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REPLY TO DISCUSSION[1] by Amod S. Dhakal and Roy C. Sidle[2]

"Ground Water Response to Forest Harvest: Implications for Hillslope Stability"[3]

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INTRODUCTION

Dhakal and Sidle (this volume) have requested clarification of some of the rationales and approaches used in analyses described by Johnson *et al.* (2007). Here we further describe hydrologic conditions typical of southeast Alaska and elaborate on an accepted methodology used for conducting analysis of covariance statistical analysis (ANCOVA). We discuss Dhakal and Sidle's four main criticisms, namely (1) use of process-based knowledge, (2) use of 48-h storms, (3) utilization of statistical results, and (4) hillslope stability modeling.

To summarize, Johnson *et al.* (2007) found differing effects of forest harvest for two study areas in the forests of southeast Alaska. We found that there was no statistical difference in saturation following 25, 75, and 100% harvest at Hanus Bay. Here, as might be expected at the toe slope of a mountainside, there was considerable variance in ground saturation associated with rainfall, likely in combination with discharge from the mountain side slope. At Portage Bay, higher on the mountainside, there was a significant difference in saturation levels of pre- and post-harvest conditions for all cutting treatments. At control sites at both study locations, there was no difference in the saturation for time periods before and after the cutting treatments. Measured changes had no significant impact on hillslope stability at either site. However, the cutting regimes studied would be applied to areas throughout the Tongass Forest, many of which have steeper slopes or deeper soils than the experimental plots. Therefore, to explore the potential influence of the observed magnitude of change, we conducted stability analyses using the hydrologic response measured at the 100% harvest site at the Portage location and extrapolated to steeper slopes and deeper soils that might be encountered during timber harvest in other areas. Our study was designed to use empirical response data to compare the potential influences of three cutting alternatives on variables that can influence slope stability.

USE OF PROCESS-BASED KNOWLEDGE

Dhakal and Sidle make valuable points about the multiplicity of process-level variables that influence soil pressure heads and slope stability. They cite numerous studies that illustrate that those processes are complex and highly variable. However, our study was not designed to further our understanding of the fine-scale details of hillslope hydrology, but rather to use empirical response data to evaluate the likelihood that proposed alternative cutting strategies could destabilize hillslopes, given the magnitude of potential changes in site saturation. The study was designed to help managers assess risks in the face of large natural variation. No forest manager will be able to quantify all the important process variables mentioned by Dhakal and Sidle (e.g., preferential flowpaths, detailed hillslope morphology, spatial

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variation in soil properties) that control the process of slope failure. Given the data available to us, we took a broad approach to provide managers with a reasonable estimate of alternative risks and do not consider our study to be in either conflict with or ignore a process-based analysis of hillslope hydrology. Although the data does provide a basis for an analysis of effective precipitation using both precipitation intensity and duration for harvested and control sites (in progress), that was not the intent of this initial analysis.

USE OF 48-h STORMS

Dhakal and Sidle request clarification regarding the reason for our selection of a 48-h period to index storm magnitude. We selected this index because storms in the area last for about 48-h (p. 138, Johnson *et al.*, 2007). This does not mean that all storms lasted 48-h, but the chosen 48-h storm period allowed us, for the given study period, to include largest storms with two conditions: (1) low pre-storm antecedent soil moisture, and (2) measurement of precipitation for the highest intensity periods of each storm. Box plots of rain duration at pre-harvest Portage Bay for all 40 storms (20 pre-harvest, 20 post-harvest) indicate that 80% of storms exceed 24-h and 85% of storms were shorter in length than 48-h (Figure 1). In addition, when comparing correlations of 48-h, 24-h, or 12-h rainfall with soil saturation for the preharvest 100% cut Portage Bay site, the best relationship was found for the 48-h rainfall index (Figure 2). Further, storm events exceeding 48-h have been associated with periods of landsliding in southeast Alaska (Johnson *et al.*, 2000).

