Once we have parameter values, we can use them to predict landslide resulting from alternate management options (Figure 3).

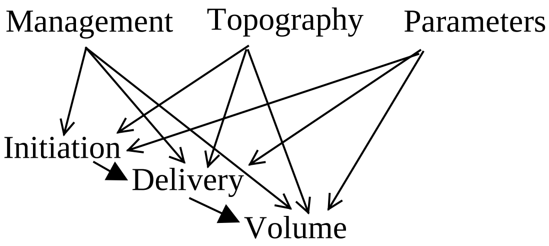

Figure 2. A model is needed into which forest managers can input management plans and other relevant information and output expected landslide sediment volume delivered to the stream.

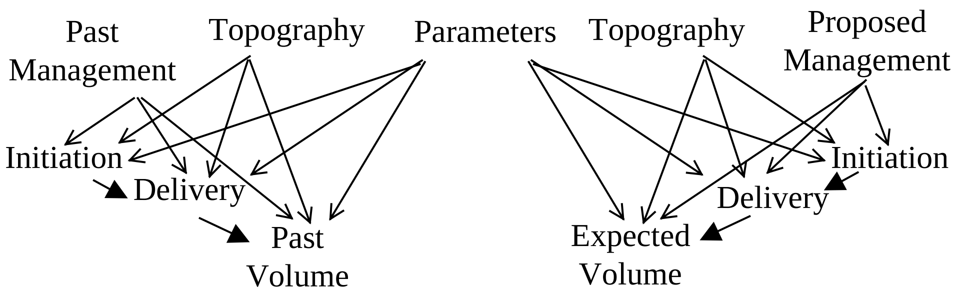

Figure 3. If a given landslide model describes landsliding in both the calibration and planning area, then we can use the topography, past management and landsliding in the calibration area to infer the parameter values that we use to predict expected landsliding under alternate management plans.

There are a wide variety of available model frameworks that we could use, but a regression framework has been chosen because ArcInfo has built in functions for calibrating regression parameters. Regression models are commonly written as

$$output = a_0 + a_1 input_1 + a_2 input_2 + a_3 input_3 + ... + \varepsilon \qquad (1)$$

In ArcInfo, the input variables in (1) are grids of values such as slope or distance to the stream or whether the cell has been logged. The output in (1) is a grid of some predicted value of interest, such as landslide probability of volume of sediment delivered. The parameters (***$a_0$*, *$a_1$*, *$a_2$***, …) in equation (1) are values that relate the inputs to the outputs. The error term $\varepsilon$ in equation (1) is a random function that allows the output to deviate from the linear relationship.

The output in (1) ranges from $-\infty$ to $+\infty$, which wouldn't work well for modeling sediment volumes that must be positive, or for initiation and delivery probabilities that must be between 0 and 1. Fortunately, several simple transformations allow regression using the same built in ArcInfo function to be used to calibrate parameters of functions that look very different. For example, the volume of sediment that a landslide delivers to the stream will be proportional to the product of its length, width, and depth.

$$volume = C * (Length * depth * width) \qquad (2)$$

The length of a slide delivering to a stream will be the downslope distance to the stream (***dist***), which can be calculated using exiting ArcInfo functions. The landslide depth will probably be the depth of the soil (***soil***), which can be found in existing soils layers. The width would be difficult to estimate, but will probably be proportional to the soil depth.

$$volume = c * (dist * soil^2) \qquad (3)$$

Taking the log of both sides of (3) gives

$$\log(volume) = \log c + \log(dist) + 2 * \log(soil) \qquad (4)$$

which looks like the regression form in (1), so we might put (4) in regression format

$$\log(y) = a_0 + a_1 * \log(x_1) + a_2 * \log(x_2) + \varepsilon \tag{5}$$

We can solve for the parameters using normal regression, then exponentiate both sides to predict expected landslide volume, as shown in Figure 4.

