Dam Safety Incident Report

Computerized Rainfall-Runoff Model for Benson Creek

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.

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 computerized rainfall-runoff model for the Benson Creek watershed and some preliminary model results are the subject of this report.

What happened on August 21st? Why did a modest storm cause so much damage? 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. 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.

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.

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Benson Creek Flood, August 2014, Okanogan County, WA

Rainfall-Runoff Model Development

Introduction

What happened on August 21st? Why did a modest storm cause so much damage? The rainfall-runoff model that is the subject of this report will attempt to answer these questions.

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.

Rainfall calculations by the National Weather Service (NWS) Spokane office and by the Department of Ecology's Dam Safety Office indicate the rainfall on Finley Canyon and the Benson Creek watershed was on the order of a 5-year event. Initial estimates of higher rainfall in Upper Finley Canyon have not been confirmed by a more detailed analysis of the NWS radar data for the August 21st storm.

The damage caused in the Benson Creek watershed by the storm of August 21st is described in more detail in a previous Dam Safety Incident Report. There were no rain gauges or stream gauges in the Benson Creek watershed to measure what actually happened, so our next option is to compile a rainfall-runoff model to estimate what probably happened. The development of the computerized rainfall-runoff model for the Benson Creek watershed and some preliminary model results are the subject of this report.

Benson Creek Watershed

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. Finley Canyon has a drainage area of 18.3 square miles. Upper Benson Creek has a drainage area of 15.6 square miles, so the combined drainage area to Lower Benson Creek is 34 square miles. Lower Benson Creek adds 4 square miles of drainage, so the total drainage area for Benson Creek is 38 square miles when it empties into the Methow River.

In Upper Finley Canyon, about 10.3 square miles of drainage area are somewhat isolated from the middle and lower canyon by a large, naturally-occurring berm at least 40 feet high that extends across the canyon. This berm appears to have been formed by alluvial fans from debris flows from both sides of the canyon. The depression upstream of this berm appears to be almost a mile long, receives stream flows from the upstream watershed, doesn't seem to have a surface outlet, but also doesn't seem to hold much water. Examination of maps and air photos show a wetland area and possibly a shallow pond, but not a large lake as would be expected to form within this topography. It appears that the gravels in the valley bottom (see Stoffel *et al*, 1991, excerpt in Appendix A) and in the cross-canyon berm are sufficiently permeable to allow runoff flows to go subsurface beneath and through this berm and re-emerge in the creek farther downstream. Volume calculations by Dam Safety hydrologists estimate this depression can impound a volume of more than 2700 acre-feet.

In Lower Finley Canyon, there are a series of five lakes known as the Wenner Lakes. Compared to the larger watershed, the surface areas and surcharge storage volumes of these lakes are quite small and are not expected to make much difference in the overall runoff calculations from large storms. Modeling for these features is discussed in a later section of this report.

Modeling approach

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). The modeling approach uses the Unit Hydrograph approach, which requires estimates for hydrologic losses (rainfall that does not become runoff), and time parameters to estimate how quickly the excess rainfall will become stream flow. The choice of the specific approaches for these elements of the model are up to the best professional judgment of the hydrologist compiling the model.

<u>Objectives</u>. The specific approaches used in the Benson Creek hydrology model have the following objectives:

- Conceptually correct, such that rainfall intensity greater than the soil infiltration rate will become runoff (Pilgrim and Cordery, page 9.2, in Maidment, 1993; Viessman *et al*, 1977, pages 105 – 106).
- Provide logical results for a wide range of storm intensities and overall rainfall volumes.
- Reasonable agreement with other approaches to estimate stream flows, specifically to the U.S. Geological Survey (USGS) regression equations.
- Sensitive to the effects of fire on ground cover and soil structure, with subsequent effects on soil infiltration rates and timing of runoff flows.
- Compatible with the findings and analyses by Burned Area Emergency Response (BAER) team hydrologists and soil scientists.

<u>Networks</u>. The overall Benson Creek watershed is modeled with 4 major sub-basins:

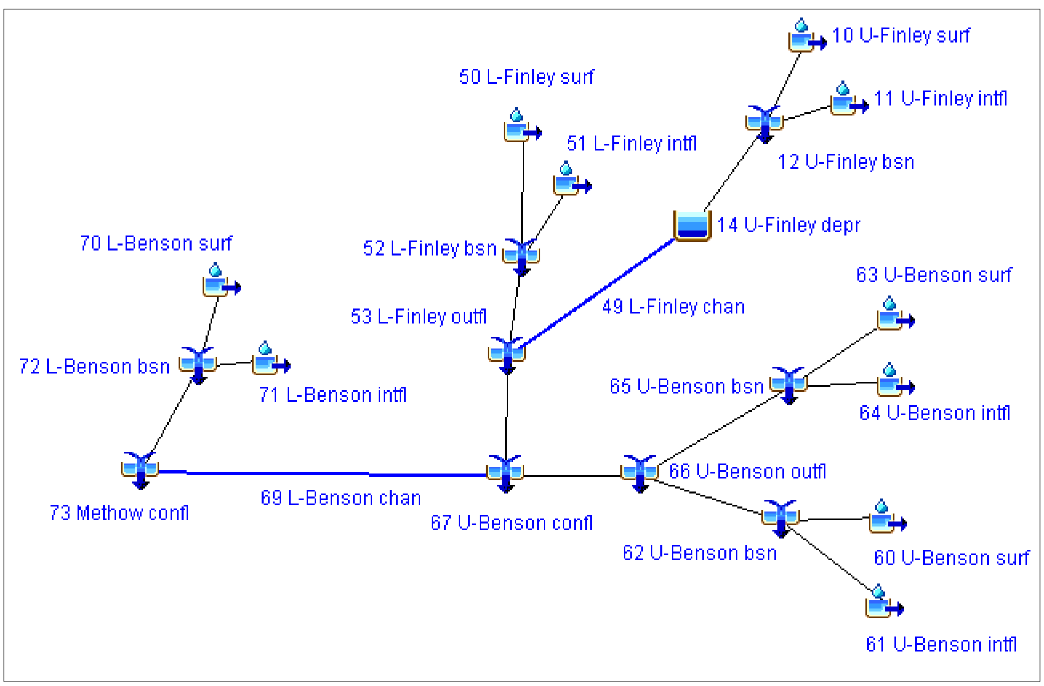
- Upper Finley Canyon, 10.3 square miles
- Lower Finley Canyon, 8.0 square miles
- Upper Benson Creek (above Finley Canyon), 15.6 square miles
- Lower Benson Creek (below Finley Canyon), 4.1 square miles

Flows from Upper Finley Canyon are temporarily detained in the large depression above the cross-canyon berm. This feature is modeled as a reservoir and spillway. The stage-discharge curve for this feature is discussed later in this report.

To account for interflow runoff, in the model, each sub-basin has a surface watershed and an interflow watershed (Barker and Johnson, 1995). Each of these watersheds has a computation method for hydrologic losses and a unit hydrograph. The losses from the surface watershed become the effective precipitation on the interflow watershed. The runoff from each of these watersheds is combined to estimate the total runoff from the particular sub-basin. The runoff from each sub-basin is routed downstream and combined with the runoff from the other sub-basins, as determined by the topography of the Benson Creek watershed.

Except for Upper Benson Creek, the post-fire basin model is substantially the same as the pre-fire basin model, with parameters from the surface watersheds revised to consider the effects of the recent forest fire. For most of the Benson Creek sub-basins, the unburned areas are a small percentage of the burned areas, so the parameters for the unburned areas were simply averaged into the parameters for the overall sub-basin. However, almost 40 % of the Upper Benson Creek sub-basin escaped the fire, so in the post-fire basin model, Upper Benson Creek is treated as two separate smaller sub-basins for the burned (9.5 square miles) vs. unburned (6.1 square miles) areas.

A diagram of the post-fire network is shown below:

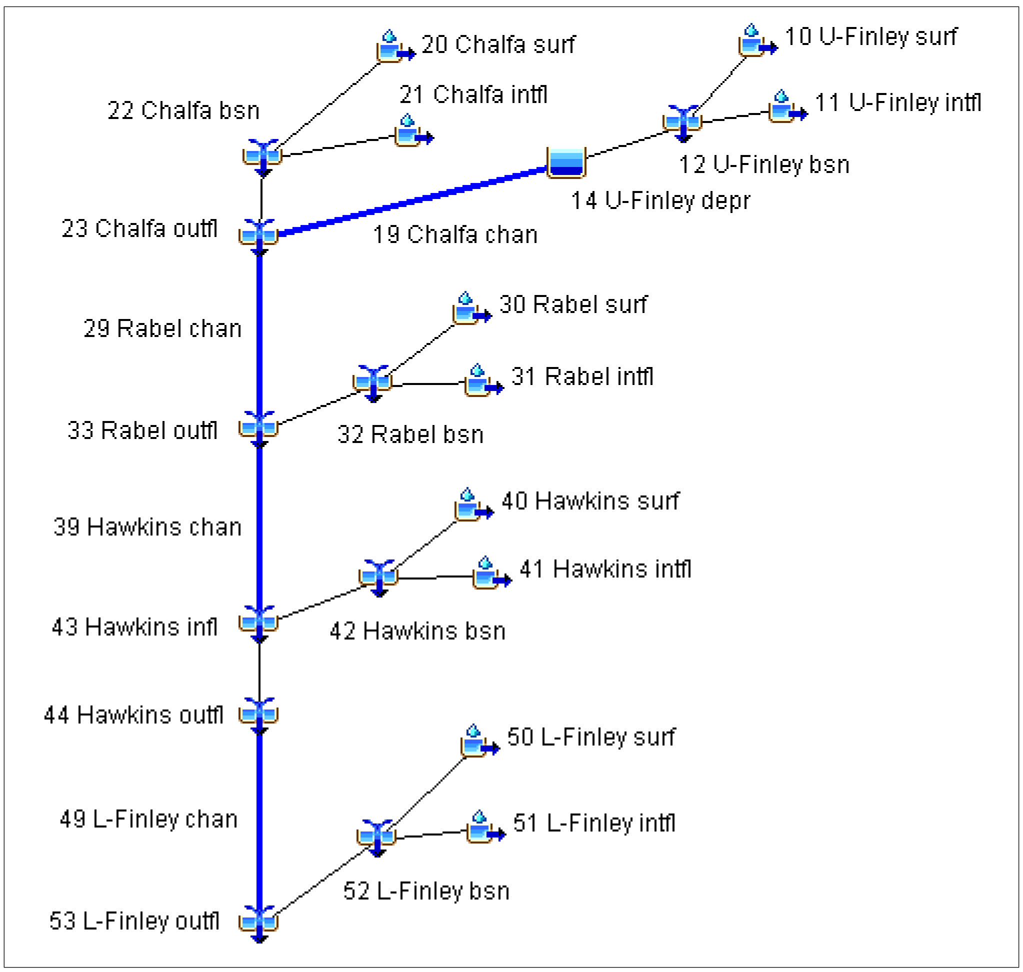


HEC-HMS network for Benson Creek basin model.

The Benson Creek basin model covers the major topographic watersheds, but does not provide flow calculations at other intermediate locations such as the various Wenner Lakes dams. To examine conditions at the three largest dams in more detail, Lower Finley Canyon (8.0 square miles) is further subdivided into smaller sub-basins directly tributary to the Chalfa, Rabel and Hawkins Dams. The resulting model for the Finley Canyon watershed has 5 sub-basins:

- Upper Finley Canyon, 10.3 square miles
- Sub-basin for Chalfa Dam, 5.3 square miles
- Sub-basin for Rabel Dam, 1.1 square miles
- Sub-basin for Hawkins Dam, 0.6 square miles
- Lower Finley Canyon below Hawkins Dam, 1.0 square miles

A diagram of the Finley Canyon network is shown below:



HEC-HMS network for Finley Canyon basin model.

Hydrologic losses. In the interest of simplifying the calculations to a manageable level, a constant infiltration rate is used to represent the hydrologic losses. For the pre-fire surface watersheds, the soil infiltration rate is based on the saturated conductivities (Ksat values) for the surface layer obtained from the USDA NRCS Web Soil Survey. A weighted average infiltration rate was calculated for each sub-basin based on soil types within the sub-basin. Pre-fire surface infiltration rates used in the model ranged from 1.78 to 1.95 inches/hour.

For the interflow watersheds, the deep infiltration rate (deep percolation to groundwater) is based on the hydrologic soil groups (A, B, C or D) for the soils within the sub-basin (ASCE, 1996, Table 3.3 on page 97; USBR, 1987, page 41), with a weighted average infiltration rate calculated for each sub-basin based on soil types within the sub-basin. After calibration to the USGS equations, deep infiltration rates used in the model ranged from 0.12 to 0.19 inches/hour.

For the post-fire surface watersheds, the surface infiltration rate is determined by the severity of burn within the sub-basin. Forest fires can affect burned-area soils by reducing the effective ground cover, reducing the amount of soil structure, and forming water repellent layers that reduce infiltration (Parsons et al, 2010, page 10). Changes between pre-fire and post-fire conditions are reflected in changes to the NRCS curve numbers (CN values) used by BAER hydrologists (USFS-MFSL, 2009). Areas of high and moderate burn severity are assigned very high CN values based on burn severity. Areas of low burn severity are assigned CN values scaled up from the original pre-fire CN values. For unburned areas, CN values are unchanged.

Although the calculations in this model do not use curve numbers directly, CN values from the BAER hydrology calculations were used to calculate post-fire soil infiltration rates that would yield the same runoff volumes as calculations that used the curve numbers directly. Post-fire surface infiltration rates used in the model ranged from 0.07 to 0.20 inches/hour. As noted previously, Upper Benson Creek is treated as two separate smaller sub-basins for the burned vs. unburned areas. CN values and post-fire infiltration rates are summarized here:

Watershed	Drainage area	Pre-fire CN values	Post-fire CN values	Post-fire infiltration
Upper Finley	10.3 sq.miles	52.1	88.4	0.066 in/hr.
Lower Finley	8.0 sq.miles	44.5	69.9	0.180 in/hr.
Upper Benson, burned	9.5 sq.miles	55.1	70.8	0.173 in/hr.
Upper Benson, unburned	6.1 sq.miles	55.1	55.1	1.849 in/hr. (pre-fire K_{sat})
Lower Benson	4.1 sq.miles	57.4	67.3	0.203 in/hr.
Benson Creek	38.0 sq.miles	52.3	72.5	0.418 in/hr.

Pre-fire vs. Post-fire NRCS Curve Numbers.

To maintain consistency between the two basin models, the surface and deep infiltration rates calculated for Lower Finley Canyon in the Benson Creek model are applied to all of the Lower

Finley sub-basins in the Finley Canyon model. This is the case for both pre-fire and post-fire conditions.

The conceptual model for these computerized numerical models is that rainfall more intense than the surface infiltration rate will become direct surface runoff. Rainfall less intense than the surface infiltration rate will infiltrate into the soil layer. Surface infiltration higher than the deep infiltration rate will re-emerge as interflow runoff. Surface infiltration less than the deep infiltration rate will percolate to groundwater and will not become runoff during the computation period for the storm.

<u>Unit hydrographs</u>. The Bureau of Reclamation (USBR) unit hydrograph considers length and slope for the representative flow path and surface roughness within the watershed to estimate the time parameter for the unit hydrograph (USBR, 1987, pages 29 – 36). Since the surface roughness will change from pre-fire to post-fire conditions, the USBR unit hydrograph was selected for use in the model in order to capture the changes in surface roughness. The actual calculations in HEC-HMS use the Snyder unit hydrograph, which has a similar theoretical basis as the USBR unit hydrograph (Viessman *et al*, 1977, pages 115, 135; ASCE, 1996, pages 359 – 360). As a practical matter, it appeared that consideration of pre-fire and post-fire conditions would be more visible in the calculations for the USBR/Snyder unit hydrograph compared to the time of concentration calculations typically done to use the SCS unit hydrograph, hence the preference for the USBR unit hydrograph for calculating surface runoff in this model.

