A GIS-BASED METHOD OF MODELING WATER INPUT FROM RAIN-ON-SNOW STORMS, FOR MANAGEMENT AND REGULATION OF CLEARCUT FOREST HARVEST

Matthew J. Brunengo, Stuart D. Smith, and Stephen C. Bernath[1]

INTRODUCTION

Timber harvest has been changing the environment of the Northwest for 140 years, helping to cause a transformation from old-growth forests to a patchwork of urban and agricultural areas, clearcuts, and plantations, surrounding shrinking fragments of primeval forest. Much of Washington's commercial forest land is at elevations where snow falls in winter, and the forest canopy structure affects snow accumulation and melt processes, particularly in middle elevations and during rain-on-snow storms. Thus, alterations of forest ecosystems have been causing changes in water systems at hillslope to basin scales [Harr, 1981, 1986; Brunengo, 1990]; we have been performing a large-scale, uncontrolled field experiment in forest hydrology. The management-regulatory environment of forestry has also changed, with increased attention to protection of woodland resources and off-site effects of forest practices, and an expanding regional population interested in forests as something more than fiber to be harvested. DNR staff and cooperators in the Timber/Fish/Wildlife agreement have begun to analyze and regulate clearcut harvest with regard to its potential to cause significant changes in water input during rain-on-snow events.

A mapping procedure based on a geographic information system (GIS) has been designed to aid in analysis. The key layer is a map of precipitation zones based on the amount of snow available for melting, interpreted from snow-survey and weather records. Analysis is based on snow accumulation before and melt during hypothetical rain-on-snow (R/S) events, and utilizes map layers and attribute files containing information on meteorological conditions and vegetation. The computer model estimates the amount of liquid water reaching the soil in each polygon, and calculates basin-averaged inputs. The differences between storm input under fully-forested conditions and under actual vegetative patterns reflect the changes in effective storm magnitude due to large-scale harvest. Results are being used to prioritize basins for watershed analysis, and will be used in the future to help predict possible hydrologic effects of harvest scenarios in sensitive basins.

SCREENING FOR HYDROLOGIC CHANGE: PROCEDURES

Several assumptions underlie the screening procedure, particularly that the purposes dictate the methods and products. The system was to produce a numerical ranking of the basins, setting priorities for basin analysis; and a set of maps showing the areas of greatest potential changes in runoff due to timber harvest, so that subsequent attention can be focused. We wanted to create a system based on the chief physical factors that influence the processes of precipitation, snow accumulation, and snowmelt in major storms, particularly R/S events as they relate to forest practices. As a matter of practicality, the process had to be based on available information that is consistent in detail and quality for the entire state, and in forms that could be combined into an ordinal rating. And the resulting combinations had to be mappable, with the maps preserving the information necessary for initial assessment and focusing of analysis efforts. In other words, we would be using a modeling approach to create an index for potential changes in water availability due to forest harvest.

The general strategy was to create a simple GIS-based model that would combine storm precipitation (of appropriate frequency and intensity) with a reasonable amount of snowmelt, given geographically variable conditions of temperature, snow accumulation, etc. Then, the liquid water reaching the ground surface over a given area could be estimated, and these values averaged over a basin to give an index of the water available for runoff due to the storm. The effects of vegetation on snowmelt could be considered by calculating the average basin effective precipitation under two sets of conditions: assuming all of the forest land in a basin supports hydrologically mature forest; and taking the vegetation pattern as it currently stands, with the resultant effects on snow accumulation and melt. The difference between the basin-averaged effective water inputs under these two sets of conditions should be an indicator of change in the apparent storm magnitude experienced in a basin due to forest harvest.

We created or adapted a number of data layers (using primarily Arc/Info and ERDAS software) to build this model of storm rain-on-snow input. Once digitized, the layers can be manipulated in the GIS, enabling us to experiment with various combinations of factor values, and permitting rapid revision of information for recalculation. The first layer created was that of the basic areal units for screening. The 62 water resource inventory areas

[1] Presented at the 60[th] Western Snow Conference (1992), Jackson Hole, Wyoming

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(WRIAs) of Washington were subdivided based on physiography, land use, and ownership. A total of 202 subbasins were delineated, of which ≈20 are entirely unforested and were not analyzed.

We are using this model to represent the amount of liquid water reaching the ground, not just the amount of precipitation falling toward it, so we had to modify a precipitation input to reflect the role of rain-on-snow. Because geomorphically effective peak flows can be expected to result from moderately frequent long-duration storms, we started with the NOAA map representing the best combination of these characteristics, the 10-yr events of 24 hr duration [Miller and others, 1973]. Since there is no map showing the magnitude and frequency of water inputs expected from R/S events, we have attempted to create an index map based on what we know about the process controls and their effects in the various climatic zones. If we assume that the seasonal storm tracks that bring warm, wet cyclonic storms to the Northwest have access to all parts of Washington, then the main factors controlling and/or reflecting the occurrence and magnitude of a R/S event in any particular place are: 1) climatic region, especially on opposite sides of major mountain ranges; 2) elevation controls temperature and orographic enhancement of precipitation; 3) latitude affects temperature, thus snow; 4) aspect affects insolation and temperature, thus melting of snow on the ground; and 5) vegetation, since the species composing forest communities can reflect the climate of an area, and the height and density of vegetation also regulate the amount of snow on the ground.

We designed the precipitation zones to reflect the amount of snow likely to be on the ground at the beginning of a model storm. We assumed that middle-elevation areas would experience the greatest water input due to R/S, because the amount of snow available would be approximately the amount that could be melted. Higher and lower elevation zones would bear diminished effects, but for opposite reasons (no snow, vs too cold to melt). We designated five zones, to allow a finer calibration of effects in the model (and reduce the importance of the dividing lines, and their inherent uncertainties). We had to choose a particular time of year for the model event: because storms are most common in November-February, and R/S seems to be more likely earlier in this period, a model date in early December might have been best. However, snow survey records were a major source of data, and few surveys are carried out before January. The average snow-water equivalents for early January measurements at about 100 snow courses and pillows were compiled; snow depths for the first week in January at about 85 weather stations were converted into SWE (by multiplying by 0.15). For each region, snow amounts were sorted by station elevation to derive a rough indicator of the relationship between snow accumulation and elevation.

The amount of snow that can be melted in a day under R/S conditions can be estimated from the simple equation developed by Corps of Engineers hydrologists [A.C.E., 1956], in which melt is indexed to temperature, wind speed, and precipitation. Using the 10-yr 24-hr precipitation (and holding temperature and wind constant), it was possible to estimate the regional variation in daily snowmelt expected from an event of that frequency (from ≈5.7 cm in the Columbia Basin to ≈9.5 cm in the Olympics). The middle elevation bands were delineated as the areas where the average amounts of snow on the ground approximated these 'ideal' amounts; the higher and lower zones were defined by greater and lesser proportions of them. We adopted the following ratios:

5. **highlands:** >4-5 times ideal snow amount; high elevation, with little likelihood of significant water input to the ground during storms; effects of harvest on snow accumulation are minor;
4. **snow-dominated zone:** from ≈1.25-1.5x ideal snow amount, up to ≈4x; melt occurs during R/S (especially during early-season storms), but effects mitigated by the lag of percolation through the snowpack;
3. **peak rain-on-snow zone:** ≈0.5-0.75x to ≈1.25x ideal SWE; middle elevations: shallow snowpacks are common in winter, so effects of R/S are greatest; typically more snow accumulation in clearings;
2. **rain-dominated zone:** ≈0.1-0.5x ideal SWE; rain occasionally falls on small amounts of snow;
1. **lowlands:** <0.1x ideal SWE; low-elevation, and rain-shadow areas; significant snow depths are rare.

The precipitation zones were mapped on overlays on 1:250,000-scale topographic maps. Because snow depth is affected by many factors, it was not possible to pick out specific contours for the boundaries. Ranges of elevations were chosen for each region, but allowance was made for the effects of subregional climates, aspect, etc. Attempts were made to make the mapping consistent within each region, and among adjacent regions.

