SIMULATION OF THREE LAHARS IN THE MOUNT ST. HELENS AREA, WASHINGTON USING A ONE-DIMENSIONAL, UNSTEADY-STATE STREAMFLOW MODEL

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CONVERSION FACTORS AND ABBREVIATIONS

For readers who may prefer to use inch-pound units rather than the the metric units (International System) used in this report, values may be converted by using the following factors:

Multiply metric unit	By	To obtain inch-pound unit
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	2.471	acre
	Volume	
cubic meter (m^3)	0.0008107	acre foot (acre-ft)
cubic meter (m^3)		cubic yards (yd^3)
	Flow	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Weight	
kilogram (kg)	2.2046	pounds (lb)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first order level nets of both the United States and Canada, formerly called "Mean Sea Level of 1929."

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ABSTRACT

A one-dimensional, unsteady-state, open-channel model was used to analytically reproduce three lahar events. Factors contributing to the success of the modeling were (1) the lahars were confined to a channel, (2) channel roughness was defined by field information, and (3) the volume of the flow remained relatively unchanged for the duration of the peak. Manning's "n" values used in computing conveyance in the model were subject to the changing rheology of the debris flow and were calculated from field cross-section information (velocities used in these calculations were derived from superelevation or run-up formulas). For the events modeled in this exercise, Manning's "n" calculations ranged from 0.020 to 0.099. In all lahar simulations, the rheology of the flow changed in a downstream direction during the course of the event. Chen's "μ", the mudflow-consistency index, changed approximately an order of magnitude for each event. The "μ" values ranged from 5 to 2,260 kilograms per meter for the three events modeled. The empirical approach adopted in this paper is useful as a tool to help predict debris-flow behavior, but does not lead to understanding the physical processes of debris flows.

INTRODUCTION

Because debris flows can frequently take lives and cause considerable property damage, it is important to better understand their behavior and to be able to predict their magnitude. Non-Newtonian dynamics of debris flow have not yet been developed to the extent where proven physical solutions can readily be used in digital-model simulation of actual events. Considerable information has already been generated by "adjusting" digital streamflow models to simulate debris-flow events. This approach has been used to simulate lahars (volcanically-originated debris flows) on Mount St. Helens (Swift and Kresch, 1983) and has been proposed as a viable technique for defining the flood-hazard assessment of the Mount Hood area. Streamflow models to simulate debris flows have also been used by others (Shen, H. T., and Huang, W., 1986; MacArthur, R. C., and others, 1987). To date, no streamflow modeling of debris flows made by the U.S. Geological Survey has been verified with actual data. This report provides this verification. The definition of rheologic parameters for a more physically-based model still needs to be evaluated. The approach described in this report can be used for many situations until a physically-based model with empirically defined rheologic parameters becomes available.

The purpose of this paper is to show that (1) a streamflow model can be used to simulate debris flows by adjusting Mannings "n", even though flow regimes of water and debris may be considerably different; (2) the Manning's "n" value computed from field measurements of run-up and superelevation is adequate to define the conveyance of that reach of a stream for that instant of time for the peak of the hyperconcentrated or debris-flow event; (3) Manning's "n" needs to be verified for a range of debris flows as has been done for water flows; and (4) additional research is needed to define the rheology of debris flows because existing data and physical solutions are insufficient to define a working debris-flow model.

Problem

In dynamic streamflow modeling there is a need to determine the channel conveyance. This normally requires a knowledge of the resistance to flow of the channel. For water, Manning's roughness coefficient (n) is often used as a parameter to define the flow resistance relation, and many publications define Manning's "n" empirically for a wide variety of situations. The familiar Manning's equation (Chow, 1959) is expressed as follows:

$$\bar{u} = \frac{R^{2/3} S^{1/2}}{n} , \qquad (1)$$

where

$\bar{u}$ = mean velocity, in meters per second (m/s);
n = coefficient of roughness;
S = slope of the energy gradient (dimensionless); and
R = hydraulic radius, in meters (m).

Most "n" value verifications have been made for low-gradient streams, and the corresponding values have ranged from 0.015 to 0.060. Jarrett (1984) has observed that "n" values are greater on steep-gradient streams where the flow regime is close to critical flow and is more turbulent. For steep-gradient streams that do not support a high rate of sand-size sediment transport, Jarrett has verified that "n" values range from 0.030 to 0.095. In flume experiments, Li and Simons (1982) found lower "n" values in flows that contained large quantities of sediment transport. Their experiments showed that "n" values can be 2 to 3 times lower than expected and streams may function as upper regime sand-bed channels with "n" values as low as 0.015.

Sediment and debris alter flow characteristics by changing bulk fluid density, viscosity, velocity distribution, and shear boundaries. Henderson (1966) has shown that "n" values can be modified according to the dependence of the Reynold's number. For debris and hyperconcentrated flows, there are more considerations:

(1) When particles deposit, the bed can be smoothed, and "n" values can decrease.

(2) When particles collide, energy is consumed, and "n" values can increase.

(3) When particles engage, suspended-sediment transport no longer occurs, and a matrix-supported debris flow exists.

For debris flows, our experience has shown that Manning's "n" can no longer be predicted by using traditional techniques of channel identification, because conveyance continually changes with the rheology of the flow. Debris flows change in consistency or behavior, or both, as they pick up or lose material and water content while moving downstream.

Chen (1983) expressed mean velocity of debris flows in terms of flow behavior, consistency, and yield stress, as follows:

$$\bar{u} = \left(\frac{\eta}{\eta + 1}\right) \left(\frac{\rho g S_o}{\mu}\right)^{\frac{1}{\eta}} \left(\frac{z_o}{h}\right)^{\frac{\eta + 1}{\eta}} \left[1 - \frac{\eta}{2\eta + 1} \left(\frac{z_o}{h}\right)\right] h^{\frac{\eta + 1}{\eta}} , \quad (2)$$

where η = the flow behavior index; ρ = bulk density of the mixture, in kilograms per cubic meter (kg/m^3); g = gravitational acceleration, in meters per square second (m/s^2); μ = the consistency index, in kilograms per meter (kg/m); z_o = distance from streambed corresponding to yield stress, in m; and h = flow depth, in m.

