Reasonable Assumptions in Routing a Dam Break Mudflow

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ABSTRACT: An active landslide threatens to dam the North Fork Cache Creek in Northern California. Releases from an upstream reservoir would result in overtopping and breaching the landslide dam resulting in a mudflow or mudflow. The FLO-2D model is applied to route the landslide dam breach mudflow and map the hazard area of inundation. Two dam landslide scenarios are analyzed. One scenario has a peak discharge in excess of 1 million cfs. By making reasonable assumptions regarding dam breach parameters, sediment concentration and mudflow fluid properties, the potential mudflow hazard can be mapped.

1 INTRODUCTION

An active landslide on the south canyon slope of the North Fork Cache Creek, located in the Coast Range of Northern California, has been identified by scarps and exposed failure planes. The landslide is located 1.5 miles downstream of Indian Valley Dam in Lake County, California. A portion of the landslide was mapped in 1989 and it was observed on the 1993 aerial photos (Wills, 1999). Rapid movement of the landslide into North Fork Cache Creek could result in a natural dam forming a reservoir that could fill with upstream Indian Valley Dam releases. The landslide dam could then overtop and breach posing a significant flood hazard to the residents of Spring Valley approximately 3 miles downstream of the landslide. The Sacramento District of the U.S. Army Corps of Engineers (Corps) contracted with Tetra Tech to analyze the potential for landslide movement and assess the potential flood hazard. Shepherd Miller Environmental and Engineering Consultants, a Tetra Tech company, conducted the geotechnical slope stability analysis. This project was undertaken as a Section 205 project between the Corps and Lake County, California, Emergency Services to investigate the potential flood hazard, assess flood mitigation alternatives and prepare a conceptual response plan. Since the natural dam would consist of landslide material, breaching the dam would result in a mud flood or mudflow.

Mudflows and mud floods are unsteady, nonuniform, viscous tempestuous fluid phenomena. Hyperconcentrated sediment flows are considered as fluids to distinguish them from granular particle motion (granular flows) or landslides. The ubiquitous term '*debris flow*' is avoided here and its use discouraged. '*Debris flow*' has been alternately used to describe a bouldery frontal wave of a flood, an oozing mudflow and boulders rolling down the side of a volcano, but provides little insight about the physical processes of the flow event. The term '*debris flow*' should be relegated to describing the motion of refrigerators, car bodies or stray cattle (Johnson, 1970).

If a water and sediment mixture deforms continuously when subjected to shear stress, it is fluid and is governed by the physics of fluid motion. Fluid motion can be classified as Newtonian where the shear stress is a linear function of the shear rate or nonNewtonian whose viscous behavior is more complex and may be divided into three groups: fluids with a non-linear relationship between shear stress and shear rate; fluids in which the shear stress not only depends on shear rate but also depends on the time of shearing; and fluid that are viscoelastic and exhibit characteristics of both elastic solids and viscous fluids. Sediment particle motion that exhibits pore water pressure or significant dispersive stress falls into the category of bulk solids movement as either landslides or granular flows and should not be considered as fluid motion.

Savage (1979) defined a bulk solid motion as an assemblage of discrete solids dispersed in a fluid such that the solid particles are in contact with their neighbors. In bulk solid flows, Savage (1979) indicated that the solid phase is dominant and motion is governed by particle cohesion, friction and collisions. While the transition from solid particle motion (rolling, tumbling, sliding and colliding) to fluid motion as water is added may be gradual through the continuum of particle motion, the existence or persistence of a pore water pressure is a clear indication of solids motion. Pore water pressure in a flow of granular material means that a portion of the overburden load is carried by both the fluid phase and the solids phase. It also means that the fluid cannot escape through the interstices or that the upward motion of fluid through the solid particles is relatively minor. The distinction between a fluid flow and a granular flow is important when formulating the equations of motion and considering whether the fluid turbulent and viscous stresses dominate or whether the dispersive stress and particle friction terms dominate.

The distinction between fluid motion and solids motion takes on more significance when considering flow initiation or cessation. An assemblage of solids with very little water will cease motion when an abrupt change in slope occurs whereas a fluid will continue to flow downslope on relatively flat gradients as a function of both momentum and water surface slope. This leads to a simple, but often ignored conclusion, the area of inundation by granular flows is almost entirely dependent on the volume of available material, whereas the area on inundation by the fluid flow is dependent on the flow characteristics as well as the volume.

