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Emergency Dam Break Analyses Following the Cerro Grande Fire near Los Alamos, New Mexico

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Abstract

The Cerro Grande fire of May 2000 severely burned the majority of several forested watersheds upstream from the city of Los Alamos, NM, and the Los Alamos National Laboratory. The fire dramatically altered the rainfall-runoff relationships in the watersheds, creating the potential for runoff volumes orders of magnitude greater than for pre-fire conditions. The dramatically increased runoff conditions created the potential for catastrophic dam-break failures of several highway embankments and a dam in the area. Following the fire, an Interagency Burned Area Emergency Rehabilitation team formed to assess damage caused by the fire and to develop and implement a rehabilitation plan to minimize loss of life and damage to property and natural resources. The U.S. Bureau of Reclamation's Technical Service Center assisted the Interagency Burned Area Emergency Rehabilitation Team with emergency dam break analyses and assessments of alternatives for dealing with the threats posed by potential dam or embankment failure. The period for making the assessments was extremely short, since July 1 marks the traditional start of the monsoon season in the area.

Introduction

The Cerro Grande fire burned roughly 47,650 acres south and west of the city of Los Alamos, New Mexico during May and June 2000. The fires burned the headwaters of several watersheds upstream from the city and the Los Alamos National Laboratory (LANL). The U.S. Department of Energy operates the Laboratory. The city and laboratory sit atop plateaus interlaced by canyons, with some infrastructure located in the canyon bottoms. The Los Alamos Canyon and Pajarito Canyon watersheds experienced high and moderate burn intensities over the majority of their areas. Hydrophobicity in the severely burned areas dramatically altered the rainfall-runoff relationship for these watersheds. Hydrophobicity is a condition in which the baked soil and organic matter repel water, creating the potential for extremely large runoff, orders of magnitude greater than for pre-fire conditions. Potential flooding threatened municipal infrastructure and laboratory facilities in the canyon bottoms following the fires. Several highway embankments and Los Alamos Dam have the potential to impound reservoirs and then fail, magnifying the threat by producing large dam-break floods.

During the fire, the National Park Service and US Forest Service formed an Interagency Burned Area Emergency Rehabilitation (BAER) team. The team assesses fire damage and develops a rehabilitation plan to prevent loss of life and property and reduce further natural resource damage. Wildlife biologists, archaeologists, soils scientists, landscape architects, geologists, ecologists, engineers, foresters, botanists, GIS and GPS specialists and other disciplines typically staff BAER Teams. The

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focus of most BAER Team efforts is watershed rehabilitation. In this situation, the goal of watershed treatments is to counteract hydrophobicity and reduce runoff by roughly 30 percent in the first season. This projected rehabilitation is not enough to remove the threat of dam failure. On June 1, 2000, the BAER Team asked the U.S. Bureau of Reclamation Technical Service Center to assist with emergency dam break analyses and assessments of alternatives for dealing with the threats posed by potential dam or highway embankment failure. The time frame for these assessments was extremely short, since the traditional start of the monsoon season in the area is July 1.

This paper describes the dam break analyses, the interaction with the BAER Team, and the role the emergency analyses played in the management decisions implemented by the BAER Team, the City of Los Alamos, and the Department of Energy. The attention to threats to infrastructure was an unusual aspect of this case, since BAER Team efforts have traditionally been focused on watershed and natural resource issues. This fire was one of a growing number that occur in a mixed urban and wildland setting, as population growth in the western U.S. continues to expand urban areas and increase population density in forested areas. These urban interface fires raise unique issues that require assessment of fire and flood effects on man made structures within affected watersheds.

TSC Team Approach and BAER Team Priorities

When the TSC Team arrived in Los Alamos, the BAER Team assigned three priorities for dam breach analysis. The first was Pueblo Canyon, second Los Alamos Canyon, and third, Pajarito Canyon. The TSC team began with a field trip to visit each of these sites and to begin collecting field data. That data included photographs, and dimensions of the embankments. The TSC Team used a laser range finder to measure the slope angles, distances, and widths of the embankments.

