INCREMENTAL ANALYSIS OF LIBBY DAM OPERATION DURING 2006 AND GAS BUBBLE TRAUMA IN KOOTENAI RIVER FISH RESULTING FROM SPILLWAY DISCHARGE

INCIDENT REPORT
ON LIBBY DAM SPILL
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Abstract

Water was released through the spillways at Libby Dam in northwestern Montana from June 8-27, 2006, causing gas supersaturation in the Kootenai River downstream. The surface elevation of Koocanusa Reservoir rose toward full pool (elevation 2459 ft msl) in early June and reservoir inflow remained greater than turbine discharge capacity. As a result, the US Army Corps of Engineers began routing excess water through the spillways on June 8, 2006. Spill caused gas supersaturation in the Kootenai River exceeding Montana's gas saturation standard of 110 percent for 20 consecutive days. Discharge peaked at 54,900 cfs on June 19th when nearly 31,000 cfs was released through the spillway, the highest combined discharge since Libby Dam was completed. Gas saturation levels peaked at 131.48 percent. The location of the spillway near the left downstream bank creates a gas saturation gradient across the river channel, with higher gas concentrations on the left downstream bank. Dissolved gas mixes across the channel approximately 8 km downstream of the dam.

Fish were visually examined for external symptoms of gas bubble trauma (GBT). Electrofishing captures along the right and left banks were recorded separately and correlated with varying exposures to supersaturated water. GBT was observed in rainbow trout (*Oncorhynchus mykiss*), westslope cutthroat trout (*O. clarki lewisii*), kokanee (*O. nerka*), bull trout (*Salvelinus confluentus*) and Mountain whitefish (*Prosopium williamsoni*). Symptoms in trout were observed on the fourth day of spill and increased in frequency as spill continued. GBT was greater on along the left downstream bank where gas supersaturation was greatest. Long-term exposure to gas increases frequency and severity of GBT symptoms with repeated exposure as fish enter shallow water. After 11 days of spill, all bull trout and westslope cutthroat trout captured had GBT, including multiple hemorrhages on the ventral surface of the body, bubbles in fins, eyes, dermis on the operculum and split fins. Hemorrhaging on the ventral body surface increased when gas saturation approached 131 percent, then apparently reduced when dissolved gas concentrations reduced toward 124 percent. Observed frequency of GBT in mountain whitefish and rainbow trout increased to 92 to 93 percent.

Population estimates before and after the 2006 spill event did not detect impacts to trout populations in the Kootenai River. Comparisons of length frequencies and recaptures of tagged fish indicated that few if any fish were displaced downstream during the high discharge event.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

Page

Introduction

Construction of Libby Dam began in 1966 after authorization by the Columbia River International Treaty of 1964 and was completed on the Kootenai River in Montana during 1972 (Knudson 1994). The Kootenai River was impounded at river mile 221.7 on March 21, 1972 creating Lake Koocanusa (Woods and Falter 1982), also called Koocanusa Reservoir, approximately 25 km upstream of Libby Montana. Libby Dam was constructed to provide flood control, hydropower generation, flood control, and other uses for the surrounding area (Bonde and Bush 1982). Since completion of the Libby Dam, the spillway has been used infrequently. A voluntary and forced spill event occurred most recently in June and July 2002. Gas saturated water hugs the left bank of the Kootenai River downstream of Libby Dam for roughly 5 to 8 miles until turbulence distributes supersaturated water across the river (Coastal and Hydraulics Laboratory U.S. Army Engineer Research and Development Center 2002). Based on results from spill monitoring during 2002, supersaturated water remains unabated downstream to Kootenai Falls, about 28 miles downstream of Libby dam.

In June 2006, the surface elevation of Koocanusa Reservoir in northwestern Montana approached full pool elevation (2459 ft msl) and inflows to the reservoir remained in excess of Libby Dam turbine discharge capacity (approx. 24 kcfs when surface elevation approaches full pool). The resulting spill operation at Libby Dam extended for 20 consecutive days, caused elevated total dissolved gas (TDG) and resulted in a total discharge from Libby Dam that has been unprecedented since its construction (Figure 1).

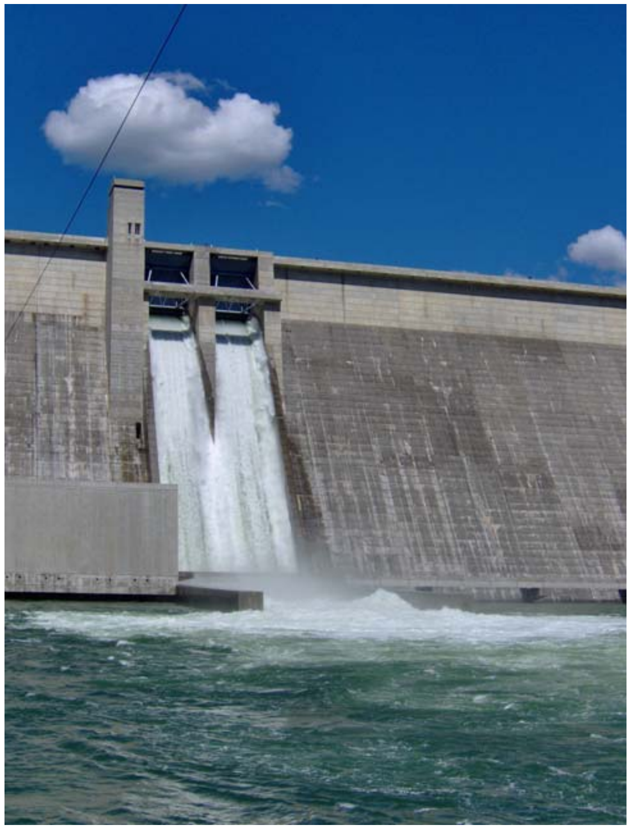


Figure 1. Photograph of water being released through the spillway at Libby Dam during the spill event in June 2006. The volume of water being released in the photograph was 31,000 cubic feet per second taken on June 19, 2006.

Methods

Electrofishing

Montana Fish, Wildlife & Parks (MFWP) conducted electrofishing surveys in the Kootenai River from the David Thompson Bridge (river mile; RM 221.6) downstream to Dunn Creek (RM 219.8; Figure 2). Electrofishing was conducted at night on June 12, 15, 19 and 22 using a jet boat-mounted Coffelt model Mark 22 electrofishing unit, with an electrical output ranging from 200-300 volts at 5-8 amps. Sampling occurred after dark when fish move into the shallows and are most vulnerable to electrofishing. The electrical field penetrates about 2.5 meters in depth, which may select for individual fish in the depth zone where gas bubble trauma (GBT) is most apparent. The location of the spillway near the left downstream bank creates a gas saturation gradient across the river channel in the sampling reach; therefore, personnel examined fish captured along the left and right banks separately.

