Dam Safety Incident Report

Benson Creek Rainfall-Runoff Model Results

Benson Creek Flood, August 2014

Okanogan County near Twisp, WA

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Report Summary

On the evening of Thursday, August 21, 2014, a rainstorm hit the recently-burned Benson Creek watershed causing considerable flood damage. By the next day, State Highway 153 was closed 6 miles south of Twisp, and three of the five Wenner Lakes in Finley Canyon were empty.

For the dam safety community, this is a significant event that should be documented, evaluated and understood in order to add to the body of knowledge about dams and dam incidents. It is hoped that the lessons learned from this incident may be used to prevent, or at least mitigate, future incidents at these or other dams in similar circumstances. Toward this end, this report (the third of three in this series) has been compiled with the following purposes and objectives:

- Evaluate and understand the hydrology of the August 2014 storm event and its impacts on the Benson Creek watershed and the Wenner Lakes dams.
- Recognize and understand the hydrologic impacts of wildfires on the watershed above a dam, and the resulting impacts on dams, spillways, and dam operations.
- Evaluate and understand the failure mechanism for the spillway failure at Hawkins Dam, and the survival mechanisms at the Chalfa and Rabel dams.
- Evaluate the relative impacts of the flood from the Hawkins spillway failure compared to the flood from natural causes that was occurring throughout the Benson Creek watershed.
- Share the findings of this analysis with interested parties in the Benson Creek watershed and with others with a professional or personal interest in this incident.
- Share the findings of this analysis with the dam safety community.

This incident provided a very dramatic illustration of the impacts that wildfire can have on dams. With wildfire effects such as decreased infiltration capacity of the soil and no ground cover to interfere with moving water, even modest storms may result in very high runoff flows from the watershed. These flows may be an order of magnitude larger than pre-fire flows and larger than the spillway capacity. Spillways may be blocked by mudslides or by floating debris. Grass-lined spillways may be vulnerable to erosion if the grass cover is damaged. For hydrologists and engineers, quantifying the potential impacts of a wildfire on the safety of the dam in a timely manner with limited data may be challenging. Understanding what happened in Benson Creek will help us develop more detailed guidance materials for dam and reservoir operations, and possible spillway modifications, in response to wildfire events.

New hydrology model runs

With regard to the specific events in this incident, there were no rain gauges or stream gauges in the Benson Creek watershed to measure what actually happened, so a rainfall-runoff model was compiled to estimate what probably happened. As reported in the previous report in this series (Walther, Jan. 2015), preliminary model runs for the August 21st storm indicate the post-fire runoff flows may be on the order of 7 to 8 times the estimated pre-fire flows for the same storm event. Those model runs also estimate that the post-fire runoff flows from the August 21st storm exceed the estimated pre-fire runoff flows from a 1,000-year storm event. High flows that would have been considered very improbable (only a 1 in 1,000 chance of occurring in any one year) for the unburned watershed in its natural condition, suddenly became much more likely to occur, and apparently actually did occur, for the post-fire, burned watershed.

This report discusses new model runs which, done in conjunction with separate spreadsheet analyses, allowed for closer examination of the overtopping that occurred at two dams (Chalfa and Rabel) and the impacts of the eroded spillway at another dam (Hawkins). Estimates are that the Chalfa Dam may have been overtopped for as long as 4 hours and by as much as 6 inches. The Rabel Dam may have been overtopped for as long as 9 hours and by as much as 7½ inches. These two dams survived the storm, although two smaller ponds (Wenner Lakes No.2 and 3) located between these two larger lakes did not survive.

The spillway at Hawkins Dam probably eroded over a time period of 2½ to 3 hours. The stored volume of 22 acre-feet released by the spillway breach represents 17% of the total flood runoff at the dam that occurred within the first 6 hours of the storm. In Benson Creek below the Finley Canyon outfall, this 22 acre-feet released by the breach represents 7.1% of the total flood runoff that occurred within the first 6 hours of the storm.

Model predictions are that the peak discharges in Finley Canyon and Benson Creek all occurred between 10:15 and 11:00 pm, about 4¼ to 5 hours after the storm began. In Lower Finley Canyon below Hawkins Dam, the peak discharge is calculated at 647 cfs, slightly less than the peak discharge out of Upper Benson Creek (664 cfs). The peak flow of 647 cfs is 58% higher than the non-failure scenario for peak flow in Lower Finley Canyon. Comparison of these flows with stage-discharge curves for three locations in Lower Finley Canyon found that, on a relative basis, the increased flow depths are 20% to 35% higher than the non-failure scenario.

In Benson Creek below the Finley Canyon outfall, the peak discharge is calculated at 1291 cfs. This peak flow is 22% higher than the non-failure scenario for peak flow in the upper reach of Lower Benson Creek within a mile of the Finley Canyon outfall. Comparison of these flows with stage-discharge curves for three locations in this reach of Benson Creek found that, on a relative basis, the increased flow depths are about 8% higher than the non-failure scenario.

Caveat: Calculations are for clean water

It must be kept in mind that these calculations are for clean water, not the sediment-water mixtures that actually occurred. The effects of bulking and debris flows (mudslides) are not considered in these calculations. Beyond the spillway erosion that occurred at the Hawkins Dam, the hill slope erosion processes that resulted in the numerous mudslides in the Benson Creek watershed are outside our areas of expertise. This is not to discount the importance of these debris flows with regard to the damage that occurred in Benson Creek, only to disclose the limits of this technical analysis.

The observed depths of flooding and sediment deposition in the Finley Canyon and Benson Creek valleys following the August 21st storm exceed these calculated flow depths by several times, so it is recognized and acknowledged that these clean-water calculations by themselves provide an incomplete description of what actually happened with the water-sediment mixtures in Finley Canyon and Benson Creek during the August 21st storm. Hopefully these insights into the water behavior will contribute toward a better understanding of the water-sediment behavior, but the reader should keep in mind the limitations of this analysis and not draw conclusions about flood impacts along Benson Creek based just on these clean-water calculations.

Acknowledgements

The Dam Safety Office gratefully acknowledges rainfall data for the August 21st storm received from the National Weather Service (NWS) Spokane office, and copies of detailed hydrologic calculations received from Burned Area Emergency Response (BAER) team hydrologists from NWS Spokane, Natural Resources Conservation Service (NRCS), and U.S. Forest Service.

I am also indebted to my Dam Safety colleagues Guy Hoyle-Dodson, P.E., and Tom Satterthwaite, P.E. Guy compiled the basin-specific rainfall data and burned areas and burn severity data from the GIS shapefiles we received from NWS Spokane and the BAER team. Tom compiled the detailed soils data from the NRCS Web Soil Survey web site.

Special acknowledgement goes to Katherine Rowden, hydrologist with NWS Spokane, for helping Dam Safety connect with the USFS BAER hydrology references and resources. This was a critical connection for our understanding of the hydrologic impacts that a wildfire can have.

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Dam Safety Incident Report

Benson Creek Rainfall-Runoff Model Results

Benson Creek Flood, August 2014, Okanogan County, WA

Rainfall-Runoff Model Updates

Introduction

What happened in Finley Canyon and Benson Creek on August 21st? Why did a modest storm cause so much damage? There were no rain gauges or stream gauges in the Benson Creek watershed to measure what actually happened, so a rainfall-runoff model was compiled to estimate what probably happened. The development of the model and some preliminary model results were discussed in a previous report issued in January 2015. This report picks up where the last one left off, describing updates to the hydrology model and more detailed model results.

On the evening of Thursday, August 21, 2014, the recently-burned Benson Creek watershed received from 0.3 to 0.6 inches of rain in a one-hour period, and from 0.8 to 1.0 inches in slightly more than two hours. High runoff flows and numerous mudslides occurred throughout the watershed. By the next day, State Highway 153 was closed 6 miles south of Twisp, and three of the five Wenner Lakes in Finley Canyon were empty. Fortunately, there were no fatalities, injuries or missing persons from this flooding.

The Benson Creek watershed is located in SW Okanogan County about 6 miles SE of Twisp, in north central Washington State. Benson Creek has four major sub-basins with a total drainage area of 38 square miles when it empties into the Methow River.

The rainfall-runoff model for Benson Creek is compiled using the HEC-HMS model developed by the Army Corps of Engineers (USACE, 2010 and 2013). A basin model was compiled for the overall Benson Creek watershed, and subsequent to that, a second basin model was compiled to focus on the Finley Canyon sub-basins where the Wenner Lakes Dams are located. Two major updates were made to the basin models for Benson Creek and Finley Canyon.

Hawkins Dam

The first update added Hawkins Dam to the Finley Canyon model as a reservoir feature. Stage-surface area-storage volume calculations for the Hawkins reservoir were done by spreadsheet, then input to the hydrology model as a paired data set. In order to use the Dam Breach feature in HEC-HMS, the spillway is modeled as a spillway structure, specifically as a broad-crested weir spillway 60 feet wide.

As measured on August 28th by engineers from the Department of Ecology's Dam Safety Office (DSO), eroded dimensions averaged 13.4 feet deep and 36.5 feet wide. From photos taken mid-day on August 22nd, there was still a large drop from the reservoir into the eroded spillway, and a significant volume of water still in pond. The overflow elevation from the reservoir into the eroded spillway appears to be about half of the eroded spillway depth, or about 6.7 feet deep.

Photos of the spillway breach also show a somewhat curved overflow from the reservoir into the eroded spillway, similar to that observed in studies by the USDA Agricultural Research Service and others (Hanson et al, 2005, ASDSO Journal of Dam Safety). For the Hawkins spillway, a 50% increase in rim overflow length is estimated compared to the eroded width of the spillway, for a total overflow length (breach width) of about 55 feet.

To develop the input parameters for the spillway breach, the erosion rate was estimated by a spreadsheet version of Danny Fread's algorithm from the BREACH model (Fread, 1988; Fread, 1996). Input parameters to this algorithm include soil gradation and a representative channel slope. In the absence of any better information, the soil gradation was estimated from the USDA Natural Resources Conservation Service (NRCS) Web Soil Survey for the Newbon Gravelly Loam soil type at the spillway location. The channel slope was initially estimated from the topography of the dam site, then calibrated to the known limits of the eroded volume. The calibration effort adjusted the representative channel slope until the erosion rate is very small, asymptotically approaching zero, for the known eroded volume of 6600 cubic yards. These calculations estimate a spillway erosion time in the range of 2½ to 3 hours.

For modeling purposes, the estimated breach is 6.7 feet deep and 55 feet wide, and the failure occurs over a time of 2.5 hours. The erosion is estimated to follow a sine wave progression where the breach grows quickly in the early part of breach development and then more slowly as it reaches maximum size. The actual erosion starting time and corresponding reservoir water level are not known. For modeling purposes, the breach starting time was selected to obtain a reasonable match between times of peak outflow for both the non-failure and spillway failure scenarios. In other words, in the model calculations, the peak outflow from the eroded spillway would occur at approximately the same time as the peak flow from the dam if the spillway had remained intact and not eroded away.