Specifically, Chen (1985) suggested letting $\frac{z_o}{h} = 1$, h = R, and η = 2 in equation 2, for a fully dynamic debris flow in a channel with an arbitrary geometric shape. The following equation then results:

$$\bar{u} = \frac{2}{5} \left(\frac{\rho g}{\mu}\right)^{1/2} S_o^{1/2} R^{3/2} . \quad (3)$$

Note that η = 2 assumes the flow behavior of a dilatant fluid (Hughes and Brighton, 1967). Chen (1985) also cautioned that "μ" values can be assumed to be anywhere between 24 and 2,400 kg/m for the lahars in question.

For much of the previous digital modeling effort by the U.S. Geological Survey (for example, Swift and Kresch, 1983), channel conveyance was adjusted by computation of Manning's "n" by the following formula, which is derived from equations 1 and 3:

$$n = \left(\frac{5}{2}\right) \left(\frac{\mu}{\rho g}\right)^{1/2} R^{-5/6} , \quad (4)$$

where "μ" values were estimated from relations developed from depth and velocity information. The rheologic parameter "μ" varies with the sediment and fluid properties, concentration, and state of the flow. It can be expressed as a function of grain density, grain size, dynamic angle of internal friction, and linear grain concentration (Takahashi, 1980). The problem was, and still is, that "μ" is a difficult parameter to obtain and is critical to the model solution when Manning's "n" is calculated by equation 4. The rheologic parameter "μ" needs more empirical definition before it can be used in computation of Manning's "n." Conveyance computed using Manning's "n" determined from field measurements can be used as a surrogate for the rheology.

Objective

The objective of this paper is to evaluate a streamflow model in the simulation of documented debris-flow events. In evaluation, model conveyance is defined by a Manning's "n" value that has been independently calculated from documented flow and cross-sectional information. Chen's "μ" value can also be back-calculated. The range and change in both Manning's "n" and Chen's "μ" for the documented events can provide guidelines for future modeling efforts. This exercise will support the rationale for using an unsteady-state streamflow model in the prediction of certain debris flow events. It will also illustrate the need for obtaining more flow-velocity and sediment data from field observations.

Approach

Previous debris flow modeling efforts by the U.S. Geological Survey in studies on Mount St. Helens used a general purpose dam-break flood simulation model (DAMBRK by Land, 1981). The Land model was adapted from an earlier model by Fread (1977). Although the Land model used conventional techniques in numerical solution (an implicit finite-difference scheme), there was instability when very high magnitude, sharply rising peak discharges were routed in steep channels. To obtain solutions for the present study, another one-dimensional open-channel flow model was used (DeLong, 1986). Both the Land and DeLong models solve the one-dimensional, unsteady flow equations of continuity and momentum. In the DeLong model, the governing equations are solved numerically, using an orthogonal-collocation, finite-element method formulated in terms of cross-sectional area and discharge. It is not the main objective of this paper to focus on the numerical model used in analysis, but rather on the results of the modeling.

To evaluate the use of a streamflow model in simulation of debris flows, it is necessary to compare model results to well-documented events. On March 19, 1982, a lahar with an initial peak discharge of about 14,000 m^3/s flowed down the North Fork of the Toutle River in Washington (fig. 1). This lahar is descibed in detail by Pierson and Scott (1985), whose report contains much of the velocity and timing information needed to test a digital model of a debris flow. Other reasonably well-documented lahar events occurred following the major eruption of Mount St. Helens on May 18, 1980. The debris flow on the North Fork Toutle and the Toutle River has been documented by Fairchild and Wigmonsta (1982), Dinehart and others (1981), Cummans (1981), and Lombard and others (1982). The debris flow on Pine Creek has been documented by Pierson (1982).

The use of a streamflow model requires an estimate of channel roughness to compute conveyance. Manning's "n" was back-calculated at cross sections where peak elevations were known and mean velocity could be determined either from rating extension (at stream-gage locations) or by superelevation or runup formulae. By assuming that friction losses are negligible, mean velocity can be roughly calculated from maximum runup of flow on banks or hills oriented perpendicular to the flow path.