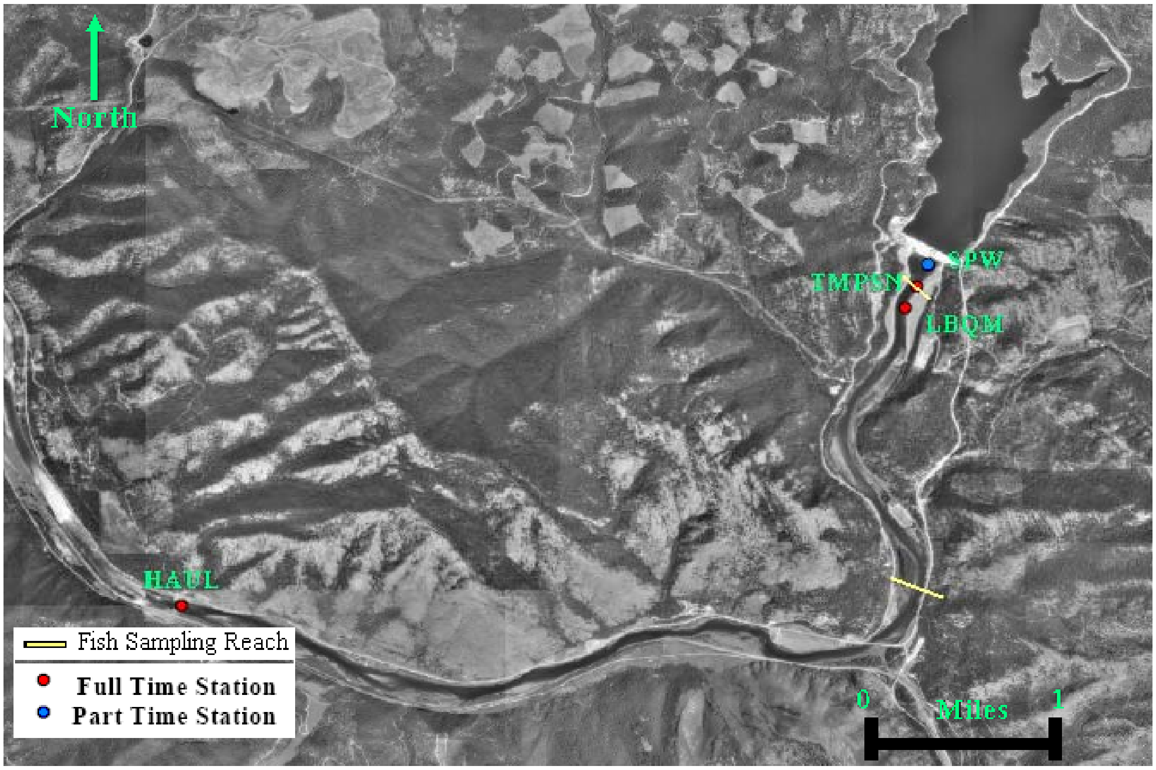


Figure 2. Location of gas saturometers (red and blue dots) and fish sampling (between yellow bars) during the spill event at Libby Dam during June 2006.

Gas saturometers were placed in the Kootenai River below the David Thompson Bridge river at mile 221.6 and at river mile 208.9 (identified as HAUL in Figure 2). Nonlinear regression was used to quantify the exposure of fish to super saturated water (days of spill) and relate that exposure to symptoms observed in free-swimming fish that were captured by electrofishing. The percentage of fish showing symptoms of GBT on each sampling night was used as the response variable in the nonlinear regression. In addition, the gas exposure models used by Dunnigan (2003) were also used to assess the impacts of spill on fishes below Libby Dam. The first index was cumulative hourly spill discharge (CSpill) a particular group of fish was exposed to, and was calculated using the following equation.

$$CSpill_j = \sum_i (HSD)$$

Where $Cspill_j$ = The cumulative hourly spill discharge for fish group j at time of examination, and HSD (Hourly Spill Discharge) = the sum of i hourly spill discharge measurements (kcfs) that fish group j was exposed to until examination. For example, if a fish were exposed to 5 kcfs spill for 10 hours, the cumulative hourly spill discharge would be 50. The second index of exposure (CSpWtd) utilized a weighting factor based on the proportion of the spill discharge relative to total discharge. We calculated cumulative spill weighted discharge ($CSpWtd_j$) for fish group j using the following equation.

$$CspWtd_j = \sum_i (HSD)*(HSD/TD)$$

Where HSD (Hourly Spill Discharge) is the hourly spill (kcfs), and TD is the total discharge at Libby Dam (kcfs) for the i^{th} hourly period. For example, if a fish were exposed to 5,000 cfs spill with at a total discharge of 10,000 cfs for 10 hours, the cumulative spill weighted discharge would be 25.

Electrofishing surveys will be repeated during fall 2006 and spring 2007 to assess changes in fish abundance by length category and species relative abundance. Recaptured PIT tagged fishes (i.e., during the spill) can be assessed for healing of previous injuries / trauma from the spill and growth can be assessed.

Gas Bubble Trauma Monitoring

Captured fish were anesthetized using an aqueous solution of MS-222, identified to species, measured for total length and weight, and examined fish for marks, tags, injuries and symptoms of gas bubble trauma (GBT), gas emboli in fins, eyes and external tissues (Dunnigan 2003).

PIT tagging

Passive Integrated Transponder (PIT) tags were used to identify recaptured fish, to assess levels of secondary infection or latent mortality and to determine if high discharges displaced fish downstream. PIT tags (models TX1411SGL and TX1400SST from Texas Instruments) were implanted in muscle tissue posterior to the dorsal fin, adjacent to the vertebra, in all trout ≥300 mm total length using a 12-gauge hypodermic needle. Prior to injecting tags in each specimen, each tag and needle was sterilized by immersion in 70% isopropyl alcohol. Once inserted, the tags were read with a Destron Fearing 2001F-ISO portable transceiver and the individual tag number was recorded in the reader, on the data sheet, and on the corresponding scale envelope if applicable. Tagged fish were also marked with an adipose fin clip to aid in visual identification of recaptured individuals.