This paper addresses fluid motion of hyperconcentrated sediment flows referred to as mudflows or mud floods. In these flows, course clastic material such as boulders, vegetation and garbage are only along for the ride and do not significantly affect the fluid behavior. The impact of this material is limited to local effects of obstruction and deflection of shallow flows. The classification of these flows is presented Table 1.

Table 1. Mudflow Behavior as a Function of Sediment Concentration

Flow Description	Sediment Concentration		Flow Characteristics
	by Volume	by Weight	
Landslide	0.65 - 0.75	0.83 - 0.89	Will not flow; failure by block sliding
	0.55 - 0.65	0.76 - 0.83	Block sliding failure with internal deformation during the slide; slow creep prior to failure
Mudflow	0.48 - 0.55	0.72 - 0.76	Flow evident; slow creep sustained mudflow; plastic deformation under its own weight; cohesive; will not spread on level surface
	0.45 - 0.48	0.69 - 0.72	Flow spreading on level surface; cohesive flow; some mixing
Mud Flood	0.40 - 0.45	0.65 - 0.69	Flow mixes easily; shows fluid properties in deformation; spreads on horizontal surface but maintains an inclined fluid surface; large particle (boulder) setting; waves appear but dissipate rapidly
	0.35 - 0.40	0.59 - 0.65	Marked settling of gravels and cobbles; spreading nearly complete on horizontal surface; liquid surface with two fluid phases appears; waves travel on surface
	0.30 - 0.35	0.54 - 0.59	Separation of water on surface; waves travel easily; most sand and gravel has settled out and moves as bedload
	0.20 - 0.30	0.41 - 0.54	Distinct wave action; fluid surface; all particles resting on bed in quiescent fluid condition
Water Flood	< 0.20	< 0.41	Water flood with conventional suspended load and bedload

3 SIMULATING HYPERCONCENTRATED SEDIMENT FLOWS

The vast majority of hyperconcentrated sediment flows experienced worldwide fall within a range of 20 to 55 percent concentration by volume and most are associated with rainfall runoff. A smaller percentage of hyperconcentrated sediment flows are initiated by snow melt and runoff and very small percentage are associated with dam breaks, landslides and volcanoes. Hyperconcentrated sediments flow are fully turbulent, unsteady and nonuniform and are characterized by surging, flow cessation, blockage and roll waves. The FLO-2D model simulates these processes by computing the dominant turbulent/dispersive or viscous and yield stresses. The magnitude of each resistive stress depends on the temporal and spatial variation in sediment concentration. At high sediment concentrations the contribution of the dispersive stress to flow resistance is estimated by an exponential function of the turbulent flow resistance Manning’s coefficient (see FLO-2D Manual, FLO-2D Software Inc., 2002)

The simulation of hyperconcentrated sediment flows should be focused on reasonable assumptions involving the following variables that control the hazard map delineation:

- Volume of water and sediment.

The potential area of inundation and predicted maximum flow depths and velocities are primarily a function of the sediment and water volumes. There is a big difference in the area inundated by the 25-year return period mudflow event versus the area inundated by 100-year return period water or mud flood event. Furthermore, mudflows are usually associated with relatively frequent flood events on the order of the 10-year to 25-year storms because there is insufficient sediment available in the watershed to create a mudflow for the 100-year return period water volumes. Extreme flood events will generally behave as a dilute mud flood (O'Brien and Julien, 1997).

- Sediment concentration.

The ratio of sediment to water governs the ability of the mixture to flow. The sediment concentration varies throughout the flood event with surging and flow cessation. The average sediment concentration determines whether the flow will pile up at the fan apex or will flow over significant distance over the alluvial fan.

- Topography, buildings, obstructions, channels and vegetation.

Topography effects local flow depth, velocity and deposition (or scour). Flow depositional features such as natural levees and berms are primarily a function of topography and flow resistance. Variations in topography that reduce slope can induce particle settling that will effect sediment concentration. Buildings and flow obstructions (flood walls) can alter the flow path, or initiate flow cessation.

- Fluid and sediment properties.

Fluid properties vary with sediment concentration. Fluid properties such as viscosity, yield stress, and density effect turbulence, flow momentum and energy dissipation. Sediment particle intergranular collisions, particle collisions with the bed and particle drag reduce the flow momentum through momentum transfer with the bed. Particle sliding friction increases fluid resistance to lesser degree.

