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GROUND-WATER RESPONSE TO FOREST HARVEST: IMPLICATIONS FOR HILLSLOPE STABILITY[1]

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ABSTRACT: Timber harvest may contribute to increased landsliding frequency through increased soil saturation or loss of soil strength as roots decay. This study assessed the effects of forest harvest on hillslope hydrology and linked hydrologic change before and after harvest with a simple model of hillslope stability. Observations of peak water table heights in 56 ground-water monitoring wells showed that soil saturation levels on hillslopes differed significantly with harvest intensity at one of the two study locations following 25%, 75%, and 100% harvest. Before the forest was cut 100%, the average rainfall needed for 50% saturation of the soil was 54 mm, but after clearcutting soils reached an equivalent saturation with 61% less rainfall (21 mm). Hillslope stability model results indicate that shallow soils at both study locations, with slopes generally < 30° (58%), were not steep enough to be affected significantly by observed increases in saturation. The stability model indicates that with 100% harvest, there is a 7% reduction in the factor of safety for slope gradients of 35° (70%) with soil depths of 1.25 m. Forest managers may be aided by an understanding that variable hydrologic effects may result from similar forest harvests having different landscape position, land contributing area, and soil depths.

(KEY TERMS: forest; harvest impact; wells; landslides; sediment delivery; watershed management.)

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INTRODUCTION

Studies in Pacific Northwest and Alaska detect a two- to ten-fold increase in landslide frequency following timber harvest (Bishop and Stevens, 1964; Dyrness, 1967; Swanson and Dyrness, 1975; Burroughs and Thomas, 1977; Swanson *et al., 1977,* 1982; Sidle, 1984, 1985; Swanston and Marion, 1991). Loss of root strength combined with increased soil saturation are the primary causes of decreased hillslope stability (Zeimer, 1981; O'Loughlin and Zeimer, 1982; Sidle *et al.,* 1985; Sidle, 1992; Schmidt *et al.,* 2001; Roering *et al.,* 2003). Tree removal by timber harvest or tree death associated with change in climate and/or insect outbreaks; forest pathogens, or wildfire (Krammer, 1965; Rice, 1973; Holsten *et al.,* 1985; Hennon and Shaw, 1994; Mason and Wickman, 1994; Jacoby *et al.,* 1997; Johnson and Wilcock, 2002) results in loss of soil cohesion as a result of decreased root strength. Reduced shear strength, associated with increased saturation, results from decreased tree canopy interception and reduced transpiration (Swanston, 1973; Harr and McCorison, 1979; Keim, 2003).

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Hydrologic effects of clearcutting may be moderated by less intensive forest harvests. Retaining timber or distributing harvest non-uniformly across a unit alters canopy interception, evapotranspiration rates, and distribution of rainfall infiltration in ways that may reduce soil saturation and subsequent slope failures. Better understanding of these processes may be gained from detailed, site specific hydrologic monitoring of a range of harvest intensities. Historically, such studies have been conducted by observing downstream alterations in stream discharge within second-growth forests (Hornbeck *et al.,* 1997). However, measuring integrated water yield as a response to management provides catchment-scale information rather than hillslope-scale information relevant to hillslope failure and may also inadvertently measure changes in soil hydrology resulting from logging-induced soil compaction and subsequent loss of macropores (Reid, 1993; Keppeler *et al.,* 1994; Block *et al.,* 2002), in addition to changes due solely to forest cover. Hillslope-scale studies encompassing a range of low-soil disturbance harvest intensities within old-growth forest settings provide a baseline from which an understanding of soil stability effects may be obtained.

This study, part of the 'Alternatives to Clearcutting' project (McClellen *et al.,* in press) within pristine old-growth forests of southeast Alaska, evaluates impacts of various harvesting intensities and spatial patterns on hillslope hydrology. The main objectives are to: (1) determine soil saturation change following different harvest intensities, (2) quantify differences where they were significant, and (3) determine whether changes in saturation change hillslope stability.

Study Sites

Slope hydrology was evaluated at two locations: Hanus Bay and Portage Bay. Hanus Bay, located northeast of Baranof Island (N57°24', W134°59'), is approximately 50 km northeast of Sitka and 100 km south-southwest of Juneau, Alaska (Figure 1). Portage Bay is located on the northeastern part of Kupreanof Island (N56°57', W133°), approximately 40 km northwest of Petersburg, Alaska. Harvest intensity types were randomly assigned to-experimental units at each of the two locations and include harvests of: 0 (uncut control), 25%, 75%, and 100% of basal area of standing timber, defined as proportion of total cross-sectional area of all tree trunks > 23 cm (McClellan *et al.,).* Tree density (diameters > 2.5 cm) averaged 612 trees/ha for Hanus Bay and 962 trees/ha for Portage Bay (McClellan, personal communication, Juneau Forestry Sciences Laboratory) (Table 1). Individual harvested areas averaged 15 ha. Hanus and Portage Bay were harvested in 1997 and 1999, respectively. Sites were helicopter logged to ensure that disturbance effects were comparable (McClellen *et al.,* in press) and to minimize impacts to the ground surface and understory vegetation. Harvest units were located between approximately 120 and 420 m elevation at Hanus Bay and between 180 and 600 m at Portage Bay (Figures 2 and 3, Table 1).

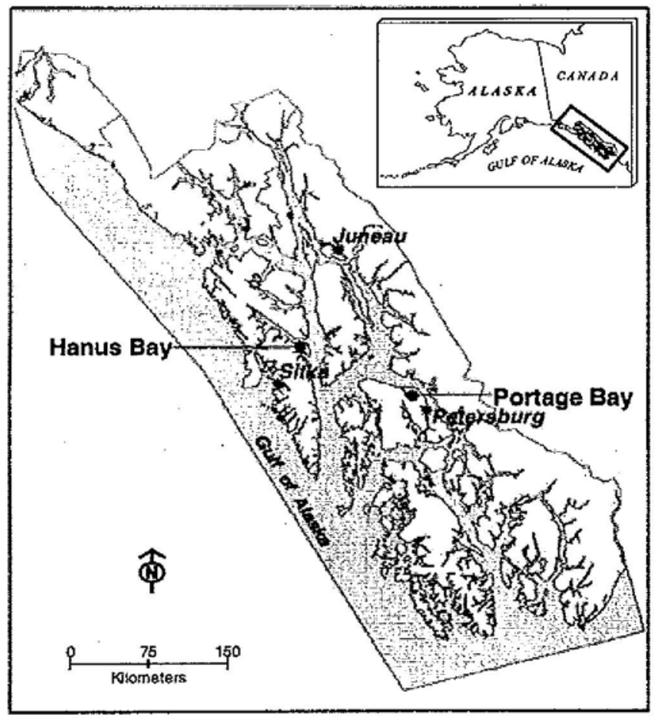

FIGURE 1. Study Site Location.