Fish Population Estimates

MFWP conducts fish population estimates using a mark and recapture techniques to assess long-term trends in resident fish populations within three sections of the Kootenai River. We target bull trout within the Libby Dam Tailrace (LDT), which extends from Libby Dam (River mile [RM] 221.7) downstream to the confluence of the Fisher River (RM 218.2) in April/May, and have conducted this survey annually since 2004. We divided the 3.5 mi. (5.63 km) reach of Kootenai River into two sections, and sampled the two sections on consecutive evenings during the marking session and approximately seven days later during the recapture session.

MFWP targets rainbow and cutthroat trout within the Flower Pipe section of the Kootenai River, which extends from the confluence of Flower Creek (RM 204.0) downstream to the confluence of Pipe Creek (RM 201.0). This section has been surveyed approximately annually since 1973, and although the sampling date has varied throughout this period, sampling since 2001 has occurred in August or September. Rainbow and cutthroat trout are also targeted in the " Rereg" section of the Kootenai River, which extends from RM 210.5 downstream to the Osprey Landing boat ramp (RM 208.9). MFWP has surveyed this section during early spring (February/March) annually since 2001, with the exception of 2002 when high turbid flows from the Fisher River limited visibility and reduced capture efficiency. A single mark and recapture session is conducted approximately seven days apart in both the Flower Pipe and Rereg sections. Population estimates are calculated using a partial log-likelihood estimator (Fisheries Analysis + © 2004, MFWP).

Fish collected for population estimates in each of the three Kootenai River sampling reaches, were captured during nighttime electrofishing using two jet boats. Each boat contained a driver and two netters. The electrofishing unit on each boat consisted of a Coffelt model Mark 22 electrofishing unit operating with an electrical output ranging from 200-350 volts at 5-8 amps powered by a 5,000 watt gasoline powered generator. We recorded the total time (minutes) that electrical current was generated in the water as a measure of effort. We examined all fish for marks, collected scale samples, measured total length (mm) and weight (g), and then released all fish near their capture location. All bull trout were marked with PIT tags (see above) and an adipose fin clip was removed to evaluate PIT tag retention. Rainbow and cutthroat trout within the Flower-Pipe and Rereg sections were marked with a fin clip. We compared the mean total length of bull trout captured during April 2004 to 2007 at the LDT section using analysis of variance and subsequent multiple comparisons (Fisher's Least Significant Difference).

We estimated trout abundance using a mark-recapture population estimation technique which assumes the population is "closed", suggesting no births, deaths or migrations occurred during sampling periods (Ricker 1958). Additional assumptions were that marked and unmarked fish have equal mortality rates, marked fish were randomly distributed throughout the study area, marks were not lost, and all marked fish captured were recognized and counted (Lagler 1956). We used the Petersen Estimator as modified by Chapman (Ricker 1958) to estimate absolute abundance of bull trout within the LDT section using the following formula.

$$N = \frac{(M + 1) \bullet (C + 1)}{R + 1} - 1$$

Where: N = population estimate,
C = total fish captured in the recapture sample(s),
M = number of marked fish at the start of recapture sample period and
R = number of marked fish in the recapture sample(s).

We used the following formula to calculate bounds (B) for 95% confidence intervals for each estimate.

$$B = 1.96 \times \sqrt{\frac{N^2 \bullet (C - R)}{(C + 1) \bullet (R + 2)}}$$

Downstream Fish Displacement

We evaluated the hypothesis that high discharges from Libby Dam during the 2006 spill event caused downstream fish displacement. Fish captured within the Rereg and Flower Pipe sections after the spill event were examined for PIT tags that were originally placed in fish at upstream locations during April-June 2006. For example, during the podt-spill, September 2006 population estimate at the Flower Pipe section, we looked for fish that were originally PIT tagged in either the LDT or Rereg sections during April-June 2006. We used the binomial distribution function in Microsoft excel to estimate maximum detectable differences for our observed displacement rates of PIT tagged fish. The binomial distribution function calculates the probability of collecting the observed number of PIT tagged fish for a given sample size, and theoretical displacement rate. We used theoretical displacement rates ranging from 0.5% to 20.0% in increments of 0.5%, and reported the maximum detectable difference for the 5% probability value. In other words, the maximum detectable difference we report is the displacement rate that may have occurred given a 5% probability of sampling the observed number of PIT tagged fish within the sample section. Too few bull trout were captured to perform a similar analysis for bull trout at these two locations.

We evaluated the hypothesis that high discharges from Libby Dam during the 2006 spill event caused downstream bull trout displacement at the LDT section by calculating the proportion of bull trout captured each year since 2004 that were originally tagged the previous year, and compared pre and post spill estimates. Our rationale was that if the spill in 2006 caused increased downstream displacement of bull trout from the LDT section, the proportion of recaptured bull trout during the April/May 2007 sampling session would be lower than previous years. We were unable to conduct this analysis at this section for rainbow trout because we did not PIT tag adequate numbers of fish in 2004 and 2005 to make a similar comparison.

Fish Growth

Recaptured PIT tagged fishes were used to assess possible differences in growth between fish that experienced spill and fish that did not. Growth was standardized to millimeters per day and grams per day instead of absolute growth to account for different periods of time between recapture events. Fish tagged in 2004 and 2005 and later recaptured in 2007 were excluded from analysis because we could not differentiate growth that occurred before and after the spill (Table 1). Fish captured during the spill were classified as “no spill” fish even though they were exposed to spill. We assumed that the secondary effects (i.e., changes in length and weight resulting from infections, blindness, hemorrhages) were not instantaneous. Only fish recaptured greater than 15 days apart were used for growth analysis to minimize the effects of measurement error, which averaged 4.6mm for all fish recaptured less than 15 days. Recaptured fish ranged in length from 30 to 87 centimeters, resulting in measurement error ranging from 0.5-1.5% of total fish length. Growth of rainbow and cutthroat trout were lumped together, due to small samples sizes of cutthroat trout.

Table 1. Tagging and recapture classification scheme for growth analysis to test the hypotheses that spill did not affect growth ($g \cdot day^{-1}$, $mm \cdot day^{-1}$) of bull trout and rainbow trout below Libby Dam.

