Incorporating Landslide Probability into Operations Planning

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ABSTRACT - Current landslide hazard analysis does a poor job of informing the planning process for forest operations in that landslide models provide maps of landslide hazard instead of quantitative measure of landslide impact. Other aspects of forest management planning (such as road surface erosion) provide quantifiable estimates of impacts such as tons of sediment delivered to the stream. This paper outlines an approach by which landslide probability is used to provide quantitative evaluation of landslide impacts of alternate forest management plans. At the local scale, landslide probability can be used to estimate the probability of landslide impact of a road crossing or a stream habitat. The number of landslides that might be expected across a landscape during a harvest rotation can also be estimated. This probability approach requires estimation of landslide probability for different forest management activities on different hillslopes. The simplest way to estimate the probability of a landslide following a given management on a given slope is to observe many similar activities on similar hillslopes and calculate the fraction that subsequently slid. A more flexible approach would be to use logistic regression, which allow empirical modeling landslide probability as a function of any landslide producing feature.

Keywords: Landslide, probability, forest management, logistic regression.

LANDSLIDE MAPPING TOOLS

Forest management can have a range of impacts on stream habitat (Salo & Cundy 1987). In particular, forest management can induce landsliding by a number of mechanisms including locally oversteepening slopes, increasing saturation, and reducing root reinforcement (Sidle et al 1985). Hillslope instability is a function of several variables, many of which vary over time, and some of which are effectively impossible to observe directly. These hillslope properties include soil depth, cohesion, friction angle, weight, porosity, hydrologic conductivity, plus the weight and root reinforcement of the vegetation, plus the hillslope steepness and storm related transient saturation.

Given all the complexities of trying to directly model hillslope stability, landslide models have instead focused on measures of relative landslide probability. One of the simplest such models is SMORPH (Shaw & Johnson 1995), which classifies hillslopes as either high, moderate, or low landslide hazard, based on their local topographic slope and curvature. A more complicated models use mechanistic models of hillslope stability to produce their own hazard rating systems. SHALSTAB (Montgomery and Dietrich 1994) calculates a rate of steady state rainfall necessary to produce landsliding. More complicated models of storm related hillslope hydrology are used by dSLAM (Wu and Sidle, 1995) to identify local Factor of Safety across a landscape. The variability of hillslope parameters is explicitly modeled in the LISA model (Hammond, et al 1992). Given the inherent uncertainty of landsliding processes and inputs however, the resulting values of these models do not predict the occurrence of landslides, but rather a value that might be related to landslide probability. Maps of these hazard ratings can however be used to guide management activities away from the most unstable slopes.

It should be noted however that decision making about other complicated processes such as logging and road building focus not on un-quantifiable notions like ‘difficulty’, but rather on actual monetary costs. A basic approach to road planning might use topographic maps to evaluate cost ‘hazards’ when evaluating alternate road alignments. Steep slopes might be viewed as high earthwork cost hazards, while flat ground might be viewed as a relatively low earthwork cost hazard. Similarly, large streams might be viewed as a high hazard (bridging) for crossing costs, while small stream might be viewed as a low hazard for crossing costs. Both ‘hazards’ will act to guide designs away from problem areas. This might suggest that landslide hazard mapping is not that different from other more traditional aspects of forest management planning.

The difference between this road construction ‘hazard’ and landslide hazard comes when evaluating designs in their entirety. Since there may be several valid approaches to accomplishing any given management goal, some method is needed for comparing alternate designs. One might for example, view different areas as high or low hazard, but then try to assign monetary values to these costs. Earthwork costs might be estimated from road design tools, which quantify earthwork volumes. A more reliable source of information about road construction costs is direct observation of costs of past projects on similar topography.

Relating a given cost ‘hazard’ to a given monetary value allows discussion of construction cost per station on that type of hillslope. These values for each station along a given proposed road alignment can then be summed to produce a total cost for that design option. Repeating for the alternate alignments allows identification of the design with the lowest cost. This identification of the low cost design option is not possible using only relative costs, without assigning a monetary value. Similarly, the design option with the lowest ecological cost can not be identified if an ecological cost is not assigned to various ecological hazards.

