BOXELDER B-2, B-3 and B-4:
Probable Maximum Flood Analyses

Larimer County, Colorado
August 2010

watershed

Boxelder B-2 embankment

Wellington

USDA Natural Resources Conservation Service
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U.S. DEPARTMENT OF AGRICULTURE
NATURAL RESOURCES CONSERVATION SERVICE
COLORADO STATE OFFICE

Lakewood, Colorado

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BOXELDER B-2, B-3 and B-4: Probable Maximum Flood Analyses

Location: Larimer County, Colorado near Wellington on Indian, Coal and Boxelder Creeks.

Summary: Rainfall-runoff analyses were performed of the probable maximum precipitation (PMP) event in the Boxelder B-4, -3 and -2 watersheds. In the event of a Probable Maximum Flood (PMF), the Boxelder B-4 structure will be substantially overtopped, by 4.0 and 2.3 feet for the 6- and 24-hour events, respectively. The existing spillways will convey about 45 percent of the PMP. The B-3 embankment will be overtopped, by 6.0 and 5.1 feet for the 6- and 24-hour events. The existing spillways will convey about 37 percent of the PMP. The B-2 embankment will be overtopped, by 8.7 and 6.1 feet for the 6- and 24-hour events. This model assumes that the B-5 and B-6 structures breach. The existing spillways will convey about 37 percent of the PMP.

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Helping People Help the Land

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INTRODUCTION

This report details the methods and results of a Probable Maximum Precipitation (PMP) analyses for the Boxelder flood-control reservoirs of Larimer County, Colorado. The analysis was performed to evaluate the structures' configuration given their upgraded hazard classification. The analyses consists of hydrologic models that simulate a PMP event for the B-2, -3, -4, -5 and -6 structure watersheds, producing runoff from sub-basins within the watersheds and routing the storm flow through channels and reservoirs to the watershed outlets. The watersheds for the five structures are illustrated in Figure 1.

The Boxelder B-4 structure controls the flow from a 13.7 square mile watershed. This watershed (Figure 1), with a range in elevation from 5380 to 5910 feet, has average annual precipitation of 15 inches. The Boxelder B-3 structure controls the flow from a

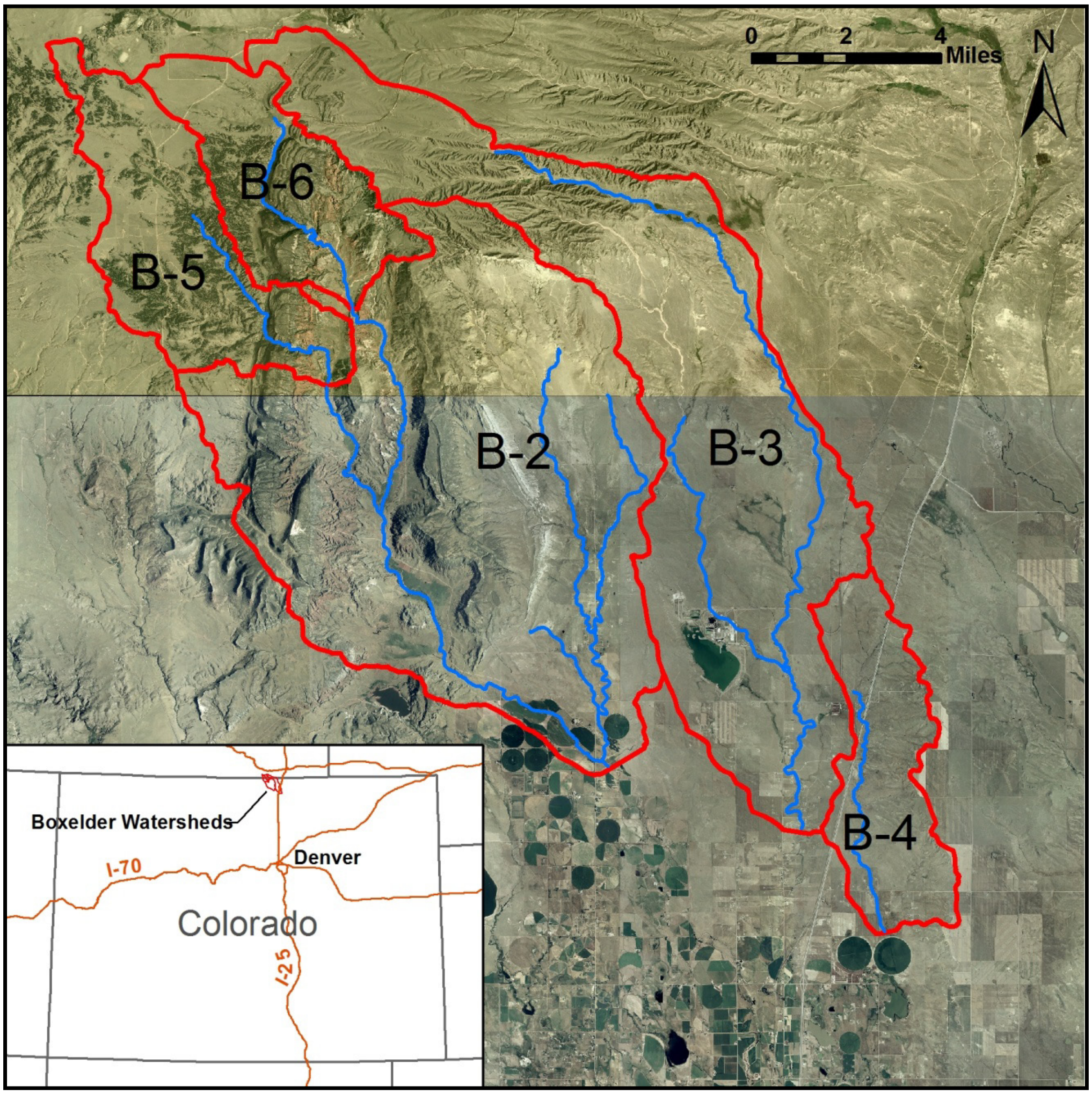

Figure 1: Modeled watersheds.

61.0 square mile watershed. This watershed, with a range in elevation from 7960 to 5460 feet, has a range of average annual precipitation from 15 to 17 inches. The Boxelder B-2 structure controls the flow from a total of 108 square miles. This watershed, with a range in elevation from 7520 to 5520 feet, also has a range of average annual precipitation from 15 to 17 inches. The B-2 structure is a dams-in-series situation, with additional flood control benefits from the B-5 and B-6 structures, which have watersheds of 19.0 and 15.0 square miles, respectively.

Vegetation within the watersheds range from mixed-grass prairie at lower elevations, shrublands dominated by mountain mahogany at mid elevations, and ponderosa with mixed-grass montane at higher elevations. The soils of the watersheds vary in their infiltration capacities, with D-level hydrologic soil groups being common at higher elevations and on steeper-gradient terrain, and B- and C-level soil groups being prevalent at lower elevations and lesser-gradient terrain. General watershed conditions are illustrated in Figures 2 and 3.

Figure 2: Upper B-2 watershed (within the B-5 and B-6 watersheds).

Figure 3: Lower B-3 watershed.

PROBABLE MAXIMUM PRECIPITATION

The National Oceanic and Atmospheric Administration (NOAA) has responsibility for providing Probable Maximum Precipitation (PMP) estimates. A PMP is the theoretical greatest depth of precipitation that is physically possible for a given duration and areal extent (Hansen et. al. 1988). HMR-55A, Probable Maximum Precipitation Estimates - United States Between the Continental Divide and the 103rd Meridian (Hansen et. al. 1988), is the applicable publication detailing the recommended PMP estimate for the Boxelder watersheds.

In the HMR-55A study, as well as other PMP studies, two storm types are assessed: the short-duration local storm (intense, small area, short duration) and longer, more general storms. HMR-55A assigns PMP values for local storms, a storm restricted in time and area to less that 500 mi^2 and less than or equal to six hours in length. General storms, that is, a storm event which produces precipitation over larger areas and duration of longer than six hours and is associated with a major synoptic weather feature (Hansen et. al. 1988), provide PMP values for events longer than 6 hours. Due to this local/intense versus longer/generalized differentiation in this PMP study, two storm lengths are used in this analysis: a 6 hour and 24 hour storm. This is also needed to satisfy NRCS TR-60 criteria (NRCS 2005a).

As extracted from HMR-55A (Figures 4 and 5), the generalized PMP for a 10-square mile watershed area varies a bit, due to closely-spaced isohyets in this area. For the 6-hour, 10 mi^2 event, the PMP is 24.0 inches in the B-4 watershed, 23.5 inches in the lower B-3 and B-2 watersheds, and 23.0 inches in the upper B-2 and B-3 watersheds, as well as the B-5 and B-6 watersheds. For the 24-hour, 10 mi^2 event, the PMP is 31.0 inches in the B-4 watershed and the lower B-3 and B-2 watersheds, and 30.0 inches in the upper B-2 and B-3 watersheds, as well as the B-5 and B-6 watersheds. The precipitation depths used to model each catchment within the five reservoir watersheds are provided in Table 1.

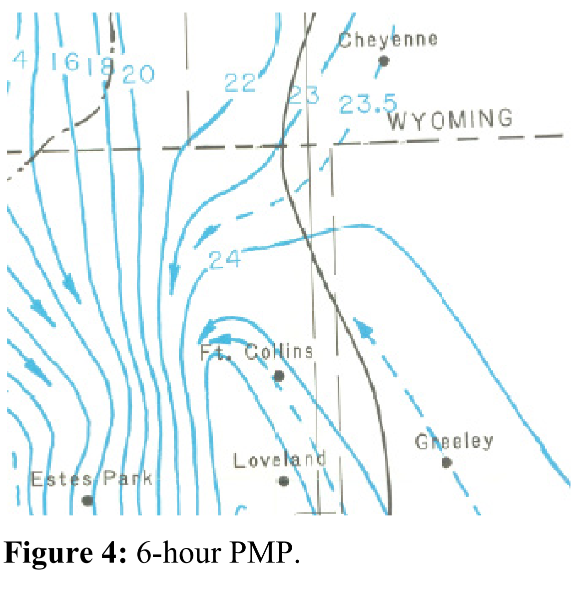

Figure 4: 6-hour PMP.

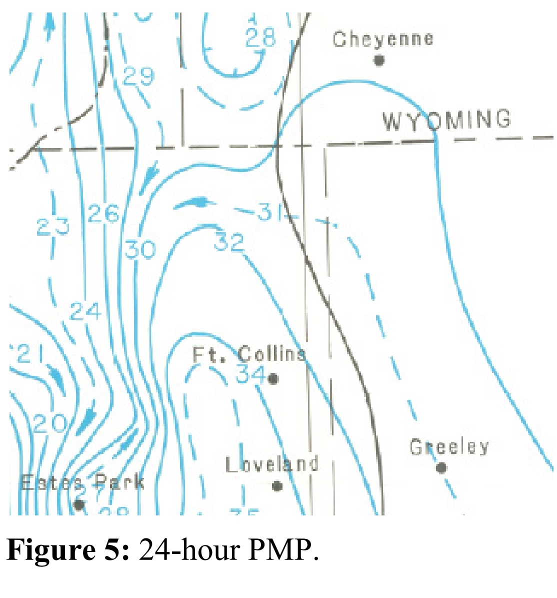

Figure 5: 24-hour PMP.

Table 1: Precipitation depth for each watershed and catchment, 6- and 24-hour PMP. Depths are raw, not aerially corrected values.

		Catchment Assignments				
		B-2	B-3	B-4	B-5	B-6
6-hr PMP:	24.0	9, 21, 23, 24, 25	13, 14, 15, 16, 17	1, 2, 3, 4		
(inches)	23.5	2, 6, 7, 8, 14, 15, 16, 18, 19, 20, 22	7, 8, 9, 12			
	23.0	1, 3, 4, 5, 10, 11, 12, 13, 17	3, 4, 5, 6, 10, 11		4, 5	4, 5, 6, 7, 8
	22.0		1, 2		1, 2, 3	1, 2, 3
		Catchment Assignments				
		B-2	B-3	B-4	B-5	B-6
24-hr PMP:	31.0	7, 8, 9, 16, 20, 21, 22, 23, 24, 25	7, 8, 9, 12, 13, 14, 15, 16, 17	1, 2, 3, 4		
(inches)	30.0	1, 2, 3, 4, 5, 6, 13, 14, 15, 18, 19	5, 6, 10, 11		2, 3, 4, 5	6, 8
	29.0	10, 11, 12, 17	1, 2, 3, 4		1	1, 2, 3, 4, 5, 7

The 10 mi^2 events were then adjusted for the various watershed areas, using the method presented in Hansen et. al. 1988 (Figure 11.4). These watersheds fall within subregion C, the South Platte River basin. For the 6-hour storm, reduction factors were 77, 83.5 and 98 percent, for B-2, B-3 and B-4 watersheds, respectively. For the 24-hour storm, reduction factors were 79, 84.5 and 98 percent, for B-2, B-3 and B-4 watersheds, respectively.

For both the 6- and 24-hour storms, the dimensionless design distribution provided in Figure 2-4 of TR-60 (NRCS 2005) was used to define the temporal distribution of the storms.

HYDROLOGIC MODELING

Hydrologic modeling was performed using the program HEC-HMS (version 3.3), a model developed by the U.S. Army Corps of Engineers' Hydrologic Engineering Center. The NRCS curve number (CN) technique for estimating direct runoff from rain events in ungaged watersheds was used in this analysis.

Model Form

As documented in NRCS (2004b), the NRCS method for estimating direct runoff from individual storm rainfall events is of the following form:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad \text{if } P > I_a$$

$$Q = 0 \qquad \text{if } P \leq I_a$$

Where Q is the depth of runoff (inches), P is the depth of rainfall (inches), I_a is the initial abstraction (inches), and S is the maximum potential retention (inches). The derivation of this equation is not physically based but does respect conservation of mass (NRCS 2004b).

The Curve Number is defined as:

$$CN = \frac{1000}{10 + S}$$

The initial abstraction was initially described and has traditionally been used as:

$$I_a = 0.2S$$

This relationship is fairly poor, as Figure 10-1 in NRCS (2004b) illustrates.

