JOURNAL OF HYDROLOGY
NEW ZEALAND

Published twice annually by the New Zealand Hydrological Society

Volume 19 1980 Number 1

PIEZOMETRIC RESPONSE TO RAINSTORMS IN FORESTED HILLSLOPE DRAINAGE DEPRESSIONS

Thomas C. Pierson

Quaternary Research Center, University of Washington,
Seattle, Washington 98195

Present address: Forest Research Institute, P.O. Box 31-011, Christchurch

ABSTRACT

Monitoring of piezometric head in three steep, adjacent, forested hillslope drainage depressions during rainstorms has shown that soil pore-water pressure is highest along depression axes, although not at the downhill ends of the depressions. A storm with a recurrence interval of only 3 to 4 years is sufficient to bring about complete saturation in the axes of some hollows. While two variables, rainfall and antecedent soil moisture, together explain over 90% of the variance in piezometric response at a hillslope site, considerable variation in piezometric response can occur between different depressions (for equal catchment area), presumably due to differences in water retention capacity of the soil. This implies that soil in apparently similar hollows on the same slope may vary greatly in its susceptibility to slope failure.

INTRODUCTION

The effect of topographically convergent hillslope sectors on runoff concentration and saturation build-up in soil has been well demonstrated in the field (Dunne and Black, 1970; Swanston, 1970; Anderson and Burt, 1978; Beven, 1978). The importance of such hillslope drainage depressions or hollows as initiation sites for landslides, especially the debris flow/debris avalanche type, has also been well demonstrated (Hack and Goodlett, 1960; Swanston, 1970; O'Loughlin, 1972; Williams and Guy, 1973; Bogucki, 1976; O'Loughlin and Pearce, 1976). The purpose of this study was to examine, as part of a larger study (Pierson, 1977), the variation in magnitude of soil piezometric head during and following rainstorms, and to isolate the factors controlling this variation, in steep drainage depressions that are typically initiation sites for debris avalanches and debris flows. Chosen for the study were three adjacent depressions (hollows) of differing catchment size and shape, situated in a steep, heavily forested watershed.

STUDY AREA

The hollows studied are located in the Perkins Creek watershed, west of the main divide, in the steeply dissected Oregon Coast Range, U.S.A. (Fig. 1). They are situated within 100 m of each other and have similar aspect, altitude, slope gradient, and vegetation, but differ in catchment area, degree of concavity and plan shape (Table 1; Fig. 2).

The colluvial mineral soil mantling these hillslope depressions is a cohesionless, brown to yellowish-brown, stony, sandy loam with weak horizon development (inceptisol). Forest litter is thin, ranging from 1 to 6 cm on the slopes and up to 10 cm on ridge crests. Underlying the soil is a hard, impermeable bedrock surface of massive feldspathic sandstone and siltstone. Soil is thickest along the axes of the hollows, generally 2 to 4 m, and thins to only a few centimetres on the spur ridges.

Particle size distribution of the soils is summarised in Table 2. These limited data and field examination of the soils indicate that in the downslope ends of hollows 2 and 3 the soil is coarser, less plastic, less aggregated, more permeable, and has better horizon development than the soil further upslope or in Hollow 1.

Average saturated hydraulic conductivity was measured in the field at the soil-bedrock interface in the lower ends of each of the hollows. Several tests were carried out at each site using the falling head method

