APPENDIX 13-C
GALORE CREEK DAM FAILURE ANALYSIS

GALORE CREEK DAM FAILURE ANALYSIS

Prepared for:

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Baird

Oceans, Lakes & Rivers

Galore Creek Dam Failure Analysis

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PROJECT UNDERSTANDING

Baird & Associates was retained by Rescan to undertake a numerical analysis of a dam failure for the proposed dam on Galore Creek, British Columbia, Canada. The dam is composed primarily of rock and earth. The impoundment or pond behind the dam is divided into two areas; a waste rock storage area and a tailings storage area. The HEC-RAS numerical model has been employed with model input terrain which is based on public topographic data sources. Model breach parameters and failure conditions have been provided to Baird by Rescan.

The dam failure analysis that is described in the following sections was performed to determine the magnitude and duration of flows from a variety of breaching scenarios of a proposed dam on Galore Creek. This analysis was performed consistent with typical practices for modeling dam failures for large hydropower dams using the numerical HEC-RAS model. As is the case for such numerical modeling studies, the interpretation of the results requires a familiarity of the assumptions used by the model, before assessing their significance. In the case of dam failure modeling, the most critical aspect of this is the underlying assumptions used for the numeric approximation of the formation of dam breaches. Although many case studies have been performed (post-mortem), there are no well-defined standards for the breach parameters. However, the results of numerical dam failure analyses can be quite useful for assessing the “range of possibilities” for this unlikely event.

This sensitivity analysis is qualitative, and the results should be used only to assess the relative difference in flooding depths due to the various permutations of breach parameters and reservoir volume. The model of the downstream river valley is based on remotely-sensed channel geometry, which is indicative of the water surface at the time of the capture of the aerial imagery, and NOT the actual channel bottom. These types of data are suitable and appropriate for numerical modeling of breach outflow, since the flow from the breached impoundment is "riding" on top of the antecedent flow. Although the resulting flood depth estimates have a degree of uncertainty regarding the exact flood elevation at a given location, this methodology is sound for determining the relative differences in flooding due to varying breach sizes, time of failure, impoundment size, etc.

In summary, this methodology is a cost-effective means of qualitatively assessing the flooding due to the uncontrolled release resulting from a dam breach. An analysis with greater detail and precision would require surveyed cross-sections of the river, utilizing GPS surveying equipment capable of sub-meter (minimally) accuracy.

METHODOLOGY AND ASSUMPTIONS

The following is a brief description of the steps used to develop the model and perform the analyses.

1. Physical data processing. The model was developed from public digital elevation data from Canada and the United States of America. These data were gathered from various sources via the web, and processed with GIS tools to derive a dataset that was suitable for developing into the framework for HEC-GeoRAS and HEC-RAS. The following data sources were used for this study.

    - The Canadian digital elevation models (DEM) were downloaded from the Geobase web portal, provided by the Government of Canada, Natural Resources, Canada Centre for Topographic Information. The 1:50000 digital elevation data are based on National Topographic Data Base (NTDB) digital data files and had a resolution of approximately 14 meters. These data are based upon paper National Topographic System (NTS) maps originally compiled in the 1960's. Ten DEMs were downloaded in order to cover the study area. These were later mosaiced using ArcToolbox – 'Mosaic to New Raster' utility (in ArcGIS 9.1) to form a single DEM for the Canadian side.

    - Digital elevation data for the United States were obtained from the USGS EROS Data Center's online Seamless Data Distribution Delivery website. A single DEM was obtained for US coverage. This DEM is considered the best available data, and is calculated to have a resolution of approximately 35 metres.

    - LandSat7 imagery was obtained from the Global Land Cover Facility website (University of Maryland). A single LandSat7 image (Path 56 Row 20) acquired 1999-Aug-12 was downloaded for the project area.

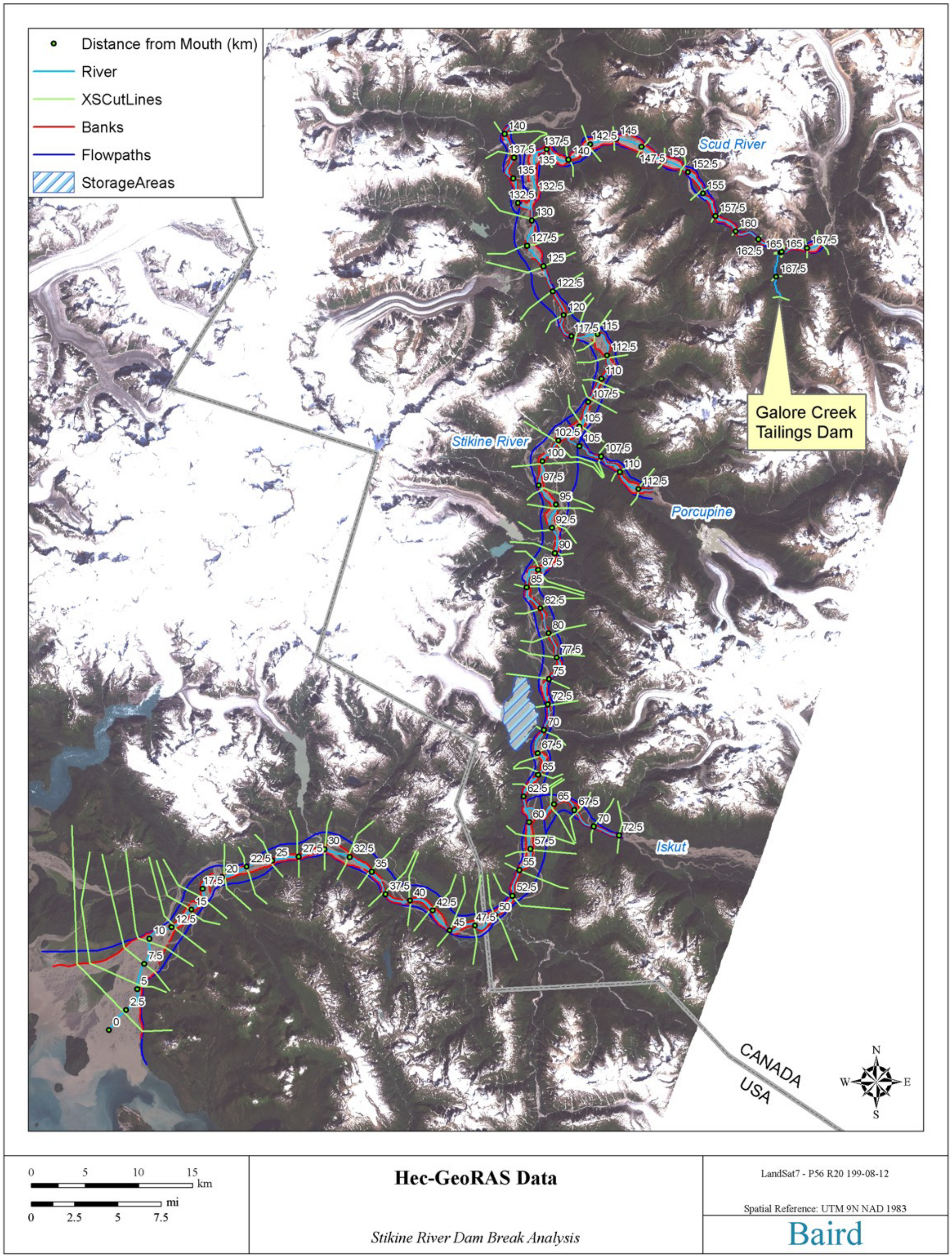

Figure 1. HEC GeoRAS Data Collection

2. HEC-GeoRAS Processing. This step involved the use of HEC-GeoRAS, which is a GIS preprocessor for HEC-RAS. It includes processing routines to develop the two-dimensional data for use with HEC-RAS.

3. HEC-RAS Model Development. This included the processing of the GIS data into the format required by the model for modeling river flows, as well as the data necessary to model the dam and breach outflows.

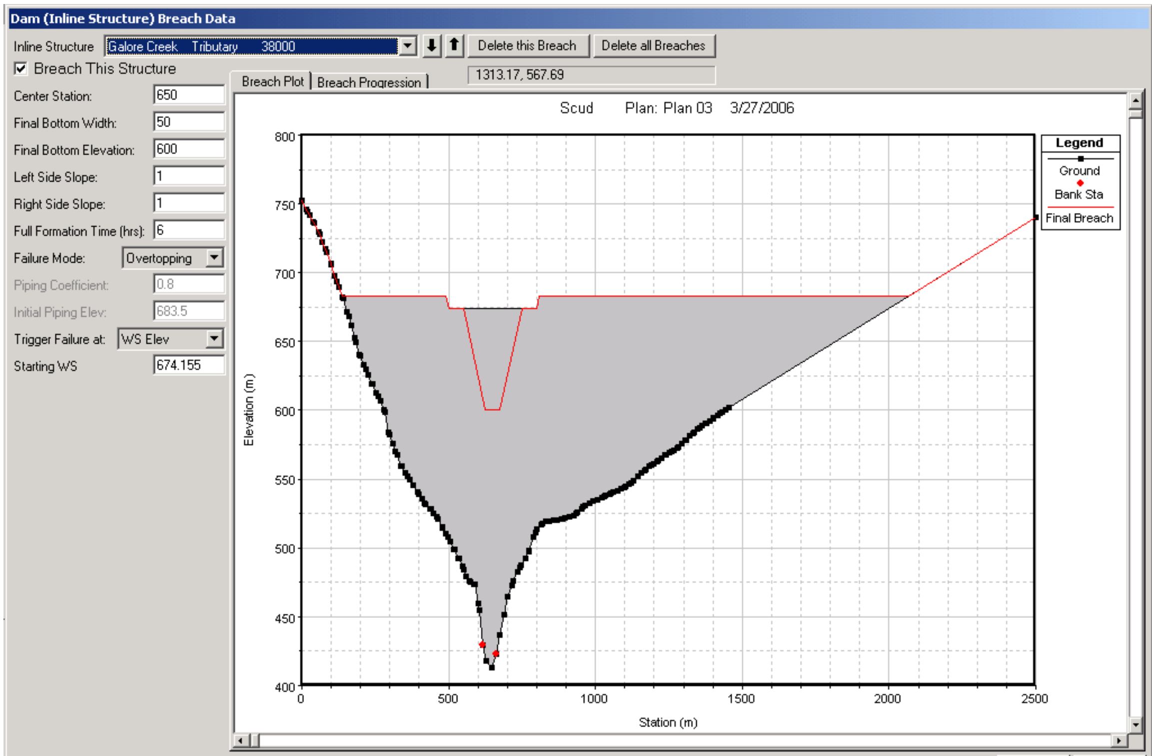

Figure 2. Screen Shot of the HEC-RAS Breach Editor

4. Flow Frequency Analysis. The flows on the Stikine River, as measured by the USGS at the Stikine Gage #15024800, were analyzed to determine the frequency and range of flows from the last 30 years of record. The flow-frequency data will be used as a comparison of breach flows to the naturally occurring flows.

5. The HEC-RAS model is designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels. The model includes two modes:

    - Steady-state – for computing flood profiles for flood peaks.

    - Unsteady-state – which uses the full St. Venant equation to account for the volume and energy associated with fluid flow.

    The unsteady-state component of the HEC-RAS modeling system is capable of simulating one-dimensional unsteady flow through a full network of open channels, and was adapted from Dr. Robert L. Barkau's UNET model. The unsteady flow component was developed primarily for subcritical flow regime calculations. The hydraulic calculations for cross-sections, bridges, culverts, and other hydraulic structures that were developed for the steady flow component were incorporated into the unsteady flow module.

6. Unsteady-State Hydrodynamic (HEC-RAS) Model Application. The geometry data, as developed in the previously-described steps, were coded into a HEC-RAS model. The model was broken into two model reaches – one from the dam to the confluence of the Scud and Stikine Rivers, and the other from just upstream of the Scud/Stikine confluence down to the mouth of the Stikine River. The base flow in the model was set at 4,500 cms, which is between a one-year and two-year event. The flows routed through the model include baseline flows, as well as flows released through the breach in the Galore Creek Dam. The HEC-RAS model included 12 distinct scenarios that covered different combinations of impoundment configurations and breach types.

FLOW FREQUENCY ANALYSIS OF THE STIKINE RIVER

A flow frequency analysis of the Stikine River was performed to characterize the flows on the river, and to be used as a basis for comparison with the flows arising from the simulated breach outflows. The USGS gauge on the Stikine River has been in continuous operation since 1976. The resulting flow frequency curve is shown graphically in Figure 3, and tabulated in Table 1. As mentioned previously, the background flows selected for use in the HEC-RAS model were less than a two-year flood. The flows on the various stream portions were pro-rated according to the appropriate drainage area.

This analysis provides a basis for comparison of breach flows to the naturally-occurring flows.

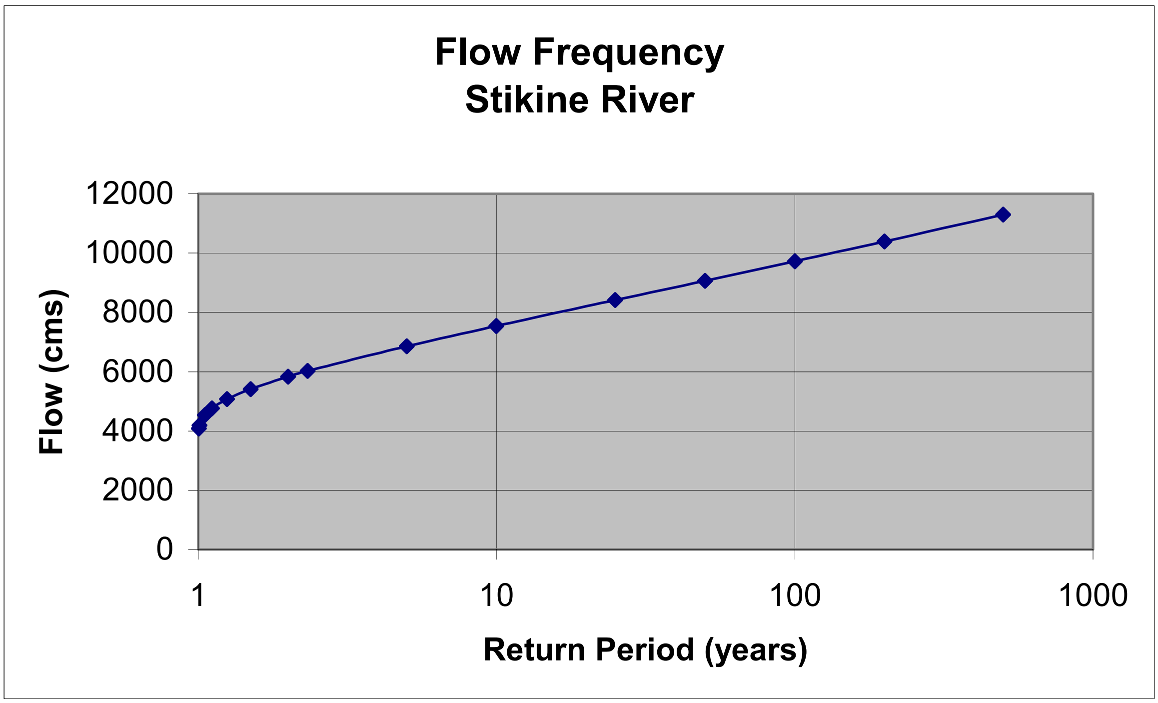

Figure 3. Flow Frequency - Stikine River

The estimated drainage area of the various stream portions include the following.

- The drainage of the entire Stikine River is 51,600 sq. km.
- The drainage area of the Scud River is 1,104 sq. km.
- The drainage area of the Scud River above Galore Creek is 625 sq. km.

Table 1. Tabulation of Flow Frequency Curve

Return Period (years)	Flow (cms)
1.01	4190
1.25	5080
1.5	5420
2	5830
2.5	6030
5	6860
10	7540
25	8410
50	9070
100	9720
200	10390
500	11300

DAM SPECIFICATIONS AND GENERAL ASSUMPTIONS

A list of notable dam specifications and general assumptions used to develop the input parameters for the HEC-RAS model analysis follows.

- The techniques employed in this analysis are consistent with methods described in the modeling and technical manuals for HEC-RAS (HEC, 2002a and 2002b), a technical paper by Dr. D.L. Fread (author of the NWS-DAMBRK model) on breach parameters (Fread, 1988), and USACE Engineering Manual 1110-2-1420 (USACE, 1997).

- The Galore Creek impoundment is divided into two areas; a waste rock storage area and a tailings storage area.

- At mid-life, the Galore Creek Dam crest elevation will be 643 metres and the spillway height will be 633 metres. At mid-life the elevation of tailings solids in the pond will be approximately 606 metres. Therefore, the depth of free water in the impoundment at this time is approximately 27 metres.

- At end-of-life, the Galore Creek Dam crest elevation will be 683 metres and the spillway height will be 674 metres. At end-of-life the elevation of tailings solids in the pond will be approximately 658 metres. Therefore, the depth of free water in the impoundment at this time is approximately 16 metres.

- The tailings material is assumed to be predominantly rock and sediment, the waste rock may contain up to 30 percent of void space. Therefore, the volume of free water in the impoundment below the noted tailings levels cannot, for the purpose of this study, be accurately described or calculated. For this reason and that of the conservative catastrophic flow event, the model treated all material behind the dam as free water.

- The piping breach elevation was assumed at elevation 600 metres for all piping-mode failures. This may be conservative, because the lowest elevation of estimated free water for the model stages is assumed to be 606 metres. The assumptions used in piping-mode failure modeling include the progression of the "pipe" orifice in upward and downward directions. This means that the circular opening enlarges from the origin until the "pipe" is large enough to fail the embankment entirely. Although somewhat conservative, it is still appropriate for a study of this nature.

HYDRODYNAMIC MODEL AND DAM BREAK SCENARIOS

The HEC-RAS model was developed to simulate flows from Galore Creek, to the Scud River, and down to the mouth of the Stikine River. The key model input data include channel cross-section shape and roughness, and antecedent flow amounts. The numerical stability, although not the theoretical accuracy, of the model is highly dependent on the computational time step used by the model. The model computes a flow profile throughout the river for each time step. For model analyses, including breaching of structures such as this study, the time steps used by the model range from less than a minute up to 6 minutes. Input files for the model were developed to include variants for the mid-life and end-of-life build-out scenarios, and for the following combinations of breaching scenarios.

Table 2. Model Scenarios

Scenario	Project Phase	Failure Mode	Breach Formation Time (hrs)
1	Mid-life	Overtopping	6
2	Mid-life	Overtopping	12
3	Mid-life	Overtopping	24
4	Mid-life	Piping	6
5	Mid-life	Piping	12
6	Mid-life	Piping	24
7	End-of-life	Overtopping	6
8	End-of-life	Overtopping	12
9	End-of-life	Overtopping	24
10	End-of-life	Piping	6
11	End-of-life	Piping	12
12	End-of-life	Piping	24

Mid-Life Overtopping Failure Parameters

The breach parameters for the mid-life dam case are:

Mid-life dam elevation:	643 metres
Spillway elevation:	633 metres
Side slope of breach:	45 degrees, (1:1 ratio)
Final breach elevation:	600 metres
Final breach width (top):	136 metres
Final breach width (base):	50 metres

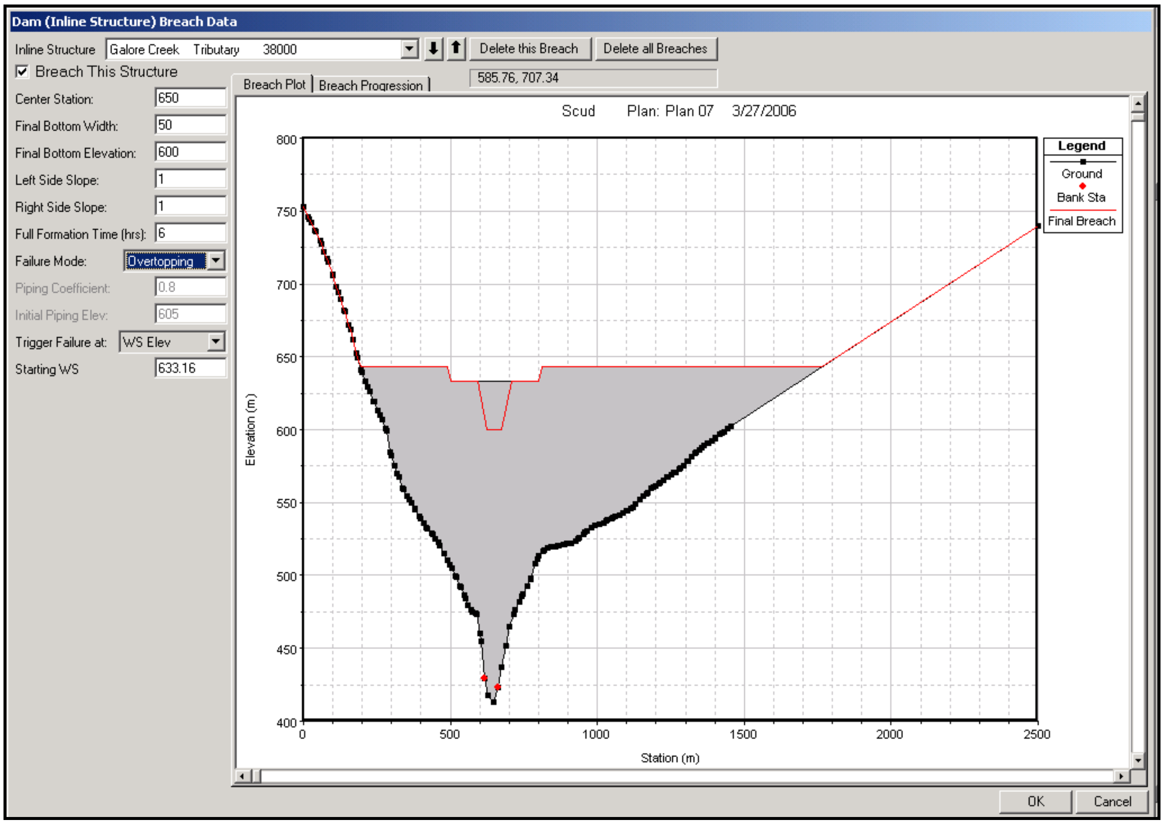

Figure 4. Breach Editor Screenshot - Mid-Life, Overtopping Breach

Mid-Life Piping Failure Parameters

The breach parameters for the mid-life dam case are:

Mid-life dam elevation:	643 metres
Spillway elevation:	633 metres
Piping failure elevation:	600 metres
Side slope of breach:	45 degrees, (1:1 ratio)
Final breach elevation:	< 600 metres
Final breach width (top):	136 metres
Final breach width (base):	50 metres