Tagging and Recapture Periods						
2004	**2005**	**April 2006**	**May 2006**	**June 2006**	**2007**	**Classification**
X	**X**					**No Spill**
X		**X**				**No Spill**
X			**X**			**No Spill**
X				**X**		**No Spill**
	X	**X**				**No Spill**
	X		**X**			**No Spill**
	X			**X**		**No Spill**
		X	**X**			**No Spill**
		X		**X**		**No Spill**
			X	**X**		**No Spill**
X					**X**	**Excluded**
	X				**X**	**Excluded**
		X			**X**	**Spill**
			X		**X**	**Spill**
				X	**X**	**Spill**

Results and Discussion

Spill and Gas Level Monitoring

The spillway was initially opened on June 8th and remained open through June 27th. By 5:00 PM on June 8, spill caused gas supersaturation in the Kootenai River exceeding Montana's gas saturation standard of 110 percent for the next 19 days. Discharge peaked at 54,900 cfs on June 19th when nearly 31,000 cfs was released through the spillway, the highest combined discharge from Libby Dam since it was completed (Figures 3 through 6). By 6:00 PM on June 8, gas levels exceeded 124 percent supersaturation and continued until June 16 when spill increased, causing an increase in gas saturation levels to 130 percent saturation (peaked at 131.48 percent; (Figure 4). Inflow to Koocanusa Reservoir was 39,900 cfs on June 13 and surface elevation was 2457.44 ft, or 1.6 ft from full. As of 10:00 AM on June 14, the National Weather Service River Forecast Center updated their forecast for inflows to the reservoir. Kootenai River stage at Bonners Ferry was 1762.24 feet, 1.76 feet below flood stage (1764 ft). The river was expected to crest at elevation 1764.2 feet during the evening of 15 June (flood stage at Bonners Ferry is 1764). More precipitation was predicted to increase inflows to Libby Reservoir on Wednesday (14 June) and into Thursday (15 June) to a peak of near 49,000 cfs and remain at this level through Friday, when inflows were predicted to recede. Based on this forecast, outflow from Libby Dam was expected to remain at 38,000 cfs through the week. In actuality, inflows continued to increase and spill increased to 31,000 cfs in excess of turbine capacity (24,000 cfs). Gas saturation gradually declined below 110 percent by 7 AM on June 27.

Only one gas saturometer was available at the US Geological Survey Station until June 14 when three additional saturometers were installed on the David Thompson Bridge and one was installed approximately 8.5 miles downstream of Libby Dam (near the site where old bridge piers were removed; identified as HAUL in Figure 2). Gas levels (TDG %) on the left bank were higher than the mid channel and right bank, with approximate mean daily TDG values of 132, 125 and 107% at the highest spill discharge of 31 kcfs (Figures 5 and 6). Gas concentrations were consistent across the channel 8 mi. (12.9 km) downstream of the dam, indicating that mixing of water had occurred (Figures 5 and 6). TDG was 10-15% higher 8 miles downstream than TMPSN3 saturometer values.

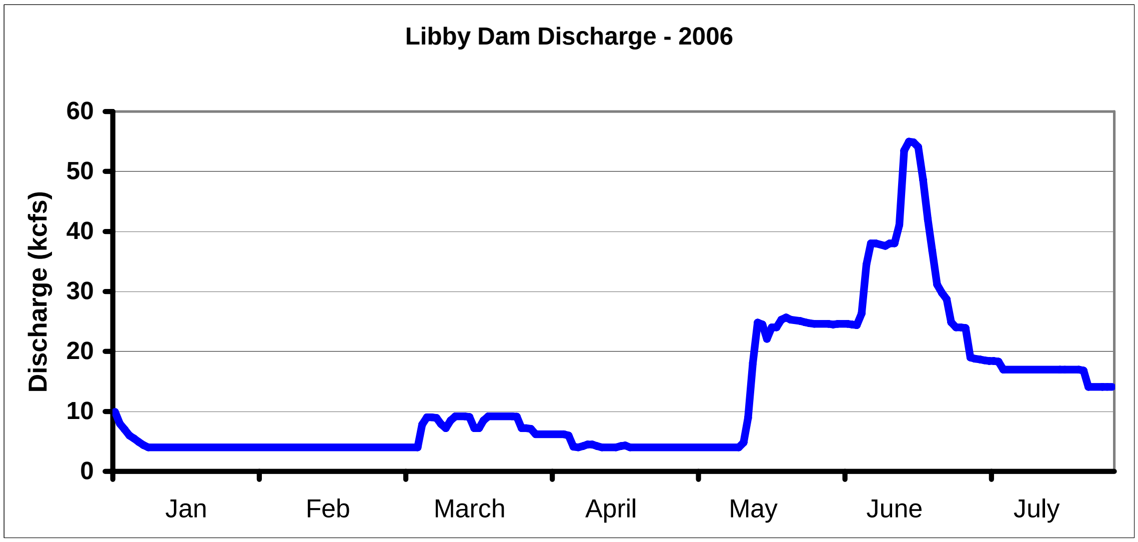


Figure 3. Discharge from Libby Dam into the Kootenai River from January 1, 2006 through July 31, 2006. Maximum capacity through the turbines was approximately 24,000 cubic feet per second during June when additional water was released via the spillway.

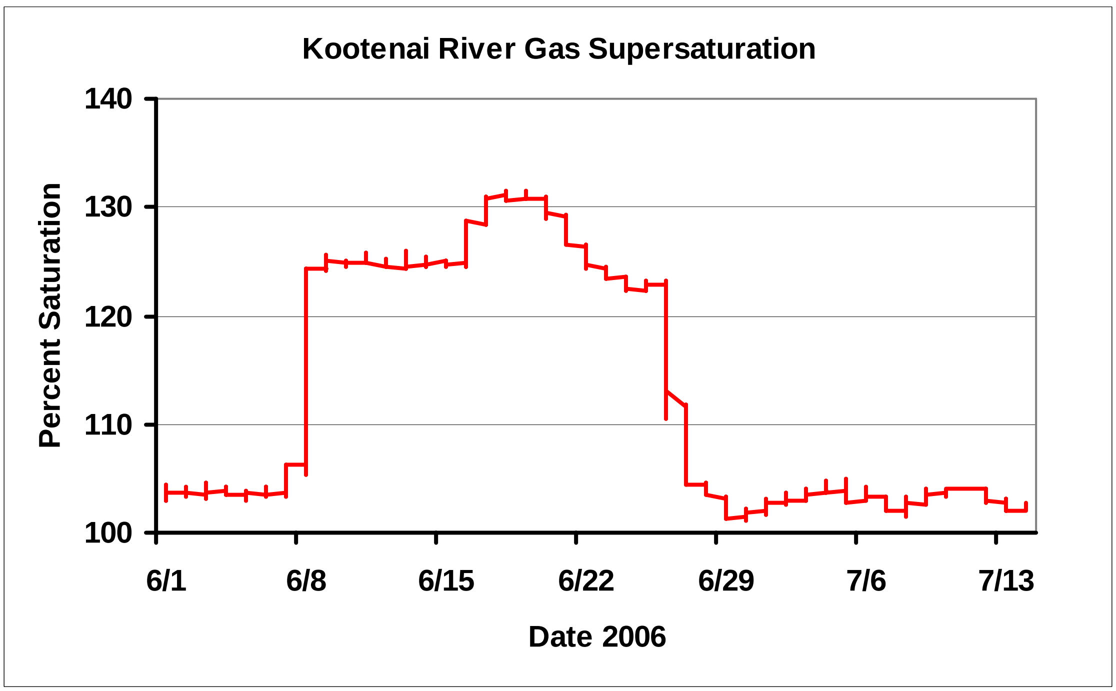


Figure 4. Percent gas supersaturation in the Kootenai River downstream of Libby Dam 2006 as measured at the USGS gauging station. Montana's water quality standard is 110 percent supersaturation.

