ESTIMATION OF FLOOD AND SEDIMENTATION HAZARDS AROUND MT. ST. HELENS* (1)

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STATEMENT OF PROBLEM

The eruption of Mt. St. Helens on May 18, 1980 caused extensive flooding and sedimentation, which have heen documented by others (U. S. Geological Survey, 1981). In the following winters there was a possibility of new flood and sedimentation hazards in the Toutle and Cowlitz River valleys (Figure 1) arising from landscape alterations caused by the eruption. There was considerable uncertainty about the nature and magnitude of these hazards, and large discrepancies existed between the predictions made by various agencies and individuals. Yet it was necessary to assess these hazards so that urgent decisions could be made about preventative and remedial actions, evacuation, or simply advice to the people living in the Lower Toutle and Cowlitz River valleys. It was necessary for scientists to make estimates before they had what they would usually regard as sufficient data. Therefore, it is not surprising that predictions varied radically between groups and between dates for any one group. The situation was similar to the aftermath of other disasters, such as the blockage of river valleys by large landslides, the influx of vast amounts of sediment from large mining operations, and of course other volcanic eruptions.

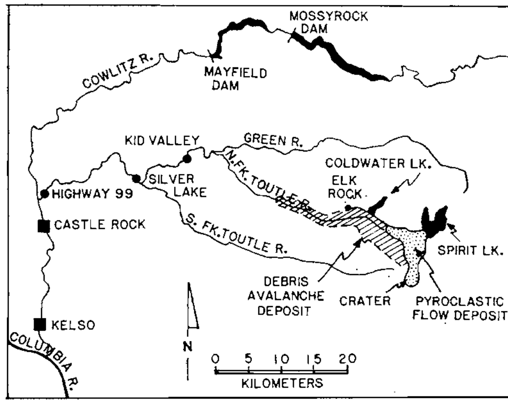

Figure 1 : Location map of Mt. St. Helens and the Toutle and Cowlitz River valleys.

The following hazards were the major subjects of debate:

1) Debris flows caused by pyroclastic flows which might occur over a thick snowpack;
2) Catastrophic breaching of debris dams emplaced across valleys during the main eruption;
3) Amplification of rain-and-snowmelt floods;
4) High rates of sediment transport and deposition in river channels.

In some cases, such as item (1), the physics of the process has never been studied formally. In others, such as (2), (3), and (4) major unpredictabilities arise because of the variability of weather, and in still others 2) and 4) there are important uncertainties because there is usually little information about the physical properties of the geological materials available immediately after an eruption.

It is also difficult to use information from other volcanoes for several reasons. First, there are important differences in geological materials, weather conditions, and other controlling variables. Second, events after most eruptions are poorly described in the literature, particularly regarding critical parameters affecting some of the most damaging processes. Third, there have been few analyses of the fundamental physics of these processes, so that there are no widely accepted schemes of logic and computation that can be used to predict the behavior of any hazard listed above, at least on the scale at which they occurred after the 1980 eruption of Mt. St. Helens.

* 昭和58年度砂防学会研究発表会，特別講演，次号に後半を掲載する。
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The purpose of this paper is not to emphasize the differences between the predictions of various groups and individuals, except to define the problem. We concentrate on describing some simple, approximate procedures that we used around around Mt. St. Helens for rapid assessment of hazards soon after the eruption. In some cases, the procedures have been improved upon by others in succeeding years, as more information became available and as there was more time for field monitoring, model development and model calibration. Some of these improvements will be referred to in the text. However, our aim is to emphasize the need for improving predictions immediately after some catastrophic disturbance. In general, more work needs to be concentrated on the mechanics of various cataclysmic processes resulting from volcanic eruptions. There is also a need for data-collection programs to be guided by theory and by accurate conceptual models based on field observations, in order to ensure the measurement of the critical physical parameters required for computations.

MUDFLOWS GENERATED BY PYROCLASTIC FLOWS OVER SNOW

Initial debate

During the months following the 1980 eruption, pyroclastic flows emerged from Mt. St. Helens with temperatures of 700—900°C, and traveled downslope at speeds of 50—70 m/s, before spreading their deposits over an area of 1—6.5 km^2. Several geologists concerned with the prediction of volcanic hazards pointed out that pyroclastic flows in other parts of the world have generated debris flows and large mudflows* as they travelled over snowpacks. Such occurrences were reported by Wolf (1878) from Cotopaxi, and Murai (1960) from Mt. Tokachi, although in this last case the term "pyroclastic flows" was probably a mis-translation, because Anyoji (1983) has interpreted the mechanism triggering the mudflows as a debris avalanche. This confusion illustrates one of the main difficulties of comparative volcanology: that of translation.

The geologists computed water volumes that might be released by pyroclastic flows of various sizes over snowpacks with a range of water equivalents typical of Mt. St. Helens. The results are shown in Table 1. If such water volumes were to be released quickly (time scales of minutes were proposed), they could mix with ash and pumice with volumes approximately twice as large as that of the meltwater; i.e. mudflows might be generated with volumes in the range $50—250\times 10^6 m^3$. For comparison, on May 18, 1980, the destructive North Fork Toutle mudflow had a volume of $140\times10^6 m^3$, but was released over a period of about 5 hours.