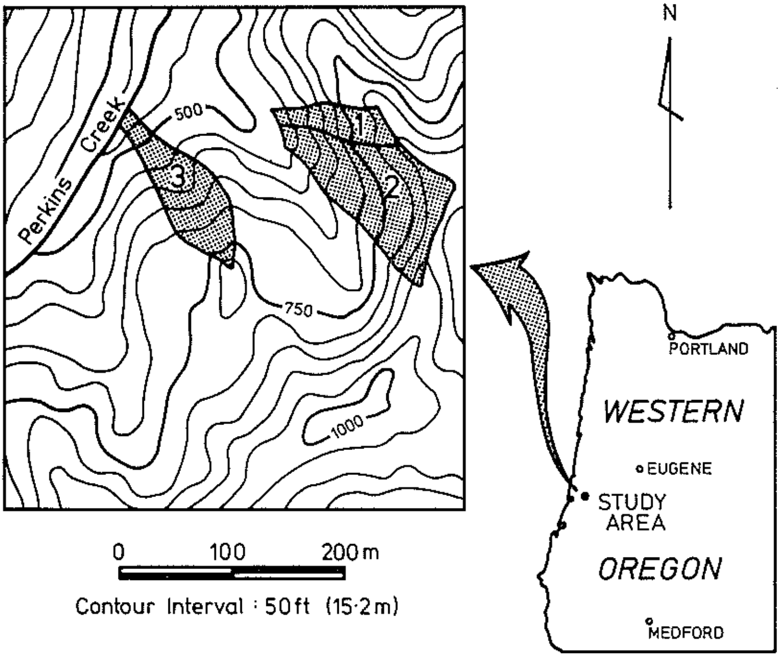

FIG. 1—Location of Perkins Creek study area and positions of the three monitored hillslope hollows.

TABLE 1—Topographic parameters of the hollows and piezometer sites at Perkins Creek.

Hillslope Hollow	Piezometer Site	Drainage Area (m^2)	Slope Angle (degrees)	Soil Thickness (perpendicular to slope) (m)	Concavity Index (depth/width at centre)	Elongation Index (Horton Form Factor, Rf[1])
1		1810	Average 39		0.15	6.1
	1A	274	36	2.2		
	1B	1321	35	1.5		
2		8580	Average 35		0.25	17.1
	2A	125	36	0.8		
	2B	1782	37	2.4		
	2C	4980	35	2.1		
	2D	7960	35	1.4		
3		6830	Average 34		0.20	12.3
	3H	100	37	1.6		
	3A	261	36	2.4		
	$3B_1$	2320	35	3.3		
	$3B_2$	50	45	1.3		
	$3C_1$	4330	32	4.0		
	$3C_2$	20	40	1.9		
	3D	5710	33	2.3		
	3E	—	39	0.5		
	3G	—	25	0.9		

[1] Strahler, 1964.

TABLE 2—Particle size distribution of soil at soil-bedrock interface at selected sites in the three hollows.

Piezometer site	Gravel (%)	Sand (%)	Silt & Clay (by dry sieving) (%)	Silt & Clay (by wet sieving) (%)	Sand-size Aggregates (%)
1A	16	75	9		
1B	26	68	6	22	16
2A	18	79	3	14	11
2D	43	55	2	6	4
$3B_1$	54	41	5		
3D	41	56	3		

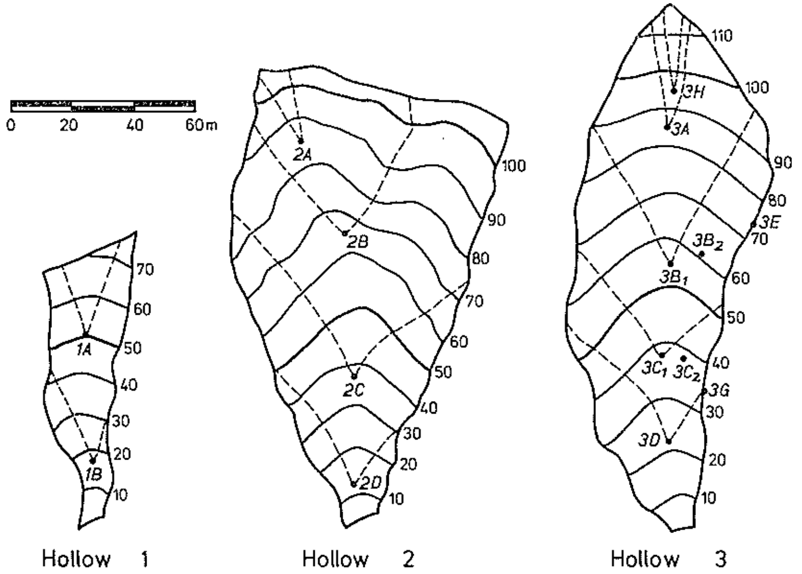

FIG. 2—Hollows monitored for the study. Piezometer sites are numbered and drainage area above each site is delineated by dashed lines.

(Reeve and Jensen, 1949) in the installed piezometers at sites 1B, 2D, and 3D. The mean permeabilities (k_{sat}) are lowest at 1B (3 cm/h), intermediate at 2D (24 cm/h), and highest at 3D (44 cm/h).

All three hollows support mature forest stands of Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western red cedar (*Thuja plicata*). Understory vegetation consists mainly of small stature hardwoods, woody shrubs, and ferns.