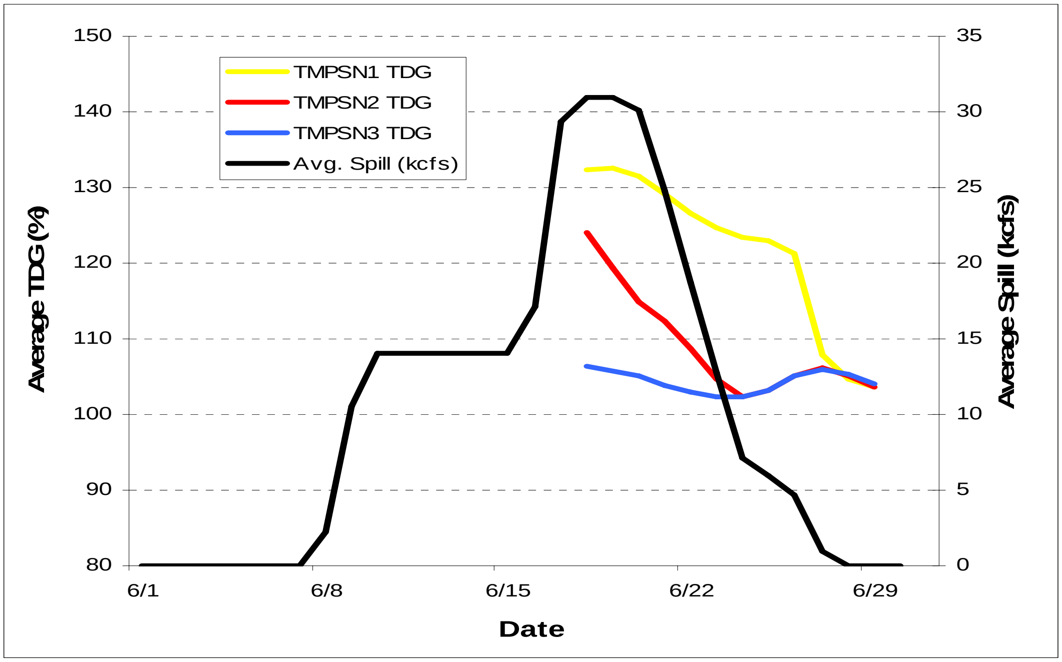


Figure 5. Comparison of Total Dissolved Gas levels (TDG; %) from 3 saturometers located at the David Thompson Bridge located just below Libby Dam. TMPSN1 was located near the left bank, TMPSN2 in the middle of the river, and TMPSN3 was located near the right bank looking downstream.

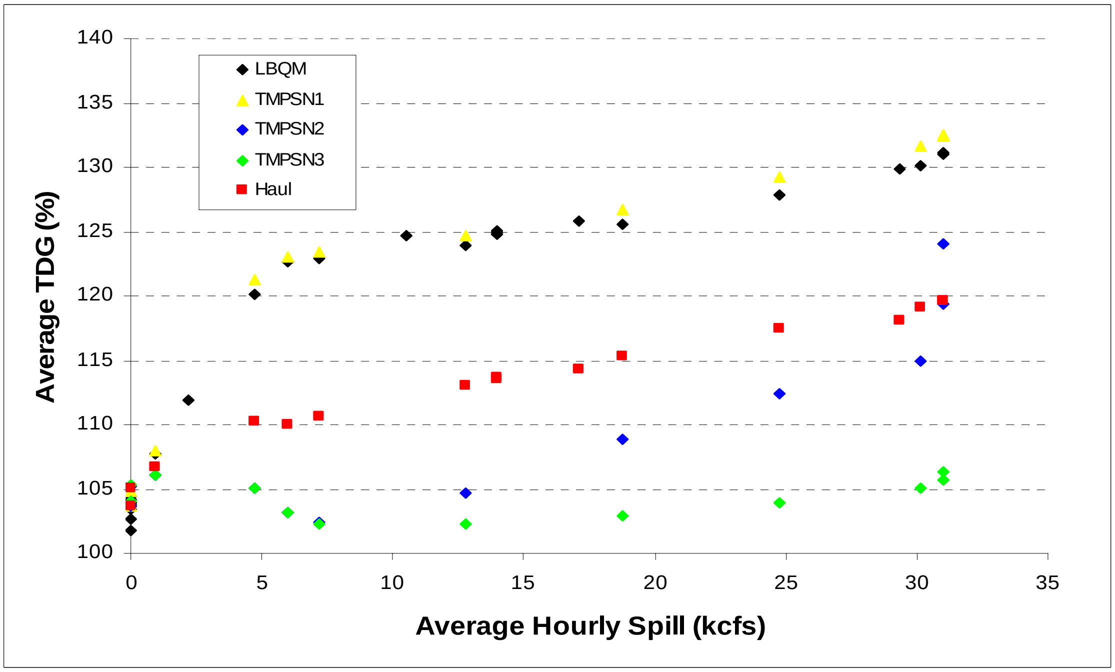


Figure 6. Total Dissolved Gas (TDG) levels recorded by saturometers located in the Kootenai River in June 2006. Location of LBQM is right below Libby Dam, location of Haul is located approximately 8.5 miles downstream of Libby Dam, and TMPSN1, 2, and 3, were located on the David Thompson Bridge downstream of Libby Dam.