A flood or mudflow routing model requires the prediction of average velocities and flow depths with a reasonable degree of accuracy to estimate the area of inundation. How can it be ascertained whether the volumes of water and sediment appear reasonable?

4 FLOOD HYDROLOGY AND SEDIMENT YIELD

Hydrologic models such as HEC-1 or FLO-2D can be used to predict design storm rainfall-runoff hydrograph. These hydrographs can then be bulked with sediment for flood routing over an alluvial fan or river floodplain. Using FLO-2D, it is possible to add sediment to the hydrograph either as a concentration by volume or as a sediment volume assigned to each increment of the discretized hydrograph. FLO-2D conserves volume while routing a flood or mudflow. The water and sediment volumes (either mudflow or conventional sediment transport) are tracked and reported including inflow and outflow volume, water losses due to infiltration or evaporation and storage remaining on the floodplain or in the channel. The routed sediment volume can then be compared with the potential sediment yield in the upstream watershed. The possible sources of sediment including:

- Landslides.
- Hillslope sloughing.
- Channel bank failure.
- Channel bed scour.
- Overland sediment yield (includes rills and gullies).

Various techniques are employed to predict sediment supply. Field observations can often provide a sufficiently accurate estimate. If landslide scarps and hillslope failure are evident, similar sediment loading mechanisms are probable during infrequent storm events. To get a rough estimate of channel bed scour, multiple the channel bed width and length by an estimate of the average scour. A similar sediment volume estimate can be made for bank failure. The estimated sediment delivery from the five potential source areas can be compared with the sediment load predicted by the FLO-2D model. If the predicted and estimated sediment yield compare reasonably well and the average sediment concentration matches the expected type of flood event shown in Table 1, then the overall area of inundation predicted by the model will be relatively accurate as will the simulated flow depths and velocities. The following project will serve as an example of how volumes of sediment and water can be accurately estimated to delineate the mud flood hazard.

5 NORTH FORK CACHE CREEK LANDSLIDE DAM AND RESERVOIR

Natural dams caused by landslides can produce a severe flood or mudflow when breached. Most landslide dams eventually fail, primarily from overtopping and subsequent erosion by surface flows, but failure may also be induced by piping (internal erosion). Failure can occur slowly or catastrophically and a landslide dam may last for only a few hours or may endure for thousands of years. According to Schuster (2000), the two most important processes that trigger landslide dams are excessive precipitation (58%) and earthquakes (33%). Whether water flooding or viscous hyperconcentrated sediment flows occur when the dam breaches depends on the nature of the landslide dam materials, water storage volume in the landslide reservoir and peak discharge from the dam breach. Landslide dams are more frequent in steep, narrow canyons because the canyons are prone to slope failures and require relatively small volumes of landslide material to completely block a stream.

The 1993 aerial photos reveal that the North Fork landslide in California has been moving for several years. These photos show a scarp that is smaller than the 1999 aerial photos. Presently the slide is approximately 1200 ft wide at the toe and 800 ft wide at midlevel. Shepherd Miller concluded that the landslide has complex movement with prominent head and lateral scarps (Photo 1). The hummocky upper portion of the slide is undergoing both rotational and slumping movement that result in areas of both compression and tension. The Shepherd Miller team including former USGS landslide expert Robert Schuster noted that more than one landslide mechanism was possible. One scenario has only the upper portion of the landslide moving while the lower portion of slide is stable. A second scenario considers that the entire landslide slope is moving. The landslide material is constricting the creek. Both landslide scenarios represent a potential for catastrophic failure.

Photo 1. North Fork Cache Creek Landslide (2001)

Slope stability analyses were conducted to back calculate the angle of internal friction and to evaluate the stability of the landslide during the 100-year, 10-day storm event. The analyses were performed assuming shallow circular and fully specified rotational failure modes. The results indicated that the factor of safety for the upper portion of the slide is 1.0 for both shallow circular and fully specified slope stability failure conditions. In the entire slide scenario, the factor of safety would be reduced to 1.0 for both shallow circular and fully specified failure conditions at different times during the 100-year, 10-day storm. Thus for a long duration storm such as the 100-year, 10-day storm the entire landslide would fail for either scenario. Failure was projected to occur about day 6 of the storm. This is an indication that a more frequent storm with high rainfall intensity may also trigger accelerated landslide movement. The rainfall depth for the 100-year, 10-day storm was estimated as 13.34 inches for Indian Valley Dam by the Corps of Engineers (2002). A storm of similar magnitude occurred during the period from January 4-13, 1995; about the time the first major tension cracks appear. This 1995 rainfall distribution was used to estimate the 100-year, 10-day storm distribution. The total rainfall for this 10-day period is 16.35

inches. The 12.85 inches of rainfall for the first six days (January 4-9, 1995) was equivalent to a 200-year 6-day storm.