For pre-fire conditions, surface roughness coefficients within the Benson Creek watershed were estimated on the order of 0.15. After calibration to the USGS regression equations, unit hydrograph lag times used in the model for pre-fire surface watersheds ranged from 7.1 to 8.9 hours. For post-fire conditions, surface roughness coefficients within the Benson Creek watershed were estimated in the range of 0.039 to 0.077. Unit hydrograph lag times used in the model for post-fire surface watersheds ranged from 2.3 to 3.8 hours.

For the interflow watersheds, the calculations use the SCS unit hydrograph with lag time based on a multiple of the lag time for the pre-fire surface watershed (see Barker and Johnson, 1995; King County SWM, 1992). Calibration to the USGS regression equations found multipliers ranging from 4.4 to 6.8 times the surface lag time. Unit hydrograph lag times used in the model for the interflow watersheds ranged from 2320 to 3635 minutes (39 to 61 hours). HEC-HMS uses minutes as the time units for the SCS unit hydrograph. As noted previously, the runoff from the surface and interflow watersheds is combined to estimate the total runoff from the particular sub-basin.

<u>Storm scenarios</u>. Dam Safety protocols for compiling design storms for hydrologic modeling are described in *Dam Safety Guidelines, Technical Note 3: Design Storm Construction* (2009). This document, along with the spreadsheets and gridded data sets needed to perform the calculations, are available on the Department of Ecology's web site. The *Technical Note 3* document is available at: https://fortress.wa.gov/ecy/publications/SummaryPages/9255g.html.

As described in *Technical Note 3*, Dam Safety uses three design storm scenarios:

- Short duration storm; brief but intense, up to 4 hours long with most of the rain falling within a one-hour period, typically considered to be a thunderstorm.
- Intermediate storm: 18 hours long, less intense but higher volume than the short storm.
- Long duration storm: 72 hours long, less intense but higher volume than the intermediate storm.

For any particular storm recurrence interval, all three storm scenarios are equally probable, so the hydrology model runs need to consider all three scenarios and compare to see which one is the controlling event.

For this analysis, two additional storm scenarios were developed. The first is a one-hour short duration thunderstorm to attempt to replicate the hydrology calculations in the BAER team report. This effort was used to calibrate the unit hydrograph parameters for post-fire conditions. The second storm scenario is an attempt to replicate the rainfall from the evening of August 21st.

Precipitation depths. For the various storm scenarios, rainfall depths for various recurrence intervals were calculated using the lookup calculator spreadsheet protocols used by Dam Safety. The spreadsheets and gridded data sets to do this are in the *Required supplement to Technical Note 3*, available from the Dam Safety page on the Department of Ecology's web site at http://www.ecy.wa.gov/programs/wr/dams/GuidanceDocs_ne.html.

For the short dam safety storm, the rainfall calculations represent point rainfalls for watersheds smaller than 1 square mile. For larger watersheds, such as those in the Benson Creek watershed, the average rainfall over the entire sub-basin must consider an areal adjustment factor based on the drainage area. The areal adjustment factors used in these calculations were scaled from Figure 16 on page 70 of *Characteristics of Extreme Precipitation Events in Washington State* (Schaefer, 1989). A link to a copy of this report is available on the Department of Ecology's web site at: https://fortress.wa.gov/ecy/publications/SummaryPages/8951.html.

The long and intermediate storms can occur during times of the year when there may be a significant snow pack on the ground, so the precipitation values for these storms include snow-melt that may occur during the storm. The snowmelt calculations used a spreadsheet version of the equations and procedures from Section 5-3 of *Runoff from Snowmelt* (USACE, 1998). The spreadsheet calculations calculated snowmelt for each storm scenario in each sub-basin, then added snowmelt to rainfall to get the total precipitation for that storm scenario. The values for total precipitation were then input to the computer model. Since snowmelt is already included in the precipitation values used in the model, the model does not perform separate snowmelt calculations.

Rainfall data for the actual August 21st storm were obtained from the NWS Spokane office, specifically as GIS shapefiles of their radar data for the storm.

Storm and interflow hyetographs. Dam Safety uses a set of design storm hyetographs based on an analysis of historical storms. The unit hyetographs for the various dam safety storms are in the *Required supplement to Technical Note 3*, available from the Department of Ecology's web site at http://www.ecy.wa.gov/programs/wr/dams/GuidanceDocs_ne.html. In the hydrology model, the rainfall depths for each sub-basin are specified separately, then the computer multiplies the rainfall depth times the ordinates from the unit hyetograph to generate the storm hyetograph to use in the rainfall-runoff calculations.

For the interflow watersheds, the interflow unit hyetograph is a variation of the storm hyetograph with the peak of the storm truncated to mimic a steady soaking infiltration into the soil during the peak of the storm. As noted previously, in each sub-basin, the losses from the surface watershed become the effective precipitation on the interflow watershed.

The calculations found that the Benson Creek watershed is within Climatic Region 14, Cascade Mountains East Slopes. The specific storm hyetographs used in the model are Hyetograph 6 for the short duration storm, Hyetograph 11 for the intermediate storm, and Hyetograph 17 for the long duration storm. An edited version of Hyetograph 6 is used to estimate the time distribution for a one-hour storm for comparison between the hydrology model calculations and the BAER team hydrology calculations.

Hyetographs for August 21st storm. Dam Safety is indebted to the NWS Spokane office for providing a copy of their radar data for the storm precipitation in a GIS format, from which we were able to estimate the peak hour rainfall and total storm rainfall over each major sub-basin. In slight contrast to previous estimates, our analysis found peak hour rainfall depths ranging from 0.27 to 0.63 inches, and total storm rainfall depths ranging from 0.80 to 1.03 inches. The specific results are shown here, along with a comparison of the peak hour to total storm rainfall.

Rainfall depths	Upper Finley	Lower Finley	Upper Benson	Lower Benson
Peak hour	0.505 in.	0.395 in.	0.628 in.	0.273 in.
Total storm	0.861 in.	0.819 in.	1.027 in.	0.796 in.
Ratio	58.6 %	48.3 %	61.1 %	34.3 %

August 21st rainfall depths.

From this information, although most of the rain fell within a one-hour period (as previously reported), it appears that the actual storm duration was on the order of 2 to 2½ hours. It also appears that there were significant differences between the upper and lower sub-basins with regard to the rainfall time distributions.

To capture this in the hydrology model, two storm hyetographs of 2.5 hours duration were compiled. For the Upper Benson and Upper Finley sub-basins, the peak hour of the storm has 61% of the total storm rainfall. For the Lower Finley and Lower Bensons sub-basins, the peak hour of the storm has 48% of the total storm rainfall. Preliminary estimates are that this approach will match the peak hour rainfalls for the Lower Finley and Upper Benson sub-basins within 0.5% of the actual rainfalls. The peak hour rainfall for the Upper Finley sub-basin may be over-estimated in the model by about 4%, although the effect on peak outflows from the Upper

Finley sub-basin will be lessened by the effects of the cross-canyon berm. The peak hour rainfall for the Lower Benson sub-basin may be over-estimated in the model by about 40%, although the effect on peak flows in Lower Benson Creek will be somewhat lessened by the relatively small drainage area for the Lower Benson sub-basin compared to the upstream sub-basins.

The hyetographs were compiled using the interduration values from *Technical Note 3*, Table 24 on text page 56, for the Intermediate storm for Climatic Region 14. The values for the peak 3 hours of the storm were used to estimate values for a 2.5-hour storm at 15-minute intervals, then adjusted for the desired peak hour percentage, then converted to 5-minute intervals. Values at 5-minute intervals for the peak 15 minutes were estimated using the interduration values from Table 23 on text page 55, for the Short duration storm for Climatic Region 14. The interduration values in *Tech Note 3* are based on Schaefer's analysis of a large database of historical storms, so while the exact time-distribution of the August 21st storm is not known, these estimated time-distributions are based on typical time-distributions for historical storms in this climatic region.

For use in the hydrology model, the storm hyetographs were assembled to assign the peak of the storm to the center of the 2.5-hour time period. In other words, the peak 5-minute rainfall occurs at time 1.25 hours; the peak 30-minute rainfall occurs between times 1.00 to 1.50 hours; and the peak 60-minute rainfall occurs between times 0.75 to 1.75 hours. As entered into the hydrology model, the rain for the August 21st storm is estimated to start at 18:00 hours (6:00pm) and end at 20:30 hours (8:30pm) on August 21, 2014.

<u>Upper Finley Canyon</u>. As noted previously, in Upper Finley Canyon, about 10.3 square miles of drainage area are somewhat isolated from the middle and lower canyon by a large, naturally-occurring berm at least 40 feet high that extends across the canyon. The depression upstream of this berm appears to be almost a mile long, receives stream flows from the upstream watershed, doesn't seem to have a surface outlet but also doesn't seem to hold much water except on a very temporary basis.

In the hydrology model, this feature is modeled as a reservoir. From topography data in our GIS system, we can calculate a stage – surface area – storage volume relationship for this depression, but the particular challenge is to estimate the stage – discharge relationship for this feature. This dilemma is resolved as follows.

Since there is no surface outlet, subsurface flow suggests that the outflow from this depression might be modeled as flow through porous media using Darcy's Law, $Q = K\ I\ A$ (Driscoll, 1986, pages 73 – 76), where K is the hydraulic conductivity of the porous material (presumed to be gravel, in this case), A is the cross-section area of flow, and I is the hydraulic gradient. The hydraulic gradient $I = H / L$, where H is the hydraulic head and L is the length of the flow path through the porous material.

From a near-by USGS stream gauge on Beaver Creek that was operated from 1960-1978, the maximum monthly average flow is 79 cfs from a 62 square mile drainage area (see Sinclair and Pitz, 1999, pages A-7, B-102), equivalent to 1.274 CSM (cfs/sq.mile). For the 10.3 square mile drainage area for Upper Finley Canyon, the estimated flow is 13.1 cfs. The land slope in the bottom of the canyon is 6.6 ft/mile = 0.00125 ft/ft, estimated to be representative of the groundwater gradient through this reach. From this information, since we have estimates for Q and I, we can estimate a value for the product of K x A = Q / I = 10,503, such that the equation for flow through the berm becomes Q = 10,503 x (H / L).

From the topographic maps in Ecology's GIS system, the flow distance through the base of the cross-canyon berm is estimated at approximately 4000 feet. The upstream face of the berm slopes at about 35 H:1V, such that the flow path shortens by 35 feet for each 1-foot increase in water level (H) behind the berm. In equation form, L = 4000 – 35 H.

With this information, for any particular value of H, we can calculate a corresponding value for L, then a value for I = H / L, then a value for Q. For various values of H, this gives us the stage – discharge curve for outflow from Upper Finley Canyon. At a flow depth of 20 feet, the estimated flow through the berm is 64 cfs. At a flow depth of 40 feet, the estimated flow through the berm is 162 cfs.

To check the reasonableness of these flow estimates, the stage – discharge curve was used to estimate a drawdown curve for the temporary lake upstream of the cross-canyon berm. From a water depth of 20 feet, the temporary lake would drain in about 6 days. From a water depth of 40 feet, the temporary lake would drain in about 9 days. These drawdown results seem consistent with observations that this feature in Upper Finley Canyon does not hold water for long periods of time.

Wenner Lakes and other small storage features. As mentioned previously, in Lower Finley Canyon, there are a series of five man-made lakes known as the Wenner Lakes. Upstream of these lakes, still within the Lower Finley sub-basin, are a couple small berms similar to the large cross-canyon berm that isolates Upper Finley Canyon but much smaller in height and in the volume they can temporarily hold. For modeling purposes, the issue is how and whether to include these features in the model. Our current thinking on this is as follows.

Compared to the larger watershed, the surface areas and surcharge storage volumes of these features are quite small and are not expected to make much difference in the overall runoff calculations from large storms. In other hydrology modeling done for other dam safety projects, it is quite common for the early part of the storm to fill up the available surcharge storage such that the peak runoff rolls through the reservoir or lake with minimal or negligible attenuation.

At this time, these small storage features are not explicitly considered in the current models for either Benson Creek or Finley Canyon. The detailed calculations from the Finley Canyon model will provide flow values at each dam location that can be used for separate hydraulic calculations and analyses.

Channel routing. For modeling purposes, the outflows from Upper Finley Canyon are routed along the creek through Lower Finley Canyon to the junction with runoff from the Lower Finley sub-basin. The combined outflows from Finley Canyon and Upper Benson Creek are routed along Benson Creek to the junction with runoff from the Lower Benson sub-basin.

Most channel routing techniques require more cross-section data for the creeks than we have for the Benson Creek watershed. In this hydrology model, channel routing used a simple lag time approach with flow travel times estimated from the bed slopes of the creeks and velocities from Table 7 in *Dam Safety Guidelines, Technical Note 1: Dam Break Inundation Analysis*. Table 7 lists representative flow velocities for various bed slopes and channel materials.

For pre-fire conditions, the creek in Lower Finley Canyon was estimated as a Type 3 channel with gravel main channel and wooded overbanks. Lower Benson Creek was estimated as a Type 2 channel with gravel main channel and overbanks with brush and scattered shrubs. For post-fire conditions, both creeks were estimated as Type 1 channels with gravel main channel and overbank conditions equivalent to grass or pasture.

Pre-fire travel (lag) times are estimated as 60 minutes for Lower Finley Canyon and 30 minutes for Lower Benson Creek. Post-fire times are estimated as 40 minutes for Lower Finley Canyon and 25 minutes for Lower Benson Creek. This channel routing technique takes the inflow hydrograph from the upstream watershed, lags it by the specified time with no other changes to the hydrograph ordinates, then uses the lagged hydrograph for the calculations downstream of the channel.

A similar approach is used in the Finley Canyon model for routing flows from upstream sub-basins across the downstream sub-basins. Outflows from Upper Finley Canyon are routed across the Chalfa sub-basin; outflows from the Chalfa Dam are routed across the Rabel sub-basin; outflows from the Rabel Dam are routed across the Hawkins sub-basin; and outflows from the Hawkins Dam are routed across the remaining Lower Finley sub-basin. To maintain consistency between the two basin models, the combined routing times used in the Finley Canyon model are equal to the routing time across Lower Finley Canyon used in the Benson Creek model; this is the case for both pre-fire and post-fire conditions.

Burned areas and parameters. Dam Safety is indebted to the BAER team hydrologists, in particular the NWS Spokane office, for sharing their data with regard to burned areas and burn severity in the Benson Creek watershed, summarized here:

Burn severity	Upper Finley	Lower Finley	Upper Benson	Lower Benson
High	2809 ac. 42.5 %	479 ac. 9.4 %	395 ac. 4.0 %	119 ac. 4.4 %
Moderate	2752 ac. 41.6 %	2023 ac. 39.7 %	1539 ac. 15.4 %	437 ac. 16.2 %
Low	754 ac. 11.4 %	2528 ac. 49.6 %	4143 ac. 41.5 %	1871 ac. 69.2 %
Not burned	294 ac. 4.4 %	68 ac. 1.3 %	3905 ac. 39.1 %	276 ac. 10.2 %

Burned areas and burn severity in Benson Creek watershed.

These data were used to revise the parameters for surface infiltration and hydrograph lag times in the model to account for post-fire conditions within each sub-basin. The ranges of pre-fire and post-fire parameters used in the model were discussed previously.

Model calibration

As used here, "calibration" means adjustments to the watershed parameters to get model results that are consistent with other approaches to estimating the stream flows in Benson Creek.