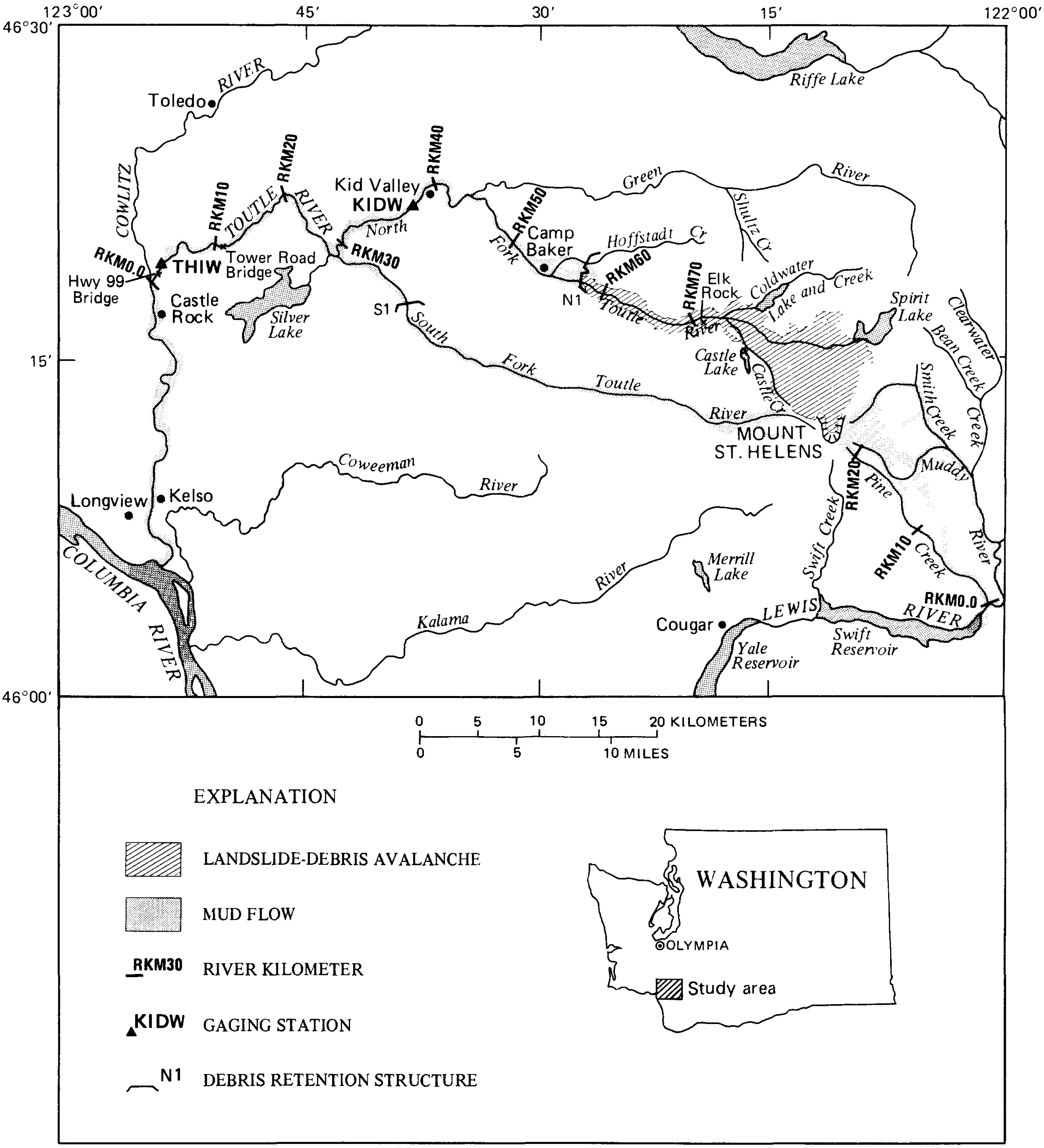

FIGURE 1.--Map of study area.

The runup formula is a simple derivation of the conservation of energy equation and is expressed as follows (Pierson, 1982):

$$\bar{u} = (2gh_r)^{1/2} , \qquad (5)$$

where h_r = amount of runup, in m. See Pierson (1982) for diagram.

The superelevation formula is based on the principle that the flow surface rises on the outside and lowers on the inside of a bend and is proportional to the mean velocity of the flow. It is an application of Newton's second law of motion, yielding the following simple equation for mean velocity (Chow, 1959):

$$\bar{u} = \left[\frac{gHr_c}{w} \right]^{1/2} , \qquad (6)$$

where r_c = centerline radius of curvature, in m; w = channel width, in m; and H = the average superelevation, in m. See Chow (1959) for diagram.

Chen's "μ" was also calculated where peak elevations were known and velocity was determinable by rating extension or by the above equations. The "μ" value was calculated by using equation 3 and only defined the range of values expected in the flows studied.

The model was used (with no adjustment) to simulate debris flows using the "back-calculated" Manning's "n" values. A discharge hydrograph was used as an upstream boundary condition; no other boundary conditions were imposed, with the exception of upstream discharge hydrograph shape, which was estimated from whatever documented evidence existed, with the peak discharge the best estimated quantity. All cross-section data remained constant for the duration of the model run, and the defined Manning's "n" values used were considered constant for depth and time. Cross sections were subdivided on the basis of channel shape, and separate model runs were made with the "n" values in the overbank subsections first raised to a value 0.010 higher than main channel "n" values and then to 9999.9 to depict inactive area (zero flow zone). A 5-minute time step (Δt) and a 610-m distance increment (Δx) were used in modeling. Surveyed cross sections were used when available and the model interpolated cross sections every 610 m. For the Pine Creek model, nine surveyed cross sections were used; for the May 1980 Toutle River model, 19 surveyed cross sections were used; and for the March 1982 Toutle River model, 39 surveyed cross sections were used.

Results of modeling were compared with observed data from three events. Accuracy was computed by comparing model results to known peak arrival times and elevations. Model sensitivity was tested by using different model input parameters and variables.

MARCH 19, 1982, LAHAR ON THE TOUTLE RIVER

The eruption-triggered lahar of March 19, 1982, at Mount St. Helens traveled down the North Fork Toutle and Toutle Rivers about 27 km as a true debris flow, about 16 km in transition, and about 40 km as a hyperconcentrated streamflow, to the confluence of the Cowlitz River. Hyperconcentration is arbitrarily defined as the sediment concentration between 40- and 80-percent solids by weight (Beverage and Culbertson, 1964).

The study reach for this report started at RKM (river kilometer) 75.3, where the flow became channelized and extended downstream to RKM 1.7 on the Toutle River.

Manning's roughness coefficient "n" and Chen's rheologic parameter "μ" were calculated from field data compiled on the lahar in transition (Pierson and Scott, 1985). Velocities used in these calculations were determined both by rating extension of the Survey's stage-discharge curves at gaging station locations and by using superelevation formulas (equation 6). Gaging stations are located at Highway 99 (THIW) and at Kid Valley (KIDW). Superelevation of the peak flow was measured around curves by high mudlines surveyed in the field at three additional locations. Table 1 shows the "n" and "μ" values computed at selected locations within the stream reach where cross-section and velocity data were available.

The calculated "n" values ranged from 0.048 to 0.020, decreasing downstream as the rheology of the lahar changed. The flow concentrations decreased from 90- to 61-percent solids by weight, from debris flow to hyperconcentrated streamflow, (Pierson and Scott, 1985). Calculated "n" values for this lahar in the upper reach (0.048 to 0.037) were not significantly different from those that might describe a clear-water flow of this magnitude. The calculated "n" value of 0.020 in the lower reach most likely occurred because the streambed became smooth during passage of the peak. On a field trip made in January 1984, the authors estimated the average "n" to be about 0.048 for a clear-water flood for the entire reach. The calculated Chen's "μ" decreased from 190 to 5 kg/m for the flow.