The TSC Team relied primarily upon regression techniques of Froehlich (1995) and Von Thun and Gillette (1990) to estimate the breach parameters. They also considered several other methods summarized in Wahl (1998). Final determinations took into account local site conditions and their limited knowledge of embankment materials (fill bridges were definitely not engineered dams and were likely to fail quickly).

The TSC Team then proceeded to build and run the FLDWAV models. In some cases it was necessary to combine outflow hydrographs for routing through downstream tributaries. At the same time, the Team identified flow conditions at critical points (i.e., facilities and populations at risk).

Modeling Dam Breach with FLDWAV

The source of channel geometry was USGS 1:24000 topographic maps. LANL supplied some 2-ft contour interval maps at 1:2400 scale. The channels are usually dry and have significant vegetation. The Manning roughness for all analyses was 0.07 in areas with thick vegetation and 0.04 to 0.05 in areas with only minor vegetation growth.

A common problem with DAMBRK is that it does not converge for transcritical flow because of the particular numerical scheme used within the model. Meselhe and Holly (1997) showed that the Preissmann four-point scheme is marginally stable based on linear analysis if critical points are encountered within the computational domain. Marginally stable means that error or perturbations are neither damped nor amplified. However, because the set of governing equations is non-linear, the scheme may actually be unstable if critical points are encountered. The National Weather Service has identified this problem within the DAMBRK model and produced a new model, NWS FLDWAV, that can model the transition between sub-critical and super-critical flow (Jin and Fread, 1997). The scheme uses an explicit flux-splitting technique to correctly identify wave propagation direction. The explicit scheme requires smaller time steps and therefore can require longer computational times. However, computational times for roughly 6 hours of simulated time were usually 10 min or less on a 266MHZ Pentium II. FLDWAV has the ability to interpolate cross sections. The spacing between the interpolated cross section spacing was reduced by factors of two until further refinement did not change the peak outflow at the downstream boundary by more than 10%.

Pueblo Canyon at Diamond Drive Avenue

The highway fill embankment crossing Pueblo Canyon on Diamond Avenue in Los Alamos, New Mexico is roughly 120-ft high, constructed of unknown materials. The fill is believed to have originated in the late 1940's and been added to by side casting over the years as the highway was enlarged. The fill in its present condition could impound a reservoir of roughly 800 ac-ft, and its only outlet is an 18-inch diameter culvert pipe with a vertical riser inlet. There is a possibility that a larger (6 to 7 ft) culvert pipe can be installed. There is a history of seepage through the embankment and migration of fines out of the embankment following storms that occurred several years ago. Diamond Avenue is the primary north-south transportation corridor the city of Los Alamos, and important utility lines are contained within the fill. The majority of the 2.26 mi^2 watershed upstream from the fill dam experienced high severity burn damage during the Cerro Grande fire of May 2000.

The flood hydrograph for the post-burn, 100-yr, 1-hr rainfall event (2.3-inch) has a rise time of 1.1 hr, peak discharge of 1,711 ft^3/s, total hydrograph duration of 2.7 hr, and total volume of 163 ac-ft. This flood will not overtop the fill dam, but water will be impounded to a depth of about 74 ft by the dam, which raises the possibility of a seepage-erosion failure of the embankment. In addition, it is possible that a larger storm or a sequence of storms could fill the reservoir and overtop the embankment, causing an overtopping failure. NWS-FLDWAV modeled the following two scenarios:

- A seepage-erosion failure occurring as a result of water impounded to a depth of about 74 ft behind the fill dam following the 100-yr, 1-hr duration rainfall event. Assume the reservoir is empty before the storm, and fire debris plugs the culvert through the embankment. Such a storm has a 1% chance of occurring in any given year, and there is about a 10% chance that such a storm will occur sometime during the next 10 years.

- An overtopping failure occurring as a result of one larger storm or a sequence of storms that completely fill the reservoir upstream from the embankment, leading to an overtopping failure.

The assumption for the embankment breach is an opening down to the existing stream channel elevation with a trapezoidal shape having a base width of 60 ft for the seepage-erosion case and 90 ft for the overtopping case. The breach side slopes are 1:1 for both cases, and fire debris plugs the 18-inch culvert (or any future larger culvert). The breach develops in 45 minutes in the seepage-erosion case, and 30 minutes in the overtopping case. The resulting breach outflow hydrographs for both cases were routed to the confluence of Pueblo and Los Alamos Canyons, and the outflow from the overtopping failure was routed downstream to the confluence with the Rio Grande.