$$volume = e^{a_0} * (dist^{a_1} * soil^{a_2}) \tag{6}$$

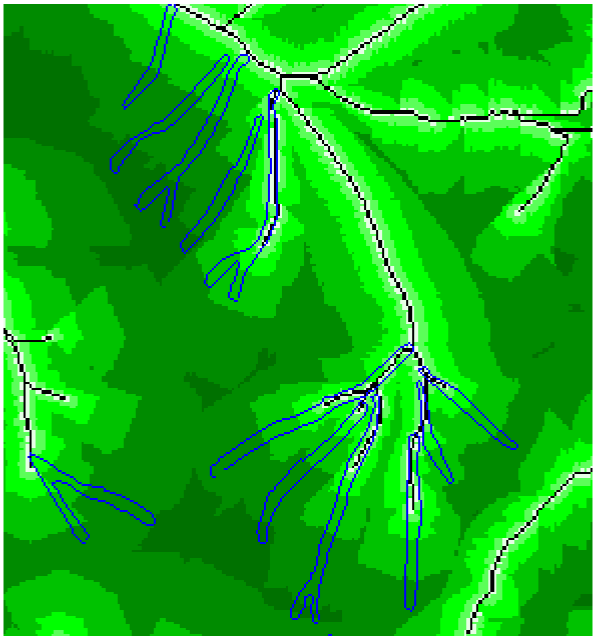

Figure 4. Landslides that originate further from the stream tend to deliver more sediment (darker areas) to the stream per equation (6).

The probability that landslides will initiate from a given cell, and that this landslide will actually deliver sediment to the stream network can be evaluated using another transformation which maps the -∞ to +∞ range of normal regression to the 0 to 1 range of probability. We can then relate the probability of delivery to the stream to proximity (***dist***) and slope (***gradient***) of the initiation point to the stream, as shown in Figure 5.

$$\Pr(delivery) = \frac{1}{1 + \exp\left(-\left(a_{base} + a_{dist}\,dist + a_{grad}\,gradient + \varepsilon\right)\right)} \tag{7}$$

We can also relate the probability of landslide initiation to the topography and management at the initiation point (Figure 6).

$$\Pr(initiation) = \frac{1}{1 + \exp\left(-\left(a_{base} + a_{slope}\,slope + a_{curve}\,curve + a_{road}\,road + a_{harv}\,harv + \varepsilon\right)\right)} \tag{8}$$

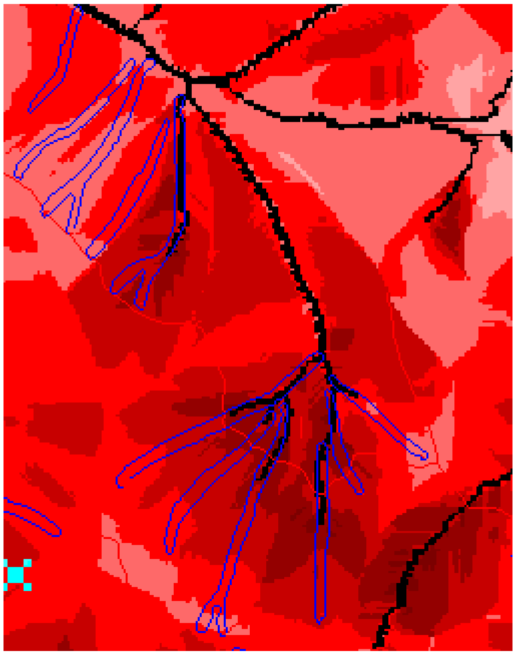

Figure 5. The probability that a landslide will reach the stream increases (shaded darker, above) with proximity and gradient of the initiation point to the stream as described in equation (7).

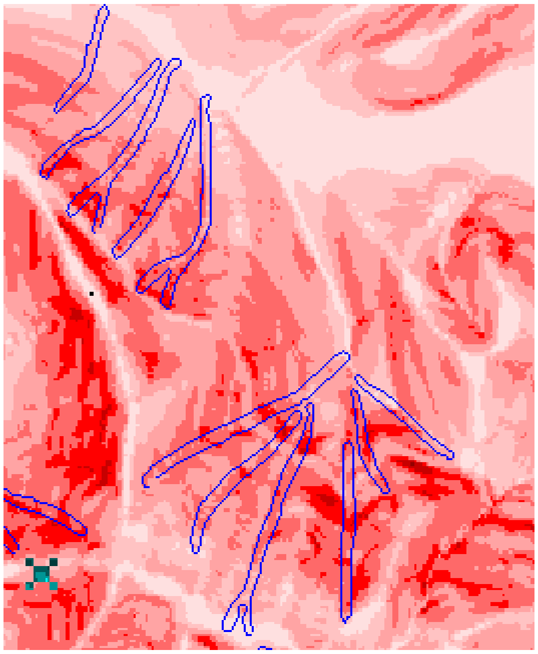

Figure 6. The probability of a landslide initiating in any cell can be inferred from observed landslides using (8). The pattern of slope and curvature can be seen in the map of landslide probability.