The stream reach can be separated into three different flow regimes: debris flow, transition flow, and hyperconcentrated flow. The debris-flow concentration ranged from 90- to 79-percent solids by weight, while mean grain-size measurements from deposits ranged from 2.6 to 0.95 millimeters (mm). The hyperconcentrated flow concentration ranged from 71- to 61-percent solids by weight, while the mean grain size ranged from 0.55 to 0.33 mm. Transition flow would have concentrations and mean grain sizes between debris-flow and hyperconcentrated-flow values.

The hyperconcentrated flow from Kid Valley (RKM 37.6) to Highway 99 Bridge (RKM 1.7) was modeled first because the input hydrograph shape was known. Using the calculated "n" values that ranged from 0.037 to 0.020 (table 1), a peak was routed downstream. This modeled peak can be compared with observed and field calculated data in table 2. The best documented field information of peak time and stage matched well (within 0.1 m and 0.1 hours) with modeled data (fig. 2). If a higher "n" value is substituted in the model run (n = 0.050), then timing and stage are off considerably (greater than 1.0 m and 1.8 hours) although peak discharge is reasonable (within 11 m^3/s [cubic meters per second]). Refer to figure 3.

The transition flow (RKM 57.9 to RKM 37.6) and debris flow (RKM 75.4 to RKM 57.9) were modeled next as separate segments. Using estimated peak hydrographs with progressively sharper rising limbs than used in the hyperconcentrated reach and using the calculated "n" values (0.048 to 0.037) shown in table 1, the modeled peak discharge, stage, and time compare favorably with observed and field-calculated values (table 2).

Table 1.--Calculation of Manning's "n" and Chen's "μ" for selected locations on the North Fork Toutle and Toutle Rivers for different lahar events

Location	Cross section	River distance, in kilometers	Peak discharge, in cubic meters per second	Mean velocity, in meters per second	Cross-section area, in square meters	R, in meters	g, in newtons per cubic meter	S, in meters per meter	n	1/ μ, in kilograms per meter	Reference
					March 19, 1982 lahar						
Hwy 99 Br.	TL1130	1.7	450	3.7	125	1.6	18,200	0.003	0.020	5	Pierson & Scott, 1985
Kid Valley	NF510	37.6	960	4.6	210	3.3	21,500	.006	.037	35	Pierson & Scott, 1985
Br. blw N1	NF390	57.9	2/ 2,300	5.2	435	2.1	22,500	.007	.027	10	Pierson & Scott, 1985
	NF320	68.4	3/ 3,400	8.0	430	3.8	22,500	.019	.042	60	Pierson & Scott, 1985
	NF130	75.4	6,800	10.0	680	6.5	23,600	.019	.048	190	Pierson & Scott, 1985
					May 18, 1980 lahar						
Hwy 99 Br.	TL1130	1.7	4/ 2,900	3.9	735	6.0	23,600	.003	.046	160	Dinehart & others, 1981
Hwy 99 Br.	TL1130	1.7	6,000	8.0	750	6.0	23,600	.003	.022	40	Fairchild & Wigmosta, 1982
	TL1010	25.5	4,500	6.8	665	8.4	23,600	.007	.051	330	Unpub. slope/area by USGS
	NF450	49.2	7,200	5.5	1,320	3.4	23,600	.0075	.035	35	Fairchild & Wigmosta, 1982
					Pine Creek Age Lahar (2,500 years old)						
Hwy 99 Br.	TL1130	1.7	40,000	11.0	3,720	15.0	23,600	.003	.030	320	Scott, written commun., 1984
Kid Valley	NF510	37.6	200,000	15.0	13,400	23.3	23,600	.006	.042	1250	Scott, written commun., 1984

1/ Chen's "μ" is calculated with z = 1, h = R, and n = 2.

2/ Estimated discharge by Pierson and Scott, 1985.

3/ Overflow section not included in discharge computation.

4/ Discharge is based on a velocity observation after the peak and, in addition, does not include a known overflow section.

Table 2.--Comparison of modeled versus observed or field calculated values for the March 19, 1982 lahar on the North Fork Toutle and Toutle Rivers

[from Pierson and Scott, 1984]

Location	Cross section	River distance, in kilometers	Elevation, in meters: Modeled	Elevation, in meters: Observed	Discharge, in cubic meters per second: Modeled	Discharge, in cubic meters per second: Field-calculated	Time to peak, in hours: Modeled	Time to peak, in hours: Observed	Volume, in millions of cubic meters: Modeled	Volume, in millions of cubic meters: Field-calculated	Flow type
Hwy 99	TL1130	1.7	18.8	18.8	606	453	2.7	2.6	3.63	2.33	Hyperconcentrated
Tower Rd	TL1060	10.4	40.4	?	643	651	2.1	1.9	3.63	2.98	Hyperconcentrated
Kid Vy	NF510	37.7	1/ 184.8	184.8	1/ 963	963	---	---	3.63	3.63	Hyperconcentrated
Kid Vy	NF510	37.7	186.3	184.8	1,130	963	1.2	1.0	4.05	3.63	Transition
N1 Dam	NF390	57.9	1/ 334.1	334.1	1/ 2,260	?	---	---	4.05	?	Transition
N1 Dam	NF390	57.9	332.5	334.1	2,360	?	0.9	0.6	4.07	?	Mudflow
	NF320	73.3	561.2	560.8	4,020	3,700	0.3	0.2	4.07	?	Mudflow
Elk Rock	NF130	75.4	1/ 694.9	694.9	1/ 6,800	6,800	---	---	4.07	?	Mudflow

1/ Initial inflow conditions (boundary conditions).