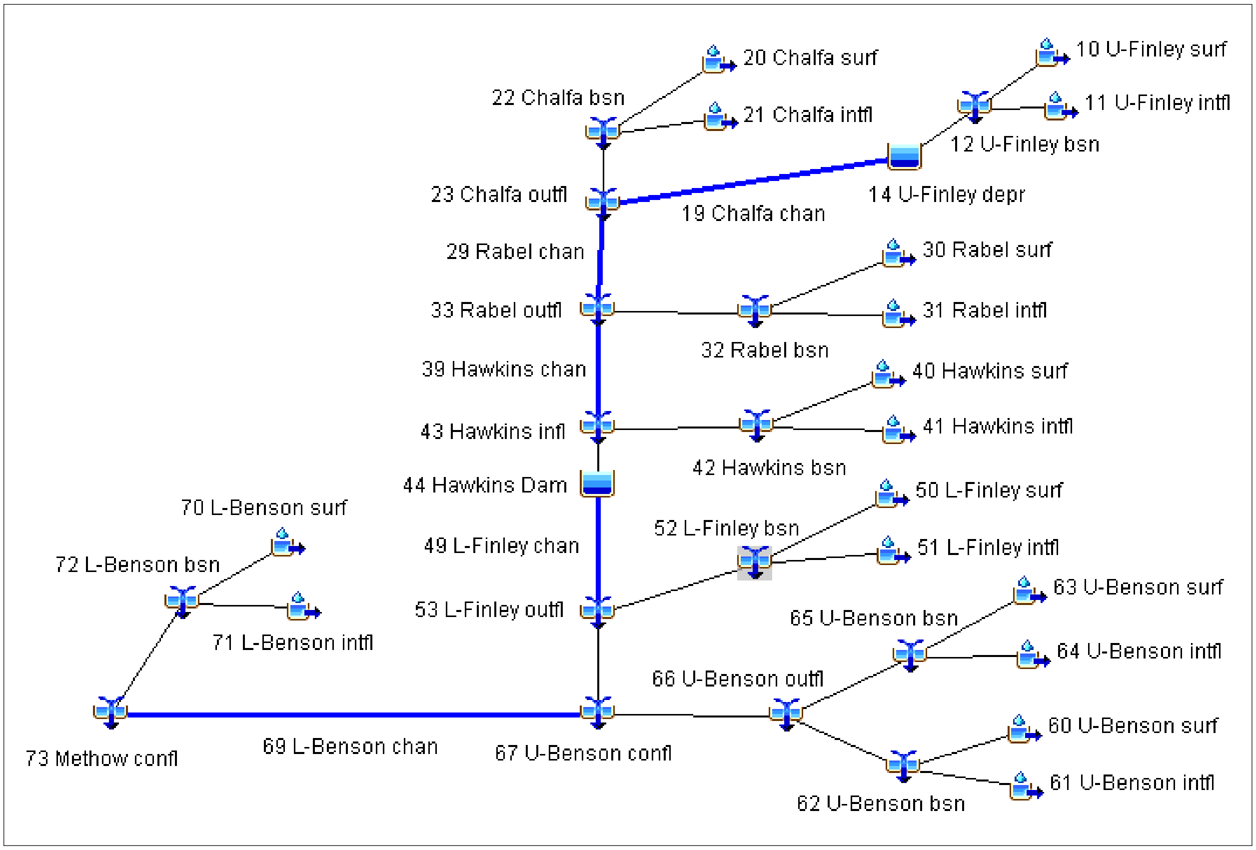
Benson-Finley basin model

The second major update combined the Benson Creek and Finley Canyon models to get a combined basin model for the Benson Creek watershed that includes calculations for the individual dam locations of the Chalfa, Rabel and Hawkins dams. As described above, this basin model includes a reservoir feature for the Hawkins Dam and spillway to consider both non-failure and failure scenarios.

The combined Benson-Finley basin model has 8 sub-basins (list continues on next page):

- Upper Finley Canyon, 10.3 sq.miles.
- Sub-basin for Chalfa Dam, 5.3 sq.miles
- Sub-basin for Rabel Dam, 1.1 sq.miles

- Sub-basin for Hawkins Dam, 0.6 sq.miles
- Finley Canyon below Hawkins Dam, 1.0 sq.miles
- Upper Benson Creek, burned area, 9.5 sq.miles
- Upper Benson Creek, unburned area, 6.1 sq.miles
- Lower Benson Creek, 4.1 sq.miles



HEC-HMS network for Benson-Finley basin model

There are some slight differences in model results between the original Benson Creek model and the combined Benson-Finley model for the same non-failure scenario at the Hawkins spillway, as shown in the table below. The peak flows all agree within 3%, and in Benson Creek, the timing of the peak flows agrees within 5 minutes. There was no difference in runoff volumes between the two basin models.

Location	Original Benson Creek model – peak outflow	Combined Benson-Finley model – peak outflow
Outfall from Lower Finley Canyon	422 cfs at 22:30 hours	410 cfs at 22:05 hours
Confluence with Upper Benson Creek	1080 cfs at 22:40 hours	1060 cfs at 22:40 hours
Benson Creek at SR-153	1220 cfs at 23:05 hours	1200 cfs at 23:00 hours

Estimate dam overtopping

Overtopping occurs when the hydrograph flow exceeds the spillway capacity for a water level at the dam crest elevation. To estimate the depth and duration of overtopping at the Chalfa and Rabel dams, time-series hydrographs from the model output were compared to separate stage-discharge calculations for the respective spillways and dam crests. Dam overtopping flows were calculated as broad-crested weir flow with the weir length equal to the dam crest length not including the spillway width. The duration of overtopping is estimated from the model output hydrograph when flows exceed the spillway capacity. The depth of overtopping is estimated from where the peak hydrograph flow falls on the stage-discharge curve for dam overtopping. After the time-series hydrograph was obtained from the computer model, the further overtopping estimates were done by spreadsheet calculations, separate from the model calculations.

Estimate flooding depths

Below Hawkins Dam, the peak flows from the model output were compared to stage-discharge calculations for the valley in Lower Finley Canyon below Hawkins Dam and for the upper 1-mile reach of Lower Benson Creek just below the confluence of Lower Finley Canyon and Upper Benson Creek. To attempt to estimate how much of the downstream flooding might be attributable to the Hawkins spillway erosion compared to the natural flooding that was already occurring, these calculations compared the peak flows and corresponding flow depths for both non-failure and spillway failure scenarios. Similar to the calculations for dam overtopping, after the peak flow values were obtained from the computer model, the further flood depth estimates were done by spreadsheet calculations, separate from the model calculations.

In the absence of any better information, the valley cross-section geometry was estimated from the terrain profile feature in the U.S. Geological Survey (USGS) Stream-Stats program. The valley cross-section geometry was estimated for 5 locations in Lower Finley Canyon and for 3 locations in the upper 1-mile reach of Lower Benson Creek.

Caveat: Calculations are for clean water

The risks to life and property and the damages caused by this type of flooding are due primarily to the depth of flooding and the velocity of the moving water, and particularly to the combined effects of flood depth and flow velocity. The hydraulics of clean water have been studied for many years and are reasonably well known. However, the addition of sediment and other debris to the mix may cause bulking and debris jams, which adds another level of complexity and uncertainty to our attempts to quantify the depth and velocity of the flood waters.

It must be kept in mind that both the HEC-HMS model calculations and the separate spreadsheet calculations are for clean water. The effects of bulking and debris flows are not considered in the model calculations or in the other spreadsheet analyses. Also, the particular focus here is on the flows in the valley bottoms along the stream corridors, not erosion or debris flows on hill slopes.

One rule-of-thumb on the U.S. Forest Service Burned Area Emergency Response (USFS BAER) web site suggests providing an allowance of 25% for bulking due to high sediment loads. This is interpreted to mean that a clean water flow of 100 cfs as predicted by the computer model or spreadsheet calculations would correspond to a sediment-laden flow of 125 cfs actual flow on the ground. It is not known whether this same (or another) bulking factor would apply to water over-flowing from a pond or reservoir out through a spillway where some of the heaviest sediment may have had some opportunity to settle out of the water. For this report, rather than estimate an unknown bulking factor, the results are simply presented as the model predictions using the clean water equations.

A related phenomenon that can occur during flooding is the formation and break-up of debris jams (personal communications with NWS and USFS BAER hydrologists). The debris flows are a mixture of water, sediment, rocks, vegetation, sticks and logs. Temporary debris jams will form that slow or block the flood flow, forcing water and sediment to collect behind the jam until the pressure reaches a threshold that blows-out the jam and the flood continues downstream. In many cases, high flood depths may be due to water and sediment that collected behind these debris jams rather than by the volume of water and sediment trying to get past a particular location at one particular time. (Aside: This phenomenon appears to be similar to ice jams that form on ice-covered rivers during the spring thaw and break-up.)

Another complicating factor is the presence of ash in the runoff after a fire. The Okanogan County Wildfire Recovery web page (http://www.okanogancd.org/Fires; posted in September 2014, specifically cited on August 31, 2015) notes that "A flash flood after a fire carries with it not only water, but also ash, making the flow material extremely dense like liquid cement."

Ash is in a class of materials called pozzolans, siliceous substances that react with lime in the presence of water and that can be used in combination with or for partial replacement of Portland cement in concrete mixtures (Merritt, 1983, pages 5-8 to 5-9). In finely divided form and in the present of moisture, pozzolans will chemically react with calcium hydroxide (lime) at ordinary temperatures to form compounds possessing cementitious properties (USBR, 1987, pages 666 to 667). With regard to runoff from burned slopes, the overall process is summarized eloquently by Burns (2007; abstract on page ii, see also pages 2 and 3):

> . . . . . Vegetative ash on the hillslope becomes entrained in the flow, along with other fine-grained sediment and increases the effective viscosity of the flow. The increase in effective viscosity decreases the settling velocity of the sediment within the flow, which in turn increases the bulk density of the flow. The increase in bulk density increases the erosivity of the flow. . . . . .

As noted in the previous report, hill slope debris flows (mudslides) are not considered in these analyses. Beyond the spillway erosion that occurred at the Hawkins Dam, the hill slope erosion processes that resulted in the numerous mudslides in the Benson Creek watershed are outside our areas of expertise. This is not to discount the importance of these debris flows with regard to the damage that occurred in Benson Creek, only to disclose the limits of this technical analysis.

The reader should not draw conclusions about flood impacts along Benson Creek based just on the clean-water analysis as presented in this report. A complete analysis of the Benson Creek flooding will require data collection, interpretation and analysis by experts in other scientific disciplines beyond the hydrology and hydraulics expertise available in the Dam Safety Office. That data collection, interpretation and analysis is outside the scope of Dam Safety's authority, and to our knowledge, at the time of this writing, that effort has not been done.

Separate guidance for burned watershed hydrology calculations

The reader may notice some slight differences between the modelling approach used in this analysis and the recommendations in Dam Safety's separate guidance for burned watershed hydrology calculations (see: http://www.ecy.wa.gov/programs/wr/dams/GuidanceDocs.html). That guidance is intended to expedite and streamline the burned watershed calculations compared to the approach used in this analysis. Also, that guidance is intended for use by engineers who are familiar with hydrology calculations in general, but might not be familiar with the wide variety of approaches to hydrology calculations described in the published scientific literature. This analysis was substantially completed before that guidance was developed. Due to limited resources, the Dam Safety Office has elected not to redo the calculations following the burned watershed guidance.

Model Findings

August 21st storm

So, what happened on August 21st?

Short answer:
Model predictions are that the peak flow at Chalfa Dam was 294 cfs. Chalfa Dam may have been overtopped for as long as 4 hours, and by as much as 6 inches. The peak flow at Rabel Dam was 332 cfs. Rabel Dam may have been overtopped for up to 9 hours, and by as much as 7½ inches. The peak flow from Hawkins Dam through the eroded spillway was 596 cfs.

The erosion of the Hawkins Dam spillway added 22 acre-feet of water to the volume of runoff from the storm. In Lower Finley Canyon below Hawkins Dam, this volume of 22 acre-feet represents 17% of the total runoff volume in the first 6 hours of the storm, and 11% of the total runoff volume in the first 12 hours of the storm.

The peak flow out of Lower Finley Canyon was 647 cfs. The peak flow from Upper Benson Creek was 664 cfs. The combined peak flow into Lower Benson Creek was 1291 cfs. The peak flow at SR-153 was 1433 cfs.

In Benson Creek below the outfall from Lower Finley Canyon, the volume of 22 acre-feet released from Hawkins Dam represents 7% of the total runoff volume in the first 6 hours of the storm, and 4% of the total runoff volume in the first 12 hours of the storm.

As noted previously, these calculations are for clean water. The effects of bulking and debris flows are not considered.

These results for the August 21st storm supersede the preliminary model findings previously reported. Those previous findings did not consider the spillway erosion at the Hawkins Dam. However, with regard to the comparisons of post-fire to pre-fire flows, the previous model findings are still valid; the current analyses did not revisit those previous comparisons.

Chalfa Dam:
When DSO engineers arrived at Chalfa Dam late on August 22nd, they observed that runoff was flowing through the spillway, but that the spillway had been partially blocked by floating debris. The Chalfa Dam embankment had been overtopped as evidenced by a mud line on vegetation on dam crest and by small erosion gullies on the downstream face of the dam. The overtopping flows had receded by the time the DSO engineers arrived at the dam.

For Chalfa Dam, model predictions are that the peak flow at the dam was 294 cfs. The peak flow occurred around 10:35 pm, about 4½ hours after the storm began.

- By midnight: the runoff volume at Chalfa Dam was 79 acre-feet, and the flow had receded to 234 cfs.

- By 6:00 am (August 22nd): the runoff volume at Chalfa Dam was 146 acre-feet, and the flow had receded to 85 cfs.
- By noon (August 22nd): the runoff volume at Chalfa Dam was 182 acre-feet, and the flow had receded to 64 cfs.

Ultimately, the runoff volume at Chalfa Dam was 506 acre-feet, including 125 acre-feet from the Chalfa sub-basin and 381 acre-feet from the Upper Finley sub-basin.

Comparing the peak flow from the computer model to the pre-fire stage-discharge curve for the Chalfa Dam spillway, it appears that the spillway had been blocked on the order of about 65%, although some of this apparent blockage may have been due to bulking of the runoff flows. For an estimate of 65% blockage, it appears that the Chalfa Dam may have been overtopped for as long as 4 hours, and by as much as 6 inches.