However, physicists studying the glaciology of Mt. St. Helens pointed out that only for the situation of a pyroclastic flow at rest on a snowpack is there sufficient understanding of heat transfer to predict the rate at which water would be melted. Pumice is a good insulator, and so the one-dimensional heat-flow equation predicted that only about 6 cm of water depth would melt during the first hour. (A typical maximum rate of snowmelt in the region under normal conditions is 3—5 mm/hr.) Such melt rates might trigger small mudflows, but are not likely to

Table 1 : Approximate volumes of water (millions of m^3) which could be released if pyroclastic flows of various sizes completely melted snowpacks of various water contents. The table also includes computed volumes of water released by heatflow from a stationary deposit of pumice.

Snowpack water equivalent (m)	Area covered by pyroclastic flow		
	5 km^2	15 km^2	25 km^2
0.5	2.5	7.5	12.5
1	5,0	15.0	25.0
2	10.0	30.0	50.0
5	25.0	75.0	125.0
Water released by melt due to conduction in:			
10 minutes	0.1	0.4	0.6
1 hour	0.3	0.9	1.6

* The term "mudflow" is used in the sense given in nhe Glossary of Geology, published by the American Geological Institute (1972). A mudflow is "a flowing mass of predominantly fine-grained earth material possessing a high degree of fluidity". The term "debris flow" is generally used if more than 50% of the material is coarser than sand.

pose a hazard to life and property in the inhabited part of the valley.

The assessment of probable mudflow volumes between these two extremes had to be made on the basis of literature review and field examination of pyroclastic flow deposits on Mt. St. Helens. The results were highly speculative, and now serve only to emphasize the need for rigorous studies of the physics of pyroclastic flows and their interaction with snowpacks.

From Wolf's (1878) account of the 1877 eruption of Cotopaxi volcano, Ecuador, Fenner (1923) interpreted the generation of mudflows as being due to the melting of snow and ice by pyroclastic flows. That interpretation is accepted by Miller et al. (1978). There is little useful information in these papers for understanding the mechanics of the interaction, but the upper slopes of the volcano have gradients in the range of 0.5—0.8. The account by Murai (1960) of the 1926 eruption of Mt. Tokachi is difficult to interpret. However, on p. 59, paragraph 2, he claims that "The snow which had accumulated on the mountain-side melted at once by their [pyroclastic flows'] heat, and consequently the melted water flooded in the valleys and on the basin". The claim is repeated on p. 69 of Murai's paper. According to the small-scale map of the volcano in the paper, the gradient on which the mudflows were mobilized was approximately 0.6. Mudflow deposits thought to have been generated by pyroclastic flows have also been recognized around Lassen Peak, California. It is also clear from the geological record that hot mudflows have previously occurred on Mt. St. Helens (Crandell and Mullineaux, 1978).

Assessment of mudflow generation

Very little is known about the physics of motion and heat transfer in pyroclastic flows. Sparks (1976) is one of the few geologists who have considered these problems. He has reported that the flows typically consist of subrounded balls of pumice, ranging in size from a few millimeters to several decimeters, dispersed in fluidized fine granular material and gas, which escape upward as the flow travels downslope at speeds of 80—250 km/hr. Sparks suggests that turbulence at the base of the flow is most likely immediately after the flow hits the ground surface and in the early stages of movement when the fluid is highly inflated and is travelling at high speed. As the flow deflates, its viscosity increases while its thickness and velocity decrease so that the flow becomes laminar, first at the base and then at increasingly higher elevations above the base.

In view of the constraints on heat flow out of a stationary layer of pumice, it seems that rapid melting of the snowpack and glaciers would require erosion of snow and ice and their turbulent incorporation into the flow. It also requires such a process to be very rapid so that the bulk of the flow would be cooled below 100°C and the major fraction of the water would not escape as steam. As a worst case, it is useful to assume that the volume of the escaping steam is negligible.

The field observations of Sparks (1976) and the present authors lead to the suggestion that turbulent mixing of a pyroclastic flow with the snowpack is likely on the steep slope immediately north of the crater of Mt. St. Helens, where the average gradient is 0.28 but large gullies are locally much steeper and have irregular profiles. In late 1980, the largest of these gullies formed the principal track for several pyroclastic flows, which scoured its walls (measurements at stakes by N. MacLeod, U.S. Geological Survey). M. Brugman (U.S.G.S., personal communication) also observed significant erosion of snow and development of gullies in the upper remnants of glaciers around Mt. St. Helens immediately after the eruption of May 18, 1980. Here, on gradients exceeding 0.50, pyroclastic flows on that day stripped all snow and 20 cm of ash and rock from some parts of the glaciers, while snow on other parts of the same glaciers survived. Thus, it seems likely that the thick snowpack which accumulates in the gully north of the crater would be completely eroded and incorporated into a pyroclastic flow, converting its base into a mudflow.