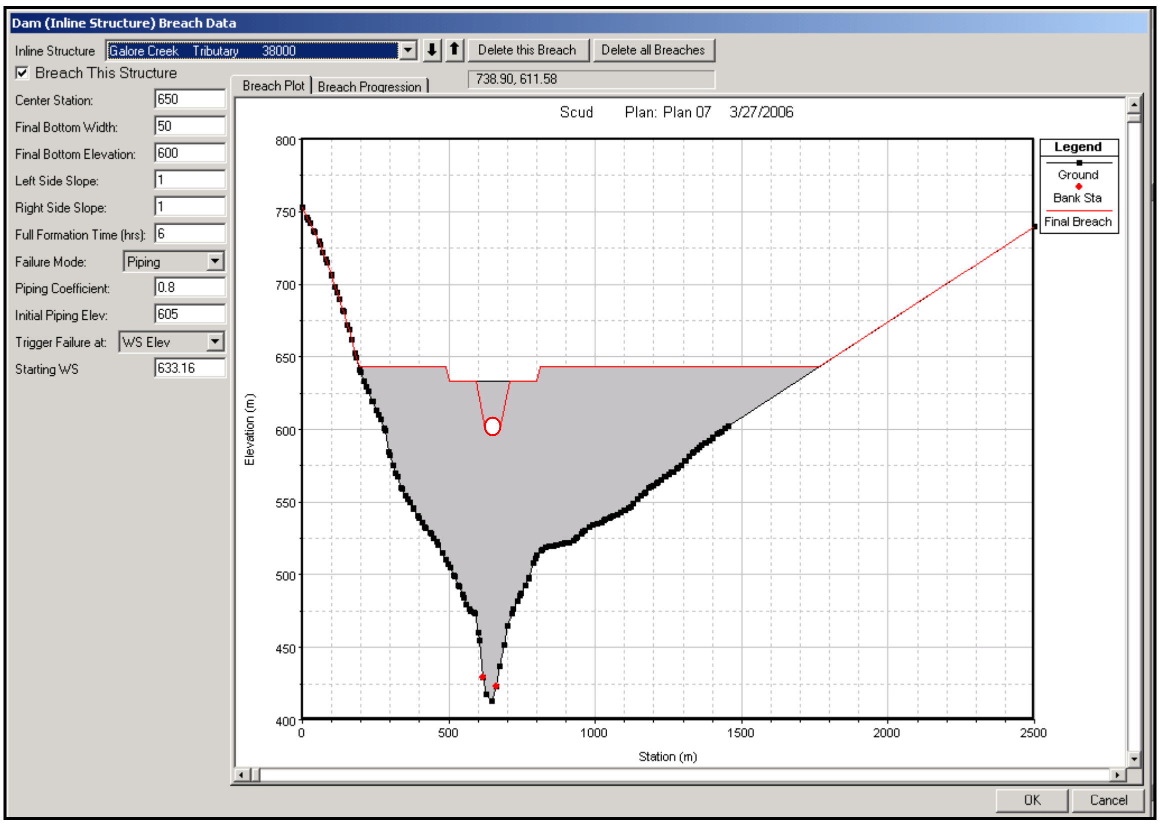

Figure 5. Breach Editor Screenshot - Mid-Life, Piping Breach

End-Of-Life Overtopping Failure Parameters

The breach parameters for the mid-life dam case are:

Mid-life dam elevation:	683 metres
Spillway elevation:	674 metres
Side slope of breach:	45 degrees, (1:1 ratio)
Final breach elevation:	600 metres
Final breach width (top):	216 metres
Final breach width (base):	50 metres

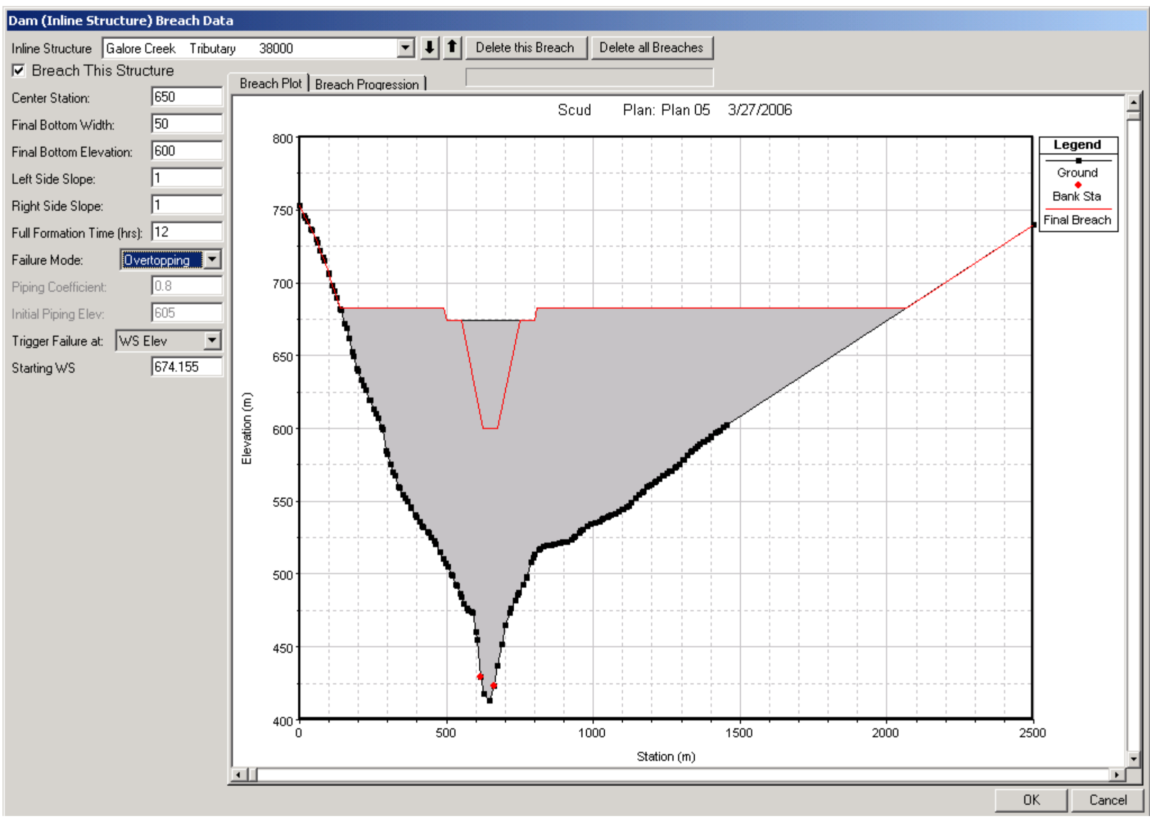

Figure 6. Breach Editor Screenshot - End-of-Life, Overtopping Breach

End-Of-Life Piping Failure Parameters

The breach parameters for the mid-life dam case are:

Mid-life dam elevation:	683 metres
Spillway elevation:	674 metres
Piping failure elevation:	600 metres
Side slope of breach:	45 degrees, (1:1 ratio)
Final breach elevation:	< 600 metres
Final breach width (top):	216 metres
Final breach width (base):	50 metres

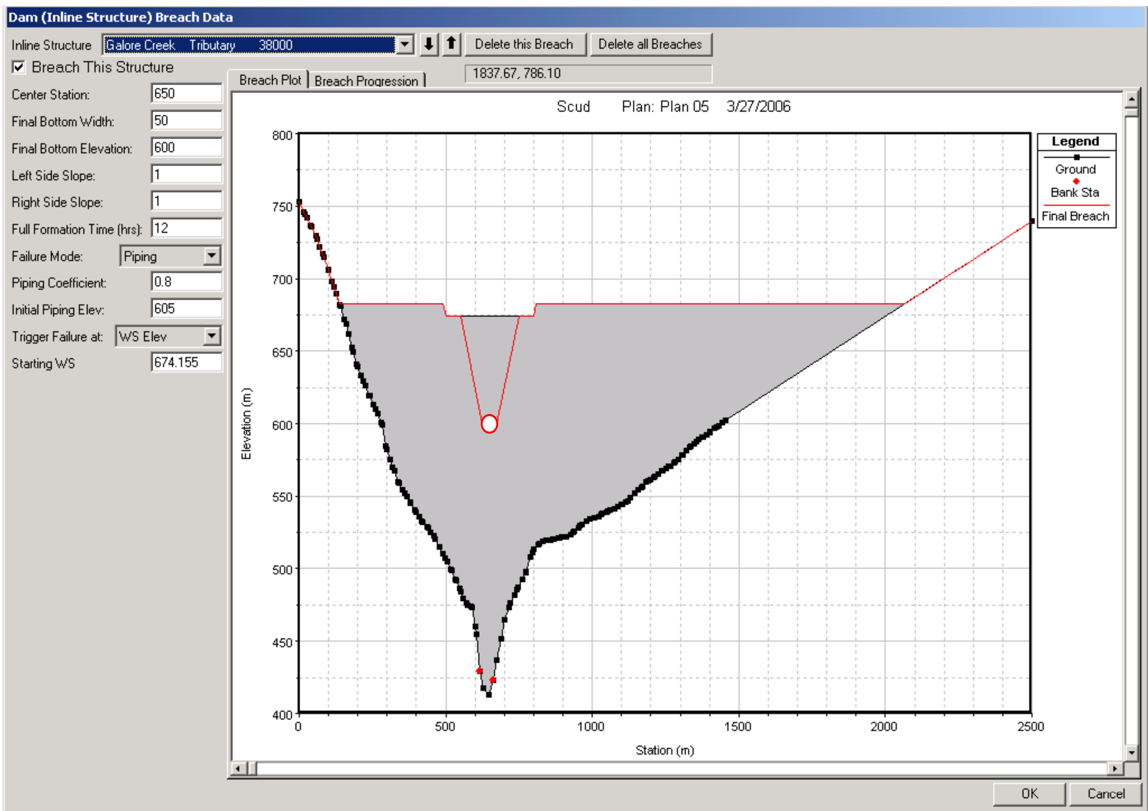

Figure 7. Breach Editor Screenshot - End-of-Life, Piping Breach

RESULTS

The model results varied as expected for the breaching scenarios. The breach outflows from the piping failures were greater than the overtopping failures scenarios. In both cases, the travel time of the peak breach flows from the dam to the mouth of the Stikine River ranges from 34 to 42 hours. The maximum floodplain boundaries and inundation depth, Figure 8 and Figure 9 respectively, were a result of the 6-hour piping breach scenario.

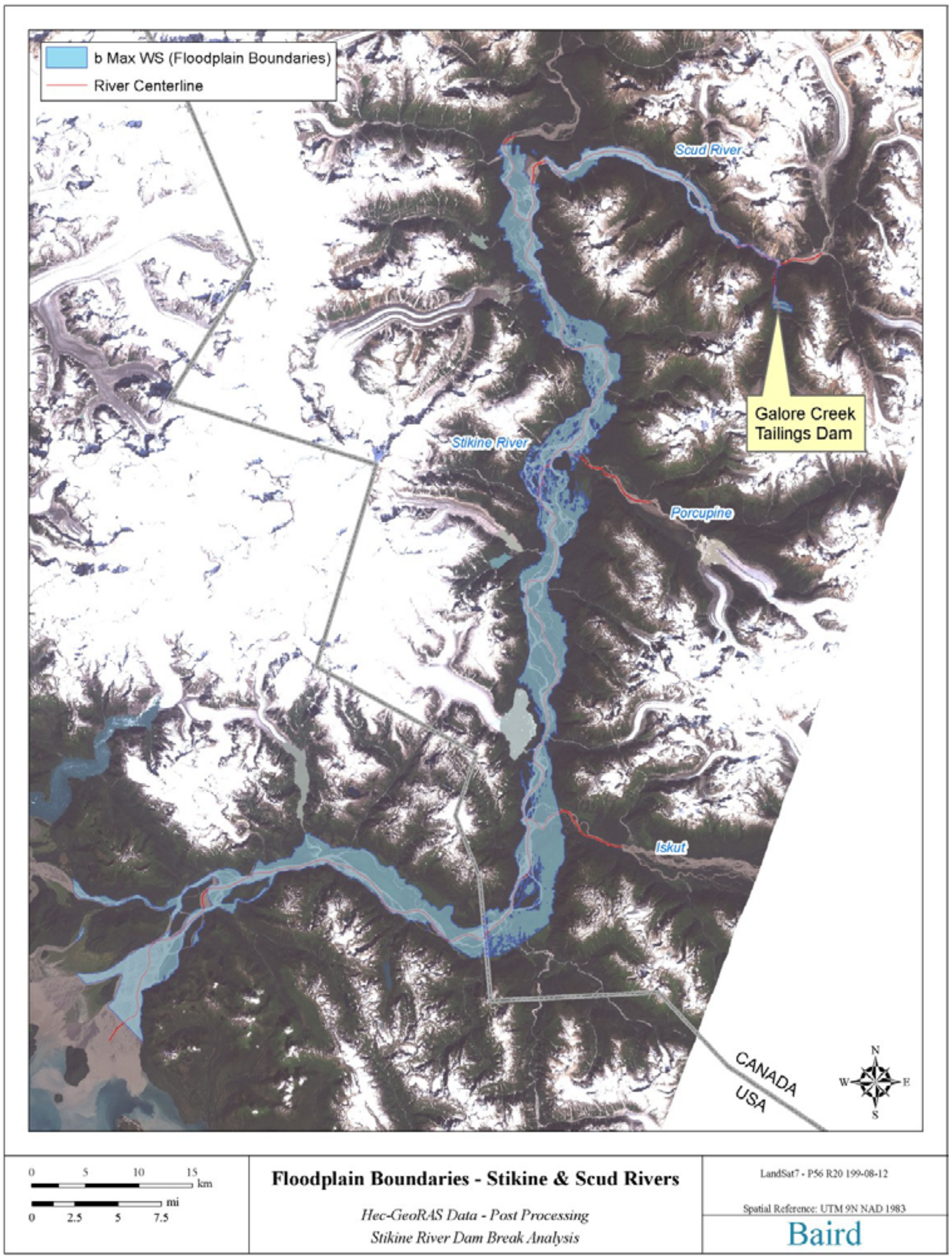

Figure 8. Floodplain Boundaries (End-of-life Reservoir, 6-hour piping breach)

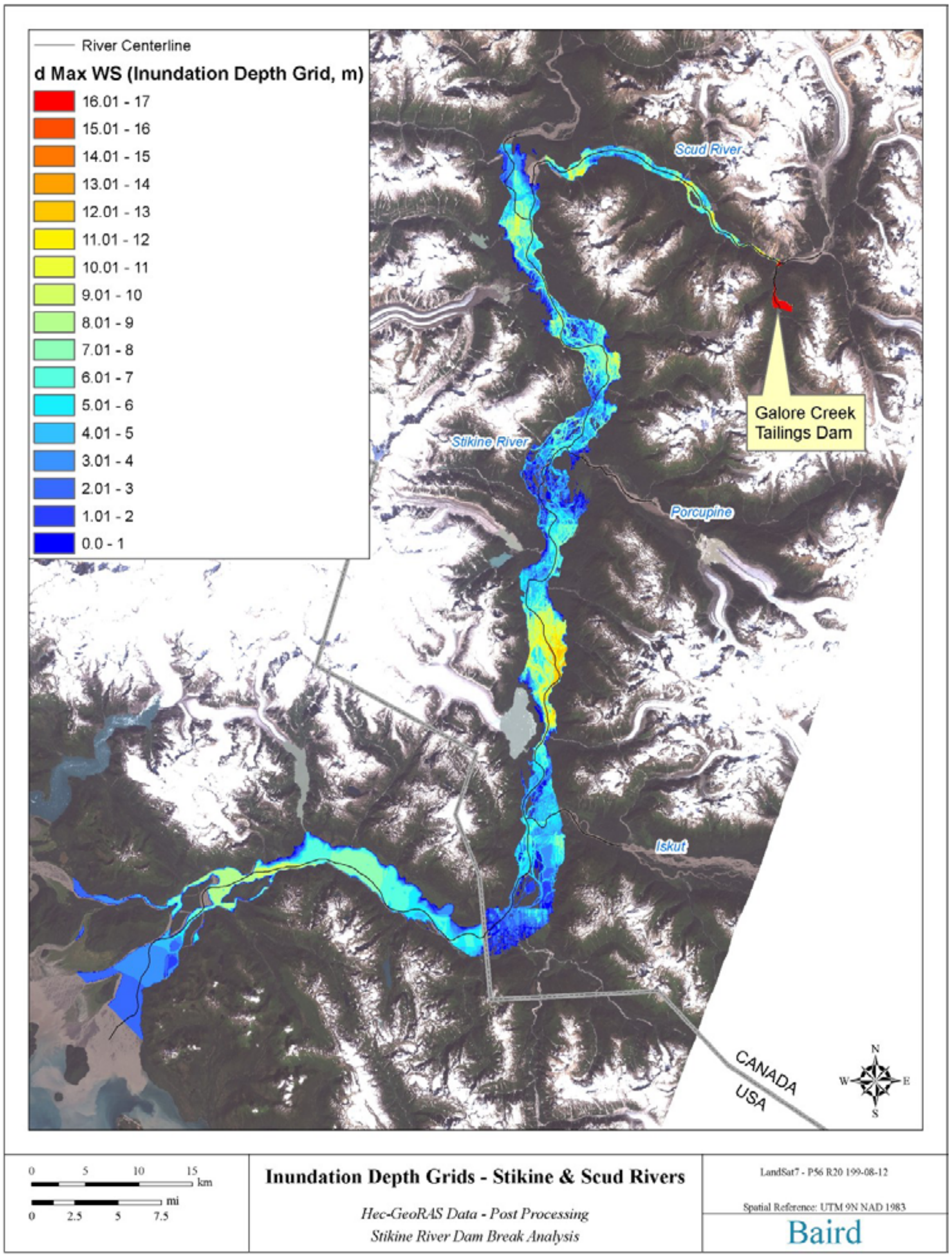

Figure 9. Peak Inundation (End-of-life Reservoir, 6-hour piping breach)

The model results suggest that flows attenuate as they progress downstream from the dam to the Lower Stikine River. The following graphs show the flow spikes from the most extreme scenario, end-of-life 6 hours pipe breach, at various locations along the river. Note that the breach begins at approximately 3:30 AM, and is fully developed by 9:30 AM. The subsequent graphs show the progression of the flood peak down the river.

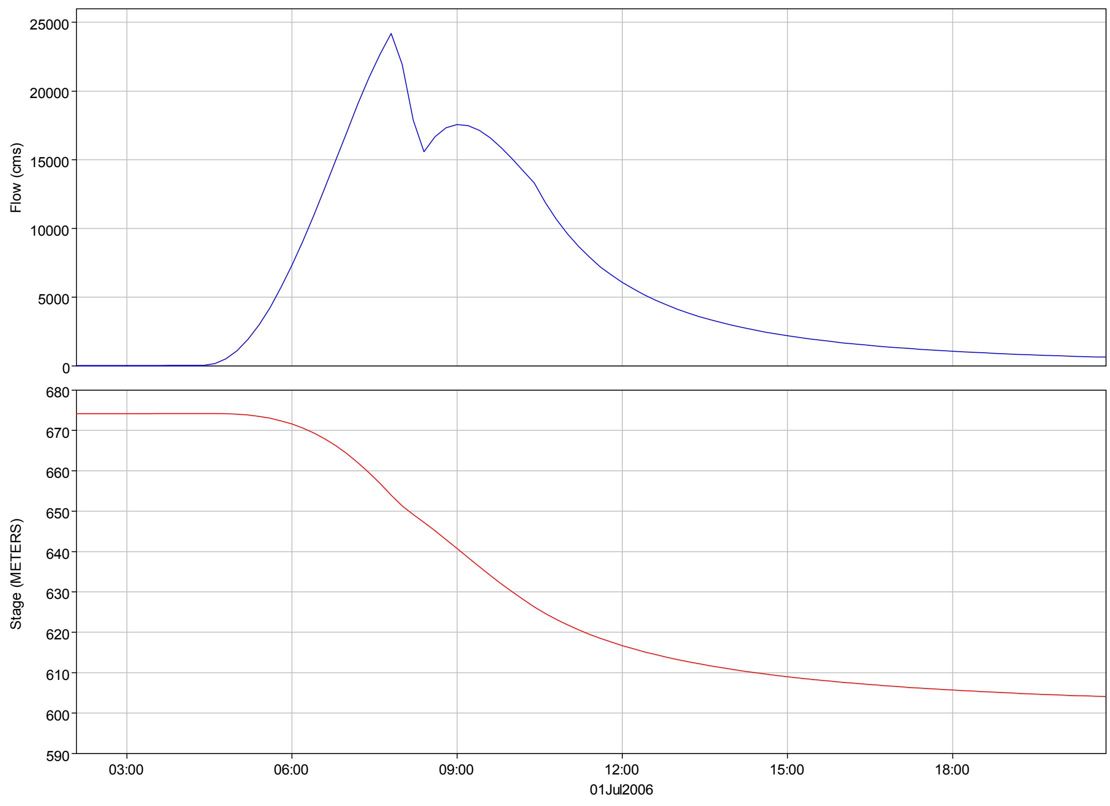

Figure 10. Breach Outflow and drawdown of the dam (End-of-life Reservoir, 6-hour piping breach)

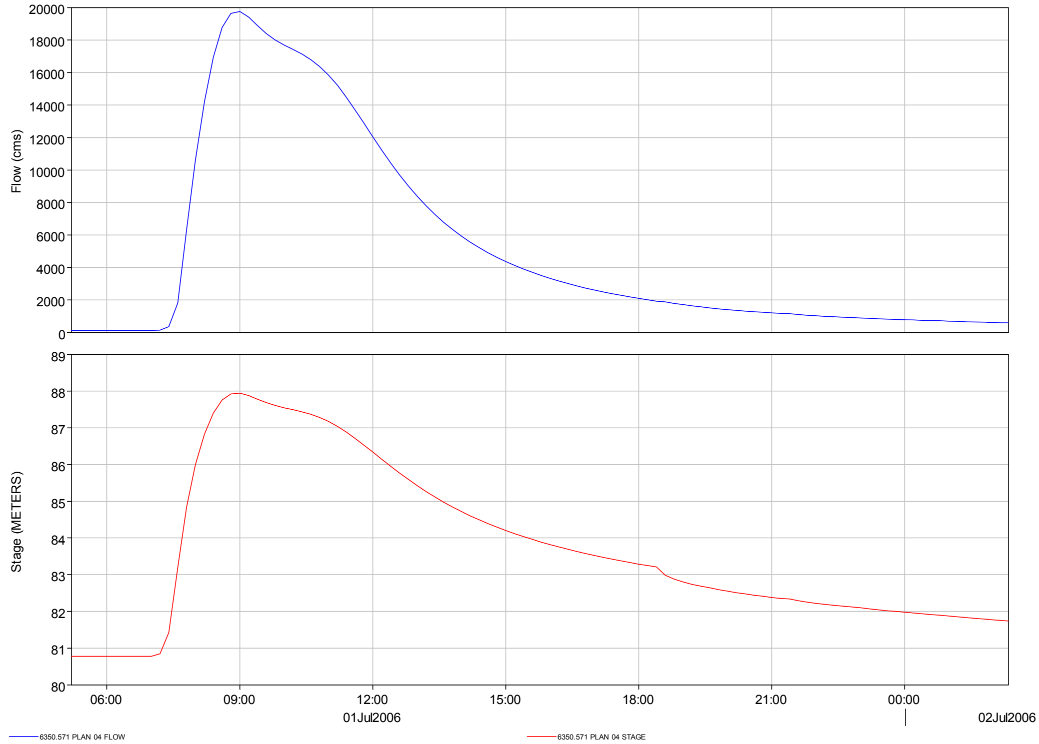

Figure 11. Flow and stage on Scud River near confluence with the Stikine River

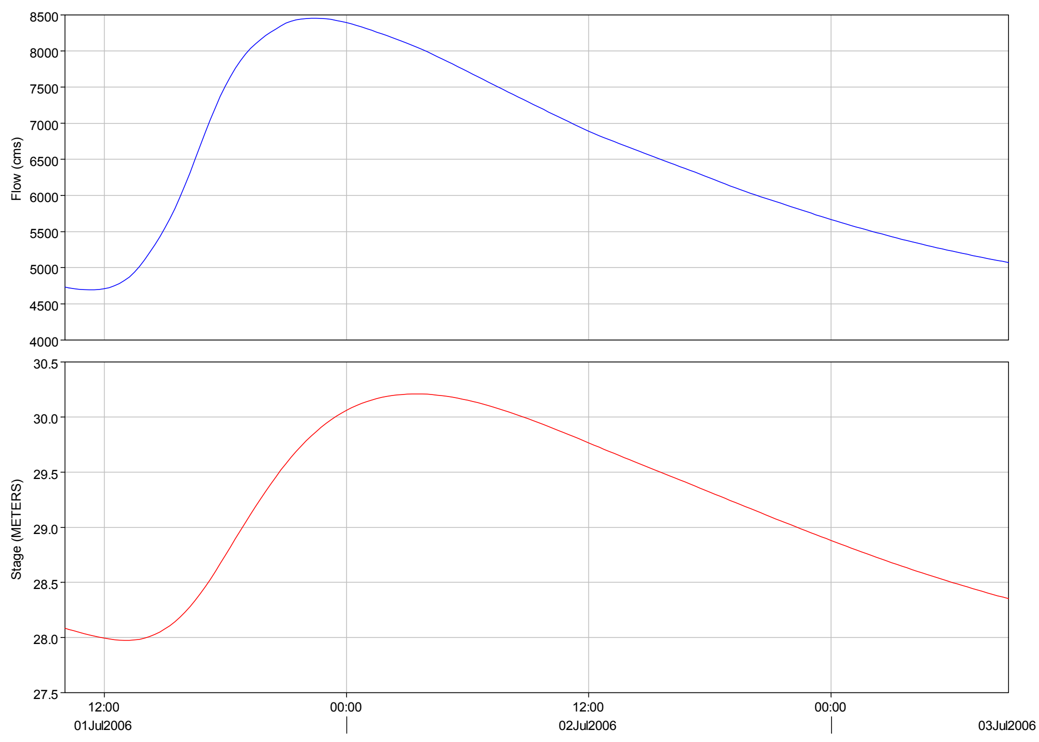

Figure 12. Flow and Stage at midpoint between the Scud River and the USGS Gage Location