Pre-fire calibration to USGS regression equations. Actual stream flow records for Benson Creek are not available to compare the model results to, so the USGS regression equations appear to be the next available option for comparison to the model results. The results from the USGS equations are available from the on-line Stream-Stats program. The Dam Safety Office also has spreadsheet versions of the USGS equations.

Comparisons were made between the USGS equations and model runs for the short, intermediate and long dam safety storms for recurrence intervals of 25, 100 and 500 years using the pre-fire watershed parameters. The long and intermediate storms included snowmelt, and the short storm included the areal adjustment factors shown in the following table. As mentioned previously, these areal adjustment factors were scaled from *Characteristics of Extreme Precipitation Events in Washington State* (Schaefer, 1989).

Short storm areal adjustment factors	Upper Finley	Lower Finley	Upper Benson	Lower Benson
Drainage area	10.3 sq.miles	8.0 sq.miles	15.6 sq.miles	4.1 sq.miles
Basin average % of point precip	84 %	87 %	80 %	94 % [not used]

Short storm areal adjustment factors for basin average precipitation.

The calibrations were done on a sub-basin by sub-basin basis, such that the runoff flows from each sub-basin as calculated by the computer model were compared to the range of runoff flows estimated by the USGS equations for that sub-basin, based on drainage area and mean annual precipitation. Since the basin average rainfall as a percentage of the calculated point rainfall is different for each sub-basin, each sub-basin had its own value for the short storm rainfall during the calibration process. The exception here is the Lower Benson sub-basin, which used the rainfall value for the Upper Benson sub-basin rather than a much higher basin-specific rainfall for Lower Benson.

The rationale here for Lower Benson is as follows. The Lower Benson sub-basin is primarily a construct of the hydrology model to account for this drainage area in the larger Benson Creek watershed, but is not by itself a topographically-defined basin. Our sense is that, hydrologically, Lower Benson would act more like an extension of the Upper Benson basin rather than like a separate, distinct basin. Also, the parameters for the Lower Benson sub-basin resulting from the calibration process seem to be consistent with the parameters for the other sub-basins. We are open to others' wisdom on this, but this is how the calculations have been done so far.

As a further clarification, the areal adjustment factors for the short storms were applied only to the rainfall depth, with no other modifications to the dam safety short storm hyetograph.

Since the basin elevations and estimated snowmelt are different for each sub-basin, for the long and intermediate storms, each sub-basin had its own value for precipitation (rainfall plus snow-melt) during the calibration process. Since the sub-basin areas are so close to the 10 square mile threshold for small vs. large watersheds for these storms, areal adjustments were not made to the rainfall values for the long and intermediate storms.

As a clarification, the long and intermediate storms are considered to be general storms where the rainfall occurs over a relatively wide area. For these storms, 10 square miles is the threshold between a small vs. large watershed. In contrast, the short duration storm is considered to be a local storm where the rainfall occurs over a more localized, smaller area. For the short storm, 1 sq. mile is the threshold between a small vs. large watershed. See *Technical Note 3* (Schaefer and Barker, 2009), page 29. See also HMR-57 (NWS, 1994), chapters 9 and 11.

In the calibration process for the Benson Creek basin model, the unit hydrograph lag times for the surface watersheds were more than doubled from original estimates to keep the model from overestimating flows at the 500-year recurrence interval. Deep infiltration rates for the interflow watersheds were reduced by 20% from original estimates to keep the model from underestimating flows at the 100-year recurrence interval. The ranges for the watershed parameters discussed above are the calibrated values for these parameters as used in the model for both pre-fire and post-fire conditions.

At these storm recurrence intervals for pre-fire conditions, the model consistently found the Intermediate storm (18 hours long) to be the controlling event, with virtually all of the runoff occurring as interflow runoff. This finding seems consistent with the very high percentages of Soil Group A and B soils in the Benson Creek watershed.

<u>Post-fire comparison to BAER hydrology calculations</u>. The BAER team report (BAER team, Sept. 2014) includes a comparison of estimated flows for various drainages within the Carlton Complex Fire, including Benson Creek, for pre-fire vs. post-fire conditions. Their hydrology calculations, shown on page 5 of the BAER report, used two different programs, Wildcat5 and AGWA, with differing predictions. However, both programs estimate post-fire flows on the order of 10 to 20 times the pre-fire flows from the same storm event, with some calculations for post-fire flows as high as 40 to 50 times the pre-fire flows. The BAER team report is available on the Okanogan Conservation District web site.

The BAER hydrology calculations considered a storm event of 0.77 inches in one hour. Model runs for this storm scenario for pre-fire and post-fire conditions showed post-fire flows on the order of 8 to 12 times pre-fire flows for most of the Benson Creek watershed. For Upper Finley

Canyon, post-fire flows were on the order of 24 times pre-fire flows, consistent with the higher percentage of high and moderate severity burned soils in Upper Finley Canyon compared to the rest of the Benson Creek watershed.

<u>Calibration for Finley Canyon model</u>. In the calibration process for the Finley Canyon basin model, the calibrations were done for each dam location based on the cumulative drainage area within Lower Finley Canyon as follows:

- Drainage to Chalfa Dam, 5.3 square miles
- Drainage to Rabel Dam, 6.4 square miles
- Drainage to Hawkins Dam, 7.0 square miles

The calculations used the precipitation values for Lower Finley Canyon as previously calculated for the Benson Creek basin model. Based on experience from calibrating the Benson Creek basin model, the calculations for the Finley Canyon basin model focused on the Short duration 500-year storm and the Intermediate 100-year storm. The pre-fire runoff flows at each location as calculated by the computer model were compared to the range of runoff flows estimated by the USGS equations for that location based on drainage area and mean annual precipitation.

Similar to the calibration effort for the Benson Creek basin model, the unit hydrograph lag times in the Finley Canyon model were adjusted to obtain a reasonable match between the computer calculations and the USGS equations. Compared to original estimates for pre-fire conditions, hydrograph lag times for both the surface and interflow watersheds were increased an additional 35% for the Chalfa sub-basin, and an additional 50% for the Rabel, Hawkins and remaining Lower Finley sub-basins. These adjustments are in addition to the previous adjustments made in calibrating the Benson Creek model. As a comparison to the Benson Creek model, calculated pre-fire outflows from Lower Finley Canyon appear to be about 4% to 5% higher in the Finley Canyon model compared to the Benson Creek model.

A further comparison between the Finley Canyon and Benson Creek models was made to the model calculations for post-fire conditions as discussed above in comparison to the BAER team hydrology calculations. For post-fire flows, compared to original estimates for post-fire conditions, hydrograph lag times for the surface watersheds were increased an additional 4% for the Chalfa, Rabel, Hawkins and Lower Finley sub-basins. These adjustments are in addition to the cumulative adjustments made in calibrating the pre-fire Finley Canyon basin model. As a comparison to the Benson Creek model, calculated post-fire outflows from Lower Finley Canyon agree within 1% for the Finley Canyon model compared to the Benson Creek model.

The Upper Finley sub-basin was calibrated for the Benson Creek basin model, so those values were simply copied into the Finley Canyon basin model.

Preliminary Model Findings

August 21st storm

So, what happened on August 21st? Why did a modest storm cause so much damage?

Short answer:
Model predictions are that the peak flow out of Lower Finley Canyon was more than 420 cfs. The peak flow from Upper Benson Creek was more than 660 cfs. The combined peak flow into Lower Benson Creek was on the order of 1080 cfs. The peak flow at SR-153 was on the order of 1220 cfs. These estimated flows are 7 to 8 times the estimated pre-fire flows, and are larger than the estimated pre-fire flows from a 1,000-year storm event.

Long answer:

1. For Lower Finley Canyon, model predictions are that the peak outflow was more than 420 cfs, including 40 cfs from Upper Finley Canyon. The peak flow occurred around 10:30pm, about 4½ hours after the storm began.

- By midnight: the runoff volume from Lower Finley Canyon was almost 115 acre-feet, including more than 100 acre-feet from the Lower Finley sub-basin and more than 10 acre-feet from the Upper Finley sub-basin.
- By 6:00am (August 22nd): the runoff volume from Lower Finley Canyon was almost 200 acre-feet, including more than 150 acre-feet from the Lower Finley sub-basin and almost 50 acre-feet from the Upper Finley sub-basin.
- By noon (August 22nd): the runoff volume from Lower Finley Canyon was more than 230 acre-feet, including almost 160 acre-feet from the Lower Finley sub-basin and more than 70 acre-feet from the Upper Finley sub-basin.

Ultimately, the runoff volume from Lower Finley Canyon was about 570 acre-feet, including almost 190 acre-feet from the Lower Finley sub-basin and 380 acre-feet from the Upper Finley sub-basin.

2. For Upper Benson Creek, model predictions are that the peak outflow was more than 660 cfs. The peak flow occurred around 10:50pm, almost 5 hours after the storm began.

- By midnight: the runoff volume from Upper Benson Creek was about 170 acre-feet.
- By 6:00am (August 22nd): the runoff volume from Upper Benson Creek was almost 290 acre-feet.
- By noon (August 22nd): the runoff volume from Upper Benson Creek was more than 305 acre-feet.

Ultimately, the runoff volume from Upper Benson Creek was more than 600 acre-feet, including 230 acre-feet of interflow runoff from the unburned portion of the Upper Benson watershed.

3. Model predictions are that the combined peak flow into Lower Benson Creek was on the order of 1080 cfs. The peak flow occurred around 10:40pm, slightly more than 4½ hours after the storm began.

- By midnight: the runoff volume into Lower Benson Creek was more than 280 acre-feet.
- By 6:00am (August 22nd): the runoff volume into Lower Benson Creek was more than 480 acre-feet.
- By noon (August 22nd): the runoff volume into Lower Benson Creek was about 540 acre-feet.

Ultimately, the runoff volume into Lower Benson Creek was more than 1170 acre-feet.

4. At State Highway SR-153, model predictions are that the peak flow in Benson Creek was on the order of 1220 cfs. The peak flow occurred around 11:05pm, slightly more than 5 hours after the storm began.

- By midnight: the runoff volume from the Benson Creek watershed was about 290 acre-feet.
- By 6:00am (August 22nd): the runoff volume from the watershed was almost 540 acre-feet.
- By noon (August 22nd): the runoff volume from the Benson Creek watershed was more than 600 acre-feet.

Ultimately, the runoff volume from the Benson Creek watershed at SR-153 was on the order of 1270 acre-feet.

Fortunately, as noted by Okanogan County Emergency Management, there were no fatalities, injuries or missing persons from this flooding.

<u>Comparisons to pre-fire conditions</u>. Two model runs were made to compare the post-fire results with pre-fire conditions. The first run considered the August 21st storm on the Benson Creek watershed in its pre-fire, unburned condition. For this scenario, model predictions are that:

- the peak flow out of Lower Finley Canyon would have been less than 60 cfs.
- the peak flow from Upper Benson Creek would have been about 90 cfs.
- the combined peak flow into Lower Benson Creek would have been slightly more than 140 cfs.
- the peak flow in Benson Creek at SR-153 would have been about 160 cfs.

In comparison, the estimated post-fire flows reported above are 7 to 8 times these estimated pre-fire flows for the August 21st storm.

The second run considered the runoff from a Design Step 2 dam safety storm on the Benson Creek watershed in its pre-fire, unburned condition. Design Step 2 has an annual exceedance probability of 0.001 (1/1000), equivalent to a recurrence interval of 1,000 years. All three storm scenarios were considered (short, intermediate and long duration), and the Intermediate duration storm was found to yield the highest runoff flows from the watershed. The Intermediate storm is 18 hours long, with 53% of the rainfall occurring within a 6-hour period and 17% occurring within a 1-hour period. Total storm precipitation depths, including snowmelt, were:

- 5.63 inches on the Upper Finley sub-basin
- 5.83 inches on the Lower Finley sub-basin
- 5.72 inches on the Upper Benson sub-basin
- 6.18 inches on the Lower Benson sub-basin.

For this scenario (Step 2 Intermediate storm), model predictions are that:
- the peak flow out of Lower Finley Canyon would be slightly more than 330 cfs.
- the peak flow from Upper Benson Creek would be almost 440 cfs.
- the combined peak flow into Lower Benson Creek would be almost 740 cfs.
- the peak flow in Benson Creek at SR-153 would be about 890 cfs.

In comparison, the estimated post-fire flows reported above for the Aug. 21st storm are all larger than these estimated pre-fire flows for a 1,000-year precipitation event.

<u>Comparison to rainfall volumes</u>. Estimated rainfall volumes for the August 21st storm are shown in the following table:

Rainfall volumes	Upper Finley	Lower Finley	Upper Benson	Lower Benson
Drainage area	10.3 sq.miles	8.0 sq.miles	15.6 sq.miles	4.1 sq.miles
Rainfall depth	0.86 inches	0.82 inches	1.03 inches	0.80 inches
Rainfall volume	473 ac-ft.	349 ac-ft.	854 ac-ft.	174 ac-ft.

August 21st rainfall depths and volumes.

For the Finley Canyon sub-basins, the total storm rainfall volume was more than 820 acre-feet. The ultimate runoff volume from Lower Finley Canyon of 570 acre-feet represents 69% of the storm rainfall on the Finley Canyon sub-basins.

For the Upper Benson Creek watershed, the total storm rainfall volume was more than 850 acre-feet. The ultimate runoff volume of 600 acre-feet represents 71% of the storm rainfall on the Upper Benson watershed.

For combined flows into Lower Benson Creek, the total storm rainfall volume was more than 1670 acre-feet. The ultimate runoff volume into Lower Benson Creek of 1170 acre-feet represents 70% of the storm rainfall on the combined Upper Benson and Finley Canyon sub-basins.

For Benson Creek at State Highway SR-153, the total storm rainfall volume was 1850 acre-feet. The ultimate runoff volume from the Benson Creek watershed of 1270 acre-feet represents 69% of the storm rainfall on the entire Benson Creek watershed.

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Future Activities

Dam Safety's primary interest in this incident is to understand what happened at the five Wenner Lakes dams, especially at the Chalfa, Rabel and Hawkins Dams. Why were some dams and spillways able to survive the storm while others did not? What lessons can be learned for these and other dams located in areas vulnerable to forest fires?

The events at the five Wenner Lakes dams occurred within the context of the events within the larger Finley Canyon and Benson Creek watersheds. Now that we have a hydrology model for the overall watershed, we can begin to conduct more detailed examinations of what happened at each of the dams. The findings from these analyses will be the subject of a future report.

At this time, we do not expect to include hill slope debris flows (mudslides) in future analyses. The spillway erosion that occurred at the Hawkins Dam obviously needs some examination, but beyond that, 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 our technical expertise. If someone else is able to investigate or analyze the hill slope erosion and debris flow processes in the Benson Creek basin, we would be interested in a professional dialogue with them.