At the base of the gully, pyroclastic flows emerge onto a fan where the gradient abruptly decreases to 0.03, and the width increases from 0.3 km to more than 1 km. The widths of deposits from the 1980 eruptions ranged from 0.5—3.5 km at a distance of 5—6 km from the fan head. It is crucial to know whether a pyroclastic flow would continue to erode snow as it moved across this fan. The smooth surface of the fan, and the slowing and thinning of the pyroclastic flow would tend to decrease the turbulence and erosion, and the fluid of dust and gas would reduce the contact between the pumice and the snowpack. If, on the other hand, local flow convergence or streams of faster flow occurred, local turbulence and significant erosion of the snowpack might occur.

To check the reasonableness of these arguments, we examined deposits on the fan at the base of the main gully on the north side of the crater. The observations indicated that the pyroclastic flow is erosive in the central part of its track across the fan, but that as the flow spreads and thins, erosion of fine-grained ash deposits (viewed here as an analog for a snowpack) becomes much less likely. Fine-grained pyroclastic flow deposits lay over laminated silts and sands deposited by runoff. The contact between the two sediments was smooth and the laminations were not truncated by the pyroclastic flow. Some deposits of cobble-sized pumice had eroded fine-grained ash deposits but not other cobble-sized deposits. On the margins of the fan, pyroclastic flows had lapped up against the gradually rising topography without eroding it. Similar field observations by Fairchild on Mt Augustine, Alaska, after the 1976 eruption, indicated that pyroclastic flows much smaller than those at Mt. St. Helens had eroded 10 cm of ash on gradients of 0.20, but did not erode ash on gradients of less than 0.08. On these latter gradients, enough snow was melted to trigger small mudflows 6—8 m downslope of the snout of the pyroclastic flows, but in most cases there was no evidence of reworking of the snout by large amounts of meltwater.

Thus, on the basis of the literature and field observations, it seems that the following scenario represents the most likely consequences of a pyroclastic flow over a snowpack on Mt. St. Helens. The pyroclastic flow would emerge from the crater along a track 100 to several hundred meters wide. It should travel down the main gully as a deep, inflated, and turbulent flow, which would incorporate all the snow lying in the steep, uneven gully. A portion of this snow would boil, and it is possible that the snowpack would be so thin that it would be vaporized completely without significantly altering the temperature and flow properties. As a worst case, we will assume that all of the melted snow would be retained and would cool the base of the pyroclastic flow, transforming it into a mudflow. One might expect the mudflow then to travel down the gully at a speed far less than that of the over-running hot fluid, and to erode a track through snow on the fan between the end of the gully and the channel of the North Fork River. All snow would be transported to the stream channel from a track 100—300 m wide and 6.5 km long, as shown schematically in Figure 2. This water would mix thoroughly with new and old pumice and ash to form a mudflow with unpredictable properties. However, to judge from the mudflows of May 18, 1980, the mudflow volumes would be approximately twice that of the water melted (Fairchild and Wigmosta, 1983). Again extrapolating from the North Fork Toutle mudflow of 1980, the debris mobilized from this central track would have speeds of upto about 10 m/s, and the entire volume would reach the North Fork channel at the base of the fan within 650 seconds. Such a discharge into the channel could begin within two minutes of a pyroclastic flow emerging from the amphitheater of the volcano, and travelling downslope at a speed of 50 m/s. The hydrograph of such a mudflow would have a rectangular shape, as shown in Figure 3.

The pyroclastic flow would spread from the base of the gully in a triangular pattern shown schematically in Figure 2. In view

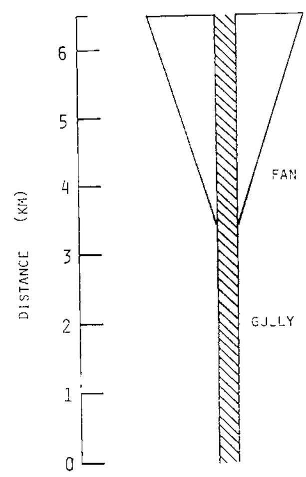

Figure 2 : Schematic representation of the area over which a pyroclastic flow would travel north from the crater of Mt. St. Helens. In the worst case, all snow would be eroded and melted in the steep, narrow upper part of the track, and the resulting mudflow would erode the snow in a track indicated by the cross-hatched area. The pyroclastic flow would spread from the gully to the triangular area indicated at a distance of 3.5—6.5 km from the center of the crater.

of the uncertainty about whether a pyroclastic flow can melt and release significant amounts of water as it spreads and settles, calculations were mede on the assumptions that: (a) 50 cm of water equivalent (125 cm of snow) and (b) 10 cm of water equivalent (25 cm of snow) could be disturbed and melted over the 3 km² triangular area in Figure 2. For comparison, rigid slab avalanches of snow, which are the most erosive kind of snow avalanche, commonly erode 30—60 cm of powder snow. If such snow is overrun by a powder avalanche, the erosion is much less, partly because a portion of the avalanche is supported by interstitial fluid pressure.

It was further assumed that the rate of meltwater release would locally overtax the capacity of the snowpack for subsurface conveyance of water, which would therefore accumulate rapidly in deep saturated snowpacks in swales and gullies. In the subarctic region of Quebec, Dunne has observed water tables rising to the surface of such snowpacks, followed by rapid flow of water across the surface and rapid incision of a channel releasing a torrent of meltwater and slush. We have assumed that on the slopes of Mt. St. Helens, the meltwater would then flow rapidly down the gullies at an average speed of 2 m/s. Water from the wide end of the fan would arrive at the channel first, followed by a triangular inflow, which would augment the mudflow generated in the central track, as shown in Figure 3.