The landslide dam geometry was estimated for a worst case condition of total failure of the two landslide scenarios. Three canyon cross sections were cut in the mapped topography to estimate the total volume of the landslide. From the center cross section, the dam crest elevation would decrease in both the upstream and downstream directions. The estimated maximum height of the landslide dam was 105 ft for the upper landslide failure and 191 ft for the complete landslide. The lower dam had a volume of 170 acre-ft and the higher dam had a volume of 850 acre-ft of sediment. The smaller dam had a downstream face slope of 5:1 and an upstream slope of 8:1. The larger dam had a downstream face slope of 3:1 and upstream slope 4.5:1. Based on these dam heights, the landslide reservoir volumes and surface area were estimated:

Table 2. North Fork Cache Creek Landslide Dam Geometry

	Scenario 1 Small Dam	Scenario 2 Large Dam
Crest Height (ft)	105	191
Crest Elevation	1320	1406
Dam Volume (acre-ft & yd^3)	170 (274,300)	850 (1,371,300)
Upstream Face Slope	8:1	4.5:1
Downstream Face Slope	5:1	3:1
Reservoir Volume (acre-ft)	2,654	10,170
Reservoir Surface Area (acres)	58	149

If the landslide dams the North Fork, a mudflow hazard would exist if the landslide reservoir fills. This flood hazard is dependent on having subsequent releases from the 150 ft high Indian Valley Dam located 1.5 miles upstream of the landslide site. If there is no release from the Indian Valley Reservoir, then there is no immediate flood risk from the landslide dam. It is necessary therefore to assess under what hydrologic conditions Indian Valley Dam releases would occur.

Indian Valley Reservoir (300,600 acre-ft) went into service in June 1974 for the purposes of providing irrigation water and flood control. The total flood control storage is 40,000 acre-ft. Based on a reservoir storage starting at the bottom of the flood conservation pool (260,600 acre-ft), the reservoir provides slightly less than a 50-yr return period flood protection. Releases from Indian Valley Dam during flood events are contingent on the discharge measured at downstream gage to avoid flooding. Dam releases that cause the gage to exceed 20,000 cfs are to be avoided. Indian Valley Dam can have releases up to 10,000 cfs with the provision that the flows at the gage cannot exceed 20,000 cfs.

The Corps of Engineers developed Indian Valley Dam release scenarios by reviewing the two largest historical inflows to Indian Valley Reservoir (January 1983 and March 1995; High, 2002). Both of these flood events approached a 50-year return period frequency. In the first release scenario, the inflow is composed of a series of moderate storms followed by the 100-year, 10-day storm. The series of moderate storms are assumed to occur during January 1 through January 10 followed by the 100-year design storm on January 11 through 20th. The landslide is then presumed to occur on January 16th at midnight, at which time the dam release is reduced to zero. No additional rainfall is presumed after the

10-day, 100-year storm. Using a HEC-5 simulation with the previously described operating rules, the excess water in the flood conservation pool was evacuated prior to the start of the 100-year, 10-day storm. After the landslide occurs, zero releases can be maintained for about 14 days (until January 31 at 9 am) until the water elevation reaches 1,502 (3 ft below the top of dam reserved for wind and wave run-up). When the water reaches that elevation, the reservoir releases would be increased to match the inflow.

In the second release scenario, the landslide is presumed to have failed prior to a 100-year 30-day storm that includes the 100-year, 10-day storm at the beginning of the design storm. This scenario, beginning on January 1, ensures fast filling of the reservoir. The entire storm volume is stored in the reservoir until releases must occur. A zero release is maintained until January 18th at 7 am when the simulated forecasted storms necessitate reservoir evacuation for anticipated future inflows. During the release of 5,000 cfs the maximum water surface maintained at 1497 (8 ft below the top of the dam.