METHODS AND INSTRUMENTATION

Open standpipe piezometers were used to monitor piezometric head (h_p) during storms at the soil-bedrock interface at 15 sites—along hollow axes, on a sideslope, and on a spur. The piezometers were constructed of 1.3 cm inside diameter plastic pipe and sealed in place with bentonite or compacted soil. Their open ends were embedded in a filter of clean medium sand. Head was continuously recorded at sites 2D and 3D with back-pressure water level recorders (Helmers, n.d.), which were adjusted to respond to head changes within minutes. All other piezometers were checked periodically during storms and maximum levels were recorded with styrofoam crest-stage floats.

Rainfall data were collected with a recording raingauge on an open ridgecrest 0.5 km southwest of the hollows and with a standard gauge in a small forest clearing at the bottom of Hollow 3.

Antecedent soil moisture was estimated by three different methods: calculation of the Antecedent Precipitation Index described by Linsley and others (1975), measurement by prestorm h_p at sites 2D and 3D and summation of precipitation during several different prestorm time intervals.

RESULTS

Between January 1976 and May 1977, 27 storms causing rises in piezometric head in the hollows were recorded. A storm is defined here as a collection of rainfall bursts less than 6 hours apart; bursts separated by longer intervals ceased to have a combined effect on head. Total rainfall of these storms ranged from 8 to 157 mm (mean 35), with durations of 2 to 61 h (mean 18). Maximum 1-h intensities ranged from 2.5 to 12.7 mm. The largest storm (7 Jan. 1976) had a recurrence interval of 3 to 4 years (Miller and others, 1973).

Piezometric response to these storms ranged from complete saturation of the soil in the lower axial zones of Hollows 2 and 3 during the largest storm (with saturated overland flow running over the forest floor) to no response at all for rainfalls less than 8 mm in 6 h, 5 mm in 2 h, or 3 mm in 1 h. A variety of responses can be seen in Figure 3.

Timing of h_p rises was affected both by antecedent soil moisture and rainfall intensity (Fig. 4). Either more intense rainfall or wetter soil conditions can shorten the response time considerably. Head began rising 3 to 9 h after storms began and lag times between rainfall peaks and h_p peaks varied between 4 and 18 h.

Differences in the magnitude of piezometric response within hollows can best be seen in Hollow 3, where piezometers were located at sites

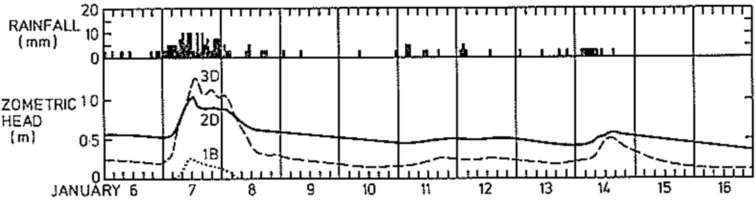

FIG. 3—Hourly rainfall and simultaneously recorded piezometric head monitored at the downhill end of each hollow for part of January, 1976, which show a range of responses. Plot for 1B passes through peak but is only sketched.

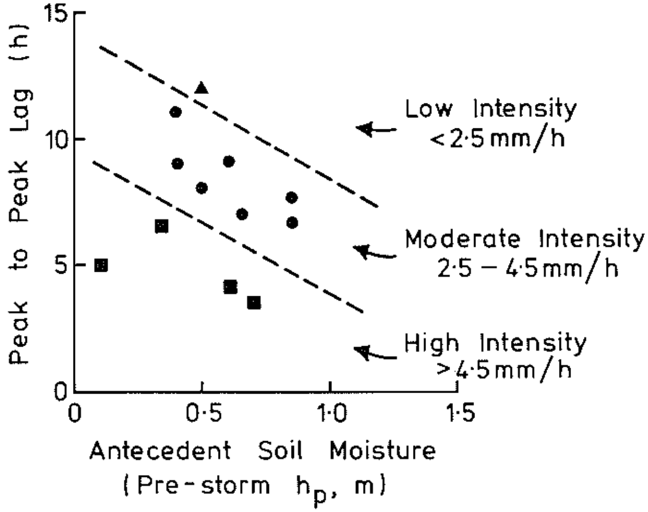

FIG. 4—Effect of antecedent soil moisture and 6-h rainfall intensity on peak to peak lag times (rainfall peak to h_p peak) at site 2D.