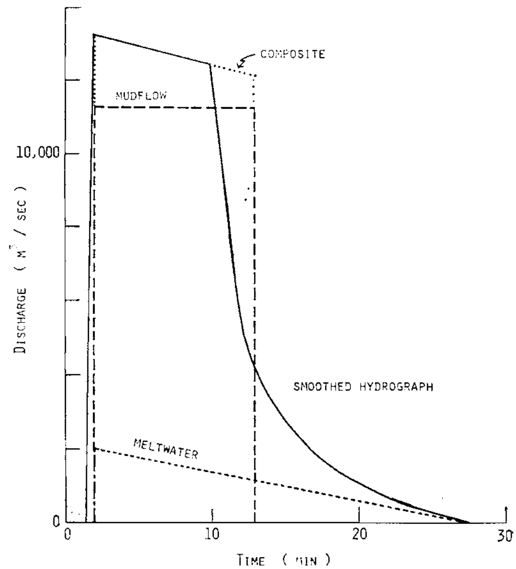

Figure 3 : Hydrograph of a mudflow combined with a snowmelt flood to yield a composite hydrograph, which was smoothed slightly to reflect progressive failure of the mudflow material and variations of velocity and ponding along the mudflow track, and to facilitate routing calculations.

Thus, under conditions that are likely to be extreme, large volumes of pumiceous mud and water could be injected into the North Fork Toutle River. In order to construct inflow hydrographs without a physically-based method of calculation, a range of assumptions had to be made about a set of processes that are complex, difficult to visualize, and impossible to predict in detail with current knowledge. Also, it is mot possible to predict the thickness of the snowpack when a pyroclastic flow might occur, except in a statistical sense. Therefore, a range of scenarios were used as a basis for constructing hydrographs, as indicated in Table 2. and Figure 4.

The field observations on the pyroclastic flow fan also indicated that heat flow by steam circulation from the 1980 deposits was intense enough to keep the fan free of snow during the first winter. However, a pyroclastic flow occurring after the cooling of these deposits would encounter a thick snowpack. The probable seasonal pattern of water content in this pack was estimated from snow-course data from sites around the mountain, but there was a need for much more intensive snow monitoring in the area of the potential hazard.

Routing of mudflow downstream

Channel storage tends to alter the shape of a flood wave travelling downvalley. Several flood routing procedures are available for computing this attenuation, but because the rheological characteristics of the mudflows from Mt. St. Helens were not well understood at the time, we used the Muskingum routing procedure (Lawler, 1964), and calibrated it against mudflow hydrographs from the Toutle valley on May 18, 1980, reconstructed from field evidence by Fairchild and Wigmosta (1983, Figures 5 and 8). The time parameter for the routing equation was estimated from the speed of the flood wave in a reach. From the field data of Cummans (1981), an average value of 2. 3 m/s was obtained for the North Fork mudflow, while for the South Fork mudflow the speed declined downstream from 9. 0 to 1. 5 m/s. The storage-weighting parameter for the routing equation was obtained by calibration against the hydrographs developed by Fairchild and Wigmosta (1983); a value of 0.3 gave the best fit to the observed hydrographs.

The Toutle River valley was divided into 300 m-long reaches, and the various mudflow hydrographs obtained as indicated in Table 2 and Figure 3 were routed downvalley. A typical set of results, in Figure 5, show the attenuation of the mudflow wave. Figure 6 depicts the results of routing several inflow hydrographs, constructed with various assumptions from Table 2. The worst case shows an initial peak of 13,300 m^3/s declining to 2800 m^3/s when it reaches the mouth of the Toutle River. Shown also in Figure 6 is the peak discharge of the North Fork mudflow on May 18, 1980. This peak persisted for a long distance downstream with little change because the generation of this mudflow continued over several hours (Fairchild and Wigmosta, 1983). The figure also includes the peak discharge of the South Fork mudflow of May, 1980, at its confluence with the main Toutle River. The discharge of this short-lived flow had decreased dramatically along the South Fork valley.

The results of the analysis suggest that initial peak rates of mudflow generated by pyroclastic flows over a snowpack could be high, but the high discharges are likely to be short-lived. Routing of the short hydrographs indicates that a mudflow wave would attenuate rapidly as it travels downvalley, and that the peak would diminish below that of 1980 before the mudflow leaves the debris avalanche. These mudflows would covse damage to some roads and bridges along the valley and transport millions of cubic meters of sediment into the river channels. They would also travel downstream with less warning than the largest 1980 mudflow, which began several hours after the eruption (Fairchild and Wigmosta, 1983).

Table 2 : Scenarios of snowpack, mudflow, and snowmelt characteristics, for which influxes to the river channel were computed. The calculations refer to a pyroclastic flow consisting of 1—1.5 km^2 of mudflow track and 3 km^2 of fan-shaped runout, as portrayed in Figure 2. The assumed water equivalent of the snowpack for each date is the average accumulation at that date, as determined from a probability analysis of snow-course data. The average water equivalent was weighted according to the length of the mudflow track in each elevation range.