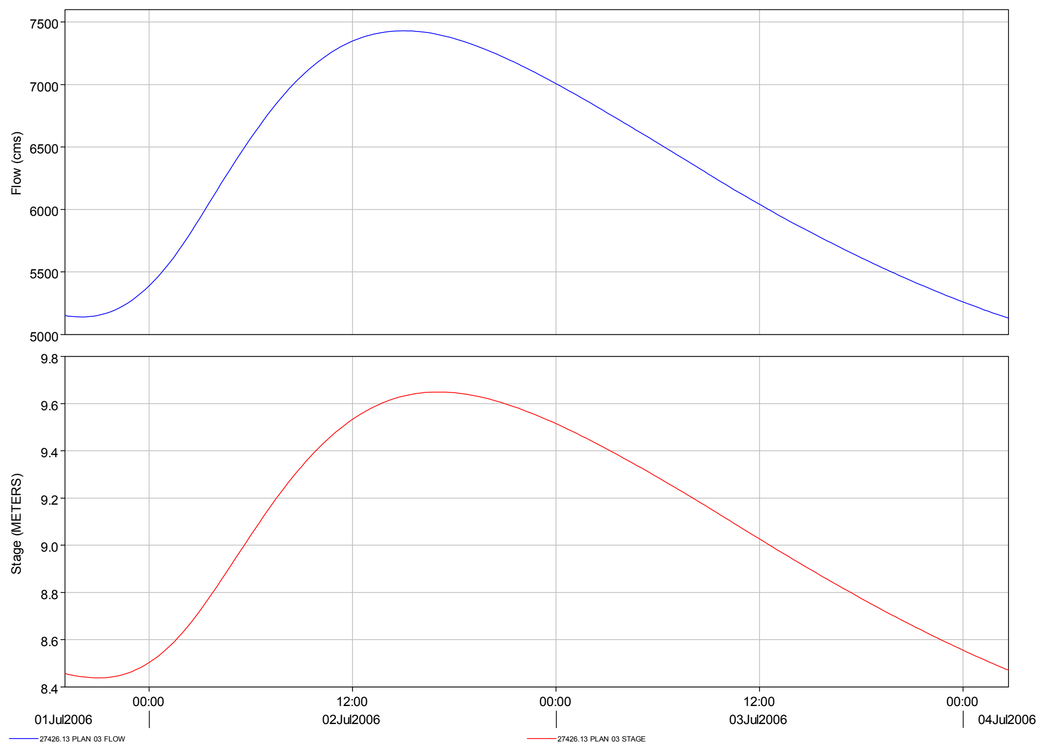

Figure 13. Flow and Stage at USGS Gage Location (6-hour breach formation)

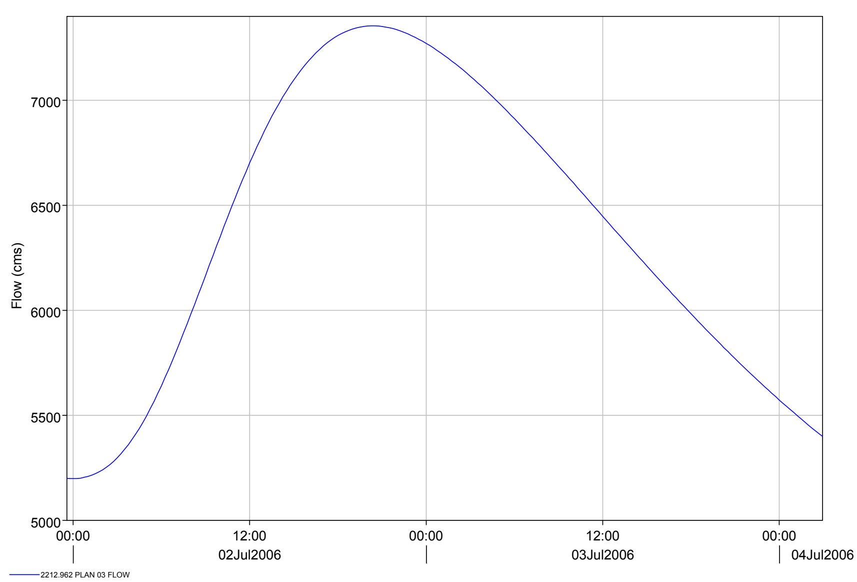

Figure 14. Breach Outflow at Mouth of the Stikine River (Note: Base Flow was approximately 4,500 cms)

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The flows and stage response to the passing of the peak breach outflow were similar for the different scenarios that were included in the modeling. The main difference was the magnitude of the peak. The other note of interest is that the peak flow at the mouth of the Stikine River is more dependent on the volume of water released due to the breach than the breach formation parameters. It is important to note that the flows at the mouth of the Stikine, as shown in the following table, include approximately 4,500 cms of antecedent flow. The flow from the dam failure can be estimated by subtracting this amount.

Table 3. Summary of Model Results

Scenario	Project Phase / Mode / Breach Time	Peak Flow at Dam (cms)	Peak Flow at Stikine Mouth (cms)	Time from Breach Initiation to Peak Flow (hr:min)	
				At Dam	At Mouth
1	Mid-life / overtopping / 6 hours	7,900	5,500	6:40	46:45
2	Mid-life / overtopping / 12 hours	4,500	5,455	13:00	51:45
3	Mid-life / overtopping / 24 hours	2,400	5,375	19:30	60:45
4	Mid-life / piping / 6 hours	8,200	5,475	4:30	45:30
5	Mid-life / piping / 12 hours	6,100	5,410	7:00	48:45
6	Mid-life / piping / 24 hours	4,200	5,405	11:20	53:30
7	End-of-life / overtopping / 6 hours	21,700	7,355	6:00	40:45
8	End-of-life /overtopping / 12 hours	11,200	7,305	9:40	45:30
9	End-of-life /overtopping / 24 hours	5,800	7,065	16:00	54:45
10	End-of-life / piping / 6 hours	24,200	7,315	4:30	41:45
11	End-of-life / piping / 12 hours	17,850	7,305	6:00	43:00
12	End-of-life / piping / 24 hours	6,200	7,090	16:00	55:00

Please see Appendix A for complete model results of all twelve scenarios.

CONCLUSIONS

The following conclusions can be drawn from the modeling analysis.

- As expected, the shorter breach formation scenarios resulted in higher peak flows.

- The flows from the breach, after traveling from the dam to the mouth of the Stikine River, would be in the range of 3,000 cms. This flow amount, by itself, is not as large as a 1 year flood. However, this flow amount when added to an ongoing flood event, such as a 5-year event, would end up resembling a 50 year flood.

- The peak flows and stages at the mouth of the Stikine River are affected strongly by the volume of water released from the impoundment, in addition to the breach formation parameters. The reason for this is that the flows released from the breach begin to arrive at the mouth in a matter of hours (approximately 34 to 42 hours) and would not subside back to normal flows for another one or two days.

- The length of river between the dam and the mouth of the Stikine River significantly attenuates the peak flows.

- The piping breach scenarios resulted in higher peak flows than for overtopping failures. The difference is not highly significant, because both breach types have timing parameters that are subjective.

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Fread, D.L., 1988 (revised 1991). *BREACH: An Erosion Model For Earth Dam Failures*. National Weather Service, NOAA , Silver Springs Maryland.

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APPENDIX A

ADDITIONAL HYDROGRAPHS

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Chart 47. Scenario 12 - Flow and Stage near USGS Gage Location
Chart 48. Scenario 12 - Flow and Stage at mouth of Stikine River