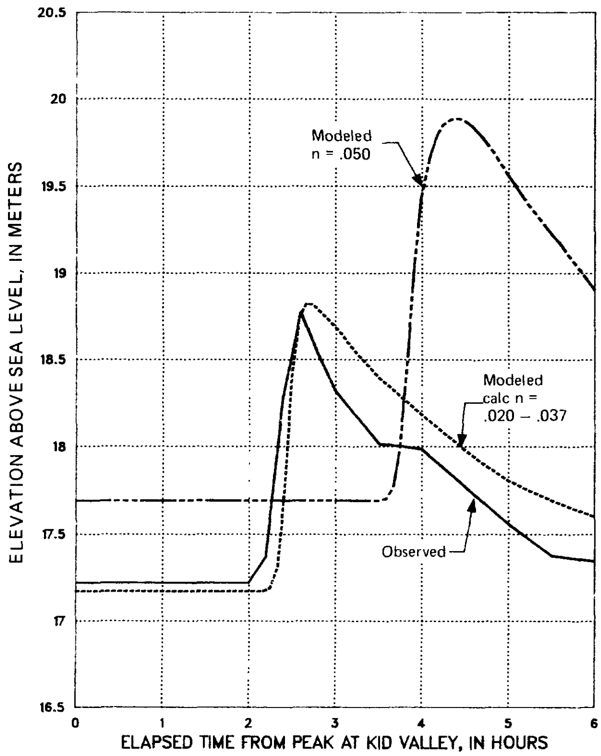

FIGURE 2.--March 19, 1982, hyperconcentrated flow at Highway 99 Bridge.

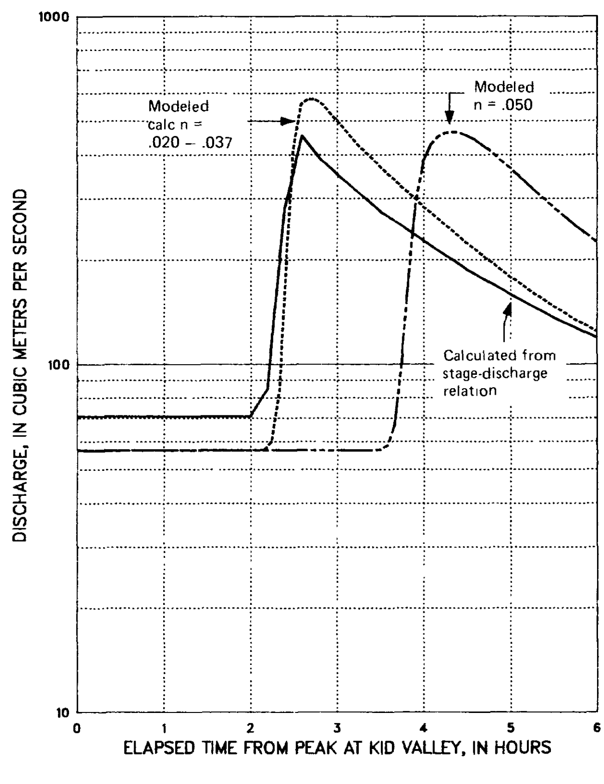

FIGURE 3.--March 19, 1982, hyperconcentrated flow at Highway 99 Bridge.

MAY 18, 1980, MAJOR LAHAR ON THE TOUTLE RIVER

Several hours after the major eruption of May 18, 1980, a massive debris flow originated when part of the debris-avalanche deposit in the upper reach of the North Fork Toutle River liquified. This flow differed from the lahar of March 19, 1982, in that the slurry had a higher clay fraction, was of considerably longer duration (the peak was sustained), and the rheology changed very little as the flow progressed downstream. The concentration remained at about 84-percent solids by weight and the mean grain size remained at approximately 0.44 mm (from measurement of deposition) for the entire flow.

Modeled peak arrival time could not be as closely constrained as with the 1982 lahar because observed peak arrivals at gaging stations and other observation points were not well documented. For the reach modeled from Kid Valley (RKM 37.6) to Highway 99 Bridge (RKM 1.7), the wave front as documented by Cummans (1981) arrived in 3.5 hours, while the peak travel time was 4.6 hours (time to peak from start of wave front at Kid Valley was 5.9 hours). The debris flow was first reported passing Green River at 3:30 p.m. at RKM 45.0, reaching Toutle Boys' Ranch at RKM 30.7 by 5:45 p.m. and the mouth of the Toutle River by 8:30 p.m. These times yielded average wave-front velocities of 11.1 kilometer per hour (km/h) from Toutle Boys' Ranch to the mouth and 6.3 km/h from Green River to Toutle Boys' Ranch. From table 2 of Cummans' report, the peak passed Weyerhaeuser Camp 19 at RKM 39.4 at 5:00 p.m. and reached Tower Road Bridge at RKM 10.4 at 9:15 p.m. These times yield an average peak velocity of 7.2 km/h.

For modeling purposes, the shape of the input discharge hydrograph was assummed to be similar to that of the stage hydrograph recorded at Castle Rock downstream on the Cowlitz River (Cummans, 1981). Two sets of information were used to calculate Manning's "n" and to determine the starting peak discharge. First, cross-section data and velocity calculations from Fairchild and Wigmosta (1982) defined "n" values that ranged from 0.035 to 0.022 and defined the peak of the input hydrograph to be approximately 7,200 m^3/s at RKM 49.2 (table 1). Figures 4 and 5 show the modeled results downstream at Highway 99 bridge crossing. The modeled peak generally arrived faster than the observed peak. The modeled peak stage was slightly higher than the observed; however, the cross section used in the model at this node was known to have an overflow section (data that were not available for this scenario). Next, data from Dinehart and others (1981) and Leonard Reed of the U.S. Geological Survey Cascade Volcano Observatory, WRD, Vancouver Project Office (oral commun., 1984) were used to calculate "n" values from 0.051 to 0.046 and a starting peak discharge of approximately 4,500 m^3/s at RKM 25.5 (table 1). The resulting peak was modeled downstream and, although matching peak stage better, was generally later in time than the observed peak.