SURFACE EROSION TOOLS

Fortunately, some ecological models provide quantitative measures of impact. In particular, soil erosion models provide outputs in terms of ton/acre/year of sediment eroded from the site or delivered to the stream network. Estimation of soil erosion is possible, not because soil erosion is as simple process, but because the inherent complexity and variability is averaged over. There are several tools for estimating sediment from forest roads. The WEPP model (Elliot and Hall 1997) explicitly models rainfall, runoff, and resulting erosion. It gets around the temporal variability of sediment production by drawing random storms from a locally observed distribution of storms. A simpler model can be found in SEDMODL (1999) which incorporates a more empirical approach into a GIS framework. Managers might even make problem specific software by coding pre-existing models such as the Universal Soil Loss Equation (USLE) into a GIS framework.

Tools that estimate sediment production or delivery as a function of physical parameters allow comparison of the sediment impacts of alternate designs, the same way that the monetary costs of alternate designs are compared. Each road segment has its own width, grade, cut and fill slope, stream proximity, soil, vegetation, etc. Each of these values can be quantified for each segment and entered into our model of choice. The resulting sediment for each road segment can be summed across the landscape to produce a total sediment rate, and the total value for each design option can be compared to identify options with lower sediment impacts to the stream. This approach does allow designers to ask questions like, “for a given monetary cost, what option produces the least sediment?’ or, “what is the least cost option that does not exceed a given sediment delivery rate?” If the model provides sufficiently rapid feedback, managers might even use these models to ‘game’ many minor variations, and move incrementally towards ecologically optimal solutions.

MANAGING WITH PROBABILITY

A similar approach with landslide impacts will require a metric of the ecological impact of landsliding. For simplicity, this discussion will focus on landslide initiation, and ignore the question of whether and how much sediment is delivered to the stream network. By substituting different equations however, this approach could be applied to the question of delivery to streams or of the quantity of sediment delivered to the streams.

Probability may not seem well suited for discussion of landsliding. It may seem preferable to do a full mechanical analysis of the stability of the hillslope to answer yes or no whether the hillslope will slide. But this would be similar to predicting which side a coin will land on using information about its intial angular and vertical momentum, the distance to the ground, and its elasticity. Mechanistic prediction of the outcome of a coin flip is however simpler than predicting whether a hillslope will slide. In discussing the outcomes of coin flips or sporting events or other complicated processes however, it is frequently most useful to use the language of probability so the probabilistic approach should also be considered for landslide models.

Probability has several useful mathematical properties that relate and combine independent events. The probability that several independent events will all occur is just the product of the probability that each will occur independently (Equation 1).

$$p(\text{A and B}\ldots) = p(A)*p(B)*\ldots \tag{1}$$

The probability that at least one of them will occur is just one minus the probability that none of them will occur, which in turn is the product of the probability that each individually will not occur (equation 2).

$$p(\text{A or B}) = 1-\{1-p(A)\}*\{1-p(B)\}*\ldots \tag{2}$$

This becomes useful in predicting landsliding because there are so many hillslopes that could slide, and so few that actually do slide. For example, the probability that a landslide will destroy a given road crossing or stream gauge is a function of the stability of all the hillslopes in its contributing area. In a steep stream basin, with steep slopes leading to a steep stream channel, any hillslope that fails might be assumed to run all the way to the stream, then turn into a debris flow and flow down the stream destroying everything in its path (until the stream flattens out). The probability that a landslide will reach (and destroy) a given site is just a question of whether any of the hillslope segments in its watershed will slide. A standard GIS tool can then be used to identify all the slopes in the contributing area and accumulate the probability $\boldsymbol{x_i}$ in each.

$$\begin{aligned} P(\text{crossing is hit}) &= 1-\Pi_{i\in \text{watershed}}(1-p(\boldsymbol{x_i})) \\ &= 1-\exp(\text{flowaccumulation}(\text{flowdirection}(\text{dem}),\ln(x_i))) \end{aligned} \tag{3}$$

This ability to calculate the probability of a downstream impact from hillslope landslide probability allows quantitative planning. For example, if a given road-stream crossing has a high probability of being destroyed by landslides then it might be best to design the crossing to survive a landslide. Alternately the upstream harvests and roads might be planned so as to reduce the probability of impacting the downstream structure. The advantage of this quantified approach is that the monetary costs of this upstream management shift and the resulting reduction in impacting the stream crossing can be compared to the cost of the redesign of the road-stream crossings.