CN Development

The CN method is a simple and widely used technique for estimating a stream hydrograph at the outlet of a watershed. Documentation is provided on the method in the NRCS National Engineering Handbook, Section 4, Hydrology, Chapters 9 and 10 (NRCS 2004a, NRCS 2004b), in Rallison (1980), as well as numerous other publications. However, little quantitative information has been published of the database on which it was developed (Maidment 1992) and many of the curves used in the development have been misplaced (Woodward 2005). The method was developed for rural non-mountainous watersheds in various parts of the United States, within 24 states; was developed for single storms, not continuous or partial storm simulation; and was not intended to recreate a specific response from an actual storm (Rallison, 1980). This latter point is disconcerting but understandable considering that typical condition CNs are being applied to the real-world variability of soil moisture, spatial precipitation variability, variation in precipitation intensity, and interception. Most fundamentally, the conceptual foundation of the CN technique can be disconnected with physical streamflow generating processes during more-frequent small to moderate rain events, where saturation excess overland flow can be dominant (as opposed to infiltration-excess or Hortonian overland flow). The CN is a simple watershed-scale method that gives simplified results at a watershed outlet for larger events. For a theoretical extreme storm such as a PMP, the method is appropriate and is thought to give good results (Woodward 2005).

A list of assigned curve numbers for each landuse type found in the modeled watersheds, given each hydrologic soil group, is provided in Table 2.

Table 2: CN Assignments, by landuse type and hydrologic condition.

Description	Hydrologic Condition	A	B	C	D
brush-mahogany	fair	----	48	57	63
brush-mahogany	good	----	30	41	48
desert shrub	poor	63	77	85	88
feed lot	----	----	86	91	94
herbacous	fair	63	71	80	89
herbacous	good	51	62	74	85
industrial	----	----	88	91	93
meadow, hay	good	----	58	71	78
paved	----	100	100	100	100
pinyon-juniper	fair	----	58	73	80
riparian	----	100	100	100	100
row crops, SR	poor	----	81	88	91
water	----	100	100	100	100
wetland	----	100	100	100	100
woods	good	----	55	70	77
woods	poor	----	66	77	83

Initial Abstraction

It has been suggested that the use of an initial abstraction, I_a, of 0.2S, where S is the maximum potential retention after runoff begins, is too high. Instead, it has been found that the use of 0.05S is more appropriate (NRCS 2005b). To make use of the most-recently available information, it would have been preferred to use an I_a of 0.05S. However, since changing the I_a assumption would change the CNs listed in NRCS (2004a), an I_a of 0.2S was used in this analysis.

Lag-Time Estimates

Using the CN methodology, precipitation that is not initially abstracted or infiltrated becomes excess precipitation that flows down-gradient to the sub-basin outlet, which is modeled using a transform method. The velocity methods documented in SCS 1972, NEH Section 4, Chapter 15, were used to compute lag estimates for each sub basin.

Stream Reach Network

To model travel time and attenuation, stream reaches were developed to route the flow from each sub-basin to the reservoirs. The Muskingum-Cunge method was used in the model. Due to model requirements, the modeled stream network was designed so that each reach had a consistent slope. For each reach, eight-point cross-sections were developed and energy slopes and Manning's *n* values for the channel and floodplain were designated.

Manning's n Estimates for Steep Reaches

Analysts often model high flows on steep reaches as supercritical flow. This assumption can be valid for rigid boundary channels, such as concrete or bedrock channels, but is a questionable practice for the natural alluvial channels (Trieste 1994). For cobble and boulder bed high-gradient streams with extreme flows, Jarrett (1984) suggests that a limiting assumption of critical depth in subsequent hydraulic analyses appears to be reasonable. Trieste (1994) suggests that modeling supercritical flow for long reaches within the National Weather Service's DAMBRK (Freud 1988) or its successor FLDWAV (Fread and Lewis, 1998) may be invalid except for possibly bedrock channels. For steep boulder and cobble-bed streams, high Froude numbers likely indicate that not all energy losses have been fully accounted for in the model (Jarrett 1987). In the modeling of the catastrophic breach of the Lawn Lake embankment dam, a 26 ft high embankment dam in Rocky Mountain National Park, Jarrett and Costa (1984) used a calibrated value Manning's *n* value of 0.20 for slopes up to 25 percent to match actual breach stage and timing. It was hypothesized that Manning *n* estimates were required to reflect flow with entrained debris, with bed scouring and deposition, instead of existing conditions. This necessitated the calibration of *n* to 0.20 which modeled as subcritical flow, from an initial *n* of 0.125 and supercritical flow. For flows up to bankfull, Yochum et al. (in review) measured average reach velocity and geometry for 15 stream reaches with slopes from 4.8 to 5.2 percent and found all flows were, on a reach-average basis, subcritical with *n* varying from 0.048 to 0.52.

Grant (1997) asserts that in steep, mobile-bed channels, interactions between hydraulics and bed configurations prevent the Froude number from exceeding 1 for more than short distances and time periods. Critical flow in steep channels is maintained by the interaction of the mobilized bed and vegetation with the water surface at high Froude numbers, resulting in the oscillating creation and destruction of bed forms. This has been shown in field observations of sand-bed streams, active braided rivers, step-pool streams, laboratory rills, lahar runout channels and some bedrock channels.

Hence, it has been shown that supercritical flow in steep sloped mountainous streams occurs only for short lengths and duration and, instead, subcritical and critical flow may be much more dominant in alluvial streamflow. In practice, this situation impacts the appropriate selection of Manning's *n* in a hydraulic model. The selection of Manning's *n* for lag-time and hydraulic modeling in this analysis were based on this philosophy, with *n* values increased in steep channels to maintain critical flow.

Boxelder B-4

Storage, attenuation and outflow from the Boxelder B-4 Reservoir were modeled in this PMP analysis using rating tables based upon as-built drawing dimensions. According to these plans the reservoir has a volume of 1273 acre-feet at the crest of the auxiliary spillway (elevation = 5401.0 feet), with a maximum capacity of 2420 acre-feet at the crest of the 30.3 foot high embankment (elevation = 5408.0 feet). Maximum capacity through the auxiliary spillway is 13,440 cfs. Both the primary and dual 200-foot-wide auxiliary spillways are modeled in the analysis. The reservoir is assumed to be initially dry. A schematic of the analysis is provided in Figure 8, an aerial image of the embankment is shown in Figure 6, and a photograph of the downstream face of the embankment is shown in Figure 7.

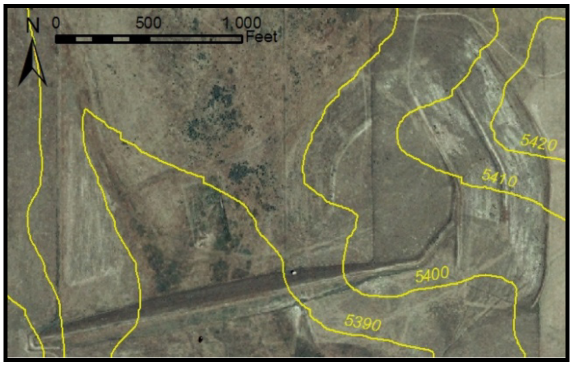

Figure 6: Aerial photograph of Boxelder B-4 embankment. 2005 image, with pre-construction contours.

Figure 7: Boxelder B-4 embankment, downstream face.

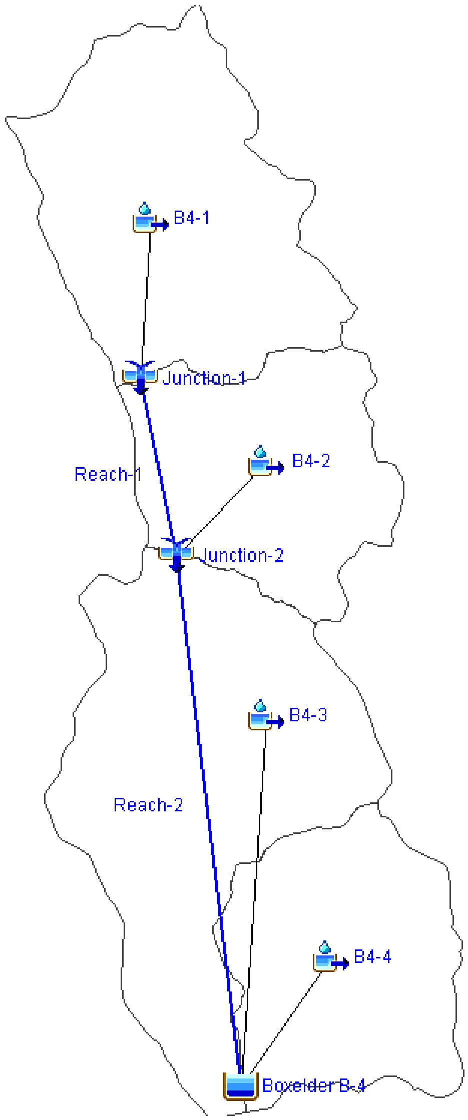

Figure 8: Schematic of the Boxelder B-4 model.

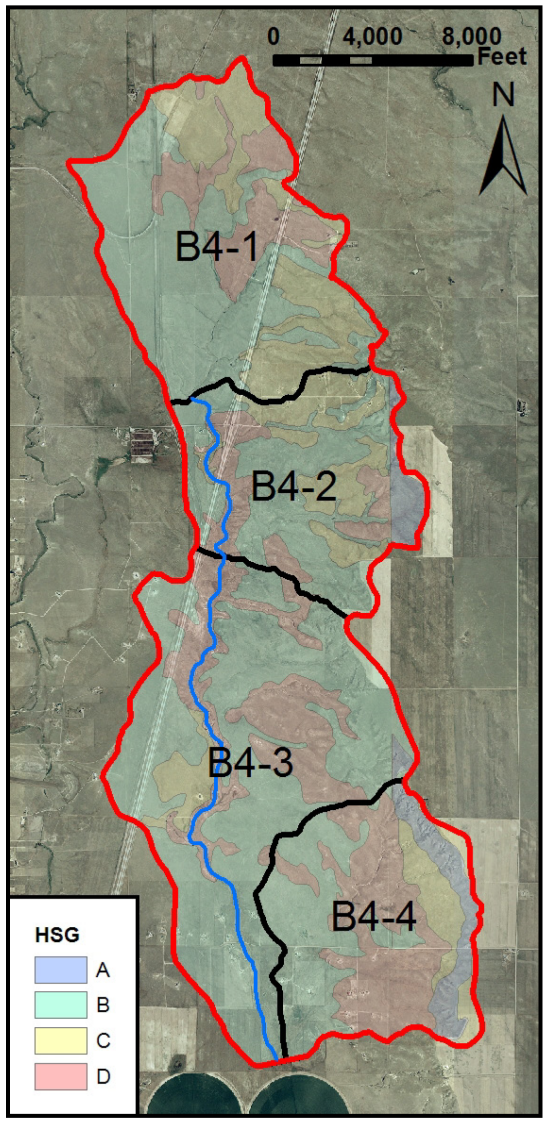

Figure 9: B-4 watershed, hydrologic soil groups (HSG).

Due to the lack of reservoir pool data, the stage-storage curve modeled would have necessitated the use of extrapolated information. This adds an unrealistically-conservative aspect to the modeling. To address this issue, a 10-meter DEM was applied to obtain above-embankment pool information. These data are approximate but are more reliable than extrapolated as-built data.

The two modeled stream segments in the B-4 watershed are typically sand-bedded, with intermittent vegetation. Reach 1 has slopes ranging from 0.006 to 0.020 ft/ft, with an average of 0.010. Reach 2 has slopes ranging from 0.004 to 0.009 ft/ft, with an average of 0.007. Reach characteristics are provided in Table 3.

A Muskingum-Cunge routing methodology was used in the analysis, using an *n* of 0.035 for in-channel flows and 0.060 for overbank areas. An 8-point section was used.

Table 3: Reach characteristics, Boxelder B-4.

Reach	Length (feet)	Bed Elevation (feet) Upstream	Bed Elevation (feet) Downstream	Average Slope (ft/ft)
R1	8060	5622	5540	0.0102
R2	23,200	5540	5386	0.0066

Catchment characteristics are provided in Table 4. Catchments varied in size from 2.5 to 4.8 square miles, with composite CNs ranging from 70.2 to 72.8. Lag times varied from 23 to 39 minutes.

Table 4: Characteristics of the Boxelder B-4 watershed.

Sub-Basin ID	Area (mi^2)	Composite CN	Initial Abstraction (inches)	Lag Time (minutes)
1	3.74	70	0.85	28.6
2	2.52	70	0.84	23.4
3	4.77	70	0.85	50.8
4	2.69	73	0.75	39.4

Boxelder B-3

Storage, attenuation and outflow from the Boxelder B-3 Reservoir were modeled in this PMP analysis using rating tables based upon as-built drawing dimensions. According to these plans the reservoir has a volume of 3840 acre-feet at the crest of the auxiliary spillway (elevation = 5481.0 feet), with a maximum capacity of 6400 acre-feet at the crest of the 44 foot high embankment (elevation = 5489 feet). Maximum capacity through the auxiliary spillway is 17,000 cfs. Both the primary and dual 200-foot-wide auxiliary spillways were modeled in the analysis. The reservoir is assumed to be initially dry. A schematic of the analysis is provided in Figure 10, photographs of the embankment faces are shown in Figure 10 and 11, and an aerial image of the embankment is shown in Figure 13.