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Dam Safety Incident Report

Computerized Rainfall-Runoff Model for Benson Creek

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

January 8, 2015
(date signed)

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Appendices

Appendix A – Maps

Appendix B – Supporting calculations

Appendix C – Graphical results

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Computerized Rainfall-Runoff Model for Benson Creek

Appendix A

Maps

Project location

Topography, drainage areas and hydraulic features

Project area geology

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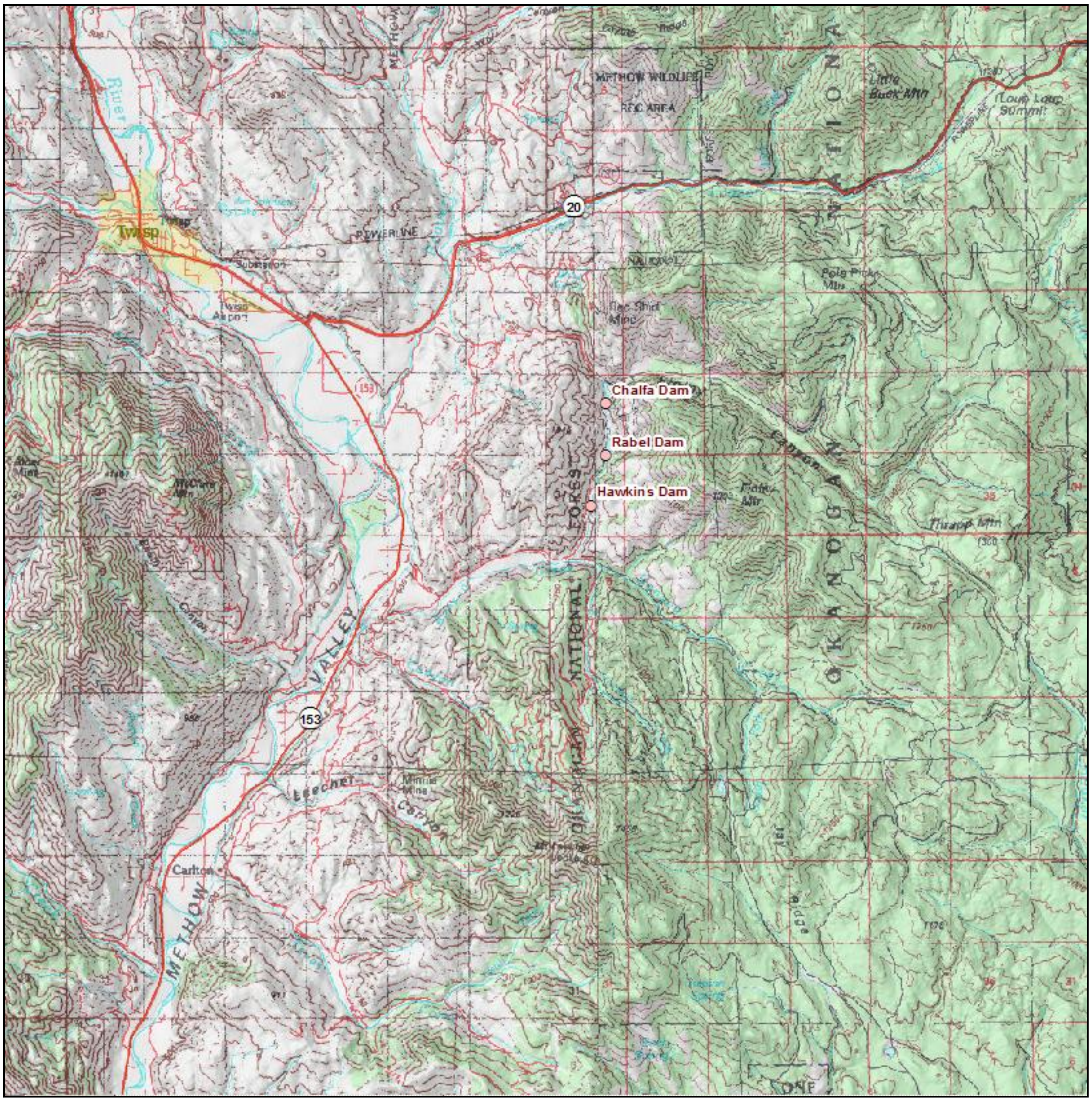
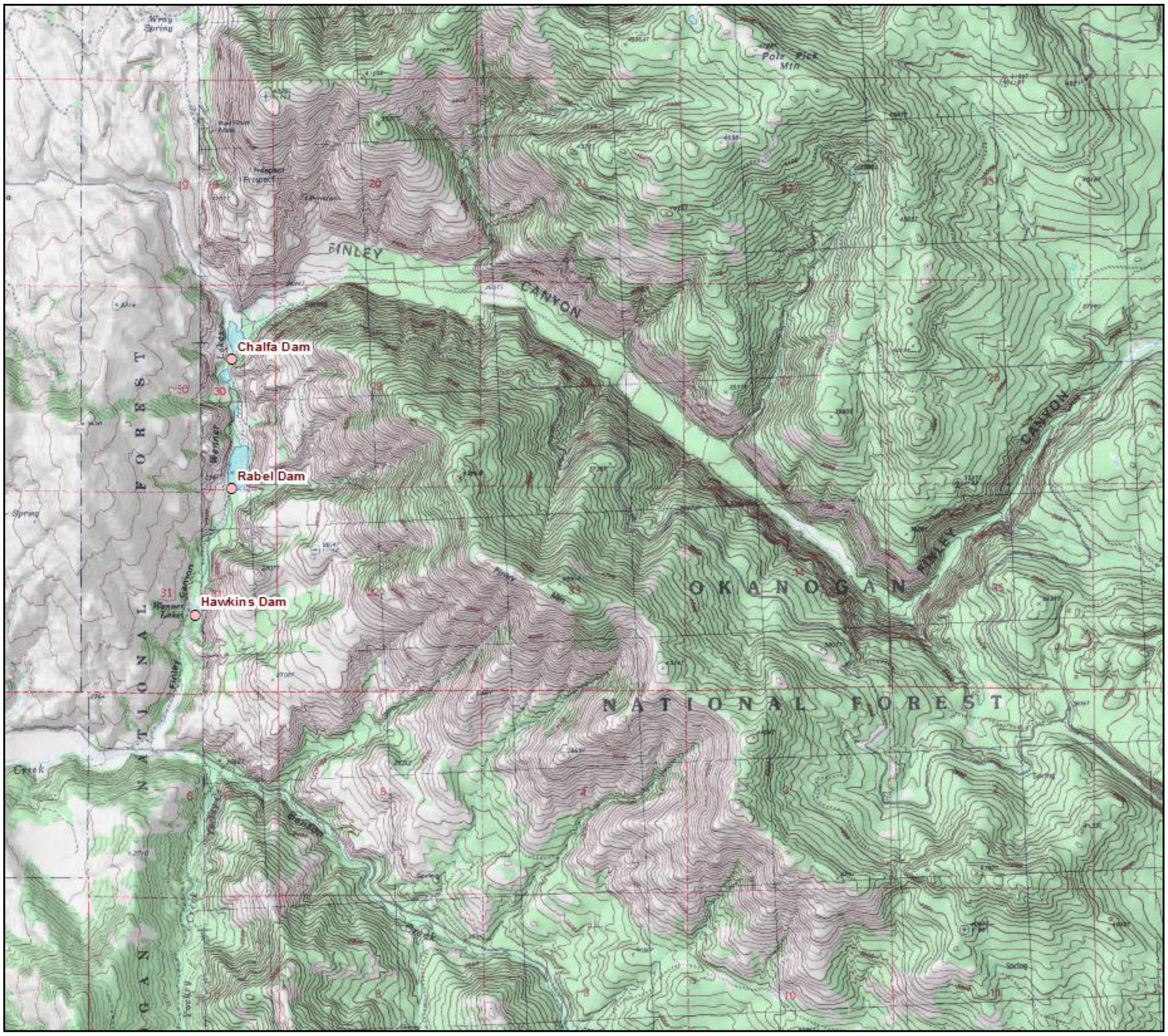
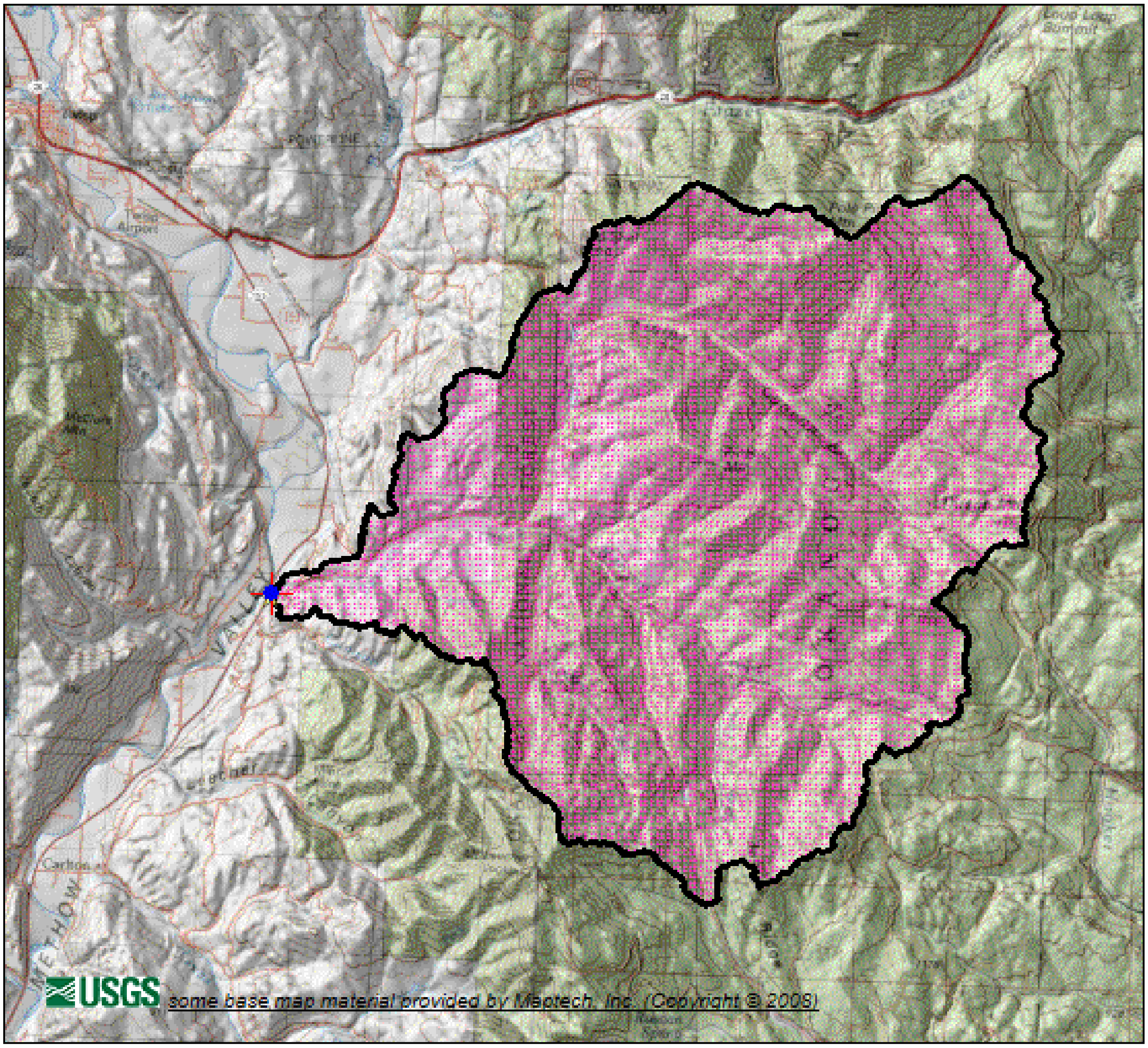


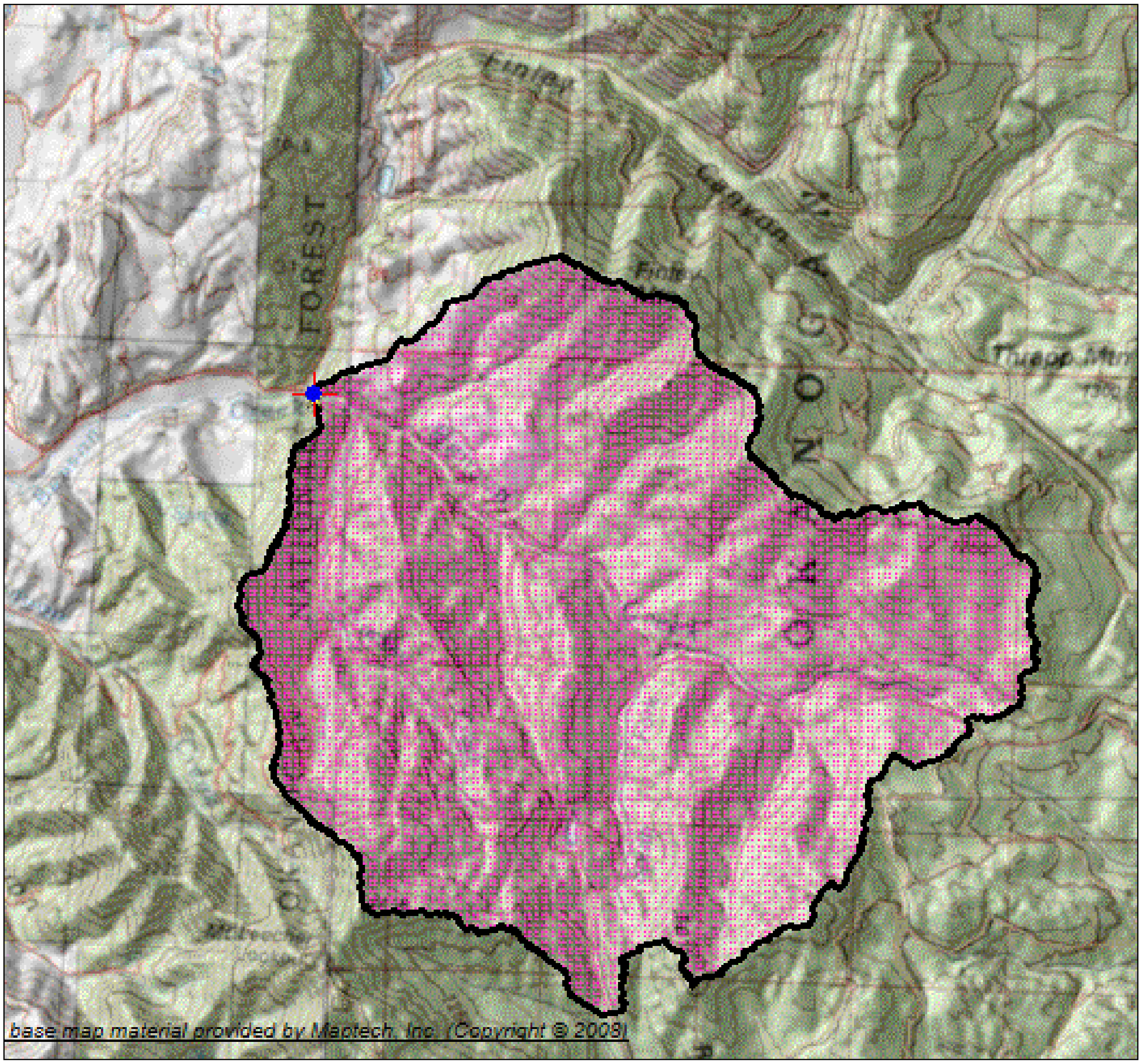
1. Vicinity map for Benson Creek watershed near Twisp in north central Washington.