Structures downstream from the fill bridge impacted by dam break flooding include the sewage treatment plant ½-mile downstream, the sewage treatment plant east of Kwage Mesa, the highway 502 road crossing about 6 miles downstream, and several structures at Totavi, roughly 10 miles downstream from the fill dam (downstream of the confluence of Pueblo and Los Alamos Canyons). Another significant impact of a breach would be the loss of highway access between the north and south sides of Los Alamos and the loss of utility lines contained in the embankment.

The dam break simulation predicts peak discharge and corresponding maximum flow depth along the length of the downstream channel. Table 1 lists discharges, flow depths, and arrival times of the peak flow. A direct determination of whether the dam break flood would cause inundation of the structures is not possible with the precision of the structure elevations at these sites.

Table 1. Peak dam-break flows.

Location	Approx. Distance downstream (mi.)	Peak Discharge (ft^3/s)	Time of Peak, after start of breach (hours)	Maximum Flow Depth at Peak Discharge (ft)
Seepage-erosion failure following 100-yr, 1-hr rainfall event				
At fill dam	0	9,000	0.43	11.6
Sewage treatment plant	0.5	9,000	0.46	10.4
Sewage treatment plant east of Kwage Mesa	5	7,300	0.92	6.5
Confluence of Pueblo & Los Alamos Canyon	7	6,100	1.16	6.8
Overtopping failure for 100-yr, 1-hr rainfall event flowing into reservoir that is initially full to crest of embankment				
At fill dam	0	36,300	0.23	21.9
Sewage treatment plant	0.5	36,200	0.25	19.6
Sewage treatment plant east of Kwage Mesa	5	32,200	0.55	12.1
Confluence of Pueblo & Los Alamos Canyon	7	29,500	0.71	12.7
Confluence with Rio Grande	12	23,200	1.07	8.5

Los Alamos Canyon

Los Alamos Dam has a hydraulic height of 26 feet, crest width of 30 feet, crest length of 150 feet, upstream and downstream slopes of 1.5:1, and an uncontrolled spillway chute over the center of the dam. The embankment is an earth and rockfill structure believed to contain a concrete corewall. The spillway control is roughly 20 feet wide, the spillway is 4.67 feet deep, and has a capacity of roughly 600-1,000 ft^3/s. The reservoir capacity at 26 feet of depth, or at the spillway crest, is 25.4 AF with a surface area of 2.02 acres. The capacity at 30.67 feet of depth, or at the dam crest, is 43.02 AF with a surface area of 2.23 acres. A stop log gate, miscellaneous debris, and remnants of old control gates, etc. partially obstruct the control section of the spillway. The TSC Team recommended the immediate removal of these features, improving passage of debris through the spillway.

The post-burn, 100-yr, 1-hr rainfall event (2.3 inches) produces a peak inflow to the reservoir of 511 ft^3/s with a time-to-peak inflow of 2.85 hours. The total volume is 111 AF. If the spillway does not plug, it is capable of safely passing this event regardless of whether the reservoir is initially empty or full. If the spillway does not function, the event will fill an initially empty reservoir in 2.25 hours and then overtop the reservoir to a depth of 1.1 feet.

A dam break simulation for the 100-yr, 1-hr event was computed using NWS-FLDWAV and assuming an overtopping failure. The reservoir was empty at the beginning of the simulation, the spillway fully plugged by debris, and the breach fully developing in 30 minutes after first overtopping. The embankment breached down to the existing stream channel elevation with a trapezoidal breach shape having a base width of 60 ft and 1:1 side slopes. FLDWAV routed the resulting breach outflow hydrograph to the confluence of Pueblo and Los Alamos Canyons.