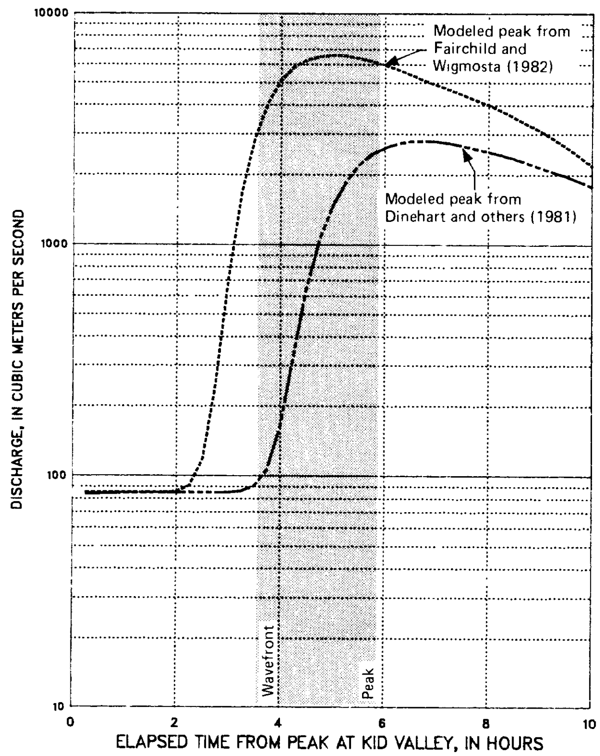

FIGURE 4.--May 18, 1980, lahar at Highway 99 Bridge.

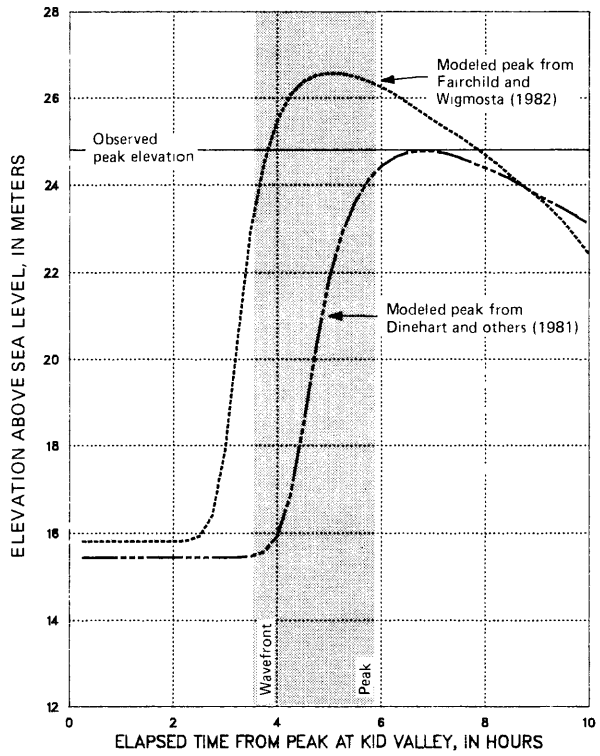

FIGURE 5.--May 18, 1980, lahar at Highway 99 Bridge.

MAY 18, 1980, LAHAR ON PINE CREEK

During the first minutes of the May 18 eruption at Mount St. Helens, debris flows developed in a number of drainages on the west, south, and east flanks of the volcano. A major lahar on Pine Creek flowed 21 km to Swift Reservoir and was confined to a narrow channel from RKM 10 to RKM 21 of its flow. Cross-section and superelevation-calculated velocity information and slurry-composition data at 11 locations (Pierson, 1982) indicate that this lahar was again somewhat different from the previous debris flows modeled. It flowed at higher velocities and the slurry composition was generally coarser than either of the two lahars previously mentioned. The average reconstituted concentration was about 84- to 86-percent solids by weight, and the average mean grain size was approximately 0.9 mm (from measurement of deposition).

Table 3 shows "n" and "μ" calculated for 11 selected locations on Pine Creek where cross-section and velocity data were available. The "n" values used in the model ranged from 0.083, the average "n" for cross sections P2 to P5, to 0.050, the average "n" for cross sections P6 to P11. Intermediate cross sections (P2.1 to P10) were assigned "n" values so that a smooth transition was made between the two averaged values.

Table 3.--Calculation of Manning's "n" and Chen's "μ" for selected locations on Pine Creek for the May 18, 1980 lahar

[Estimated pg = 23,600 newtons per cubic meter]

Cross section	River distance, in kilometers	Peak discharge, in cubic meters per second	Mean velocity, in meters per second	Cross-section area, in square meters	R, in meters	S, in meters per meter	n	Average n	μ, in kilograms per meter
P2	11.8	28,000	20.8	1350	11.9	0.092	0.089		1870
P2.1	--	25,000	20.2	1240	10.1	.065	.057		580
P3	11.0	28,000	13.1	2140	12.2	.041	.082		1630
P4	10.4	21,500	12.4	1730	11.9	.042	.086		1730
P5	9.6	20,000	10.7	1870	11.9	.043	.099	0.083	2260
P6	7.6	21,000	14.2	1480	11.0	.036	.066		910
P7	7.0	19,000	21.1	900	8.6	.031	.035		170
P8	5.1	10,000	15.3	650	5.2	.026	.032		60
P9	2.3	6,300	9.3	680	7.4	.027	.067		480
P10	--	8,900	11.0	810	7.5	.019	.048		250
P11	0.9	9,100	12.2	750	6.5	.030	.049	.050	210

For this event, the travel time for the 21-km flow generally was known only to be between 18-30 minutes, while the shape of the hydrograph was totally unknown. As an estimate, a triangle-shaped input hydrograph was used with a 2.5-minute time to peak and a maximum discharge of 28,000 m^3/s. The best estimate of volume was judged to be approximately 57 percent of the total volume recorded as inflow into Swift Reservoir by Cummans, 1981. That percentage is based on estimated peak discharge for Pine Creek, divided by the sum of the estimated peak discharge for the combined Pine Creek and Muddy River flow. Table 4 shows model results compared to field observations and estimates. Timing was good, and peak stage and discharge attenuation are reasonable. Table 5 shows peak timing and attenuation for different shaped hydrographs defined by different starting volumes. From tables 4 and 5 it appears that 5.5 million m^3 (cubic meters) might be the best estimate of volume because it yields results closest to observed values for timing and elevation and closest to the calculated values for discharge.

ANCIENT LAHAR ON THE TOUTLE RIVER

Manning's "n" and Chen's "μ" values were also calculated for a 2,500-year-old event, believed to be an ancient Spirit Lake breakout, documented by Scott (written commun., 1984). These results were included in this paper to show that field data can be obtained for other than recent debris flows in order to estimate "n" and "μ" values (table 1). If additional volumetric data were available, this lahar would provide another important flow to model.