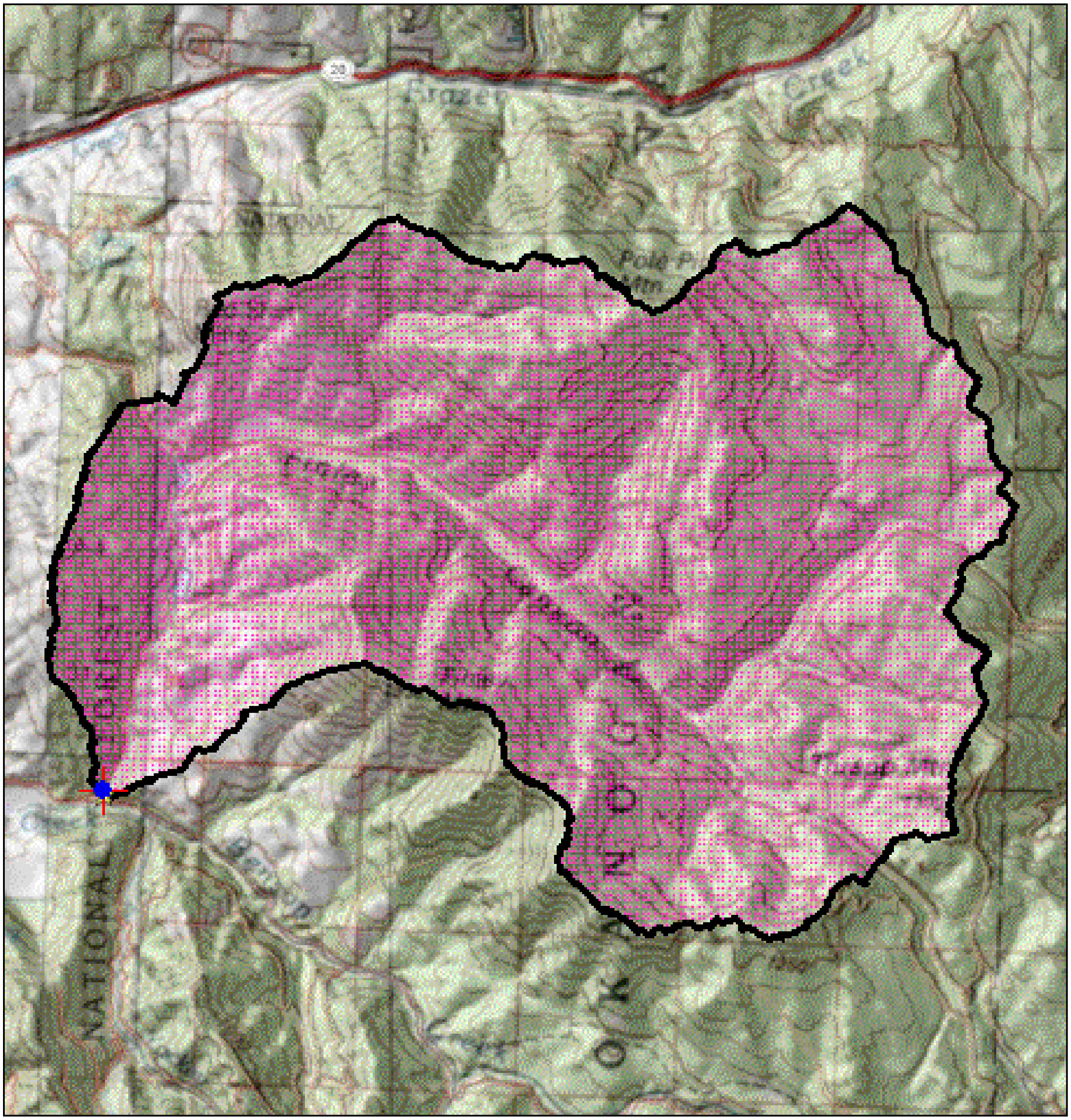
2. Dam locations in Benson Creek Finley Canyon sub-basin.



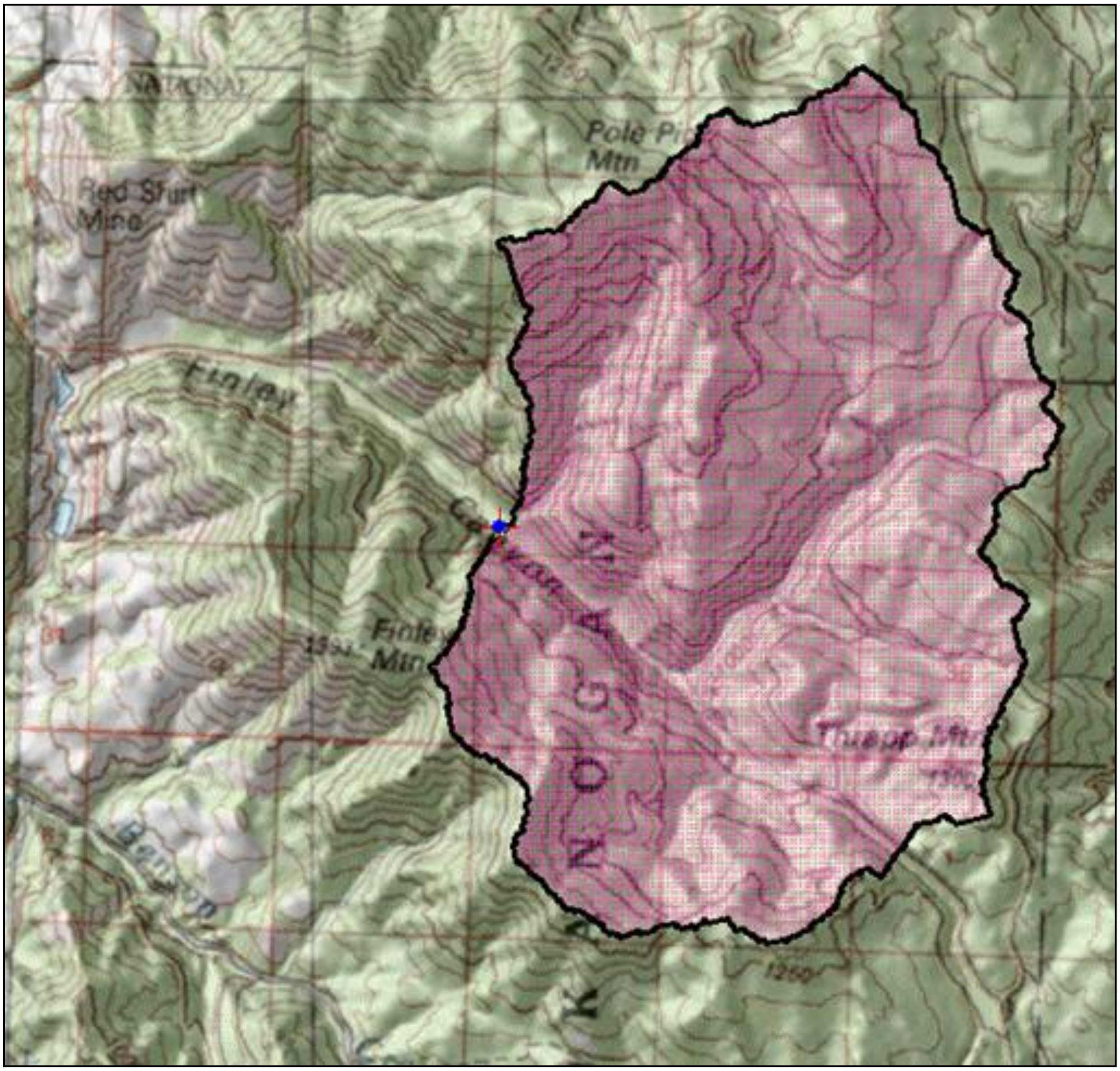
3. Benson Creek watershed near Twisp. Drainage area 38 sq.miles.



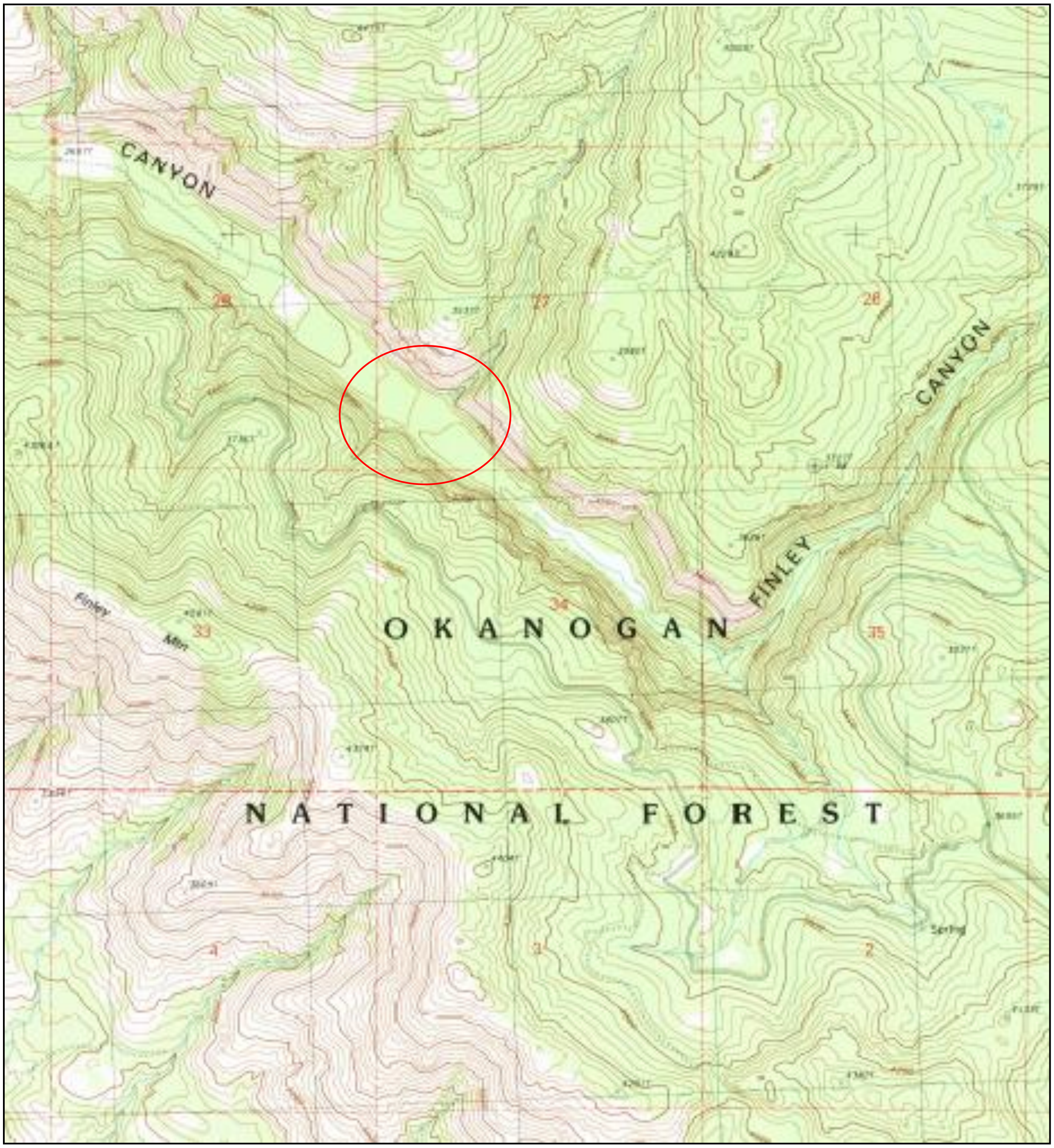
4. Upper Benson Creek sub-basin. Drainage area 15.6 sq.miles.



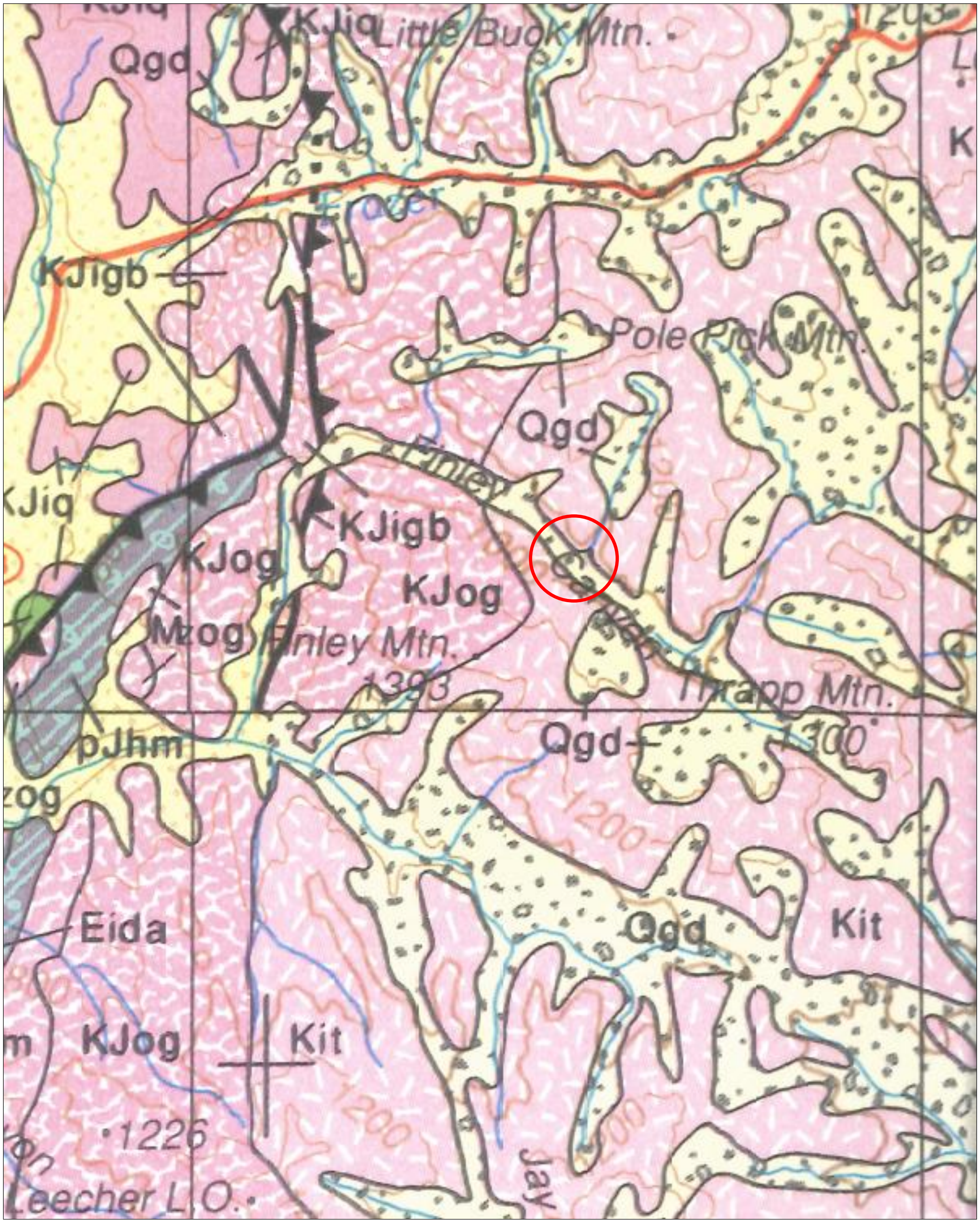
5. Benson Creek Finley Canyon sub-basins. Drainage area 18.3 sq.miles.



6. Upper Finley Canyon above cross-canyon berm. Drainage area 10.3 sq.miles.



7. Upper Finley Canyon, cross-canyon berm. Upstream drainage area 10.3 sq.miles. Map contour interval is 40 feet.



8. Geology of Finley Canyon and Upper Benson Creek. Approx location of cross-canyon berm. Qdg = glacial drift. Ref: Stoffel *et al*, 1991.