Forests within the study locations are dominated by western hemlock *(Tsuga heterophylla),* Sitka spruce *(Picea sitchensis),* and mountain hemlock *(Tsuga mertensiana).* Yellow-cedar *(Chamaecyparis nootkatensis)* grows at the wetter sites. Understory plant species include red huckleberry *(Vaccinium paroifloium),* Alaska blueberry *(Vaccinium alaskaense),* rusty menziesia *(Menziesia ferruginea),* and devil's club *(Oplopanax horridus).* Skunk cabbage *(Lysichitom americanus)* and false hellebore *(Veratrum eschscholtzii)* grow in the wettest areas. Although windthrow is considered the dominant forest disturbance (Harris *et al.,* 1974; Harris, 1989; Nowacki and Kramer, 1998), it was not found to be a dominant disturbance mechanism during the last 100 years at the ATC sites (Hennon and McClellan, 2003). Fire disturbance is of little significance in southeast Alaska (Neste, 1979), a region considered a temperate rainforest.

TABLE 1. A Summary of Study Site Features.

Location	Treatment Prescription (% cut)	Trees per Hectare[1] (ha)	Tree Basal Area Prior to Harvest[1] (m^2/ha)	Volume[1] (m^3/ha)	Actual % of Basal Area Harvested[2]	Number Trees: Cut / Left Standing at Hollow	Mean Elevation (m)	Aspect	Percent Basal Area[1]; Hemlock, Spruce, and Yellow Cedar, Respectively	Mean Soil Depth (m) [Standard Deviation]	Mean Slope (°) [Standard Deviation]	Hollow Area (m^2)
Hanus	0	1112	112.4	940.1	0	0/6	180	South	72, 19, 2	0.45 [0.11]	22 [7.17]	300
	25	287	76.2	835.9	38.1	3/5	180	Southwest	59, 12, 17	0.46 [0.15]	23 [8.78]	175
	75	612	97.2	1110.9	87.2	5/7	240	West	54, 18, 19	0.41 [0.11]	31 [3.76]	200
	100	612	97.2	1110.8	99.7	13/13	120	Northeast	48, 10, 42	0.44 [0.11]	23 [6.20]	350
Portage	0	237	21.1	213.5	0.1	0/15	550	South	75, 21, 4	1.02 [0.18]	27 [6.45]	1000
	25	275	29.3	272.5	67.8	4/14	305	South	90, 8, 0	0.71 [0.27]	27 [4.76]	220
	75	412	90.1	1104.7	86.3	16/20	490	South	42, 23, 34	0.58 [0.10]	25 [2.36]	375
	100	2925	64.5	554.9	99.6	35/35	185	Southeast	75, 25, 0	0.75 [0.22]	21 [2.93]	500

[1]Multiple study plots were made in each cutting treatment. The information listed (personal communication, Michael McClellan, Juneau Forestry Sciences Laboratory) was obtained from the plot closest to the instrumented hollows.
[2]Post harvested basal area is estimated from entire cutting treatment (personal communication, Michael McClellan, Juneau Forestry Sciences Laboratory).

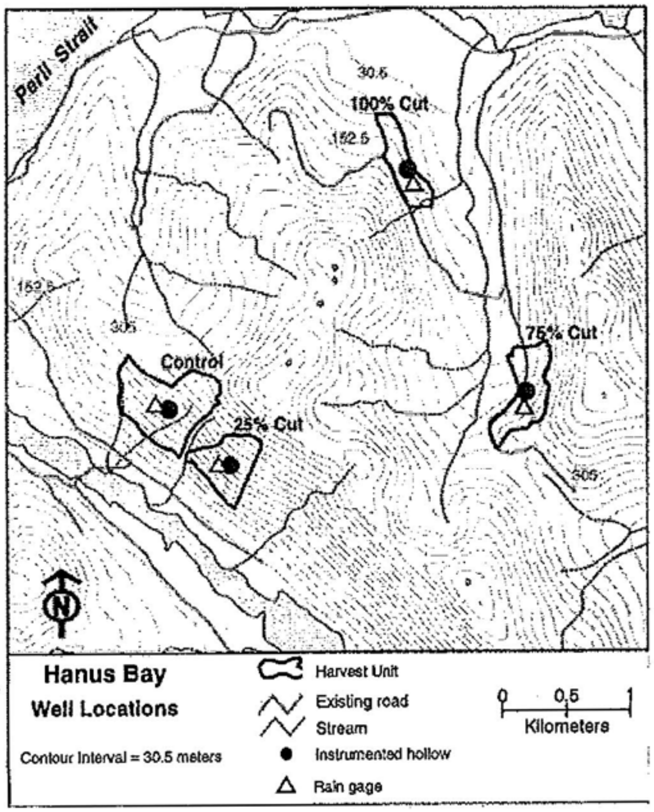

FIGURE 2. Study Site Locations Within the Various Harvest Types for Hanus Bay.

Portage Bay is in the Gravina Belt, composed primarily of a Cretaceous phyllite associated with turbidites of the Seymour Canal Formation (Loney *et al.*, 1975). Soils at this location are shallow, ranging **in** depth from 0.41 to 1.28 m with a mean depth of 0.76 m (Table 1). The alpine region above the Portage sites (> 600 m) is composed of Cretaceous granodiorites and tonalites (Gehrels and Berg, 1992). At Hanus Bay, two of the sites (the control and the 25% cut) lie southeast of the Peril Straight Fault and are composed of Triassic and/or Jurassic metamorphic rocks including pyhllite, quartzite, greywacke, and greenschist. The remaining two Hanus sites (75% and 100% harvest) are located northwest of the fault where the geology is predominantly intrusive hornblende tonalite of the Cretaceous era (Brew *et al.*, 1984). At Hanus, till is only found at the bedrock-soil interface of the 100% cut site (USDA, unpublished). Soil depths at Hanus range from 0.27 to 0.76 m with a mean depth of 0.44 m (Table 1). Soils at Hanus Bay and Portage Bay are mostly that of the Kupreanof-Mitkof association, classified as loamy-skeletal, mixed Typic Humicryods (USDA, Forest Service, 1992a, b).

The regional climate is characterized by mild, wet winters and cool, wet summers. Annual rainfall

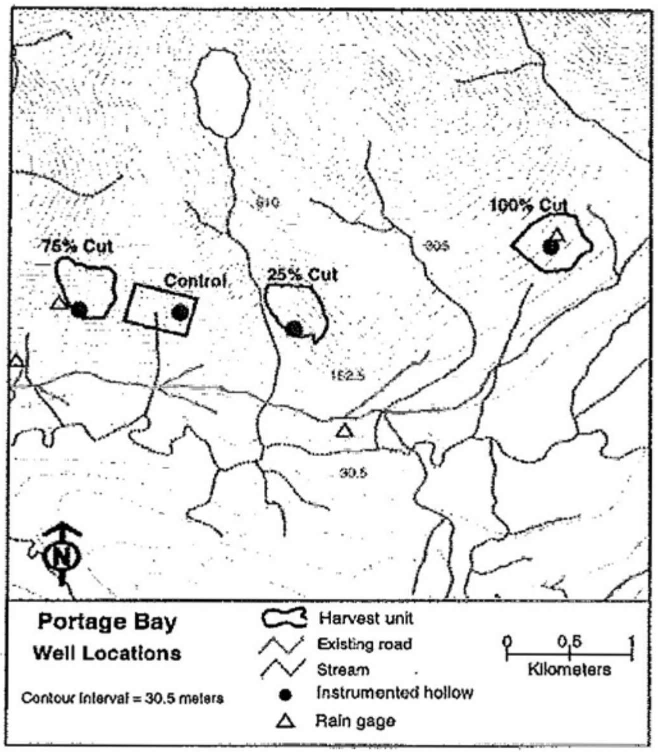

FIGURE 3. Study Site Locations within the Various Harvest Types for Portage Bay.