Gas Bubble Trauma in Kootenai River Fish

During the 2006 spill, gas bubble trauma (GBT) was observed in rainbow trout (*Oncorhynchus mykiss*), westslope cutthroat trout (*O. clarki lewisii*), kokanee (*O. nerka*), bull trout (*Salvelinus confluentus*) and Mountain whitefish (*Prosopium williamsoni*). We may have under-estimated the number of fish with GBT because we did not include fish with split fins unless gas bubbles or localized hemorrhaging was also present. Fin splits may be caused by necrosis of the fin tissue between the fin rays resulting from previous injury caused by GBT that had begun to heal (Dunnigan 2003) or may have resulted from physical injury. Following four days of spill, sampling on Monday night June 12, 2006 revealed that 26 percent of rainbow trout on the downstream left bank had GBT (Table 2). In contrast, only 6 percent of the rainbow trout captured on the right bank, where gas saturation is lower, had GBT symptoms. Initially, GBT was mainly observed in the fins and only a few specimens had bubbles in the eyes and gills. Since only 4 bull trout were captured that night, all on the right bank (low gas), no evidence of GBT was observed in bull trout examined. The frequency of GBT in bull trout increased as spill continued. Thirty-six percent of the whitefish on the left bank and 19 percent on the right bank had GBT. One hundred percent of kokanee captured on the left bank and 20 percent on the right bank had GBT (Table 2). Dead and dying kokanee were observed; all had physical trauma (scrapes, lacerations, lost body parts etc.), indicating that the fish had passed through the spillway from Koocanusa Reservoir. Remarkably, most of the kokanee had survived passage over the spillway and two kokanee yearclasses; young of the year (YOY) and age 1+ about 4-5 inches long, were observed in the Kootenai River during electrofishing surveys. We discontinued sampling kokanee after the first night and focused on fish species that inhabit the Kootenai River.

As of Thursday night (June 15), after seven days of spill, GBT was evident as bubbles in fins and eyes, external tissue hemorrhages and split fins. Symptoms were common on both sides of the river (at lower spill volumes, supersaturated water flows along the left bank for about 5-8 miles before mixing across). Rainbow trout GBT increased to 68 percent on the left bank and 65 percent on the right bank. Mountain whitefish GBT increased to 62 percent on the left bank and 55 percent on the right bank. Only five bull trout were captured and two had GBT (40 percent incidence; Table 2).

As of Monday night (June 19, 2006), after 11 days of spill, all 16 bull trout captured had GBT. Symptoms included multiple hemorrhages on the ventral surface of the body that appeared as random pinpricks, as well as bubbles in fins, eyes, dermis on the operculum and split fins. Rainbow trout GBT was observed in 67 percent on the left bank and 86 percent on the right bank (an overall slight increase since the night of June 15). Mountain whitefish GBT symptoms increased to 86 percent on the left bank and 80 percent on the right bank (Table 2). Observation of symptoms and Total Dissolved Gas (TDG) levels recorded by saturometers suggested that supersaturated water may have become more consistent on both sides of the river at higher spill volumes.

As of Thursday night (June 22), after 14 days of spill, all 12 bull trout examined had GBT. Ninety-five percent of the rainbow trout on the left bank and 91 percent on the right bank had GBT. Symptoms were observed in 85 percent of the mountain whitefish captured on the left bank and 79 percent on the right bank (Table 2).

Long-term exposure to gas causes a greater frequency of GBT symptoms with increasing levels of gas supersaturation and repeated exposure as fish utilize shallow river margins. Roughly half of the fish in the sampling reach had GBT symptoms after the first week of spill and the severity of GBT increased over time. Results were used to develop relationships between the duration of spill and the frequency of GBT observed in each species (Figures 7-10 and 11-14). After June 19th, the 11th day of spill onward, 100 percent of bull trout examined had GBT. Hemorrhaging on the ventral body surface increased when gas saturation approached 131 percent, then apparently reduced when dissolved gas concentrations reduced toward 124 percent on June 22. Electrofishing surveys were conducted through spring 2007 to determine if survivors showed evidence of secondary complications from external lesions (e.g. split fins, hemorrhaging, abrasions). Weitkamp (1976) found fungal infections were responsible for delayed mortality of juvenile Chinook salmon that had survived GBT lesions and hemorrhages near the base of the caudal fin.

Results of the spill monitoring of free ranging fish during the 2006 event were similar to the result found during the 2002 spill event (Dunnigan et al. 2003). During the 2002 spill activities, high percentages of free ranging fishes were observed with symptoms of GBT. Rainbow trout (67-86%), bull trout (44-80%), and mountain whitefish (31-83%) incidence of symptoms varied from left bank to the right bank and as the duration and magnitude of spill changed.

Table 2. Percent of fishes with symptoms of gas bubble trauma during the spill event below Libby Dam in June 2006. Species abbreviations are as follows: BT = bull trout; KOK = kokanee; MWF = mountain whitefish; RBT = rainbow trout; and WCT = westslope cutthroat trout. Additional species monitored for the grand total include northern pikeminnow, coarsescale and finescale suckers, and peamouth.

Date	Days of Spill	Bank	BT	KOK	MWF	RBT	WCT	Grand Total
6/12/2006	4	L	0		36	26		52
6/15/2006	7	L	33		62	71		65
6/19/2006	11	L	100		86	67	100	80
6/22/2006	14	L	100		85	95	100	92
6/12/2006	4	R	0		19	6		13
6/15/2006	7	R	50		55	67		60
6/19/2006	11	R	100		80	86		86
6/22/2006	14	R	100		79	91		85
6/12/2006	4	Total	0		26	18		35
6/15/2006	7	Total	40		58	69		63
6/19/2006	11	Total	100		83	77	100	83
6/22/2006	14	Total	100		82	93	100	88

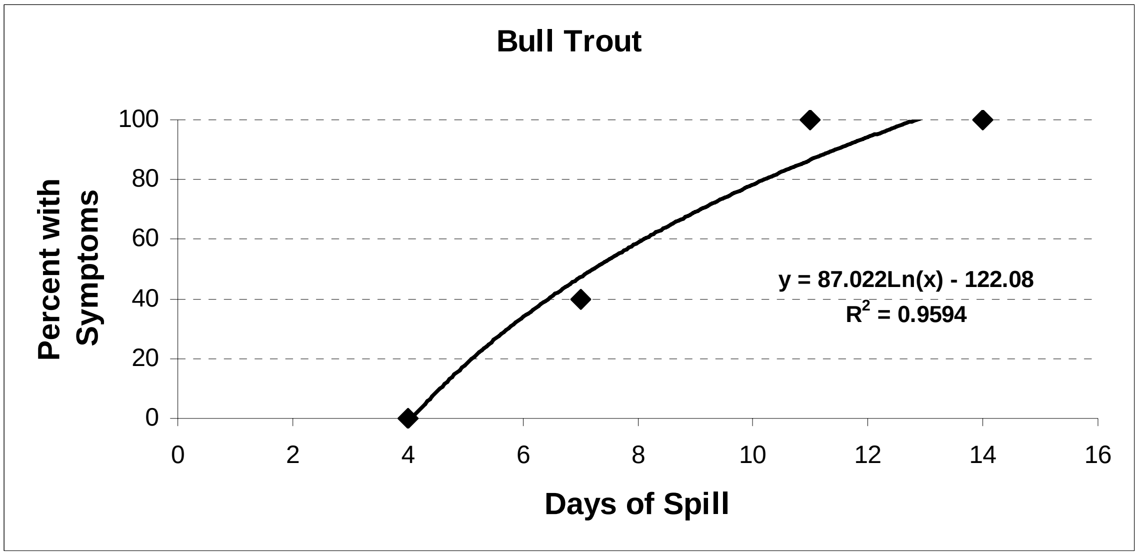


Figure 7. Relationship between the number of days spilled and percentage of bull trout impacted by gas bubble trauma observed during twice-weekly electrofishing surveys, 2006.