Some anomalies require explanation. Much of western Washington is mapped in the lowland or highland zones; rain-on-snow does occur in those areas, but <u>on average</u> with less frequency and hydrologic significance than in the middle three zones. Most of central and eastern Washington is mapped in the rain-dominated zone, despite meager precipitation there; this means only that the amount of snow likely to be on the ground is small, and the rain makes up most of the storm-water inputs. Much of northeastern Washington is mapped in the peak R/S zone, despite the fact that such events are less common there than on the west side. This is due to the fact that there is less increase in snow depth with elevation, so a wider elevation band has appropriate snow amounts; plus, much of that region lies within that elevation band. This does not reflect the lower <u>frequency</u> of such R/S storms in that area, which must be accounted for in other parts of the modeling procedures.

Vegetation characteristics affect both accumulation and melt of snow. There is typically more snow on the ground in areas of sparse vegetation than in mature forests (at and below middle elevations), mainly due to interstorm melt of snow intercepted in forest canopies. Openings in the forest allow higher wind speed near the ground, thus more efficient flux of sensible and latent heat to the snowpack. Therefore, clearings tend to have more snow available to be melted when a storm begins, and to allow it to be melted more quickly. The ability of a stand to behave like a mature forest, with respect to snow accumulation and melt, has been termed hydrologic maturity. The effect on runoff processes of a large proportion of a basin in hydrologically immature vegetation is supposed to be causing changes in peak flow. This model attempts to assess these potential changes in rain-on-snow hydrology by estimating the effects on snowmelt processes caused by past changes in the size and structure of forest vegetation. In order to use the characteristics of vegetation to indicate the probable effects on snowmelt, we have adapted interpretations[2] of vegetation from Landsat imagery to help indicate conditions of hydrologic maturity.

Calculation of the available-water index combined storm precipitation and model snowmelt, as conditioned by climate and vegetation. We designed the program to augment the precipitation by varying amounts: in the peak R/S zone, the isohyetal values are increased the most; lesser amounts are added in the snow-dominated and rain-dominated zones. Input amounts are defined to be zero in the highlands, and equal to precipitation in the lowlands. We use the equation for snowmelt during R/S conditions, with appropriate temperatures and snow depths indexed to precipitation zone. The method also accounts for differences in snow depth and wind speed between forested and cleared areas, and thus can be used to evaluate the potential for increased runoff due to harvest.

For each of ≈180 basins, the layers representing storm precipitation, precipitation zone, and vegetation were overlaid to produce a mosaic of pixels. For each pixel a set of calculations was performed under two sets of assumptions. First, we assumed that all forest lands support stands tall and dense enough to be hydrologically mature. The calculation of 24-hr snowmelt (SM_{24h}) for each pixel, using the Corps of Engineers equation [A.C.E., 1956], depends on the precipitation, temperature (controlled by elevation zone), and wind speed (controlled by vegetation class). Then, the snowmelt and precipitation were combined in an equation that accounts for the amount of snow available and the lag in percolation through deep snow, to calculate water available for runoff, WA_f:

$$WA_f = m \left[P_{24h} + \frac{SM_{24h}\, x_f}{n} \right]$$

for n = proportion of the 'ideal' SWE likely to be available, = f(precip zone)
m = proportion of the R+SM likely to reach the ground surface in 24 hr, = f(precip zone)
x_f = a multiplier reflecting the effect of hydrologic immaturity on snow accumulation

Values of the variables were derived from data or experience. The multiplier x represents the increased amount of snow available in clearings relative to mature forest. Assuming all forest land is HM, all lands have amounts of snow appropriate to their elevation zones available at the beginning of the storm, i.e. $x_f = 1.0$ for all forest lands.

The available water for each pixel was weighted by its area ($WA_{fi} = a\ WA_f$, for a = pixel area); all of the weighted values for a basin were summed, and the average calculated by dividing by the total basin area (A), to obtain the basin-averaged water available for fully-forested conditions, WA_{fb}:

$$WA_{fb} = \frac{1}{A} \sum_i WA_{f_i}$$

A similar set of calculations was carried out under an assumption of the actual mixture of mature and immature vegetation. Snowmelt for each pixel was recalculated (higher wind speeds on immature forests); then available water was recalculated, yielding WA_c. In this calculation, the multiplier (x_c) represents the additional amount of snow available in clearings, ranging from 1.0 for mature forest and all land at high elevations, to ≈3 for open land at low elevations (based on data summarized by Brunengo [unpubl]). That is, about three times as much snow is likely to be on the ground in low-elevation clearings as in adjacent forests; older plantation stands are given intermediate values. Again, the values for each pixel were weighted by area ($WA_{ci} = a\ WA_c$), summed, and used to generate a basin-wide average of storm input, WA_{cb}, for current vegetation.

The next step in the procedure was the calculation of an index number from the areally weighted values of model water input for the constituent areas of the basin. The index is based on the difference between the available-

[2] The Landsat interpretations were processed by Lisa Lackey of Pacific Meridian Resources, Portland; images were acquired in summer 1988 (most) and 1990. Lackey also programmed and performed the ERDAS model calculations.

water values estimated for fully-forested and current-vegetation conditions:

$$\Delta WA = f\,[\,WA_{c_E} - WA_{f_E}\,]$$

The frequency factor f, essentially the proportion of 10-yr 24-hr storms occurring under R/S conditions, allows us to account for differences in the incidence of rain-on-snow storms in different geographic areas. So far, we have used simple ratios to compare the eastern regions with the west side: we surmised that R/S storms are approximately half as likely on the east slope of the Cascades and about one-third as likely in northeast Washington, and thus use 0.5 and 0.33 as the frequency factors. In any case, the principle is that any rise in the frequency-magnitude curves due to enhancement of water input during R/S events will be modulated by the proportion of time it takes place. If R/S occurs in many storms, then enhancement of snowmelt input in clearings will have ample opportunity to boost the water available for runoff. If the events are rare, the effect of forest removal on R/S will rarely apply, and there will probably be no change in basin runoff.

RESULTS OF THE SCREENING: DISCUSSION

Most of the numbers obtained for basins in western Washington are reasonable. Basins occupying lowlands and highlands have low ΔWA values, because the model assumes that there is little snowmelt at extreme elevations, thus no influence of vegetation. Basins having large tracts of mature forests likewise have low ΔWA values, reflecting little difference between fully-forested and actual conditions. Basins having considerable acreage of immature forests in the middle elevations yielded higher ΔWA values: the highest were 2.3 cm in the Kalama basin, and 1.7 cm in the Tilton-Kiona and Toutle basins (the latter affected by the Mt. St. Helens blast zone). The distribution of outputs for west-side basins shows a mode near zero and a mean of 0.53 ± 0.48 (1σ) (i.e. it is strongly right-skewed). For comparison, a two-centimeter enhancement of precipitation by snowmelt represents an increase of approximately 15%, or an amount roughly sufficient to raise a 10-yr storm to a 20-yr event.

Available-water values in central and eastern Washington are more problematic. The results reflect the larger areas mapped in the three R/S-influenced zones, so ΔAWs are generally higher than those for the west side. In the eastern Cascades, average ΔWA is 0.97 ± 0.71 cm; for the northeast, the mean is 1.35 ± 0.48. The distributions for these regions are also right-skewed, because of some unbelievably high values (particularly one at 3.58 cm, by far the highest in the state). We believe that these values are artifacts of the edges of the Landsat coverage and the areal weighting calculations. That is, for a small basin dominantly in sparse or logged forest in the R/S zones, the model generates proportionally higher WA_c, and thus ΔWA, than for larger basins with a broader range of elevations and forest types. Using the simple f ratios, we calculated a set of modified index values for the basins in those regions. This procedure brings the distributions for the east-side regions into the body of the western group; the statistics for the adjusted values are 0.43 ± 0.25 for the eastern Cascades and 0.43 ± 0.15 for the northeast, a "good" match (comparable, but a bit lower) for the west-side basins (0.53 ± 0.48).

Using the raw ΔWA numbers for western basins and the adjusted values for the eastern regions, we simply multiplied by 100 to obtain the final index values for the hydrologic screen, representing the basin-wide potential for change in runoff due to timber harvest. All of the 15 highest-priority basins (rated 41-90) are on the west side, as are 13 of the 14 with index scores of zero. The ≈70 basins of central and eastern Washington and ≈80 of the west-side basins are clustered together in the middle of the priority list.

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[longer version of an article in the 1992 Western Snow Conference proceedings]

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97-1 Primer on WAU

I assume that other folks have some candidates, too ?