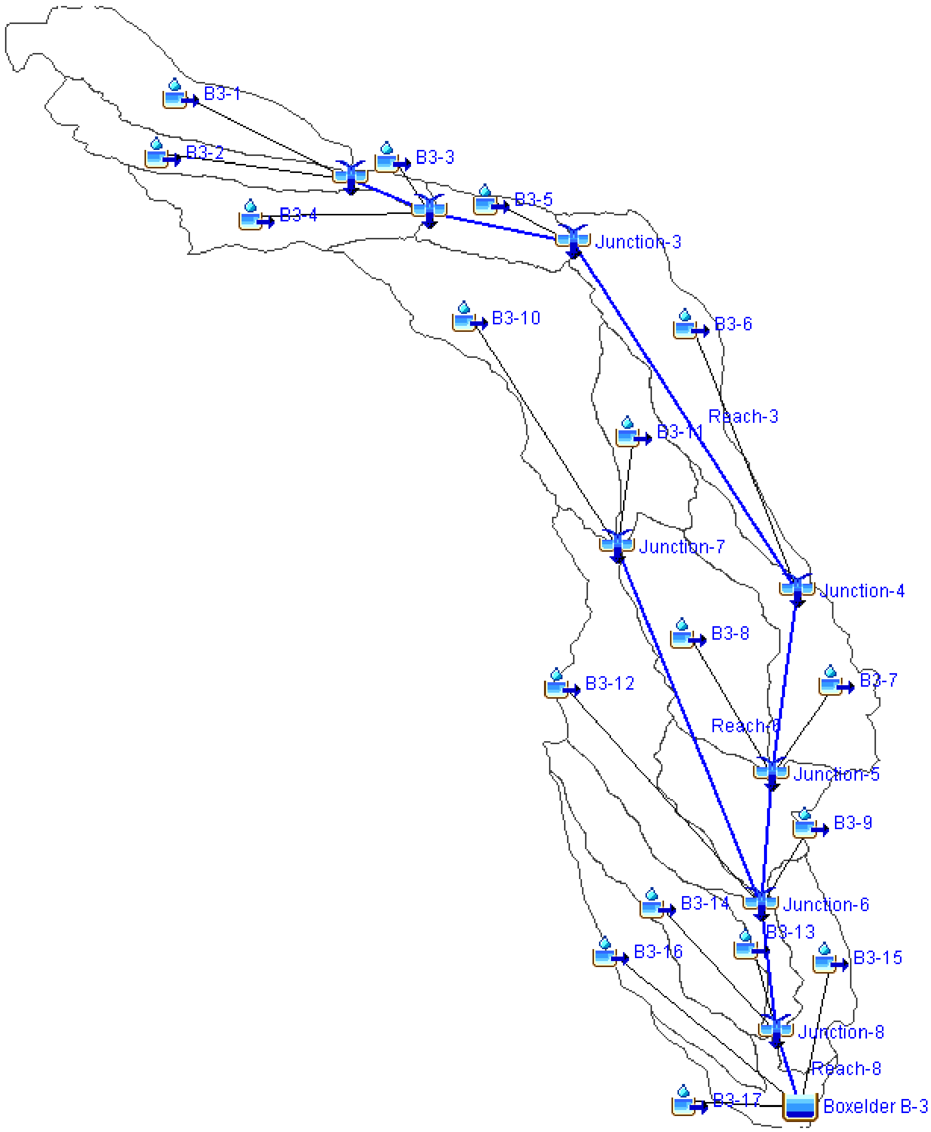

Figure 10: Schematic of the Boxelder B-3 model.

Figure 11: Upstream face of B-3 embankment.

Figure 12: Downstream face of B-3 embankment.

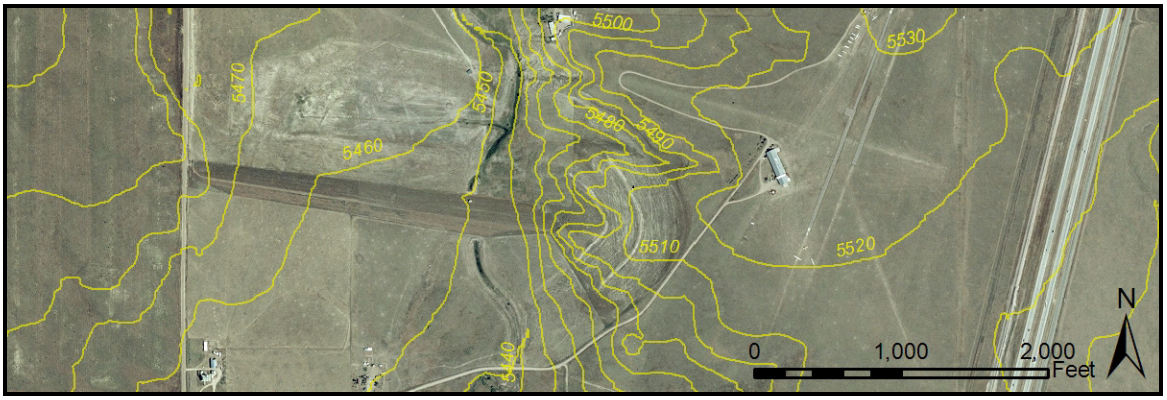

Figure 13: Aerial photograph of Boxelder B-3 embankment. 2005 image, with pre-construction contours.

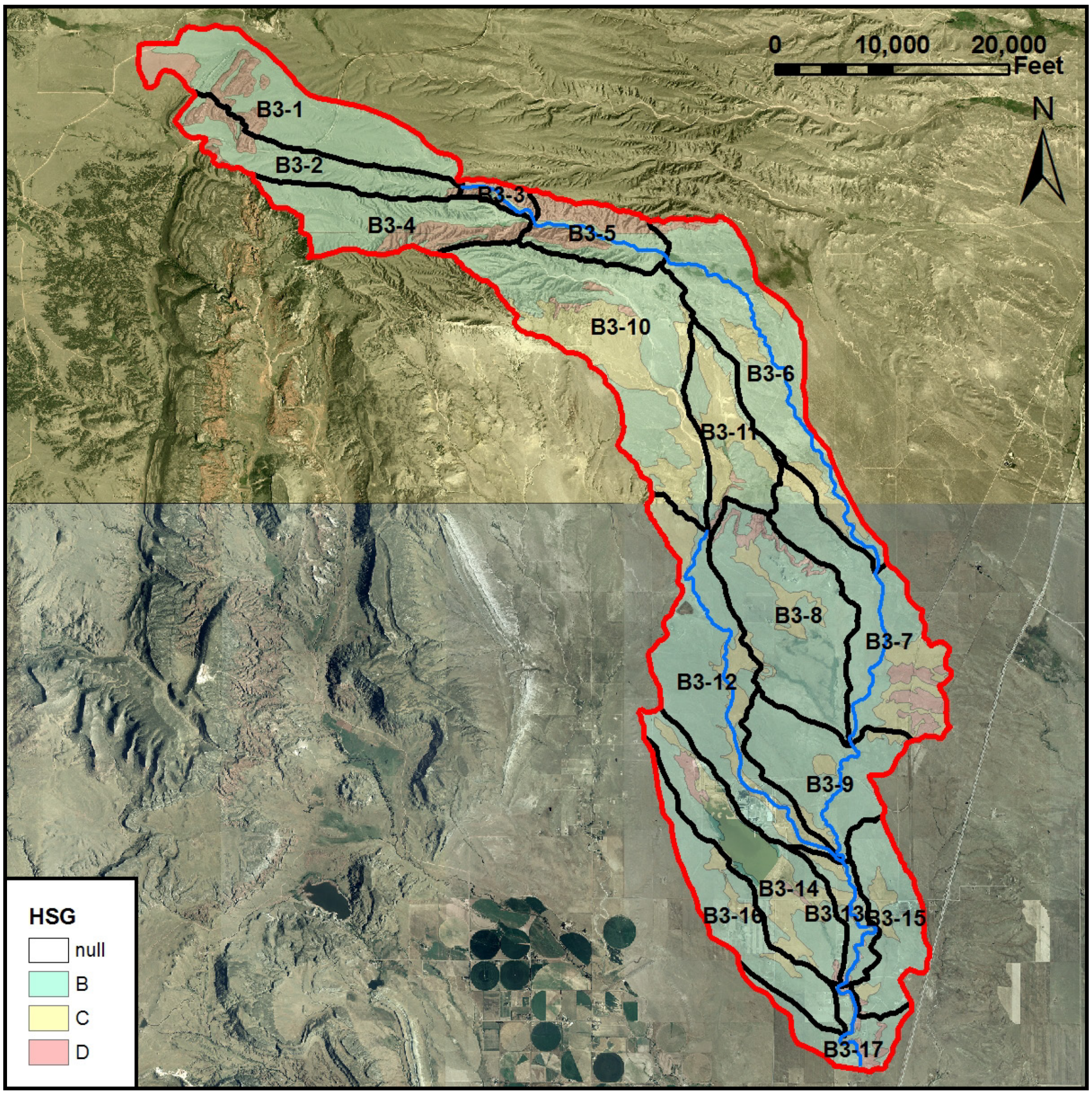

Figure 14: B-3 watershed, hydrologic soil groups (HSG).

Due to the lack of reservoir pool data, the stage-storage curve modeled would have necessitated the use of extrapolated information. This adds an unrealistically-conservative aspect to the modeling. To address this issue, the 10-meter DEM was applied to obtain above-embankment pool information. These data are approximate but are more reliable than extrapolated as-built data.

A Muskingum-Cunge routing methodology was used in the analysis, using an *n* of 0.035 to 0.045 for in-channel flows and 0.060 for overbank areas. An 8-point section was used. Channel slopes ranged from 0.4 to 2.3 percent. Reach characteristics are provided in Table 5.

Table 5: Reach characteristics, Boxelder B-3.

Reach	Length (feet)	Bed Elevation (feet) Upstream	Downstream	Average Slope (ft/ft)
R1	7720	6903	6724	0.023
R2	12,620	6724	6487	0.019
R3	38,800	6487	5893	0.015
R4	16,620	5893	5663	0.014
R5	14,040	5663	5570	0.0066
R6	37,670	5960	5570	0.010
R7	15,280	5570	5489	0.0053
R8	10,120	5489	5446	0.0042

Catchment characteristics are provided in Table 6. Hydrologic soil groups of the B-3 watershed are provided in Figure 14. Catchments varied in size from 0.4 to 7.7 square miles, with composite CNs ranging from 58.5 to 80.9. Lag times varied from 18 to 128 minutes.

Table 6: Characteristics of the Boxelder B-3 watershed.

Sub-Basin ID	Area (mi^2)	Composite CN	Initial Abstraction (inches)	Lag Time (minutes)
1	4.80	63	1.18	64
2	2.54	62	1.25	41
3	0.44	81	0.47	18
4	3.34	59	1.42	48
5	1.93	61	1.29	22
6	5.78	67	1.00	74
7	4.96	68	0.96	58
8	5.34	66	1.02	47
9	3.55	64	1.11	37
10	7.70	58	1.46	65
11	2.68	68	0.93	34
12	5.66	68	0.95	80
13	1.09	70	0.88	61
14	4.22	75	0.65	65
15	2.54	65	1.08	57
16	2.95	68	0.93	128
17	1.54	73	0.74	61

Boxelder B-2

The Boxelder B-2 watershed is a dams-in-series situation, with the B-5 and B-6 structures nested within the B-2 watershed. A schematic of the B-2 model is illustrated in Figure 15. According to NRCS TR-60 criteria (NRCS 2005a), the hydrologic criteria of the upper dams must be the same or more conservative than the lower dam if failure of the upper structures can contribute to the failure of the lower structure. If the upper structures are overtopped they should be considered breached and the composite breach and uncontrolled area hydrographs routed downstream to the lower structure for design purposes.

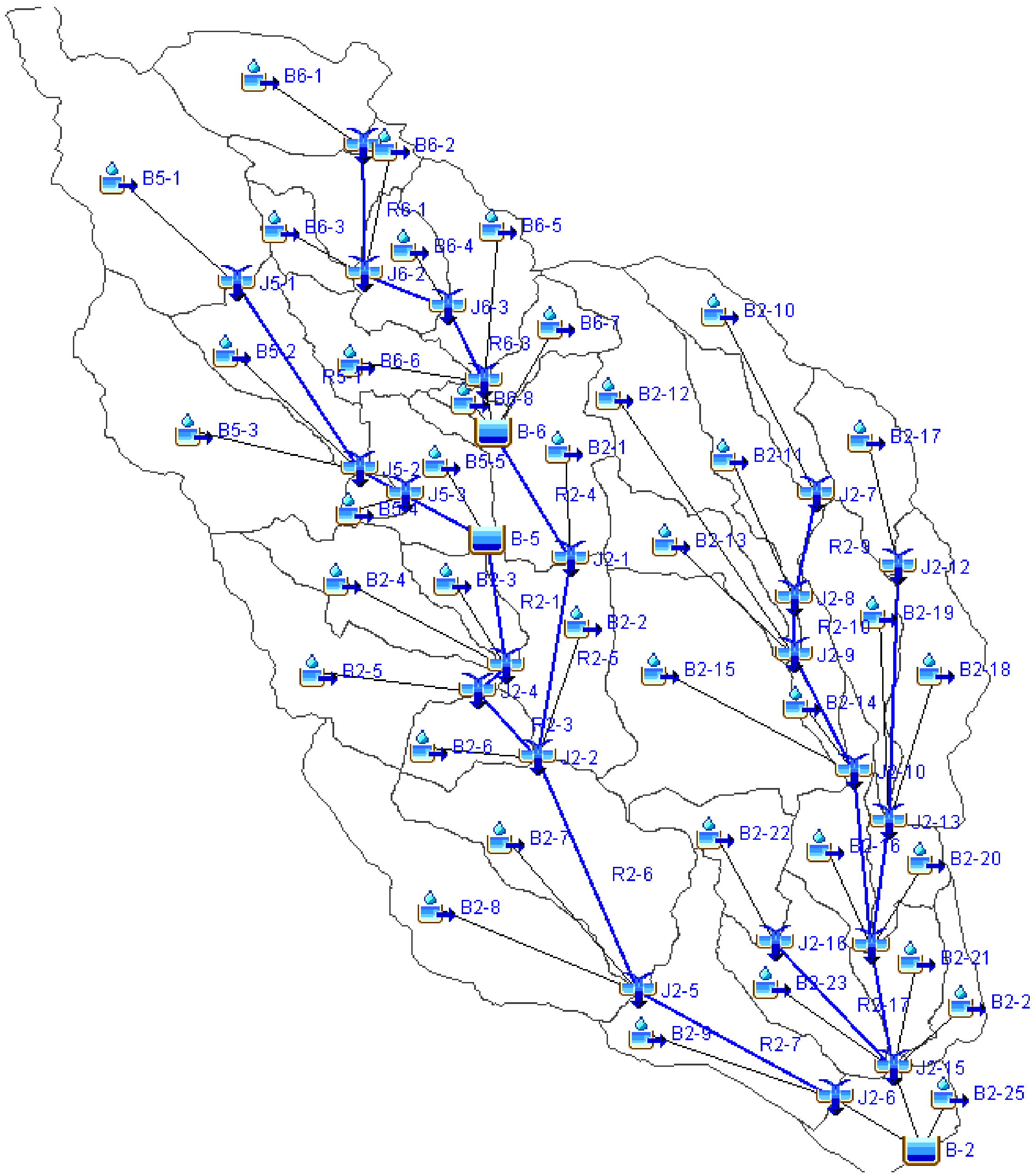

Figure 15: Schematic of the Boxelder B-2 watershed model.

Storage, attenuation and outflow from the Boxelder B-2 Reservoir were modeled in this PMP analysis using rating tables based upon as-built drawing dimensions. According to these plans the reservoir has a volume of 6470 acre-feet at the crest of the auxiliary spillway (elevation = 5564.35 feet), with a maximum capacity of 12,000 acre-feet at the crest of the 59.4 foot high embankment (elevation = 5574.35 feet). Maximum capacity through the auxiliary spillway is 17,500 cfs. Both the primary spillway and 178 foot wide concrete auxiliary spillway were modeled in the analysis. The reservoir was assumed to be initially dry. A schematic of the analysis is provided in Figure 15, photographs of the embankment faces are shown in Figure 16 and 17, and an aerial image of the embankment is shown in Figure 18. Hydrologic soil groups of the entire B-2 watershed are illustrated in Figure 19.