<u>Rabel Dam</u>:
When DSO engineers arrived at Rabel Dam late on August 22nd, the dam owner and contractor were re-excavating and repairing the spillway. Prior to the re-excavation, debris flows from the adjacent hill side and from a small valley adjacent to and aimed at the spillway had almost completely blocked (filled in) the previous spillway channel. The Rabel Dam embankment had been overtopped as evidenced by small erosion gullies on the downstream face of the dam, although the overtopping flows had receded by the time the owners arrived at the dam mid-day on the 22nd.

For Rabel Dam, model predictions are that the peak flow at the dam was 332 cfs. The peak flow occurred around 10:15 pm, 4¼ hours after the storm began.

- By midnight: the runoff volume at Rabel Dam was 98 acre-feet, and the flow had receded to 250 cfs.
- By 6:00 am (August 22nd): the runoff volume at Rabel Dam was 167 acre-feet, and the flow had receded to 87 cfs.
- By 9:00 am (August 22nd): the flow at Rabel Dam had receded to 73 cfs.
- By noon (August 22nd): the runoff volume at Rabel Dam was 204 acre-feet, and the flow had receded to 66 cfs.

Ultimately, the runoff volume at Rabel Dam was 532 acre-feet, including 151 acre-feet from the Chalfa and Rabel sub-basins and 381 acre-feet from the Upper Finley sub-basin.

From visual observations at Rabel Dam, it appears that the spillway was completely blocked by the debris flows from the adjacent valley and hill sides. However, estimating 100% blockage of the spillway would predict dam overtopping for a much longer period of time than was actually observed by the dam owners when they arrived at the dam mid-day on August 22nd. It appears that the runoff flows may have eroded enough of a path through the newly deposited, but poorly compacted, sediments to provide an outlet for the continuing flows and reduce the length of time that the embankment was overtopped.

For purposes of this analysis, it is estimated that the effective blockage of the Rabel Dam spillway was on the order of 70%. Comparing the peak flow from the computer model to the pre-fire stage-discharge curve for the Rabel Dam spillway with an estimate of 70% blockage, it appears that the Rabel Dam was probably overtopped for about 9 hours, and by at least 7½ inches.

For a spillway 70% blocked, at the 9:00 am flow of 73 cfs, the water level in the reservoir would be 3 inches below the dam crest; at the 12:00 noon flow of 66 cfs, the water level in the reservoir would be 3½ inches below the dam crest. These water levels agree with observations and photographs by the dam owner and other responders who arrived at the dam by mid-day on the 22nd.

Hawkins Dam:
When DSO engineers arrived at Hawkins Dam late on August 22nd, the spillway had eroded approximately to the bottom of the pond, although the erosion head-cutting was still working its way into the pond. Photos taken by the Hawkins Dam owner mid-day on the 22nd show the pond water level down by about half the depth of the pond, with a waterfall visually estimated to be on the order of 6 to 7 feet high dropping from the pond into the eroded channel. In contrast to the Chalfa and Rabel Dams, the Hawkins Dam embankment had not been overtopped. From visual observation of sediment deposition and patterns in the vegetation in the Hawkins Dam spillway and on the embankment, it appears that the water level rose to within a foot of the dam crest.

For Hawkins Dam, model predictions are that the peak inflow at the dam was 358 cfs. The peak outflow through the eroded spillway was 596 cfs. The peak outflow occurred around 10:15 pm, about 4¼ hours after the storm began.

- By midnight: the runoff volume from Hawkins Dam was 126 acre-feet, and the flow had receded to 272 cfs. The stored volume of 22 acre-feet released by the spillway breach represents 17% of this runoff volume.
- By 6:00 am (August 22nd): the runoff volume from Hawkins Dam was 199 acre-feet, and the flow had receded to 90 cfs. The stored volume of 22 acre-feet released by the spillway breach represents 11% of this runoff volume.
- By noon (August 22nd): the runoff volume from Hawkins Dam was 237 acre-feet, and the flow had receded to 68 cfs. The stored volume of 22 acre-feet released by the spillway breach represents 9.3% of this runoff volume.

Ultimately, the runoff volume from Hawkins Dam was 568 acre-feet, including 165 acre-feet from the Chalfa, Rabel and Hawkins sub-basins and 381 acre-feet from the Upper Finley sub-basin. The stored volume of 22 acre-feet released by the Hawkins spillway breach represents 3.9% of the total runoff volume from Hawkins Dam.

The distinguishing difference between the Hawkins Dam and the Chalfa and Rabel dams seems to be that Hawkins Dam did not overtop; the flow remained concentrated in the spillway. The factors that contributed to the spillway erosion are not completely known. From the pre-fire stage-discharge calculations for the spillway, peak flow velocities in the spillway were on the order of 5 to 5½ ft/sec. It is not known whether the grass lining in the spillway may have been damaged by the fire, or whether the proximity to a moist channel may have helped to reduce or minimize the fire damage to the grass cover. It appears that the spillway area received some debris flows from the adjacent hill slope, but whether these debris flows may have damaged the grass lining or otherwise contributed to initiating the erosion process is not known. The effects of increased viscosity, density and erosivity of runoff flows (as discussed on page 9) may have also been a factor. The spillway had a concrete buried erosion cutoff wall on the left side to protect the embankment from lateral erosion, but did not have any features to prevent downward erosion other than the grass lining.

Measurements taken by DSO engineers on August 28th estimate the volume of material eroded from the spillway at almost 6,600 cubic yards. As a comparison, Lower Finley Canyon has a valley bottom area of at least 25 acres. The volume of material eroded from the spillway represents an average sediment depth of about 2 inches in Lower Finley Canyon.

<u>Lower Finley Canyon</u>:
For Lower Finley Canyon below Hawkins Dam, model predictions are that the peak flow at the mouth of the canyon was 647 cfs. The peak flow occurred around 10:20 pm, slightly more than 4¼ hours after the storm began.

- By midnight: the runoff volume at the mouth of Lower Finley Canyon was 141 acre-feet, and the flow had receded to 301 cfs. The stored volume of 22 acre-feet released by the Hawkins spillway breach represents 16% of this runoff volume.
- By 6:00 am (August 22nd): the runoff volume at the mouth of Lower Finley Canyon was 219 acre-feet, and the flow had receded to 91 cfs. The stored volume of 22 acre-feet released by the Hawkins spillway breach represents 10% of this runoff volume.
- By noon (August 22nd): the runoff volume at the mouth of Lower Finley Canyon was 257 acre-feet, and the flow had receded to 69 cfs. The stored volume of 22 acre-feet released by the Hawkins spillway breach represents 8.6% of this runoff volume.

Ultimately, the runoff volume at the mouth of Lower Finley Canyon was 592 acre-feet, including 189 acre-feet from the Lower Finley Canyon sub-basins and 381 acre-feet from the Upper Finley sub-basin. The stored volume of 22 acre-feet released by the Hawkins spillway breach represents 3.7% of the total runoff volume from Lower Finley Canyon.

<u>Flow into Lower Benson Creek</u>:
For Lower Benson Creek just below the confluence of Lower Finley Canyon and Upper Benson Creek, model predictions are that the peak flow into Lower Benson Creek was 1291 cfs. The peak flow occurred around 10:25 pm, almost 4½ hours after the storm began.

- By midnight: the runoff volume in Benson Creek below Finley Canyon was 311 acre-feet, and the flow had receded to 838 cfs. The stored volume of 22 acre-feet released by the Hawkins spillway breach represents 7.1% of this runoff volume.
- By 6:00 am (August 22nd): the runoff volume in Benson Creek below Finley Canyon was 506 acre-feet, and the flow had receded to 169 cfs. The stored volume of 22 acre-feet released by the Hawkins spillway breach represents 4.3% of this runoff volume.
- By noon (August 22nd): the runoff volume in Benson Creek below Finley Canyon was 563 acre-feet, and the flow had receded to 87 cfs. The stored volume of 22 acre-feet released by the Hawkins spillway breach represents 3.9% of this runoff volume.

Ultimately, the runoff volume in Benson Creek below Finley Canyon was 1195 acre-feet, including more than 592 acre-feet from the Finley Canyon sub-basins and 603 acre-feet from Upper Benson Creek. The stored volume of 22 acre-feet released by the Hawkins spillway breach represents 1.8% of the total runoff volume into Lower Benson Creek.

Benson Creek at SR-153:
For Benson Creek at SR-153, model predictions are that the peak flow out of Benson Creek was 1433 cfs. The peak flow occurred around 10:50 pm, almost 5 hours after the storm began.

- By midnight: the runoff volume at SR-153 was 317 acre-feet, and the flow had receded to 1089 cfs. The stored volume of 22 acre-feet released by the Hawkins spillway breach represents 6.9% of this runoff volume.
- By 6:00 am (August 22nd): the runoff volume at SR-153 was 561 acre-feet, and the flow had receded to 199 cfs. The stored volume of 22 acre-feet released by the Hawkins spillway breach represents 3.9% of this runoff volume.
- By noon (August 22nd): the runoff volume at SR-153 was 625 acre-feet, and the flow had receded to 93 cfs. The stored volume of 22 acre-feet released by the Hawkins spillway breach represents 3.5% of this runoff volume.

Ultimately, the runoff volume at SR-153 was 1292 acre-feet. The stored volume of 22 acre-feet released by the Hawkins spillway breach represents 1.7% of the total runoff volume in Benson Creek at SR-153.

Comparison to non-failure scenario

How much did the failure of the Hawkins spillway contribute to peak flows and peak flood levels downstream compared to the flooding from natural causes (without the spillway breach)?

Short answer: As may be expected, the relative impacts of the spillway breach were higher closer to the dam, and attenuated with increasing distance downstream. Within ½ mile of the dam, model predictions indicate the peak flow was 67% higher than the non-failure scenario. Flood depths were calculated at 22% to 40% higher than the non-failure scenario, although due to the valley cross-section geometry, the larger percent increases are associated with the smaller magnitude increases. In Lower Finley Canyon more than ½ mile below the dam, the peak flow was 58% higher than the non-failure scenario. Flood depths were 20% to 35% higher; again, due to valley cross-section geometry, the larger percent increases are associated with the smaller magnitude increases. In Benson Creek below Finley Canyon, the peak flow was 22% higher than the non-failure scenario, and flood depths were calculated at 8% higher. Most of the structures damaged by the flooding were located along Benson Creek between Finley Canyon and SR-153.

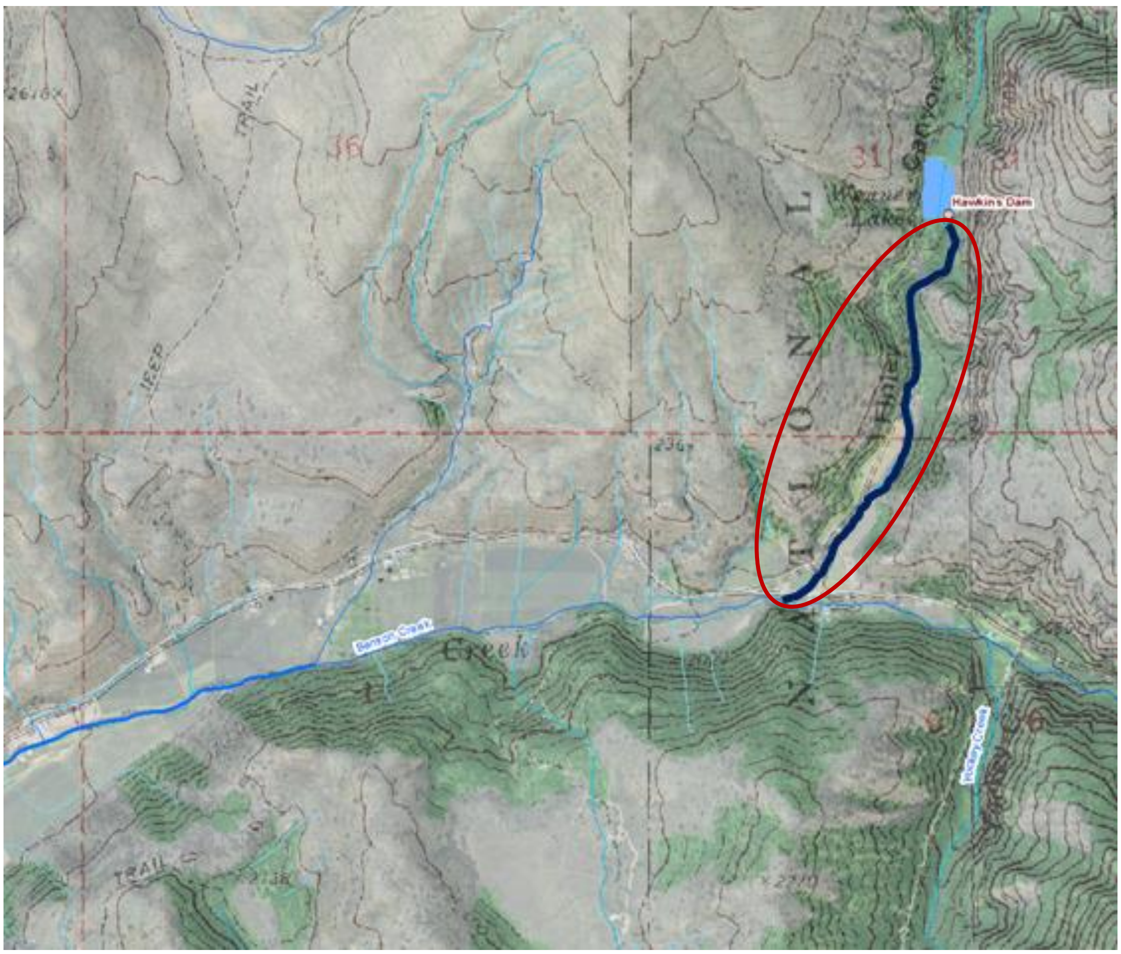
As calculated in this analysis, the increased flood depths are all within 8 inches of the non-failure scenario, and most are within 4 inches. However, as mentioned previously, it must be kept in mind that these calculations are for clean water. The effects of bulking and debris flows are not considered in these calculations

Hawkins Dam:
At Hawkins Dam, without the spillway breach, model predictions are that the peak below the dam would have been 358 cfs. With the spillway breach, model predictions are that the peak flow at this location was 596 cfs. This peak flow is 67% higher than the non-failure scenario.