PROPOSAL - OPEN-FILE REPORTS

TO: Susan, Nancy, Steve
FROM: Matt
DATE: November 18, 1996

RE: Forest Practices Div. Open-File Reports

We've often talked about developing an OFR series as a place to "publish" our otherwise-unpublishable stuff - extended technical memos, data compilations, subsidiary/explanatory matter for watershed analysis, gray literature (even some symposium papers, etc. that technically have been published, but are not really available), etc. We've even started assigning numbers to some of these (see below), and citing them in the WSA manual.

Many months ago, I talked to Kitty Reed about what would be required to do this right (or at least unembarrassingly). Our conversation raised several points, including:

1) Format: we should have a relatively consistent look (title pages and/or covers, type style, etc.) - how far do we go toward central editing ?

2) "Advertising" (for want of a better term): we should occasionally (how often ?) distribute our publication lists to libraries, universities, and other interested parties - which ones ?

3) Distribution: assuming people will want copies (I hope), we would need to have a central distribution point - more work for our staff.

Points 2 and 3 remain to be addressed. Regarding point 1, since I have a large back-log of such papers, I am humbly submitting a proposed format (attached). I don't necessarily mean for us to spend a lot of time reworking old material to make it conform; and I assume that we will just leave already-published material the way it is. But we should try, from now on, to cast our papers in this (or some similar) format.

There is also the matter of peer review. Since these papers are not high-class science (we'll publish that in real journals), I don't foresee that we would need to do a huge amount of review on these OFRs. However, some degree of internal review is probably necessary - perhaps having each paper read by at least one or two of us, for content, style, etc.

There are many points open to discussion - let's talk about it some time.

WASHINGTON DEPARTMENT OF NATURAL RESOURCES
FOREST PRACTICES DIVISION
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ESTIMATION OF SNOW AVAILABLE FOR MELTING DURING MODEL RAIN-ON-SNOW EVENTS

Matthew J. Brunengo
Washington Department of Natural Resources

Open-File Report 95-2

December 3, 1995

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ESTIMATION OF SNOW AVAILABLE FOR MELTING DURING MODEL RAIN-ON-SNOW EVENTS

Matthew J. Brunengo
Washington Department of Natural Resources

Forest Practices Division Open-File Report 95–2
December 3, 1995[1]

Introduction

The potential for forest practices to cause cumulative effects on elements of the environment has been a topic of interest for many years (see Geppert and others, 1984). Commencing with the Sustainable Forestry Roundtable in 1989, state, tribal, and private entities in Washington began to co-operatively develop an approach to the assessment of cumulative watershed effects through the unified analysis of basin-scale areas. New forest practices rules (Chapter 222-22 WAC), adopted by the Washington Forest Practices Board in June 1992, codified this watershed analysis approach. As the legal and political system evolved, technical staff of the cooperating groups, acting as the Cumulative Effects Steering Committee (CESC) of the T/F/W Cooperative Monitoring, Evaluation, and Research Committee, adopted and/or developed a collection of techniques to be used in broad-scale resource analysis. In October 1992, the Board adopted CESC's product, *Standard Methodology for Conducting Watershed Analysis*, as part of the Board Manual; the current version (v 3.0) was approved in November 1995.

The watershed analysis process is divided into several major components, including resource assessment, synthesis, prescriptions, and monitoring. Within the resource assessment portion, modules address the basin situation with regard to watershed processes (e.g. mass wasting, riparian function) and resource conditions (e.g. channels, fish habitat).

The hydrologic change module is intended to examine basin water input and runoff processes, and the potential for significant changes in their frequency, rates, and/or magnitudes due to forest management activities. Through the development of watershed analysis, the enhancement of storm runoff during rain-on-snow events has been identified as the most obvious means by which large-scale harvest activities might cause cumulative hydrologic effects. Thus, at this point, the only processes explicitly addressed in this module are the potential for increases in runoff during R/S as a result of timber harvest, and the possibility of translation of increased runoff into higher peak streamflows.

Methods of Estimation of Snowpack Volume

The hydrology module utilizes a modeling procedure to estimate the effects of rain-on-snow events, given the geographic and vegetation pattern of a particular basin. In this model, the estimation of input and runoff depends on the amount of snow expected to be on the ground ....

[1] This paper supersedes earlier editions, dated February 5, 1993, and February 2, 1995.

.... snow-elevation equations. Some possibilities for improvement of these relationships include:

1) More data: Incorporation of measurements at NWS stations before 1959 might increase the record period and improve the statistical validity of the averages. Data from weather stations in Oregon or Idaho, or snow-survey sites in British Columbia, could be included for border areas.

2) Better data: Use of data from a select group of stations, closer (or otherwise more geographically or climatically relevant) to the basin of interest, to generate regressions, rather than use of regional equations based on more distant (in space or elevation) sites. The disadvantage is that any problems with data validity could be magnified by using fewer of them.

3) Better regressions: In some regions, use of third-order regressions or segmented lines could improve the estimates of snow available in the lower-elevation zones.

It is anticipated that some of these improvements will be incorporated in future editions of the watershed analysis manual. In the meantime, if one or another of these adjustments is made in the course of an analysis, the purpose and nature of the modifications should be noted with sufficient detail that a knowledgeable reviewer can understand the procedures and results.

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Style

FONT = CGScalbSC, 11 pt (10 pt - footnotes

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Landslides: Investigation and Mitigation

(Special Report 247)

This Transportation Research Board report is a greatly expanded edition of the previous Special Report on landslides published in 1978. The new report, which has been designed with an even broader international scope, contains comprehensive, practical discussions of field investigations, laboratory testing, and stability analysis procedures and technologies; comprehensive references to the literature; and discussions of case studies, state-of-the-art techniques, and research directions. The report comprises five sections: principles, definitions, and assessment; investigation; strength and stability analysis; mitigation; and special cases and materials, including tropical and residual soils, colluvium and talus, shales and degradable materials, hydraulic tailings, loess, soft sensitive clays, and permafrost. The report will be of interest to transportation engineers responsible for landslide investigations, university students studying landslides, and researchers desiring a definitive reference for landslide investigation and mitigation procedures. ISBN 0-309-06151-2 (hardcover), ISBN 0-309-06208-X (pbk.); 1996, 672 pages, 8 1/2X 11, index. Hardcover: nonaffiliates, $65.00; TRB affiliates, $48.75. Softcover: nonaffiliates, $45.00; TRB affiliates, $33.75. Prices effective through 3/31/97.

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Landslides: Investigation and Mitigation

(Special Report 247)

This Transportation Research Board report is a greatly expanded edition of the previous Special Report on landslides published in 1978. The new report, which has been designed with an even broader international scope, contains comprehensive, practical discussions of field investigations, laboratory testing, and stability analysis procedures and technologies; comprehensive references to the literature; and discussions of case studies, state-of-the-art techniques, and research directions. The report comprises five sections: principles, definitions, and assessment; investigation; strength and stability analysis; mitigation; and special cases and materials, including tropical and residual soils, colluvium and talus, shales and degradable materials, hydraulic tailings, loess, soft sensitive clays, and permafrost. The report will be of interest to transportation engineers responsible for landslide investigations, university students studying landslides, and researchers desiring a definitive reference for landslide investigation and mitigation procedures. ISBN 0-309-06151-2 (hardcover), ISBN 0-309-06208-X (pbk.); 1996, 672 pages, 8 1/2X 11, index. Hardcover: nonaffiliates, $65.00; TRB affiliates, $48.75. Softcover: nonaffiliates, $45.00; TRB affiliates, $33.75. Prices effective through 3/31/97.

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Using GIS and image processing to prioritize cumulative effects assessment[1]

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Abstract

Concern for the potential cumulative effects of forest practices on wildlife, hydrology, fish, and erosion/sedimentation has become critical throughout the West. In an effort to analyze the cumulative effects of forest practices in Washington, the state's Department of Natural Resources has initiated a project to assess the potential for cumulative impacts for each forested basin across the state. Because detailed assessments in basins or across the landscape cannot occur simultaneously state-wide, a system of priorities for identifying basins that are most susceptible to cumulative effects has been developed using GIS and image processing technologies.