Date	Weighted average water equivalent of snowpack (cm)	Width of mudflow track (m)	Speed of mudflow (m/s)	Depth of snowmelt on fan (cm of water)	Peak influx rate to channel (m^3/s)
Feb. 1	110	300	10	50	8,700
Feb. 1	110	300	10	10	6,900
Feb. 1	110	300	5	10	3,700
Feb. 1	110	100	5	50	3,100
Apr. 1	190	300	10	10	11,800
Apr. 1	190	100	10	50	5,750
Apr.	190	100	5	50	3,900
Apr. 1	190	100	5	10	2,300

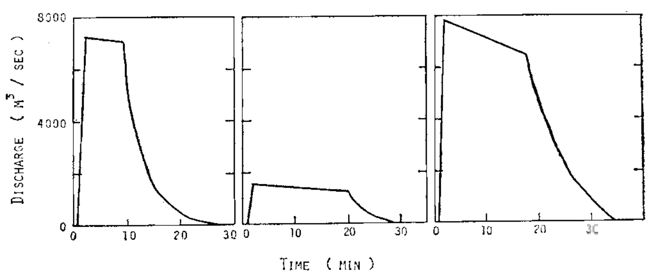

Figure 4 : Examples of mudflow hydrographs computed from alternative assumptions concerning the contributions of meltwater runoff and mudflow discharges resulting from a pyroclastic flow over snow. The peak discharges differ under these assumptions but each scenario shows a decline in discharge to small values within 30 minutes.

Summary

There did appear to be a significant mudflow hazard from pyroclastic flows running over the snowpack, but it was judged to be less catastrophic than the events of May, 1980, and probably much less dangerous than would be estimated by simple extrapolation from the volcanological literature.

In the case of a large pyroclastic flow encountering the seasonal maximum snowpack, it would probably generate within 10—20 minutes a mudflow with a volume of one to several million cubic meters, and a peak discharge of 10^3—10^4 m^3/s. After entering the stream channels the mudflow

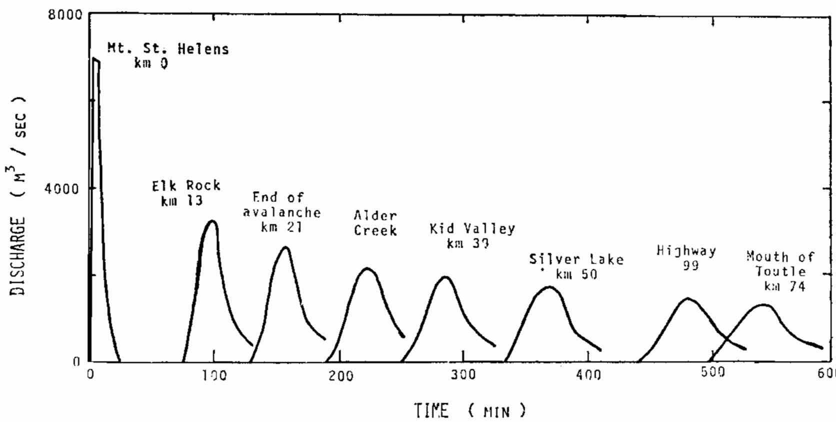

Figure 5 : Hydrographs of mudflows originating from a pyroclastic flow onto a snowpack and routed downvalley to the mouth of the Toutle valley. This computation involved routing through 243 segments, 300 m in length.

wave would attenuate quickly downchannel in the manner observed in the South Fork valley in May, 1980.

Although the attention of this study was on the north side of the mountain, a pyroclastic flow over the snowpack on the south side of the volcano could have similar consequences, possibly eroding larger volumes of snow from the longer, steep slopes. Mudflows were generated in a roughly similar manner in the South Fork Toutle, as well as Pine Creek and Muddy River on May 18, 1980 (see the descriptions by Janda et al., 1981).

Recent work on mudflow routing

After the initial hazard estimates were made, various field and modeling studies of the mudflows continued. Fink et al. (1981) interpreted the rheological characteristics of small mudflows on the south side of the volcano from the flow marks and deposits of May, 1980. Wigmosta (1983) used the same and different kinds of evidence to interpret the flow and rheology of the larger mudflows in the Toutle drainage. He used superelevation of mudlines at bends and on single trees, as well as the size of broken and surviving trees.

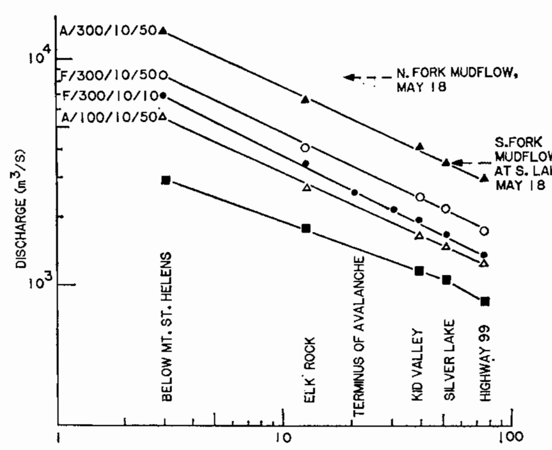

Figure 6 : Downstream variation of peak discharge for mudflows originating from pyroclastic flows and routed downvalley. Assumed conditions governing the initial hydrograph are summarized by labels at the upper left. The sequence of symbols in these labels refer to scenarios in Table 2, as follows: month of average snowpack used; width of mudflow track; speed of mudflow; depth of snowmelt on fan. Also shown are field estimates of peak discharges for the mudflows of May 18, 1980.