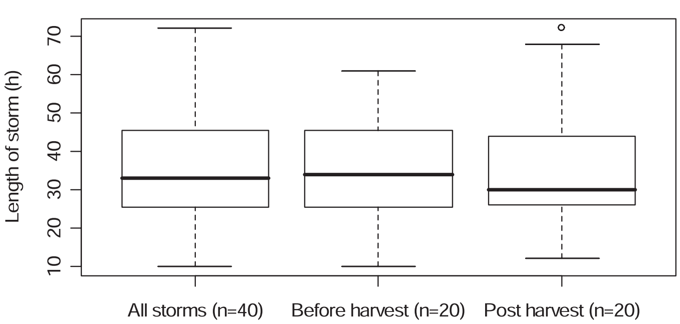

FIGURE 1. Boxplots of Storm Length Illustrating That Over 75% of the Storm Length (as indicated by the quartile boxes) Are Captured by Incorporation of Chosen 48-h Storms. Note that if 24-h storms had been chosen used in the analysis, <25% of storm length the storms would have been included.

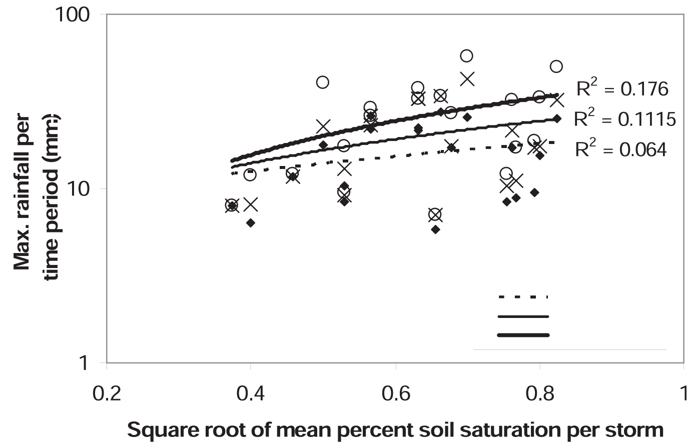

FIGURE 2. Maximum Intensity Rainfall per 12, 24, and 48-h Time Periods Associated With Mean Saturation Per Storm at the Pre-Harvest 100% Cut Site at Portage Bay. All relationships were improved by log transforming maximum rainfall and square root transforming mean saturation per storm. Regression statistics for regression relationships are as follows: 48-h rainfall index has standard error of 0.124, F-statistic of 4.491, and with $p = 0.048$ is the only significant relationship; whereas 24-h rainfall index standard error of 0.129, an F-statistic of 3.044, and $p = 0.098$; and 12-h rainfall index has a standard error of 0.134, an F-statistic of 1.442 and p-value of 0.254.

CUTTING TREATMENTS

Dhakal and Sidle raise the concern that actual harvest intensity at instrumented sites is not necessarily equivalent to that prescribed. Typically, harvesting prescriptions cannot be carried out uniformly across a logging unit because of site conditions, logistics, and tree distribution. We accepted the 0, 25, 75 and 100% harvest levels for our analysis because the relevant harvest intensity includes the areas immediately upslope of the instrumented hollow (local swale or topographic concavity) as well as the area within the hollow and silviculturalists, on subsequent visits to the harvest units, were generally satisfied with the level of forest harvests (personal communication, Michael McClellan, USDA Forest Service, PNW Research Station, Juneau Forestry Sciences Laboratory, Juneau, Alaska).

STATISTICAL ANALYSIS

Statistical analyses of Johnson *et al.* under scrutiny by Dhakal and Sidle include analysis of control sites, use of mean and maximum measures of saturation, and use of analysis of covariance methods. Dhakal and Sidle suggest that establishment of a preharvest regression relationship between control and treatment sites would have been appropriate. However, we found that because of inter-site variability, it was more useful to use data from control sites to test for differences in control saturation levels between the two periods. Finding no statistically significant difference, we could then conclude that pretreatment weather conditions were likely to be similar enough to posttreatment conditions that it was reasonable to test for a treatment response at the treated sites.

Dhakal and Sidle note that neither the mean value for well response at a site (incorporating seven wells) nor the maximum value for the site (which might be from any of the seven wells) reflects the response at particular well locations. However, because we are interested in the general response in the broadly defined hollows, we do not focus on response at specific well locations. As Dhakal and Sidle point out, response at any specific location can be influenced by a wide variety of factors, and the fact that the maximum value did not occur in the same well for each storm indicates that the relative importance of influences may vary between storms. Consequently, we employed the mean value for wells at each site to compensate for intra-site variability between storms. In other words, for this analysis, we considered our site to be the hollow, not the individual wells.