For example, harvest in the rain-on-snow zone of the Pacific Northwest can change the runoff characteristics of a basin affecting channel morphology, water quality, and fish habitat. The water available for runoff can be calculated from (1) NOAA 10-year 24 hour precipitation data, (2) rain-on-snow information, and (3) classification of the size and crown closure of forest stands based on interpretation of Landsat imagery. Such data can be used to prioritize basins as to the risk of sustaining adverse cumulative effects. Management and/or regulatory strategies for harvest can be formulated to avoid significant environmental impacts.

Background

Definition — Cumulative effects (in the forest) are the changes to the environment caused by the spatial and temporal interaction of natural ecosystem processes with the effects of two or more forest practices.

Washington's State Forest Practices Board[2] (FPB) has recognized concerns regarding cumulative effects (CE) for more than 10 years. In 1982, in an effort to begin to address CE, Ecosystems, Inc. was hired by the FPB to prepare a document that presented current knowledge of CE with respect to forest practices (Geppert et al., 1984). A second task in the original request for proposal was to conduct basin examinations in Washington relative to CE; this activity never began.

In the following three years pressure mounted for further regulation of forest practices. The pressure manifested itself in legislative power struggles between the interested parties, wars between experts in front of the FPB, and litigation. In an effort to curtail these divisive activities, the Timber-Fish-Wildlife (TFW) agreement (1987) was negotiated by four interest groups: Indian tribes, state agencies, forest landowners, and environmental organizations. This agreement ultimately changed the Forest Practices Act[3], the forest practices regulations[4], and inspired cooperative efforts, including joint research and a commitment to work together on the ground. However, the agreement and subsequent changes in the regulation of forest practices did not result in a process or method for dealing with CE.

In 1989, the TFW cooperators approved an issue paper (Golde et al., 1989) recognizing that CE should be addressed comprehensively. That effort resulted in asking TFW's Cooperative Monitoring, Evaluation and Research (CMER) committee to focus more of its energy into research that would fill the holes in our knowledge regarding CE. In addition, the FPB had not addressed CE specifically in the regulations. This limited the conditioning of forest practice applications for CE (Olson, 1989) by the Department of Natural Resources[5] (DNR).

Two events occurred in 1989 prompting action in addressing issues that had not been resolved in TFW. The first was a lawsuit concerning CE as a result of proposed harvest around Lake Roesiger. The other was a second round of negotiations, known as the Sustainable Forestry Roundtable (SFR).

During the SFR negotiations, the same parties that participated in the TFW Agreement plus a new interest group, local governments, asked CMER: "Given current knowledge, what kind of technical approach could be used to begin dealing with cumulative effects?" CMER responded to the request with an initial report to SFR regarding how CE might be addressed (1990). While SFR incorporated this information into their proposal (1990), the negotiations ultimately failed. Several attempts were made during the 1991 legislative session to codify some of the concepts contained in the SFR proposal, including analysis of CE, but these, too, were unsuccessful. What the Legislature did provide was incentive. If the FPB would, by July 1, 1992, adopt regulations that address CE, wetlands, wildlife, rate of harvest, and clearcut size and timing, then dollars for implementation of the new rules would be made available.

To identify a methodology for approaching CE, the DNR, in consultation with CMER, was directed to complete the work originally initiated by SFR and to provide a scientifically-based tool for the FPB by March 1, 1992 (WAC 222-16-046). This effort has culminated in a proposed framework for dealing technically with CE on a watershed basis for state-regulated forest lands in Washington (12 million acres).

Cumulative effects assessment[6]

Currently, regulatory decisions on forest practices rely mostly on professional knowledge and evaluations regarding *local* conditions, i.e., the state of the forest-practice unit and areas directly adjacent to it. The ecosystem-and basin-wide perspectives are typically absent. Similarly, the resource information necessary for assessing existing or potential cumulative problems, the methods of analyzing the information, and standardized means of communicating the results among interested parties are generally inadequate or nonexistent.

A basic premise behind CE assessment is that landscapes differ in their sensitivities to forestry activities. Hydrologic and geomorphic processes vary spatially with differences in climate, geologic materials, structure, and terrain; vegetation and habitat conditions are partly controlled by these processes and by the history of natural and human-caused events in the forest. Furthermore, the broad class of activities encompassed in 'forest practices' has an equally broad spectrum of potential effects on the environment.

Because of the diversity of operations and conditions, all areas are not equally sensitive to any particular forest practice, and probably no area is sensitive to all possible negative effects. Consequently, the risks to water quality, fish and wildlife habitat, and public improvements associated with the range of management activities vary from place to place.

The essence of our approach is to develop a more explicit and objective procedure for performing and displaying basin-scale environmental evaluations. The results will be used by managers to design local strategies to address identified CE problems.

The design

The CE assessment examines basins for existing ecosystem conditions, actual and/or potential vegetation changes, accelerated erosion, increased flooding, deterioration of water quality, and changes in stream morphology. Many of these factors are evaluated with respect to fish and wildlife habitat needs. Resource impacts resulting from both natural background conditions and past human activities are considered.

The assessment of basin-wide hazards and the forestry activities likely to affect them can assist managers in minimizing both local and cumulative problems by aiding in the design of watershed-specific harvest plans. Subsequent operations may incorporate best management practices specified in the forest practices regulations, or alternative measures where appropriate.

Evaluation of risk to public resources helps in establishing appropriate decision criteria based on water- and habitat-quality standards. Appropriate conditioning of forest practices to minimize the potential for significant adverse effects is the result. In addition, the assessment can be used to identify opportunities for monitoring to determine the effectiveness of management and regulatory actions in meeting public-resource objectives.

It is intended that CE assessment will eventually take place in all basins containing state and private forest land. However, staff and funds are not available to perform all work on all basins in a short time. Therefore, the CE assessment has been organized into two phases of analysis. Level 1 analysis is intended to be performed over approximately six months. Existing information, regional staff, and local expertise will be used to look at all the basins of the state containing forest lands. Level 2 analysis will be performed using 'certified' watershed analysis teams, funded by the legislature or provided by others (such as landowners or tribes). This analysis will deal more intensively with basins of concern, gather more information, and identify critical decision criteria.

Watershed screening will determine the order in which the basins will be examined, regionally for Level 1 analysis and state-wide for Level 2 analysis, by prioritizing them on the basis of broad-scale environmental factors. The prioritization will not preclude others from performing Level 2 watershed analysis in watersheds of concern when desired. Neither will the initial prioritization prevent potential adjustments to the state-wide priorities as Level 1 is performed. Watershed screening will provide some information, not previously available, to the CE assessment in each basin.

Designation of basins

The first step was to delineate basins for the purpose of screening and analysis. It was presupposed that the basins should be contained within the water resource inventory areas (WRIAs[7]), and be fourth- to fifth-order in size. Adjustments were made to the latter criterion based on physiography, land use, and ownership. Using these criteria, 204 basins were designated, with one to seven basins in each WRIA. (Designation of these basins does not preclude further subdivision for detailed analysis.) Approximately 30 of the basins will be excluded from screening because they do not contain significant tracts of commercial forest. The boundaries of these basins have been digitized and are reproducible from DNR's GIS.

Prioritization of basins

The remainder of this paper is focused on how GIS and remote sensing are being used to prioritize basins for CE assessment across the state. To prioritize basins on a regional and state-wide basis in a timely fashion, information had to be easily obtained from maps, GIS, or satellite imagery. The following screens[8] were identified for key categories of hazard and risk.

Slope instability screen

The assumptions underlying the slope-hazard screen included that it be based on physical factors relevant to slope stability, that it use available information, and that the information is in forms that can be incorporated into a general instability rating.

Existing slope-hazard ratings are available for state and private commercial forest lands in the soils layer stored on the DNR GIS; the ratings for national forest lands are being obtained from the US Forest Service. Information on slope gradients is being obtained by purchasing sets of digital elevation data from the US Geological Survey and processing them to produce slope maps.

A storm-input layer is being developed to reflect the role that storm precipitation plays in triggering landslides. The isohyetal map of 10-year 24-hour precipitation (from NOAA) has been digitized, and a precipitation zones map has been developed. These will be combined into a model rating of potential storm-water input (see Hydrologic Screen section below).

The combination of the slope-hazard ratings and slope gradient information will show where steep and unstable areas are located. The storm-input layer will overlay the soils-slope layer to show where storms could be most effective in causing slides. The resultant combinations will be given numerical slope-hazard ratings.