In both storm scenarios, there is a considerable period of time after the landslide occurs before reservoir releases are required; 14 days for storm Scenario 1 and at least 8 days for storm Scenario 2. In Scenario 2, it is assumed that landslide has occurred sometime prior to the storm. Both of these scenarios were developed to create a relatively conservative approach to simulating the dam release. While other scenarios could be tested for various other return period storms, it has been determined that these two storm scenarios would result in dam releases that will fill the landslide reservoir.

6 LANDSLIDE DAM BREACH ANALYSIS

The computer program Breach (Fread, 1991) was used to generate the dam breach hydrograph. The Breach model is a physical process, numerical model that predicts dam breach characteristics (shape and timing) and the resultant discharge outflow from the breach. The model couples conservation of mass (reservoir inflow, reservoir storage, spillway outflow and breach outflow) with the sediment transport capacity of the unsteady uniform flows in a scoured breach channel. The breach analysis was based on the two landslide scenarios; small (105 ft high) and large (191 ft high). The corresponding reservoir volumes were 2,654 acre-ft and 10,170 acre-ft respectively (Table 2).

Four dam breach scenarios involving the two landslide dam heights and the two Indian Valley Reservoir release hydrographs were analyzed to estimate when the landslide reservoir volume would fill and begin to overtop the dam. The dam release volume from storm Scenarios 1 and 2 are 17,680 acre-ft and 160,356 acre-ft respectively. Both the landslide reservoirs would be filled and the landslide dams overtopped by these release volumes. The time and dates of overtopping is presented in Table 3. The minimum time from the landslide failure to the overtopping of the landslide dam is about 15 days for the small dam and 20 days for the large dam.

Table 3. Landslide Dam Overtopping Time and Date

	Storm 1 (1,524 cfs)	Storm 2 (5,000 cfs)
Small Dam	07:30 on 2/1	20:20 on 1/18
Large Dam	0:00 on 2/14	7:30 on 1/20

Some of the geotechnical parameters used in the Breach program were derived from a soil sample analysis. The geotechnical properties of the landslide defined the rate of breach width opening and erosional characteristics of the dam face. The adopted geotechnical properties of the simulated landslide dam are presented in Table 4. The dam cohesive properties is representative of a saturated failure soil with a low cohesive strength.

Table 4. Landslide Dam Properties

Property	Value
Plastic Index	8
Liquid Limit	24
Cohesive Strength	10 lbs/ft^2
Internal Angle of Friction	29 degrees
Median Sediment Size	2.36 mm
Porosity	0.40
Unit Weight	78.7 lb/ft^3
D_{90}/D_{30} Ratio	19.44
Manning's n-value	0.05

The breach discharge hydrograph is also a function of the shape of the landslide dam that will be eroded away. Most of the dam's geometry crest length and slope was dictated by the canyon topography or the landslide shape and volume. The dam crest width had to be assumed. A sensitivity analysis was conducted on the geotechnical parameters to maximize the outflow hydrograph peak discharge.

Table 5 lists the breach peak discharges for the landslide dam scenarios. For the high landslide dam, the breach hydrographs are approximately the same for either Indian Dam release scenario. For the smaller landslide dam, the second storm inflow hydrograph with a peak discharge of 5,000 cfs results in a higher peak breach discharge. The breach discharge hydrograph was bulked with sediment concentration to account for the landslide dam erosion. The sediment concentration was distributed non-uniformly on the rising limb of the hydrograph with a peak concentration of 45% by volume. The breach hydrograph with sediment bulking (mudflow) for the small landslide is displayed in Figure 1. The large landslide dam breach hydrograph is similar. These bulked breach hydrographs constituted the inflow to the FLO-2D flood routing model.