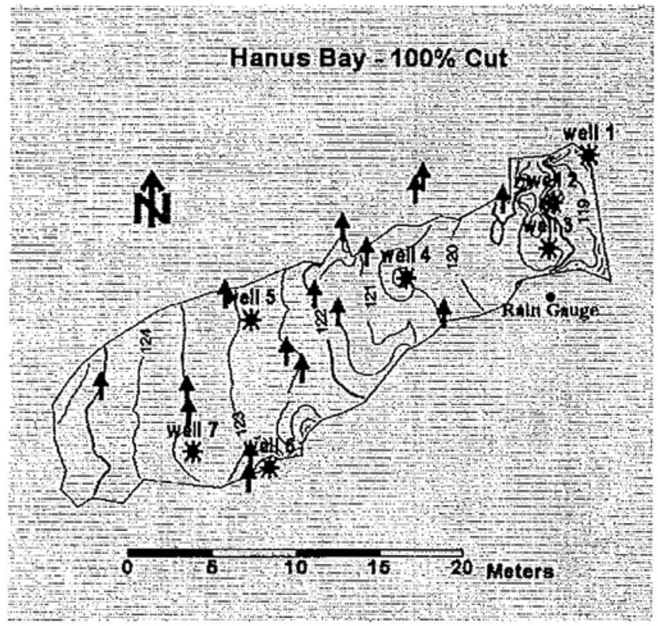

FIGURE 4. Instrumented Hollow with Well Sites and Tree Locations Before Harvest at Hanus Bay. Note: Tree placement is accurate, but not drawn to scale. All elevations are a relative measure from a 100 m datum. See Table 1 for actual elevation.

averages 250 cm with a mean annual temperature of 7°C. Rainfall is generally heaviest from September to November (Selkregg, 1976). Rainfall is frequent, generally falling >80% of the days of the year. During the study, winter snow pack observed at Hanus Bay sites in May disappeared during June. At Portage Bay, the snow pack disppeared consistently during April.

METHODS

Ground- Water Monitoring

Clusters of seven ground-water monitoring wells were installed within single hollows (Figures 4 and 5), defined as nonchannelized bedrock controlled concavities on hillsides. Hollows typically collect colluvium, woody debris, and water; and have been considered primary source areas of landslides (Dietrich and Dunne, 1978). Wells were installed within each of the harvest intensity types (two locations each with four treatments, totalling 56 wells). Because the harvests were uniform, it was assumed that the instrumented site (hollow) had the same

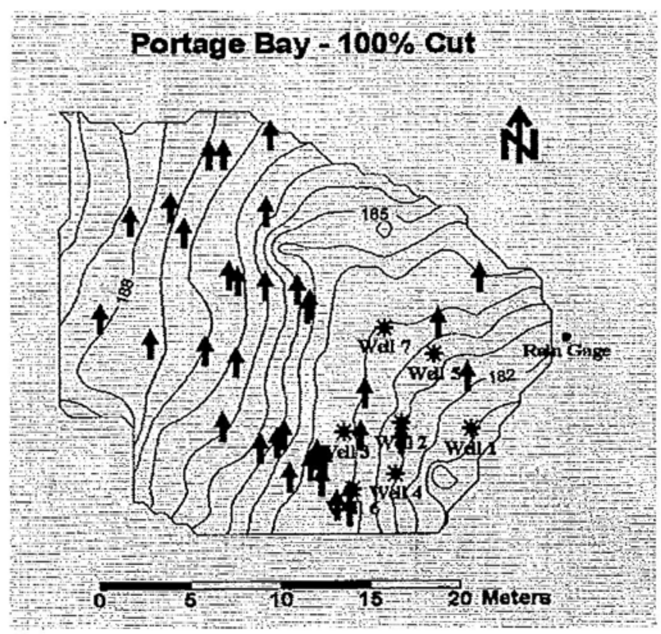

FIGURE 5. Instrumented Hollow with Well Sites and Tree Locations Before Harvest at Portage Bay. Tree placement is accurate, but not drawn to scale. All elevations are a relative measure from a 100 m datum. See Table 1 for actual elevation.

percent basal area standing timber as the harvest unit. Although harvest units, with various treatment types were random, site selection within the treatments was subjective. Sites were selected to avoid any influence of road surfaces, have hollow topography, and soil depths >0.25 m. Wells, installed to the perceived bedrock contact, were spaced 2-10 m apart to avoid large woody debris, extensive tree roots, and large rocks. Thus, soil depths at the wells were the same as the well depth.

The wells were connected to pressure transducers and data loggers. Data loggers, scanning every 5 s, recorded mean water levels (resolution of 0.001 m) at 0.5-1.0 h intervals. Preharvest water levels were recorded continuously from October 1994 to August 1996 at Hanus Bay and continuously from June through October 1996, April through October 1997, and May through August 1998 at Portage Bay. Postharvest water levels were recorded continuously from May through October 1998 and May through November 1999 at Hanus Bay and from May through October 2000 and May through October 2001 at Portage Bay. A few periods of freezing, identified by temperature gages, were excluded from the data set. Rainfall was measured with tipping-bucket rain gages (resolution of 0.01 in. or 0.25 mm) at or near the site (Figures 2 and 3). Alternate rain gages, needed when mechanical failure occurred, were located within 2.5 km. Mechanical failure occurred as a result of vandals, bear, or small mammal activity. Following site preparation, maps of sites, including well and tree location, were developed from 1 m resolution topographic data derived from surveys made with a laser total station. Slope gradient at each well was determined from these maps. As the survey was not conducted above the perceived hollow, we did not attempt to quantify the total area contributing to each well.

Statistical Analysis

The twenty 48-h. storms with the greatest amount of total rainfall were selected from the dataset before and after harvest for each of the four harvest types at the two locations. The storms were selected in nonfreezing periods with no snow pack during the months of April through November. Storms, often lasting 48-h, had peak levels of saturation during the same time period. Only storms preceded by < 5 mm of total rainfall for the three days prior to each storm event were used in the dataset. This criterion insured having soil measurements with low antecedent soil moisture and enough storms for data analysis. .The dataset would have included less than twenty storms to analyze if <5:4 mm of rain was required between storm periods. Total 48-h precipitation in selected storms ranged from 5 to 100 mm. Rainfall intensities ranging from 5 to 42 mm/h, all increased the levels of saturation. Highest levels of saturation did not always coincide with the highest rainfall amounts. The dataset captured the observed peak leve1s of saturation for this period of record.