To validate the ratings and add information regarding potentially unstable rock types, landforms, and known problem areas (information not otherwise contained in the slope-hazard ratings), teams of geologists and soil scientists familiar with different areas of the state will be brought together. These experts will use aerial photography, geologic maps, reports on historic slides, and personal experience to check the designations. This will provide verification that the identified 'unstable' zones are appropriate, and allow for modification of ratings with additional information.

Fisheries screen

The two criteria recommended for the state-wide fish screen recognize the importance of (1) streams that supply water to fish hatcheries, and (2) streams that support the state's natural/wild fish populations.

The value of including waters supplying fish cultural facilities is self-evident, since production is fully dependent on reliable, high-quality water. The inclusion of the proportion of utilized habitat, indicated by the presence of fish species in the basin by river mile, will identify where the habitat is being used.

The Washington Rivers Information System (WARIS), a GIS data base maintained by the Washington Department of Wildlife, contains site-specific information on state, tribal, and federal hatchery facilities and the presence and absence of fish species. These data have been further updated and verified, and currently resides on the DNR GIS.

Wildlife screen

The wildlife screen will score each WRIA for five factors: (1) the proportion of the forested area[9] in late-successional habitat, (2) the proportion in functional (60-acre patches) late-successional habitat, (3) the proportion in large patches (640 acres) of late-successional habitat, (4) the distribution of 60-acre patches, and (5) the proportion of vegetative cover in mid-successional forest.

The use of late-successional forest in the wildlife screen focuses on providing diversity of habitat for species not found in earlier successional stages. The criteria regarding size and distribution of patches are incorporated because these factors influence the dispersal of wildlife. The consideration of the mid-successional stage reflects the need for preserving natural diversity in a basin by identifying the habitat that is between early and late successional stages.

The classification of vegetation for wildlife habitat types is a result of processing Landsat images, as explained below. The evaluation of the classifications for wildlife will be performed using the ERDAS (Atlanta, Georgia) Clump and Sieve algorithm.

Hydrologic screen

The primary hydrologic problem related to forest management in Washington is the impact of timber harvest on runoff during rain-on-snow events. In the Pacific Northwest, the heaviest rains generally occur when cyclonic-frontal winter storms bring warm, moist air from the southwest. Since there is likely to be some snow on the ground at middle and higher elevations when these storms occur, snowmelt can combine with rainfall to aggravate floods and trigger landslides. The distribution of forest stands with varying degrees of hydrologic maturity (i.e., their ability to function like mature forests with respect to snow accumulation and melt processes), and their similarity to stands with natural runoff characteristics, will be used to rate the basins for the potential to alter peak flows and channel morphology.

To perform this exercise, several GIS layers are being adapted or developed for an analysis that is based on modeling of hypothetical rain-on-snow storms. The 10-year 24-hour storm isohyets were digitized from the NOAA atlas (Miller et al., 1973). Using data from the National Weather Service and cooperative snow surveys, a map of five precipitation zones was created to delineate areas likely to have various amounts of snow on the ground (in early January). The peak rain-on-snow zone was defined as the area in which the amount of snow available is approximately the same as could be melted by the 10-year 24-hour rainstorm (assuming reasonable temperature and winds). Below this peak rain-on-snow zone are the lowlands (little snow on the ground) and rain-dominated (some snow, but rain is the primary source of water input) zones; above are the highlands (too cold, so little liquid water generated) and snow-dominated (some snowmelt, but delay during percolation through the snowpack) zones. Although the distribution of these zones is controlled primarily by elevation, other climatic and geographic factors (e.g., latitude, aspect, storm tracks, mountain ranges) also affect their locations. These were reflected in the mapping.

The hydrologic maturity of forest vegetation is being identified through processing of Landsat imagery (as identified below). Recovery of a young forest to hydrologic maturity occurs when the properties controlling snow accumulation and melt, such as canopy closure, match those of a mature forest. These characteristics, adjusted for region, species, etc., can be used as standards of maturity.

Using these data layers, an approximation of the amount of water available for runoff from a hypothetical rain-on-snow storm can be generated using ERDAS GISMO. The 10-year 24-hour precipitation amounts are combined with the amounts of snowmelt appropriate for each zone (none in the highlands and lowlands, a maximum amount in the peak R/S zone) and each vegetation type (more snow available and faster melting in hydrologically immature stands and nonforested areas). The GIS calculates the areally-weighted averages of storm precipitation plus snowmelt for each basin under two sets of assumptions: (1) all forest lands support hydrologically mature vegetation (i.e., fully-forested conditions); and (2) the pattern of vegetation is as interpreted from the Landsat imagery (i.e., current conditions). The difference between these calculated values for a given basin represents the change in water available for runoff that could occur in a storm like the one modeled, as a result of timber harvest: the greater the difference (say, over 2-3 in. of increased water over a whole basin), the greater the potential for increased peak flows and damaging effects downstream.

Thus, the hydrologic screen will score each basin by calculating the change in water available for runoff from a mature forested condition to current conditions, for a model 24-hour rain-on-snow storm.

Vegetation classification

The vegetation classifications for both the wildlife and hydrologic screens are being performed under contract by Pacific Meridian Resources. The classes include: (1) late-successional conifer stands, (2) mid-successional conifer stands, (3) early-successional conifer stands, (4) other forest lands, and (5) water. These classifications have been processed through the use of geocoded and terrain-corrected 1988 Landsat TM imagery (EOSAT, Lanham, Maryland) and ERDAS image-processing software.

Six national forests and three national parks have already been mapped using more detailed vegetation classification of 16 and 31 categories, respectively (Teply and Green, 1991); these public lands have been recoded to fit the five-class scheme. The remaining forested areas are being classified using an unsupervised classification in combination with aerial photo interpretation, field recon-naissance, and the expertise of DNR regional foresters. The resulting classification is filtered and polygons less than five acres eliminated. The wildlife and hydrologic analyses are then carried out for each WRIA.

The wildlife screen will utilize the late-successional and mid-successional vegetation types of the forested areas of Washington. The hydrologic screen will consider mid- and late-successional vegetation classes to be hydrologically mature.

Summary

Attempts at evaluating cumulative effects have been continuing in Washington for over ten years. In response to concerns before the FPB and litigation, DNR, in consultation with its TFW partners, has constructed a framework for performing CE assessment on state and private forest lands. Such assessments could take from five to ten years state-wide. In order to prioritize where cumulative effects assessment should take place first, a watershed screening process is being utilized. GIS and remote-sensing techniques are being employed to gather and analyze broad-scale environmental data to prioritize basins. This exercise serves as an example of how data that are already resident on a GIS system, or that are easily obtainable, can be used in a timely fashion to identify where a CE assessment might be focused.

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Footnotes

[1] The opinions, findings, conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of any participant in, or committee of, the Timber/Fish/Wildlife agreement, the Washington State Forest Practices Board, or the Washington State Department of Natural Resources; nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

[2] The Washington Forest Practices Board was created in 1974 under the Forest Practices Act to promulgate forest practices regulations.

[3] The Forest Practices Act was passed by the state legislature in 1974 establishing a policy of protecting the public resources of the state coincident with the maintenance of a viable forest products industry.

[4] Best management practices and rules for administering the Forest Practices Act.

[5] The state agency responsible for administering the Forest Practices Act.

[6] Parts of the information in the following sections were taken from a report to the Forest Practices Board by DNR and TFW (1991).

[7] Water resource inventory areas (WRIAs) are the hydrologic administrative units of Washington adopted by the Washington Department of Ecology.

[8] Screening, as used here, is the process of focusing where CE of a particular type may be of concern.

[9] The forested area in Washington has been determined through the use of USGS digitized land-use

Matt -

Here's that DNR FPD open-file report!... thought you would know what to do with it (e.g., add it to all your reports on a shelf somewhere)...

95-1

- Susan

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SLOPE MORPHOLOGY MODEL DERIVED FROM DIGITAL ELEVATION DATA

In the Pacific Northwest, hillslope gradient and form (e.g. concave, convex, planar) play primary roles in governing the presence and behavior of landslides. Other physical factors such as hydrologic conditions, soil properties, bedrock geology, and land-use practices also dictate the frequency and timing of landslides. The initiation point of most such occurrences, however, may be predicted solely on the basis of slope morphology. Debris avalanches (e.g. shallow, rapid landslides, excluding those triggered by roads) often occur on steep ground, particularly in concave topography which forms a collection point for water, soils, and debris. These materials become destabilized when the forces promoting mass movement (e.g. gravity, soil saturation) overcome those resisting motion (e.g. soil shear strength). Therefore, slope gradient and form can be used as tools for locating potential sites of debris avalanches. This information is especially useful for land managers who do not have access to field inventories of mass-wasting sites.