Lang and Dent (1983) developed a numerical solution of the Navier-Stokes equation for a laminar or turbulent, Newtonian mudflow travelling down valleys around Mt. St. Helens and entering a lake. The model must be calibrated with measured discharge values to obtain an index of viscosity and will yield flow depths, velocities, and the amplitude of waves generated by the entry of a mudflow into a lake. In order to compute the potential volume of the mudflow, however, the authors simply assumed that all snow in the source area would be melted and would transform the lower part of any pyroclastic flow or surge into a mudflow.

Waitt et al. (1983) described a mudflow that travelled down the North Fork Toutle River after being generated by meltwater which accumulated in the crater floor during a small eruption in 1982. An initial avalanche of lava blocks, ash, and pumice flowed out of the crater along the path envisaged earlier in this paper. Although the avalanche was not the kind of pyroclastic flow which we had considered, its interaction with the snowpack was similar to our scenario. "Along its axis, the avalanche eroded the snowpack in the breach and into pumice and rockfall deposited in 1980 and 1981. But near its lateral margins the avalanche was much less erosive; locally it plowed up large snow blocks, but in general it barely disturbed the snow,..." (Waitt et al., 1983, p. 1394). This avalanche was too cool to melt large volumes of snow. However, melting did result from the blast within the crater, and formed a lake which flowed through a breach and eroded enough sediment to become a mudflow with an estimated peak discharge of 13,800 m^3/s, some of which entered Spirit Lake (Figure 1), while the remainder flowed down the Toutle valley. The material evolved from a mudflow to a hyperconcentrated water flow as its sediment concentration declined along its path, and the peak discharge declined rapidly downstream. In the inhabited portion of the valley "Peak discharge was an order of magnitude less than that of lahars [mudflows].... on 18 May 1980" (Waitt et al., 1983, p. 1396).

However, three years after the 1980 eruption, there is no published analysis of the fundamental physics of the interaction between hot flows and a snowpack.

CATASTROPHIC BREACHING OF DEBRIS DAMS

Initial debate

The large debris avalanche, which travelled from the cone of Mt. St. Helens down the North Fork Toutle valley in 1980, blocked several important tributary valleys, impounding lakes. The largest of these, at the mouth of Coldwater Creek (Figure 1), had a storage capacity of approximately 123×10^6 m^3. Because of the high precipitation in the drainage basin of this lake the possibility existed that runoff would exceed the storage capacity of the impoundment and lead to a catastrophic release of water down the North Fork Toutle River, which might generate a muddy flood or a mudflow.

The response of various groups ranged from uncertainty about whether the inflow would eventually be balanced by infiltration without overtopping of the dam to the conclusion that filling of the impoundment might occur within the first winter, causing either a mass failure or overtopping and scouring. The first group recommended continued monitoring of hydrologic conditions, and the second group argued that the debris dam should be artifically breached as soon as possible before the lake rose to a dangerous level. However, there was no formal analysis of the downstream consequences of a dam failure.

Analysis of lake filling

Seasonal water budgets for the lake were computed using the annual mean, 10-year minimum and 10-year maximum, precipitation values. Infiltration and evapotranspiration were assumed to be negligible because of the absence of vegetation and the low infiltration capacity (approximately 0.2 mm/hr) of the surface ash cover. The reduction of lake volume due to the influx of sediment was assessed to be small on the basis of extrapolated field measurements of erosion (Collins et al., 1981). Seepage losses into the bed of the expanding lake were also estimated to be small on the basis of hydraulic conductivity values calculated from the rate of lowering of water levels in six small lakes on the debris avalanche deposit. A volume-elevation curve was constructed from a 1:4800-scale topographic map of the lake basin produced within months after the eruption by the U. S. Geoogical Survey. The various weather scenarios led to predictions of the lake reaching the lowest point on the debris dam between 17 and 21 months after the eruption.

Potential for breaching the debris dam

The debris dam could be breached by a mass failure as the fluid pressure in the material increased, or by vertical erosion as a stream of water flowed over the barrier. The latter process would occur rapidly in the unconsolidated debris once the water level reached the critical elevation, probably between the dates referred to above.

Personnel of the U.S. Forest Service, the U.S. Army Corps of Engineers, and the authors analyzed the stability of the barrier using laboratory values of shear strength, and flow nets constructed for various lake levels. The general conclusion was that the steepest portion of the downstream face of the dam would be at or close to failure with respect to shallow planar sliding as the lake approached its maximum possible elevation. This condition might be delayed by the time required for percolation from the bed of the expanding lake into the unsaturated debris of the barrier. Thus it seems likely that the rupture would take place with the lake elevation at or close to the lowest point on the barrier irrespective of whether the debris barrier were finally breached by a shallow landslide or by fluvial incision.