For the twenty storms before and twenty storms after harvest for each treatment type, we regressed ground saturation and percent of saturation (water height/soil depth) against total 48-h rainfall. We ran separate regressions for pretreatment and post-treatment conditions for each harvest type at each study location using two measures of percent of ground saturation: 48-h maximum and 48-h mean. Forty-eight hour maximum values were used from wells within each treatment had the highest response (not always the same well) and 48-h. mean is the arithmetic average of all wells within each treatment. Differences between the slopes of regression lines (pretreatment *vs.* post-treatment) were then tested for statistical significance using analysis of covariance ($a = 0.05$). Analysis of covariance, commonly used in observational studies to compare pretreatment and post-treatment effects, was warranted because ofthe innate uncontrollable environmental conditions (Cochran, 1983; Snedecor and Cochran, 1989) including variation in storm duration and intensity. Such non-uniformity of storms, made use of simple t-tests invalid. Tests were conducted for eachresponse measure (maximum and mean) per harvest treatment type (0%, 25%, 75%, and 100%). When analysis of covariance indicated no significant difference between the slopes of the regression lines, differences in the *y* intercept were tested using a common regression slope (Zar, 1999). Residual plots, used to assess variance of data, assured that assumptions of covariance tests were met.

Slope Stability

Once any difference in soil saturation was quantified using equations derived from analysis of covariance tests, resulting values were used in an infinite slope stability equation, a simple model, appropriate for the shallow and wide landslides of the area. The model was used to evaluate the relative influence of changes in soil saturation between old-growth forests and forests that had been cut 100%. We did not conduct stability analyses on 25% and 75% harvests because of the uncertainties in estimating loss of cohesion as a result of changes in root strength. The infinite slope stability model calculates the factor of safety (FS): the ratio of the shear strength (S) to shear stress (r) along potential failure surfaces where theoretically, a critically stable slope would have a

TABLE 2. Parameters Used to Determine Factor of Safety for the Stability of Hillslopes within Cut and Uncut Forests.

Parameter	Definition	Source	Field Location	
			Hanus	Portage
Z (m)	Soil depth		0.27-0.76	0.41-1.28
M	Fraction of saturation	Direct measurement	0.0-1.0	0.0-1.0
α (degrees)	Slope	Direct measurement	14.0-35.0	16.0-35.0
C' (kPa)	Soil cohesion	Schroeder, 1983	7.3	7.3
C (kPa)	Cohesion from roots	Swanston, 1970; Burroughs and Thomas, 1977; Wu *et al.*, 1979; O'Loughlin and Zeimer, 1982	0.9 for clearcuts, 4.6 for forest at Hanus and Portage	
γsat (kN/m^3)	Sat. unit weight of soil	Schroeder, 1983	13.45	13.5
γm (kN/m^3)	Field unit weight of soil	Schroeder, 1983	8.6	10.7
γw (kN/m^3)	Unit weight of water		9.81	9.81
Wt (kN/m^3)	Unit weight of vegetation	Sidle, 1992	5.0	5.0
Ø (degrees)	Internal angle of friction	Schroeder, 1983	36.2	36.2

FS = 1 (Terzaghi, 1943; Sidle *et al.*, 1985). Theoretically, an unstable slope would have a FS < 1, but because of other unknown conditions present a factor of safety less than 1.3 has been considered unstable (Senneset, 1996). We assumed slope-parallel flow and relatively impervious bedrock aridlor till, a reasonable assumption based upon field observations of water flow at cut banks and the large difference in the permeability of the soil arid till or bedrock. Although the mechanics of hillslope failure are greatly simplified in the infinite slope model (i.e., two-dimensional representation of the slope with homogenous soils), reasonable agreement between analyses of effective strength (based on parameters reported here) have been found for an actual landslide in southeast Alaska (Sidle and Swanston, 1982). The factor of safety has been defined as (see Table 2 for a summary of parameters):

$$FS = \frac{S}{\tau} \quad (1)$$

where

$$S = C' + C + (\sigma - u)\tan\theta$$

$$\tau = [(1 - M)\gamma_m + M\gamma_{sat}Z\sin\alpha\cos\alpha + Wt\sin\alpha$$

$$u = MZ\gamma_w\cos^2\alpha$$

$$\sigma = [(1 - M)\gamma m + M\gamma_{sat}]Z\cos^2\alpha + Wt\cos^2\alpha$$

$$M = h/Z$$

Percent saturation (referred to simply as saturation later in the text) of the soil (M) was determined by the vertical height of the water table above the bedrock (h) and site-specific values of soil depth (Z) (Figure 6). Site-specific values of slope (a) were also used in the calculations. Other parameters, including saturated unit weight of soils (ym), unit weight of vegetation (Wt), and internal angle of friction (O/) were taken from other studies in SE Alaska to evaluate hillslope stability in healthy mature forests and forests that had been clearcut (Schroeder, 1983; Sidle, 1992).

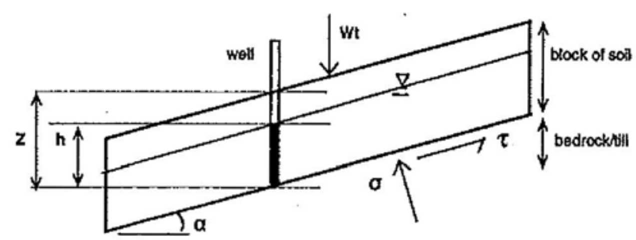

FIGURE 6. Illustration of Terms Used in the Infinite Slope Stability Equation. Illustration modified from Johnson and Wilcock (2002).

Cohesion as a result of root strength (C) was assumed to be 6.4 kPa before trees were cut. This value is the average of root cohesion values found for healthy forests of SE Alaska, Oregon, and Idaho, where estimated values of apparent soil strength contributed by roots have been found to fall between 1.0 and 17.5 kPa (Swanston, 1970; Burroughs and Thomas, 1977; Wu *et al.*, 1979). Following harvest, we assumed the cohesion due to roots was reduced to 0.9 kPa (because of the removal of trees), using an 86% reduction in cohesion in root strength found by others (O'Loughlin and Zeimer, 1982). Values as low as 0.0 kPa (100% loss of cohesion because of the root strength) have been used in hillslope stability equations in southeast Alaska where high lead logging techniques tended to destroy understory vegetation (Sidle, 1984). In this project, helicopter logging reduced ground disturbance, understory vegetation was not severely impacted, and an 86% reduction in cohesion as a result of root strength was more.

applicable. We assumed that the cohesion due to root strength is the same at Portage Bay and Hanus Bay.

RESULTS

Saturation

Increased 48 h rainfall was associated with increased percent soil saturation for the 0%, 25%, 75%, and 100% harvest treatments. At the Hanus uncut control, 40 mm of rain completely saturated the soil profile (saturation is 1.0, water height is equal to soil depth; if >1.0 water flowed on ground surface; Figure 7c), whereas at the Portage control site, 40 mm of rain corresponded to a maximum level of 0.52 (Figures 7c and 7a); differences attributed to the shallower soils at Hanus Bay.