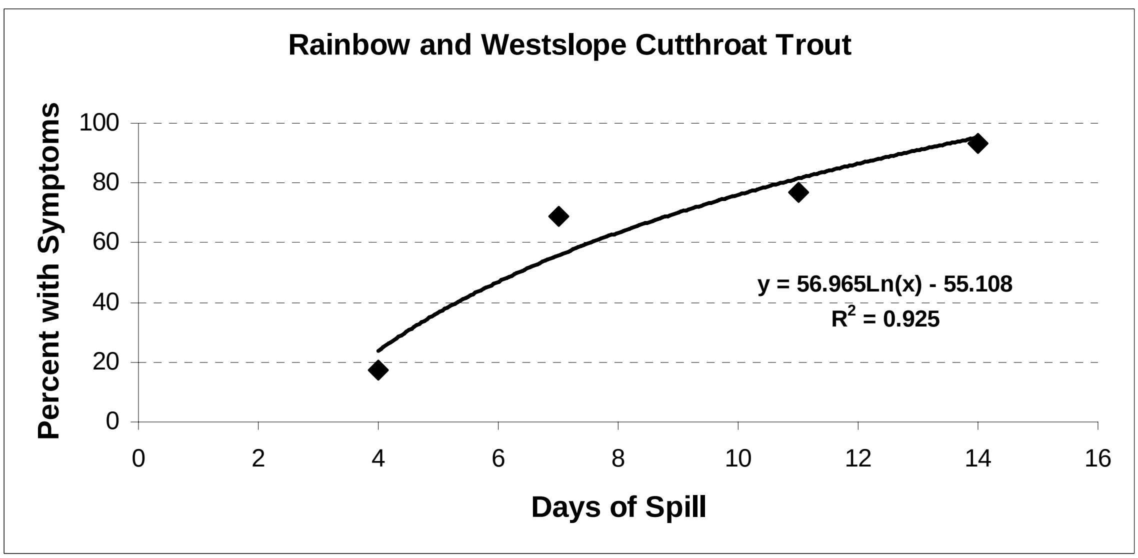


Figure 8. Relationship between the number of days spilled and percentage of rainbow trout and westslope cutthroat trout (data were pooled) impacted by gas bubble trauma observed during twice-weekly electrofishing surveys, 2006.

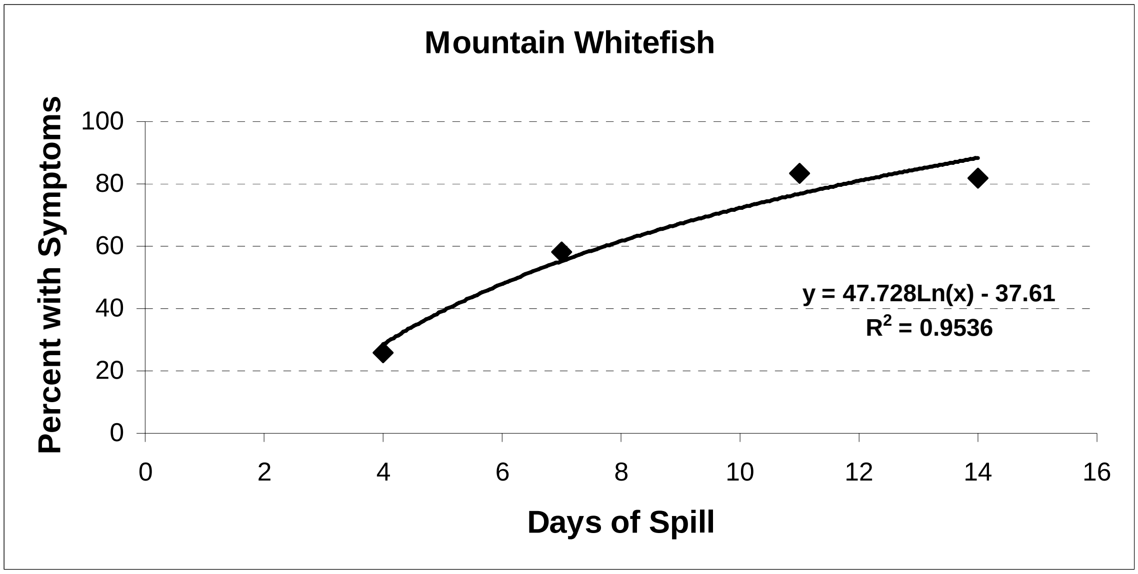


Figure 9. Relationship between the number of days spilled and percentage of mountain whitefish impacted by gas bubble trauma observed during twice-weekly electrofishing surveys, 2006.