This approach also means that although particular wells may not respond further to increasing rainfall after attaining a maximum saturation level, the mean value may continue to increase, reflecting increases in wells at which maximum levels have not yet been attained. A continued increase in average well level with increasing 48-h rainfall would be consistent with a broadening of the area of saturation, as would be expected at sites where variable-source runoff is common (Dunne *et al.*, 1975). Those locales saturated early and often would likely remain stable, while marginally stable sites farther up the hollow or on sideslopes – for which considerably more rainfall is necessary for saturation – are the ones more likely to fail during a major storm and the ones likely to be most influenced by management-related hydrologic changes. Under these conditions, use of a multi-well mean provides a broader index of hydrologic conditions in a hillslope hollow than would data from an individual well. In contrast, analysis of data from specific wells would provide considerable information about the spatial distribution of intra-site responses.

Dhakal and Sidle point out that significance in regressions of groups of data prior to ANCOVA are strongly suggested by Sokal and Rohlf (1995). However, Sokal and Rohlf also indicate that it is possible to do analysis of covariance given a lack of significance for regression lines for groups of data. A weak or non-significant R^2 may be due to large variation or simply because the slope coefficient may be small. In regard to incorporation of low and insignificant R^2 analyses Pearce (1982) states "in presenting results it is more convincing to report that some quantity or characteristic was allowed for but had in fact made little difference than to ignore it." A covariate may be included in analysis regardless of the statistical significance of the regression lines. In an ANCOVA, differences in groups or treatments is tested, so it is of primary importance to first test for differences in slopes (as opposed to significance of slopes) because the slopes should be parallel (Sokal and Rohle, 1995; Zar, 1999). When analysis of covariance indicates no significant difference between the slopes of the regression lines, differences in the y intercept are tested using a common regression slope (Zar, 1999). Residual plots, used to assess variance of data, assured that assumptions of covariance tests were met. We conducted an ANCOVA using standard methodology finding significance in relationships based on the mean square error, degrees of freedom, and an F-statistic.

EFFECTS OF SOIL SATURATION ON HILLSLOPE STABILITY

In southeast Alaska, landslides have been known to occur in conjunction with the first storms following clearcutting with only 50 mm rain in August or early September, before fall heavy rains (D. J. Landwehr, unpublished report, Ketchikan, Alaska). Our study included 20 storms of 50 mm or greater. Finding a significant difference in saturation postharvest for one out of two sites, we proceeded on to the second objective of our study, a determination of the influence of measured increase in site saturation on an assessment of hillslope stability. The regression equations used for this analysis are the ones derived from analysis of covariance – using computed parallel slopes. Finding little reduction in the hillslope stability of the sites because of low slopes and shallow soils, we conducted a hypothetical analysis of the adjacent slopes having higher gradients and deeper soils. Dhakal and Sidle postulate that tree removal could not contribute to slope instability because the only impact on soil hydrology is reduced interception storage and the influence of that is restricted to early stages of very intense storms. Given that 18 and 21% interception has been found to occur with precipitation totaling 198 mm and 200 mm (Patric, 1966; Reid and Lewis, 2007; respectively), we contend that interception potentially plays an important role on hillslope stability even with larger rainstorms.

CONCLUSION

We discuss Dhakal and Sidle's (this issue) four main criticisms of Johnson *et al.* (2007): (1) use of process-based knowledge, (2) use of rainfall data (3) statistical results for soil saturation, and (4) use of data in hillslope stability modeling. Chosen 48-h storm period was used as it characterizes the majority of storms whereby a database could be created to include the highest magnitude storms having low pre-storm antecedent soil moisture, and include maximum soil saturation corresponding to each storm. Analysis of covariance, conducted by consulting referenced standard statistical procedures, was used to determine that a significant difference in saturation existed for one out of two study locations for all levels of forest harvest. Although our analysis has limited application because of the lower magnitude storms measured during the study period, the statistical methodology was sound and is applicable for use given higher magnitude rainstorms in the assessment of soil saturation and soil cohesion due to root cohesion on hillslope stability.

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