Once we have determined the parameters of landslide initiation, delivery, and volume, then the expected volume of sediment delivery is just the expected volume of that slide, times the probability that it is delivered, times the probability that it initiates.

$$Delivered\ volume = \Pr(initiate) * \Pr(deliver) * volume \qquad (9)$$

The resulting map of expected sediment volume delivered from each cell (Figure 7) can then be used as a hazard map. Light colored areas of low expected delivery might be a focus for road options. Dark colored areas of high expected delivery might be considered for no-touch wildlife areas. This analysis can go further however, to quantify total expected sediment volume delivered from alternate landscape management plans. The values in (8) and thus (9) vary with management activities such as harvest and road building, so forest managers can then use this approach to compare the expected sediment delivery resulting from alternate management options. Alternate management options can be compared by repeating (8) and (9) for the mapped management activities of each option. For example, we can compare the consequences of having built the road network (Figure 8) to the expected landsliding if no roads had been built (Figure 7), the difference being the additional expected volume due to the road construction. The total expected volume of delivered landslide sediment for an entire landscape can be estimated by summing the expected values from each cell.

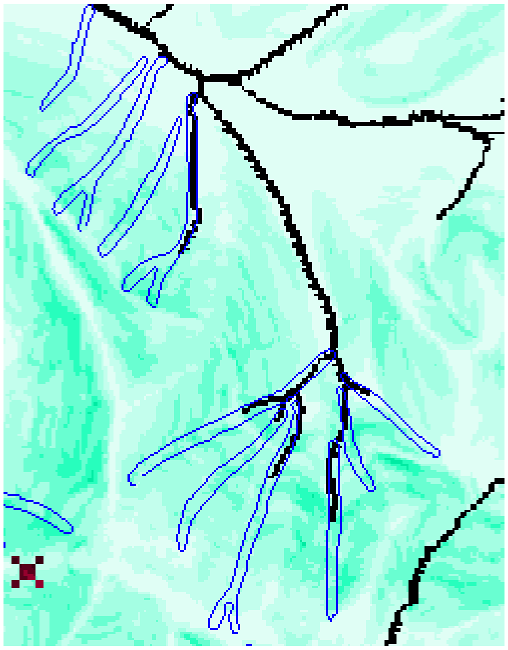

Figure 7. The expected volume of landslide sediment that will be delivered from each cell in the landscape will be the probability of a landslide initiating in that cell, times the probability that it will deliver sediment to the stream, times the expected size of a landslide that does. Since initiation probability is the most variable of these, the map of expected delivered volume will look much like Figure 6.

