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

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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

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[1] Presented at the 60th 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 on average 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 frequency 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}:

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

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-

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[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:

$$\Delta WA = f\,[\,WA_{c_{\Sigma}} - WA_{f_{\Sigma}}\,]$$

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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