Figure 16: Upstream face of B-2 embankment.

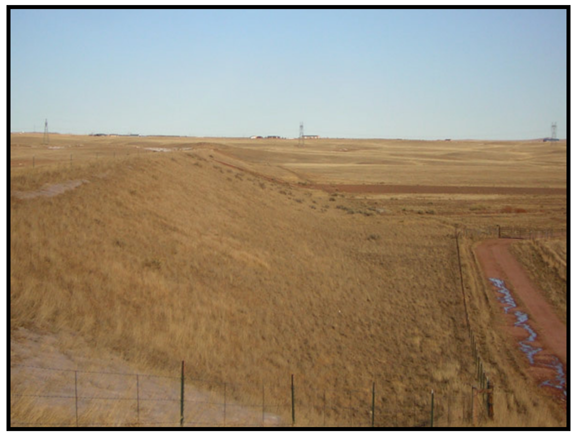

Figure 17: Downstream face of B-2 embankment.

Figure 18: Aerial photograph of Boxelder B-2 embankment. 2005 image, with pre-construction contours.

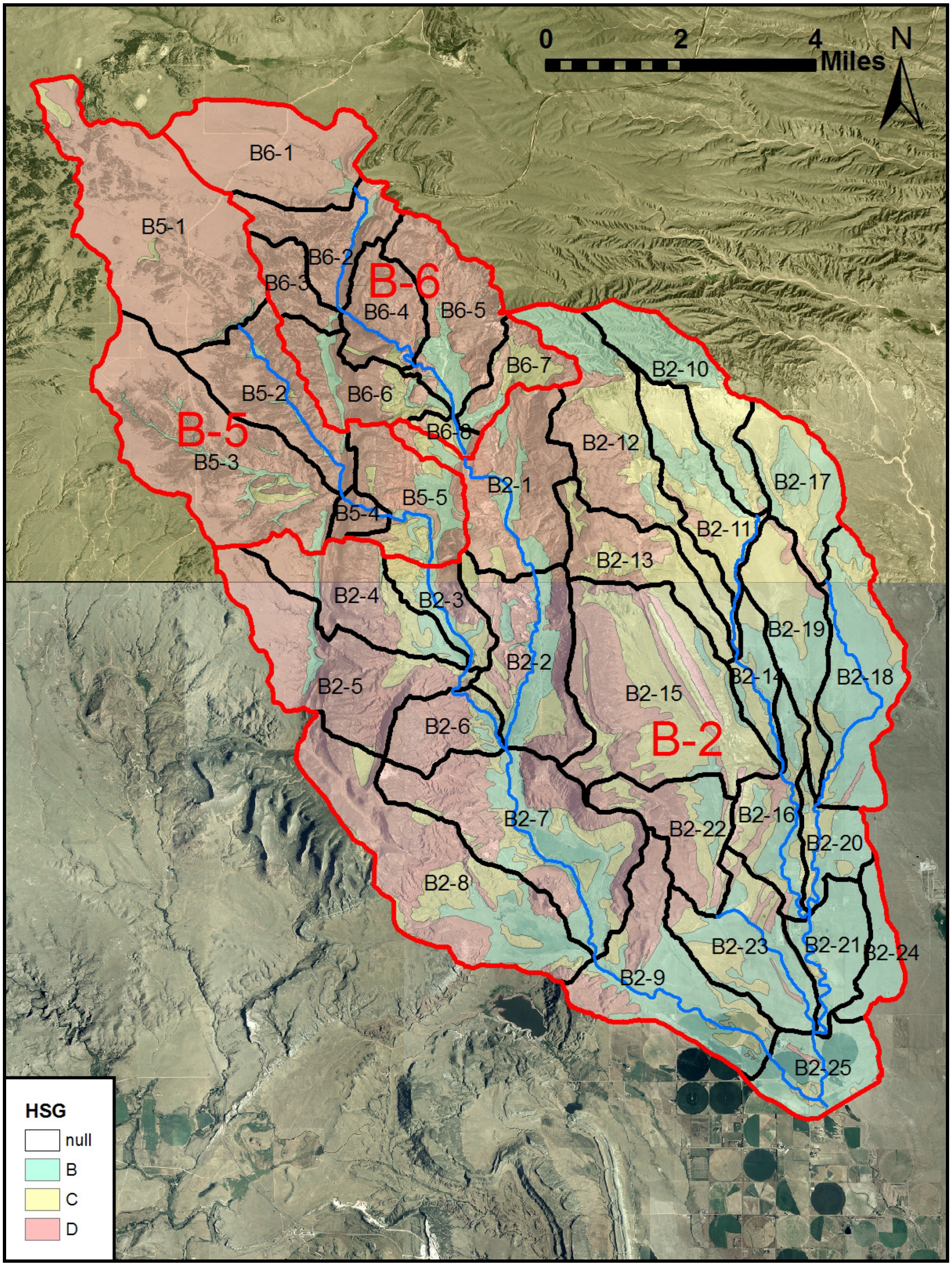

Figure 19: B-2 watershed, hydrologic soil groups (HSG).

Due to the lack of reservoir pool data, the stage-storage curve modeled would have necessitated the use of extrapolated information. This adds an unrealistically-conservative aspect to the modeling. To address this issue, the 10-meter DEM was applied to obtain above-embankment pool information. These data are approximate but are more reliable than extrapolated as-built data.

A Muskingum-Cunge routing methodology was used in the analysis, using an *n* of 0.035 to 0.060 for in-channel flows and 0.060 for overbank areas. An 8-point section was used. Average channel slopes ranged from 0.6 to 3.8 percent. Reach characteristics are provided in Table 7.

Table 7: Reach characteristics, Boxelder B-2, -5, -6.

Reach	Length (feet)	Bed Elevation (feet)		Average Slope (ft/ft)
		Upstream	Downstream	
R6-1	10,860	7243	6904	0.031
R6-2	9,140	6904	6551	0.038
R6-3	6,150	6551	6398	0.025
R5-1	17,250	7199	6548	0.038
R5-2	4,620	6548	6372	0.038
R5-3	7,560	6372	6206	0.022
R2-1	9,160	6203	6088	0.013
R2-2	2,260	6088	6042	0.020
R2-3	7,210	6042	5954	0.012
R2-4	12,980	6334	6136	0.015
R2-5	15,860	6136	5957	0.011
R2-6	20,810	5957	5743	0.010
R2-7	18,100	5743	5594	0.012
R2-9	8,440	6145	5982	0.019
R2-10	4,440	5982	5900	0.018
R2-11	10,450	5900	5771	0.012
R2-12	14,970	5771	5651	0.0080
R2-13	21,910	6022	5737	0.013
R2-14	11,290	5737	5651	0.0076
R2-15	14,040	5651	5570	0.0058
R2-17	14,100	5707	5570	0.0097

Catchment characteristics are provided in Table 8. Catchments varied in size from 0.34 to 7.0 square miles, with composite CNs ranging from 58.3 to 82.4. Lag times varied from 17 to 72 minutes.

Table 8: Characteristics of the Boxelder B-2, -5, -6 watersheds.

Sub-Basin ID	Area (mi^2)	Composite CN	Initial Abstraction (inches)	Lag Time (minutes)
B6-1	3.63	84	0.37	58.3
B6-2	2.02	79	0.53	33.8
B6-3	0.97	77	0.61	20.6
B6-4	1.76	79	0.54	29.6
B6-5	2.93	76	0.62	38.0
B6-6	2.05	75	0.67	33.6
B6-7	1.26	75	0.67	26.5
B6-8	0.34	80	0.50	16.1
B5-1	7.03	82	0.43	55.9
B5-2	2.80	76	0.63	48.2
B5-3	6.19	79	0.53	53.0
B5-4	0.46	69	0.90	16.7
B5-5	2.47	78	0.56	25.6
B2-1	3.94	68	0.96	29.9
B2-2	3.63	69	0.90	49.1
B2-3	1.28	67	0.97	27.6
B2-4	2.74	78	0.58	47.0
B2-5	4.36	80	0.52	47.0
B2-6	1.57	76	0.62	17.9
B2-7	5.81	69	0.91	59.9
B2-8	6.03	71	0.81	68.9
B2-9	4.15	71	0.82	43.7
B2-10	2.58	58	1.43	48.0
B2-11	2.41	71	0.82	43.7
B2-12	4.24	63	1.16	72.4
B2-13	2.26	69	0.89	44.5
B2-14	1.11	67	0.98	39.4
B2-15	6.80	67	0.99	49.0
B2-16	2.14	71	0.82	54.4
B2-17	2.22	68	0.93	35.8
B2-18	3.68	64	1.11	53.6
B2-19	2.50	70	0.87	50.8
B2-20	1.26	71	0.83	58.2
B2-21	1.67	68	0.92	37.8
B2-22	2.28	65	1.09	27.3
B2-23	3.00	69	0.89	36.4
B2-24	1.00	62	1.21	52.9
B2-25	1.96	72	0.77	38.4

Boxelder B-6

Storage, attenuation and outflow from the Boxelder B-6 Reservoir were modeled in this analysis using the geometric configuration of the structure. The principal spillway was not modeled in the breached versions of the models, with all outflow simulated to flow through the auxiliary spillway and over the embankment crest. According to the as-built plans the reservoir has a volume of 1500 acre-feet at the crest of the auxiliary spillway (elevation = 6397.5 feet), with a maximum capacity of 2020 acre-feet at the crest of the 72.5 foot high embankment (elevation = 6404.5 feet). Maximum capacity through the auxiliary spillway is 10,800 cfs. The auxiliary spillway is 280 feet wide, with 2:1 side slopes and a crest elevation of 6397.5 feet. The reservoir is assumed to be initially dry. Photographs of the embankment faces are shown in Figure 20 and 21 and an aerial image of the embankment and auxiliary spillway is shown in Figure 22.

Figure 20: Upstream face of B-6 embankment.

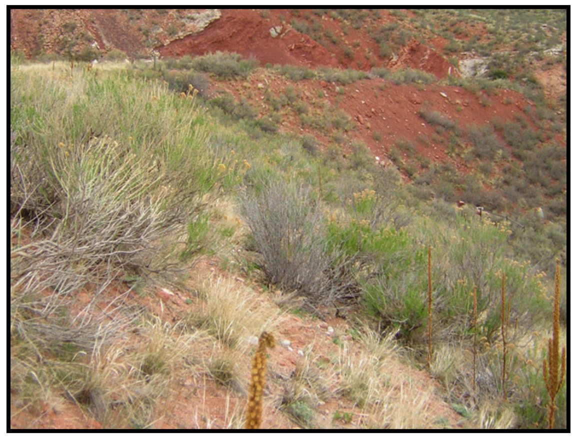

Figure 21: Downstream face of B-6 embankment.

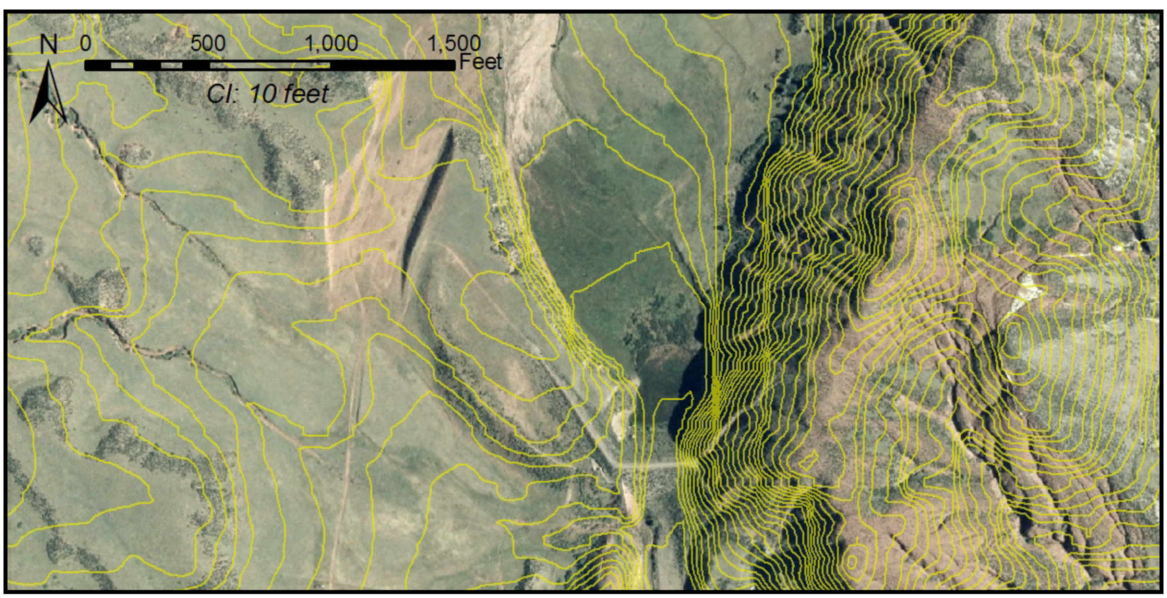

Figure 22: Aerial photograph of Boxelder B-6 embankment. 2005 image, with pre-construction contours.

The Boxelder B-6 structure will overtop if a PMP event occurs in the watershed. In the case of significant overtopping, the embankment will likely fail. The embankment failure trigger was assumed to be when the crest is overtopped to a depth of 0.5 feet.

The average breach width was estimated using Froehlich (1995), specifically:

$$\overline{B} = 15 k_0 V_{wm}^{0.32} h_w^{\ 0.19}$$

where V_{wm} is the reservoir volume at the time of failure (millions of m^3), h_w is the height of the final breach (meters), and k_o is equal to 1.4 for an overtopping failure mode or 1.0 for piping. With a reservoir volume of 2,492,000 m^3 at the crest of the embankment and depth of water of 22.1 m, this method predicts an average breach width of 50.6 m (166 feet). It is assumed that the side slopes are the average of what Froehlich (1995) found to be the case of overtopping failures: 1.4. Hence, the bottom width was assumed to be 64.5 feet.

Breach development time was estimated using a Froehlich regression equation (Froehlich 1995), specifically:

$$t_f = 3.84 V_{wm}^{0.53} h_w^{-0.90}$$

where t_f is the breach formation time (hours). This method predicts a relatively short development time of 0.38 hours.