Computerized Rainfall-Runoff Model for Benson Creek

Appendix B

Supporting calculations

Watershed hydrology

Channel and reservoir parameters

Results from computerized hydrologic analysis

Selected input data

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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 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
Results from computerized hydrologic analysis	
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

Selected input data (on following pages)

Network for hydrologic model

Upper Finley stage-discharge curve

Input parameters for each sub-basin

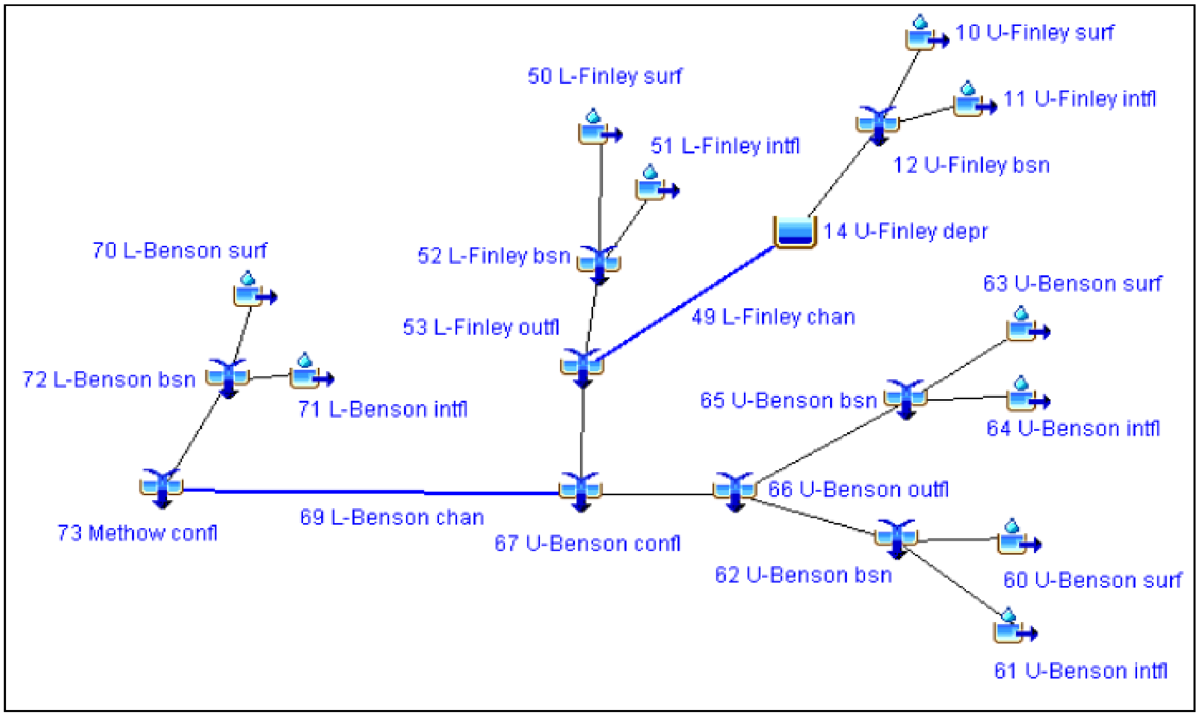
August 21st storm hyetographs

Description of sub-basins, confluence points, routing reaches, and detention facilities (ponds or reservoirs) used in hydrology computer program --

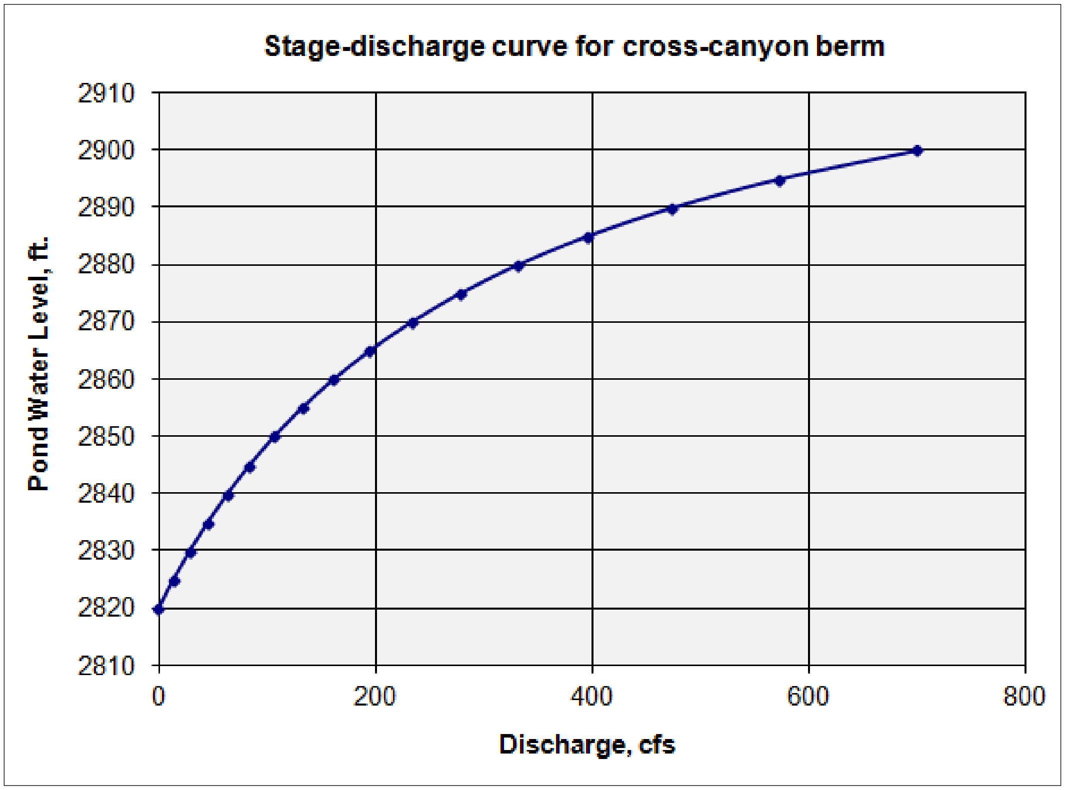
10 U-Finley surf	Direct surface runoff from	Upper Finley watershed
11 U-Finley intfl	Interflow runoff from	Upper Finley watershed
12 U-Finley bsn	Combined/total runoff from	Upper Finley watershed
14 U-Finley depr	Upper Finley depression (temporary storm pond)	
49 L-Finley chan	Channel for flows across	Lower Finley watershed
50 L-Finley surf	Direct surface runoff from	Lower Finley watershed
51 L-Finley intfl	Interflow runoff from	Lower Finley watershed
52 L-Finley bsn	Combined/total runoff from	Lower Finley watershed
53 L-Finley outfl	Combined/total runoff below	Lower Finley watershed
60 U-Benson surf	Direct surface runoff from	Upper Benson unburned area
61 U-Benson intfl	Interflow runoff from	Upper Benson unburned area
62 U-Benson bsn	Combined/total runoff from	Upper Benson unburned area
63 U-Benson surf	Direct surface runoff from	Upper Benson - burned area
64 U-Benson intfl	Interflow runoff from	Upper Benson - burned area
65 U-Benson bsn	Combined/total runoff from	Upper Benson - burned area
66 U-Benson outfl	Combined/total runoff from	Upper Benson watershed
67 U-Benson confl	Combined/total runoff into	Lower Benson sub-basin
69 L-Benson chan	Channel for flows across	Lower Benson sub-basin
70 L-Benson surf	Direct surface runoff from	Lower Benson sub-basin
71 L-Benson intfl	Interflow runoff from	Lower Benson sub-basin
72 L-Benson bsn	Combined/total runoff from	Lower Benson sub-basin
73 Methow confl	Combined/total runoff into	Methow River

Network for hydrologic model.

(See also diagram on next page.)



Network for hydrologic model.



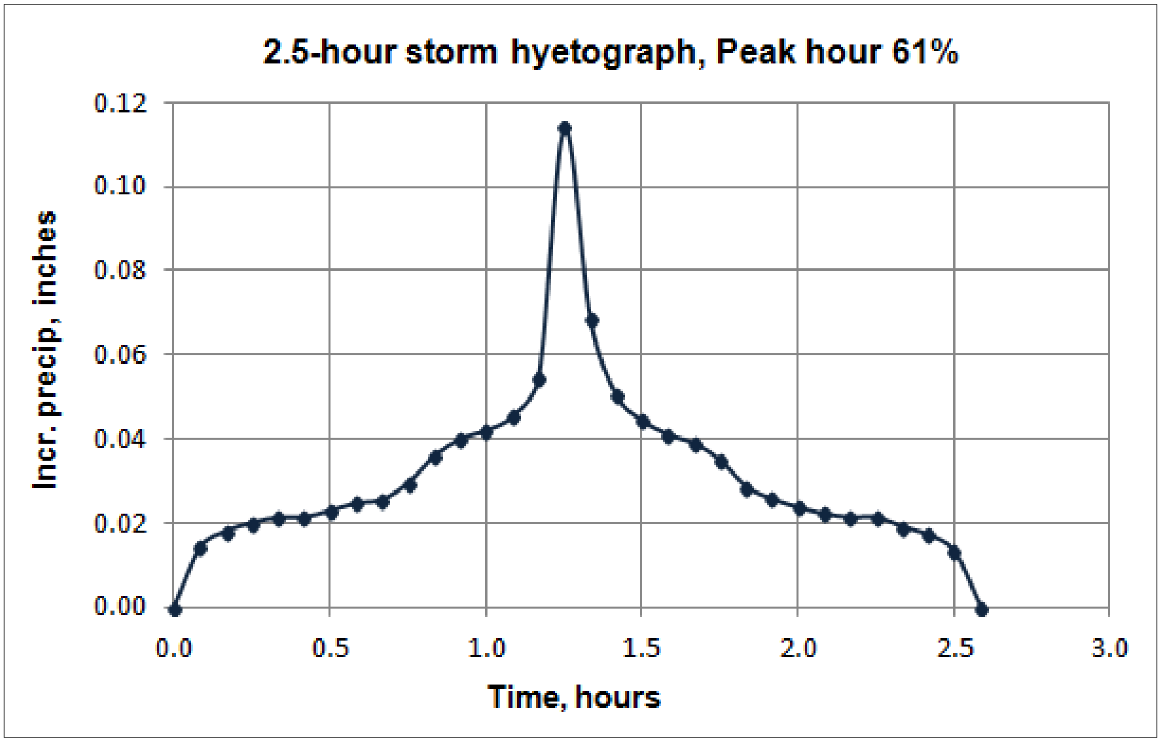
Upper Finley Canyon stage-discharge curve.

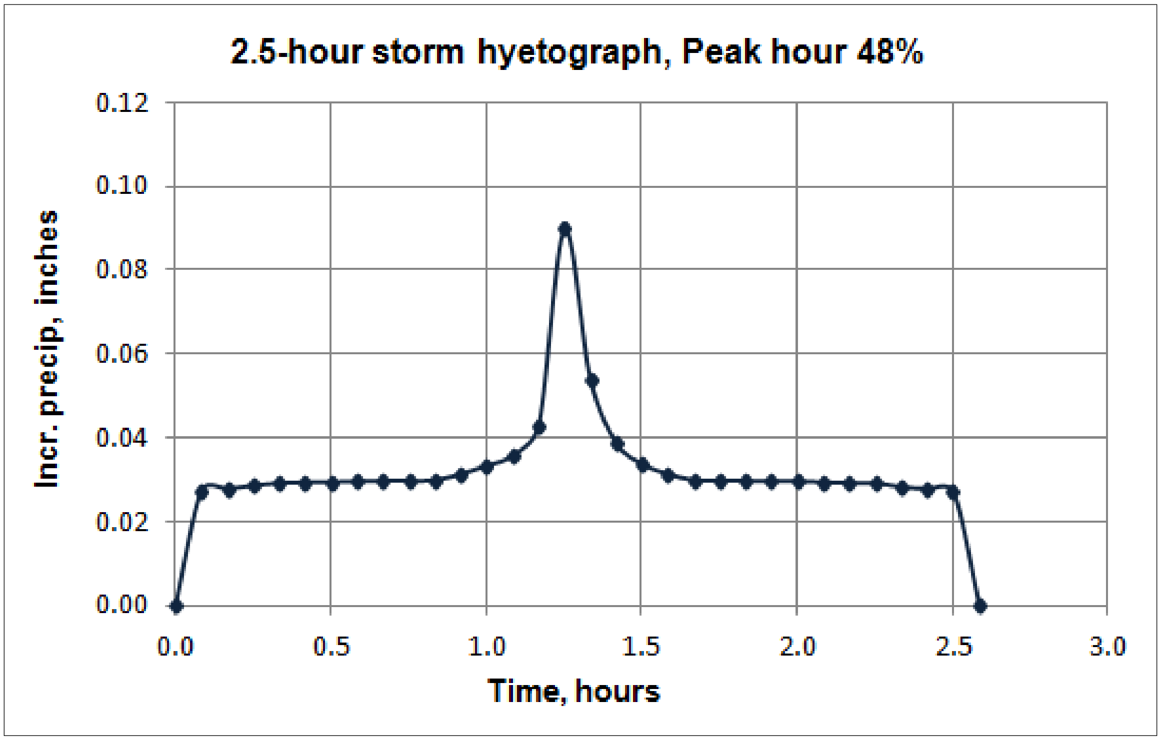
HEC-HMS model MDW, 12/08/14

Input parameters

Sub-basin	Area sq.miles		Initial loss, in.	Loss in/hr.	Impv %	USBR/Snyder U.H. lag time hr.	USBR/Snyder U.H. peak coeff	SCS U.H. lag time min.
Pre-fire								
10 U-Finley surf	10.3		0	1.925	0	8.7	0.678	
11 U-Finley intfl	10.3		0	0.151	0			2820
50 L-Finley surf	8.0		0	1.949	0	8.8	0.678	
51 L-Finley intfl	8.0		0	0.186	0			2320
60 U-Benson surf	15.6		0	1.849	0	8.9	0.678	
61 U-Benson intfl	15.6		0	0.124	0			3635
70 L-Benson surf	4.1		0	1.776	0	7.1	0.678	
71 L-Benson intfl	4.1		0	0.153	0			2380
49 L-Finley chan	60	min.	channel routing lag time					
69 L-Benson chan	30	min.	channel routing lag time					
Post-fire						(calibrated)		
10 U-Finley surf	10.3		0	0.066	0	2.26	0.678	
11 U-Finley intfl	10.3		0	0.151	0			2820
50 L-Finley surf	8.0		0	0.180	0	3.28	0.678	
51 L-Finley intfl	8.0		0	0.186	0			2320
60 U-Benson surf	6.1		0	1.849	0	8.9	0.678	
61 U-Benson intfl	6.1		0	0.124	0			3635
63 U-Benson surf	9.5		0	0.173	0	3.79	0.678	
64 U-Benson intfl	9.5		0	0.124	0			3635
70 L-Benson surf	4.1		0	0.203	0	3.62	0.678	
71 L-Benson intfl	4.1		0	0.153	0			2380
49 L-Finley chan	40	min.	channel routing lag time					
69 L-Benson chan	25	min.	channel routing lag time					