SCENARIO 1

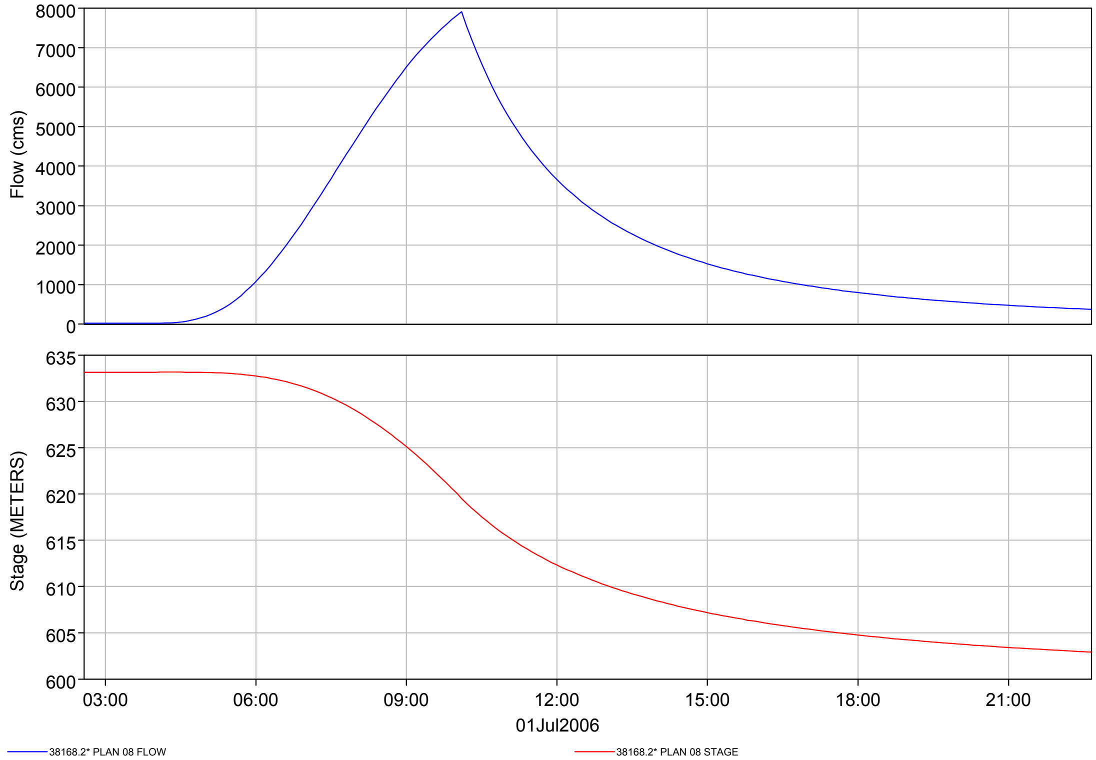

Chart 1. Scenario 1 - Flow and Stage near dam

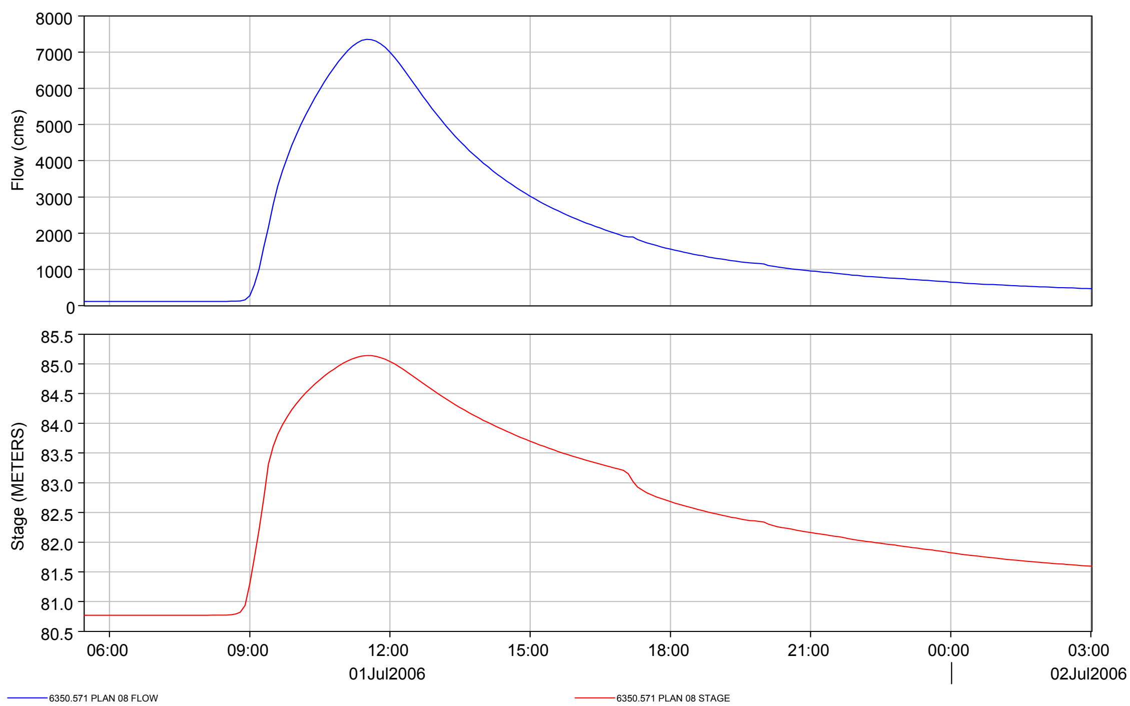

Chart 2. Scenario 1 - Flow and Stage at mouth of Scud River

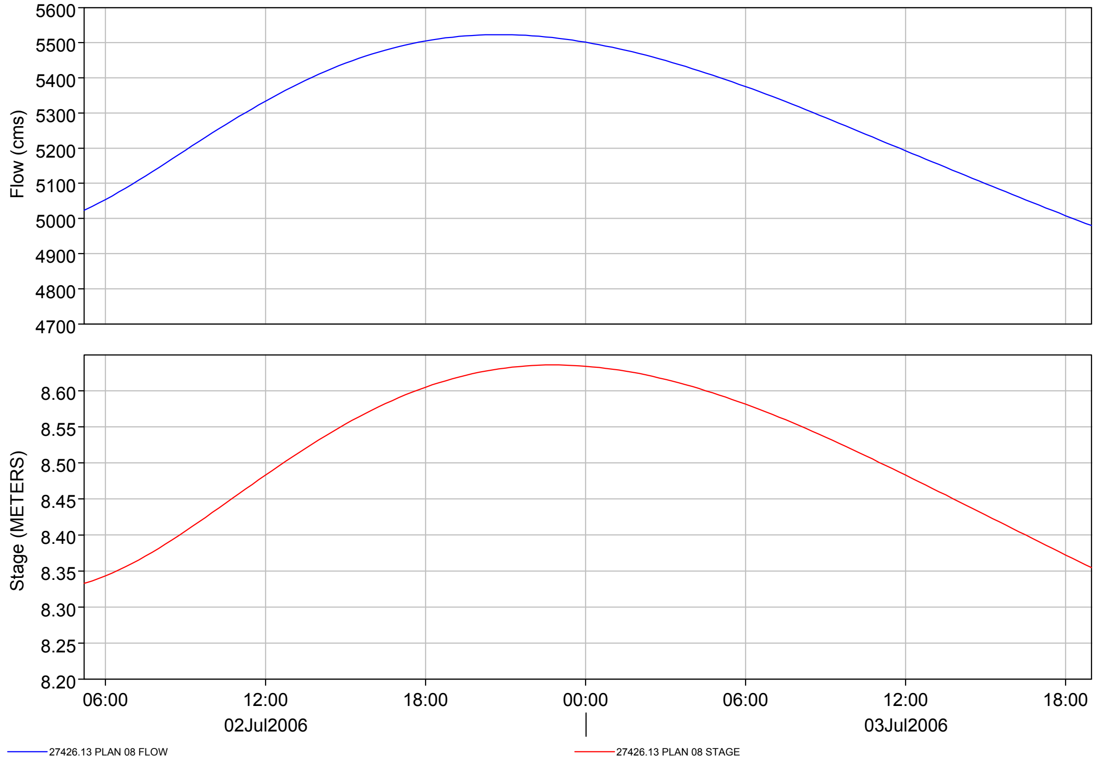

Chart 3. Scenario 1 - Flow and Stage near USGS Gage Location

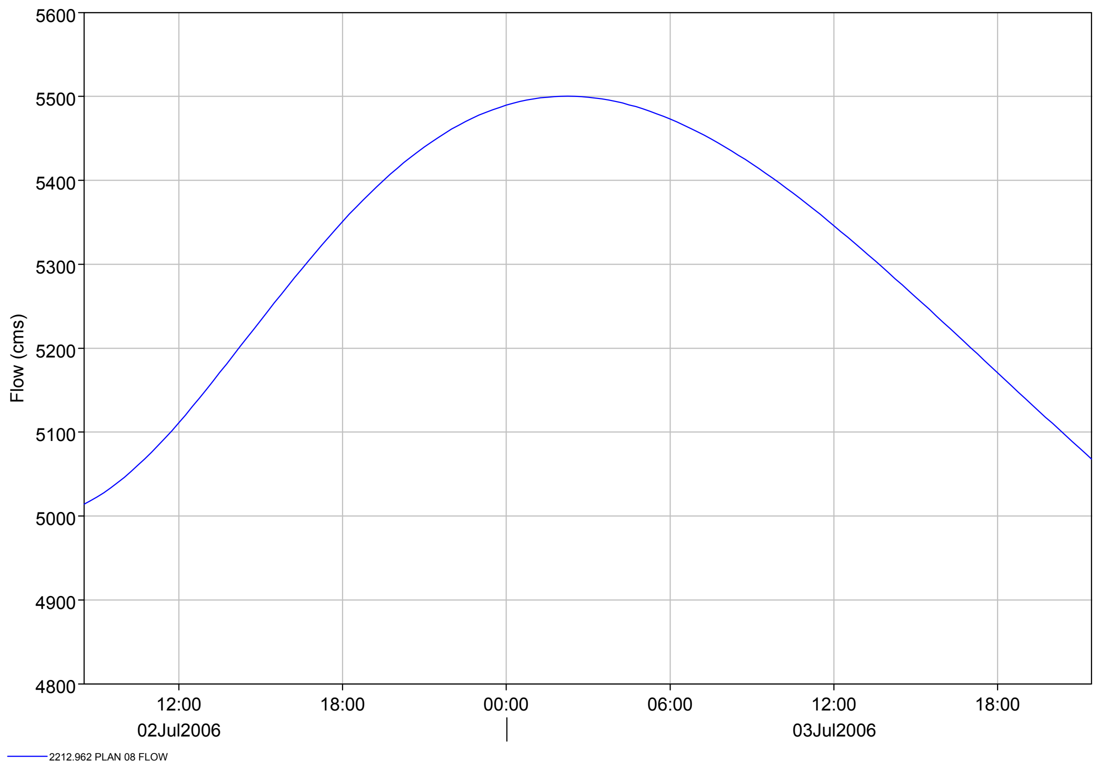

Chart 4. Scenario 1 - Flow at mouth of Stikine River

SCENARIO 2

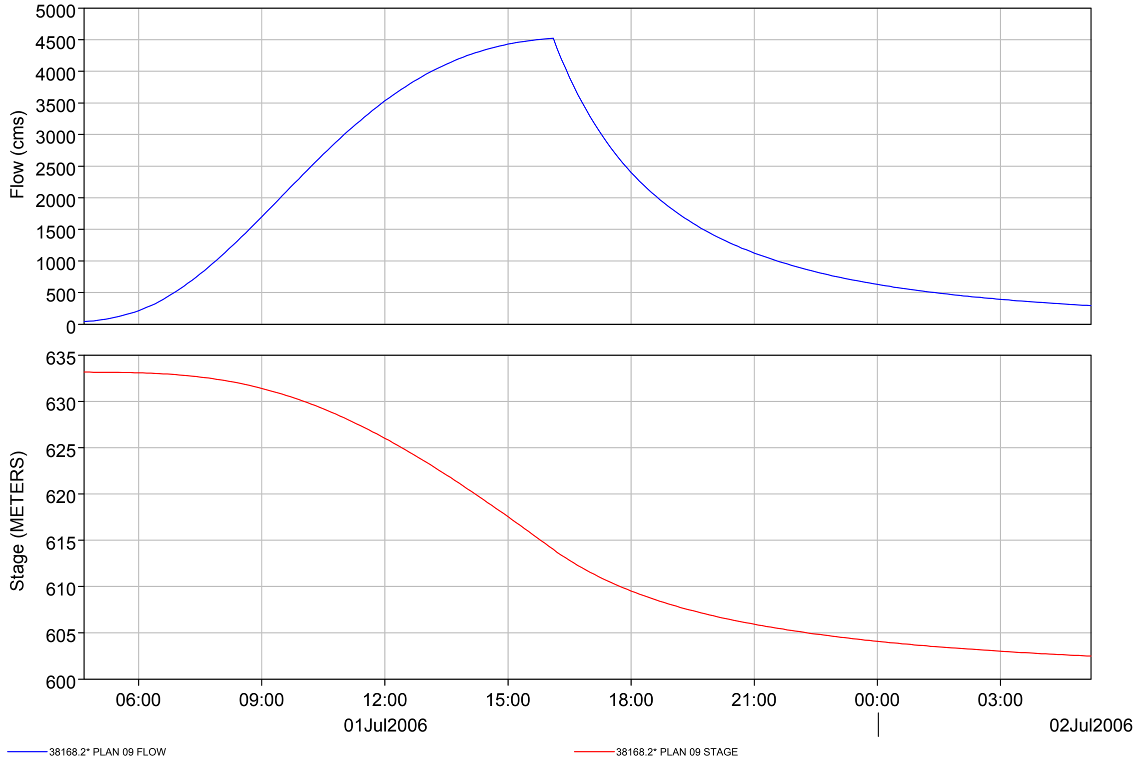

Chart 5. Scenario 2 - Flow and Stage near dam

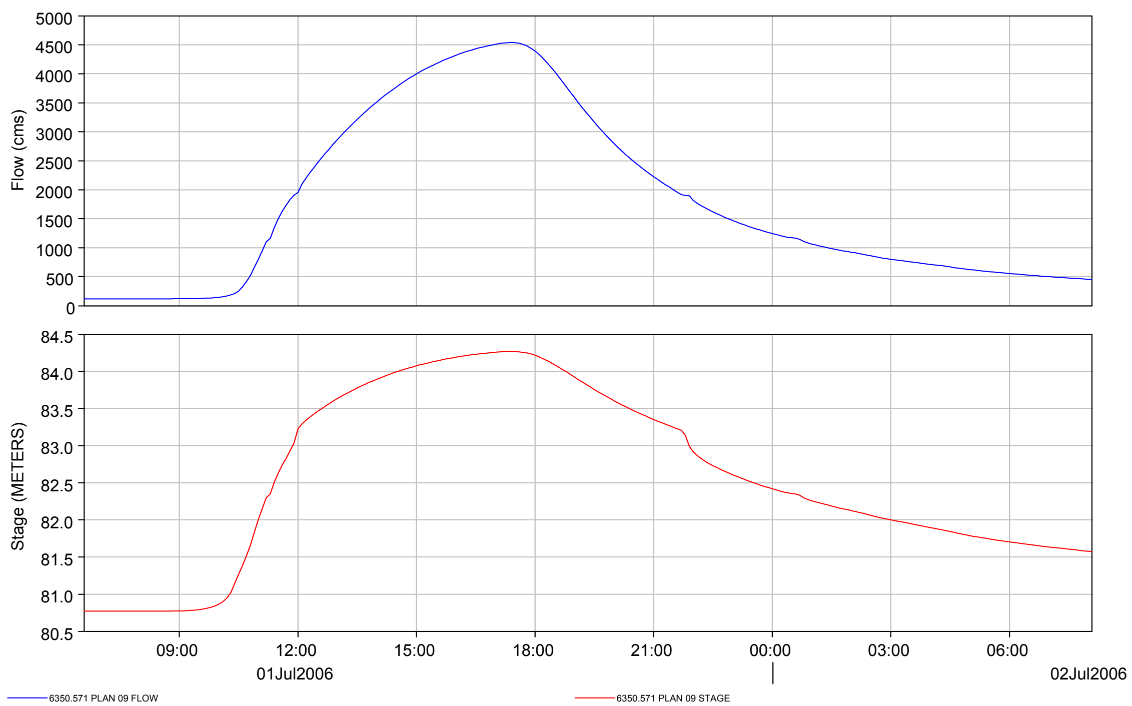

Chart 6. Scenario 2 - Flow and Stage at mouth of Scud River

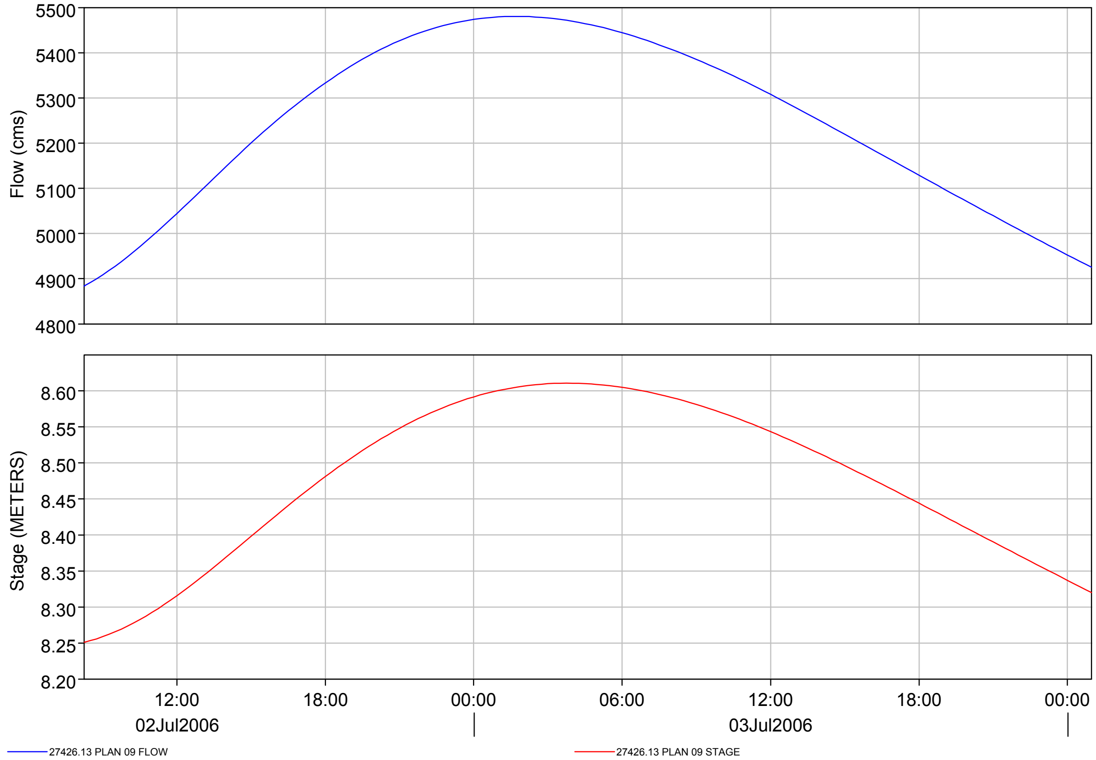

Chart 7. Scenario 2 - Flow and Stage near USGS Gage Location

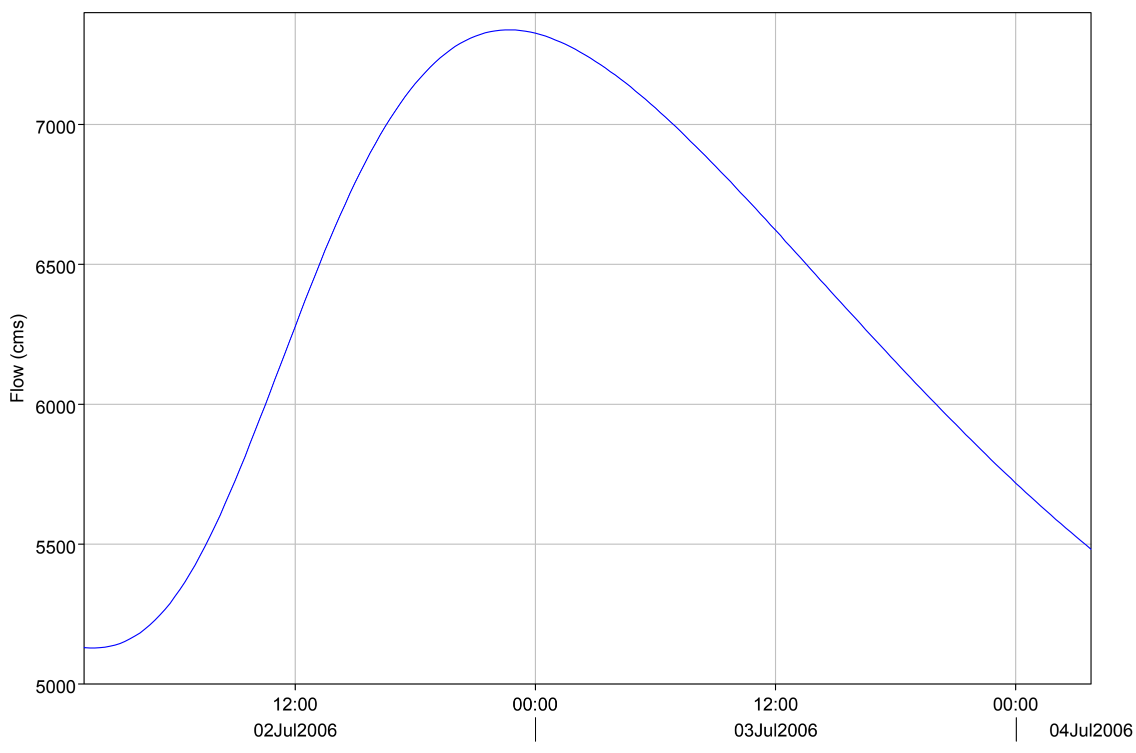

Chart 8. Scenario 2 - Flow at mouth of Stikine River

SCENARIO 3

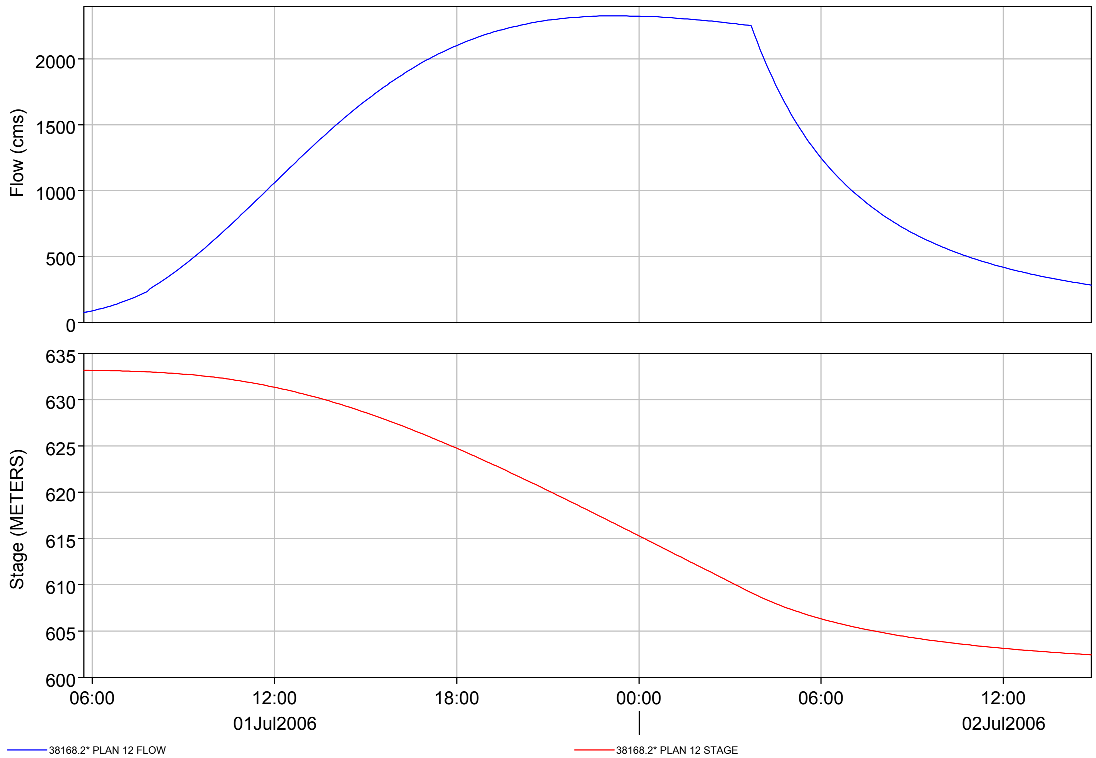

Chart 9. Scenario 3 - Flow and Stage near dam

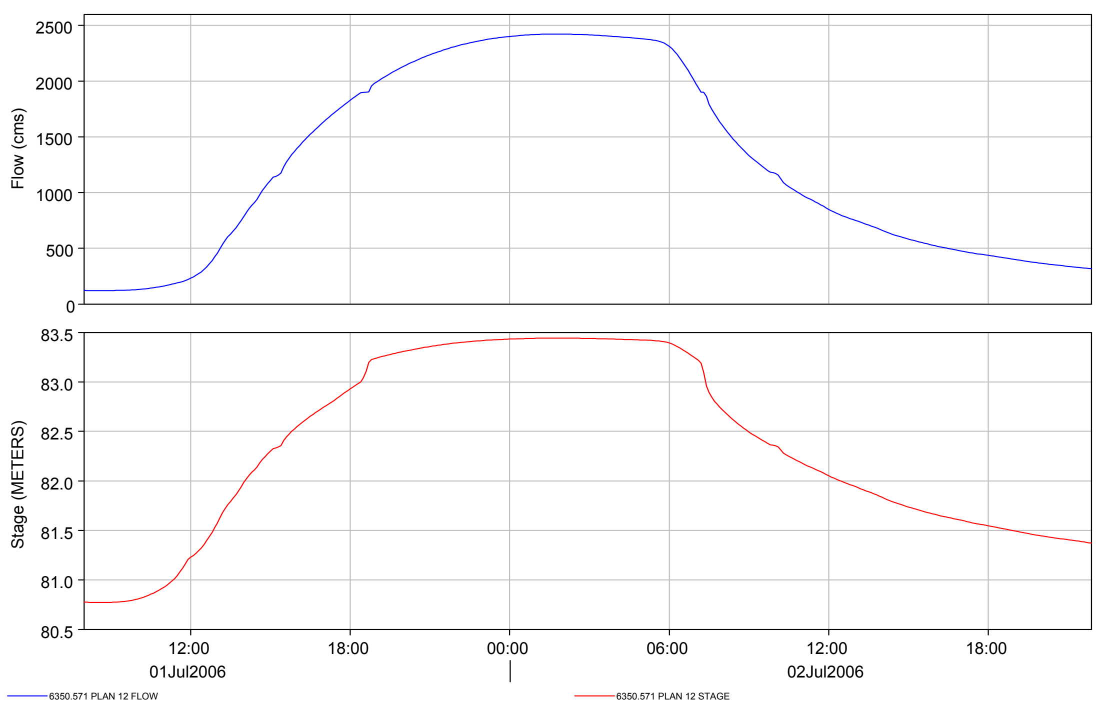