Consequences of breaching

Experience with the failure of artificial earth dams indicates that a breach grows rapidly (to a maximum in a few tens of minutes) as the impounded water flows through it. We tried to calculate this effect by constructing various scenarios for the rate of erosion of the outlet. The discharge hydrograph shown in Figure 7 is based upon the assumption of a vertical erosion rate of 0.3 m/minute, maintaining a rectangular cross-section with a width/depth ratio of 2, and a maximum incision of 30 m. Water discharge through the breach was calculated from the broad-crested weir formula.

The estimated peak water discharge for this scenario was almost 14,000 m^3/s, occurring 100 minutes after the original breach. Other reasonable scenarios provide similar results. When such a tremendous volume of water is released onto unconsolidated sediments, the result could be either a muddy flood with sediment concentrations ranging upto 300,000—500,000 mg/liter (as already observed in the Toutle River during the breaching of small lake barriers), or a mudflow with sediment concentrations of approximately 1,800,000 mg/liter. The former seems more likely on an empirical basis, but since the physics of the sediment transport mechanisms are not well-understood it seemed prudent to consider the possibility of each occurring. Thus, the water discharge values out of the breached dam were enlarged to take account of the volume increase associated with the incorporation of sediment upto concentrations of 300,000 and 1,800,000 mg/liter.

Routing of floodwaves

The Muskingum procedure was again used to route the dam-break hydrographs downstream. Routing parameters for the mudflow were obtained from the 1980 North Fork mudflow hydrographs, as described above. Parameters for routing the muddy flood were calibrated from a valuable set of hydrographs obtained for the Toutle River by Carpenter and Cummans (1980) during the failure of a smaller debris barrier on the avalanche deposit.

The routing results, shown in Figure 7, indicate that breaching of a debris barrier by a lake as large as the Coldwater impoundment would produce much higher and longer hydrographs than those to be expected from a pyroclastic flow on the scale of the Mt. St. Helens examples. The longer and larger hydrographs would not be attenuated as rapidly as the cases discussed earlier, and at the Toutle-Cowlitz confluence they would exceed the peak discharge of May, 1980. There would be no volcanic eruption to warn of the approaching floodwave, and the results would be catastrophic. It was concluded that the lake level should be breached and held at a controlled elevation as soon as possible. Soon thereafter, the

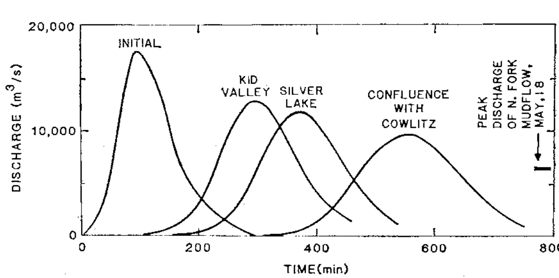

Figure 7: Computed hydrographs of a muddy flood generated by the potential breaching of the Coldwater debris barrier, releasing water at a peak rate of 18,000 m^3/s. The hydrographs were routed downstream by the Muskingum procedure.

Corps of Engineers excavated a bedrock-floored outlet channel from Coldwater Lake across the nose of a ridge that adjoins the debris barrier.

Spirit Lake

The significant hazard at Coldwater led us to consider the possibility that Spirit Lake (Figure 1) might also breach its debris barrier. Field investigations immediately after the May eruption had suggested that there was no significant threat of rapid breaching due to slope failure, piping, or overtopping, even if Spirit Lake (and Coldwater Lake) rose to the top of the barrier. However, the analysis was based on the geometry of the barrier in May, 1980. In the succeeding autumn, large gullies had eroded headward towards the barrier, and it was becoming apparent that the ultimate drainage density of channels on the debris avalanche deposit would be high. Therefore, erosion by major gullies could steepen the topographic and hydraulic gradients at the barrier, just as the lake level was approaching the lowest point on the dam surface. Also, the original assessment was made before the large volume of the lake basin was appreciated and before large canyons, cut across the avalanche deposit, could efficiently channel floods and mudflows downstream.

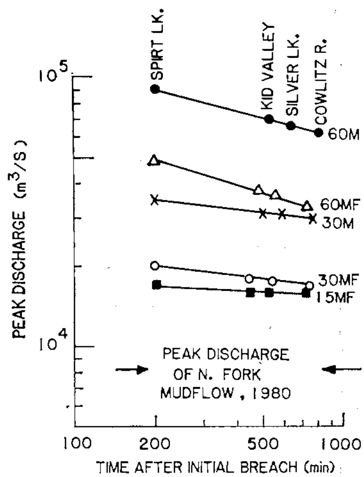

Figure 8 : Computed peak discharges of mudflows and muddy floods generated under various hypothetical scenarios for the potential breaching of the Spirit Lake debris barrier. The rumber on each curve indicales the maximum depth of incision of the barrier allowed in the calculation of the initial outburst hydrograph. The latters M and MF refer to a mudflow and a muddy flood respectively.