Input parameters for each sub-basin





Estimated time-distributions for August 21st storm

Computerized Rainfall-Runoff Model for Benson Creek

Appendix C

Graphical results for August 21st storm

Table output from model

Runoff hydrographs – 18 hours

Runoff hydrographs – 9 days

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HEC-HMS model MDW, 12/09/14

Model output

Storm: Aug 21st

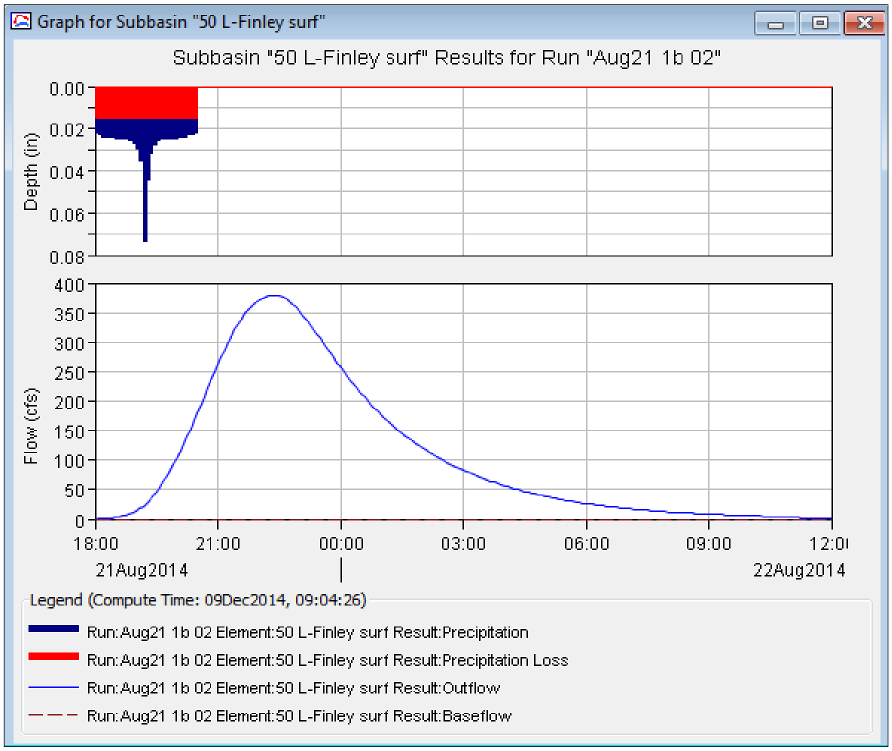
Event: Post-fire

Gauge	Precip
Aug21-LB	0.80
Aug21-LB-intflo	0.51
Aug21-LF	0.82
Aug21-LF-intflo	0.45
Aug21-UB	1.03
Aug21-UB-intflo-post	0.43
Aug21-UB-intflo-pre	1.03
Aug21-UF	0.86
Aug21-UF-intflo	0.17

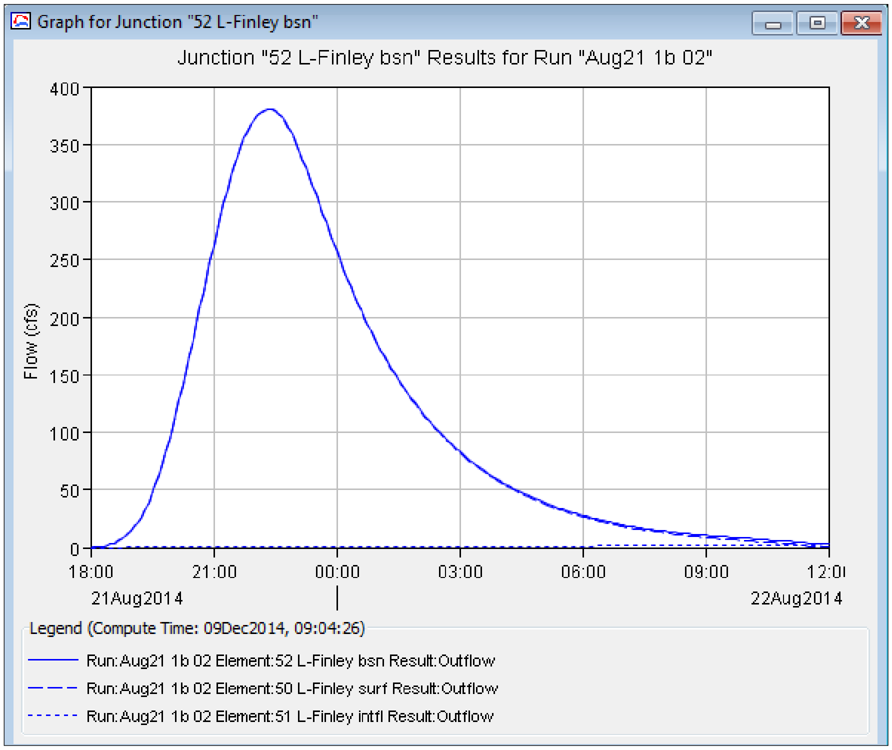
Basin	Precip Balance
U-Finley	0.000
L-Finley	0.000
U-Benson-post	0.000
U-Benson-pre	0.000
L-Benson	0.000

Element	Area sq.miles	Peak Q, cfs	Time of peak	Runoff vol. in.	Runoff ac-ft.	% of precip
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
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	
49 L-Finley chan	20.6	66.1	22Aug2014, 03:55	0.35	381.6	
50 L-Finley surf	8.0	379.9	21Aug2014, 22:20	0.37	157.9	45.1
51 L-Finley intfl	8.0	7.1	23Aug2014, 09:55	0.07	30.5	8.5
52 L-Finley bsn	16.0	380.1	21Aug2014, 22:20	0.22	188.4	53.7
53 L-Finley outfl	36.6	**421.9**	21Aug2014, 22:30	0.29	**570.0**	
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
63 U-Benson surf	9.5	663.0	21Aug2014, 22:50	0.60	303.2	58.3
64 U-Benson intfl	9.5	10.3	24Aug2014, 07:50	0.13	68.2	12.6
65 U-Benson bsn	19.0	663.2	21Aug2014, 22:50	0.37	371.4	70.9
66 U-Benson outfl	31.2	**663.8**	21Aug2014, 22:50	0.36	**603.0**	
67 U-Benson confl	67.8	**1080.5**	21Aug2014, 22:40	0.32	**1173.0**	
69 L-Benson chan	67.8	1080.5	21Aug2014, 23:05	0.32	1173.0	
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	**1219.9**	21Aug2014, 23:05	0.31	**1270.2**	

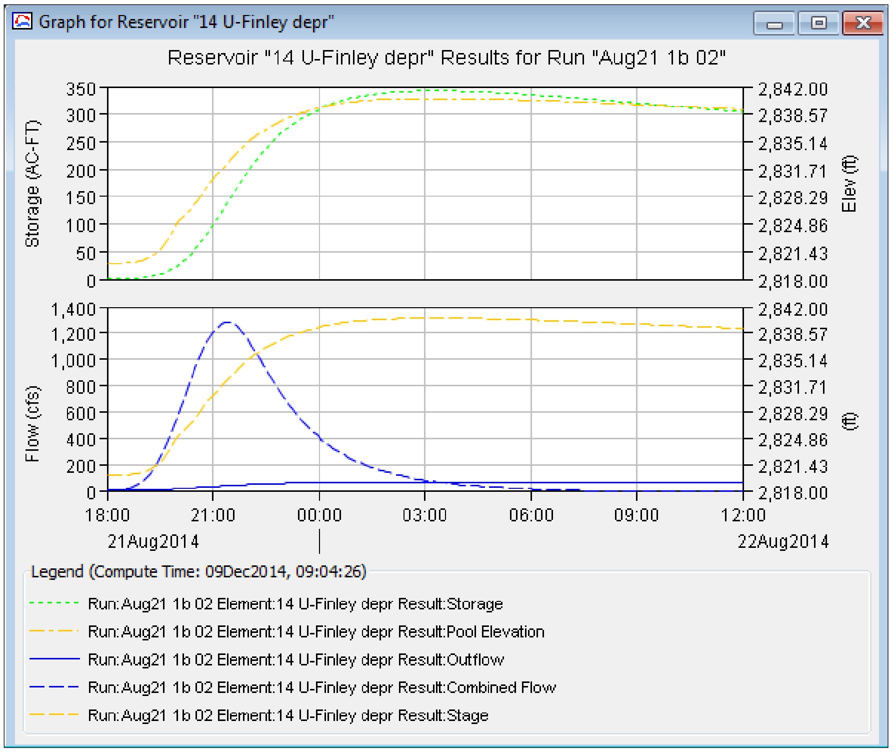
1. Table output from HEC-HMS model, August 21st storm



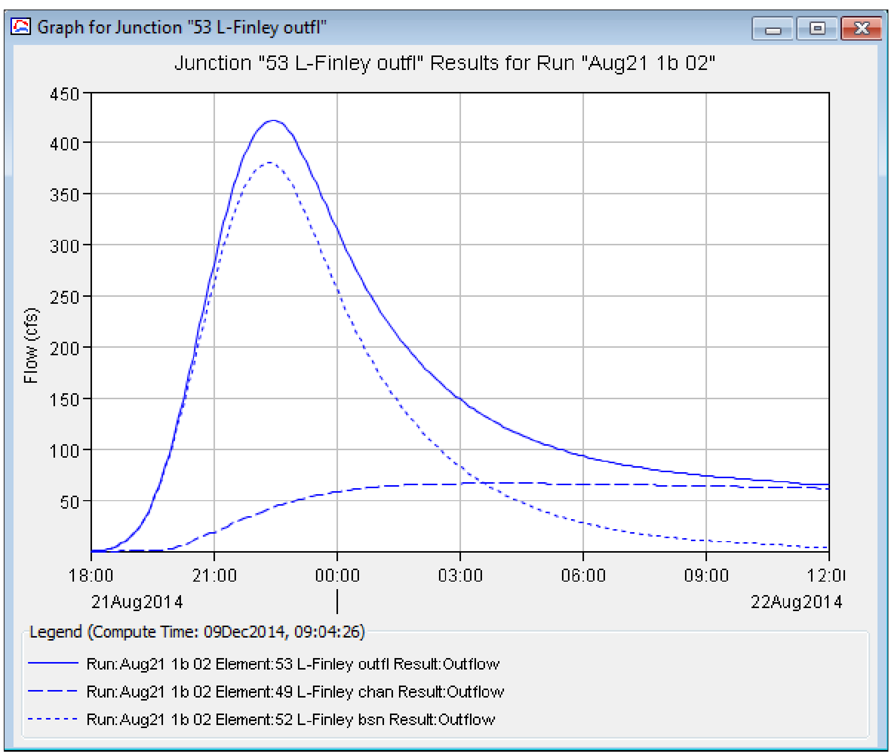
2. Surface runoff from Lower Finley sub-basin



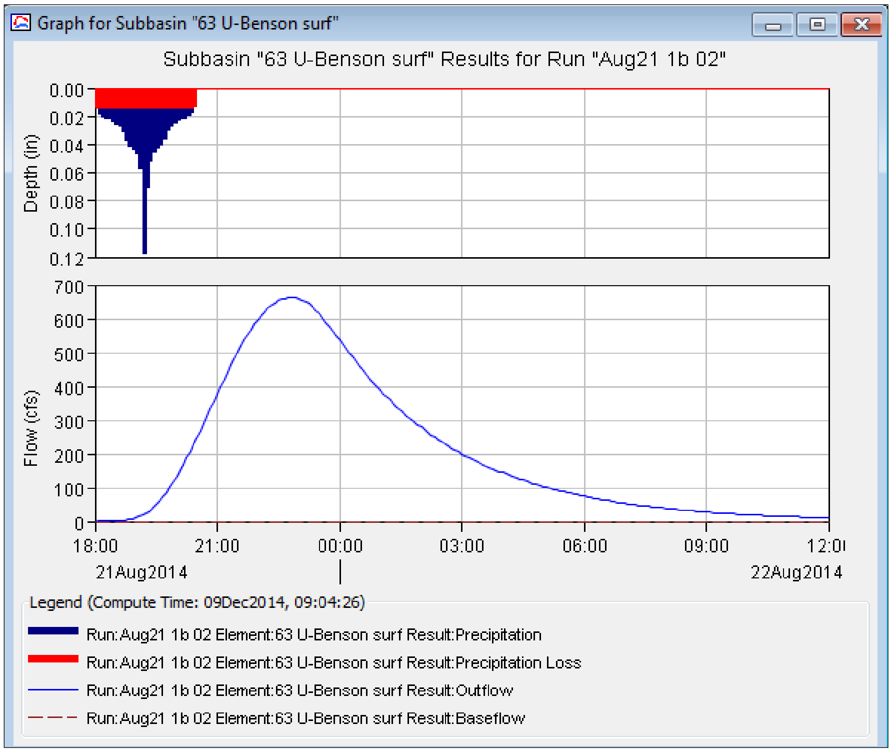
3. Runoff from Lower Finley sub-basin



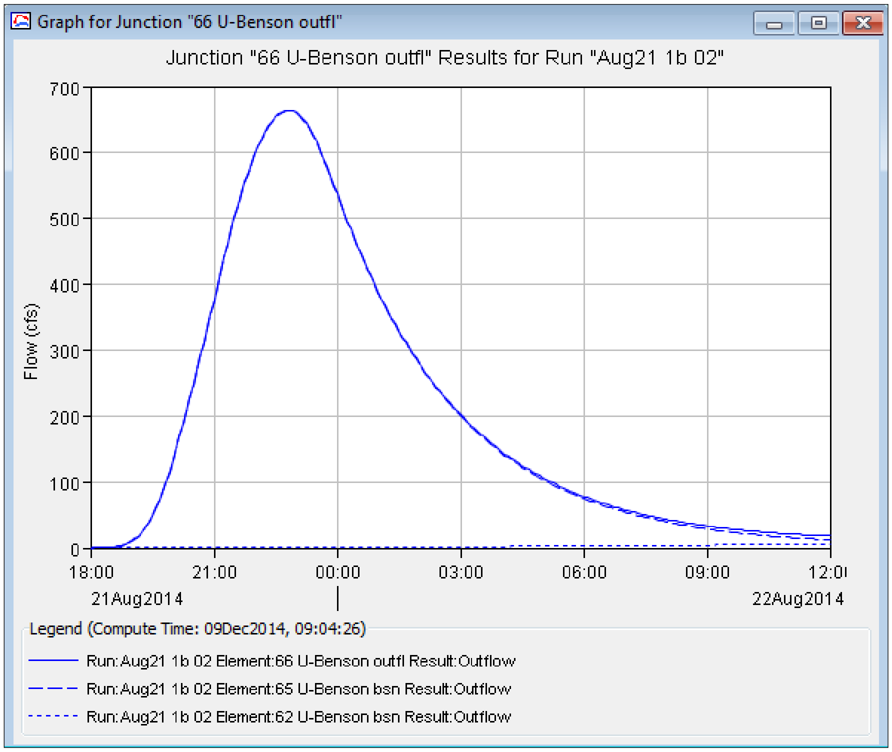
4. Inflow to and outflow from Upper Finley Canyon



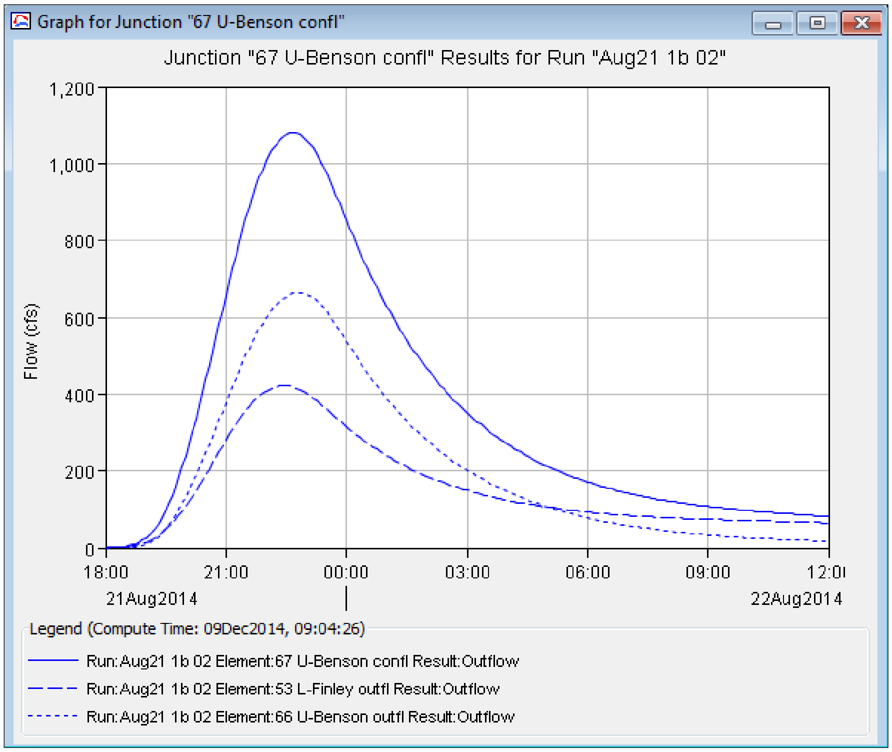
5. Combined outflow from Finley Canyon to Lower Benson Creek