Chart 10. Scenario 3 - Flow and Stage at mouth of Scud River

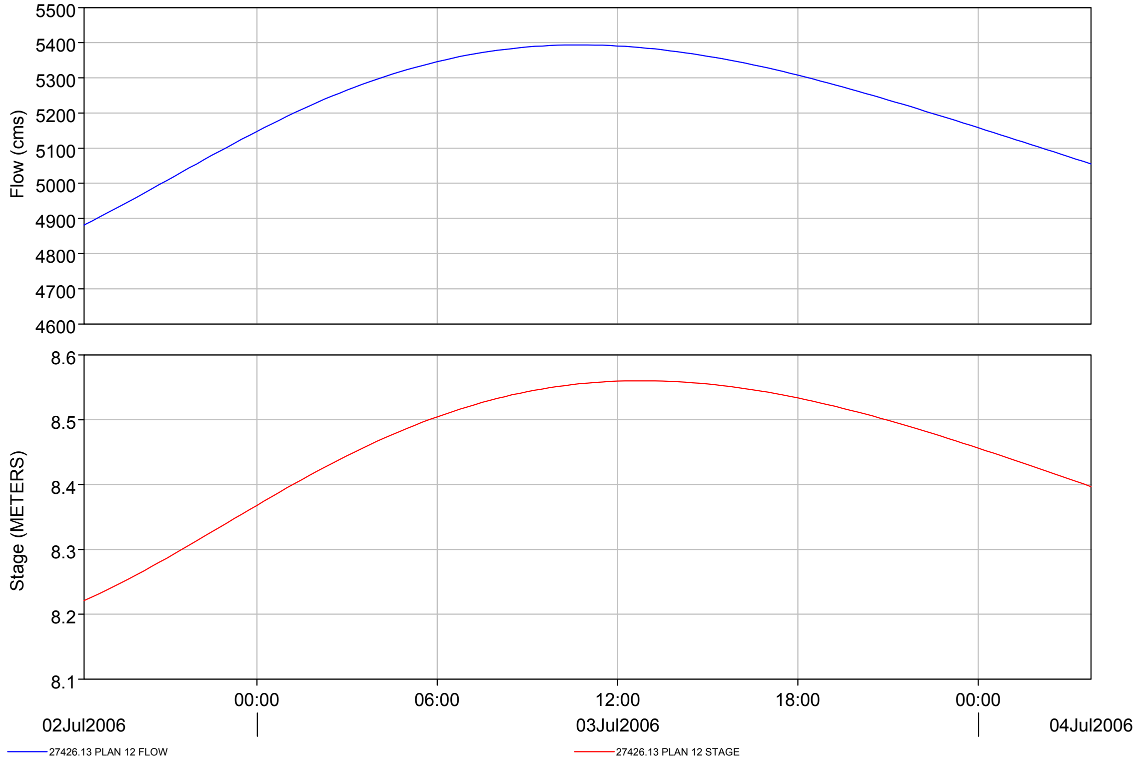

Chart 11. Scenario 3 - Flow and Stage near USGS Gage Location

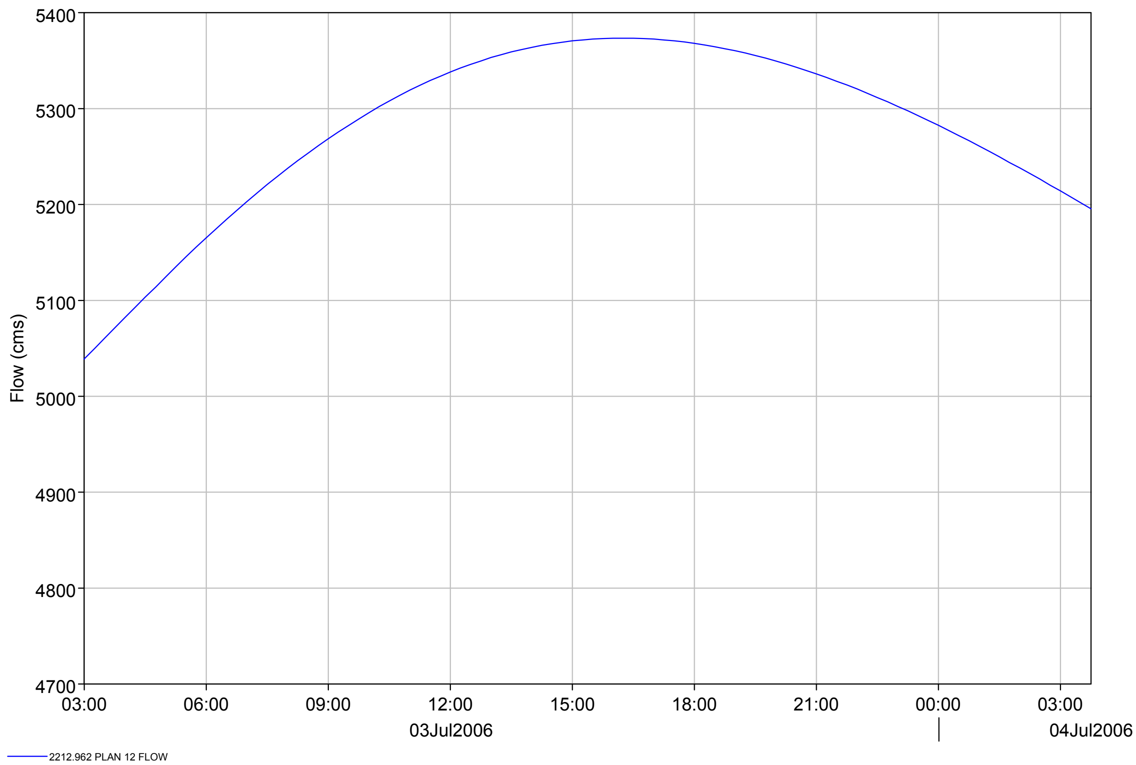

Chart 12. Scenario 3 - Flow at mouth of Stikine River

SCENARIO 4

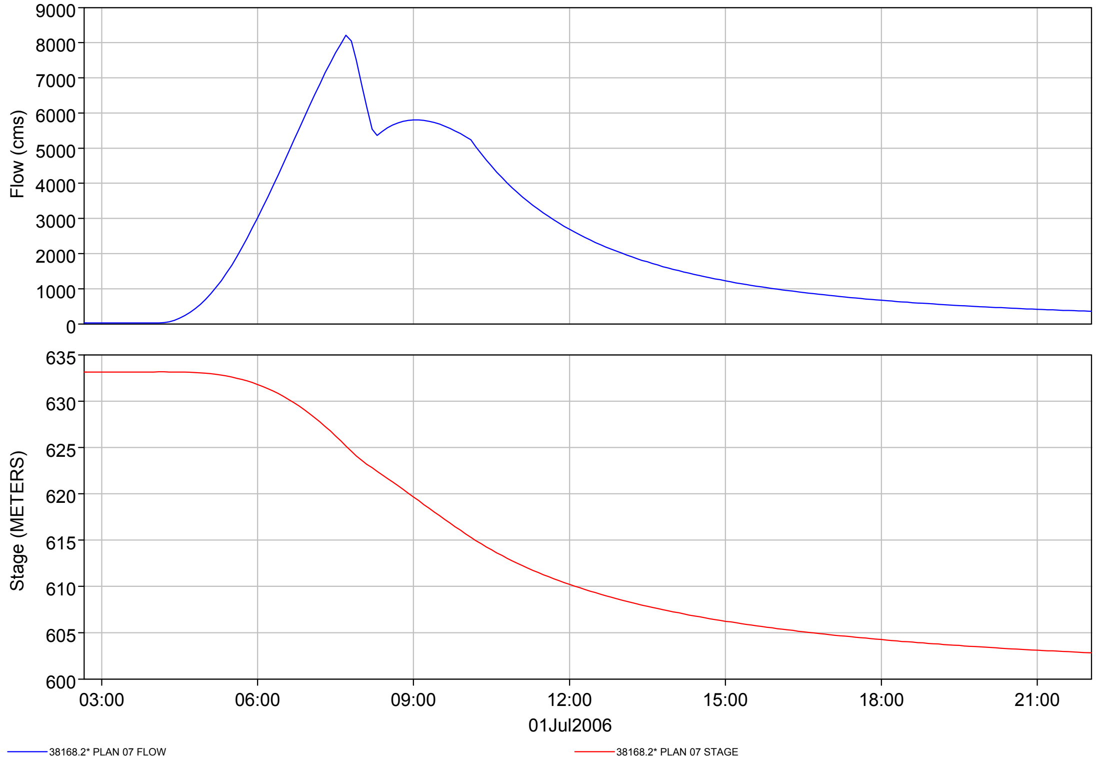

Chart 13. Scenario 4 - Flow and Stage near dam

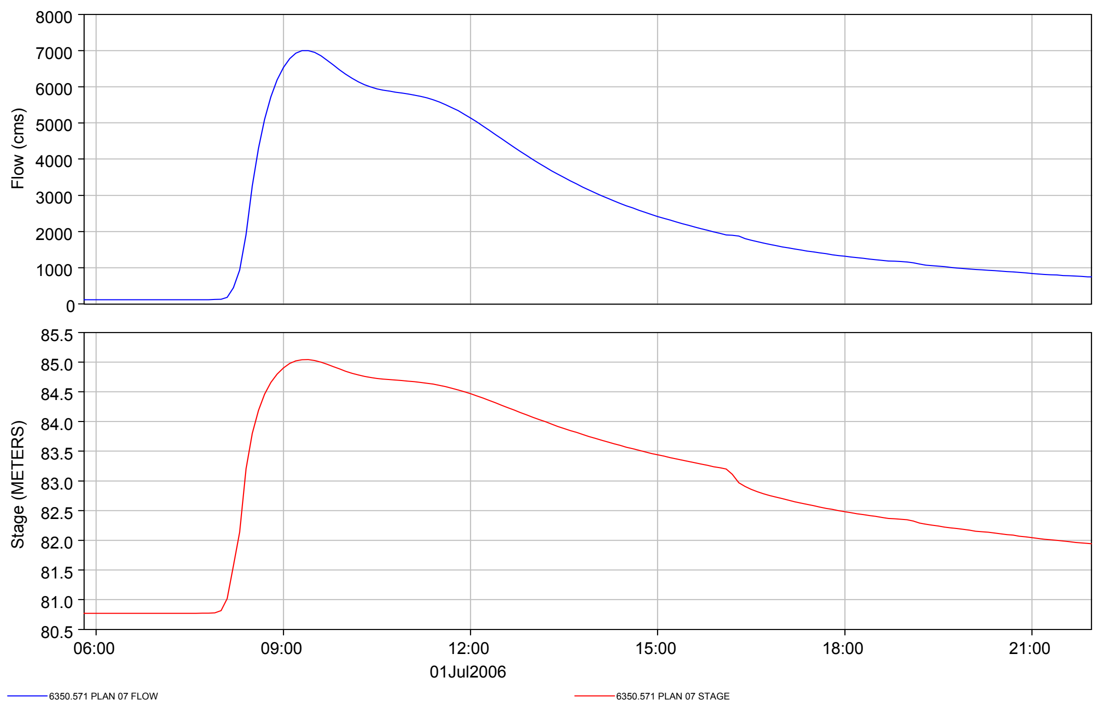

Chart 14. Scenario 4 - Flow and Stage at mouth of Scud River

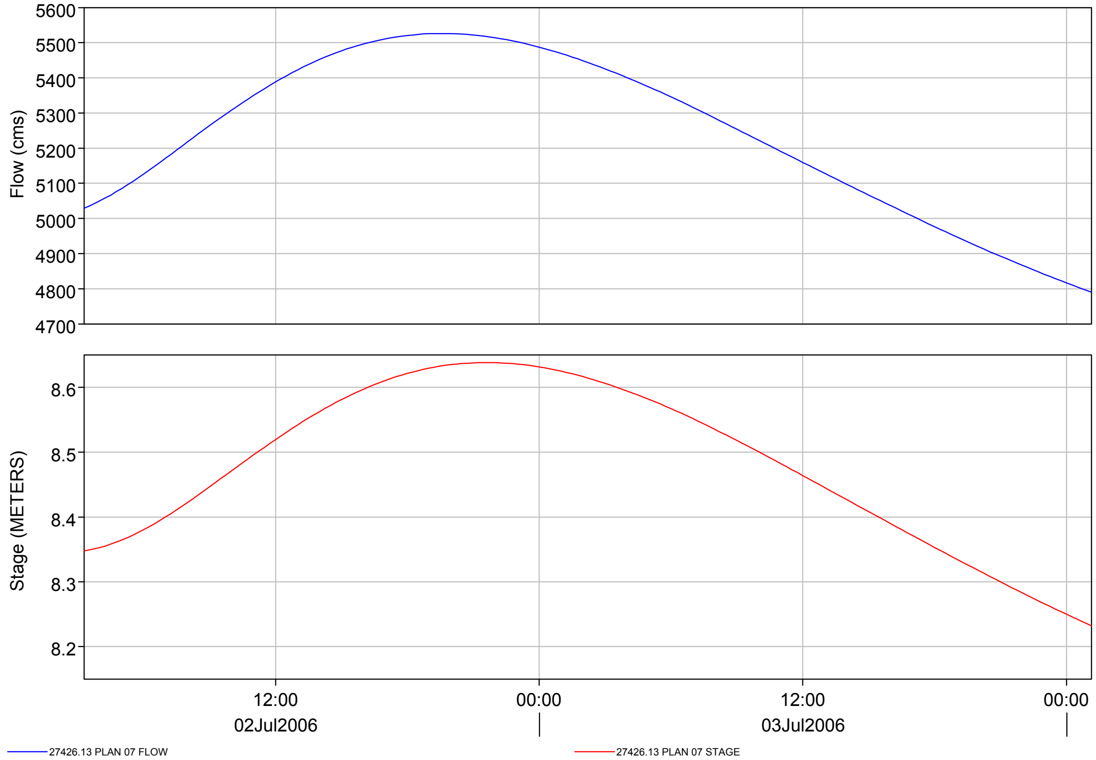

Chart 15. Scenario 4 - Flow and Stage near USGS Gage Location

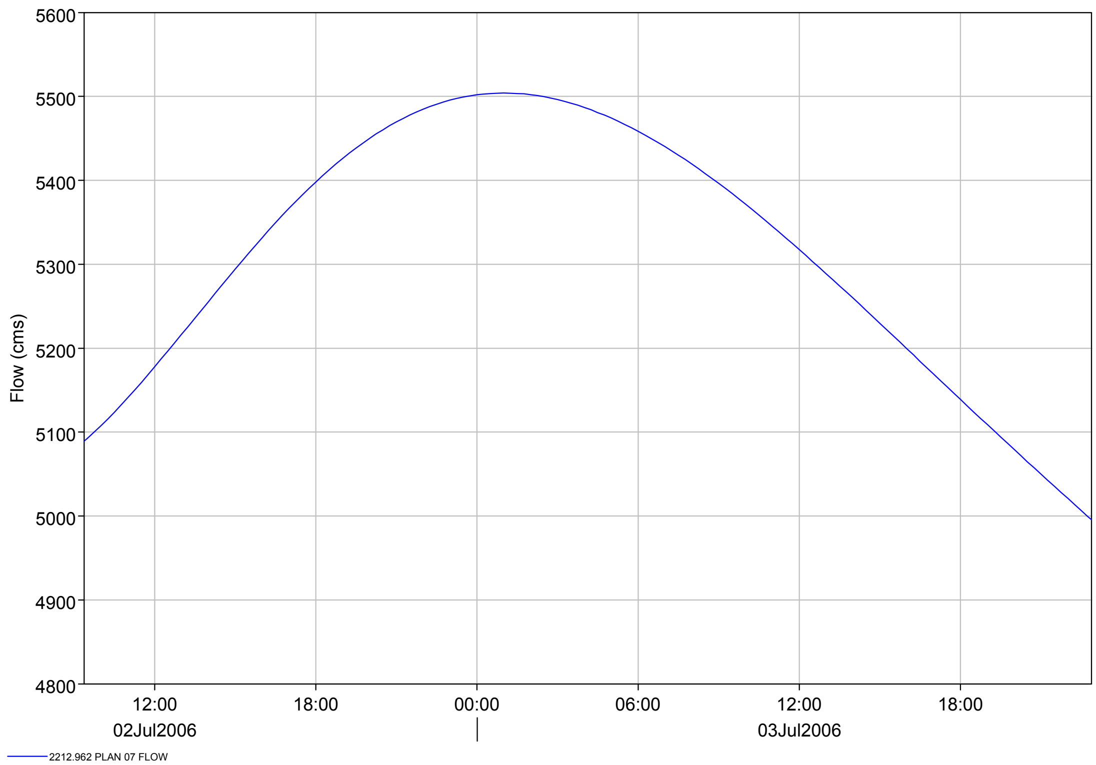

Chart 16. Scenario 4 - Flow at mouth of Stikine River

SCENARIO 5

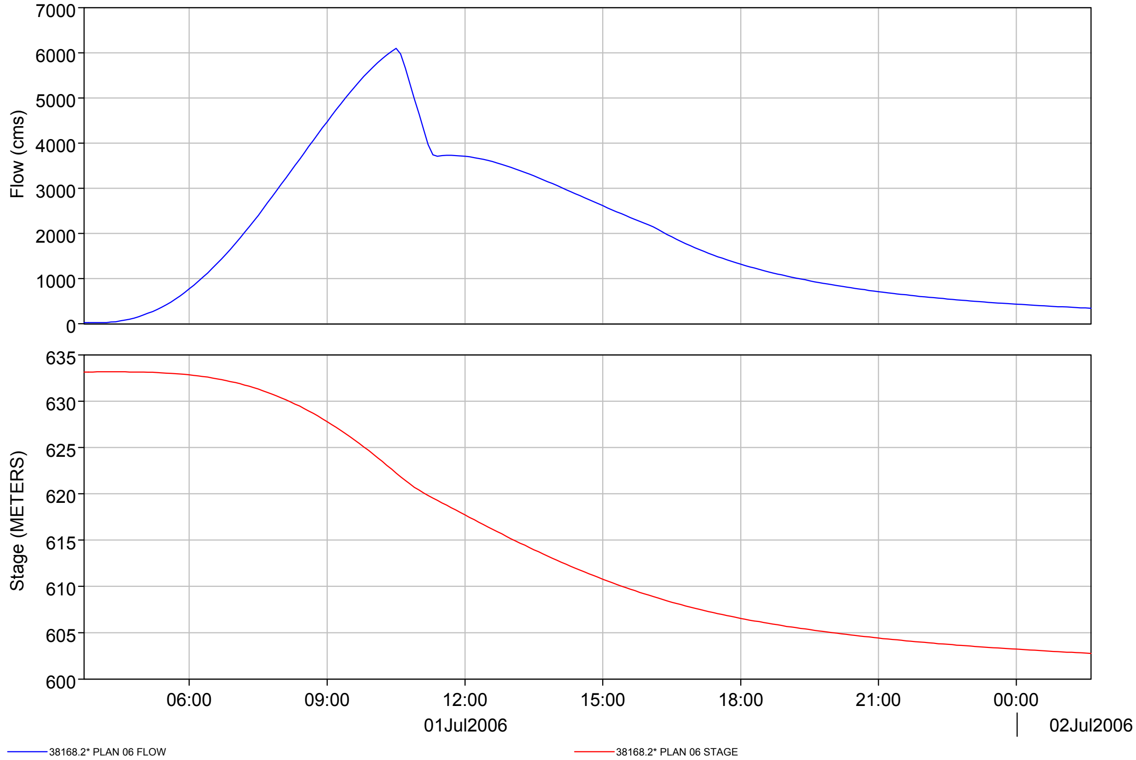

Chart 17. Scenario 5 - Flow and Stage near dam

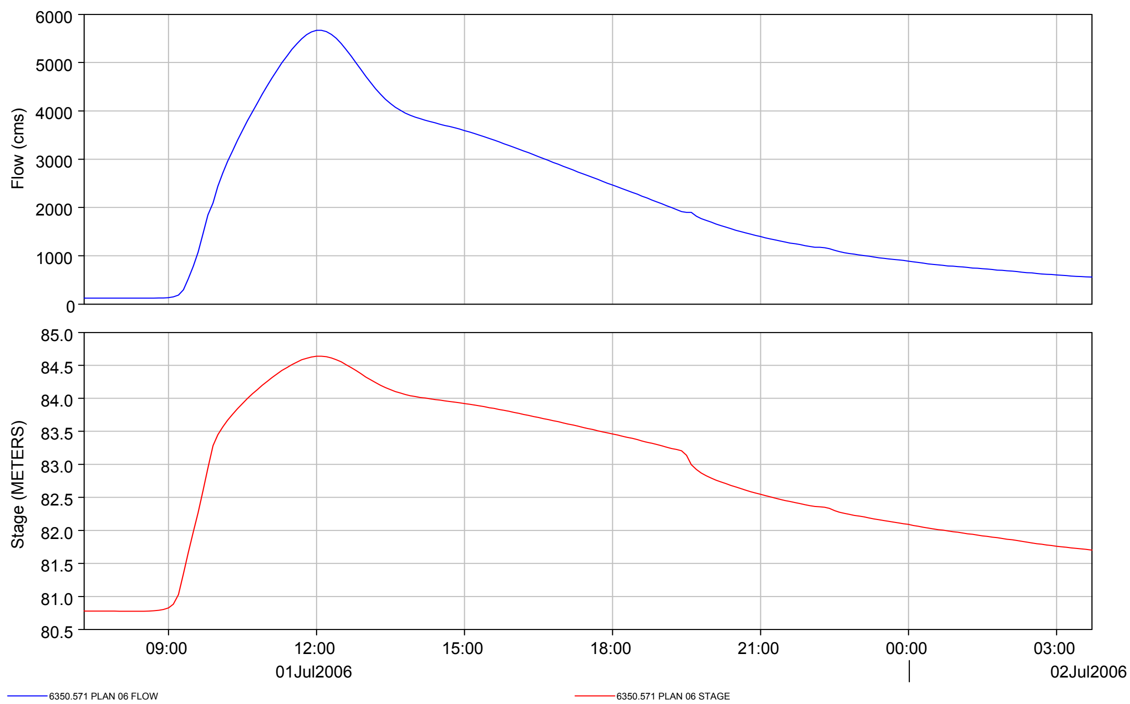

Chart 18. Scenario 5 - Flow and Stage at mouth of Scud River

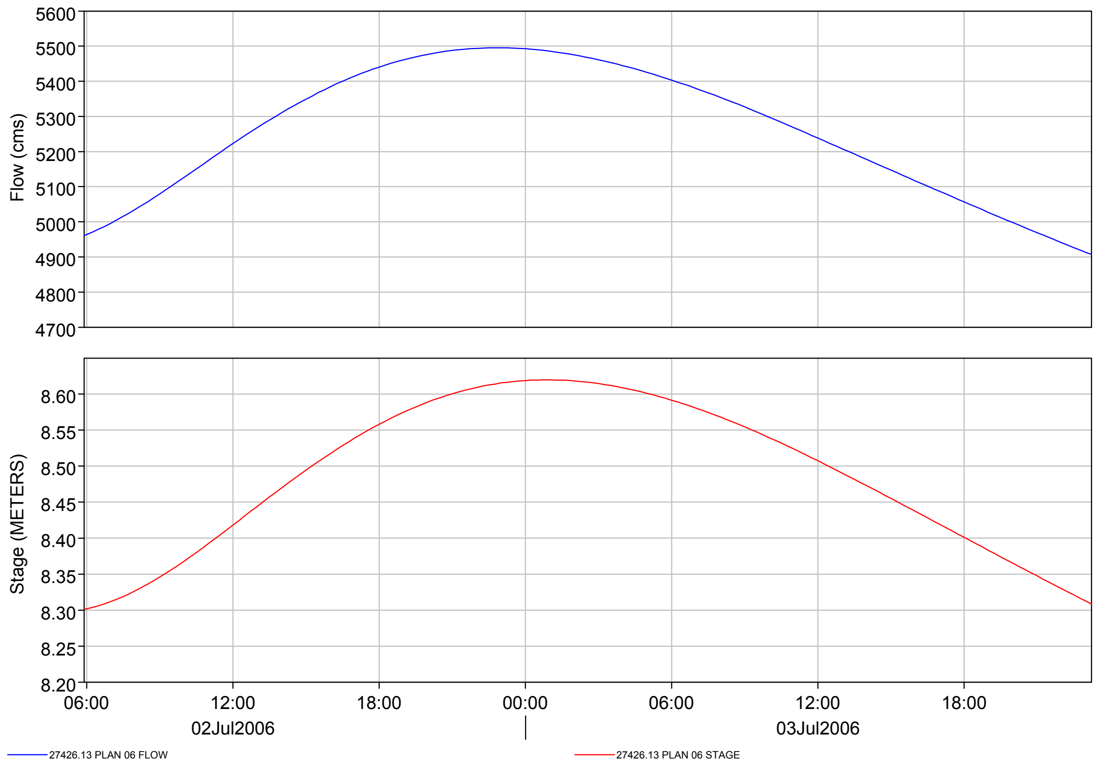

Chart 19. Scenario 5 - Flow and Stage near USGS Gage Location

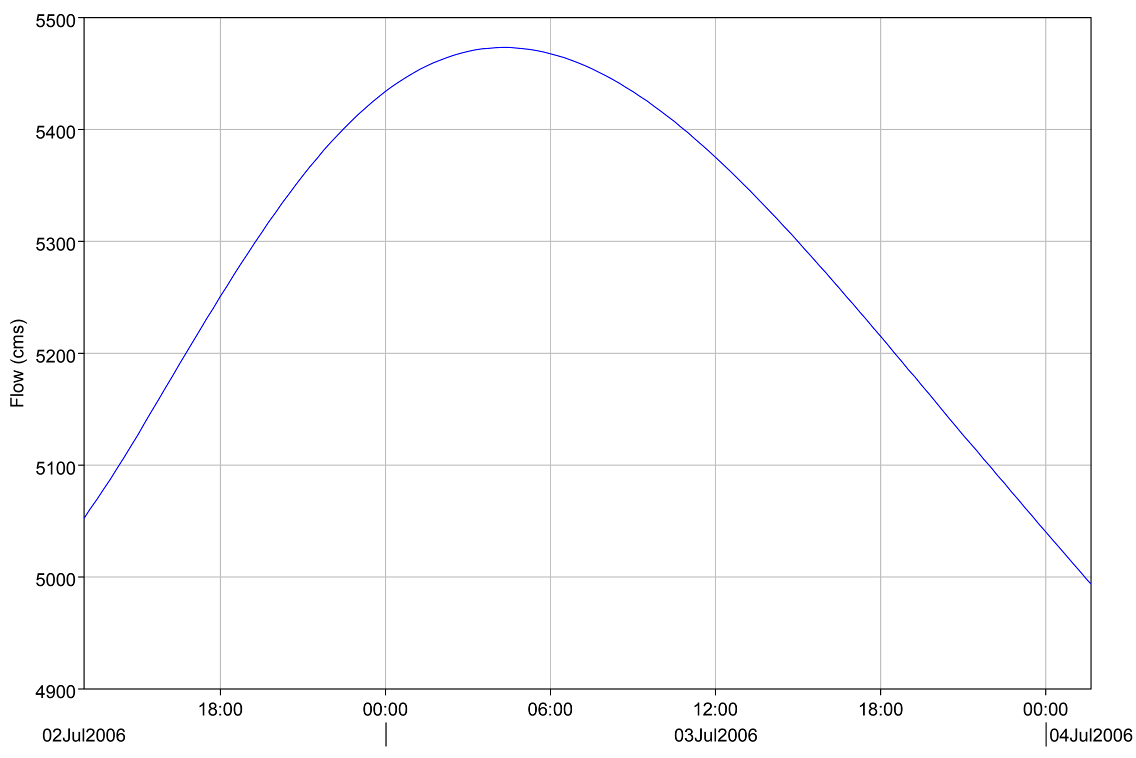