In order to make a rough assessment of this hazard, we used the methods employed at Coldwater. No post-eruption topographic map was available and so the drainage area, volume-elevation relationship, and unfilled volume of the lake basin were obtained with stereoscopic parallax measurements on aerial photographs, checked with a helicopter altimeter. The unfilled volume on the day of the aerial photography was 4.8×10^8 m^3. The approach used at Coldwater produced dates for overtopping ranging from 56 to 94 months with 69 months being the most probable. Field examination of the probable breach point and flow path indicated that 30 m was the most likely maximum depth of incision, but outflow hydrographs were also computed for incision depths of 15 and 60 m to evaluate the sensitivity of the prediction to this parameter. Hydrographs of both mudflows and muddy floods were routed downvalley.

The large volume of Spirit Lake generated flood waves with broad, high peaks which diminished slowly downstream. The predicted hydrographs indicate that under any conceivable scenario the peak discharges (Figure 8) in the inhabited portion of the valley would range from damaging to catastrophic. Only a muddy flood, limited to 15 m of incision at the barrier, would produce a peak discharge at the confluence as low as that of May 18—19, 1980.

Early in 1981, it seemed that the Spirit Lake debris barrier should be breached and controlled as soon as possible after Coldwater was regulated. However, the necessary investigations and plans were not made until the lake level had risen to a dangerous height. An expensive, temporary solution has since been installed, which involves pumping water out of the lake from two floating barges and into a 1.5 km long pipe, by-passing the steepest portion of the debris barrier.

REFERENCES

Anyoji, N. and Ikeya, H. (1983) Sediment Discharge and Countermeasures in the Toutle and the cowlitz Rivers after the Eruption of Mt. St. Helens, 1980; *Proc. National Meeting of the Erosion Control Engineering Society of Jopan*, Kyoto.

Collins, B.D., Dunne, T., and Lehre, A.K. (1981) Sediment influx to the Toutle River from erosion of tephra, May 1980—May 1981; *Proc. Conf. on Mt. St. Helens: Effects on Water Resources*, State of

Washington Water Research Center, 82-97.

Crandell, D.R. and Mullineaux, D.R. (1978) Potential hazards from future eruptions of Mount St. Helens volcano, Washington; *U.S. Geological Survey Bulletin* 1383-C.

Fairchild, L.H. and Wigmosta, M. (1983) Dynamic and volumetric characteristics of the 18 May, 1980 lahars on the Toutle River, Washington; *Proc. Symp. on Erosion-Control in Volcanic Areas, Seattle, 1982;* Tech. Memorandum of PWRI No. 1908, Government of Japan, 131-154.

Fenner, J. (1923) Geological communications from Ecuador (translation of article by Wolf (1878)), U.S. Geological Survey Files.

Cummans, J. (1981) Mudflows resulting from the May 18, 1980, eruption of Mount St. Helens, Washington; *U.S. Geological Survey Circular* 850-B.

Lang, T.E. and Dent, J.D. (1983) *Evaluation of the fluid dynamic properties of mudflows on Mount St. Helens;* U.S. Dept. of Interior, Contract 14-4-0001-1471 Final Report, Washington, D.C., 78 p.

Lawler, E.A. (1964) Flood routing; Section 25-II in *Handbook of Applied Hydrology* (ed. Vente Chow), McGraw-Hill, N.Y.

Miller, C.D., Mullineaux, D.R., and Hall, M.L. (1978) Reconnaissance map of potential volcanic hazards from Cotopaxi Volcano, Ecuador; *U.S. Geological Survey Miscellaneous Investigations Series*, Map I-1072.

Murai, I. (1960) On the mudflows of the 1926 volcano Tokachi-dake, Central Hokkaido, Japan; *Bulletin Earthquake Research Insitute*, 38, 55-70.

Newhall, C. (1980) Volcano Hazards at Mt. St. Helens; *U.S. Geological Survey Volcanic Hazards Release*, Vancouver, WA.

Sparks, R.S.J. (1976) Grain-size variations in ignimbrites and implications for the transport of pyroclastic flows; *Sedimentology* 23, 147-188.

Swanson, F.J., Collins, B., Dunne, T., and Wicherski, B.P. (1982) Erosion of hillslopes affected by volcanic eruptions; *Proc. of the Symposium on Erosion Control in Volcanic Areas*, Tech. Memorandum of PWRI No. 1980, Government of Japan, 183-222.

Wolf, T. (1878) Der Cotopaxi und seine letzte eruption am 26 Juni, 1877; *Neues Jchrbuch Mineralogie*, 113-167.

■ 特 別 講 演 会 ■

日本地形学連合主催　砂防学会後援

テーマ：河川のシステム

1) Geomorphic thresholds, complex response and episodic behavior of the fluvial system.
   Stanley A. Schumm (コロラド州立大学，ホートン賞等受賞者)
2) 日本における河川地形学の現況　徳永英二(中央大学)
3) 沖積河川の水理学的側面　林　泰造（中央大学　紫綬褒章等受賞者）
4) 総合討論（通訳付）

期　日：1984年4月21日（土）　午後1：00時～6：00時

中央大学理工学部5号館（〒112 東京都文京区春日1－13－27）

地下鉄丸ノ内線「後楽園」または都営地下鉄三田線「春日」下車，徒歩5分

連絡先：中央大学理工学部地学教室（電話 03－813－4171，内線 642，鈴木隆介）