Boxelder B-5

Storage, attenuation and outflow from the Boxelder B-5 Reservoir were modeled in this analysis using the geometric configuration of the structure. The principal spillway was not modeled in the breached versions of the models, with all outflow simulated to flow through the auxiliary spillway and over the embankment crest. According to the as-built plans the reservoir has a volume of 1580 acre-feet at the crest of the auxiliary spillway (elevation = 6270.0 feet), with a maximum capacity of 2700 acre-feet at the crest of the 75.0 foot high embankment (elevation = 6282.0 feet). Maximum capacity through the auxiliary spillway is 14,800 cfs. The auxiliary spillway is 130 feet wide, with 2:1 side slopes and a crest elevation of 6270.0 feet. The reservoir is assumed to be initially dry. Photographs of the embankment faces are shown in Figure 23 and 24 and an aerial image of the embankment and auxiliary spillway is shown in Figure 25.

Figure 23: Upstream face of B-5 embankment.

Figure 24: Downstream face of B-5 embankment.

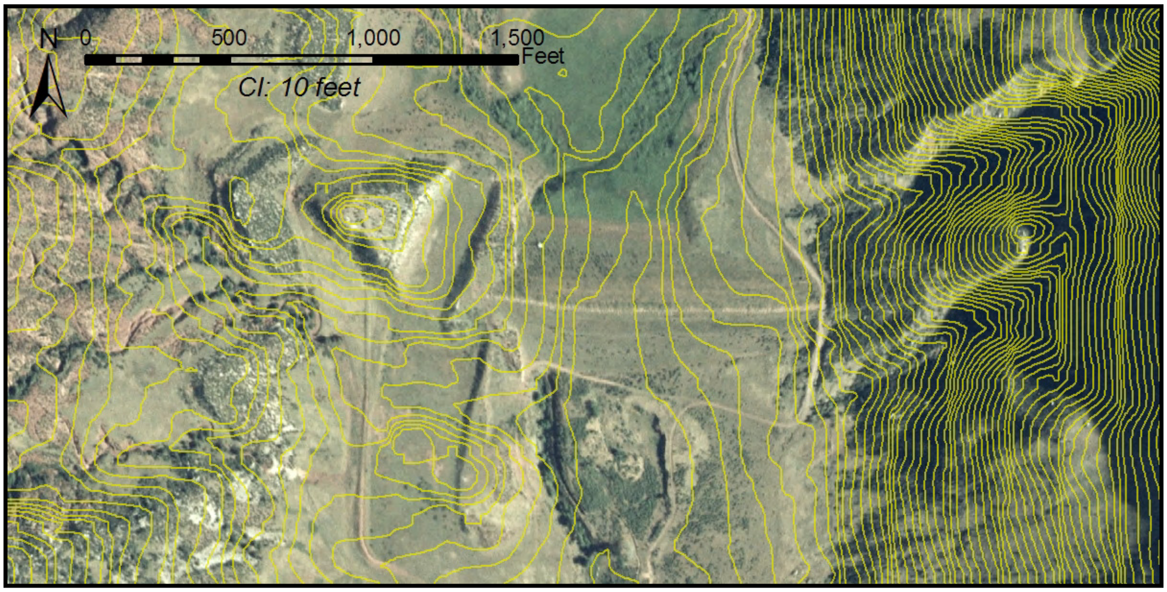

Figure 25: Aerial photograph of Boxelder B-5 embankment. 2005 image, with pre-construction contours.

The Boxelder B-5 structure will overtop if a PMP event occurs in the watershed. In the case of significant overtopping, the embankment will likely fail. The embankment failure trigger was assumed to be when the crest is overtopped to a depth of 0.5 feet.

The average breach width was estimated using Froehlich (1995). With a reservoir volume of 3,332,000 m^3 at the crest of the embankment and depth of water of 22.9 m, this method predicts an average breach width of 56.0 m (184 feet). It is assumed that the side slopes are the average of what Froehlich (1995) found to be the case of overtopping failures: 1.4. Hence, the bottom width was assumed to be 79 feet.

Breach development time was estimated using a Froehlich regression equation (Froehlich 1995). This method predicts a relatively short development time of 0.43 hours.

MODELING RESULTS

Two scenarios were simulated for each of the three hydrologic models: the 6-hour and 24-hour PMP events. The 6-hour storm was modeled for 24 hours while the 24-hour storm was modeled for 48 hours. Hydrographs immediately upstream and downstream of each reservoir as well as tabular results of each simulation are provided. Peak discharges and runoff volumes at calculation nodes within the model are also provided. Additionally, the rainfall depth were reduced to calculate the percentage of the PMP event that can be passed through the embankment without overtopping. All storms are simulated to initiate at noon on 19 July 2009. The limitations of this modeling, discussed above, should be noted. Accordingly, these results need to be considered approximate.

Boxelder B-4

Hydrologic modeling of the Boxelder B-4 watershed indicates that if a PMP event occurs, 14,000 and 19,000 acre feet of water will flow into the reservoir for the 6- and 24-hour events, respectively. These volumes are substantially greater than the storage capacity of the reservoir, 2420 acre-feet. The embankment will be substantially overtopped, by 4.0 and 2.3 feet for the 6- and 24-hour events, respectively. The existing spillways will convey about 45 and 47 percent of the PMP event, respectively, without overtopping the embankment. Hydrographs at the head and outlet of the reservoir, as well as the reservoir pool elevations, are shown in Figure 26.

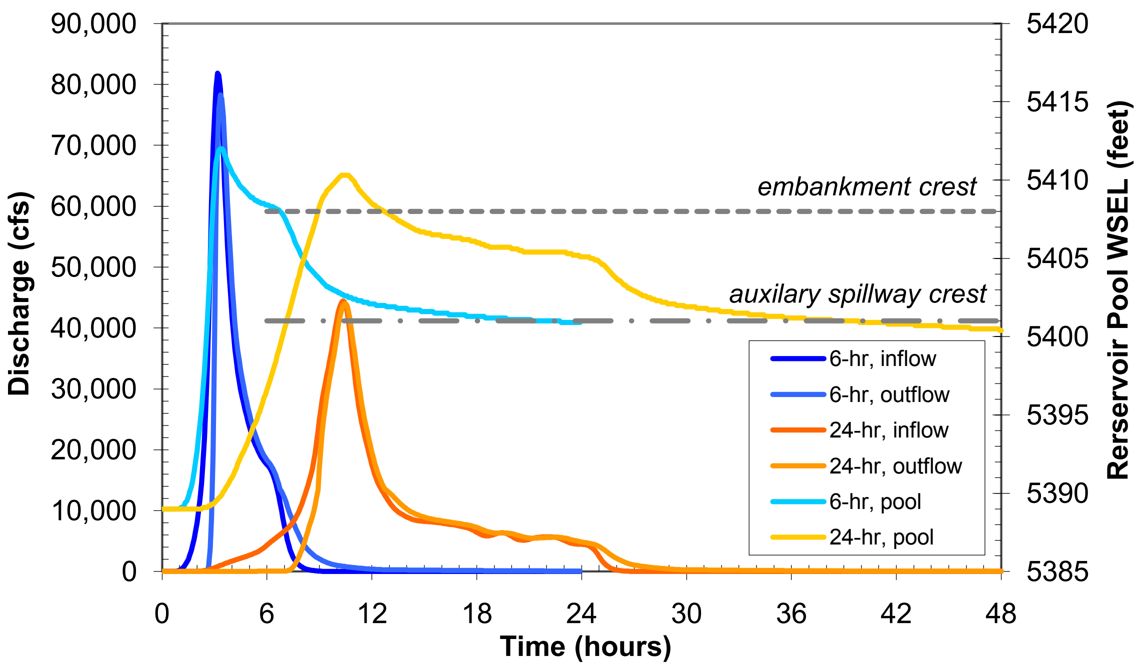

Figure 26: Hydrographs at the head and outlet of the B-4 reservoir, for the 6- and 24-hour storms.

Results from the 6-hour PMP analysis are shown in Table 9. This analysis indicates that the peak flow at the outlet of B-4 reservoir will be 78,200 cfs, which represents a peak flow yield of 5700 cfs/mi^2. The auxilary spillway has a conveyance capacity of about 13,400 cfs; the spillway can only convey about **17 percen**t of the peak flow resulting from the 6-hour PMP. At the 78,200 cfs peak flow, the embankment would be overtopped by a maximum of 4.0 feet, with an overtopping duration of 3.8 hours. Considering the lack of armor and patchy vegetative cover of the downstream face (Figure 7), the embankment will most likely fail in the case of a 6-hour PMP in the Boxelder B-4 watershed. For the 6-hour storm, the existing structure will convey approximately **45 percent** of the PMP event.

Table 9: B-4 hydrologic model results, 6-hour PMP event.

Hydrologic Element	Peak Discharge (cfs)	Time of Peak	Total Volume (ac-ft)	Runoff Depth (inches)	Contributing Area (mi^2)	Peak Yield (cfs/mi^2)
B4-1	25,800	19Jul2009, 14:50	3,823	19.2	3.74	6900
Junction-1	25,800	19Jul2009, 14:50	3,823	19.2	3.74	6900
B4-2	18,800	19Jul2009, 14:45	2,567	19.1	2.52	7440
Junction-2	42,400	19Jul2009, 14:50	6,390	19.1	6.26	6780
B4-3	24,800	19Jul2009, 15:15	4,856	19.1	4.77	5190
B4-4	16,300	19Jul2009, 15:00	2,805	19.6	2.69	6070
Boxelder B-4, inlet	81,900	19Jul2009, 15:10	14,100	19.2	13.72	5970
Boxelder B-4, outlet	78,200	19Jul2009, 15:20	12,987	17.8	13.72	5700

Results from the 24-hour PMP analysis are shown in Table 10. This analysis indicates that the peak flow at the outlet of B-4 reservoir will be 44,000 cfs, which represents a peak flow yield of 3210 cfs/mi^2. The spillway can only convey about 30 percent of the peak flow resulting from the 24-hour PMP. At the 44,000 cfs peak flow, the embankment would be overtopped by a maximum of 2.3 feet, with an overtopping duration of 3.7 hours. For the 24-hour storm, the existing structure will convey approximately 46 percent of the PMP event.

Table 10: B-4 hydrologic model results, 24-hour PMP event.

Hydrologic Element	Peak Discharge (cfs)	Time of Peak	Total Volume (ac-ft)	Runoff Depth (inches)	Contributing Area (mi^2)	Peak Yield (cfs/mi^2)
B4-1	12,700	19Jul2009, 22:05	5,166	25.9	3.74	3400
Junction-1	12,700	19Jul2009, 22:05	5,166	25.9	3.74	3400
B4-2	8,700	19Jul2009, 22:00	3,470	25.9	2.52	3450
Junction-2	21,300	19Jul2009, 22:05	8,636	25.9	6.26	3400
B4-3	14,800	19Jul2009, 22:20	6,566	25.8	4.77	3100
B4-4	8,900	19Jul2009, 22:10	3,774	26.3	2.69	2310
Boxelder B-4, inlet	44,400	19Jul2009, 22:20	18,975	25.9	13.72	3240
Boxelder B-4, outlet	44,000	19Jul2009, 22:30	17,964	24.6	13.72	3210

Boxelder B-3

Hydrologic modeling of the Boxelder B-4 watershed indicates that if a PMP event occurs, 46,200 and 65,700 acre feet of water will flow into the reservoir for the 6- and 24-hour events, respectively. In comparison, the storage capacity of the reservoir is 6400 acre-feet. The embankment will be substantially overtopped, by 6.0 and 5.1 feet for the 6- and 24-hour events, respectively. The existing spillways will convey about 36 percent of the PMP without overtopping the embankment. Hydrographs at the head and outlet of the reservoir, as well as the reservoir pool elevations, are shown in Figure 27.

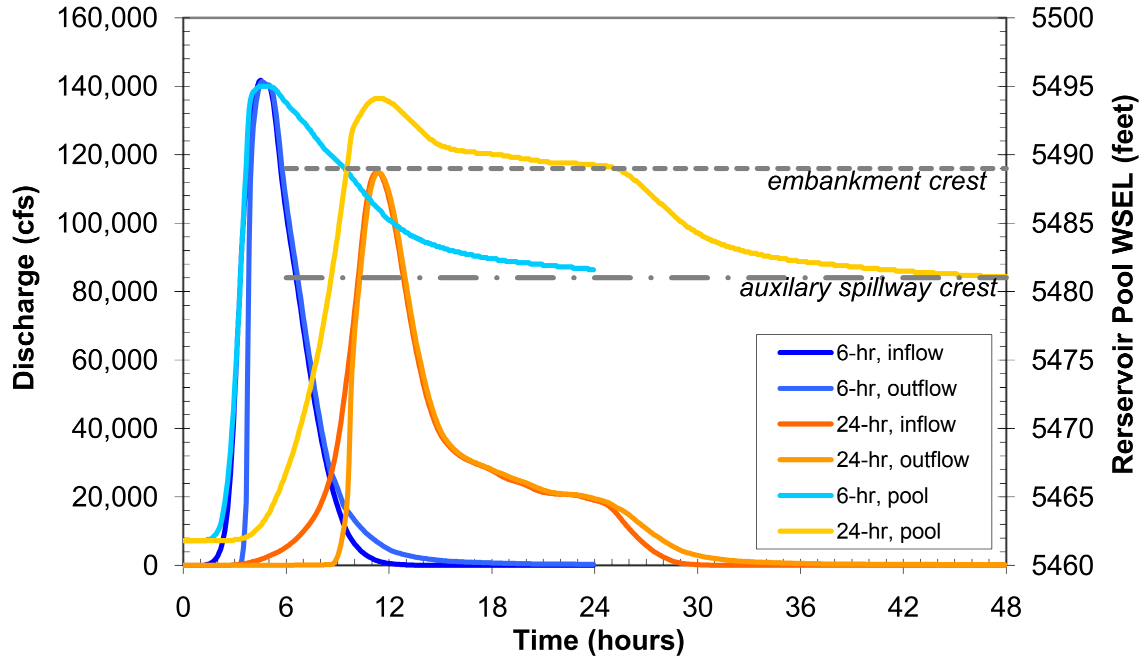

Figure 27: Hydrographs at the head and outlet of the B-3 reservoir, for the 6- and 24-hour storms.