Chart 20. Scenario 5 - Flow at mouth of Stikine River

SCENARIO 6

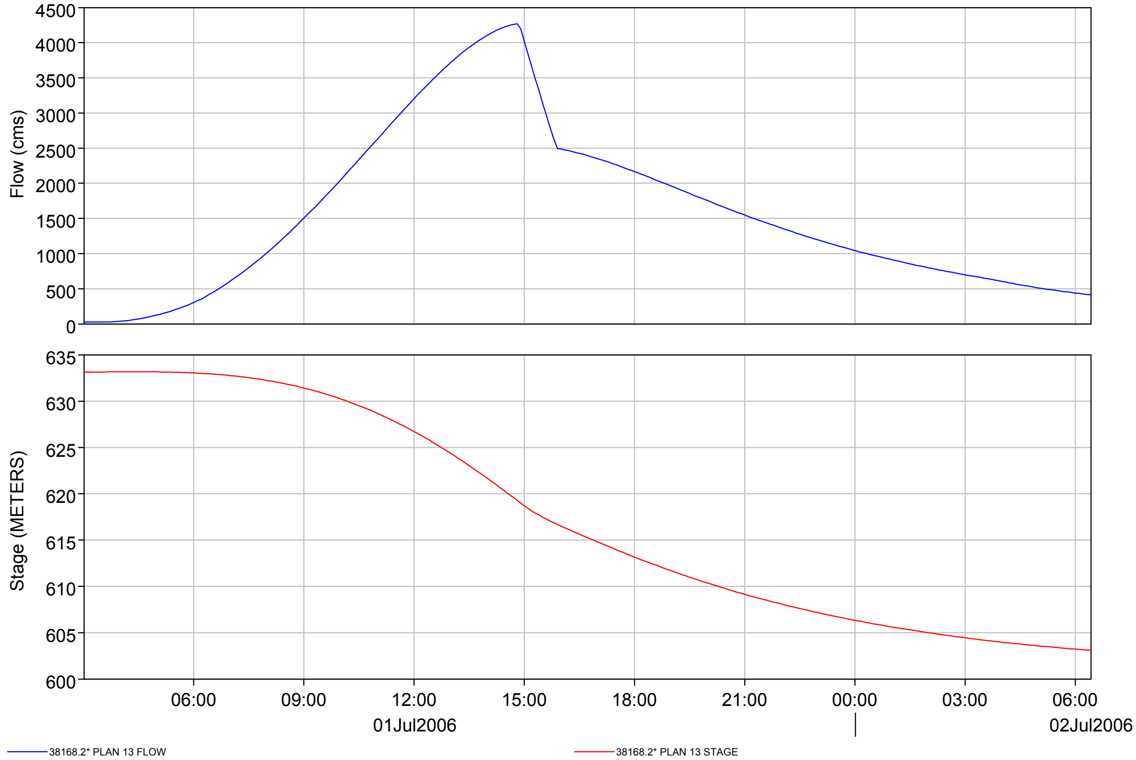

Chart 21. Scenario 6 - Flow and Stage near dam

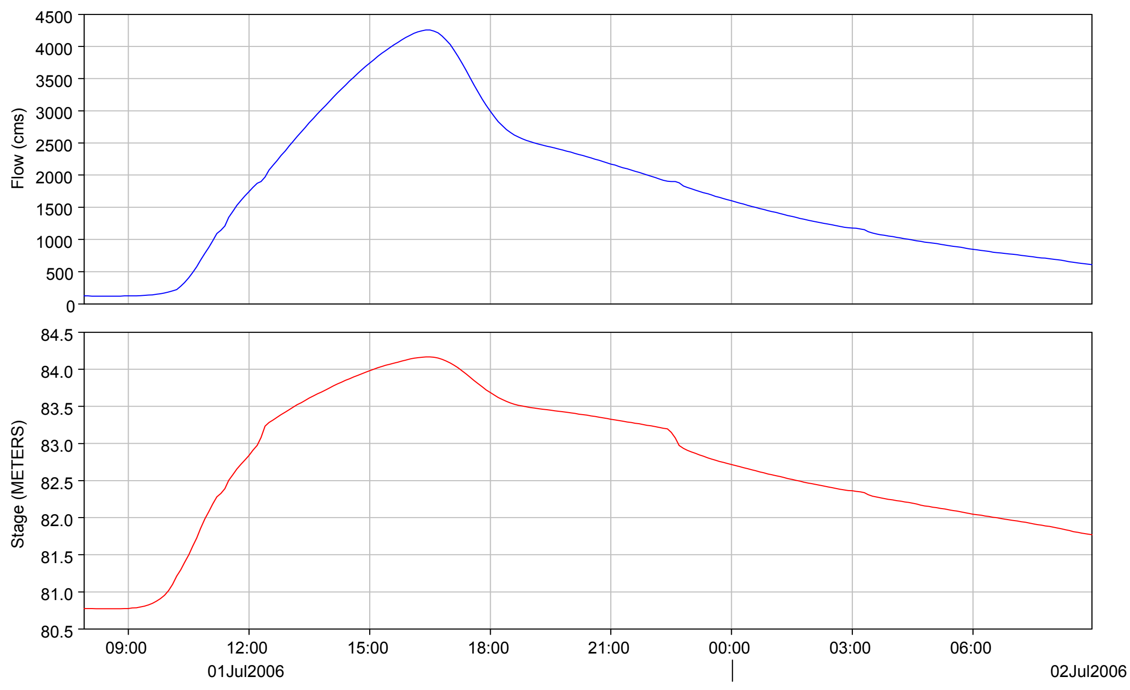

Chart 22. Scenario 6 - Flow and Stage at mouth of Scud River

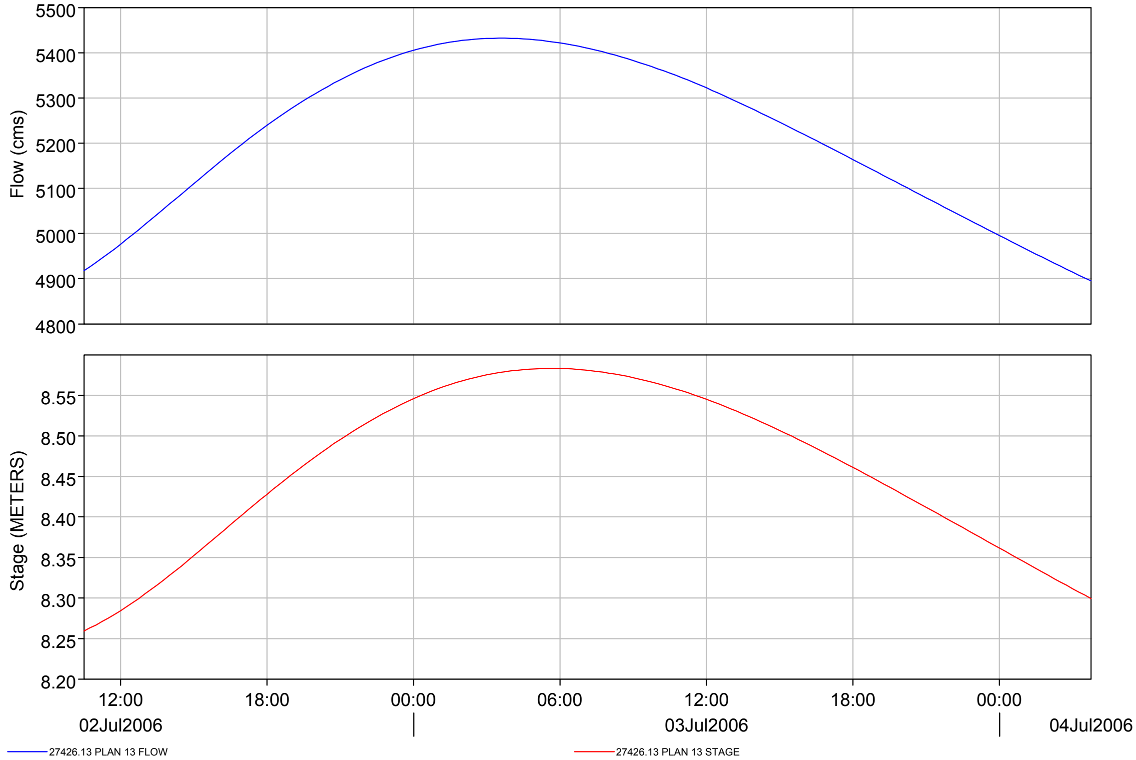

Chart 23. Scenario 6 - Flow and Stage near USGS Gage Location

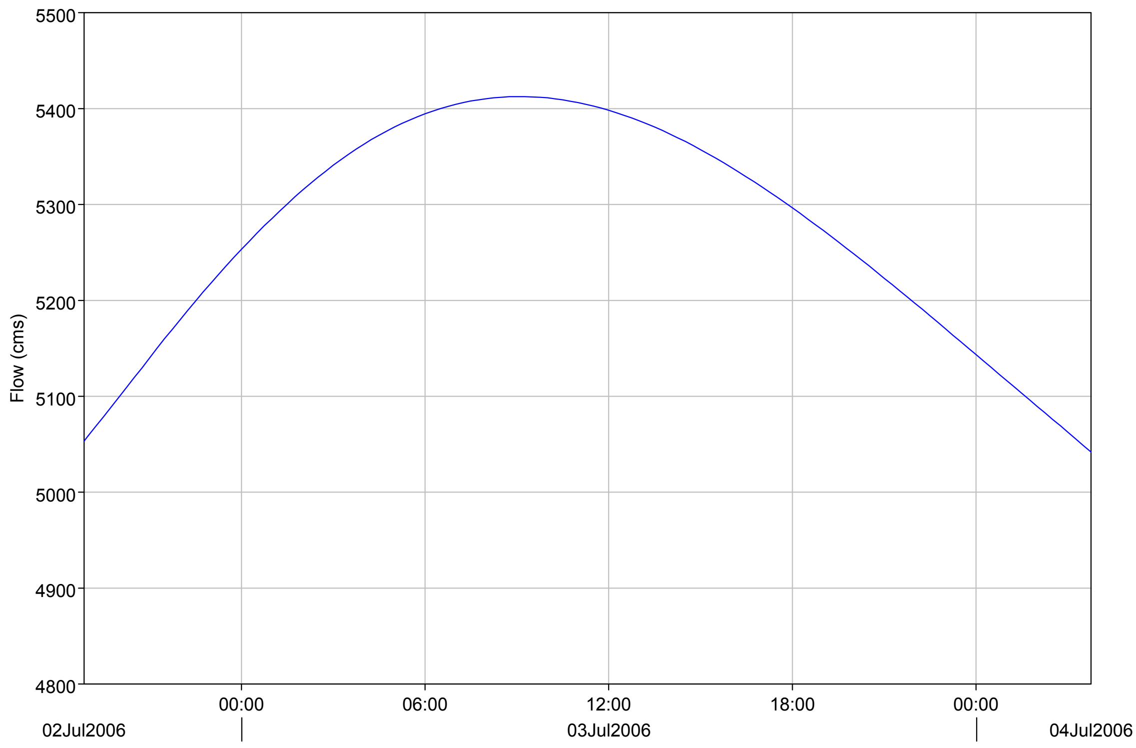

Chart 24. Scenario 6 - Flow at mouth of Stikine River

SCENARIO 7

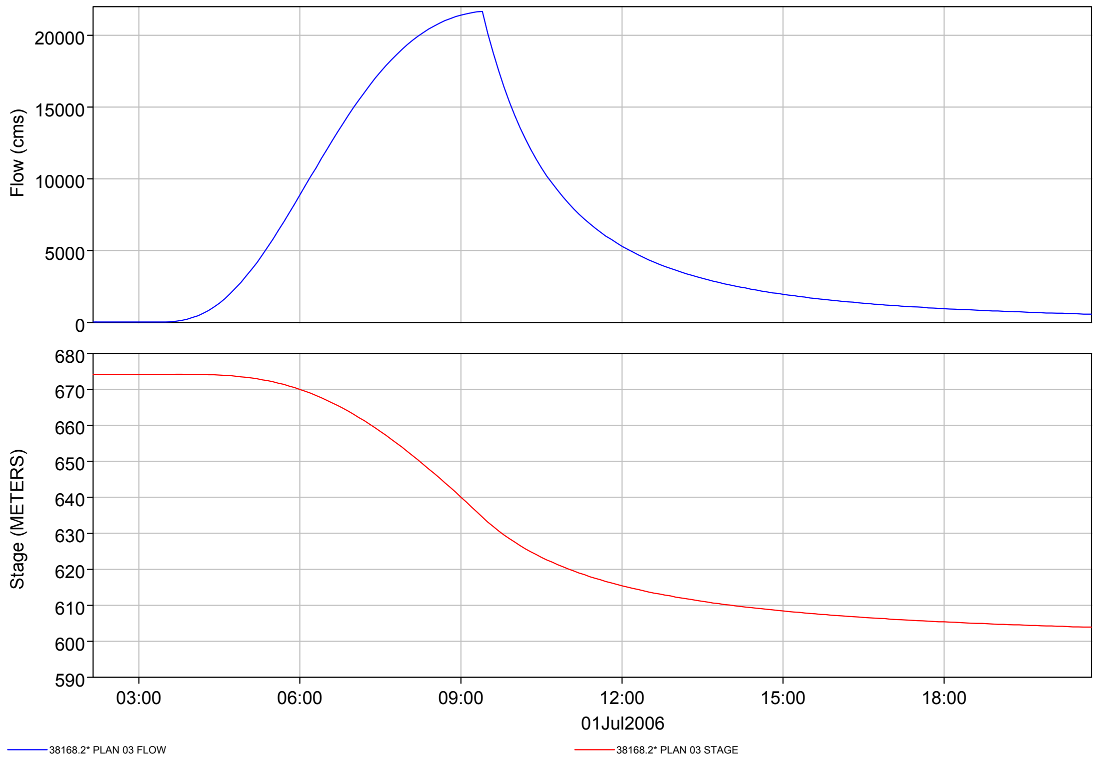

Chart 25. Scenario 7 - Flow and Stage near dam

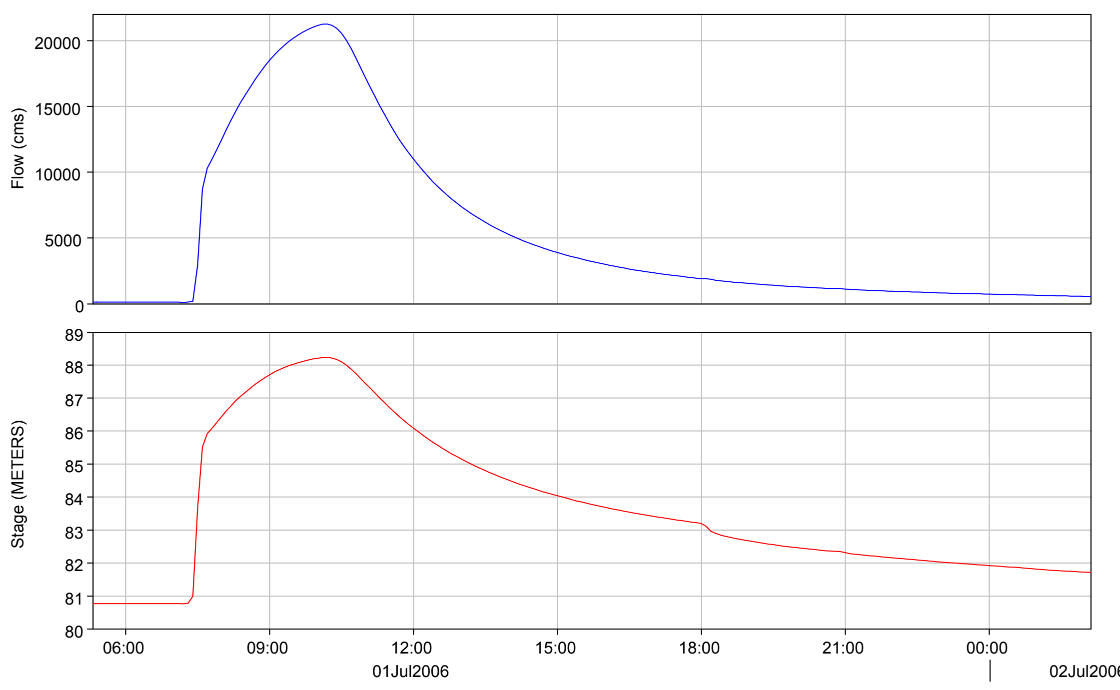

Chart 26. Scenario 7 - Flow and Stage at mouth of Scud River

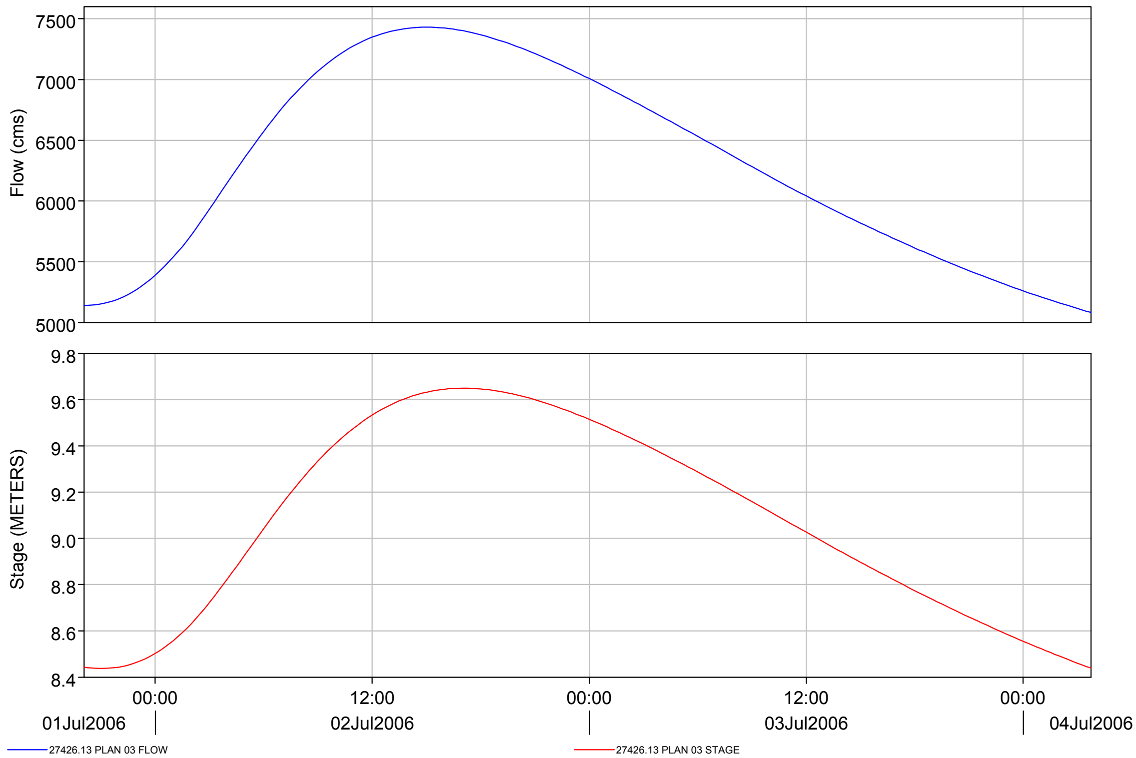

Chart 27. Scenario 7 - Flow and Stage near USGS Gage Location

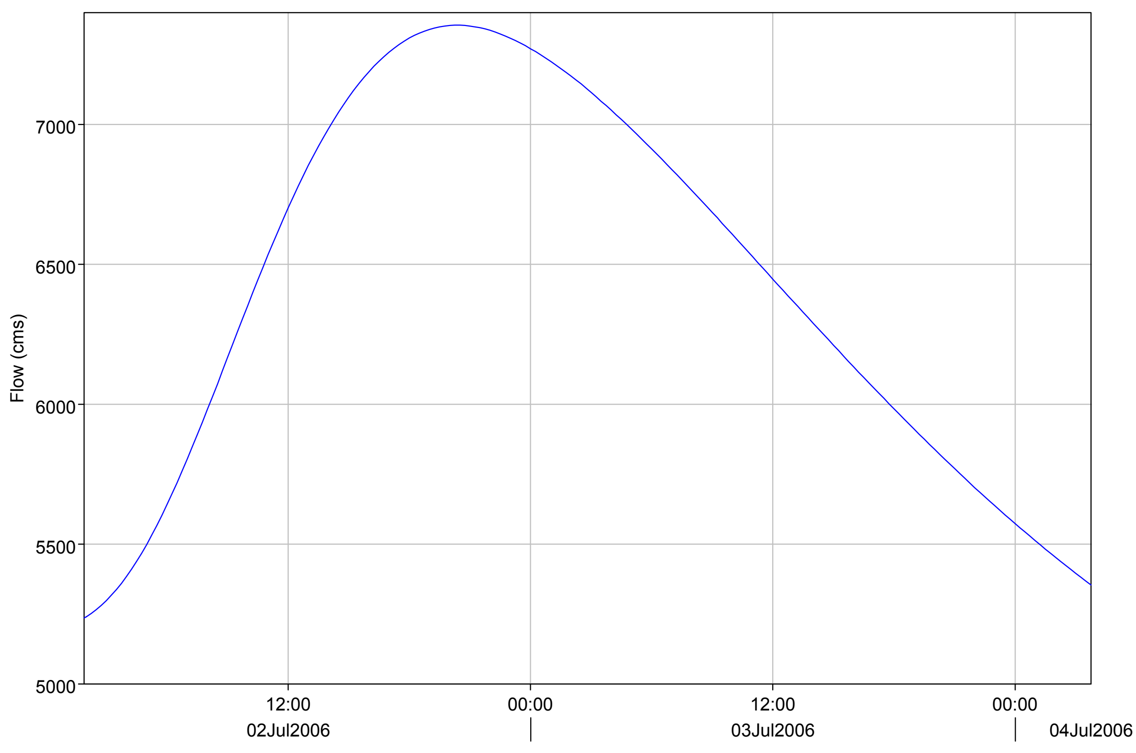

Chart 28. Scenario 7 - Flow and Stage at mouth of Stikine River

SCENARIO 8

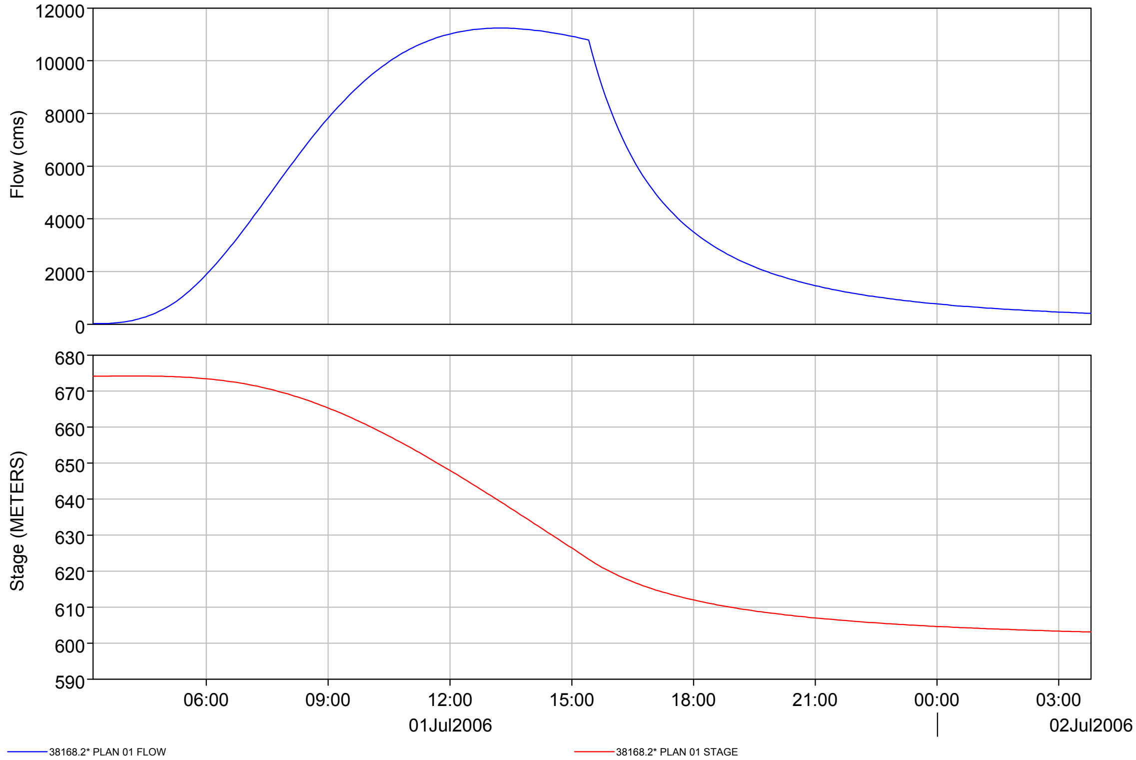

Chart 29. Scenario 8 - Flow and Stage near dam