- At a location 200 feet downstream from the dam, the valley cross-section is roughly trapezoidal in shape and about 106 feet wide. Comparison of these flows with a stage-discharge curve for the valley cross-section estimated flow depths of 0.7 feet for 358 cfs and 1.0 feet for 596 cfs. The increased flow depth is about 3 inches higher than the non-failure scenario. On a relative basis, the increased depth is about 40% higher than the non-failure scenario.

- At a location 1000 feet downstream from the dam, the valley cross-section is roughly triangular in shape with side slopes averaging 6.8 H:1V. Comparison of these flows with a stage-discharge curve for the valley cross-section estimated flow depths of 2.8 feet for 358 cfs and 3.4 feet for 596 cfs. The increased flow depth is about 7½ inches higher than the non-failure scenario. On a relative basis, the increased depth is about 22% higher than the non-failure scenario.

Lower Finley Canyon:



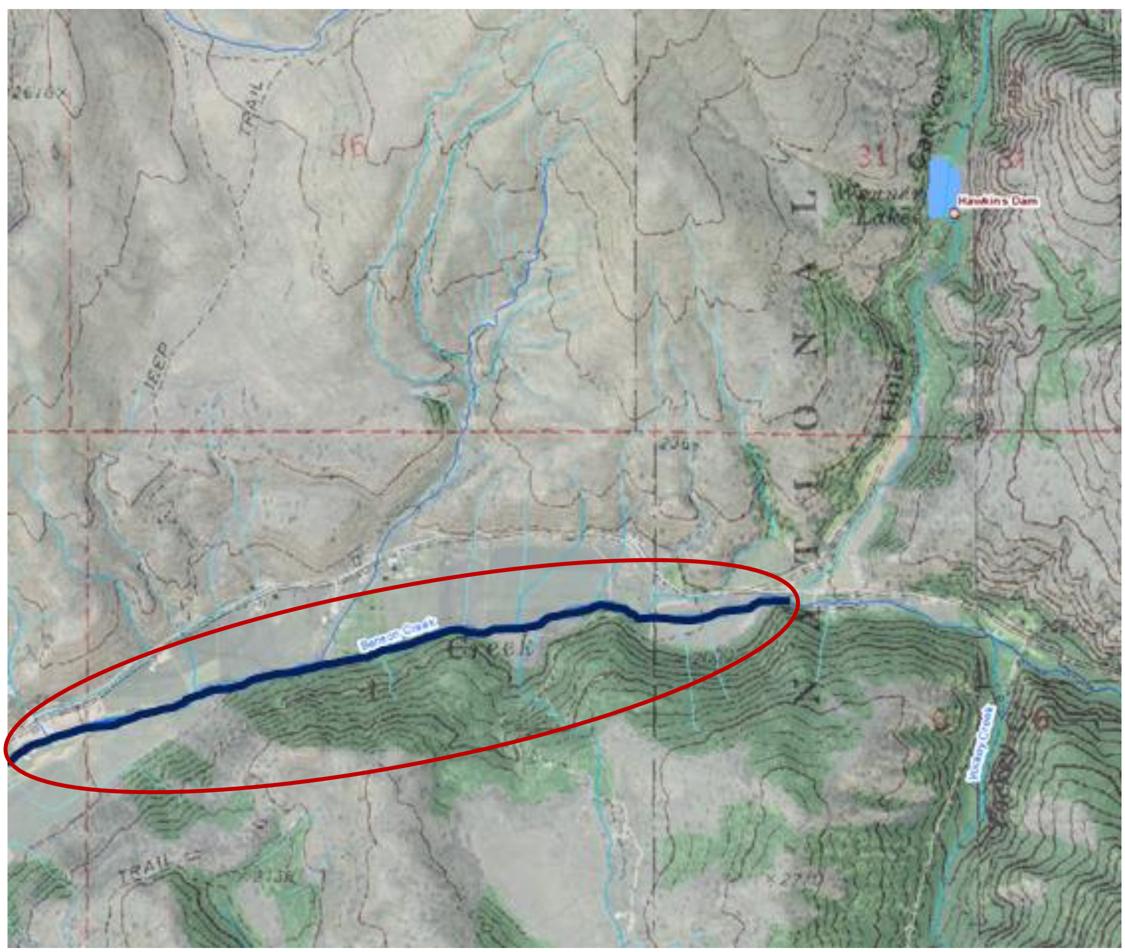
Lower Finley Canyon below Hawkins Dam

For Lower Finley Canyon below Hawkins Dam, without the spillway breach, model predictions are that the peak flow at the mouth of the canyon would have been 410 cfs. With the spillway breach, model predictions are that the peak flow at this location was 647 cfs.   This peak flow is 58% higher than the non-failure scenario.

- At a location 2300 feet downstream from the dam and 2500 feet upstream from the confluence with Benson Creek, the valley cross-section is roughly triangular in shape with side slopes averaging 15 H:1V. Comparison of these flows with a stage-discharge curve for the valley cross-section estimated flow depths of 2.1 feet for 410 cfs and 2.6 feet for 647 cfs. The increased flow depth is about 5 inches higher than the non-failure scenario. On a relative basis, the increased depth is about 20% higher than the non-failure scenario.

- At a location 3200 feet downstream from the dam and 1600 feet upstream from the confluence with Benson Creek, the valley cross-section is roughly trapezoidal in shape and about 264 feet wide. Comparison of these flows with a stage-discharge curve for the valley cross-section estimated flow depths of 0.4 feet for 410 cfs and 0.6 feet for 647 cfs. The increased flow depth is about 2 inches higher than the non-failure scenario. On a relative basis, the increased depth is about 35% higher than the non-failure scenario.
- At a location 4200 feet downstream from the dam and 600 feet upstream from the confluence with Benson Creek, the valley cross-section is roughly triangular in shape with side slopes averaging 9.6 H:1V. Comparison of these flows with a stage-discharge curve for the valley cross-section estimated flow depths of 2.6 feet for 410 cfs and 3.1 feet for 647 cfs. The increased flow depth is about 6 inches higher than the non-failure scenario. On a relative basis, the increased depth is about 20% higher than the non-failure scenario.

<u>Flow into Lower Benson Creek</u>:



Lower Benson Creek below Finley Canyon

For Lower Benson Creek just below the confluence of Lower Finley Canyon and Upper Benson Creek, without the spillway breach, model predictions are that the peak flow into Lower Benson Creek would have been 1059 cfs. With the spillway breach, model predictions are that the peak flow at this location was 1291 cfs. This peak flow is 22% higher than the non-failure scenario.

- At a location 0.12 miles (600 feet) downstream from Finley Canyon, the valley cross-section is roughly triangular in shape with side slopes averaging 12.6 H:1V. Comparison of these flows with a stage-discharge curve for the valley cross-section estimated flow depths of 3.4 feet for 1059 cfs and 3.7 feet for 1291 cfs. The increased flow depth is about 3 inches higher than the non-failure scenario. On a relative basis, the increased depth is about 8% higher than the non-failure scenario.
- At a location 0.45 miles (2400 feet) downstream from Finley Canyon, the valley cross-section is roughly triangular in shape with side slopes averaging 28 H:1V. Comparison of these flows with a stage-discharge curve for the valley cross-section estimated flow depths of 2.5 feet for 1059 cfs and 2.7 feet for 1291 cfs. The increased flow depth is about 2½ inches higher than the non-failure scenario. On a relative basis, the increased depth is about 8% higher than the non-failure scenario.
- At a location 0.92 miles (4900 feet) downstream from Finley Canyon, the valley cross-section is roughly triangular in shape with side slopes averaging 10.3 H:1V. Comparison of these flows with a stage-discharge curve for the valley cross-section estimated flow depths of 3.7 feet for 1059 cfs and 4.0 feet for 1291 cfs. The increased flow depth is about 3½ inches higher than the non-failure scenario. On a relative basis, the increased depth is about 8% higher than the non-failure scenario.

Most of the structures damaged by the August 2014 flooding were located along Lower Benson Creek between Finley Canyon and SR-153.

<u>Benson Creek at SR-153</u>:
For Benson Creek at SR-153, without the spillway breach, model predictions are that the peak flow out of Benson Creek would have been 1200 cfs. With the spillway breach, model predictions are that the peak flow at this location was 1433 cfs. This peak flow is 19% higher than the non-failure scenario. Dam Safety's analysis did not examine flow depths at this location.

<u>Caveat</u>:
As discussed previously, it must be kept in mind that these calculations are for clean water. The effects of bulking and debris flows are not considered in these calculations.

The observed depths of flooding and sediment deposition in the Finley Canyon and Benson Creek valleys following the August 21st storm exceed these calculated flow depths by several times, so it is recognized and acknowledged that these clean-water calculations by themselves provide an incomplete description of what actually happened with the water-sediment mixtures in Finley Canyon and Benson Creek during the August 21st storm. Hopefully these insights into the water behavior will contribute toward a better understanding of the water-sediment behavior, but the reader should not draw conclusions about flood impacts along Benson Creek based just on these clean-water calculations.

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Dam Safety Incident Report

Benson Creek Rainfall-Runoff Model Results

This hydrologic analysis of the Benson Creek watershed and the engineering analyses and technical material presented in this report were prepared by the undersigned professional engineer.

Martin Walther, P.E.
Hydrology and Hydraulics Specialist
Dam Safety Office
Water Resources Program

November 10, 2015
(date signed)