We have developed a slope morphology model for use in land management, by combining this understanding of geomorphic processes with GIS methods for analyzing surface topography. This model is intended as a flagging tool, to be used in conjunction with field information, for making management decisions regarding protection of unstable slopes. The advantage of this model is that it relies on information currently available on the GIS system. Digital elevation data are analyzed using a modified version of the curvature tool found in the ArcInfo/GRID package. Slope-form classes derived from this analysis are assigned failure potentials based on known landslide criteria for specific geomorphic units. These criteria are set from available site-specific information and extrapolated to other parts of the region in which little or no data exist. The model may be applied generally across a geologic province in which precipitation regimes and soil properties are similar; separate model runs must be made for discrete geologic provinces. With the use of various look-up tables, the model can be more closely tailored to areas with unique topology. Model output comprises maps in which 900 m^2 pixels (i.e. the resolution scale of the DEM data) are color-coded to degrees of failure potential. We have mapped the western portion of Washington and currently are developing GIS coverages for the state east of the Cascade Range.

INTRODUCTION

Land managers in the Pacific Northwest often have few databases available with which to evaluate landslide potential. Information on site characteristics and failure behavior typically is confined to small geographic areas or landslide sites in which case studies, mass-wasting inventories, geomorphic research, or theoretical stability analyses have been performed. In recent years, state forest-practices regulators (e.g., Washington Forest Practices Board, 1994) and private landowners (e.g., Beschta et al., 1992) have initiated watershed analyses for specific landscape units, whereby landslide inventories are compiled with the aid of aerial photographs and field reconnaissance. Watershed analyses, however, generally are conducted on tight schedules and with limited resources (e.g., incomplete aerial-photo records, sparse soils and geology information), in order to minimize costs and meet regulatory timeframes. Computer models designed to identify landslide potential, therefore, are useful tools because model results can be used as a preliminary screen to locate potentially unstable ground and assist managers and scientists in determining where harvest or restorative efforts should be concentrated. Moreover, model results can be extrapolated to geologically similar areas in which little to no data are available for making management decisions.

The GIS-based model described herein originally was developed in 1993 as a flagging tool for assisting foresters with locating unstable ground in proposed timber sales on state-trusts lands of the western Olympic Peninsula (Hoh Tribe and Washington Department of Natural Resources (DNR), 1993). The scientific and technical concepts of this model are not new. For the past several decades, geologists and engineers have recognized the critical role that land topography plays in governing sedimentary and hydrologic processes. Likewise, mathematicians and geophysicists have explored the realm of describing land surfaces with complex numerical equations, in order to simulate and analyze terrain features. The contribution of this paper, therefore, is a practical application of such concepts to the analysis of landslide features, in a format that can be implemented readily by natural-resource scientists and managers.

METHODS

Summary. This computational model analyzes, on the basis of hillslope gradient and form, the susceptibility of terrain to landslide processes. The two required inputs are topographic data and a geomorphic interpretation of landforms prone to erosion by landsliding in the area of concern. Digital elevation model (DEM) data are used, because they constitute the most commonly used and readily available source of topographic data on GIS systems, although the model could equally accommodate other types of digitally formatted data. A modified version of the GRID tool, "curvature", in ArcInfo is employed to analyze slope morphology and failure potential. Modifications to the GRID software are described in this paper.

A slope-morphology matrix is formed by the union of slope gradient and form (i.e., concave, planar, convex). This matrix is based, for a given geomorphic unit, on field determinations of the characteristic hillslope configurations in which natural landslide processes occur. A geomorphic unit is an area in which the earth-surface processes (e.g., landform development, soil generation) and precipitation regimes are relatively uniform. The slope-morphology criteria are set from analyses of landslide behavior in a number of representative sites within a geomorphic unit and then extrapolated to similar units within a geologic province, or regional area with a distinct tectonic (e.g., mountain-building) history. Model output consists of maps in which pixels or cells representing $900m^2$ on the ground (i.e., the resolution of the DEM data) are differentiated by degree of failure potential.

We first summarize the geologic basis and rationale for this method, and then discuss the GIS tools used by the model. A number of important model assumptions will be addressed, as well as the uses and limitations of applying this analytical method to management of unstable terrain.

<u>Geologic basis and rationale</u>

Several natural factors contribute to the intensity and frequency of landsliding in the Pacific Northwest. They include (e.g., see Sidle et al., 1985): (1) geomorphic factors, such as substrate type, bedrock structure, and slope morphology; (2) soil properties, particularly soil strength and cohesion; (3) hydrologic processes, including plant transpiration, soil saturation, and surface runoff; (4) vegetation composition and root strength; and (5) seismic activity. A principal assumption of this model is that slope morphology (i.e., slope gradient and form) constitutes the dominant driving force promoting episodic, shallow landslides in areas of similar geomorphology, hydrology, and soil genesis within Washington state. Although earthquakes have the potential for triggering catastrophic landslides and rock avalanches, these events have occurred relatively infrequently in the recent past and are hard to address from a land-management perspective. Consequently, seismically induced slope failures are not considered.

The geomorphic community remains divided on the issue of employing slope gradient and form as a simple predictor of slope stability. Independent testing of this theory with field data and historical information in Washington, however, suggests that slope morphology generally can be used to predict the initiation point of certain natural forms of mass wasting (e.g., debris avalanches and flows) in greater than 80% of known cases. Field tests on the western Olympic Peninsula indicate that 90% of all existent shallow-landslide sites can be identified with slope gradient and form criteria. Road-related failures are not treated explicitly by the model, other than those roads built on slopes naturally prone to debris avalanches or shallow landsliding.

The theory relating slope morphology to mass-wasting potential, if applied in a physically sound way to geomorphically similar portions of the landscape, proves advantageous from a land-management perspective. Many state agencies and private landowners currently lack the requisite databases for accurately predicting landslide potential, or have limited resources for collecting the quality and quantity of field information necessary to use theoretical slope-stability models or more sophisticated DEM models. Models, such as those developed by O'Loughlin (1986), Vertessy et al. (1990), and Dietrich et al. (1993), variously require detailed information on soil properties, surface and subsurface flow regimes, and bedrock geology. Hence, basing a preliminary analysis of potential landslide sites on readily available topographic information provides an efficient and cost-effective means for prioritizing further management planning and fieldwork.

The two aspects of slope morphology considered here are slope gradient and form. Gradient has been closely correlated with debris avalanches (i.e., shallow, rapid landsliding) in several geological provinces of the Pacific Northwest (Sidle et al.,1985). The threshold gradient at which mass movement occurs, however, varies with the regional geology, climate, topography, and land-use practices. This variability precludes making too many generalizations; however, it appears from field evidence that many slopes over 47% (25°) in the Pacific Northwest are susceptible to shallow, rapid landsliding. In wet climates, landslides can occur on even gentler slopes. On the western Olympic Peninsula, for example, shallow landslides are triggered on 25% (14°) slopes due to increased soil moisture and corresponding loss of soil strength during the wet winter months (Logan et al., 1991; Hoh Tribe and Wash. DNR, 1993).

Slope form influences mass-wasting processes by governing the distribution of soil water. Slopes that are convex in plan form (e.g., ridges) tend to disperse groundwater, impede the formation of perched water tables, and suppress the development of high water pressures in the pores between soil particles which contributes to slope instability (Sidle et al., 1985). Concave slopes (e.g., tributary valleys), in contrast, tend to develop perched water tables and concentrate groundwater, surface water, sediment, and organic debris. In these slope depressions, the forces promoting mass movement (e.g., gravity, soil pore pressures, material weight) can exceed those resisting movement (e.g., soil shear strength, buoyancy effects of soil pore water). It is, therefore, not a coincidence that the majority of debris avalanches and flows originate in concave slope forms like incised channels and depressions upslope of channel heads. Landslides on steep, concave slopes often recur over a period of centuries as the depressions fill, flush, and refill with sediment and other debris (Dietrich and Dunne, 1978; Swanson and Fredriksen, 1982). Shallow, rapid landslides also occur on planar slopes that exceed the angle of repose for unconsolidated materials (70% or 35°).