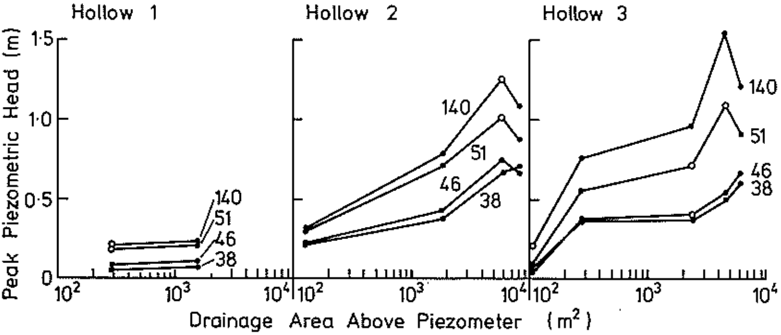

FIG. 5—Peak piezometric head achieved at axial sites plotted against drainage area for four different storms. The 24-h rainfall totals in mm are labelled. Missing values were estimated and indicated as open circles.

other than along depression axes. Highest h_p developed along the depression axis and generally increased in the downslope direction (Fig. 5). Maximum h_p during larger storms did not, however, occur at the site furthest downslope in this hollow or in Hollow 2 because of the draw-down effect at the downhill end (Schmid and Luthin, 1964), and/or because of decreasing soil thickness in the downslope direction. Thin saturated layers developed locally on the monitored side slope and spur during larger storms, but only at sites $3B_2$ and 3E. Total soil saturation was even observed on some side slopes where soils were particularly thin (0.2 m or less). The soil at sites $3C_2$ and 3G, however, never became saturated.

Differences in h_p magnitude between different hollows can readily be seen when piezometric head is plotted against hillslope catchment area (Fig. 5). The response in Hollow 1 was significantly smaller than in the other two. Larger storms were required for a saturated zone to appear at all (at least 30 mm in 24 hours), and even during the largest storm (140 mm in 24 h), h_p in Hollow 1 did not exceed 0.24 m—less than a third of the levels reached at equivalent catchment areas in the other two hollows. A further difference was that h_p at site 1B was never observed to be more than a few centimetres greater than further uphill at 1A, which contrasts with the downslope build-up of saturation in Hollows 2 and 3.

Blockage of the piezometers was at first suspected to be the cause of these abnormally low readings. As a correction, new holes were augered and new piezometers installed next to the old ones. Still, the abnormally low readings continued. As a further check water was poured down the piezometer pipes; it dissipated readily into the soil, indicating an open connection. Interestingly, the soil from the lower profile excavated during installation of the new piezometers appeared to be saturated when handled, yet free water did not enter the auger holes.

Although Hollows 2 and 3 responded similarly, there were some minor differences between them as well, especially in rate of change in head (Fig. 3). Hollow 3 responded more quickly, having both steeper rising and falling limbs on its h_p-hydrograph than the larger Hollow 2. For small to moderate storms, Hollow 2 took roughly 50% longer to peak after its rise had begun, but for large storms there was much less difference between the two. Following storms, drainage (drop in h_p) proceeded 2½ to 5 times faster in Hollow 3 than in 2. After several days to a week of relatively rapid change, h_p levels in both became more constant, falling at rates of only 3 to 9 mm/d. Both of these hollows maintained saturated zones along their axes for weeks following storms. Baseflow from bedrock seepage, observed in many outcrops during dry periods, probably helped maintain this saturation in the lower parts of the soil profile.

The relationship between rainfall (RF) and h_p is shown in Figure 6 for the monitoring sites at the downslope end of each hollow. The data points for each hollow fit logarithmic curves of the form

$$h_p = a + b \log RF$$

with r^2 values of 0.77, 0.79 and 0.91 for Hollows 1, 2 and 3 respectively. Regression analyses were carried out with 24-h rainfall as RF. Total storm rainfall and 3, 6, 12, 36, 42, 60 and 72 hour rainfall totals turned out to be inferior indices of rainfall in terms of overall degree of correlation.