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Appendices

Appendix A – Maps and Photos

Appendix B – Supporting calculations

Appendix C – Graphical results

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Appendix A

Maps and Selected Photos

Project location

Topography and drainage areas

Spillway breach

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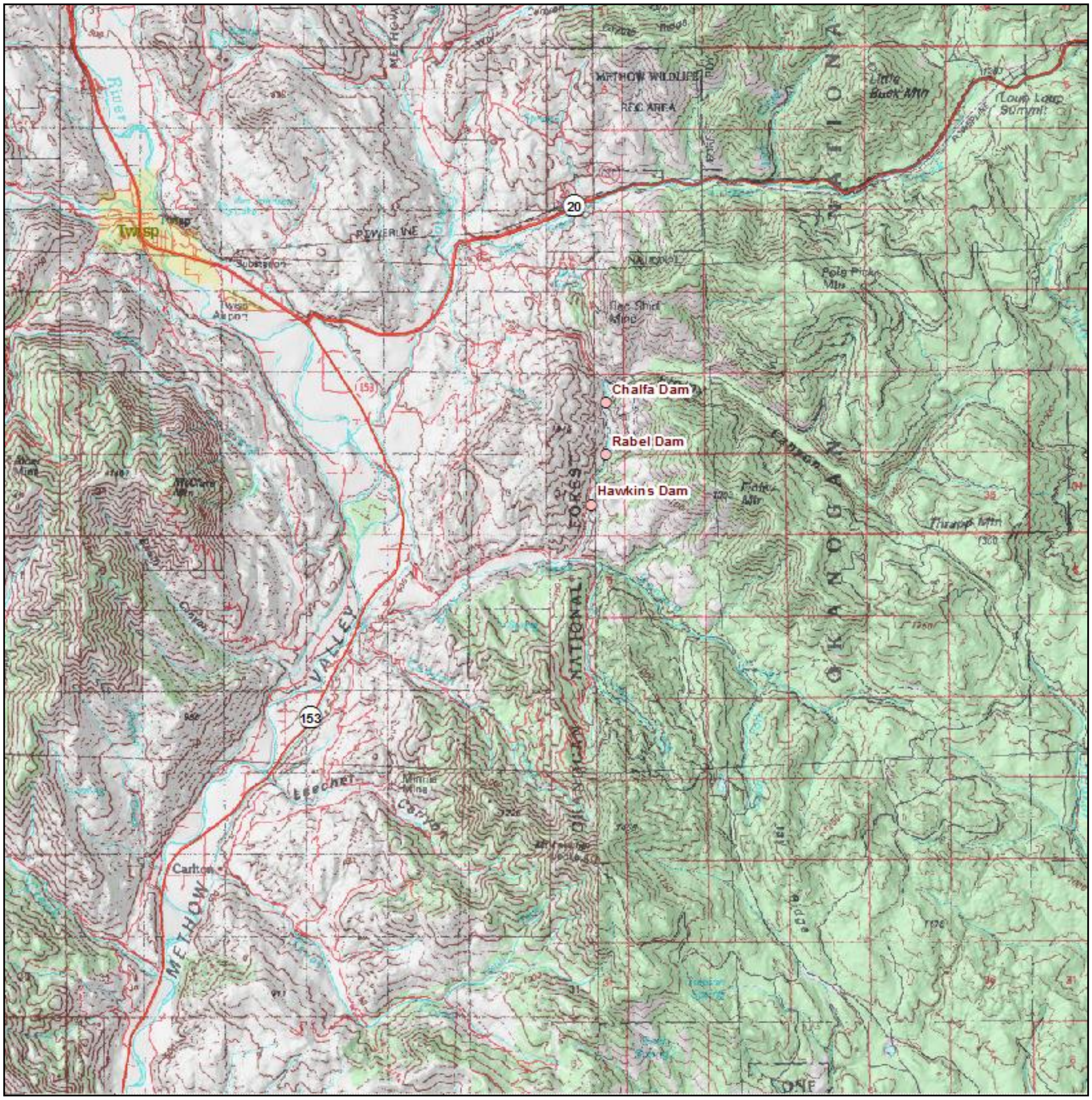
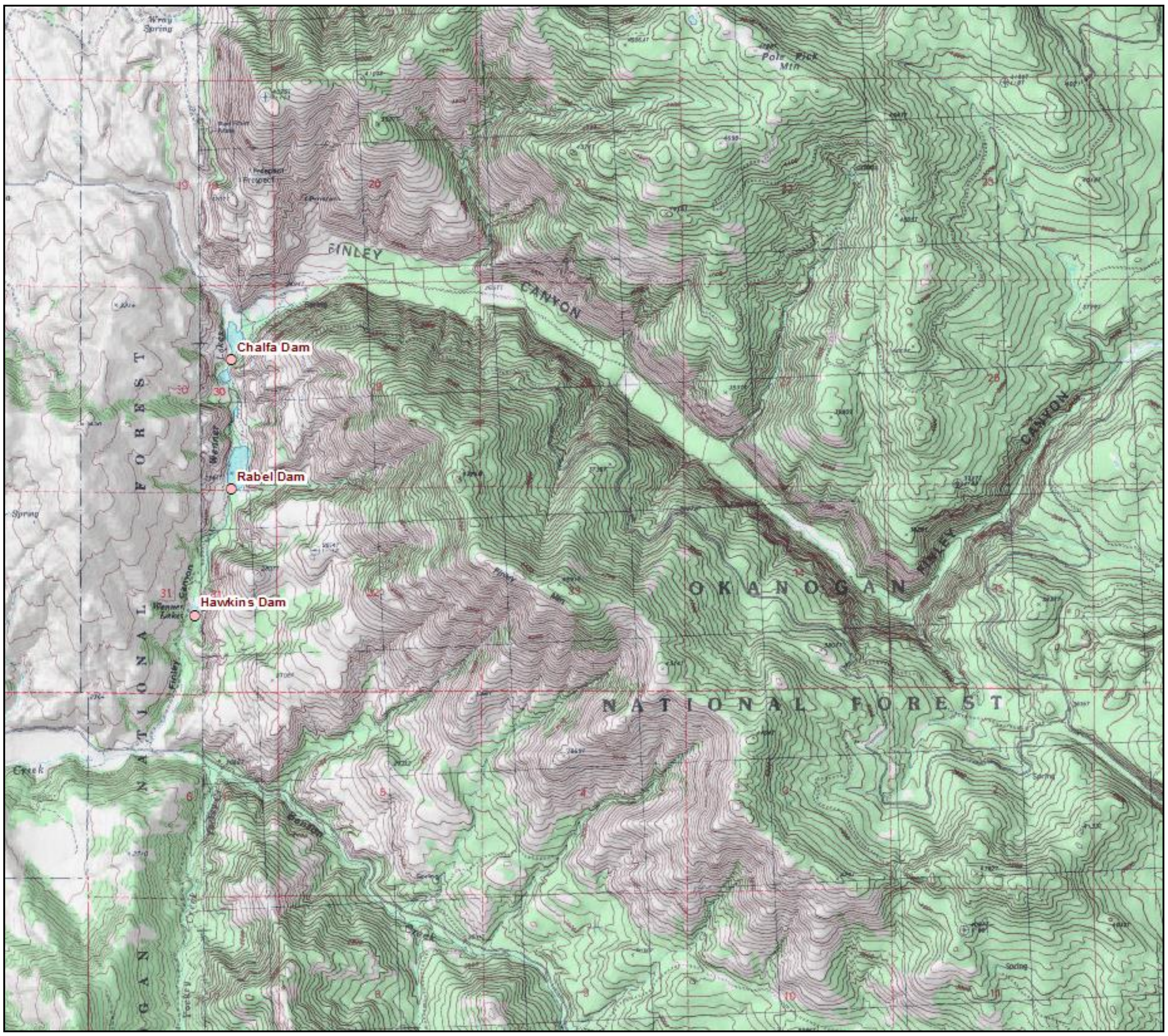
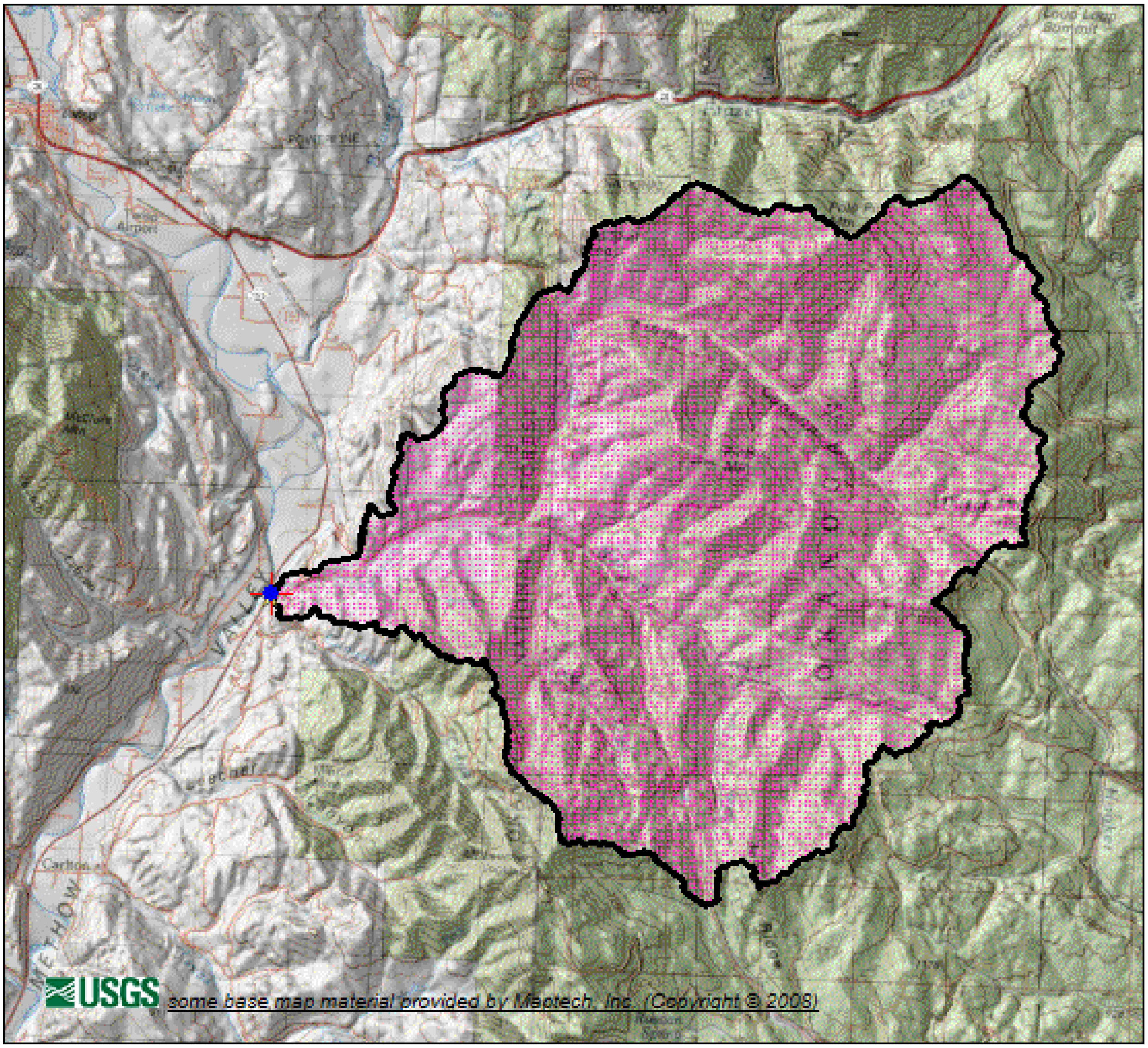


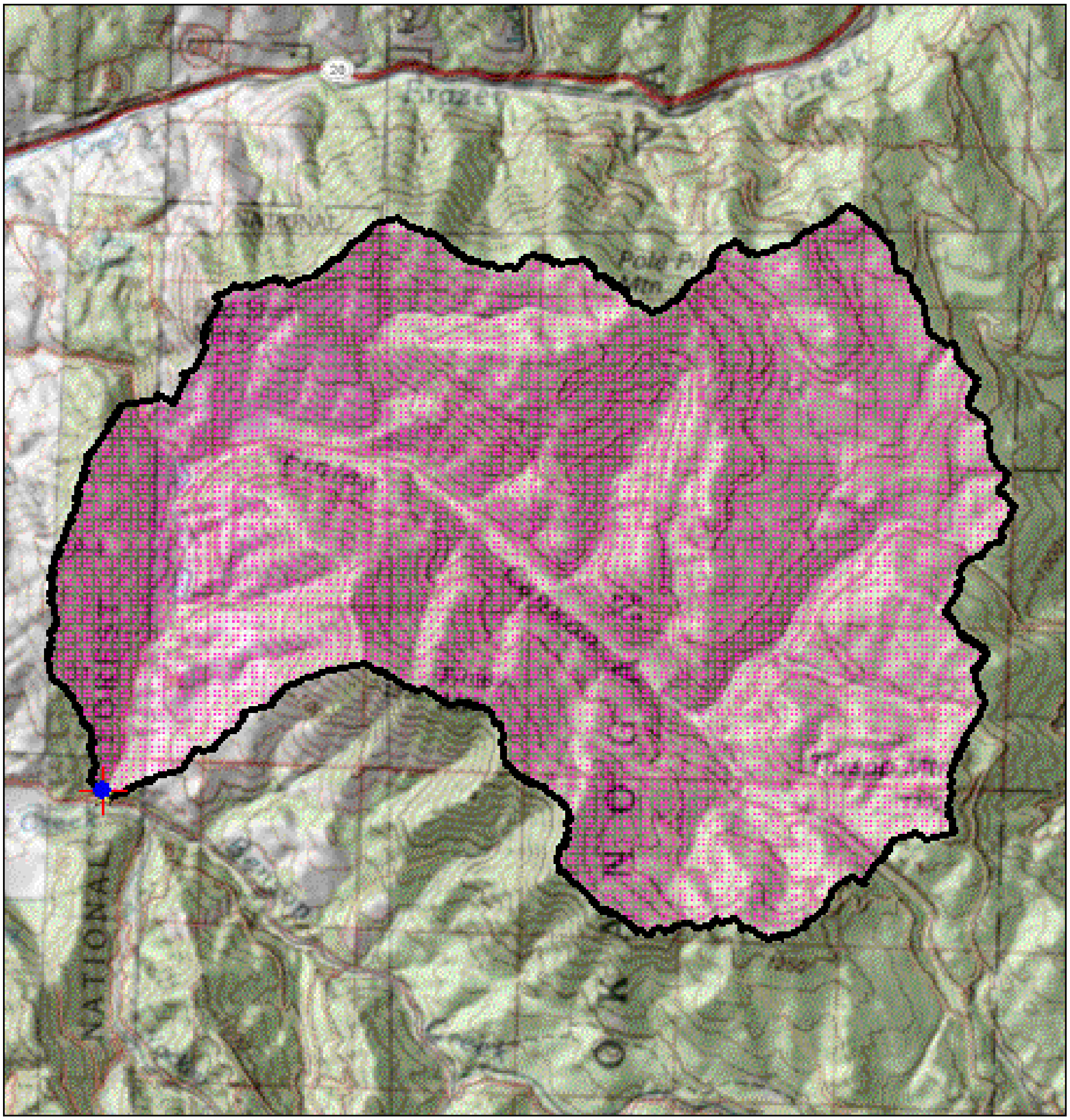
1. Vicinity map for Benson Creek watershed near Twisp in north central Washington.