Table 5. Dam Breach Peak Discharges (cfs)

Landslide Dam Height	Water	Bulked Mud Flood
Small Dam		
Storm Scenario 1	25,720	41,020
Storm Scenario 2	34,890	54,490
Large Dam		
Storm Scenario 1	830,650	1,441,800
Storm Scenario 2	830,650	1,441,800

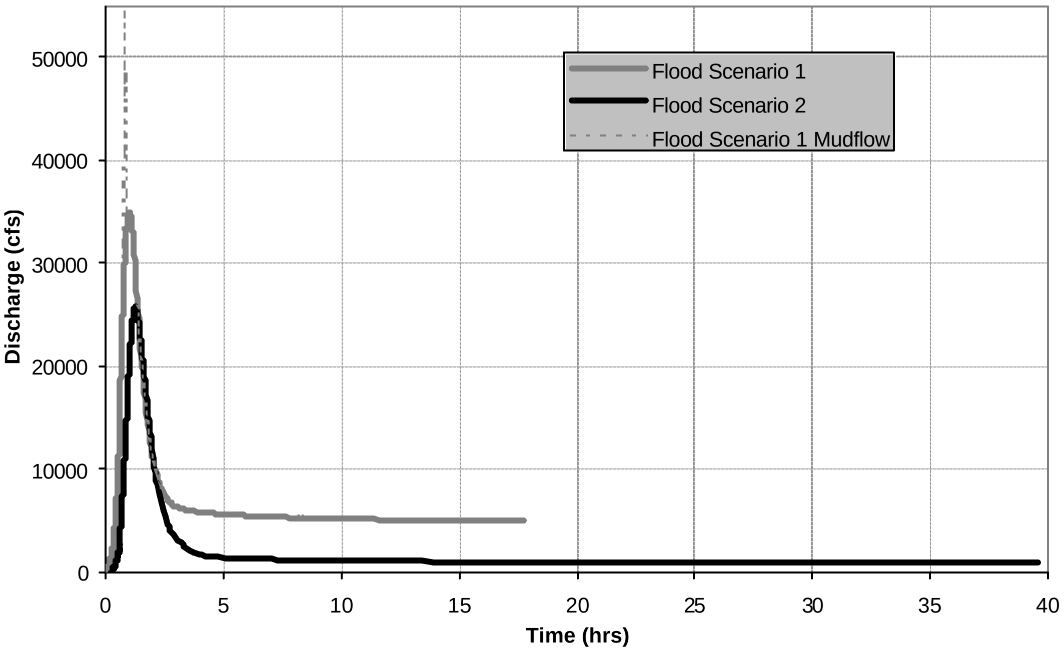

Figure 1. Low Landslide Dam Breach Discharge

7 FLO-2D FLOOD ROUTING ANALYSIS

FLO-2D is a two dimensional flood routing model with both channel and unconfined overland flow components. It is a FEMA approved hydraulic model for both riverine flooding and unconfined alluvial fan flows for creating flood insurance rate maps (FIRMS). FLO-2D is a finite difference model that uses a square system of grid elements overlaid on the topographic mapping. The flood hydrograph is routed using the full dynamic wave approximation to the momentum equation. When routing hyperconcentrated sediment flows such as mudflows and mud floods, the momentum equation includes the viscous and yield stresses. See the FLO-2D User's Manual for a complete discussion of the model attributes (FLO-2D Software, Inc, 2002).

In the selection of a grid element size, it is necessary to balance the mapping resolution with the inflow peak discharge flux. The selected grid element size was 250 feet which resulted in 1,498 elements and 178 channel elements. The Manning's n-values were 0.075 for the floodplain and 0.065 to 0.080 for the channel. These high n-values reflect the variation in the canyon cross section shape.

The mudflow component was used route the bulked breach discharge to account for the landslide dam sediment volume, 170 acre-ft and 850 acre-ft for the small and large dams respectively. This is a relatively small percentage of the reservoir water storage of the 2,650 acre-ft and 10,170 acre-ft for the two landslide dam scenarios. To conservatively maximize the peak discharge, the entire landslide dam was assumed to erode on the rising limb. In other words, the landslide dam was essentially washed away prior to the peak discharge in approximately 5 minutes for the high dam and roughly 31 to 40 minutes for the low landslide dam. A sediment concentration by volume was assigned to each of the discretized breach hydrograph intervals ranging from 1 % to 45 % volume. The sediment concentration was distributed in the breach hydrograph such that the total volume of sediment routed downstream matched exactly the landslide dam volume.

To simulate the landslide dam failure as a mudflow or debris flow, mudflow parameters for the viscous and yield stresses were selected from Table 8 of the FLO-2D Users' Manual (FLO-2D Software, Inc. 2002). Mudflow sample parameters from this table were chosen to represent a viscous mudflow similar to wet cement. The period during which this mudflow would occur is very short on the order of 10 seconds for the high dam and less than a minute for the small dam.