This approach might be extended to predicting impacts to several stream locations throughout a watershed. Equation 2 could be used to estimate the probability that any of these sites are disturbed. A more common question however is not whether any stream sites will be impacted, but rather how many sites on a landscape will be impacted. On this landscape scale, it would be good to know how much landsliding will be reduced by alternate strategies for harvest leave areas and road alignment. Using GIS technologies, it is now possible to estimate the monetary costs of implementing alternate management strategies. A similar measure of the landslide impact is needed to determine whether the monetary costs of alternate ecosystem-friendly strategies can be justified.

Estimating the number of landslides that will be observed across a landscape involves combining the outcomes x_i from very many hillslopes, each having its own landslide probability p_i. Probability is again convenient in that this *expected number* of landslides in a landscape in question is the sum of the landslide probabilities across the landscape.

$$E(\Sigma_i x_i)=\Sigma_i E(x_i)=\Sigma_i p_i \tag{4}$$

This approach can then be used to guide management decisions anywhere landslide probability is known for each combination of management option and hillslope type in the landscape. In Figure 1, the addition of a spur road and the harvesting of the unit resulted in an additional 0.3 landslides expected from this area.

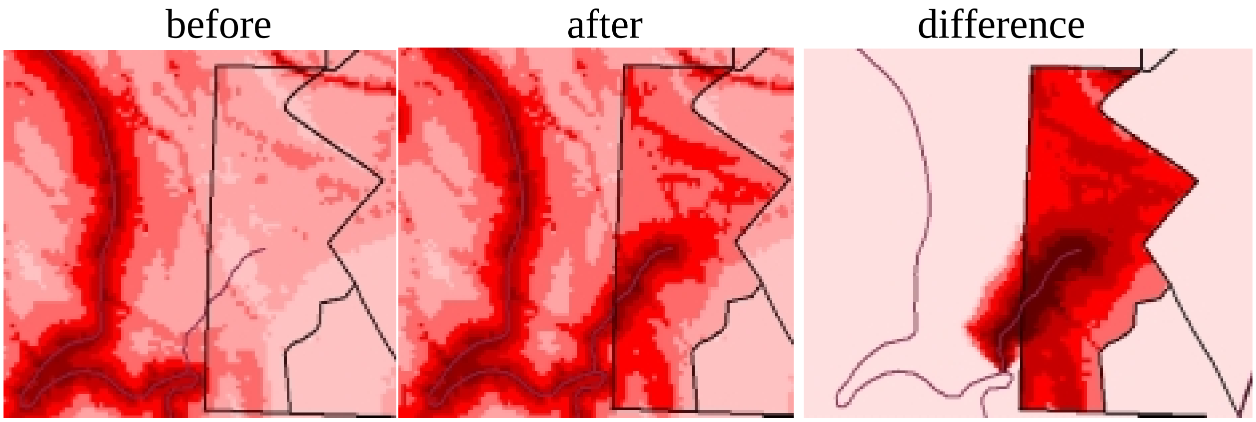

Figure 1. The preexisting (left) areas of instability (darker red) are concentrated near the existing road. Away from the road, the shades grade with reducing instability to the flats in the lower right corner. Harvesting the unit in the middle of the map increases the landslide probability (middle) of each hillslope in the unit. Adding the spur road to access that unit results in a very concentrated instability right around it. The expected number of landslides resulting from the decision to harvest this unit, The management impact is the difference (right) between the post-harvest instability (middle) and the preexisting instability (left) in each hillslope.

ESTIMATING PROBABILITY

Both the expected number approach and the probability of impact approach to planning require estimates of the probability with which each hillslope will slide. One approach to estimating landslide probability is presented in Hammond and others (1992). In this LISA a value is drawn from the distribution of possible values for each hillslope parameter (saturation depth, soil depth, soil cohesion, root reinforcement, etc.). Each value is then passed into the Infinite Hillslope model of hillslope instability to calculate whether a landslide would occur. This process is then repeated very many times and the proportion of times in which a landslide occurred is called the probability of failure. If the infinite hillslope model were completely accurate, and if our understanding of the variability of each of the hillslope parameters were similarly accurate, then the resulting probabilities could be used in the expected number approach and the probability of impact approach. Until such time, an empirical approach will probably be more satisfactory.