2. Dam locations in Benson Creek Finley Canyon sub-basin.



3. Benson Creek watershed near Twisp. Drainage area 38 sq.miles.



4. Benson Creek Finley Canyon sub-basins. Drainage area 18.3 sq.miles.

5. Hawkins Dam (Wenner Lake No.5) spillway, mid-day on August 22nd.

6. Hawkins Dam (Wenner Lake No.5) spillway, mid-day on August 22nd.

Benson Creek Rainfall-Runoff Model Results

Appendix B

Supporting calculations

Watershed hydrology

Channel and reservoir parameters

Results from preliminary analyses

Spillway erosion

Results from detailed analyses

Dam overtopping

Downstream flood depths

Selected summary output

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Supporting calculations

In recent years, Dam Safety's paper and electronic files have become very integrated such that some documents exist only in electronic form. Consistent with this development, and in the interest of expediting this report, the spreadsheet computations for this hydrologic analysis are not copied here, but are incorporated into this report by reference. Copies of these spreadsheets (either electronic or paper format) are available from the Dam Safety Office.

Spreadsheet calculations were used to develop the input data to a HEC-HMS computer model, with the results from the HEC-HMS model runs copied to other spreadsheets to record them for posterity. The specific spreadsheets used in this hydrologic analysis are listed below. These are all in MS Excel 2007 format.

Watershed hydrology

	Spreadsheet file name
Network for hydrologic model	DataIn3b_network.xlsx
Time and rainfall parameters	DataIn1_time-precip.xlsx
Runoff parameters	DataIn2_runoff-parameters-2.xlsx
Unit hydrograph	Unit Hyd_USBR-Casc_high-Kn.xlsx Soils burned.xlsx
Infiltration computations	Soils HSG.xlsx Soils Ksat-surf.xlsx Storm Hyetographs CN calib-2.xlsx
Design storm precipitation	Precip Lat-Long.xlsx PrecipFinley-1Shrt.xlsm PrecipFinley-2Intm.xlsm PrecipFinley-3Long.xlsm PrecipBenson-1Shrt.xlsm PrecipBenson-2Intm.xlsm PrecipBenson-3Long.xlsm
Actual Aug 21st storm precipitation	Benson summary DSO.xlsx

	Spreadsheet file name
Watershed hydrology	
Snowmelt computations	Snowmelt_DF100.xlsx
Storm, interflow and loss hyetographs	Storm Hyetographs HMS-1.xlsx Storm Hyetographs HMS-2.xlsx
Channel routing and reservoir parameters	
Channel routing	Benson stream-stats_9-18-14.xlsx
Stage-discharge curve	U-Finley stage-disch-5.xlsx
Stage-surface area-storage volume	U-Finley stor vol-5.xlsx Hawkins pond stor vol.xlsx
Results from preliminary hydrologic analyses	
Network for hydrologic model	DataIn3b_network.xlsx
Range of natural streamflows	Q100yr_StrStats+TN3.xlsx
Comparison to pre-fire streamflows	DataOut1e_calib-100.xlsx DataOut1e_calib-Finley.xlsx
Comparison to post-fire estimates	DataOut1f_BAER.xlsx DataOut1g_BAER-Finley.xlsx
Actual August 21st storm	DataOut1h_Aug21.xlsx
Step 2 design storm (1/1000 AEP)	DataOut1k_1000yr.xlsx
Hawkins spillway erosion	
Eroded volume	Hawkins erosion volume.xlsx
Erosion rate, breach formation time	Hawkins spillway soils.xlsx Hawkins erosion rate.xlsx

	Spreadsheet file name
Results from detailed hydrologic analyses	
Network for hydrologic model	DataIn3b_network.xlsx
August 21st storm	DataOut7b_Benson-Aug21.xlsx
Overtopping at Chalfa and Rabel Dams	
Runoff hydrographs	DataOut7b_Benson-Aug21.xlsx
Stage-discharge curves	Chalfa spillway Aug21.xlsx Rabel spillway Aug21.xlsx
Downstream flood depths	
Runoff hydrographs	DataOut7b_Benson-Aug21.xlsx
Channel geometry	L-Finley stream-stats_2-03-15.xlsx L-Benson stream-stats_2-12-15.xlsx
Stage-discharge curves	L-Finley channel capacity.xlsx L-Benson channel capacity.xlsx

Selected summary output (on following pages)

Summary of peak flows

Table output from HEC-HMS

Summary of peak flows					MDW, 3/19/15
	end 21 Aug, 24:00 hrs.				
		Peak discharge, cfs		Increased peak flow	
Location		No breach	Hawkins breach	flow, cfs	per cent
Chalfa Dam		293.8	293.8	0	0
Rabel Dam		331.9	331.9	0	0
Hawkins Dam		356.7	595.5	238.8	66.9
Lower Finley outfall		410.0	646.8	236.8	57.8
Benson/Finley confl		1059.2	1290.6	231.4	21.8
Benson Cr at SR-153		1199.8	1433.1	233.3	19.4
	end 21 Aug, 24:00 hrs.				
		6-hour runoff volume, Ac-ft.		Increased 6-hour volume	
Location		No breach	Hawkins breach	vol, ac-ft.	per cent
Chalfa Dam		78.9	78.9	0	0
Rabel Dam		97.9	97.9	0	0
Hawkins Dam		100.3	125.8	25.5	25.4
Lower Finley outfall		115.1	140.6	25.5	22.2
Benson/Finley confl		285.3	310.8	25.5	8.9
Benson Cr at SR-153		292.3	317.4	25.1	8.6

Peak runoff flows within first 6 hours of August 21st storm.

Summary of peak flows				MDW, 3/19/15
end 22 Aug, 06:00 hrs.				
	12-hour runoff volume, Ac-ft.		Increased 12-hour volume	
Location	No breach	Hawkins breach	vol, ac-ft.	per cent
Chalfa Dam	145.9	145.9	0	0
Rabel Dam	167.5	167.5	0	0
Hawkins Dam	175.7	199.3	23.6	13.4
Lower Finley outfall	194.9	218.6	23.7	12.2
Benson/Finley confl	482.5	506.2	23.7	4.9
Benson Cr at SR-153	537.8	561.5	23.7	4.4
end 22 Aug, 12:00 hrs.				
	18-hour runoff volume, Ac-ft.		Increased 18-hour volume	
Location	No breach	Hawkins breach	vol, ac-ft.	per cent
Chalfa Dam	181.6	181.6	0	0
Rabel Dam	204.3	204.3	0	0
Hawkins Dam	213.6	237.0	23.4	11.0
Lower Finley outfall	233.4	256.8	23.4	10.0
Benson/Finley confl	539.8	563.2	23.4	4.3
Benson Cr at SR-153	602.0	625.4	23.4	3.9

Runoff volumes within first 12 and 18 hours of August 21st storm.

HEC-HMS model			MDW, 3/09/15			Area	Peak	Time	Runoff	Runoff	% of
					Element	sq.miles	Q, cfs	of peak	vol. in.	ac-ft.	precip
Model output		**Benson-Finley** model			10 U-Finley surf	10.3	1281.6	21Aug2014, 21:25	0.69	381.8	80.2
					11 U-Finley intfl	10.3	0.0	21Aug2014, 18:00	0	0.0	0.0
	Storm	Aug 21st	end 30 Aug, 12:00 hrs.		12 U-Finley bsn	20.6	1281.6	21Aug2014, 21:25	0.35	381.8	80.2
					14 U-Finley depr	20.6	66.1	22Aug2014, 03:15	0.35	381.6	
	Event	Post-fire	**Hawkins breach**		19 Chalfa chan	20.6	66.1	22Aug2014, 03:40	0.35	381.6	
					20 Chalfa surf	5.3	246.9	21Aug2014, 22:25	0.37	104.6	45.1
					21 Chalfa intfl	5.3	4.8	23Aug2014, 09:25	0.07	20.2	8.5
	Gauge		Precip		22 Chalfa bsn	10.6	247.0	21Aug2014, 22:25	0.22	124.8	53.7
	Aug21-LB		0.80		23 Chalfa outfl	31.2	293.8	21Aug2014, 22:35	0.30	506.4	
	Aug21-LB-intflo		0.51		29 Rabel chan	31.2	293.8	21Aug2014, 22:40	0.30	506.4	
	Aug21-LF		0.82		30 Rabel surf	1.1	91.5	21Aug2014, 20:50	0.37	21.7	45.1
	Aug21-LF-intflo		0.45		31 Rabel intfl	1.1	2.1	22Aug2014, 13:05	0.07	4.2	8.5
	Aug21-UB		1.03		32 Rabel bsn	2.2	91.6	21Aug2014, 20:50	0.22	25.9	53.7
	Aug21-UB-intflo-post		0.43		33 Rabel outfl	33.4	331.9	21Aug2014, 22:15	0.30	532.3	
	Aug21-UB-intflo-pre		1.03		39 Hawkins chan	33.4	331.9	21Aug2014, 22:20	0.30	532.3	
	Aug21-UF		0.86		40 Hawkins surf	0.6	48.8	21Aug2014, 20:50	0.37	11.8	45.1
	Aug21-UF-intflo		0.17		41 Hawkins intfl	0.6	1.1	22Aug2014, 13:35	0.07	2.3	8.5
					42 Hawkins bsn	1.2	48.9	21Aug2014, 20:50	0.22	14.1	53.7
					43 Hawkins infl	34.6	358.3	21Aug2014, 22:05	0.30	546.5	
			Precip		44 Hawkins Dam	34.6	**595.5**	21Aug2014, 22:15	0.31	**568.6**	
	Basin		Balance		49 L-Finley chan	34.6	595.5	21Aug2014, 22:20	0.31	568.6	
	U-Finley		0.000		50 L-Finley surf	1.0	64.6	21Aug2014, 21:25	0.37	19.7	45.1
	Chalfa		0.000		51 L-Finley intfl	1.0	1.4	22Aug2014, 20:45	0.07	3.8	8.5
	Rabel		0.000		52 L-Finley bsn	2.0	64.6	21Aug2014, 21:25	0.22	23.6	53.7
	Hawkins		0.000		53 L-Finley outfl	36.6	**646.8**	21Aug2014, 22:20	0.30	**592.1**	
	L-Finley		0.000		63 U-Benson surf	9.5	663.0	21Aug2014, 22:50	0.60	303.2	58.3
	U-Benson-post		0.000		64 U-Benson intfl	9.5	10.3	24Aug2014, 07:50	0.13	68.2	12.6
	U-Benson-pre		0.000		65 U-Benson bsn	19.0	663.2	21Aug2014, 22:50	0.37	371.4	70.9
	L-Benson		0.000		60 U-Benson surf	6.1	0.0	21Aug2014, 18:00	0	0.0	0.0
					61 U-Benson intfl	6.1	35.0	24Aug2014, 07:50	0.71	231.6	68.9
					62 U-Benson bsn	12.2	35.0	24Aug2014, 07:50	0.36	231.6	68.9
					66 U-Benson outfl	31.2	663.8	21Aug2014, 22:50	0.36	603.0	
					67 U-Benson confl	67.8	**1290.6**	21Aug2014, 22:25	0.33	**1195.1**	
					69 L-Benson chan	67.8	1290.6	21Aug2014, 22:50	0.33	1195.1	
					70 L-Benson surf	4.1	142.9	21Aug2014, 22:40	0.29	64.0	36.3
					71 L-Benson intfl	4.1	7.6	23Aug2014, 10:55	0.15	33.2	18.8
					72 L-Benson bsn	8.2	143.1	21Aug2014, 22:40	0.22	97.2	55.0
					73 Methow confl	76.0	**1433.1**	21Aug2014, 22:50	0.32	**1292.3**	