Table 1 shows a matrix relating slope gradient and form to the potential for shallow, rapid landsliding. The number and distribution of slope-gradient classes (e.g., A through E) are initially set, for a specific geomorphic unit, with the aid of mass-wasting inventories and slope-stability analyses. The matrix is then extrapolated to areas without precise landslide information. Slope-gradient classes and assignments of landslide potential are verified, and modified if necessary, with each new mass-wasting inventory performed in the region. Model matrices have been established for the Olympic Peninsula and portions of the western slopes of the Cascade Range, as well as steeper terrain in southwestern Washington. The mass-wasting potential for slopes in each gradient-form class is represented by a color that is used to identify each DEM cell in the mapping process. Red indicates those slopes most susceptible to shallow, rapid landsliding, yellow denotes moderate susceptibility, and green indicates low susceptibility. Typically, the highest density of landsliding occurs on the least stable slopes.

TABLE 1. Matrix relating slope form and gradient to shallow-landslide potential.

Slope form	Slope gradient (percent)				
	A	B	C	D	E
Convex	green	green	green	green	yellow
Planar	green	green	green	yellow	red
Concave	green	yellow	red	red	red

This slope morphology model only addresses the potential for debris avalanches, or shallow landslides. These landslides typically involve the soil mantle and underlying regolith (i.e., materials accumulated from weathering and erosion of the bedrock surface), which average less than 10 m. deep. In contrast, earthflows or chronic deep-seated failures occur in thick sequences of soil and regolith, and often are characterized by complex, hummocky topography with multiple failure blocks whose individual length scales are smaller than the width of a DEM cell. This model, thus, is not capable of evaluating the potential for earthflows or deep-seated failures.

GIS methods

The analysis of topographic data, with respect to the slope gradient and form criteria established for each geomorphic unit, was first accomplished with the Arc command VIP. This command was used with a 100% selection to create a point coverage with one point for every cell of a USGS 7.5-minute DEM lattice. The following values represented a DEM surface: 2 for a local surface maximum, -2 for a minimum, 1 for a convexity or edge point, -1 for a concavity, and 0 for a point with both a local maximum and minimum (e.g., a saddle). These point values were stored in SFCODE. A grid was then generated around the points, with the same cell size and origin as the original DEM. A polygon topology was created by merging the grid with the points coverage and dissolving the coverage around SFCODE. The resulting coverage represented the computer-generated shape of the surface. A union of the surface shape with its slope created a new coverage in which each cell could be assigned a mass-wasting potential according to the matrix presented in Table 1.

We currently use the "curvature" function in ArcInfo GRID (ESRI, 1992), which provides a somewhat more straightforward and sophisticated method for performing this slope-morphology analysis. This tool calculates the curvature of a surface at each cell center of a USGS 7.5-minute DEM lattice, by evaluating slope gradient, aspect, planform curvature, and profile curvature. Slope gradient influences the rate of sediment and water transport across a slope. Aspect defines the slope direction and, therefore, the direction of transport. Planform curvature is measured transverse to the slope direction and influences flow concentration or dispersal. Profile curvature, or the rate of change of slope, governs flow acceleration and deceleration and, thereby, sediment deposition and erosion. The mathematical derivation of curvature used in the ESRI (1992) package is developed in a paper by Zevenbergen and Thorne (1987; see their literature review), in which a topographic surface is described by a fourth-order polynomial equation of the form:

$$Z = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I. \qquad (1)$$

The four topographic indices are analyzed with respect to a central point (origin) on a 3x3 matrix of surface cells. The 9 elevations of this matrix are used to calculate parameters A through I in equation 1. Planform curvature is the second derivative of Z with respect to D, and profile curvature is the second derivative of Z with respect to E. The curvature of a surface at each DEM cell center is given as the LaPlacian of Z evaluated at the origin, or the divergence of the gradient (i.e., normal vector to a plane tangent to a point on the topographic surface):

$$\text{Curvature} = \nabla^2 Z = 2D + 2E. \qquad (2)$$

See Zeverbergen and Thorne (1987) and Moore et al. (1991) for a full derivation of these equations.

The output of the GRID "curvature" function is given as equation 2 in the ESRI package. We found, however, that the software package did not account properly for a mathematical sign change; in addition, slope is calculated as a dimensional term by ESRI (1992), whereas equation 2 is derived analytically from (1) in terms of dimensionless slope. We, therefore, modified the equation in "curvature" to read:

$$\text{Curvature} = -2(D+E)100. \qquad (3)$$

The "curvature" function requires one input and two output grids (see discussion in Appendix). The input grid represents a continuous topographic surface, for example, the USGS 7.5-minute DEM. The two output grids are the planform and profile curvatures for each cell in the grid. A slope grid, sliced in slope-percent classes as previously defined (see Table 1), is created from the same input grid. A curvature grid is obtained by subtracting the profile grid from the planform grid (i.e., see eqn. 3). A positive curvature at a particular grid cell indicates that the surface is upwardly convex, whereas a negative curvature corresponds to an upwardly concave surface. A curvature value of zero signifies a flat or planar surface. Planform and profile grids at a particular cell have different signs, that is, one is convex and the other concave, in 80% to 90% of all cases. Planform and profile grids in the remaining cases, however, have like signs due to the local landform characteristics (e.g., ridgelines saddles, sinks in flat terrain). Grids, therefore, are added rather than subtracted, to accurately preserve these features in the slope-morphology analysis. The resulting three shape grids are merged to form a corrected curvature grid. This grid is then sliced into three classes (i.e., concave, convex, and planar) according to criteria based on field evaluations of slope morphology in a given geomorphic unit. Nondimensional values are assigned to these criteria, ranging from -4 (highly concave) to 4 (highly convex). The sliced curvature grid can then be added to the sliced slope grid to yield a grid or 3xN matrix, where N represents the number of slope classes selected. In the example given in Table 1, a 3x5 matrix results from this union. Classes of mass-wasting susceptibility are assigned through a remap table, as described in the Appendix.

DISCUSSION

The results of applying this GIS method to the preliminary analysis of slope stability are shown in the examples below. Figure 1 displays the GIS-defined areas of high susceptibility to mass wasting on a shaded relief map of the Willoughby Creek watershed on the western Olympic Peninsula. [Field maps used by foresters and managers in this area would indicate these areas in red, for example as denoted in Table 1.] Areas of highest susceptibility to shallow landsliding in this landscape are the steepest, most concave portions of the slope. Figure 2 shows the locations of shallow landslides as determined by field and aerial-photo analyses in the watershed. Comparison of Figures 1 and 2 demonstrates a high degree of correlation between the computer-defined areas of high mass-wasting potential and the actual, field-verified landslide sites. Furthermore, red pixels not matched with landslide sites in Figure 2 correlate well with unstable ground, as identified by field analyses.

The cells identified in Figure 1 generally correspond to areas of high landslide potential. This does not mean, however, that the entire area of the pixel represents a landslide; unstable ground may be present in all or only a small fraction of the 900 m^2 area. Hence, pixel size does not accurately reflect the magnitude of the slide-prone area. The latter must be determined from field information or analyses. The output of this slope-morphology model, therefore, does not substitute for on-the-ground slope evaluations. Rather, it should be used as a preliminary screen, supplemented by other sources of information (e.g., geologic and soils maps, aerial photos, and other technical tools of the field analyst).

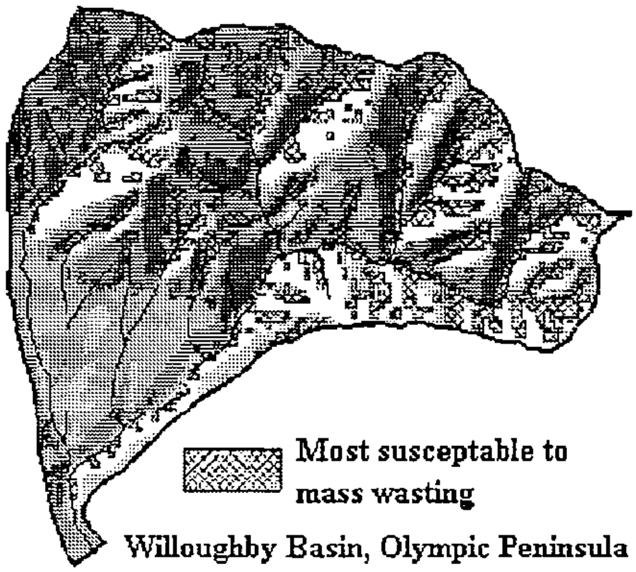

FIGURE 1. GIS-defined areas of high susceptibility to mass wasting (i.e., shallow landslides) in the 2000-acre Willoughby Creek watershed on the western Olympic Peninsula, Washington.