Because analysis of covariance indicated no significant difference between the slopes of the regression lines before and after harvest for any treatment at any site (Figures 7-10), differences in the *y* intercept were tested using a common regression slope average (Ave. sat.) and maximum saturation (Max. sat.). Through this analysis, it was found that changes within five out of eight treatments were not significant statistically (Table 3). At the uncut control sites, for both average and maximum response, there was no significant change in the years before harvest and years after harvest (p = 0.09-0.62) (Figures 7-10, Table 3). There was also no significant difference in the well with highest response or the arithmetic average of all wells within each treatment following 25%, 75%, and 100% forest harvest at Hanus Bay (p = 0.14-0.62, Table 3). Maximum and mean saturation at Portage Bay were significantly different following 25%, 75%, and 100% cutting treatments ($p < 0.01$) except for mean saturation at the 75% cutting treatment (p = 0.11, Table 3).

Equations derived from analysis of covariance tests, for statistically significant changes in saturation (Table 4), were used to estimate the amount of rain (mm) needed for given levels of saturation before harvest and within the various harvest treatments. Before the forest was cut 100% the average amount of rain needed for 50% saturation of the soil was 54 mm, but after cutting, the amount of rain needed for 50% saturation was 21 mm, After 100% harvest, the maximum saturation for 62 mm of min was 0.9, corresponding to a preharvest saturation of 0.74 (Figure 11). There was a 22%, 29%, and 34% reduction in rainfall needed to saturate the soils at the respective 25%, 75%, and 100% harvested Portage Bay sites.

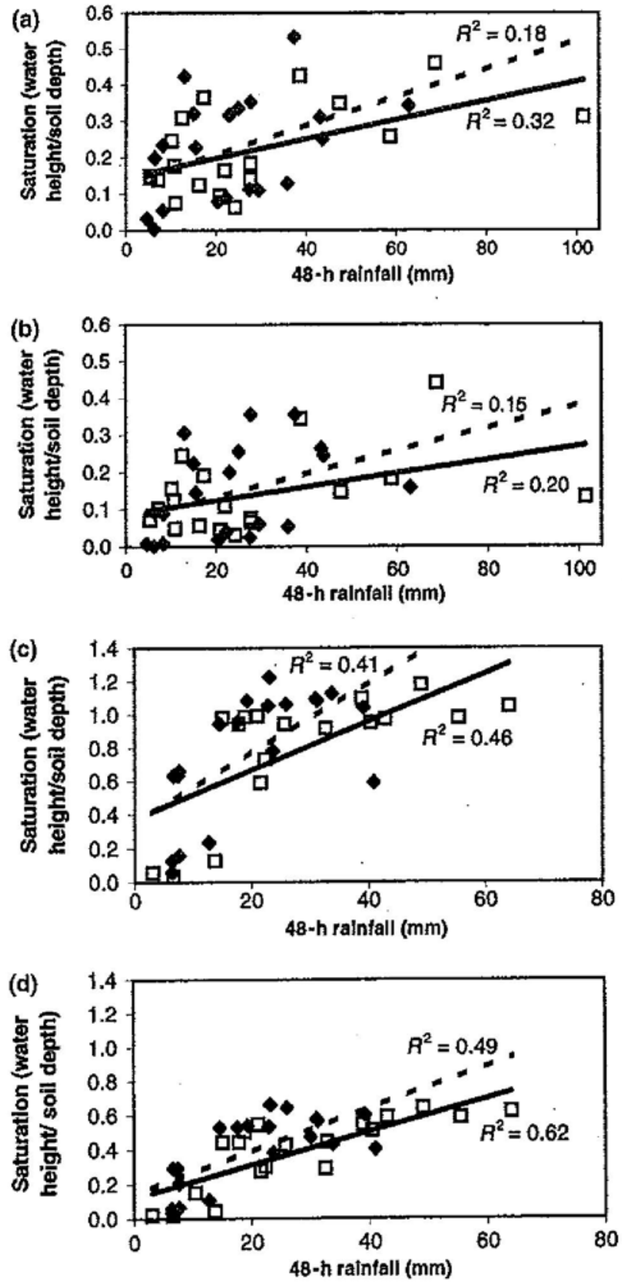

FIGURE 7. Comparison of Pre-Harvest and Post-Treatment Time Periods at the Control (Non-Harvested) Sites: (a) Portage Bay, Maximum Response; (b) Portage Bay, Mean Response; (c) Hanus Bay Maximum Response; (d) Hanus Bay Mean Response. Black diamonds and dotted lines indicate saturation before pre-treatment time period. Open squares and solid lines represent post-treatment time period. Because no significant difference exists between the slopes of the regression lines before and after harvest for treatment, differences in the y intercept were tested using a common slope. There is no significant difference between the two time periods (p = 0.09-0.62). See Table 3 for more results of statistical tests.