Results from the 6-hour PMP analysis are shown in Table 11. This analysis indicates that the peak flow at the outlet of B-3 reservoir will be 141,000 cfs, which represents a peak flow yield of 2300 cfs/mi^2. The auxilary spillway has a conveyance capacity of about 17,000 cfs; the spillway can only convey about **12 percent** of the peak flow resulting from the 6-hour PMP. At the 140,000 cfs peak flow, the embankment would be overtopped by a maximum of 6.0 feet, with an overtopping duration of 5.8 hours. Considering the lack of armor and patchy vegetative cover of the downstream face (Figure 12), the embankment will most likely fail in the case of a 6-hour PMP in the Boxelder B-3 watershed. For the 6-hour storm, the existing structure will convey approximately **36 percent** of the PMP event.

Results from the 24-hour PMP analysis are shown in Table 12. This analysis indicates that the peak flow at the outlet of B-3 reservoir will be 113,000 cfs, which represents a peak flow yield of 1860 cfs/mi^2. The spillway can only convey about **15 percent** of the peak flow resulting from the 24-hour PMP. At the 113,000 cfs peak flow, the embankment would be overtopped by a maximum of 5.1 feet, with an overtopping duration of 15.5 hours. For the 24-hour storm, the existing structure will convey approximately **37 percent** of the PMP event.

Table 11: B-3 hydrologic model results, 6-hour PMP event.

Hydrologic Element	Peak Discharge (cfs)	Time of Peak	Total Volume (ac-ft)	Runoff Depth (inches)	Contributing Area (mi^2)	Peak Yield (cfs/mi^2)
B3-1	12,100	19Jul2009, 16:00	3,279	12.8	4.80	2519
B3-2	8,400	19Jul2009, 15:20	1,699	12.5	2.54	3304
Junction-1	18,800	19Jul2009, 15:40	4,978	12.7	7.35	2560
B3-3	3,300	19Jul2009, 14:35	388	16.6	0.44	7551
B3-4	11,700	19Jul2009, 15:15	2,265	12.7	3.34	3504
Junction-2	29,600	19Jul2009, 15:30	7,632	12.9	11.12	2662
B3-5	10,200	19Jul2009, 14:45	1,359	13.2	1.93	5277
Junction-3	33,000	19Jul2009, 15:35	8,991	12.9	13.05	2528
B3-6	17,800	19Jul2009, 15:45	4,398	14.3	5.78	3082
Junction-4	46,400	19Jul2009, 16:25	13,390	13.3	18.83	2464
B3-7	18,500	19Jul2009, 15:25	3,920	14.8	4.96	3733
B3-8	21,300	19Jul2009, 15:15	4,161	14.6	5.34	3990
Junction-5	64,300	19Jul2009, 16:40	21,475	13.8	29.13	2208
B3-9	15,400	19Jul2009, 15:05	2,696	14.2	3.55	4338
B3-10	22,300	19Jul2009, 15:35	5,162	12.6	7.70	2898
B3-11	13,000	19Jul2009, 14:55	2,080	14.6	2.68	4854
Junction-7	31,100	19Jul2009, 15:20	7,242	13.1	10.37	2998
B3-12	17,500	19Jul2009, 15:50	4,484	14.9	5.66	3094
Junction-6	113,700	19Jul2009, 16:05	35,898	13.8	48.71	2334
B3-13	3,700	19Jul2009, 15:40	906	15.6	1.09	3394
B3-14	15,700	19Jul2009, 15:35	3,732	16.6	4.22	3723
Junction-8	127,900	19Jul2009, 16:20	40,528	14.1	54.01	2368
B3-15	9,100	19Jul2009, 15:25	1,998	14.8	2.54	3583
B3-16	5,900	19Jul2009, 17:40	2,419	15.4	2.95	2001
B3-17	5,800	19Jul2009, 15:30	1,328	16.2	1.54	3769
Boxelder B-3 inlet	140,900	19Jul2009, 16:30	46,251	14.2	61.04	2308
Boxelder B-3 outlet	140,500	19Jul2009, 16:35	42,749	13.1	61.04	2302

Table 12: B-3 hydrologic model results, 24-hour PMP event.

Hydrologic Element	Peak Discharge (cfs)	Time of Peak	Total Volume (ac-ft)	Runoff Depth (inches)	Contributing Area (mi^2)	Peak Yield (cfs/mi^2)
B3-1	9,300	19Jul2009, 22:55	4770	18.6	4.80	1933
B3-2	5,700	19Jul2009, 22:25	2484	18.3	2.54	2237
Junction-1	14,500	19Jul2009, 22:35	7255	18.5	7.35	1974
B3-3	1,300	19Jul2009, 22:00	510	21.9	0.44	2913
B3-4	7,400	19Jul2009, 22:20	3146	17.7	3.34	2208
Junction-2	22,000	19Jul2009, 22:30	10911	18.4	11.12	1977
B3-5	5,100	19Jul2009, 22:05	1956	19.0	1.93	2642
Junction-3	25,100	19Jul2009, 22:25	12867	18.5	13.05	1920
B3-6	12,700	19Jul2009, 22:40	6219	20.2	5.78	2201
Junction-4	35,900	19Jul2009, 23:20	19086	19.0	18.83	1905
B3-7	12,300	19Jul2009, 22:30	5602	21.2	4.96	2488
B3-8	13,700	19Jul2009, 22:20	5967	21.0	5.34	2558
Junction-5	51,500	19Jul2009, 23:05	30656	19.7	29.13	1769
B3-9	9,300	19Jul2009, 22:15	3890	20.5	3.55	2632
B3-10	16,100	19Jul2009, 22:35	7510	18.3	7.70	2098
B3-11	7,200	19Jul2009, 22:10	2928	20.5	2.68	2684
Junction-7	22,500	19Jul2009, 22:20	10439	18.9	10.37	2169
B3-12	12,800	19Jul2009, 22:45	6405	21.2	5.66	2258
Junction-6	91,000	19Jul2009, 23:10	51389	19.8	48.71	1869
B3-13	2,600	19Jul2009, 22:40	1255	21.6	1.09	2356
B3-14	10,400	19Jul2009, 22:35	5095	22.7	4.22	2469
Junction-8	101,900	19Jul2009, 23:15	57736	20.0	54.01	1886
B3-15	6,100	19Jul2009, 22:30	2800	20.7	2.54	2402
B3-16	4,800	20Jul2009, 00:15	3358	21.4	2.95	1643
B3-17	3,800	19Jul2009, 22:35	1823	22.2	1.54	2487
Boxelder B-3 inlet	113,500	19Jul2009, 23:20	65700	20.2	61.04	1859
Boxelder B-3 outlet	113,300	19Jul2009, 23:25	62374	19.2	61.04	1857

Boxelder B-2

Hydrologic modeling of the Boxelder B-2 watershed indicates that if a PMP event occurs, 83,300 and 117,000 acre feet of water will flow into the B-2 reservoir for the 6- and 24-hour events, respectively. In comparison, the storage capacity of the reservoir is 12,000 acre-feet. This is assuming that the B-5 and B-6 structures are breached when overtopped by more than 0.5 feet. The B-2 embankment will be substantially overtopped, by 8.7 and 6.1 feet for the 6- and 24-hour events, respectively in the case of B-5 and B-6 breaches and by 7.6 and 6.0 feet for the 6- and 24-hour events, respectively in the case of no upper dam failures. The existing spillways will convey about 37 percent of the PMP event without overtopping the B-2 embankment. Hydrographs at the head and outlet of the reservoir, as well as the reservoir pool elevations, are shown in Figure 28 for the case of B-5 and B-6 breaches and Figure 29 in the case of no upper dam failures.

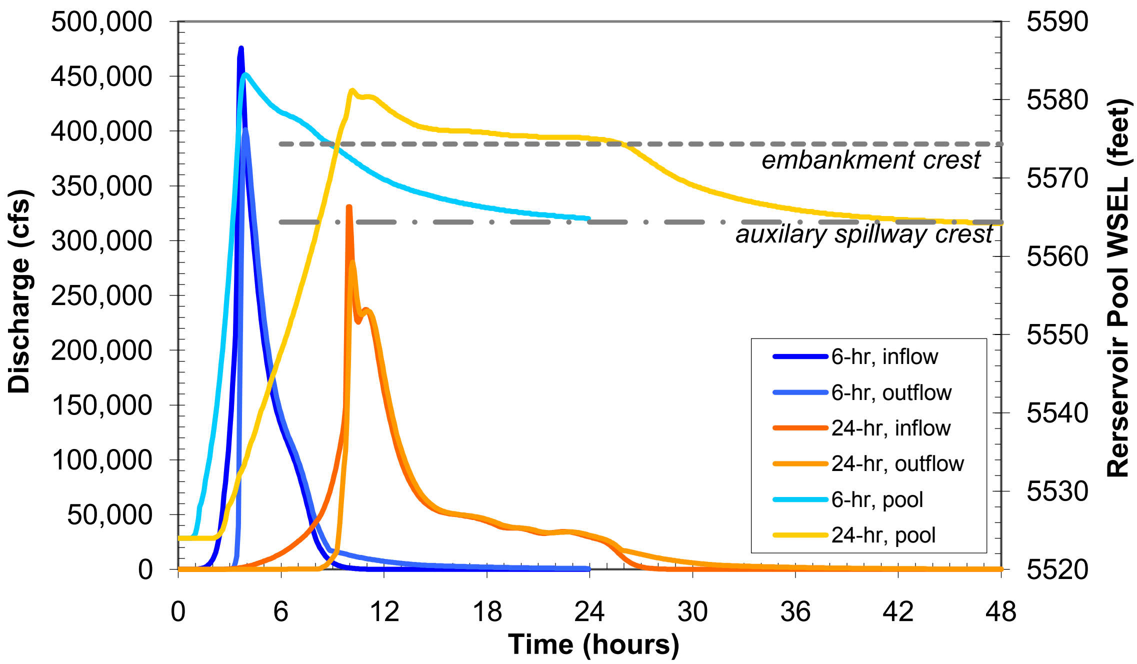

Figure 28: Hydrographs at the head and outlet of the B-2 reservoir, for the 6- and 24-hour storms, assuming breached B-5 and B-6 embankments.

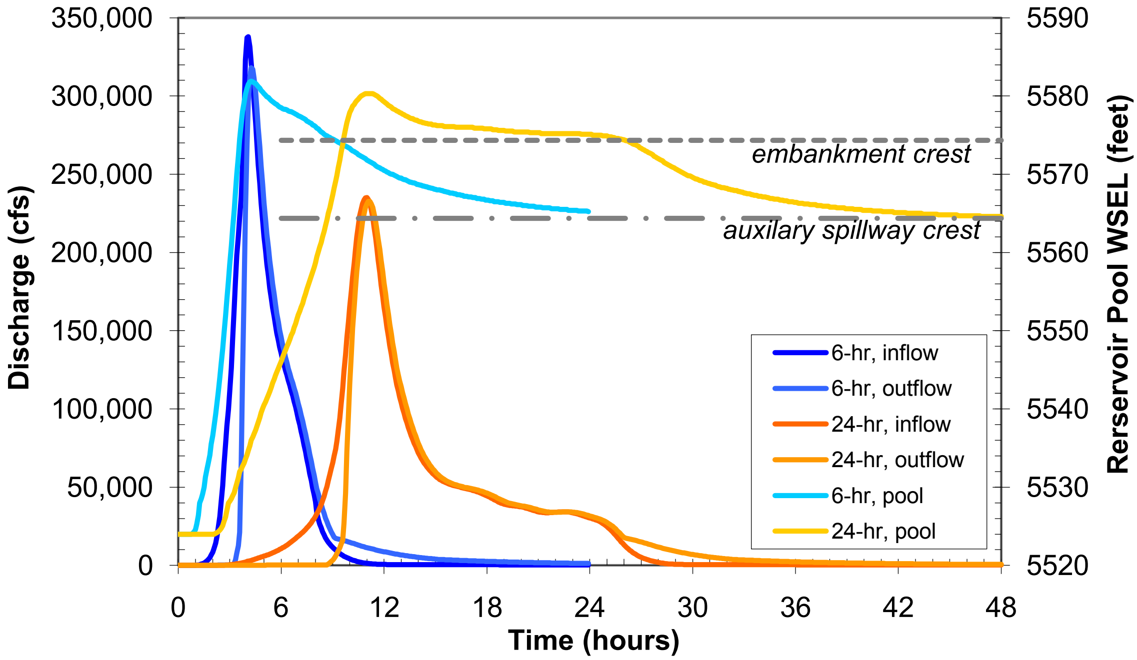

Figure 29: Hydrographs at the head and outlet of the B-2 reservoir, for the 6- and 24-hour storms, assuming the B-5 and B-6 embankments do not breach.

Results from the 6-hour PMP analysis are shown in Table 13. This analysis indicates that, in the case both the B-5 and B-6 embankments breaching, the peak flow at the outlet of B-2 reservoir will be 390,000 cfs, which represents a peak flow yield of 3600 cfs/mi^2. If the upper embankments do not fail, peak flow will be 276,000 cfs. The B-2 auxilary spillway has a conveyance capacity of about 17,500 cfs; the spillway can only convey about **4 percent** of the peak flow resulting from the 6-hour PMP (including the breaches) and **6 percent** of the peak flow assuming no upper dam breaches. At the 390,000 cfs peak flow, the embankment would be overtopped by a maximum of 8.7 feet, with an overtopping duration of 5.3 hours. Considering the lack of armor, patchy vegetative cover of the downstream face (Figure 17), and the degree of overtopping, the embankment will almost certainly fail in the case of a 6-hour PMP in the Boxelder B-2 watershed. For the 6-hour storm, the existing structure will convey approximately **37 percent** of the PMP event.

Results from the 24-hour PMP analysis are shown in Table 14. This analysis indicates that, in the case both the B-5 and B-6 embankments breaching, the peak flow at the outlet of B-2 reservoir will be 276,000 cfs, which represents a peak flow yield of 2550 cfs/mi^2. If the upper embankments do not fail, peak flow will be 231,000 cfs. The spillway can only convey about **6 percent** of the peak flow resulting from the 24-hour PMP, and **8 percent** of the peak flow assuming no upper dam breaches. At the 276,000 cfs peak flow, the embankment would be overtopped by a maximum of 6.1 feet, with an overtopping duration of 16.5 hours. For the 24-hour storm, the existing structure will convey approximately **37 percent** of the PMP event.

Table 13: B-2 hydrologic model results, 6-hour PMP event. Storm begins at 12:00.