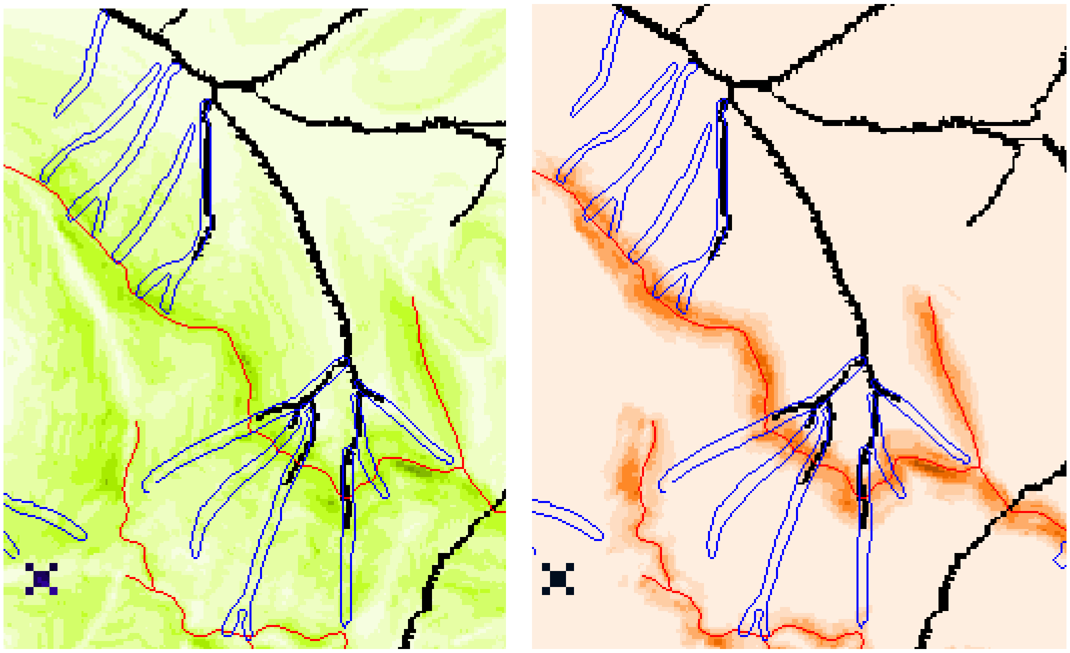

Figure 8. Adding a road will increase expected volume of landslide sediment delivered (left) as compared with the no-road option in Figure 7. The difference in source areas between the road and no-road option (right) is concentrated along the mid-slope road (middle of image) with lesser deliver from the ridge road (bottom of image).

## Documentation

The application of this process will be fairly simple, especially when already coded into user-friendly ArcInfo macros. There are several interesting issues however that will need to be explained in the documentation:

**Regionalism** – Landslide frequency, for slopes of similar slope and curvature, is observed to vary across the state. This suggests that regional variation in lithology, climate, tectonics, and management must be included in predicting landslide sediment delivery to streams. Fortunately, these can all be mapped and thus incorporated into the regression models.

**Data Quality** – The quality of the landslide inventories and other GIS coverages varies widely. This variability will impact the inferred parameter values and thus the predicted landsliding.

**Observation vs. Occurrence** – This modeling approach regresses topography and management against observed landslides. If a landslide is not observed, then it is assumed to have not occurred. This approach will rely heavily on landslide inventories compiled largely from aerial photography, and thus will be vulnerable to under estimating landslide probability in fully forested conditions, and thus over estimating the impacts of timber harvest on sediment delivery. Basic steps can be taken however to incorporate sediment delivered from landslides obscured by canopy.

**Randomness** – Landsliding is an intrinsically random process, requiring just the right combination of soil, rainfall, and stand disturbance. A landslide inventory is a collection of such random occurrences, so the resulting inferred values and predicted volumes is subject to some randomness. It is thus not possible to say that there will be a specific number of landslides in the next

**Time Scale** – Landslide sediment delivery is a rare event, so time scales of sediment delivery are frequently difficult to determine. Fortunately, the empirical nature of this approach means that the sediment volumes predicted by this approach are matched to the period of the landslide inventory. If the model is calibrated to a 50 year inventory of landslides, then the predicted volumes under alternate management options are for the next 50 years.

## Proposal

In this project, we propose to do the following:

1. Infer model parameters using existing coverages of topography, management, and resulting landsliding.

2. Develop an ArcInfo macro that will allow field staff to
   - Map landslide hazards.
   - Input proposed management plans (roads and harvests) and predict resulting expected landslide sediment delivery to streams.

3. Develop an ArcInfo macro that will allow regional and divisional geotechnical specialists to alter the model and parameters to:
   - Incorporate new and better landslide inventories, topography, etc.
   - Further refine regional differences in lithology, climate, etc.
   - Incorporate new scientific understanding of landslide process.

4. Develop user manuals and peer reviewed papers that will demonstrate the validity of this approach and make the macros more understandable and defensible.

## Schedule

**Autumn 2000** – Develop basic ArcInfo macros and parameter values

**Winter 2001** – Test usability and comprehensibility in grid-based watershed analysis class

**Spring 2001** – Submit reports to peer reviewed journals

**Summer 2001** – Write user manuals and develop front-end to make macros more intuitive and flexible to data formats.

## References

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