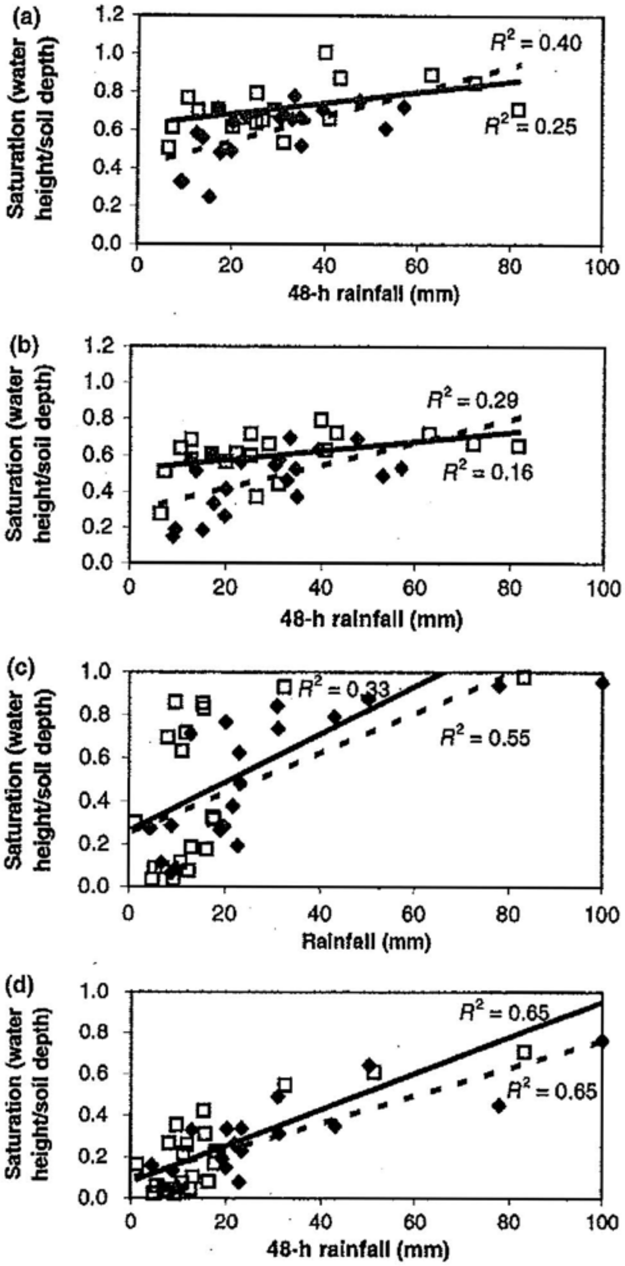

FIGURE 8. Twenty-Five Percent Cut Treatment Results for: (a) Portage Bay, Maximum Response; (b) Portage Bay, Mean Response; (c) Hanus Bay Maximum Response; (d) Hanus Bay Mean Response. Black diamonds and dotted lines indicate saturation before treatment. Open squares and solid lines represent saturation after treatment. Because no significant difference exists between the slopes of the regression lines before and after harvest for treatment, differences in the y intercept were tested using a common slope. There is significant difference after treatment for maximum response and average response for Portage ($p < 0.01$). There is no significant difference after treatment at Hanus ($p = 0.46$). See Table 3 for more results of statistical tests.

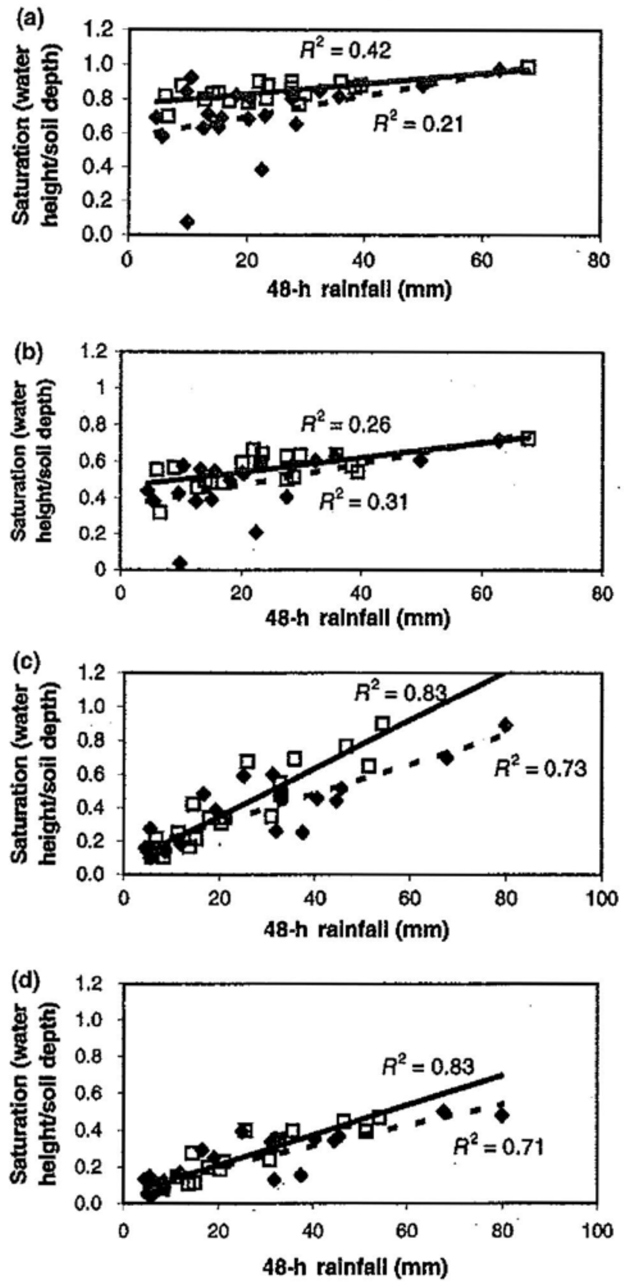

FIGURE 9. Seventy-Five Percent Cut Treatment Results for: (a) Portage Bay, Maximum Response; (b) Portage Bay, Mean Response; (c) Hanus Bay Maximum Response; (d) Hanus Bay Mean Response. Black diamonds and dotted lines indicate saturation before treatment. Open squares and solid lines represent saturation after treatment. Because no significant difference exists between the slopes of the regression lines before and after harvest for treatment, differences in the y intercept were tested using a common slope. There is no significant difference after any treatment at Hanus ($p = 0.09$–0.14) or for average saturation at Portage ($p = 0.11$) while the change in maximum saturation at Portage is significant ($p < 0.01$). See Table 3 for more results of statistical tests.

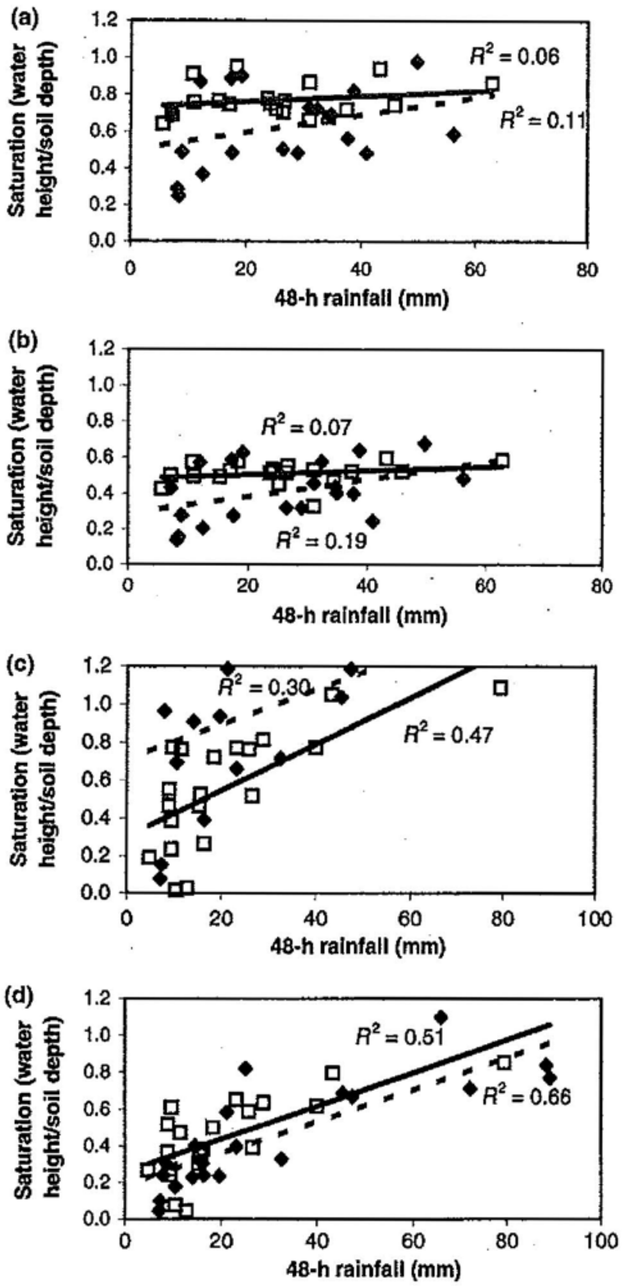

FIGURE 10. Cut Treatment Results (100%) for: (a) Portage Bay, Maximum Response; (b) Portage Bay, Mean Response; (c) Hanus Bay Maximum Response; (d) Hanus Bay Mean Response. Black diamonds and dotted lines indicate saturation before treatment. Open squares and solid lines represent saturation after treatment. Because no significant difference exists between the slopes of the regression lines before and after harvest for treatment, differences in the y intercept were tested using a common slope. There is a significant difference after treatment for maximum response and average response for Portage ($p < 0.01$), but no significant difference after harvest at Hanus ($p = 0.13$-0.62, see also Table 3).