Hydrologic Element	Contributing Area (mi^2)	**With** B-5 and B-6 Breaches Peak Discharge (cfs)	Time of Peak	Total Volume (ac-ft)	Runoff Depth (inches)	Peak Yield (cfs/mi^2)	**Without** B-5 and B-6 Breaches Peak Discharge (cfs)	Time of Peak	Total Volume (ac-ft)	Peak Yield (cfs/mi^2)
B5-1	7.0	26,400	15:20	5,479	14.6	3757	26,400	15:20	5,479	3,757
B5-2	2.8	8,600	15:35	2,045	13.7	3068	8,600	15:35	2,045	3,068
B5-3	6.2	20,600	15:30	4,653	14.1	3331	20,600	15:30	4,653	3,331
J5-2	16.0	55,600	15:30	12,178	14.3	3472	55,600	15:30	12,178	3,472
B5-4	0.5	2,700	14:40	327	13.3	5832	2,700	14:40	327	5,832
J5-3	16.5	56,200	15:30	12,506	14.2	3411	56,200	15:30	12,506	3,411
B5-5	2.5	13,600	14:45	1,942	14.7	5506	13,600	14:45	1,942	5,506
B-5 outlet	18.9	172,900	15:10	16,101	15.9	9125	60,700	15:40	12,840	3,204
B6-1	3.6	11,500	15:40	2,889	14.9	3165	11,500	15:40	2,889	3,165
B6-2	2.0	9,500	14:55	1,519	14.1	4705	9,500	14:55	1,519	4,705
B6-3	1.0	5,400	14:40	713	13.8	5561	5,400	14:40	713	5,561
J6-2	6.6	19600	15:00	5,121	14.5	2959	19600	15:00	5,121	2959
B6-4	1.8	9,200	14:50	1,392	14.8	5227	9,200	14:50	1,392	5227
J6-3	8.4	28100	15:00	6,514	14.6	3352	28100	15:00	6,514	3352
B6-5	2.9	13,400	15:00	2,260	14.5	4573	13,400	15:00	2,260	4573
B6-6	2.1	9,800	14:55	1,559	14.3	4781	9,800	14:55	1,559	4781
J6-4	13.4	51100	15:00	10,334	14.5	3824	51100	15:00	10,334	3824
B6-7	1.3	6,700	14:50	959	14.2	5305	6,700	14:50	959	5,305
B6-8	0.3	2,400	14:35	271	15.0	7101	2,400	14:35	271	7,101
B-6 outlet	15.0	144,600	14:45	13,118	16.4	9663	53,600	15:10	10,188	3,582
B2-1	3.9	18,000	14:50	2,737	13.0	4569	18,000	14:50	2,737	4,569
J2-1	18.9	156,300	14:55	15,861	15.7	8268	65,800	15:15	12,930	3,481
B2-3	1.3	6,100	14:50	888	13.0	4754	6,100	14:50	888	4,754
B2-4	2.7	11,400	15:10	2,144	14.7	4155	11,400	15:10	2,144	4,155
J2-3	23.0	179,200	15:15	19,118	15.6	7800	70,800	15:45	15,873	3,082
B2-5	4.4	18,500	15:10	3,472	14.9	4245	18,500	15:10	3,472	4,245
J2-4	27.3	195,000	15:15	22,595	15.5	7134	84,300	15:40	19,345	3,084
B2-2	3.6	13,700	15:15	2,639	13.6	3772	13,700	15:15	2,639	3,772
B2-6	1.6	10,000	14:40	1,247	14.9	6353	10,000	14:40	1,247	6,353
J2-2	51.4	303,500	15:15	42,311	15.4	5900	159,900	15:40	36,151	3,108
B2-7	5.8	19,500	15:25	4,212	13.6	3359	19,500	15:25	4,212	3,359
B2-8	6.0	18,700	15:40	4,513	14.0	3100	18,700	15:40	4,513	3,100
J2-5	63.3	331,800	15:30	51,030	15.1	5243	192,800	15:55	44,862	3,047
B2-9	4.1	17,300	15:10	3,304	14.9	4173	17,300	15:10	3,304	4,173
J2-6	67.4	336,400	15:40	54,362	15.1	4989	201,300	16:10	48,157	2,986
B2-10	2.6	8,000	15:15	1,558	11.3	3097	8,000	15:15	1,558	3,097
B2-11	2.4	9,600	15:05	1,750	13.6	3980	9,600	15:05	1,750	3,980
J2-8	5.0	17,300	15:15	3,308	12.4	3463	17,300	15:15	3,308	3,463
B2-12	4.2	11,000	15:45	2,766	12.2	2596	11,000	15:45	2,766	2,596
B2-13	2.3	8,700	15:10	1,600	13.3	3858	8,700	15:10	1,600	3,858
J2-9	11.5	35,100	15:20	7,674	12.5	3055	35,100	15:20	7,674	3,055
B2-14	1.1	4,900	14:55	787	13.3	4426	4,900	14:55	787	4,426
B2-15	6.8	24,900	15:15	4,821	13.3	3661	24,900	15:15	4,821	3,661
J2-10	19.4	62,400	15:20	13,283	12.8	3217	62,400	15:20	13,283	3,217
B2-17	2.2	8,600	15:05	1,555	13.1	3872	8,600	15:05	1,555	3,872
B2-18	3.7	11,900	15:25	2,518	12.8	3232	11,900	15:25	2,518	3,232
B2-19	2.5	9,300	15:15	1,837	13.8	3716	9,300	15:15	1,837	3,716
J2-13	8.4	28,700	15:30	5,911	13.2	3414	28,700	15:30	5,911	3,414
B2-16	2.1	7,000	15:30	1,593	14.0	3277	7,000	15:30	1,593	3,277
B2-20	1.3	3,800	15:40	934	13.9	3018	3,800	15:40	934	3,018
J2-11	31.2	101,200	15:40	21,715	13.1	3244	101,200	15:40	21,715	3,244
B2-21	1.7	7,300	15:00	1,235	13.9	4382	7,300	15:00	1,235	4,382
B2-22	2.3	9,600	15:00	1,569	12.9	4203	9,600	15:00	1,569	4,203
B2-23	3.0	13,600	15:00	2,248	14.1	4535	13,600	15:00	2,248	4,535
B2-24	1.0	2,800	15:40	679	12.8	2811	2,800	15:40	679	2,811
J2-15	39.1	116,700	16:00	27,437	13.1	2981	116,700	16:00	27,437	2,981
B2-25	2.0	9,000	15:00	1,521	14.5	4587	9,000	15:00	1,521	4,587
B-2 inlet	108.5	448,800	15:45	83,300	14.4	4135	319,700	16:05	77,100	2,946
B-2 outlet	108.5	389,800	16:00	76,606	13.2	3592	304,000	16:20	70,190	2,801

Table 14: B-2 hydrologic model results, 24-hour PMP event. Storm begins at 12:00.

		With B-5 and B-6 Breaches					**Without** B-5 and B-6 Breaches			
Hydrologic Element	Contributing Area (mi^2)	Peak Discharge (cfs)	Time of Peak	Total Volume (ac-ft)	Runoff Depth (inches)	Peak Yield (cfs/mi^2)	Peak Discharge (cfs)	Time of Peak	Total Volume (ac-ft)	Peak Yield (cfs/mi^2)
B5-1	7.0	16,600	22:25	7,694	20.5	2363	16,600	22:25	7,694	2,363
B5-2	2.8	6,200	22:35	3,036	20.3	2212	6,200	22:35	3,036	2,212
B5-3	6.2	14,300	22:30	6,851	20.8	2312	14,300	22:30	6,851	2,312
J5-2	16.0	37,200	22:35	17,581	20.6	2323	37,200	22:35	17,581	2,323
B5-4	0.5	1,200	22:00	470	19.0	2592	1,200	22:00	470	2,592
J5-3	16.5	37,700	22:35	18,051	20.5	2288	37,700	22:35	18,051	2,288
B5-5	2.5	6,700	22:05	2,719	20.6	2713	6,700	22:05	2,719	2,713
B-5 outlet	18.9	149,100	21:25	22,387	22.2	7869	41,900	22:35	19,240	2,211
B6-1	3.6	7,900	22:40	4,036	20.8	2175	7,900	22:40	4,036	2,175
B6-2	2.0	5,200	22:10	2,152	20.0	2576	5,200	22:10	2,152	2,576
B6-3	1.0	2,600	22:00	1,017	19.6	2678	2,600	22:00	1,017	2,678
J6-2	6.6	14400	22:10	7,205	20.4	2174	14400	22:10	7,205	2,174
B6-4	1.8	4,600	22:05	1,873	20.0	2614	4,600	22:05	1,873	2,614
J6-3	8.4	18800	22:15	9,078	20.31	2243	18800	22:15	9,078	2,243
B6-5	2.9	7,300	22:10	3,057	19.6	2491	7,300	22:10	3,057	2,491
B6-6	2.1	5,300	22:10	2,200	20.1	2585	5,300	22:10	2,200	2,585
J6-4	13.4	31200	22:15	14,336	20.11	2335	31200	22:15	14,336	2,335
B6-7	1.3	3,200	22:05	1,302	19.3	2534	3,200	22:05	1,302	2,534
B6-8	0.3	1,000	22:00	377	20.9	2959	1,000	22:00	377	2,959
B-6 outlet	15.0	125,000	21:05	17,556	22.0	8353	34,600	22:20	14,720	2,312
B2-1	3.9	9,900	22:05	3,947	18.8	2513	9,900	22:05	3,947	2,513
J2-1	18.9	118,100	21:15	21,513	21.3	6247	43,300	22:20	18,665	2,291
B2-3	1.3	3,300	22:05	1,281	18.7	2572	3,300	22:05	1,281	2,572
B2-4	2.7	6,800	22:20	3,006	20.5	2478	6,800	22:20	3,006	2,478
J2-3	23.0	148,700	21:30	26,671	21.8	6473	50,500	22:30	23,526	2,198
B2-5	4.4	11,000	22:15	4,846	20.9	2524	11,000	22:15	4,846	2,524
J2-4	27.3	155,800	21:30	31,522	21.6	5700	61,100	22:30	28,372	2,235
B2-2	3.6	8,500	22:20	3,686	19.0	2340	8,500	22:20	3,686	2,340
B2-6	1.6	4,300	22:00	1,709	20.4	2732	4,300	22:00	1,709	2,732
J2-2	51.4	254,700	21:30	58,407	21.3	4951	114,600	22:30	52,425	2,228
B2-7	5.8	13,400	22:30	6,124	19.8	2308	13,400	22:30	6,124	2,308
B2-8	6.0	13,400	22:40	6,513	20.2	2221	13,400	22:40	6,513	2,221
J2-5	63.3	263,500	21:45	70,995	21.0	4164	140,500	22:45	65,051	2,220
B2-9	4.1	10,500	22:20	4,606	20.8	2533	10,500	22:20	4,606	2,533
J2-6	67.4	262,300	22:00	75,620	21.0	3890	147,800	23:00	69,645	2,192
B2-10	2.6	5,200	22:20	2,220	16.1	2013	5,200	22:20	2,220	2,013
B2-11	2.4	5,600	22:15	2,399	18.7	2322	5,600	22:15	2,399	2,322
J2-8	5.0	10,800	22:20	4,619	17.3	2162	10,800	22:20	4,619	2,162
B2-12	4.2	7,900	22:45	3,877	17.2	1864	7,900	22:45	3,877	1,864
B2-13	2.3	5,400	22:15	2,295	19.1	2395	5,400	22:15	2,295	2,395
J2-9	11.5	23,700	22:25	10,791	17.6	2063	23,700	22:25	10,791	2,063
B2-14	1.1	2,700	22:10	1,104	18.7	2439	2,700	22:10	1,104	2,439
B2-15	6.8	15,700	22:20	6,771	18.7	2308	15,700	22:20	6,771	2,308
J2-10	19.4	41,300	22:25	18,667	18.0	2129	41,300	22:25	18,667	2,129
B2-17	2.2	5,100	22:15	2,148	18.1	2296	5,100	22:15	2,148	2,296
B2-18	3.7	8,000	22:25	3,565	18.2	2173	8,000	22:25	3,565	2,173
B2-19	2.5	5800	22:20	2,560	19.2	2317	5800	22:20	2,560	2,317
J2-13	8.4	18,400	22:30	8,273	18.5	2189	18,400	22:30	8,273	2,189
B2-16	2.1	4,900	22:35	2,300	20.2	2294	4,900	22:35	2,300	2,294
B2-20	1.3	2800	22:40	1,351	20.1	2224	2800	22:40	1,351	2,224
J2-11	31.2	67,000	22:45	30,589	18.4	2148	67,000	22:45	30,589	2,148
B2-21	1.7	4,200	22:10	1,751	19.7	2521	4,200	22:10	1,751	2,521
B2-22	2.3	5,700	22:10	2,311	19.0	2496	5,700	22:10	2,311	2,496
B2-23	3.0	7700	22:10	3,179	19.9	2568	7700	22:10	3,179	2,568
B2-24	1.0	2,000	22:40	982	18.5	2008	2,000	22:40	982	2,008
J2-15	39.1	80,300	22:55	38,810	18.6	2052	80,300	22:55	38,810	2,052
B2-25	2.0	5,100	22:10	2,134	20.4	2599	5,100	22:10	2,134	2,599
B-2 inlet	108.5	329,100	22:00	116,600	20.1	3032	231,200	23:00	110,600	2,130
B-2 outlet	108.5	276,400	22:10	110,151	19.0	2547	228,700	23:10	104,003	2,107

Boxelder B-6

In the case of a PMP event in the Boxelder B-6 watershed, peak discharge is modeled to be 145,000 cfs at the outlet (54,000 cfs with an assumption of no breach and a maximum of 5.4 feet of overtopping for 3.8 hours) for the 6-hour event. For the 24-hour event, the peak flow is 125,000 cfs, with 35,000 cfs modeled assuming no breach and a maximum of 3.5 feet of overtopping for 4.4 hours. Additional details on peak flows within this watershed are provided in Tables 13 and 14.