Structures downstream from the dam include the ice rink (1.7 miles), TA-41 building complex on the Los Alamos National Laboratory (LANL) (3.5 miles), TA-2 (4 miles), Highway 502 at the confluence with Pueblo Canyon, and several small structures at Totavi, (~10 miles) downstream of the confluence of Pueblo and Los Alamos Canyons. The computed peak outflow from the breached embankment is 2,220 ft^3/s. At the ice rink the peak flow is about 2,200 ft^3/s, and the flow depth is about 5.4 ft. At the TA-41 building complex, the peak flow attenuates to 2,050 ft^3/s, and the peak flow depth is about 5.1 ft. At the TA-2 reactor, the peak flow is about 2,000 ft^3/s and the peak flow depth is about 5.5 ft. At the confluence of Pueblo and Los Alamos Canyons, the peak flow is 1,100 ft^3/s and the peak depth is 3.6 ft. Elevations and stations of the structures at these sites were not known with sufficient precision to allow a direct determination of whether the dam break flood would cause inundation of the structures.

Routing Pueblo and Los Alamos Canyons to the Rio Grande River

The flood hydrographs from the breach of Los Alamos Dam during a 100-yr storm and the breach of Diamond Avenue fill bridge during a 100-yr storm were combined so that their peak flows occurred simultaneously at the confluence of Los Alamos Canyon and Pueblo Canyon. The combined flood hydrograph was routed to the confluence with the Rio Grande River. The peak flow from Los Alamos Canyon arrives roughly 3.8 hours after the start of the storm, and the peak from Pueblo Canyon arrives roughly 3.9 hours after the start of the storm. Los Alamos Reservoir begins to breach at 2.2 hours and Fill Bridge begins to breach at 2.7 hours.

Figure 1 shows the flood hydrographs at the confluence of Los Alamos and Pueblo Canyons and at the confluence with the Rio Grande River. The time shown in Figure 1 is relative to the beginning of the storm. The peak flow rate at the confluence was 7,200 ft^3/s at the confluence Los Alamos and Pueblo Canyons and attenuates to 5,400 ft^3/s near the Rio Grande. Los Alamos Canyon contributes roughly 1,100 ft^3/s to the flow and Pueblo canyon contributes roughly 6,100 ft^3/s.

Table 2 lists the hydraulic conditions at structures that are at potential risk. Visual inspection indicates that the service station and Totavi are almost at the elevation of the riverbank. The combination of the depth and velocity are sufficient to be a serious threat to humans and cause significant damage to the structures. Note that the hydraulic conditions resulting from the overtopping of Diamond Avenue Fill Bridge are much more severe. The conditions resulting from such an event would be sufficient to destroy the structures.

Table 2. Hydraulic conditions from breach of Los Alamos Dam and Fill Bridge during 100-yr storm.

Structure	Distance from Confluence (miles)	Peak Travel Time (hr)	Flow rate (ft^3/s)	Velocity (ft/s)	Depth (ft)
Highway 502 Crossing	0.00	0.00	7200	17	5.5
Service Station	1.90	0.12	6900	13	5.9
Totavi	1.95	0.13	6900	12	5.9
Otawi	4.60	0.47	5500	10	4.8

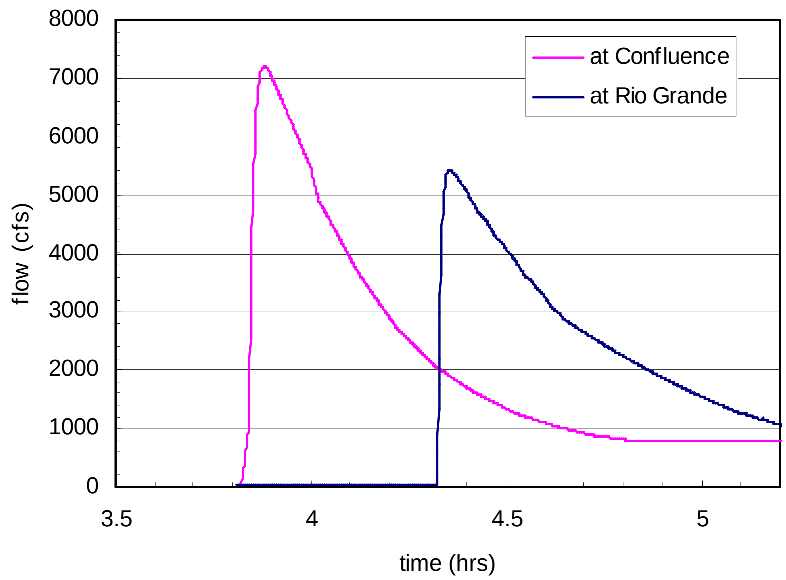

Figure 1. Flood hydrographs at the confluence of Pueblo and Los Alamos Canyons, and Rio Grande River.