Table 4.--Modeled discharge and elevation for best estimate of mudflow volume for the May 18, 1980 lahar on Pine Creek

Volume = 5.5 million cubic meters (57 percent of the total volume of combined mudflows into Cougar Reservoir). The observed time of the event was between 18-30 minutes for 21 km total travel, and the modeled traveltime of the peak was 14 minutes for 10.9 km of reach.

Cross Section	River distance, in kilometers	Elevation, in meters		Discharge, in cubic meters per second 1/		"n" values	
		Modeled	Observed	Modeled	Calculated	In model	Calculated
P2	11.8	2/ 713	713	2/ 28,000	28,000	0.083	0.089
P3	11.8	676	667	25,300	28,000	.076	.082
P4	10.4	643	647	20,600	21,500	.073	.086
P5	9.6	606	611	19,300	20,000	.069	.099
P6	7.6	539	540	16,400	21,000	.066	.066
P7	7.0	504	506	15,800	19,000	.063	.035
P8	5.1	452	457	13,600	10,000	.060	.032
P9	2.3	376	385	11,900	6,300	.056	.067
P11	0.9	342	340	10,900	9,100	.050	.049

1/ Velocities used in discharge computation are calculated by superelevation formula.
2/ Initial starting conditions (boundary conditions).

Table 5.--Modeled discharge and elevation for selected mudflow volumes to display the effect of peak shape (sharpness) for the May 18, 1980 lahar on Pine Creek

Cross section	River distance, in kilometers	Elevation, in meters		Discharge, in cubic meters per second	
		Modeled	Observed	Modeled	Calculated 1/
Volume = 2.8 million cubic meters, Duration = 9 minutes, Traveltime = 14 minutes					
P2	11.8	2/ 713	713	2/ 28,000	28,000
P7	7.0	502	506	13,600	19,000
P11	0.9	340	340	8,400	9,100
Volume = 8.4 million cubic meters, Duration = 28 minutes, Traveltime = 13 minutes					
P2	11.8	2/ 713	713	2/ 28,000	28,000
P7	7.0	505	506	17,000	19,000
P11	0.9	343	340	12,300	9,100
Volume = 16.7 million cubic meters, Duration = 56 minutes, Traveltime = 12 minutes					
P2	11.8	2/ 713	713	2/ 28,000	28,000
P7	7.0	507	506	21,200	19,000
P11	0.9	345	340	17,400	9,100
Volume = 41.7 million cubic meters, Duration = 140 minutes, Traveltime = 12 minutes					
P2	11.8	2/ 713	713	2/ 28,000	28,000
P7	7.0	508	506	24,600	19,000
P11	0.9	347	340	22,500	9,100

1/ Velocities used in discharge computation are calculated by superelevation formula.

2/ Starting initial conditions (boundary conditions).

ACCURACY ANALYSIS

Observations and data collected for the March 19, 1982 lahar on the Toutle River and for the May 18, 1980 lahar on Pine Creek are used for comparison with model results. Observations from the May 18, 1980 lahar on the Toutle River were not used because of conflicting data sets. For debris-flow elevation, the model produced an average deviation of ±2.1 m from observations (an approximate ±10-percent flow- depth accuracy). For peak time, the modeled results were within ±1.6 hours on the average (an approximate ±20-percent timing accuracy). Modeled results also showed simulated peak discharges to be within an average ±18 percent of those calculated from field information. Generally, the given tolerances indicate the successful use of a one-dimensional, unsteady-state streamflow model in simulation of debris- flow events.

Since the model does not have an algorithm for the deposition of debris material, it was assumed that the volume of the hydrograph was constant throughout the reach. This in all probability is not the circumstance. Debris was deposited in limited quantities all along the study reach. Table 2 shows field calculations of event volumes for the hyperconcentrated flow of March 19, 1982. These calculations indicate a loss of volume which the model cannot duplicate because of the constant-concentration, constant-volume (conservation of mass) assumption. Fortunately volume losses are small and probably affected peak attenuation only slightly. Had the study channel not been as confining and had more debris deposition occurred, modeled results might not have been as close.

COMPARISON TO OTHER MODELING

A report by Lang and Dent of Montana State University (1983) evaluated the use of a snow avalanche model in the simulation of debris flows down Muddy Creek, Pine Creek, and the Toutle River drainages for the May 1980 event. In contrast to the modeling done for this report, the effort by Lang and Dent used the observed timing and velocity information for direct calibration. This calibration then gave them a reference from which to size the physical parameters of their model.

The model used by Lang and Dent presented some interesting conclusions. Their simulations required average kinematic viscosities of 0.25 m^2/s (square meters per second) for the Pine Creek flow and 0.125 m^2/s for the North Fork Toutle River flow. The difference in viscosity roughly corresponds to the difference in average Manning's "n" for the two flows in this report. In the Lang and Dent report, the corresponding "n" values were crudely calculated to be about an average of 0.11 for the Pine Creek flow and an average 0.024 for the North Fork Toutle River flow. These values can be compared to the corresponding average "n" values of 0.067 and 0.028 calculated in this report. The Pine Creek simulation by Lang and Dent flow took 24 minutes to travel the total distance of 20 km from summit to reservoir, which is comparable to the 14 minutes of traveltime simulated by the streamflow model for the lower 11 km of channel.

SENSITIVITY ANALYSIS

A sensitivity analysis of selected model parameters and variables was performed for the Toutle River reach in order to acquire a working knowledge of both the model and the input parameters (tables 6 and 7). The hyperconcentrated streamflow from Kid Valley to Highway 99 Bridge was selected for analysis because it contained the most complete observations of peak stage and traveltime of those data evaluated. Initial model parameter conditions reflect the model run presented in table 2 and figures 2 and 3.

Table 6.--Sensitivity of peak discharge, stage, and time to peak with respect to various parameters in the DeLong Orthogonal-Collocation model (DeLong, 1984)

Peak information at Tower Road bridge (KM 10.4) and Highway 99 bridge (KM 1.7) is in response to an input hydrograph of the March 19, 1982 lahar on the North Fork Toutle River at Kid Valley (KM 37.7).