Some improvement in correlation was gained by adding another independent variable, AM (antecedent moisture as pre-storm h_p at the site), to the regression equation. Multiple regressions of the form

$$h_p = a + b \log RF + c\,AM$$

yielded improved coefficients of determination (R^2), namely 0.93 for

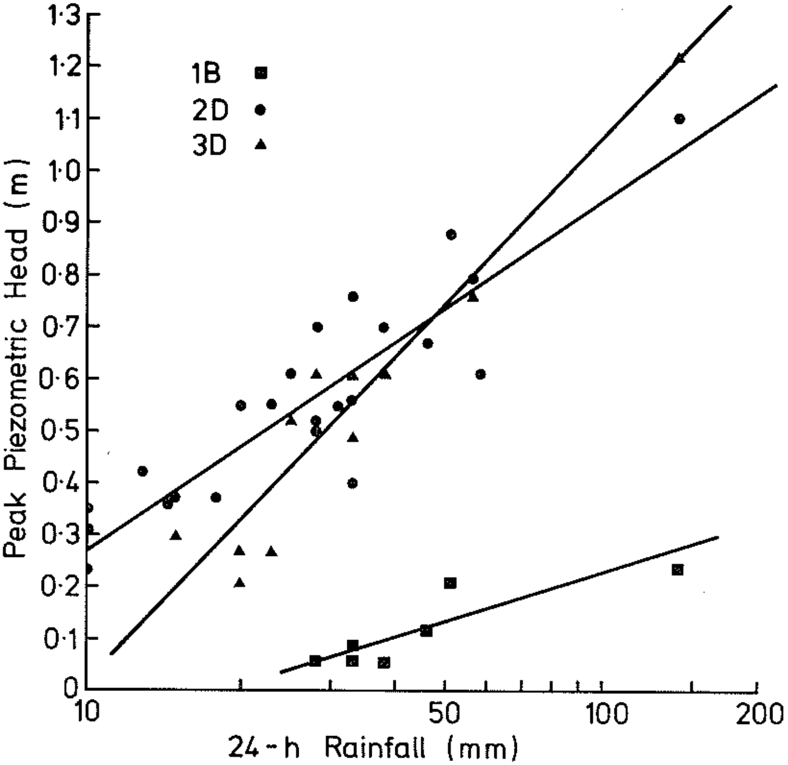

FIG. 6—Peak piezometric head at the axial sites furthest downhill plotted as a function of 24-h rainfall.

Hollow 2 and 0.92 for Hollow 3, improvements of 14% and 1% respectively. The other indices of antecedent soil moisture also improved the correlation, but not to the same degree as pre-storm h_p. An indication of how much piezometric head can be affected by antecedent soil moisture is revealed in the comparison of the responses to two different 33 mm storms in Hollow 2. The storm coming during wet antecedent conditions (prestorm h_p = 0.44 m) produced a head 0.36 m (90%) higher than the storm coming during dry antecedent conditions (prestorm h_p = 0.09 m) even though the first storm was much less intense (5.1 mm/h against 12.7 mm/h).

DISCUSSION

Piezometric response to rainstorms depends on a number of factors. Within a given drainage depression rainfall, catchment area, and antecedent moisture explain over 90% of the variation in response. But between different drainage depressions, differences in the magnitude of response can be very pronounced, and these three factors alone are inadequate to predict what piezometric head will be from one hollow to the next during a rainstorm.

Several possible explanations may account for the small piezometric response from Hollow 1, namely: (a) control may be exerted by catchment shape and topography, (b) soil water may be bypassing the soil matrix through preferred pathways such as root channels or bedrock fractures, or (c) the soil in Hollow 1 may have greater capacity for water retention.

The importance of shape and topography is unclear. The smallest piezometric response (per unit drainage area) did come from the catchment with lowest degree of concavity and the greatest elongation, as would be expected for larger drainage basins (Strahler, 1964), but the greatest response did not come from the most concave and least elongated catchment.

The second hypothesis was not supported by observations when soil pits at 1A and 1B were dug to bedrock. The soil appeared homogeneous with no obvious macropores or zones of flow concentration. A few small root channels were encountered but only in the upper metre of the profile. The bedrock surface beneath the soil was fresh and hard, with no open fractures.