Table output from HEC-HMS model, August 21st storm

Benson Creek Rainfall-Runoff Model Results

Appendix C

Graphical results for August 21st storm

Runoff hydrographs – 18 hours

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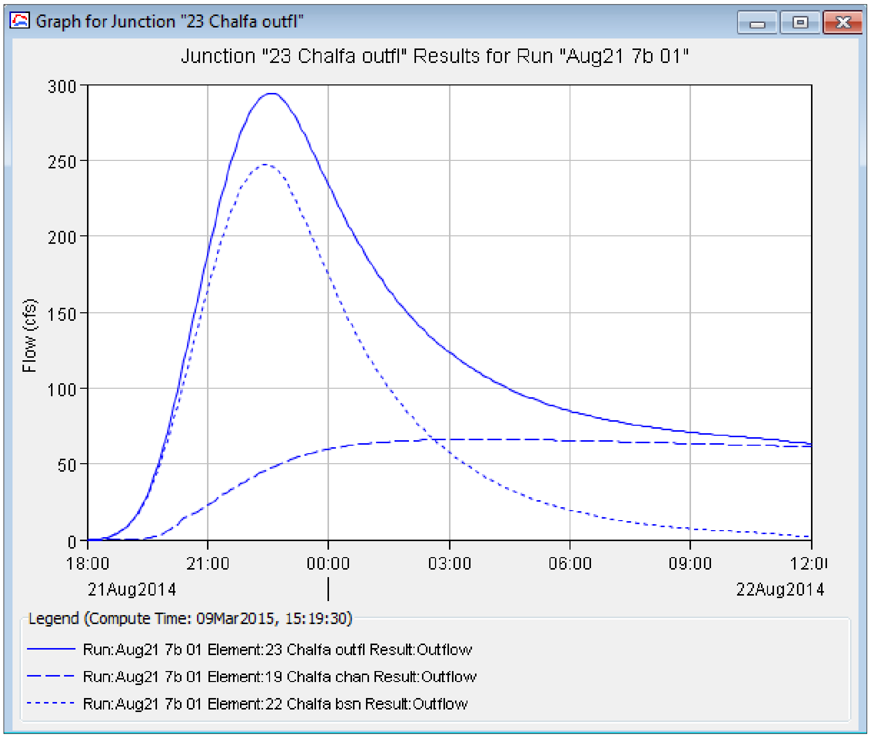
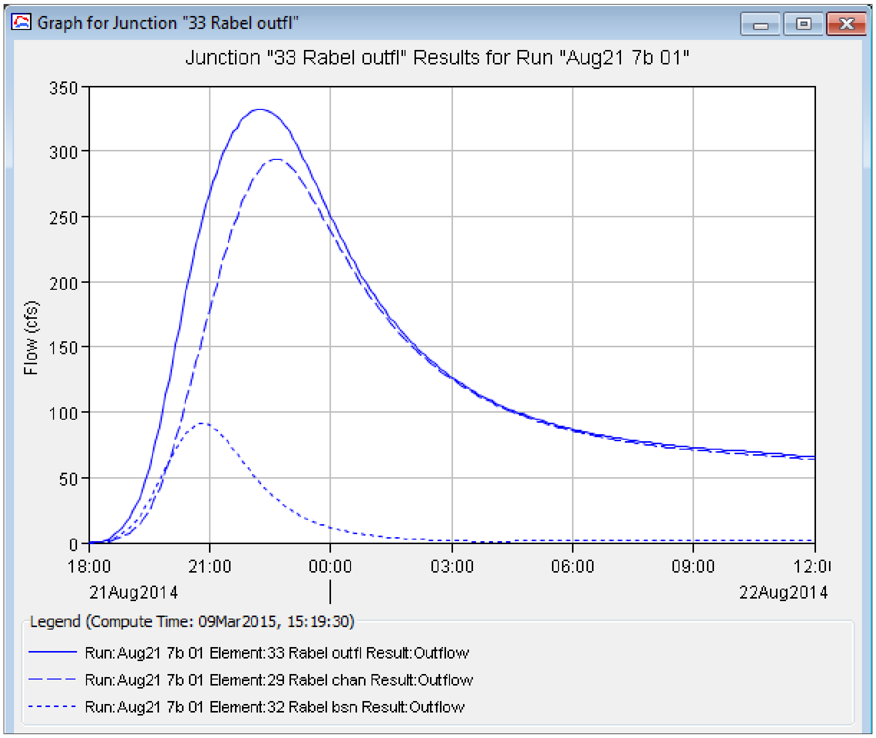
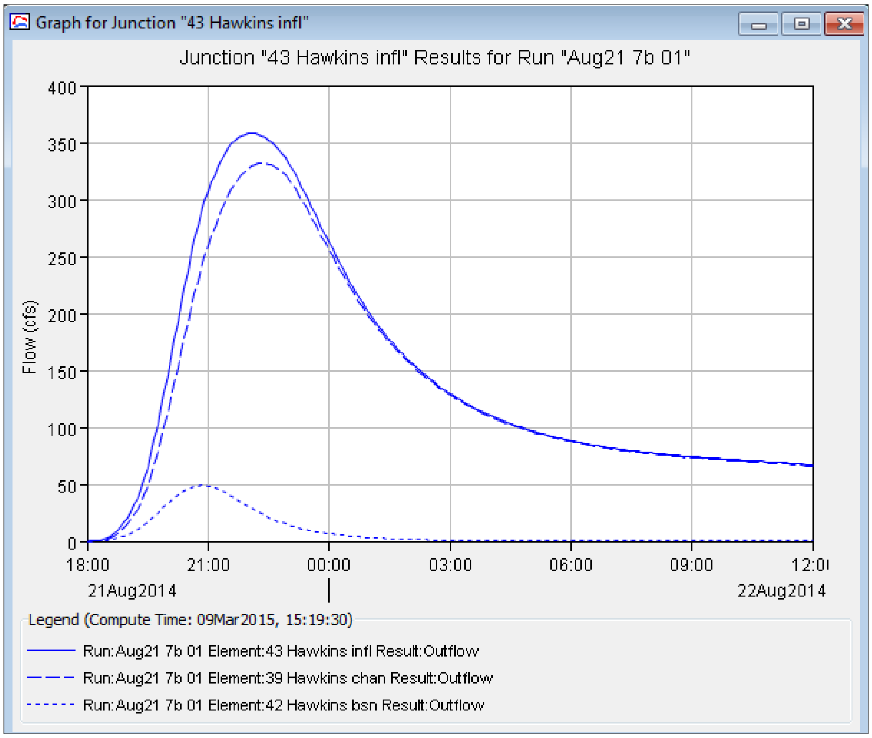