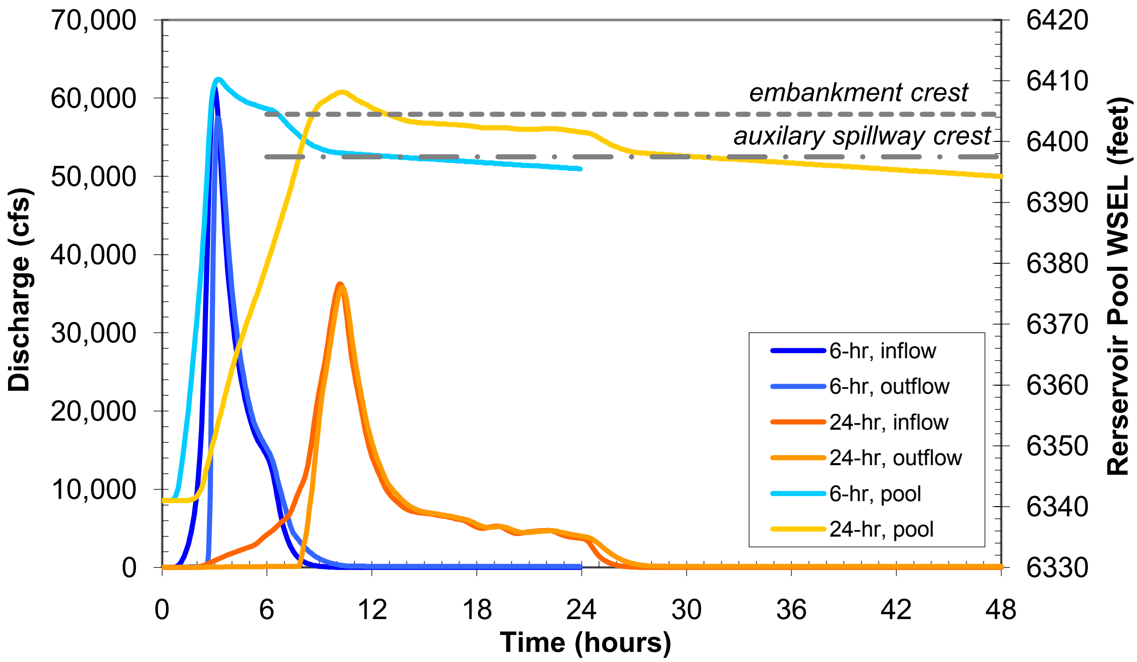

Figure 30: Hydrographs at the head and outlet of the B-6 reservoir, for the 6- and 24-hour storms, assuming the embankment **does not** breach.

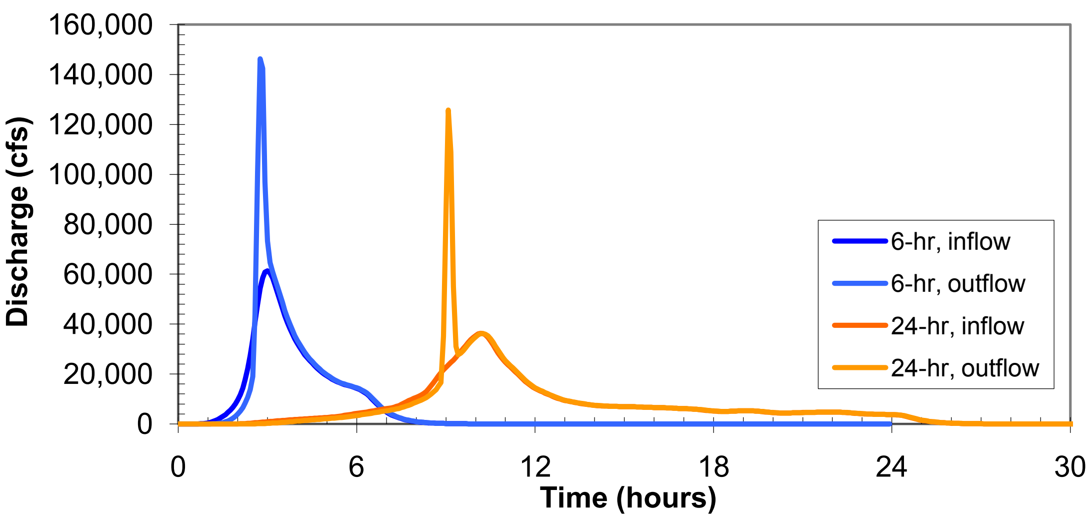

Figure 31: Hydrographs at the head and outlet of the B-6 reservoir, for the 6- and 24-hour storms, assuming the embankment **does** breach.

Boxelder B-5

In the case of a PMP event in the Boxelder B-5 watershed, peak discharge is modeled to be 173,000 cfs at the outlet (61,000 cfs with an assumption of no breach and a maximum of 5.2 feet of overtopping for 3.3 hours) for the 6-hour event. For the 24-hour event, the peak flow is 149,000 cfs, with 42,000 cfs modeled assuming no breach and a maximum of 3.6 feet of overtopping for 3.1 hours. Additional details on peak flows within this watershed are provided in Tables 13 and 14.

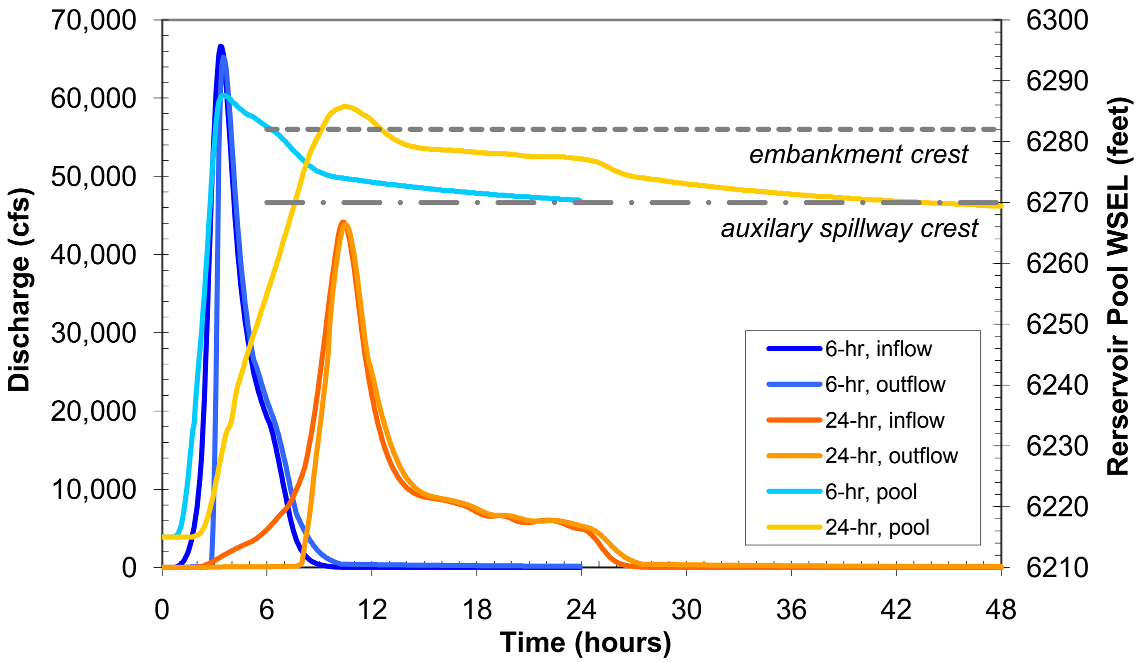

Figure 32: Hydrographs at the head and outlet of the B-5 reservoir, for the 6- and 24-hour storms, assuming the embankment **does not** breach.

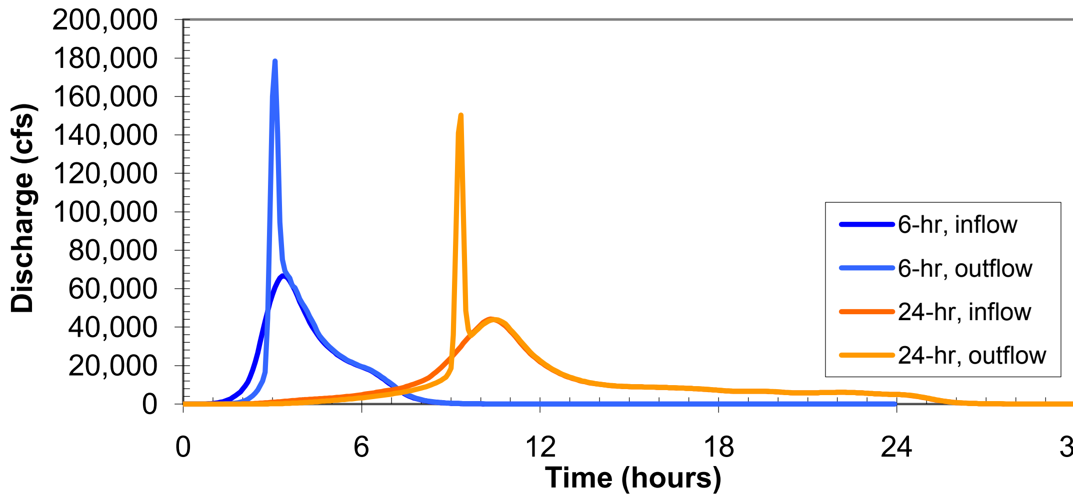

Figure 33: Hydrographs at the head and outlet of the B-5 reservoir, for the 6- and 24-hour storms, assuming the embankment **does** breach.

Comparison to Past Storms

At first glance, the extreme runoff may seem unreasonable. Comparing this simulated runoff with the runoff response from actual extreme events can help judge the reasonableness of these predictions.

On May 30 and 31, 1935 a series of convective storms (Cherry Creek storm) broke out in Colorado east of Colorado Springs between the Front Range and the Kansas border. These storms were small in aerial extent but extreme in intensity. Within the Kiowa Creek watershed, a non-mountainous watershed flowing off of elevated forest and lower rangeland (having a similar setting as the Boxelder watersheds), an extreme localized cell dropped up to 24 inches of rain in 6-hours (Hansen et. al. 1988) within or adjacent to the Kiowa Creek watershed. (Note that the 10-mi^2 6-hour PMP in the Boxelder watersheds is 23 to 24 inches.) The resulting flood had a peak flow of 43,500 cfs on 5/30/1935 at USGS streamgage *Kiowa Creek at Elbert* (ID 06758000, elevation 6740 feet), a 28.6 square mile watershed. This flow represents a peak flow yield of 1520 cfs/mi^2. This yield is comparable to the modeled yields in the B-3 and B-2 watersheds.

From June 13 through 20, 1965, heavy convective rainstorms (Plum Creek storm) occurred in the vicinity as the Cherry Creek storm. During the most intense period, on June 16 and 17, up to 18.1 inches of rain fell within a 24-hour period, with rainfall depths over 5 inches common (Hansen et. al. 1988). Up to 14 inches of precipitation fell just south of the Kiowa Creek watershed. The 28.6 square mile Kiowa Creek at Elbert gage recorded a peak flow of 41,500 cfs from this event. This flow represents a peak flow yield of 1450 cfs/mi^2. It is quite interesting that two such large rainfall-runoff events occurred (and were recorded) in the same watershed during a span of three decades.

Numerous other extreme precipitation events have occurred along Colorado's Front Range, with the older events used in the computation of PMP estimates for these areas. Examples include the Big Elk Meadow event (5/4 to 5/8/1969), with up to 20 inches of rain over 4 days over a broad swath of the foothills from Fort Collins to Castle Rock; the notorious Big Thompson event (7/31 to 8/1/1976), with up to 12 inches of rain in 4 hours; and the Fort Collins event (7/28/1997), with up to 5 inches of rain in 1.5 hours, 10 inches in 5 hours and 14.5 inches in two days (Doesken and McKee 1998). It is clear that extreme precipitation events, though they occur infrequently, do regularly occur in this region.

CONCLUSIONS

Rainfall-runoff analyses were performed to assess the impact of a probable maximum precipitation (PMP) event on the Boxelder flood control structures. The analysis consists of hydrologic models that simulate a PMP event for the B-2, -3, -4, -5 and -6 structure watersheds, producing runoff from sub-basins within the watersheds and routing the storm flow through channels and reservoirs to the watershed outlets. The B-2 structure is a dams-in-series situation, with the B-5 and B-6 structures nested upstream.

The generalized PMP for a 10 mi^2 watershed area varies, from 24 to 23 inches for the 6-hour event and 31 to 30 inches for the 24-hour event. Accounting for watershed area, these precipitation depths were adjusted from 77 to 98 percent of the 10 mi^2 storm.

Composite CNs for the watersheds catchments range from 70.2 to 70.8 for B-4, 57.8 to 75.4 for B-3, and 58.3 to 84.4 for B-2. Lag times of the catchements ranged from 23 to 51 minutes for B-4, 18 to 128 minutes for B-3, and 16 to 72 minutes for B-2.

For the 6-hour storm, peak flow at the outlet of **B-4** reservoir will be **78,200 cfs**, which represents a peak flow yield of 5700 cfs/mi^2. At this peak flow, the embankment would be overtopped by a maximum of **4.0 feet**, with an overtopping duration of 3.8 hours. The existing B-4 structure will convey approximately **45 percent** of the PMP event. Peak flow at the outlet of **B-3** reservoir will be **141,000 cfs**, which represents a peak flow yield of 2300 cfs/mi^2. At this peak flow, the embankment would be overtopped by a maximum of **6.0 feet**, with an overtopping duration of 5.8 hours. The existing B-3 structure will convey approximately **36 percent** of the PMP event. Peak flow at the outlet of **B-2** reservoir will be **390,000 cfs** (assuming B-5 and B-6 dam breaches), which represents a peak flow yield of 3600 cfs/mi^2. If the upper embankments do not fail, peak flow will be **304,000 cfs**. At the 390,000 cfs peak flow, the embankment would be overtopped by a maximum of **8.7 feet**, with an overtopping duration of 5.3 hours. For the 6-hour storm, the existing B-2 structure will convey approximately **37 percent** of the PMP event.

For the 24-hour storm, peak flow at the outlet of **B-4** reservoir will be **44,000 cfs**, which represents a peak flow yield of 3210 cfs/mi^2. At this peak flow, the embankment would be overtopped by a maximum of **2.3 feet**, with an overtopping duration of 3.7 hours. The existing B-4 structure will convey approximately **46 percent** of the PMP event. The peak flow at the outlet of **B-3** reservoir will be **113,000 cfs**, which represents a peak flow yield of 1860 cfs/mi^2. At this peak flow, the embankment would be overtopped by a maximum of 5.1 feet, with an overtopping duration of 15.5 hours. The existing B-3 structure will convey approximately **37 percent** of the PMP event. Peak flow at the outlet of the **B-2** reservoir B-2 reservoir will be **276,000 cfs** (assuming B-5 and B-6 breaches), which represents a peak flow yield of 2550 cfs/mi^2. If the upper embankments do not fail, peak flow will be **229,000 cfs**. At the 276,000 cfs peak flow, the B-2 embankment would be overtopped by a maximum of 6.1 feet, with an overtopping duration of 16.5 hours. For the 24-hour storm, the existing B-2 structure will convey approximately **37 percent** of the PMP event.

Considering the lack of armor, patchy vegetative cover of the downstream face, and substantial depth and duration of overtopping for all five Boxelder flood control reservoirs, all the embankments will likely fail in the case of either a 6-hour or 24-hour PMP event.

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