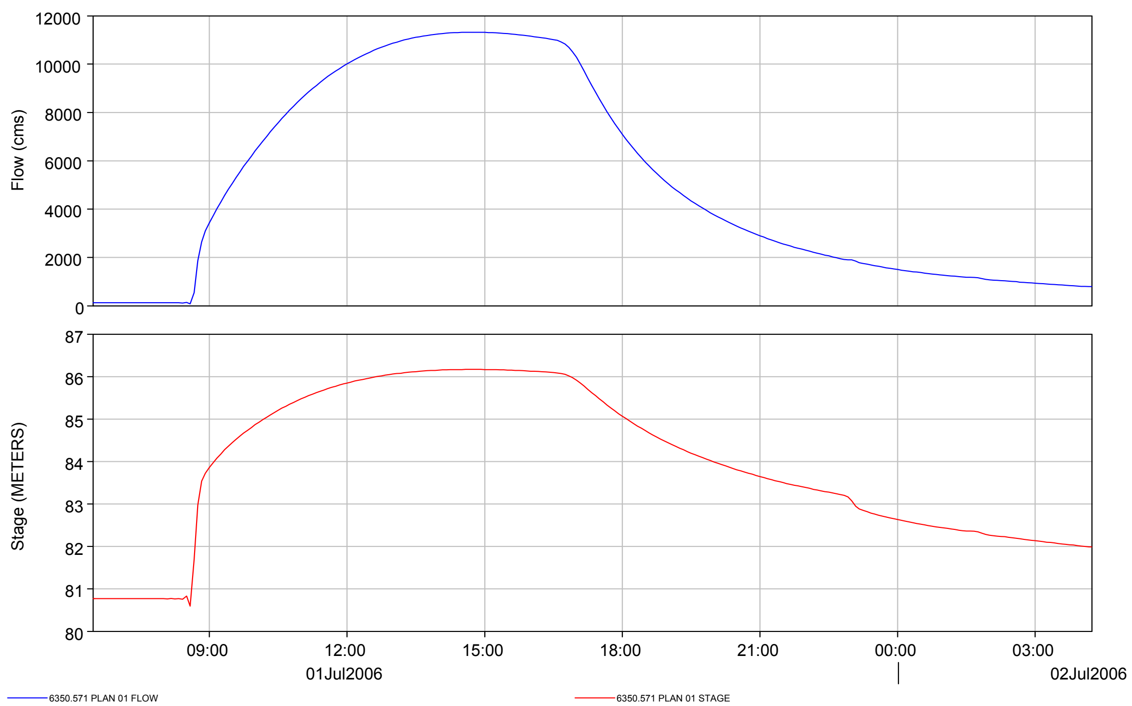

Chart 30. Scenario 8 - Flow and Stage at mouth of Scud River

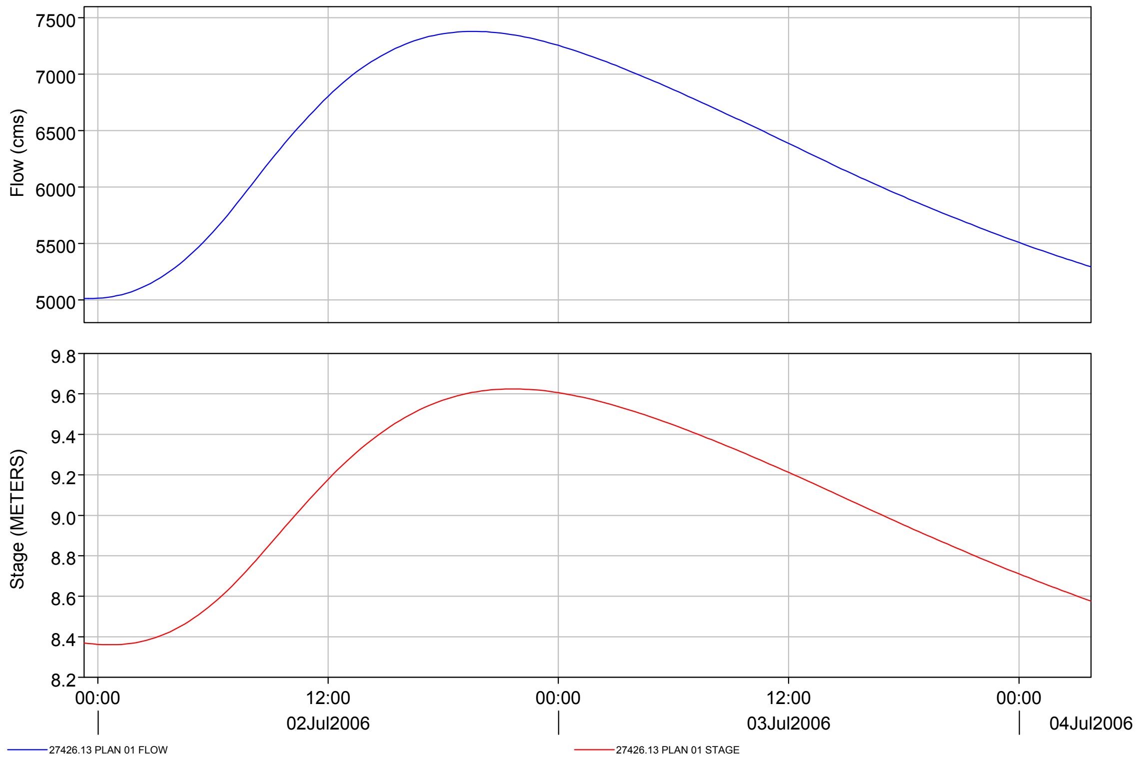

Chart 31. Scenario 8 - Flow and Stage near USGS Gage Location

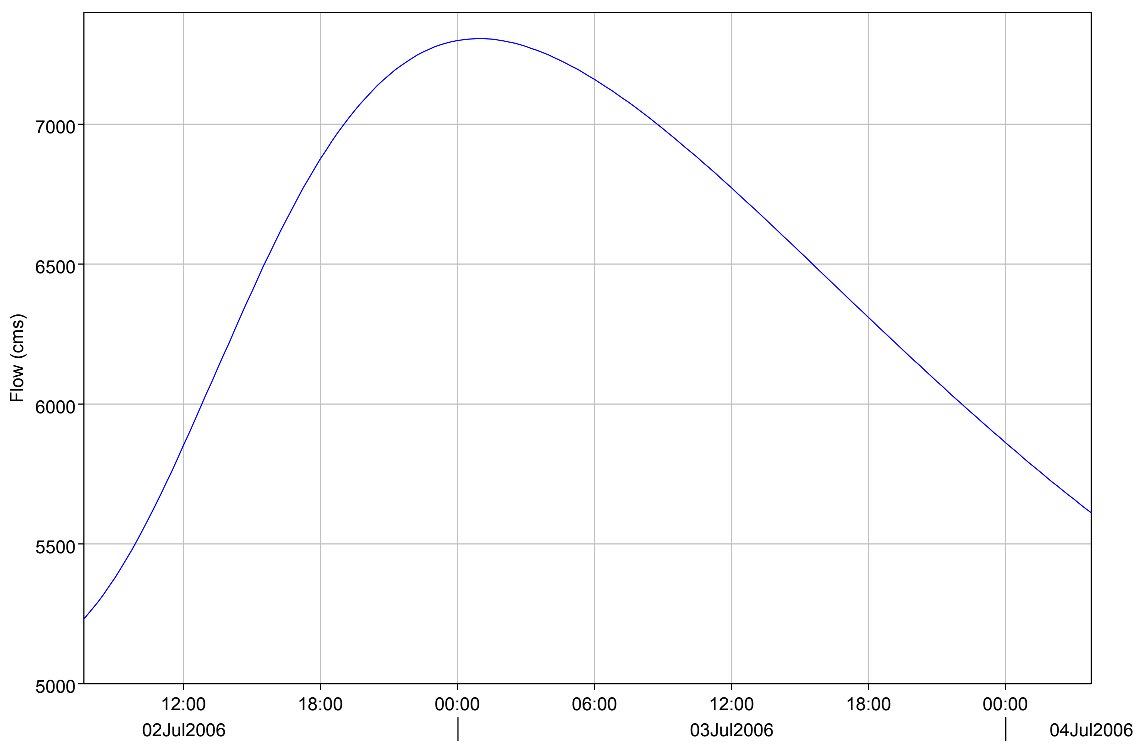

Chart 32. Scenario 8 - Flow at mouth of Stikine River

SCENARIO 9

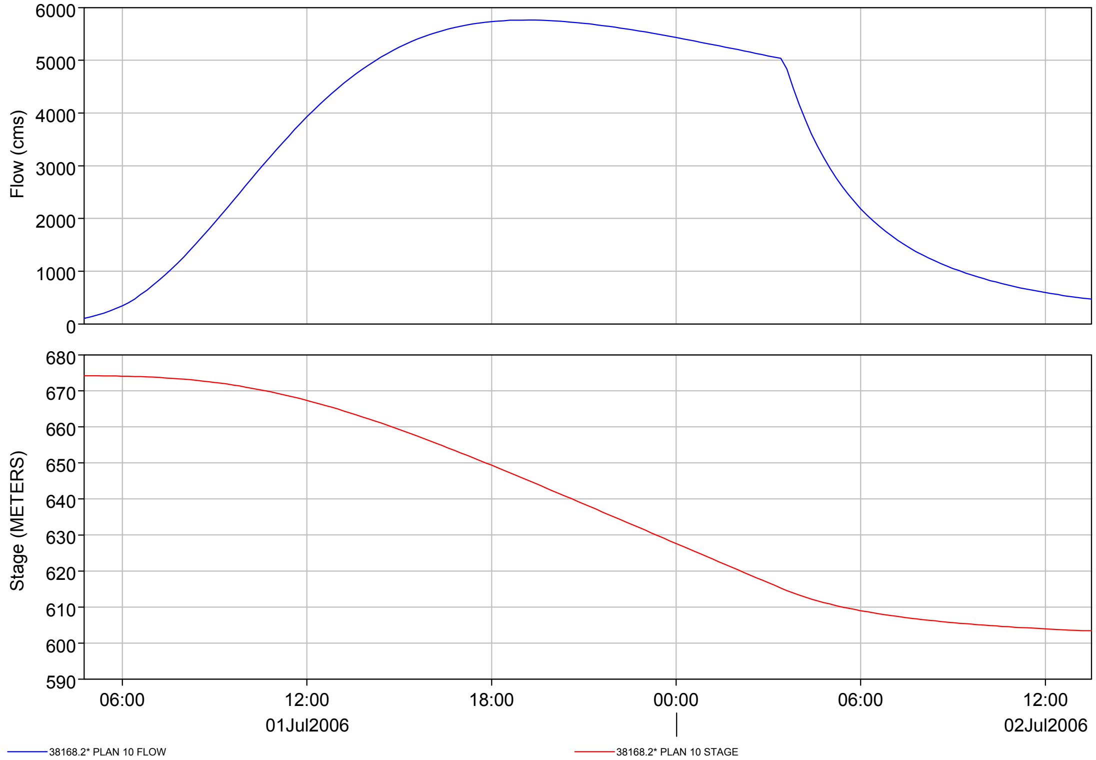

Chart 33. Scenario 9 - Flow and Stage near dam

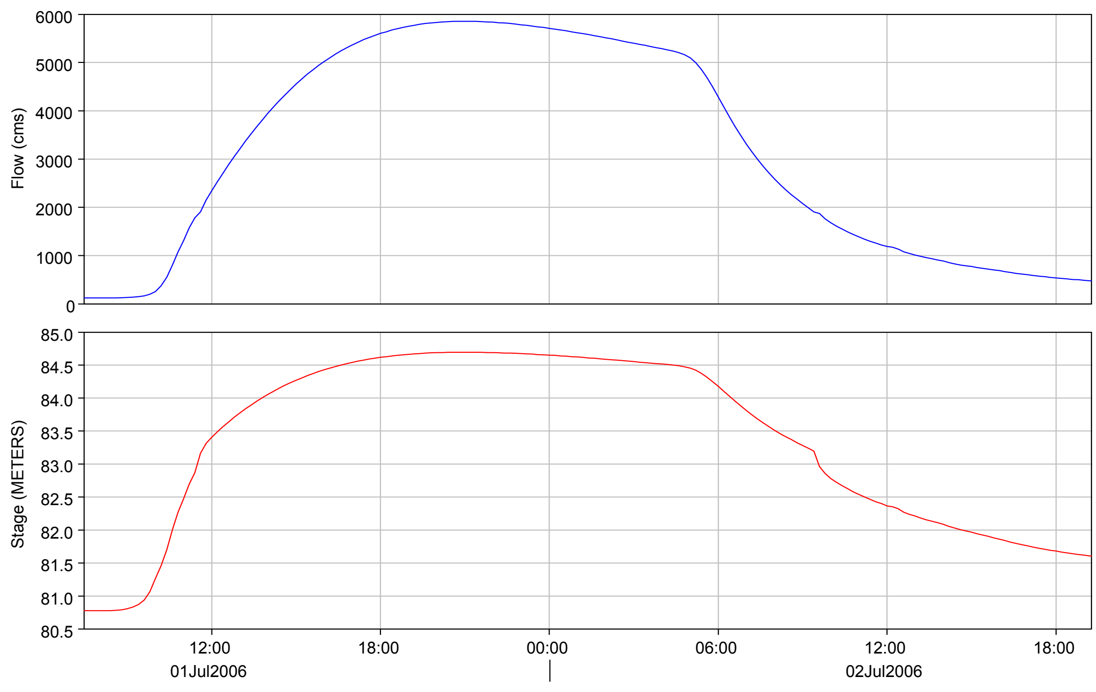

Chart 34. Scenario 9 - Flow and Stage at mouth of Scud River

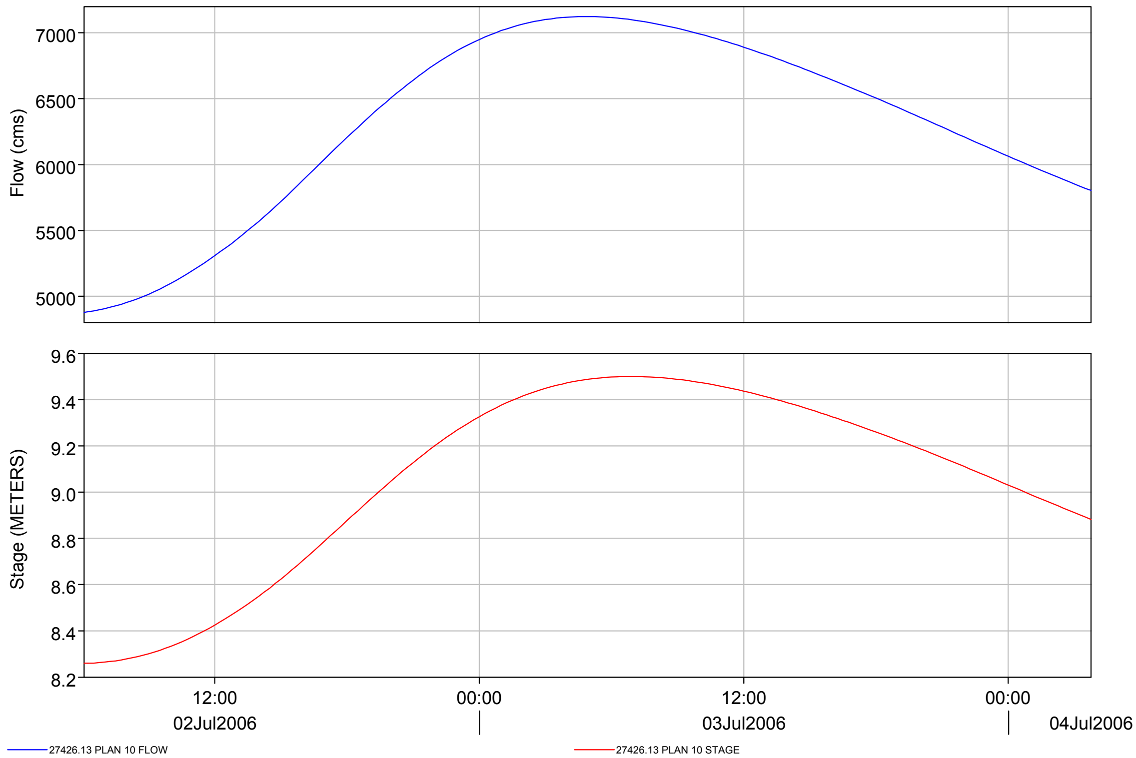

Chart 35. Scenario 9 - Flow and Stage near USGS Gage Location

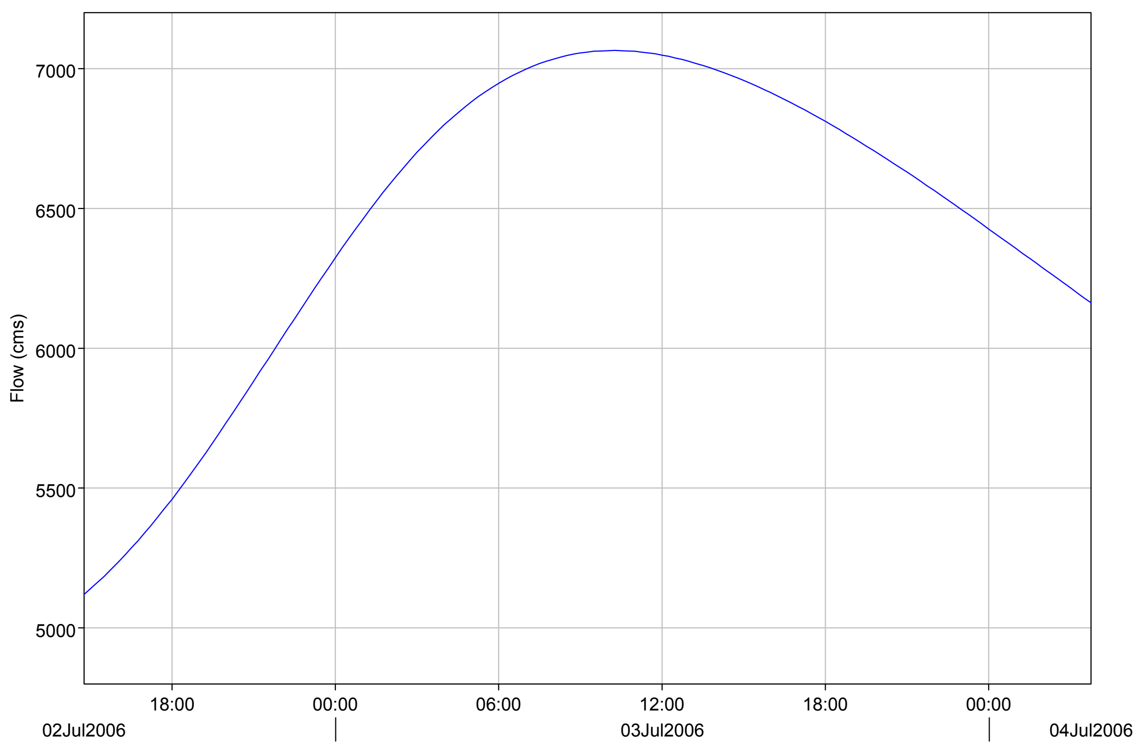

Chart 36. Scenario 9 - Flow at mouth of Stikine River

SCENARIO 10

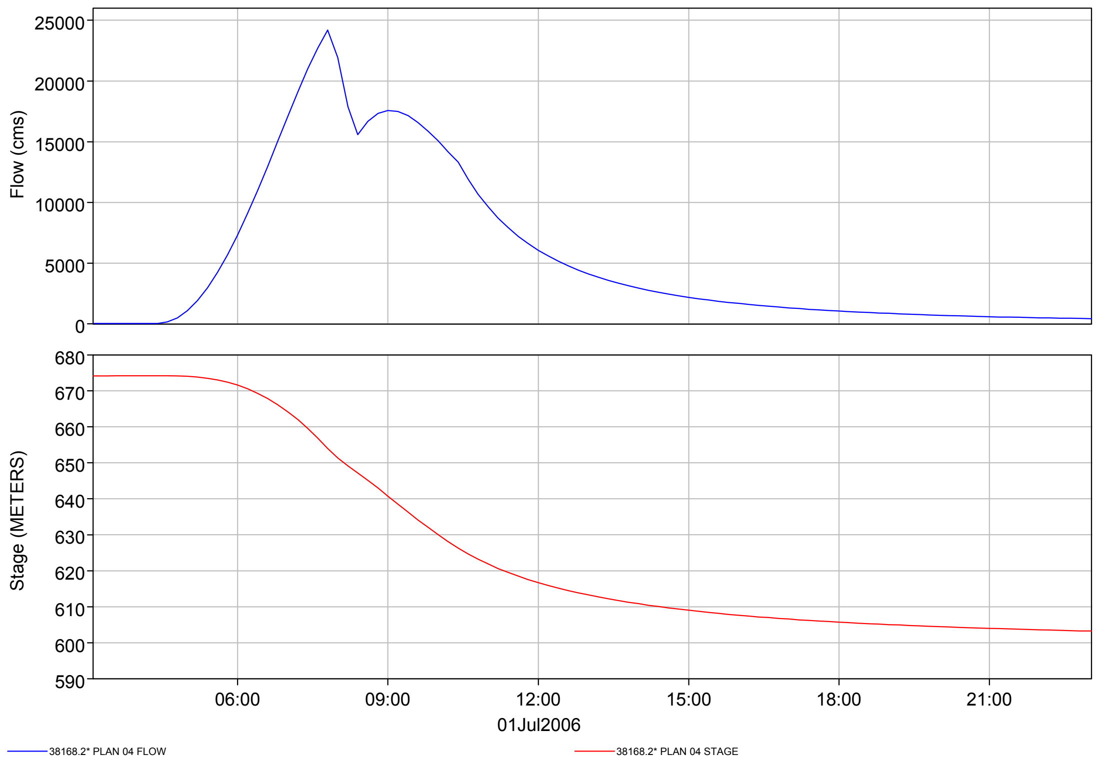

Chart 37. Scenario 10 - Flow and Stage near dam

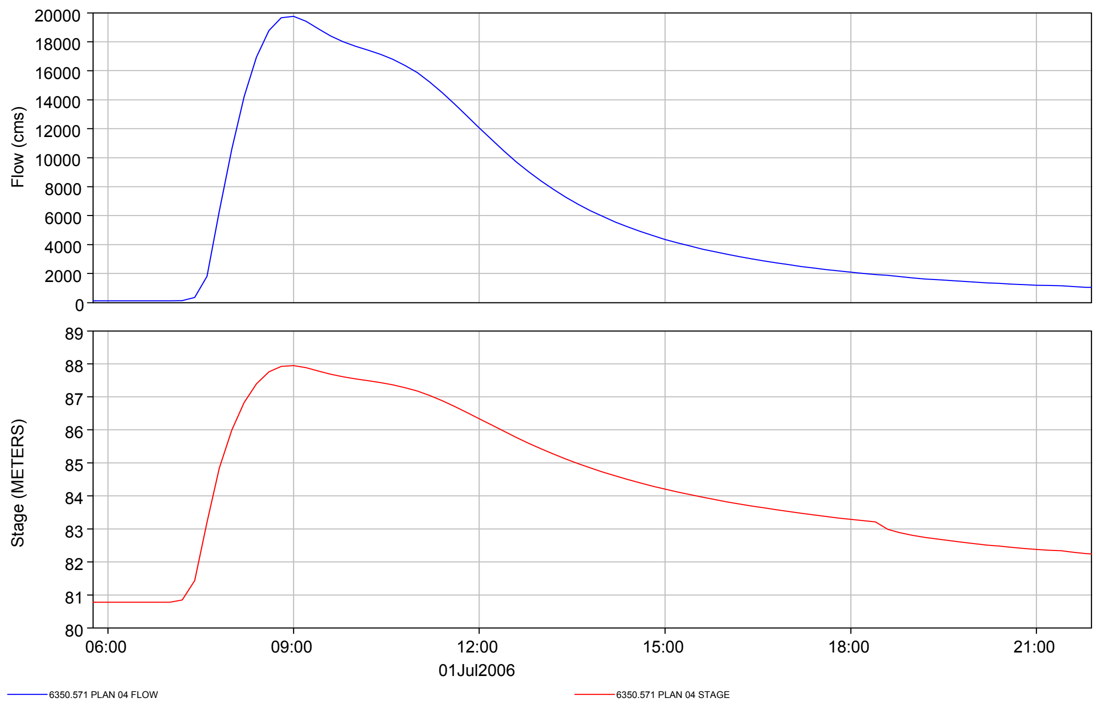

Chart 38. Scenario 10 - Flow and Stage at mouth of Scud River

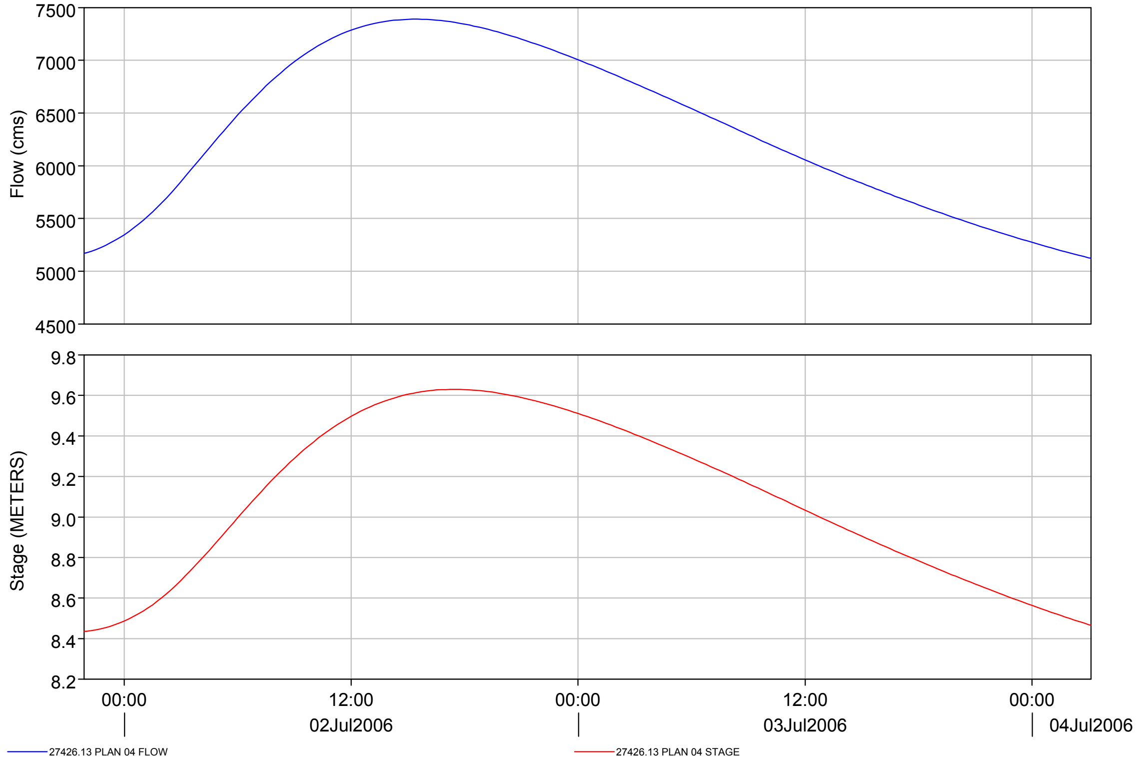