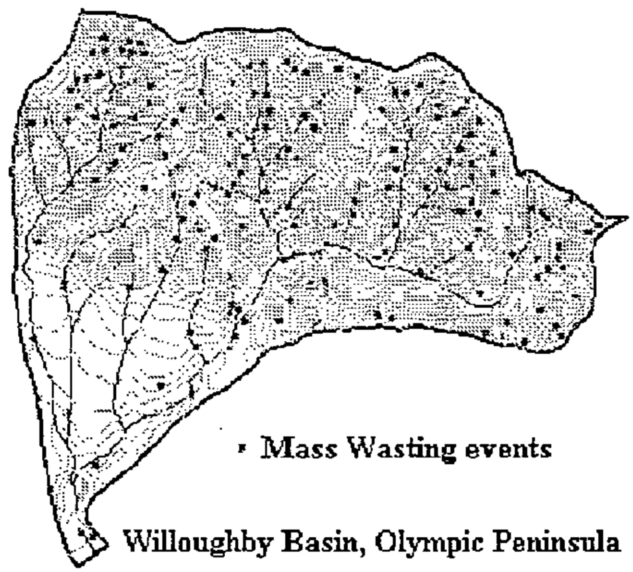

FIGURE 2. Mapped inventory of shallow landslides in the Willoughby Creek watershed, western Olympic Peninsula. The inventory is based on field slope-stability analyses and aerial-photo interpretation. Compare with Figure 1.

As with any predictive model, the output is only as accurate as the input information used to generate or run the model. There are two primary sources of error with this model. The first is the DEM data. The quality of these data vary considerably over some portions of the landscape, leading to anomalous slope gradient and form calculations. Furthermore, the resolution of the data (i.e., 900 m^2 grid cells) precludes analyzing the finest scale features of the landscape, including the exact location of channel heads and the smallest channel orders in low-relief terrain. Also, topographic contours developed from DEM data have not been calibrated across map quadrangle boundaries, resulting in spurious straight lines in the model output. These errors, however, should not unduly influence forest-management practices because model output is only intended as a preliminary guide for planning and fieldwork.

An additional limitation of the model is that it cannot account for artificial slope features that are susceptible to mass wasting, including road fills, quarries, reservoir walls, and stream-crossing structures. These objects rarely are indicated as three-dimensional in the DEM data. Furthermore, the slope-morphology model cannot predict earthflows or deep-seated movement over complex topography.

This model has been used primarily on the Olympic Peninsula and has been tested extensively over the past two years with independently generated mass-wasting inventories and site studies. The Washington DNR currently is conducting field tests throughout the state to determine the range of applicability of the model to areas with diverse landform, climate, topographic, and land-use conditions.

CONCLUSIONS

This paper describes the application of a GIS method for evaluating digital terrain information (e.g., USGS DEM data) to the analysis of landslide potential. A modified version of the "curvature" function in ArcInfo GRID (ESRI, 1992) is used to calculate slope gradient and form (i.e., concave, planar, convex surfaces). This information is merged with a geomorphic interpretation of slope morphologies prone to landslide processes, to yield a map of areas prone to shallow landsliding and debris flows. This method is advantageous for land managers because it only requires information that typically is readily available: (1) topographic data (e.g., DEM), and (2) a knowledge of the mass-wasting characteristics for selected areas within a given geomorphic unit. The latter may be determined from representative mass-wasting inventories of the type normally produced during watershed analysis. The model is intended as a preliminary planning tool only, and a field analysis must be performed to locate actual landslides within the areas of mass-wasting susceptibility identified by the model. Until more sophisticated and accurate models become available in the land-management arena, this simple method allows managers to evaluate the potential costs and physical impacts of land-use activities prior to investing in more detailed analyses and planning efforts.

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APPENDIX

The model program contains the following grid manipulations:

```
1:     crvgrd = curvature(<demgrd>,{progrd},{plangrd})
2:     slopegrd= slope(<demgrd>,{percentrise})
3:     slpsligrd = slice(<slopegrd>,<table>,<slo_sli.rmt>)
4:     planprogrd = (plangrd - progrd)
5:     concavegrd = con(plangrd lt 0 and progrd lt 0,plangrd + progrd)
6:     convexgrd = con(plangrd gt 0 and progrd gt 0,plangrd + progrd)
7:     cavevexgrd = merge(concavegrd,convexgrd,planprogrd)
8:     cavevexgrd1 = (slice(<cavevexgrd>,<table>,<curvature.rmt>) +
              slpsligrd)
9:     geogrd = slice(<cavevexgrd1>,<table>,<rgy_sli.rmt>)
```

Line 1: The curvature function is used to create three grids. "Crvgrd" is a standard output grid not used in this version of the model; <demgrd> is the input grid representing a continuous surface; {progrd} is the output grid representing the profile curvature; {plangrd} is the output grid representing the planform curvature.

Line 2: "Slopegrd" is created from the same DEM grid as the curvature/shape grids. The {percentrise} option is used to correspond with the slope percent classes identified in Table 1.

Line 3: "Slosligrd" is the result of slicing the slope grid into slope percent classes identified by a geomorphic evaluation of the area of concern (see Table 1). Slicing employs a remap table, for example:

```
          (slo_sli.rmt)
A B : 10            /* relatively flat
B C : 20            /* low gradient
C D : 30            /* moderate gradient
D E : 40            /* high gradient
E ∞ : 50            /* extreme gradient
```

This produces a grid with 5 gradient classes that can be assigned numbers (e.g., 10,20...50) for use later in the curvature grid.

Line 4: "Planprogrd" is created by subtracting {progrd} from {plangrd}. See text for explanation. For cases where {progrd} and {plangrd} have opposite signs.

Line 5: For cases where {progrd} and {plangrd} have like signs. Concave cells are added together.

Line 6: For cases where {progrd} and {plangrd} have like signs. Convex cells are added together.

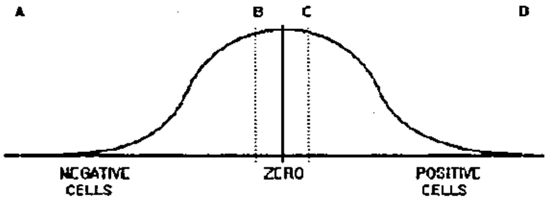
Line 7: The three curvature grids are merged to form a corrected curvature grid, "cavevexgrd".

Line 8: "Cavevexgrd" is sliced into three classes (i.e., concave, convex, planar) using a remap table similar to the following:

```
          (curvature.rmt)
-a -b : 1           /* concave surface
-b c : 2            /* planar surface
```

c d : 3 /* convex surface

The numerical criteria for defining slices must be determined on the basis of local knowledge regarding slope form. Very few grid manipulations result in values of zero, and there are few planar slopes. The histogram below illustrates a sample distribution of cell values for the corrected curvature grid:



Line 9: The sliced "Cavevexgrd" is added to the sliced slope table from above to create a grid with N classes, or a 3xN matrix as shown in Table 1, where N is the number of specified slope-percent classes:

Slope form	Slope gradient (percent)				
	A	B	C	D	E
(a-b) Convex	11	21	31	41	51
(b-c) Planar	12	22	32	42	52
(c-d) Concave	13	23	33	43	53

The matrix can then be sliced into slope-stability-potential classes with, for example, the following remap table and map color codes:

```
(rgy_sli.rmt)
11 13 : 1     /* green, stable
21 21 : 2     /* yellow, moderately unstable
22 23 : 1     /* green, stable
31 31 : 3     /* red, highly unstable
32 33 : 1     /* green, stable
41 41 : 3     /* red, highly unstable
42 42 : 2     /* yellow, moderately unstable
43 43 : 1     /* green, stable
51 52 : 3     /* red, highly unstable
53 53 : 2     /* yellow, moderately unstable
```

as shown in Table 1.

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