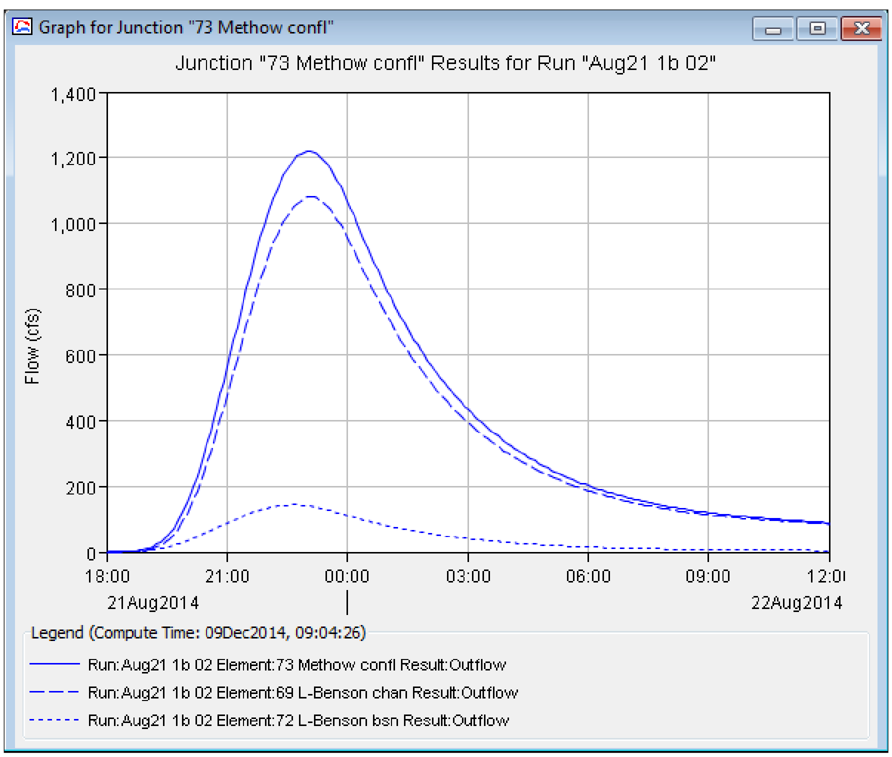
6. Surface runoff from Upper Benson sub-basin



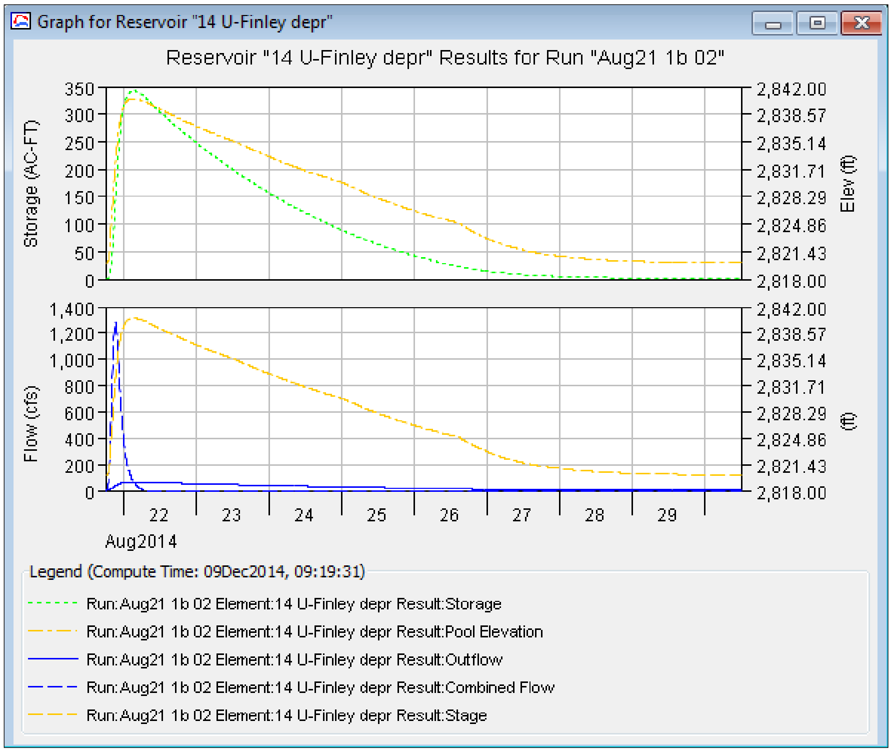
7. Runoff from Upper Benson sub-basin



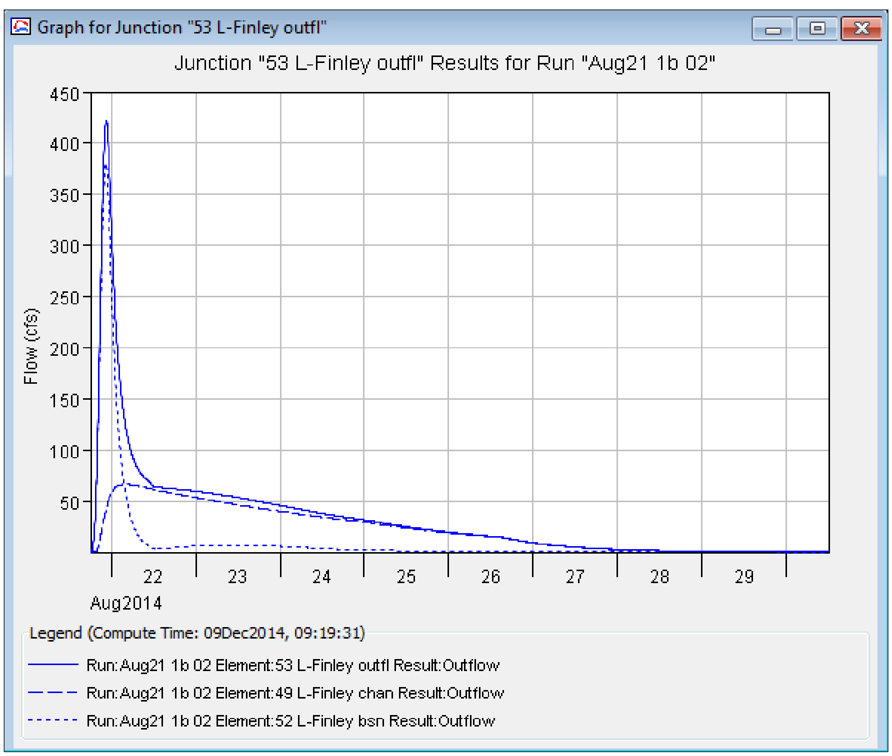
8. Combined flow into Lower Benson Creek



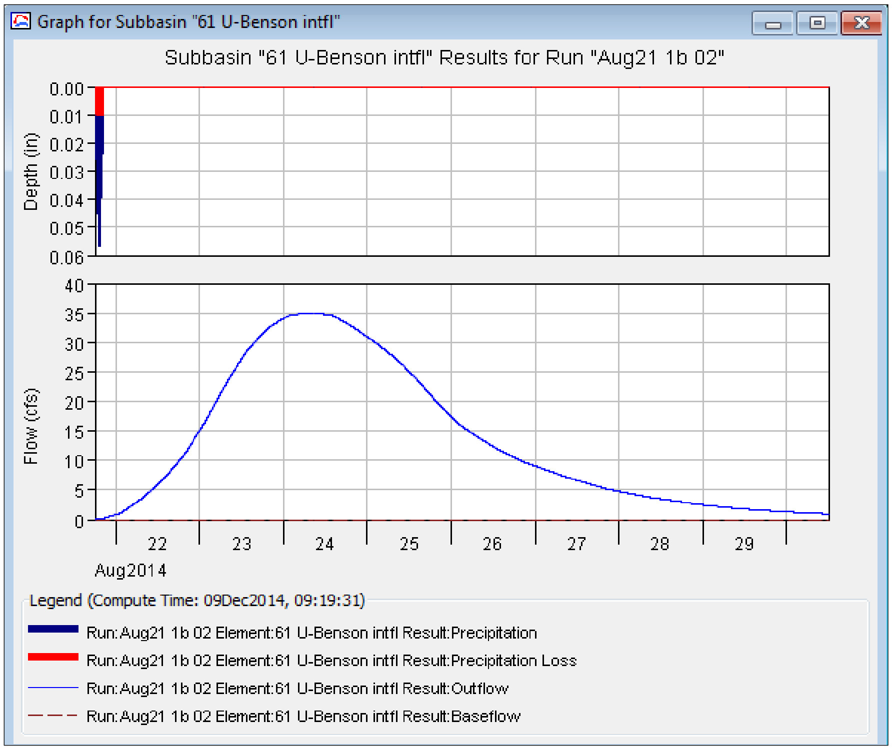
9. Runoff flow in Benson Creek at SR-153



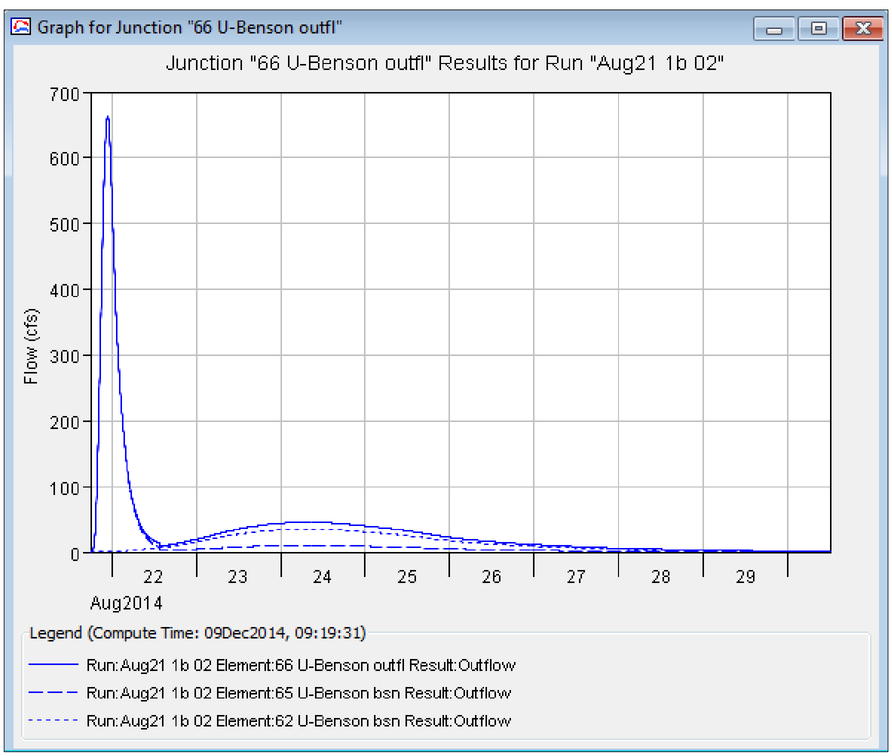
10. 9-day outflow from Upper Finley Canyon



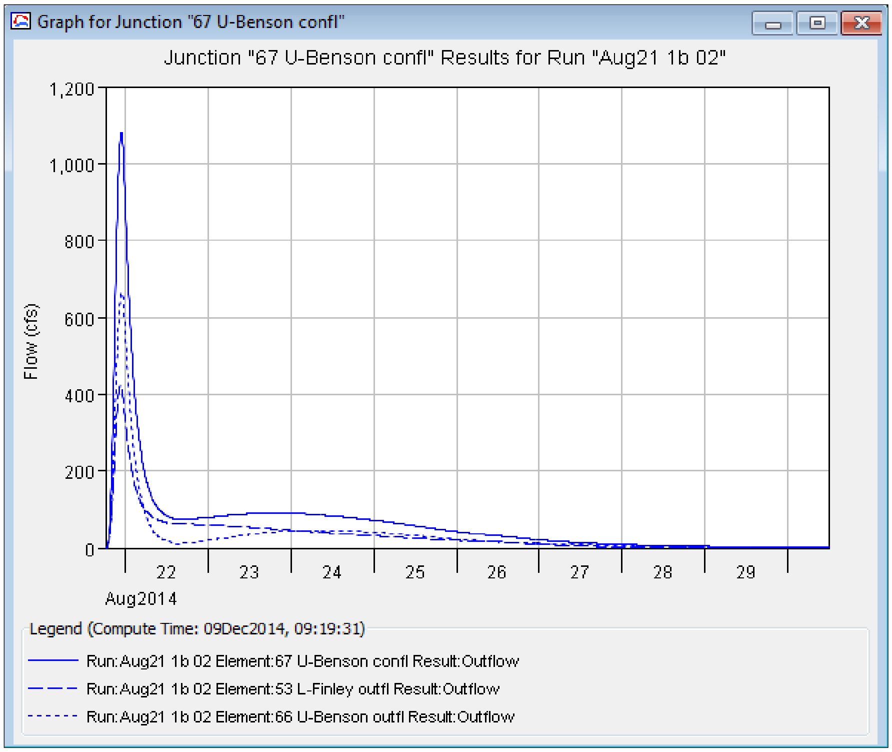
11. 9-day outflow from Finley Canyon to Lower Benson Creek



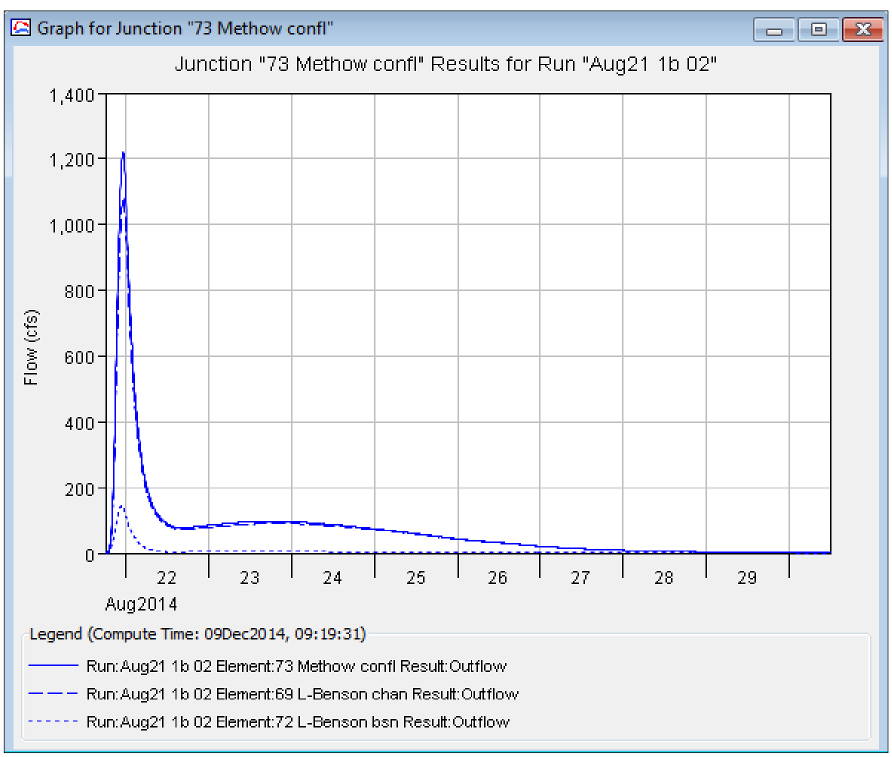
12. Interflow runoff from Upper Benson sub-basin



13. 9-day runoff from Upper Benson sub-basin



14. 9-day flow into Lower Benson Creek



15. 9-day flow in Benson Creek at SR-153