Slope Stability

For the observed storms, the infinite slope stability equation indicated that the selected sites were stable before and after cutting treatments. At the Portage 100% harvest site, changes in average saturation from 0.49 to 0.60, given .53mm of rain, resulted in FS of 2.5 and 1.8 for the two most unstable well locations. Soil depths and slopes at those wells were 0.8 m and 35°, and 1.1 m and 24°, respectively, Maximum levels of saturation for these. same sites, increased from 0.74 to 0.92, and had FS of 2.2 and 1.5. For all combinations of soil depth, slope gradient, and saturation found at the Portage 100% cut sites, FS varied from 3,0 to 1.8 before harvest to 2.8 to 1.5 after harvest. The highest levels of saturation occurred when rainfall fell on wet soil. This typically occurred during 48-h. storms having several periods of high intensity rain. When total saturation of the soil was assumed, the FS was 1.6 (0.88 m soil depth and 22° slope gradient).

Using the slope stability model and observed saturation responses, we varied slope gradient to determine at what gradients destabilization of slopes would theoretically occur. For destabilization of the hillslope, slopes gradients would have needed to be >36°. At a soil depth of 1.25 m and slope gradient of 36°, the FS decreased to 1.2, nearing instability (Figure 12).

DISCUSSION

Soil Saturation

Portage Bay ground-water height is raised as much as 0.06, 0.14, and 0.14 m, respectively following 25%, 75%, and 100% harvest. These values are derived from differences in Equations (8) and (9), (10) and (11), and (12) and (13), in conjunction with the soil depths of 0.52, 1.18, and 0.87 m, respectively for maximum levels of saturation found at individual ground-water monitoring wells.

A lack of difference in soil saturation following harvest at Hanus Bay may be due to site characteristics. Although harvest was generally executed to assure specific basal area reduction, other features including tree density and spacing, regional landform, contributing area, soil depth, and soil macropores were not control1ed.

Because trees were not uniformly distributed and harvest was not exactly uniform, the intended harvest goals were not reached precisely throughout the harvest unit or within the measured hollows. The act-

TABLE 3. Results of Covariance Statistical Tests for Differences in Ground Saturation Associated with Cutting Treatments.

Location and Treatment (% Harvest)	Maximum Saturation			Average Saturation		
	p-Value	R^2	MSE	p-Value	R^2	MSE
Portage						
0	0.62	0.23	0.12	0.60	0.53	0.14
25	<0.01	0.41	0.12	<0.01	0.35	0.13
75	<0.01	0.34	0.14	0.11	0.33	0.11
100	<0.01	0.27	0.16	<0.01	0.26	0.12
Hanus						
0	0.50	0.37	0.29	0.09	0.53	0.14
25	0.46	0.66	0.12	0.46	0.66	0.12
75	0.09	0.78	0.12	0.14	0.62	0.09
100	0.60	0.35	0.33	0.13	0.60	0.16

Analysis of covariance indicated no significant difference between the slopes of the regression lines before and after harvest for any treatment at any site, so differences in the y intercept were tested using a common regression slope. Differences are judged to be significant at $p \leq 0.05$, MSE = mean squared error. Significant differences are highlighted in bold type. Regression equations were developed for significant differences (Table 4).

TABLE 4. Regression Equations Derived from Analysis of Covariance Statistical Tests.

	Equation number
Ave. sat. $_{before}$ 25% cut = 0.3677 + 0.0036 * (rain)	(4)
Ave. sat. $_{after}$ 25% cut = 0.4867 + 0.0036 * (rain)	(5)
Ave. sat. $_{before}$ 100% cut = 0.3321 + 0.0031 * (rain)	(6)
Ave. sat. $_{after}$ 100% cut = 0.4351 + 0.0031 * (rain)	(7)
Max. sat. $_{before}$ 25% cut = 0.4801 + 0.0040 * (rain)	(8)
Max. sat. $_{after}$ 25% cut = 0.5923 + 0.0040 * (rain)	(9)
Max. sat. $_{before}$ 75% cut = 0.6188 + 0.0041 * (rain)	(10)
Max. sat. $_{after}$ 75% cut = 0.7368 + 0.0041 * (rain)	(11)
Max. sat. $_{before}$ 100% cut = 0.5370 + 0.0033 * (rain)	(12)
Max. sat. $_{after}$ 100% cut = 0.6956 + 0.0033 * (rain)	(13)

With Analysis of covariance indicating no significant difference between the slopes of the regression lines before and after harvest for any treatment at any site, differences in the y intercept were tested using a common regression slope. Only equations reflecting significant differences in saturation following harvest are presented. Significant differences were only found at the Portage Bay sites. Average saturation = ave. sat., maximum saturation = max. sat.

ual number of trees cut in the instrumented hollow at the Hanus 25% unit was 60% (3 out of 5 trees) whereas at the Portage Bay 25% harvest unit, 29% of the trees in the instrumented hollow were removed (4 out of 14 trees). The exact number of trees affecting hydrology of the instrumented sites is undetermined and therefore, the assumption was made that tree removal in the contributing area occurred at the intended intensity. Given that the average tree in the Hanus unit has three times the volume of the average tree in the Portage unit (different basal area, similar number of trees; Table 1), it would be expected that the soil saturation change following harvest would be greater at Hanus than Portage.

Locations of frequent soil saturation, as indicated by forest composition, are affected more by regional landform than by forest harvest.. Yellow cedar, a species associated with wetter soils (Neiland, 1971; Hennon *et al.,* 1990) comprises more than 40% of the trees at the Hanus Bay 100% harvest site whereas on the rest of the sites, vegetation is gener-

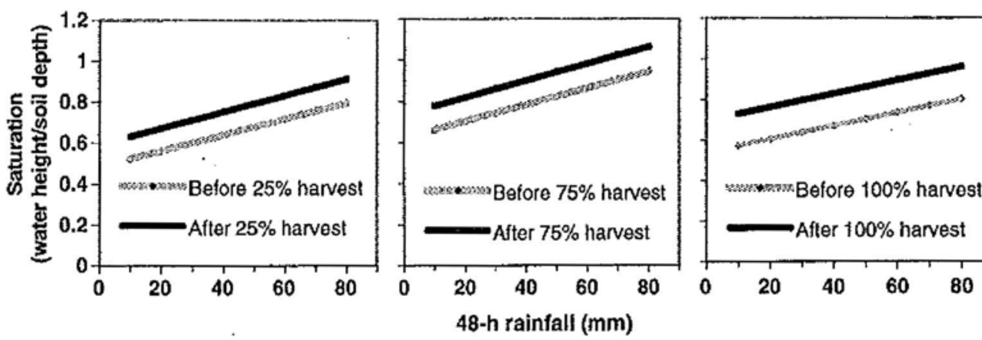

FIGURE 11. Maximum Saturation as a Function of 48-h Rainfall Using Equations Derived from Analysis of Covarience Statistical Tests (Table 4). This analysis pertains to all sites at Portage Bay.