Pajarito Canyon

Several roadfill embankments cross Pajarito and Two-Mile Canyons and their tributaries in the area south and west of Los Alamos, New Mexico. Figure 2 shows a schematic diagram of the embankments and reservoirs that could form upstream from them, with each identified by letter. Table 3 contains relevant characteristics for dam break analysis.

- A - The highway 501 embankment crossing Pajarito Canyon
- B - A roadfill embankment on Anchor Ranch Road where it crosses Pajarito Canyon, on LANL property roughly ¼ mile downstream from highway 501
- C - A roadfill embankment on an abandoned stub of Anchor Ranch Road crossing Two Mile Canyon roughly 300 yards downstream from highway 501. This embankment is just north of the guard shack at the LANL entrance off Highway 501. Two other small embankments are located between embankments C and D, but both will be fully submerged within the reservoir impounded by embankment C.
- D – A roadfill embankment on highway 501 where it crosses Two Mile Canyon
- E – A roadfill embankment on Upper Two Mile Canyon (north tributary to Two Mile Canyon). This embankment is located on an extension of Mercury Road going west from Bikini Atoll Road on LANL property.

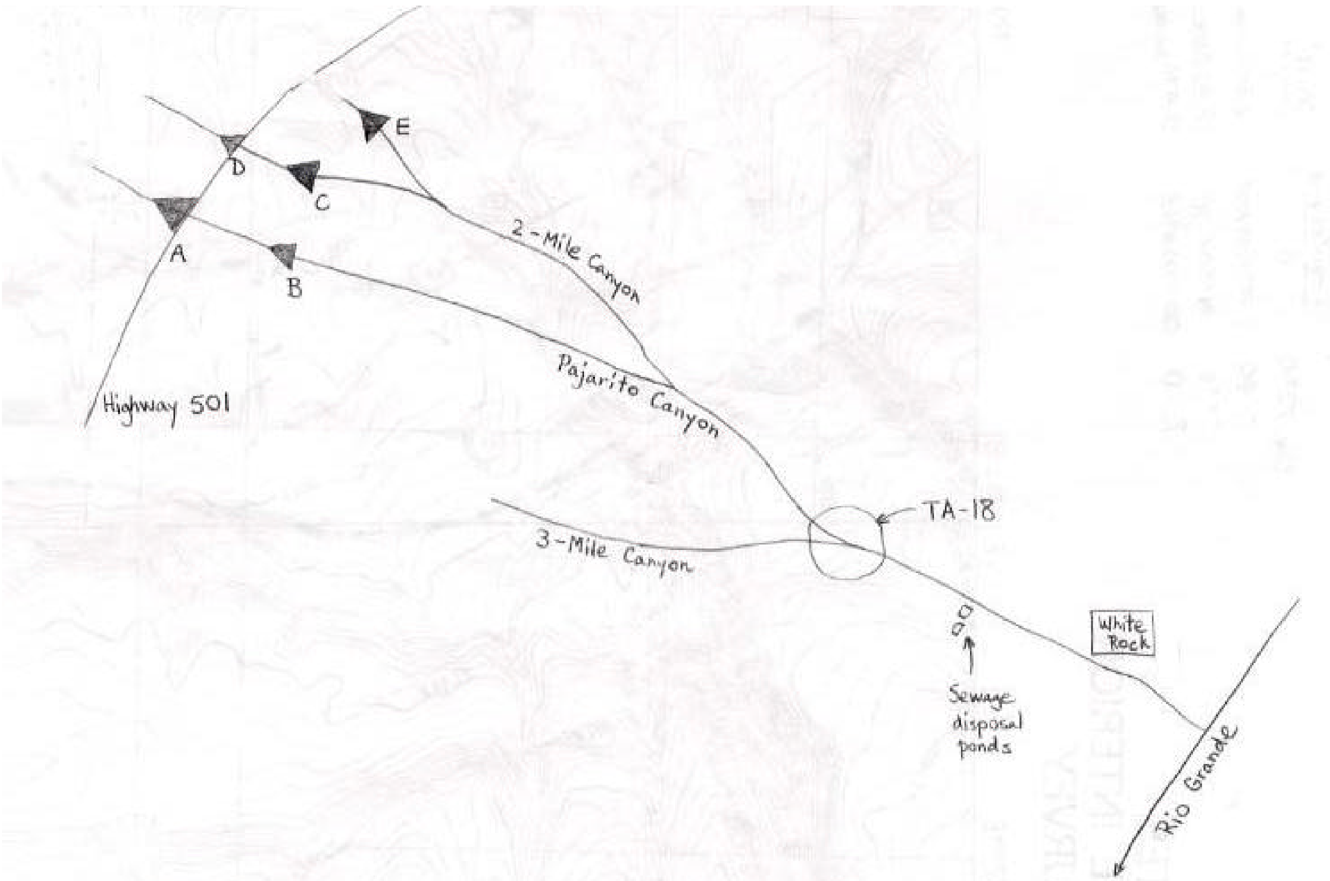

Figure 2. Triangles indicate a road embankment.

Table 3. Embankment characteristics (-- indicates that the item was not computed).

Embankment	Hydraulic Height (ft)	Impoundment Volume (acre-ft)	Peak inflow of 100-yr flood (ft^3/s)	Volume of 100-yr flood (acre-ft)	Culverts
A	28	22	683	86	2 – 42 inch
B	15	4	683	86	3 – 48 inch
C	40	33.5	667	50	54 inch
D	--	1	667	50	none
E	60	--	50	--	93 inch