Chart 39. Scenario 10 - Flow and Stage near USGS Gage Location

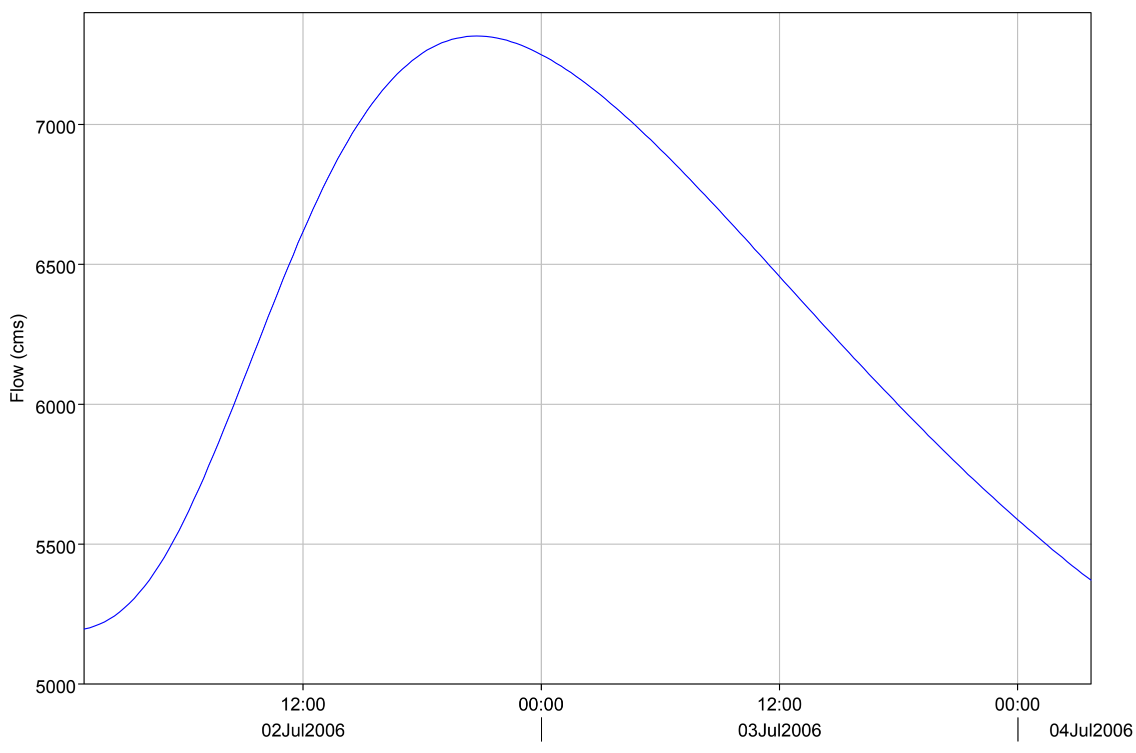

Chart 40. Scenario 10 - Flow at mouth of Stikine River

SCENARIO 11

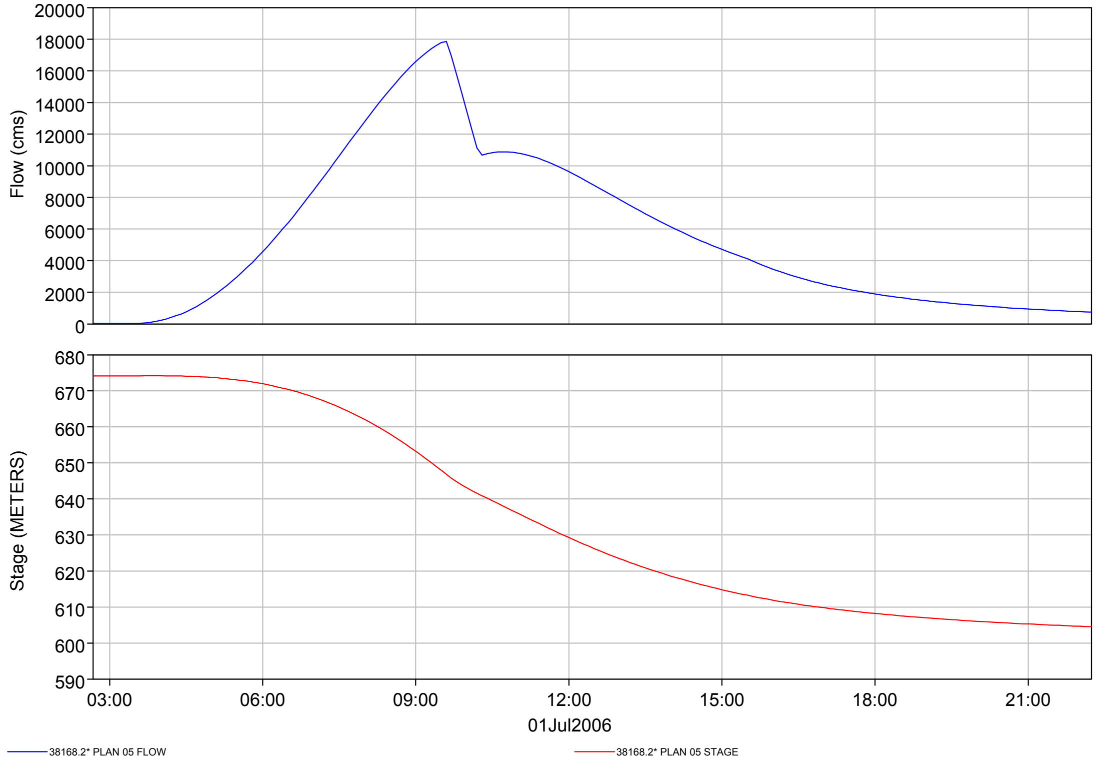

Chart 41. Scenario 11 - Flow and Stage near dam

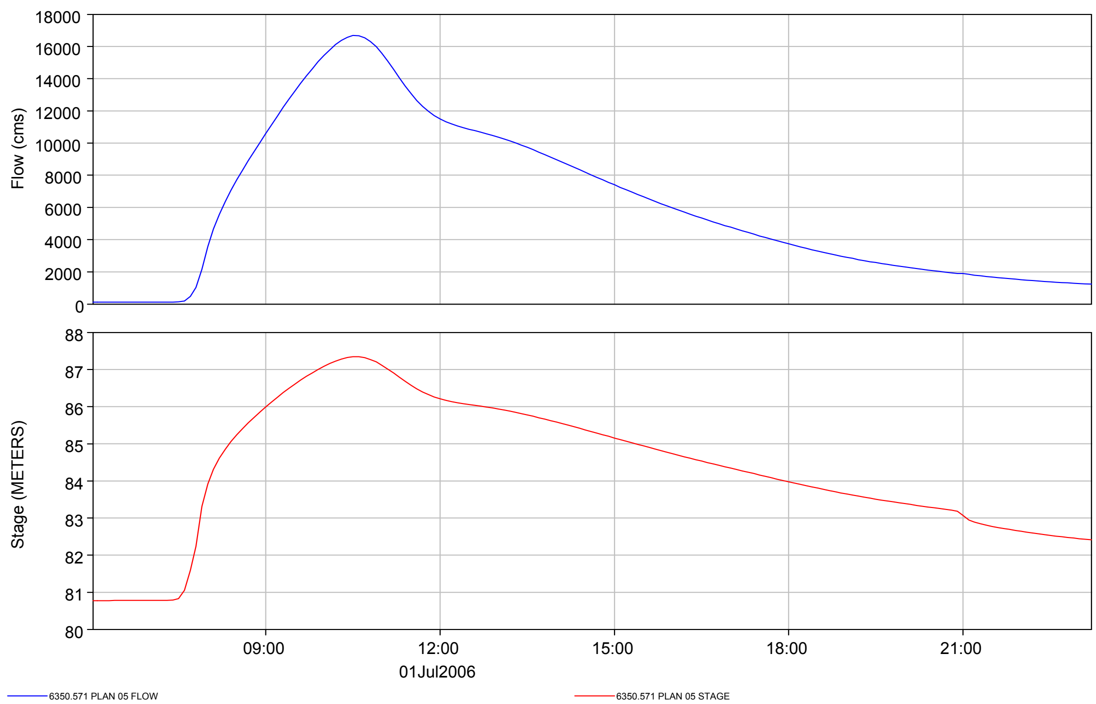

Chart 42. Scenario 11 - Flow and Stage at mouth of Scud River

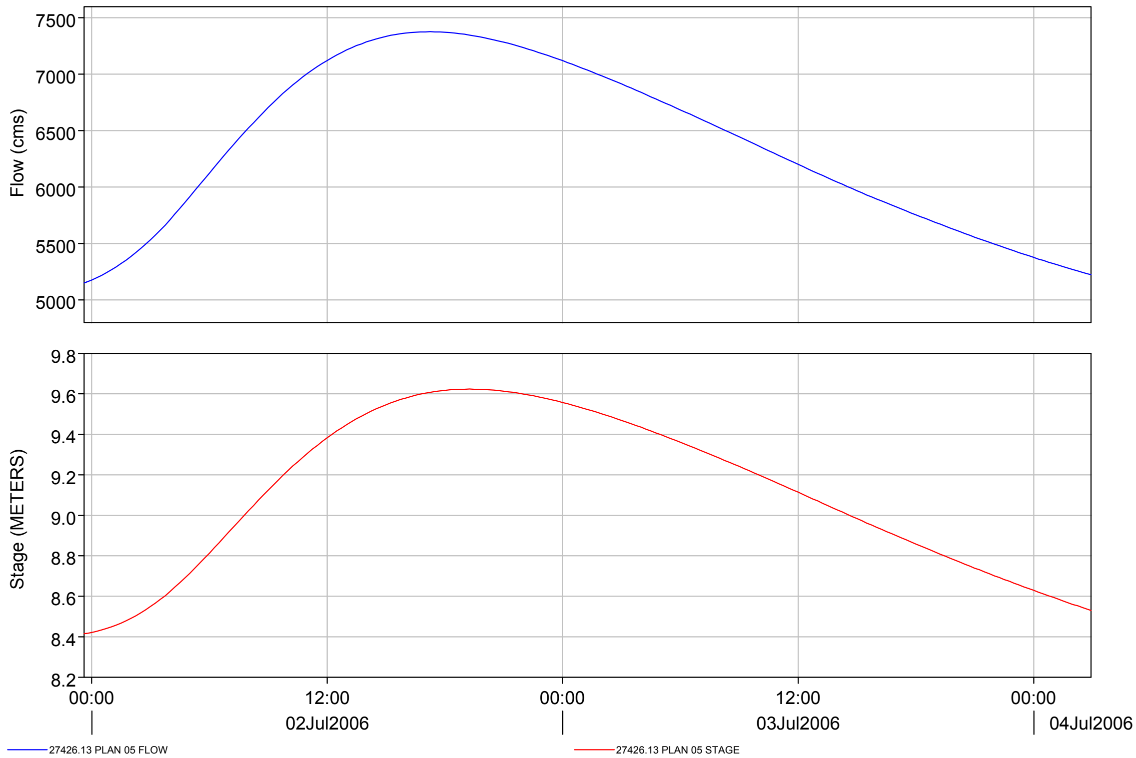

Chart 43. Scenario 11 - Flow and Stage near USGS Gage Location

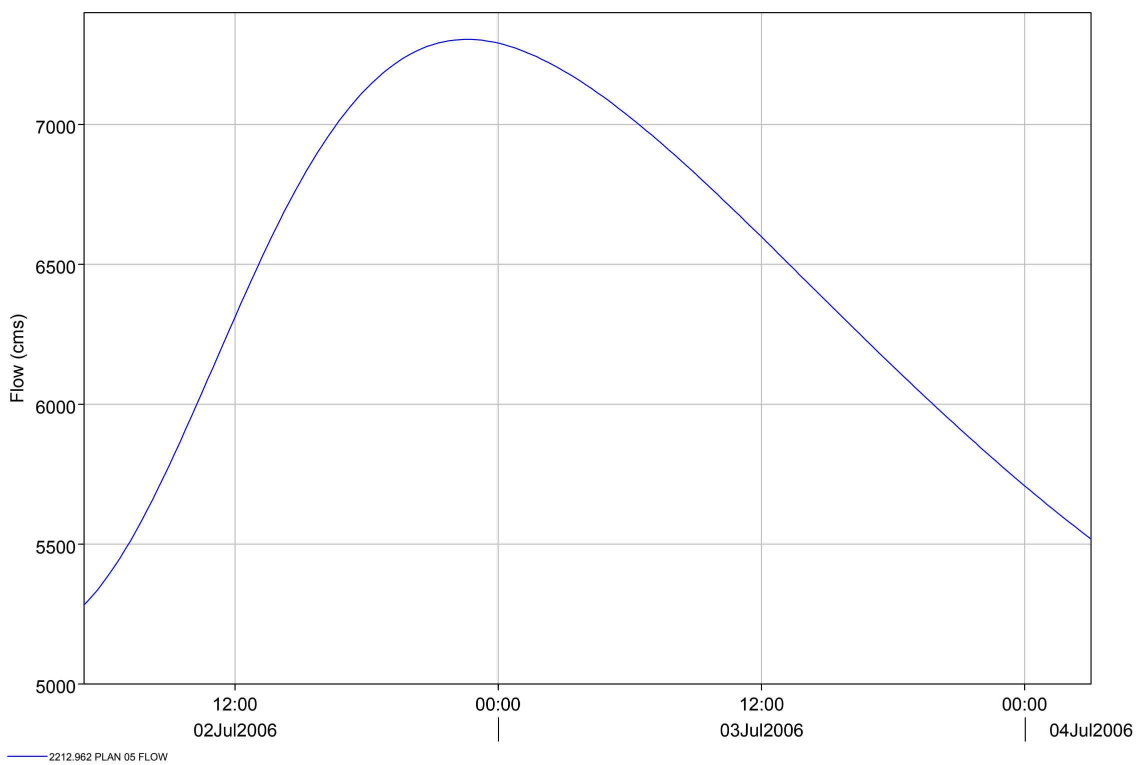

Chart 44. Scenario 11 - Flow at mouth of Stikine River

SCENARIO 12

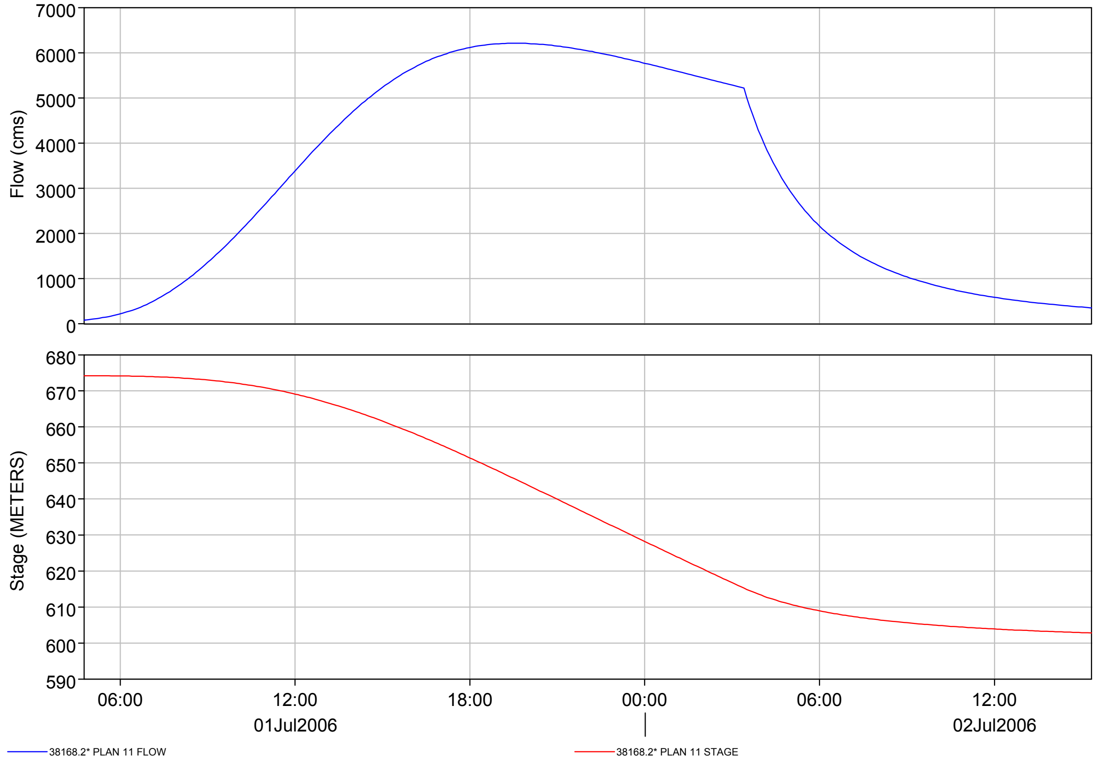

Chart 45. Scenario 12 - Flow and Stage near dam

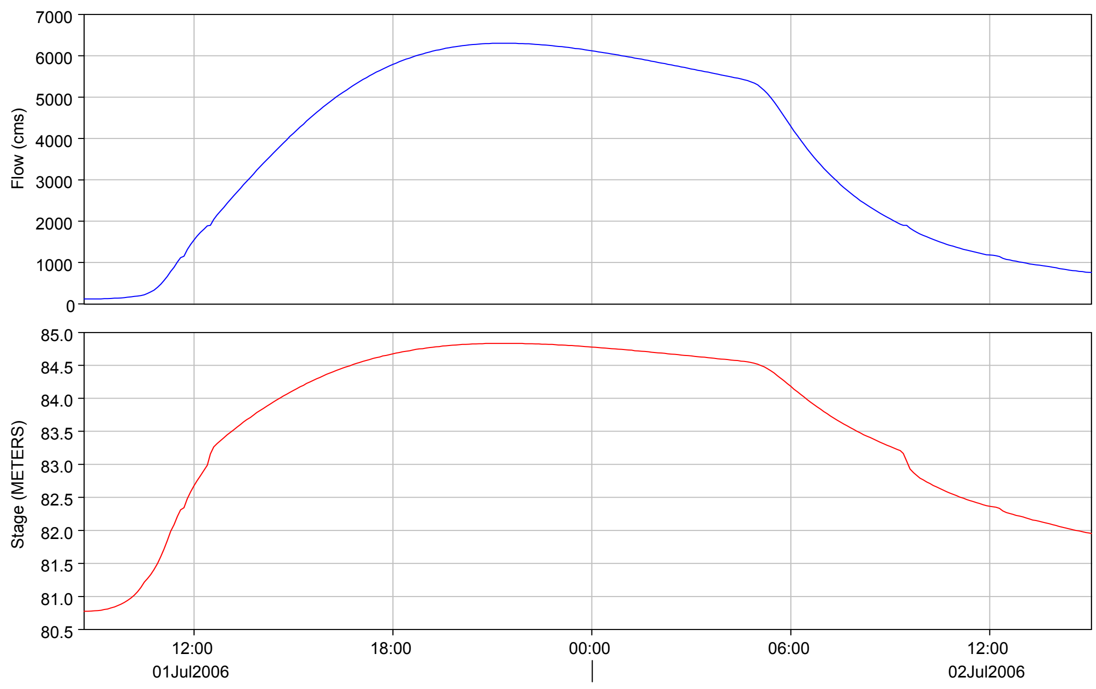

Chart 46. Scenario 12 - Flow and Stage at mouth of Scud River

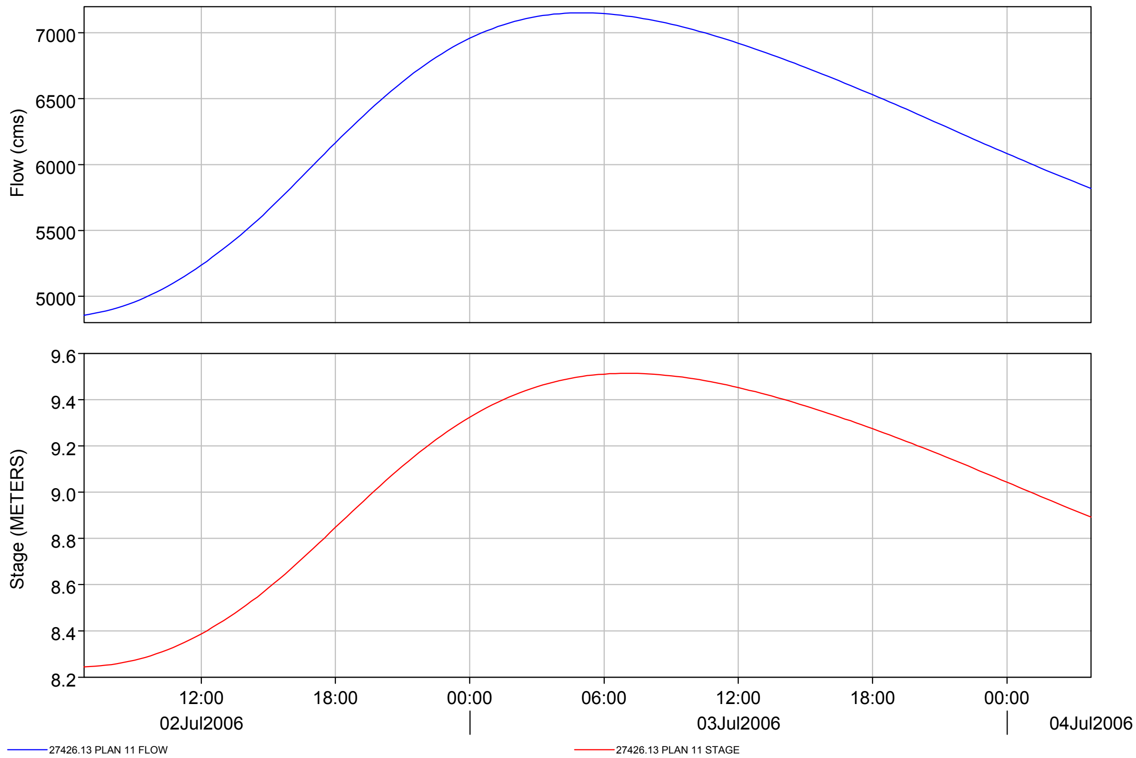

Chart 47. Scenario 12 - Flow and Stage near USGS Gage Location

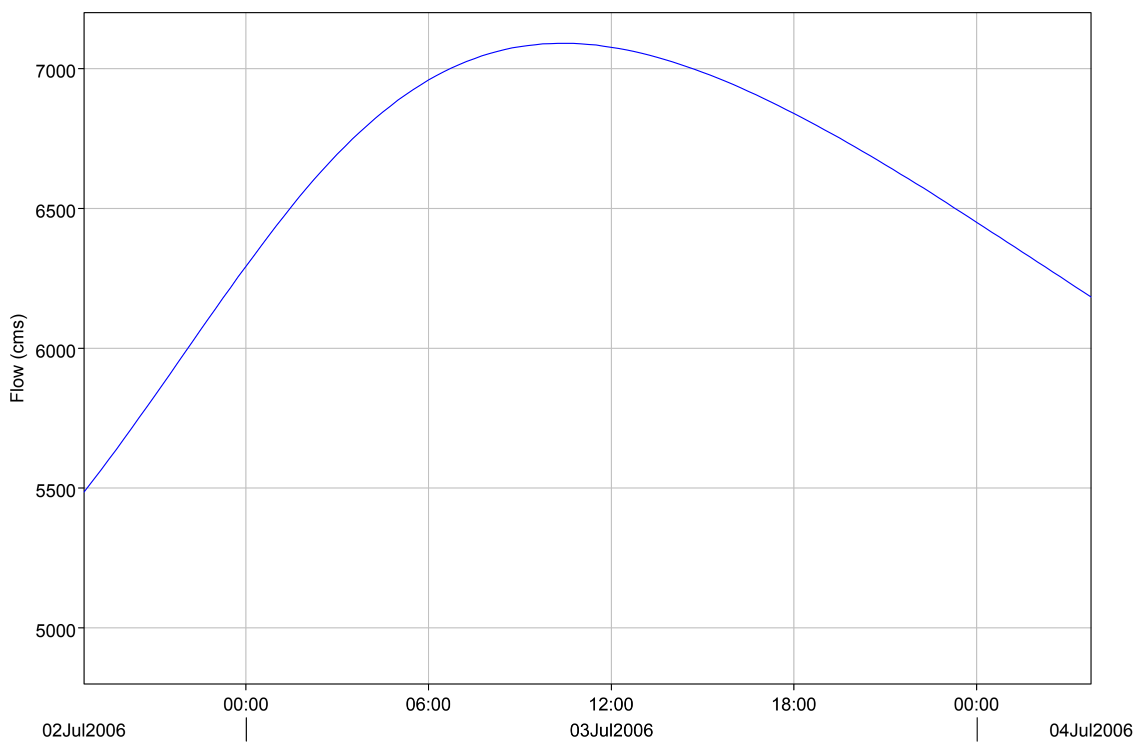

Chart 48. Scenario 12 - Flow at mouth of Stikine River