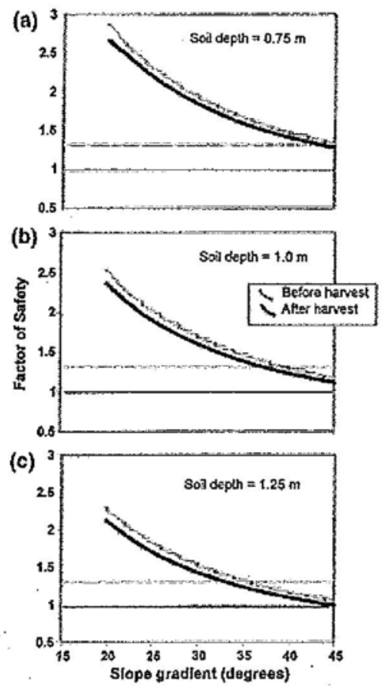

FIGURE 12. The Effect of Increasing Soil Depth and Slope Gradient with Maximum Soil Saturation Before and After 100% Harvest on the factor of safety (FS) Given 53 mm of Rain. Gray lines indicate factor of safety before harvest and black lines indicate factor of safety after harvest. Theoretically, an unstable slope would have a FS ≤ 1, but because of other unknown conditions present a factor of safety less than 1.3 has been considered unstable (Senneset, 1996).

ally a uniform mix of hemlock and spruce, indicative of drier soils (Table 1). The presence of yellow cedar suggests that the sample location is in an area of ground-water discharge, The two wells at Hanus (wells 6 and 7) having greatest change in saturation following harvest are at the top of the bedrock hollow and thereby have small contributing area with little influence from the cutting treatment (Figure 4). Wet soils at this site may indicate that soil saturation is associated more with broader landscape position than with cutting treatment and bedrock hollow topography,

Frequent soil saturation may be affected more by distances to rivers than by cutting treatments. Unlike the Portage Bay sites, two of the four Hanus Bay sites were located on mountain foot slopes at a distance of < 0.5 km to a river (Figure 2)..Others have found that ground-water height may relate more closely to distance to streams than to contributing area size (Seibert *et al.,* 2003),

Given the same amount of rain· and similar forest attributes, sites with shallower soil depths should become more saturated than sites with deeper soils. Hanus Bay, with shallower soils does tend to have higher levels of saturation both before and after cutting than Portage Bay. For example, given < 40 cm of rain at the average l00% cut sites, saturation surpasses 0.80 at Hanus and is <0.65 at Portage (Figure 10). Because soil saturation change is not statistically significantly different following harvest at Hanus Bay, any comparison of an overall trend is inconclusive.

Given the likelihood of subsurface flow through macropores (McDonnell, 1990; Anderson *et al., 1997;* Keim, 2003; Dhakal and Sidle, 2004), it is possible our wells did not measure total change in ground saturation following harvest. Smaller sites with fewer trees might not appear to· change following timber harvest because subsurface flows have been routed away from the site through macropores. Of the two hollows, the Portage Bay 100% cut site is larger and preceding harvest had >10 trees above each of the wells while Hanus Bay site had fewer trees (<10) above the wells. Because a ground survey was not conducted above the perceived hollow, we did not attempt to quantify the total area contributing to each well.

Ideally, the area contributing to each instrumented site would be known, detailed soil depth and snow depth information would be available, the area above the wells would have uniform spacing of similar sized trees, and the harvests would have been made on similar elevations. Having this detailed information, creation of a physically based model to predict saturation would have been possible. In lieu of these absences, statistical analysis was used to assess change in saturation following harvesting.

Slope Stability

Although changes in soil saturation following timber harvest may have a dramatic effect on hillslope stability, that was not the case at the chosen field sites for the range of storms observed. Increases in saturation lead to FS reductions of up to 17% for the soil characteristics found at in our study. At the slope gradients and soil depths of the Portage Bay field site, these reductions do not affect the potential for landslides dramatically; the largest drop in factor of safety goes from 1.8 to 1,5.

While landslide producing storms are infrequent and difficult to capture during short-term monitoring efforts, observed increases in saturation could destabilize nearby hillslopes having greater slope gradient or deeper soils. Study sites, oxcluding slope, are similar to sites where hillslope failure is common (Sidle and Swanston, 1982); and soil failures have occurred within distances of 0.25 km to the Hanus and Portage Bay sites. Because future harvest will occur on inherently less stable sites (in southeast Alaska and elsewhere), model results are useful in determining how observed saturation could affect hillslope stability in sites having greater soil depths and steeper slopes. Results indicate that forests in the Portage Bay area could experience increased landsliding following 100% harvest in steeper areas or where soils are deeper.

Because hil1slope responses were measured with wells instead of piezometers, our model predictions likely underestimate the potential for hillslope destabilization. Piezometers would have allowed measurement of artesian pore pressure (saturation >1.0) which· greatly reduces hillslope stability through liquifaction of the soil (Terzaghi, 1943). At pore pressures >1.0, hillslope failure can occur on lower slope gradients and on shallower soils than were examined in this study. For example, using the infinite slope stability equation for the soil conditions used in our analyses, a FS of 1.0 is possible with a slope gradient as low as 32° having a soil depth of 1.25 m and a pore pressure of 1.1 (saturation of 1.38). A FS of <1.3 is possible with a soil depth of 0.8, a pore pressure of 1.2, with a slope gradient of 36°.

CONCLUSION

Understanding the potential change in ground-water height following harvest is important in predicting the influence of timber harvest on hillslope stability. This understanding, currently lacking in many regions of the world undergoing forest harvest, benefits management plans geared at limiting increases in stream sediment loading resulting from mass wasting. In this study, the influence of harvest varied greatly with location and local site characteristics. One of the two study locations showed statistically significant maximum soil saturation (water height/soil depth) increases of 0.14, 0.12· and 0.11 following 100%, 75%, and 25% harvest, respectively, while average soil saturation increases were 0.10 for 100% harvest and 0.11 for 25% harvest ($p < 0.05$). Given the characteristics of the chosen field sites, these irioreases do not dramatically affect hillslope stability, but could do so in nearby areas with greater slope andlor greater soil depth. Ground-water height, and thus, soil saturation, was largely dependent on various hillslope characteristics including forest type and density, slope gradient, soil depth, and proximity to surface drainage features. Although it was not in the scope of this study to test hypotheses associated with various factors influencing saturation such as contributing area, number of trees harvested, and regional location, it is clear that additional research on those factors would address fundamental issues in landscape hydrology that have application to forest management.

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