Embankments A, B, and C are the primary focus of these studies. Embankment D impounds a total volume of roughly one acre-foot (AF), and is thus of negligible importance compared to the other embankments. Embankment E is roughly 60-ft high and could impound a large volume of water, but the 0.52 mi^2 watershed upstream from it was relatively unaffected by the Cerro Grande fire (0.13 mi^2 no-burn, 0.37 mi^2 low-intensity burn, 0.02 mi^2 high-intensity burn). Therefore, the peak inflow to embankment E for the 100-yr storm is only 50 ft^3/s, and is easily conveyed through the 93-inch culvert pipe that drains the embankment.

There are several sites of concern downstream from these embankments, including:

- Technical Area 18 (TA-18) location on the property of the Los Alamos National Laboratory (LANL) in Pajarito Canyon, downstream from its confluence with Two Mile Canyon.
- Sewage disposal ponds roughly ½ mile downstream from TA-18
- Homes in the vicinity of the town of White Rock

Sections are from 2-ft contour interval maps near structures at TA-18 and near White Rock. The basis of all simulations were existing channel conditions, ignoring any recent or proposed changes to the stream channels made for erosion protection purposes. The dam break failure scenario used for this study was a sequenced failure of embankments A (Pajarito Canyon at 501) and B (Pajarito Canyon at Anchor Ranch Road). In addition, embankment C (Two-Mile Canyon at 501) fails such that its peak outflow arrives at the confluence of the two canyons simultaneously with the peak flow from the A and B failures.

The combined flood waves were routed downstream from the confluence of the canyons, past TA-18, and finally to Sherwood Avenue in White Rock. Tributary inflows from Upper Two-Mile Canyon and Three-Mile Canyon were neglected, since they were small in comparison to the dam break outflows (approx. 100 ft^3/s total for both tributaries). Downstream from White Rock, Pajarito Canyon drops very rapidly to the Rio Grande. The flood wave was not routed through this reach due to the very steep slopes and lack of threatened structures. There would likely be very little attenuation of the flood wave in this reach.