The simplest and most reliable way to estimate landslide probability for a given management activity on a given hillslope is to observe similar hillslopes that were managed in a similar way, count the number of resulting landslides and divide by the number of hillslopes. It is important to clearly identify what defines a 'hillslope' and how one can tell if they are 'similar'. Landslide probability observed in terms of landslides per acre must be re-scaled if it is used on hillslopes defined in terms of hectares. Similarly, a convenient GIS technique is to divide the landscape into a grid of square 'cells' and define each cell as its own hillslope. In this case, it would be necessary to explicitly state the size of the grid spacing.

Before the landslide probability for a given activity on a given slope type can be calculated, that activity must have been conducted on many such slopes, and given long enough for any instability to have displayed itself. If roads are rarely built across a given type of hillslope, then there is no empirical definition for its landslide probability. Any new technique will be similarly constrained, since it is not possible to discuss the landslide probability of a technique that has not been tested.

In order to plan alternatives, each combination of hillslope type and management activities will need its own probability. So if there are ***m*** types of hillslopes and ***n*** possible activities, ***m*n*** probability values will be needed. This becomes a problem as finer gradations of hillslope and management options are considered. Each of these probabilities will require many prior applications before their instability can be empirically described. The problem grows geometrically if region, geology, or other landslide related factors are added to management activity and hillslope type. The probability of inducing a landslide by applying a given activity on a given hillslope type on a given geology in a given region, will require observation of many of each combination, which could rapidly balloon with increasing issues and gradations.

Unfortunately, many landslide related hillslope properties take continuous rather than discrete values. Factors such as hillslope gradient, contributing area, retention level, soil cohesion, etc. can be forced into discrete categories, but they are more naturally defined in terms of continuous values. An infinite number of gradations would prevent any sort of empirical statement about the ratio of landslides to hillslopes for similar activities on similar hillslopes. Fortunately this intuitive ratio approach is not the only option available.

Another common way to relate inputs to outputs is with regression (Equation 5).

$$y=a+bx+\varepsilon \qquad (5)$$

While most real models are rarely this simple, if the value of some observed property ***y*** really does increase with some other observed property ***x*** (or many other observed properties), then observed values of ***x*** and ***y*** can be used to estimate values for ***a*** and ***b***, which in turn allows consideration of how ***y*** varies as we change ***x***.

This same approach can be applied to predicting landsliding

$$Landslide = a + b*slope + c*retention + d*road + \varepsilon \tag{6}$$

Dividing the landscape up into hillslopes, and recording the local slope, post harvest retention level, whether there was a landslide (0 or 1), and whether there was a road, would then allow estimation of the values for ***a***, ***b***, ***c***, and ***d***. These values of ***a***, ***b***, ***c***, and ***d*** could then be used to estimate landslide probability under alternate combinations of retention and road alignment. One problem with this simple equation is that since the inputs are continuous, the resulting landslide values will rarely be 0 (no landslide) or 1 (landslide). This might be fixed in part by considering the resulting landslide value as the probability of landsliding (which is continuous) rather than the occurrence of landsliding (which is 0 or 1). A further problem however is that while probability can go from 0 to 1, this equation can produce values that can be much greater than 1 or much less than 0.

The solution to these problems is the logistic regression coded into many GIS packages. While the resulting Equation 7 is more complicated, it has all the useful features of normal regression, and the computer handles all the necessary calculations.

$$p_i = 1/\left(1 + \exp\left(-\left(a_{base} + a_{slope}slope_i + a_{curve}curve_i + a_{road}road_i + a_{harv}harv_i\right)\right)\right) \tag{7}$$

This was the model used in Figure 1, and the values for the ‘a’ coefficients were fitted from a local landslide inventory. In this case, the road value was distance to the road.

CONCLUSION

Observations of past landslides can be used to quantitatively guide management decisions. Either by regressing past management activities against the resulting landsliding, or by observing the fraction of hillslopes on which similar management has produced landsliding, landslide probability can be estimated for each management activity on each type of hillslope. The resulting probability can then be used to estimate the total number of landslides that will occur on a landscape as a function of management strategy. This probability can alternately be used to estimate the probability of a landslide impacting a specific reach of stream habitat or road-stream crossing. By integrating over the relevant upslope instability, the resulting expected number or probability of impact thus predicts management consequences, rather than just the relative hazard rating provided by existing landslide models.

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