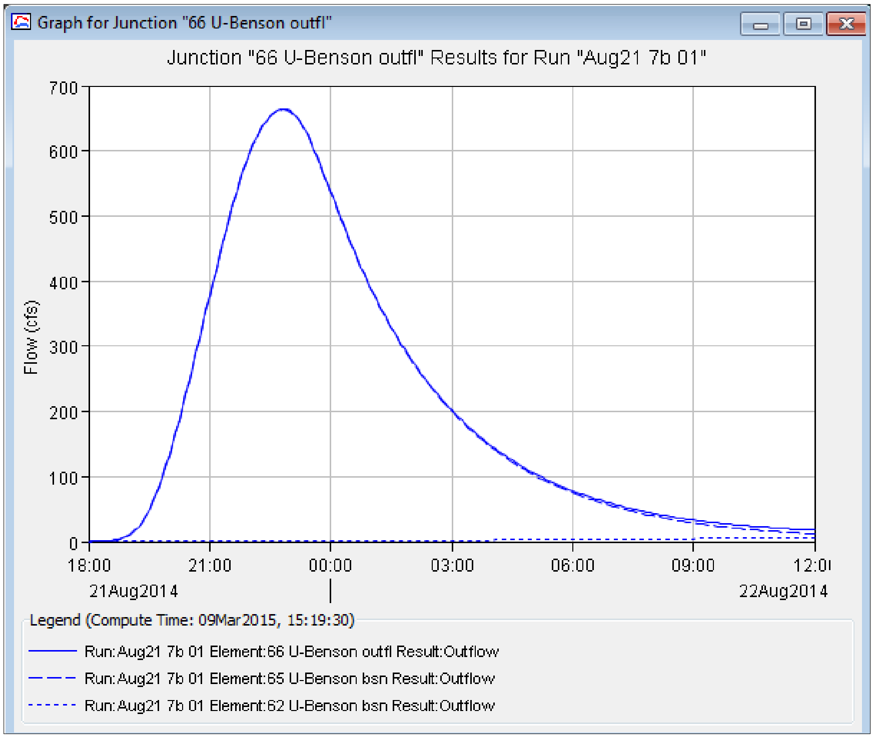
1. Outflow from Chalfa Dam



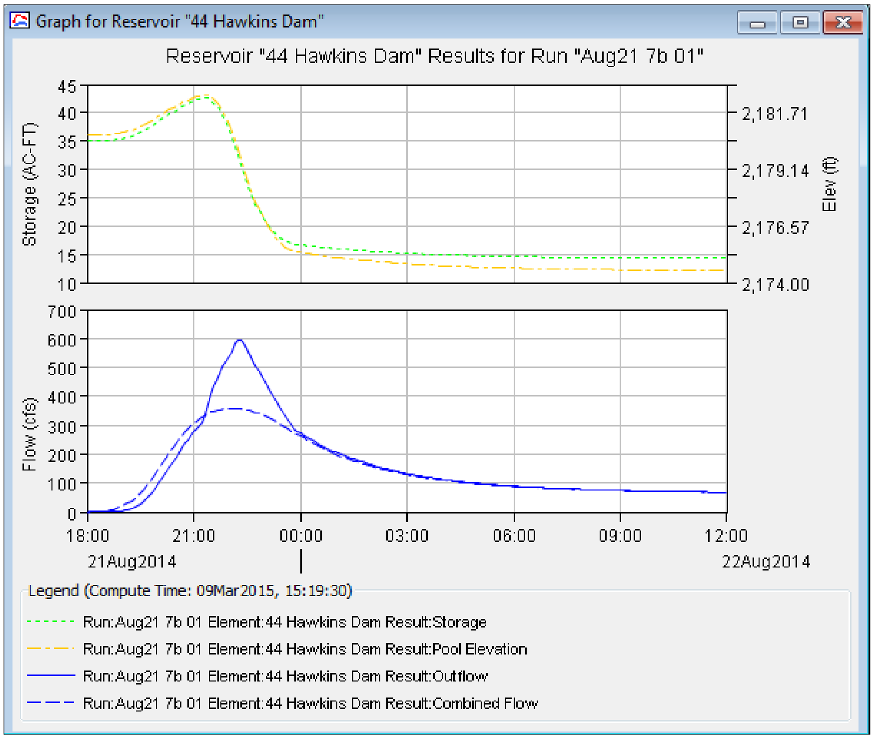
2. Outflow from Rabel Dam



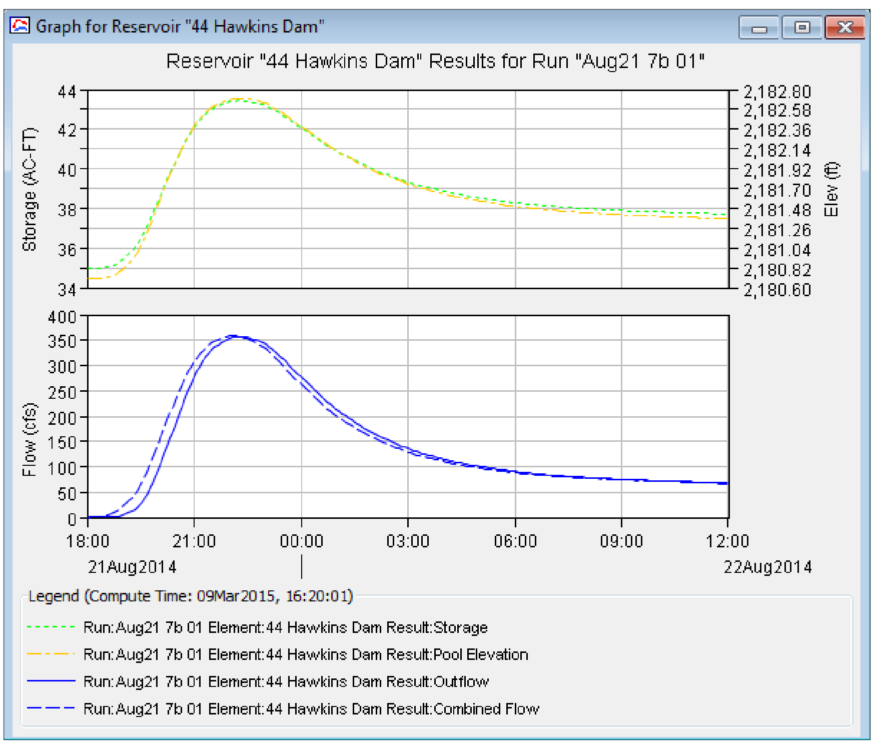
3. Inflow to Hawkins Dam



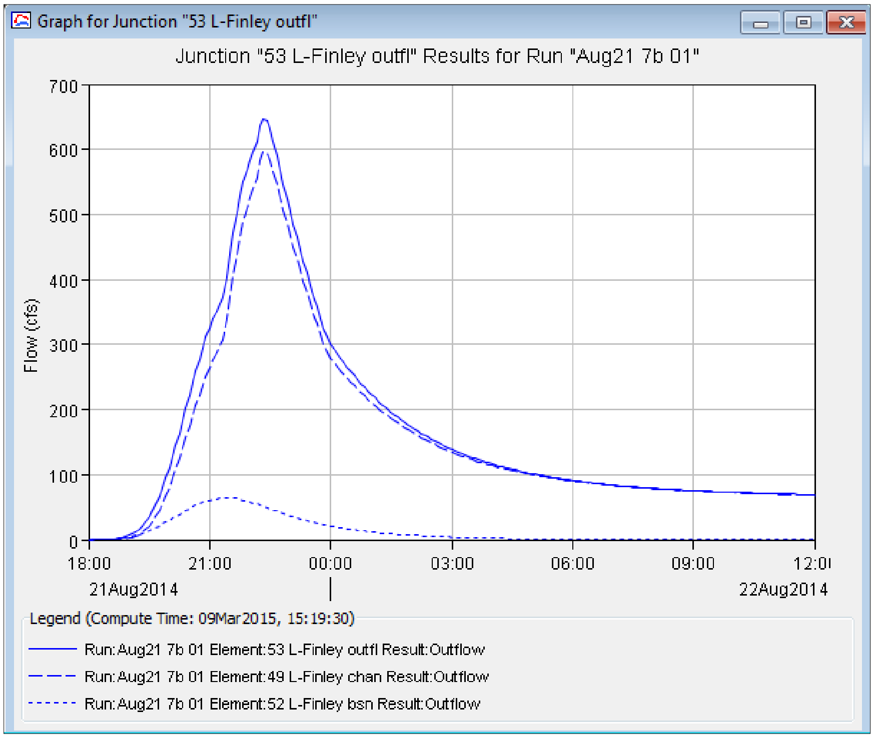
4. Outflow from Upper Benson Creek



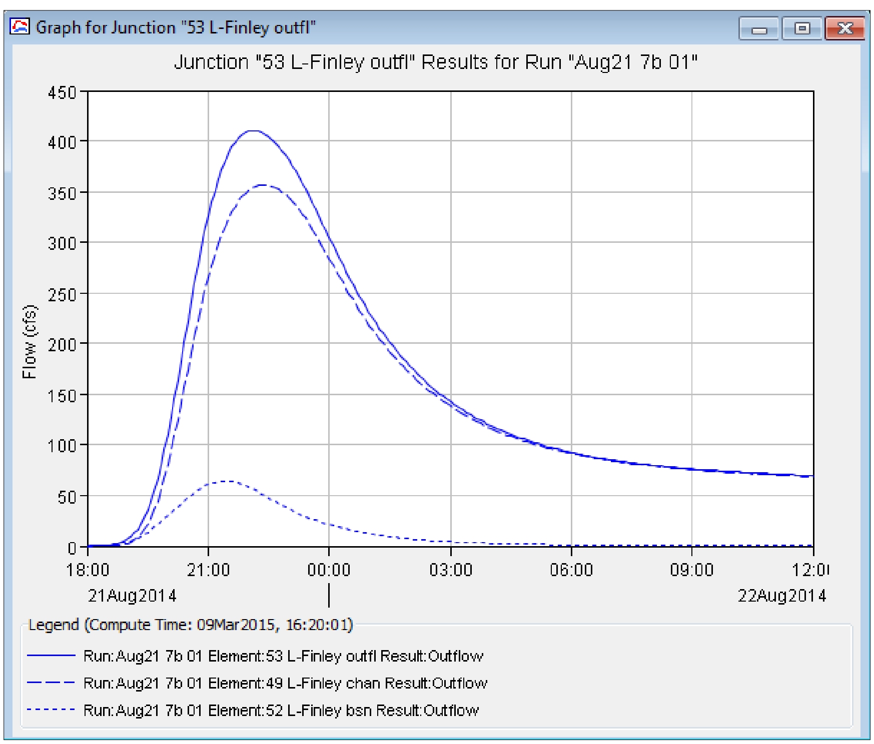
5. Outflow from Hawkins Dam



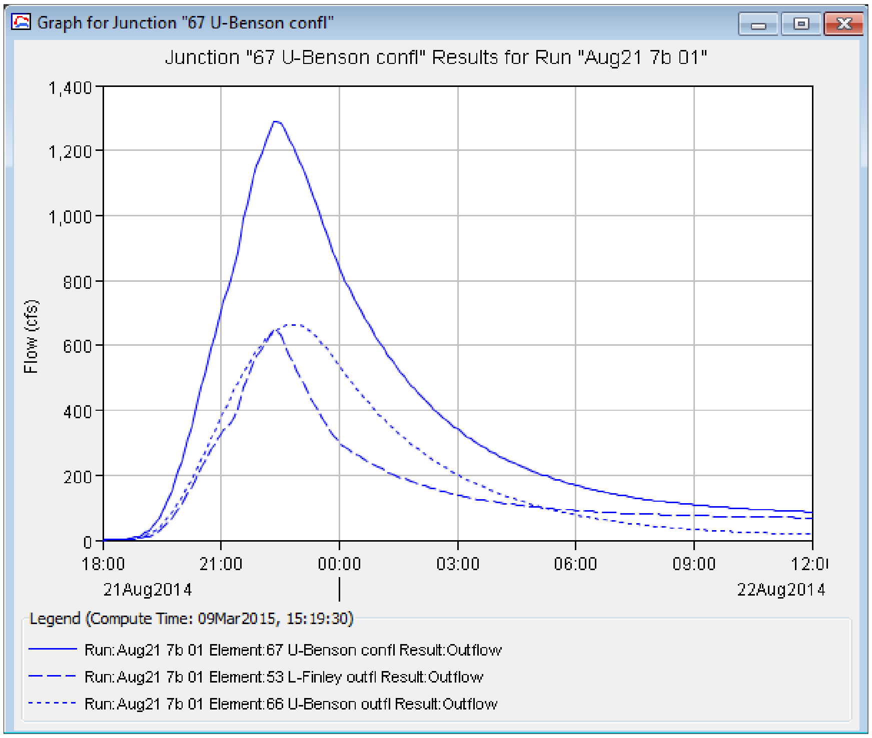
6. Outflow from Hawkins Dam without breach



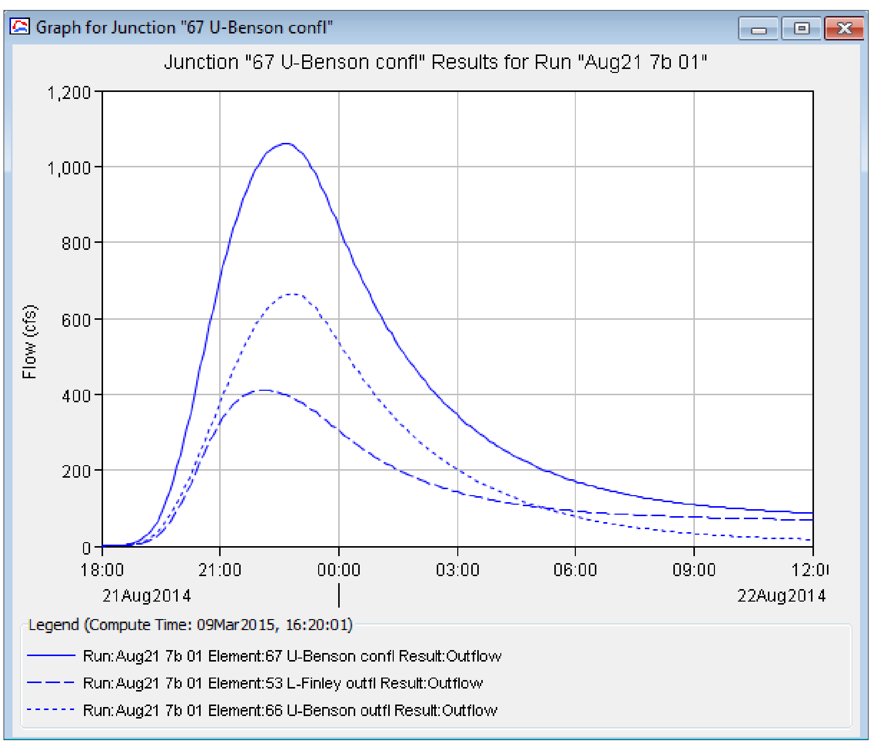
7. Outflow from Lower Finley Canyon



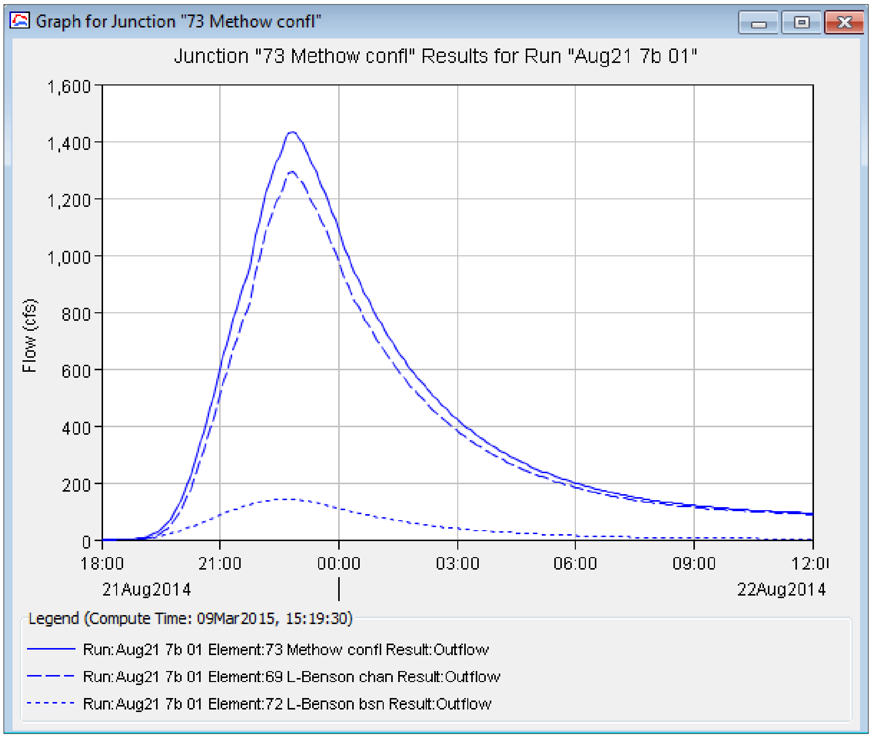
8. Outflow from Finley Canyon without breach



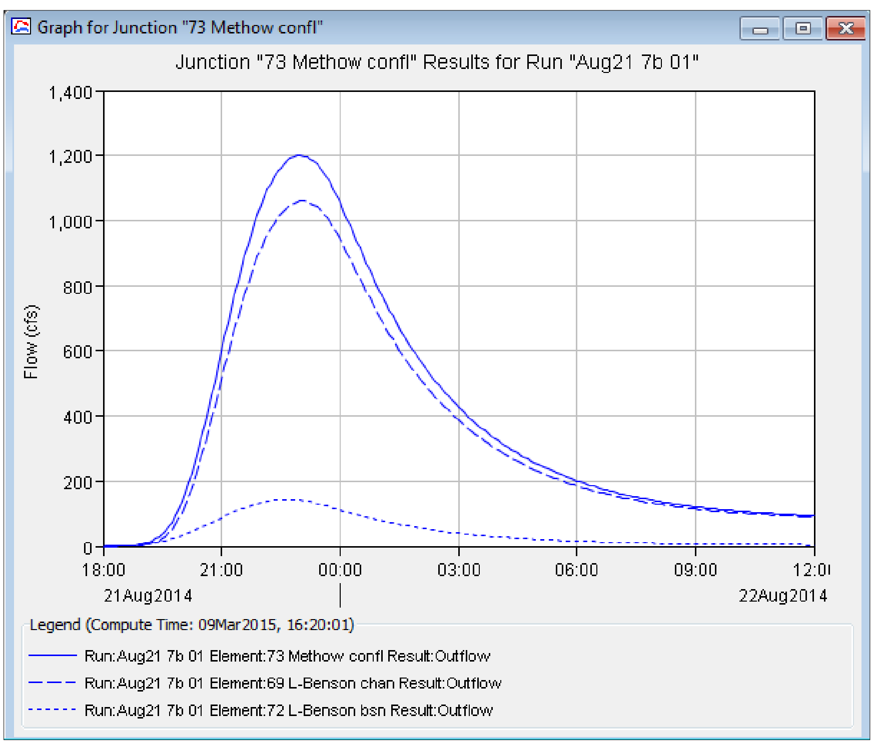
9. Combined flow into Lower Benson Creek



10. Flow into Lower Benson Creek without breach



11. Flow in Benson Creek at SR-153



12. Flow at SR-153 without breach