The soil in both Hollow 1 soil pits did appear to be close to saturation, however, when sampled at depth immediately after storms, even though no free water had entered the piezometers. This observation, coupled with the higher silt and clay content (Table 2), lends support to the third hypothesis. Soil with a higher fines content would have a higher capacity for water retention storage because of the higher matrix potential afforded by the smaller pores. Only when this higher matrix potential is satisfied would water be able to enter the larger pores, drain to the base of the profile, and completely saturate the soil there. In keeping with this reasoning, positive pore pressures were monitored at the base of the profile at 1A and 1B only during the largest storms. If the soils in different hollows vary significantly in soil depth or in their grain size distribution, water retention capacity may also vary significantly and be reflected in differences in piezometric response. This hypothesis is only tenuously supported by field observations and limited soil data. Much more detailed work on variation in soil physical properties and subsurface flow pathways is needed to adequately explain such differences in piezometric response between hollows on a hillslope.

Despite the limited scope of this study, a clear implication for slope stability in such hollows is that, because depth of the saturation zone plays a key role in soil shear strength, adjacent, superficially similar hollows on a slope may vary significantly in their susceptibility to slope failure.

ACKNOWLEDGEMENTS

This investigation was supported by grants from the USDA Forest Service, the Geological Society of America, and the University of Washington. Special assistance was provided by D. N. Swanston, B. R. Thomas, the Dept. of Forest Engineering at Oregon State University, and the staff of the Mapleton District Office of the Siuslaw National

Forest. The contributions of A. L. Washburn and T. Dunne are gratefully acknowledged.

REFERENCES

Anderson, M. G.; Burt, T. P. 1978: The role of topography in controlling throughflow generation. *Earth Surface Processes 3:* 331-344.

Beven, K. 1978: The hydrological response of headwater and sideslope areas. *Hydrologic Sciences Bulletin 23:* 419-437.

Bogucki, D. J. 1976: Debris slides in the Mt Le Conte area, Great Smokey Mountains National Park, USA. *Geografiska Annaler 58A:* 179-191.

Dunne, T.; Black, R. G. 1970: Partial area contributions to storm runoff in a small New England watershed. *Water Resources Research 6:* 1296-1311.

Hack, J. T.; Goodlett, J. C. 1960: Geomorphology and forest ecology of a mountain region in the central Appalachians. *U.S. Geological Survey, Professional Paper 347.* 64 p.

Helmers, A. E. (nd): A versatile gas-operated water level recorder. Unpublished report, U.S. Dept. of Agriculture, Forest Service, Institute of Northern Forestry, Juneau, Alaska, 7 p.

Linsley, R. K.; Kohler, M. A.; Paulhus, J. L. H. 1975: *Hydrology for Engineers,* McGraw-Hill, New York. 482 p.

Miller, J. F.; Fredericks, R. H.; Tracey, R. J. 1973: *Precipitation-frequency atlas of the western United States, V. 10, Oregon,* U.S. Dept. of Commerce, Washington, D.C., 43 p.

O'Loughlin, C. L. 1972: A preliminary study of landslides in the Coast Mountains of southwestern British Columbia. p 101-11 in Slaymaker, H. O.; McPherson, H. J. (Eds): *Mountain Geomorphology,* B.C. Geographical Series No. 14, Tantalus, Ltd., Vancouver.

O'Loughlin, C. L.; Pearce, A. J. 1976: Influence of Cenozoic geology on mass movement and sediment yield response to forest removal, North Westland, New Zealand: *Bulletin of the International Association of Engineering Geology 14:* 41-46.

Pierson, T. C. 1977: Factors controlling debris-flow initiation on forested hillslopes in the Oregon Coast Range. Unpubl. Ph.D. Dissertation, University of Washington, Seattle. 166 p.

Reeve, R. C.; Jensen, M. C. 1949: Piezometers for groundwater flow studies and measurement of subsoil permeability. *Agricultural Engineering,* Sept. Issue: 435-438.

Schmid, P.; Luthin, J. 1964: The drainage of sloping lands. *Journal of Geophysical Research 69:* 1525-1529.

Strahler, A. N. 1964: Quantitative geomorphology of drainage basins and channel network. p 439-476 in Chow, V. T. (Ed): *Handbook of Applied Hydrology,* McGraw-Hill, New York.

Swanston, D. N. 1970: Mechanics of debris avalanching in shallow till soils of southeast Alaska. *U.S. Dept. of Agriculture, Forest Service, Research Paper PNW-103,* 17 p.

Williams, G. P.; Guy, H. P. 1973: Erosional and depositional aspects of Hurricane Camille in Virginia, 1969. *U.S. Geological Survey Professional Paper 804,* 80 p.