It was noted that in all the simulations, volume conservation was observed on the order of 0.02 acre-ft or less. The floodwave attenuation is significant downstream from the landslide dam. Table 6 shows the floodwave attenuation for the hyperconcentrated sediment flow (includes the dam sediment) for both landslide scenarios.

Table 6. Floodwave Attenuation (Mud Flood in cfs)

	Landslide Dam Peak Discharge	Peak Discharge at Treatment Plant (2.5 miles downstream)	Peak Discharge Highway 20 (7 miles downstream)
High Dam	1,441,800	319,700	49,600
Low Dam (High Inflow)	54,500	34,500	13,800

For the high landslide dam breach, the maximum flow depths range from 22 to 34 ft on the lower floodplain terrace with maximum velocities ranging from 9 to 12 fps. For the low landslide dam breach the maximum flow depths and velocities are 6 to 10 ft and 2 to 5 fps respectively on the lower floodplain terrace in Spring Valley. This illustrates the dramatic difference in the magnitude of potential flooding associated with the 105 ft high landslide dam versus the 191 ft high dam. The difference arises primarily from the magnitude of storage in the landslide reservoir.

The FLO-2D mudflow inundation area was plotted on a series of topographic base maps. The DTM ground elevation points were subtracted from the predicted grid element water surface elevations to generate a detailed color contour map with the DTM computed flow depths. An example is shown in Figure 2 for the small landslide dam.

8 CONCLUSIONS

Detailed flood inundation hazards maps for mud floods and mudflows can be created for delineating flood risk and implementing zoning restrictions. By making reasonable assumptions of water and sediment volumes, sediment concentrations and fluid properties, mudflows and mud floods can be routed with the two-dimensional flood routing model FLO-2D accounting for floodwave attenuation, flow obstructions, cessation or other flow phenomena. Maps created with the FLO-2D model results are now being used by federal agencies and flood control districts to delineate both water flood and mudflow hazards.

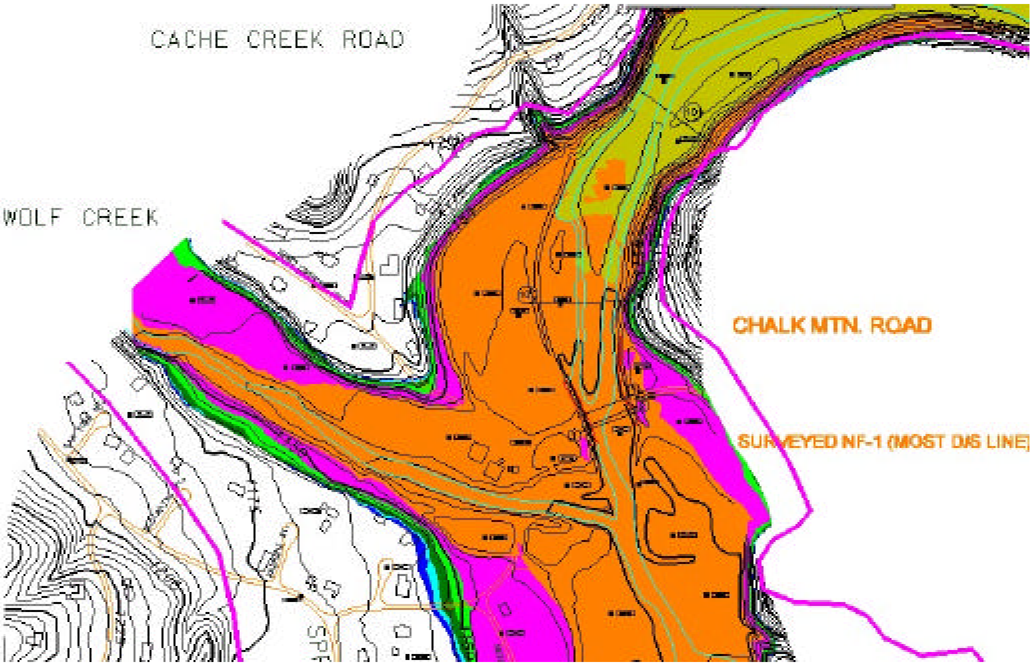

Figure 2. FLO-2D Maximum Depth Inundation Maps

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