All dams were assumed to breach down to the existing stream channel elevation. The breach width prediction equations referenced above were used to compute estimates of average breach width. These estimates ranged from 30 to 90 ft for embankment A, 15 to 60 ft for embankment B, and 30 to 120 ft for embankment C. Considering the width of the canyons at each site, which can limit the width of a breach, base widths of 40 ft, 20 ft, and 20 ft were selected for embankments A, B, and C, respectively. Side slopes of 1:1 were selected for all breaches, yielding average breach widths (average of top width and base width of the trapezoidal breach) of 68, 35, and 60 ft, respectively.

Breach formation times predicted by the various equations ranged from as little as 5 minutes to as long as 70 minutes for all three embankments. Based on our site inspections and expected mechanics of breach development at each site, breach formation times of 15, 45, and 15 minutes were selected for embankments A, B, and C, respectively. Embankment B is expected to breach much slower than A or C due to its flatter upstream and downstream slopes, the presence of the toe berm on the downstream side, and the fact that it is expected to breach through the downstream corner of the roadway crossing (i.e., along the groin), rather than through the main body of the embankment.

Results

Table 5 shows the results of the FLDWAV simulations. The peak outflow from the breached dams in Pajarito Canyon is about 3,100 ft^3/s, attenuating to about 2,000 ft^3/s at the confluence with Two-Mile Canyon. The peak outflow from embankment C on Two-Mile Canyon is roughly 4,900 ft^3/s, with the peak flow attenuating to 3,000 ft^3/s at the confluence with Pajarito Canyon. The routing from the confluence of the two canyons down to White Rock shows continued attenuation of the combined peak flow due to the relatively flat slope and broad floodplain through this reach.

Peak discharge near TA-18 is roughly 2,200 ft^3/s, and the peak flow depth is roughly 5 ft above the crest of the roadway on the downstream side of TA-18. These flow rates and depths are high enough to be of concern for the structures at this facility. These results do not consider recent emergency channel modifications, or any future modifications that might restrict the channel. Debris flows and interaction of debris with security fences may significantly affect these results.

The peak flow rate near White Rock dissipates to roughly 1,400 ft^3/s, with a flow depth of 4 ft above the crest of the roadway at Sherwood Avenue. These discharges and depths are also of concern for homes along the stream channel. Clearing of dense vegetation and debris in the stream channel in this reach might ensure that the channel stays clear during the flood wave. The possibility should also be considered for flooding in this area from storms of greater intensity or duration than the 100-yr, 1-hr storm used for these analyses.

Table 4. Peak dam-break flows due to failure of embankments A, B, and C.

Location	Peak Discharge (ft^3/s)	Time of Peak, after start of breach (hours)	Average Flow Depth at Peak Discharge (ft)	Maximum water surface elevation (ft)
Embankment A	3,200	1.41	6.0	—
Embankment B	3,100	1.42	6.1	—
Embankment C	4,900	1.29	16	—
Pajarito & Two Mile Canyons	5,200	1.55*	3.7	—
Road DS TA-18	2,200	2.05*	5.0 (above road crest)	6731
White Rock (Sherwood Ave.)	1,400	2.15*	4.0 (above road crest)	6432

* Relative to start of storm in Two Mile Canyon. For peak flows to arrive simultaneously at confluence, storm in Pajarito Canyon must begin 0.4 hours before storm in Two-Mile Canyon.

Recommendations and Evaluation of Alternatives

The TSC Team recommended immediate actions at Los Alamos Dam and near TA-18 in Pajarito Canyon to mitigate against dam break or to prevent dam break. They concluded that armoring of downstream face of Diamond Ave. embankment would be useless. Boring a larger culvert would be helpful. They also recommended armoring Los Alamos Dam, and building a retention structure in Pajarito Canyon, upstream of TA-18. The TSC Team briefed the BAER Team along with the Assistant Secretary of Energy and Deputy Secretary of Defense on the findings of the dam break analyses.

Epilogue

Following these analysis the Department of Energy undertook several projects based upon recommendations made by the TSC team. The October 2000 issue of Civil Engineering (Fortner, 2000) describes some of these projects, including a new culvert in the Diamond Ave. fill bridge, armoring Los Alamos Dam, and constructing a retention structure above TA-18 in Pajarito Canyon.

Acknowledgments

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