Parameter		Initial values	Parameter change										
BETA (momentum coefficient)		1.10	1.25										
THETA (implicitness coefficient)		0.75		0.60	0.90								
Solution time increment, t, in minutes		5				2.5	10						
Solution distance increment, x, in meters		610						305	914				
Peak volume, in million cubic meters		4.28				2.14	8.57			2.14	8.57		
Peak discharge, in cubic meters per second		953								477	1910		
"n" in main channel		0.020-.037											0.050
"n" in overfow sections		0.030-.047										0.9999	.060
		Peak discharge, in cubic meters per second											
River distance in kilometers	10.4	566	566	642	522	606	502	566	566	279	1120	494	564
	1.7	519	519	586	479	502	463	519	519	261	1030	423	519
		Time to peak, in hours											
River distance in kilometers	10.4	2.17	2.17	2.09	2.25	2.16	2.33	2.11	2.17	2.59	2.09	3.25	2.25
	1.7	2.75	2.75	2.67	2.84	2.79	3.00	2.75	2.75	3.34	2.67	4.42	2.84
		Peak elevation, in meters											
River distance in kilometers	10.4	40.2	40.2	40.4	40.1	40.3	40.0	40.2	40.2	38.2	41.4	41.2	40.2
	1.7	18.1	18.1	18.3	18.0	18.0	18.0	18.1	18.1	17.2	18.8	19.2	18.1

Table 7.--Sensitivity of peak discharge, stage, and time to peak with respect to various parameters in the DeLong Orthogonal-Collocation model (DeLong, 1984)

Peak information at Tower Road bridge (KM 10.4) and Highway 99 bridge (KM 1.7) is in response to an input hydrograph of the March 19, 1982 lahar on the North Fork Toutle River at Kid Valley (KM 37.7).

Parameter		Initial values	Parameter change				
-- Chen's consistency index		0.0 kilogram per meter	24	24	240	2400	2400
g -- bulk density x gravity		0.0 newton per cubic meter	21500	23600	21500	23600	23600
OPTFRIC -- limiting "n" value		9999					0.180
		Peak discharge, in cubic meters per second					
River distance	10.4	566	479	480	289	151	262
in kilometers	1.7	519	437	443	267	137	224
		Time to peak, in hours					
River distance	10.4	2.17	3.09	3.09	7.50	19.42	10.84
in kilometers	1.7	2.75	3.92	3.92	9.62	25.92	14.42
		Peak elevation, in meters					
River distance	10.4	40.2	40.9	40.9	41.9	43.2	43.0
in kilometers	1.7	18.1	18.8	18.8	19.7	20.6	20.5

As shown in table 6, a change in the momentum coefficient (BETA) to a value closer to that in more viscous liquids did not change results. Increasing BETA changes the shape of the vertical velocity profile, making it more non-uniform from top to bottom.

THETA is the time-weighting factor that defines the implicitness of the solution scheme, a factor of 1.0 being fully implicit and a value of 0.0 being fully explicit. Decreasing the weighting factor (THETA) decreased the time to peak and increased the peak discharge slightly. This increases the accuracy of the solution but the model becomes more unstable in higher peak-discharge situations and cannot converge on a solution.

The finite difference increment ($\Delta x/\Delta t$) was also checked to verify the stability of the solution. In separate computer runs, the Δt increment was halved and doubled, while the Δx increment was halved and increased by 50 percent. Changing the solution time increment (Δt) and the solution distance increment (Δx) with no appreciable change in solution indicated the stability.

Increasing event volume (holding peak discharge the same) decreased peak attenuation and time. Increasing the "n" value in the main channel section attenuated peak discharge and increased time and stage significantly. Increasing the "n" value in the overbank subsections (creating inactive area) increased the time to peak slightly but did not attenuate the peak significantly. This, in all probability, is because the subsections make up only a small portion of the entire cross section.

Table 7 shows results of changing rheologic parameters by changing ρ and "μ" values. For this test, "n" was calculated using equation 4 internally in the model. Changing ρ has little effect on results. Increasing "μ" increases the time to peak, attenuates the peak discharge, and increases the peak stage significantly. Present results are based on the premise that the rheology remains constant for the entire flow, which does not appear to be true; however, the results give a relative base to evaluate the rheologic parameters proposed by Chen.

This sensitivity analysis suggests that, if Manning's "n" or Chen's "μ" were known adequately (these are the most sensitive parameters), debris flows could probably be predicted with reasonable accuracy using a streamflow model.

SUMMARY

Probably the single most important conclusion that can be drawn from this exercise is that an existing one-dimensional, unsteady-state streamflow model can adequately predict debris flows provided (1) the flow is confined to a channel and (2) the channel friction coefficients can be estimated with some degree of certainty.

Few observed data were available for comparison with model results. In addition, the observations were crude in many instances. However, differences between observed and simulated data averaged $\pm$10 percent for peak flow depth and $\pm$20 percent for peak time and discharge.

The lahars modeled were for the most part confined to relatively narrow channels where most deposition occurred after the peak. If large areas had been available for deposition (additionally attenuating the peak flow and reducing the total volume significantly), the model study would probably not show such accurate results.

Manning's "n" values used in computing conveyance in the model were subject to the changing rheology of the debris flow. The "n" values were calculated independently using field cross-section information and velocities derived primarily from superelevation formulas. For the events modeled, Manning's "n" ranged from 0.020 (hyperconcentrated flow) to 0.099 (debris flow).

Verification of "n" values for debris flows is necessary in order to use a streamflow model in debris-flow prediction. Additional research and field effort needs to be directed toward this verification. Depositional information in the field pertaining to recent and past debris flows can be used to identify the superelevation and (or) runup for estimating velocities associated with the events and the corresponding computation of Manning's "n" values.

Little could be defined by this study regarding the relation of Chen's "η" and "μ" values to the rheology of the debris flows. In all lahar reconstructions the rheology of the flow changed in a downstream direction during the course of the event. Chen's "μ" changed approximately an order of magnitude for each event. The "μ" values ranged from 5 to 2,260 kg/m for the three events modeled. Flow magnitude and consistency definitely seem to affect the character of the flow as Chen's equation suggests.

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