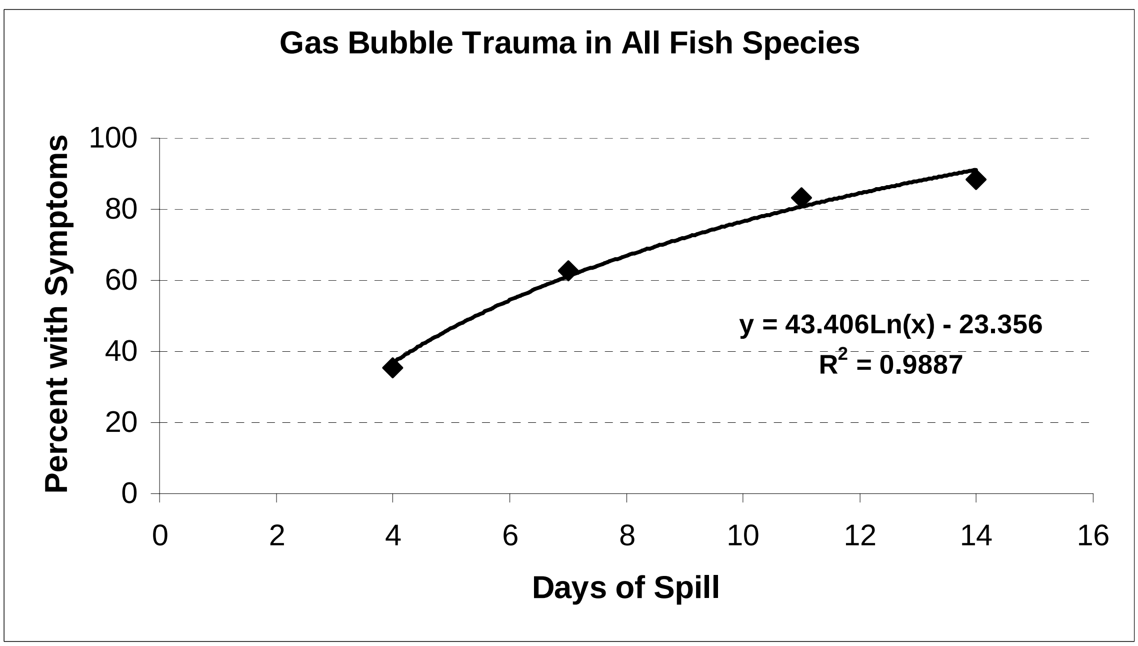
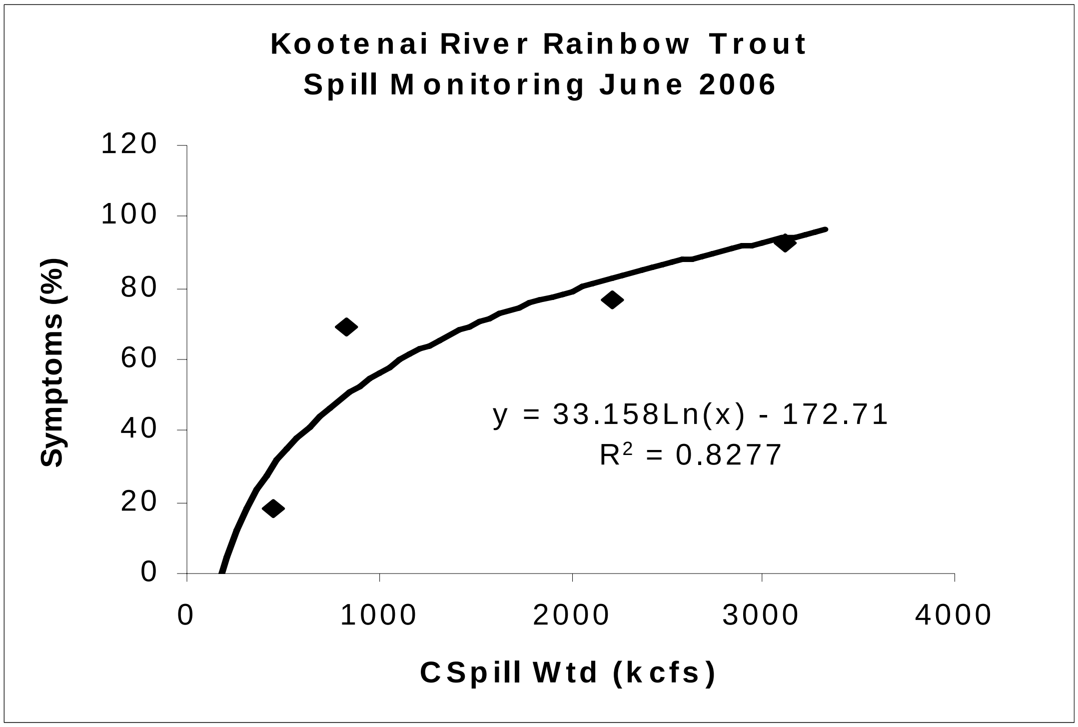


Figure 10. Relationship between the number of days spilled and percentage of fish (all species combined) impacted by gas bubble trauma observed during twice-weekly electrofishing surveys, 2006.



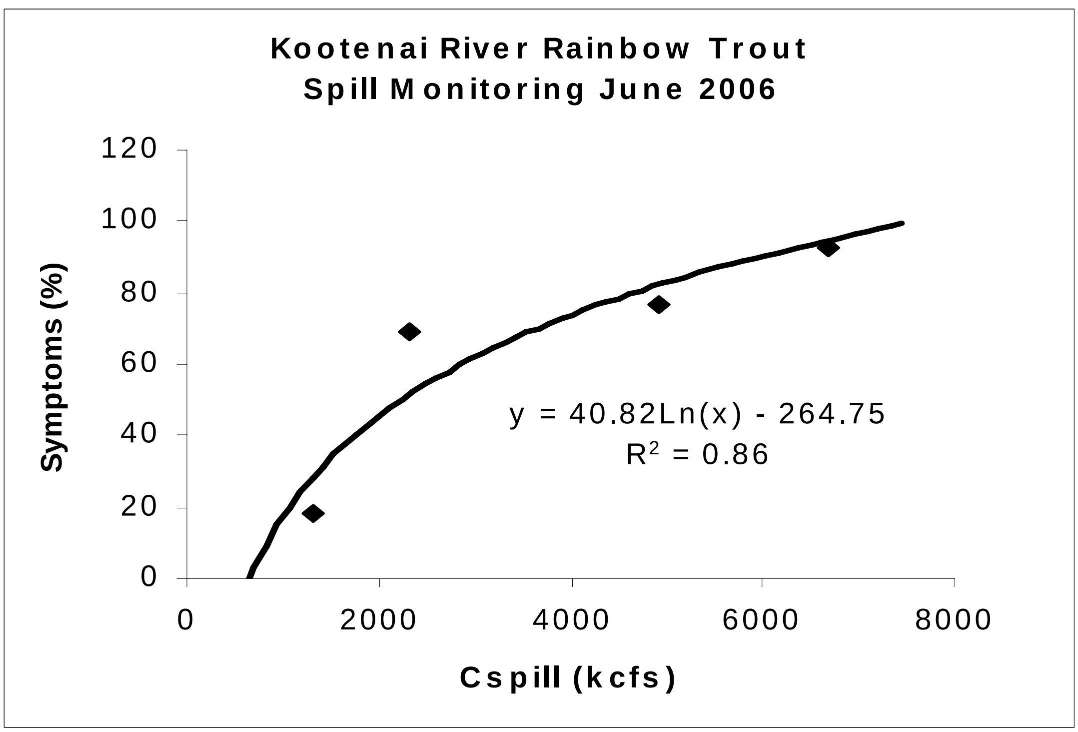
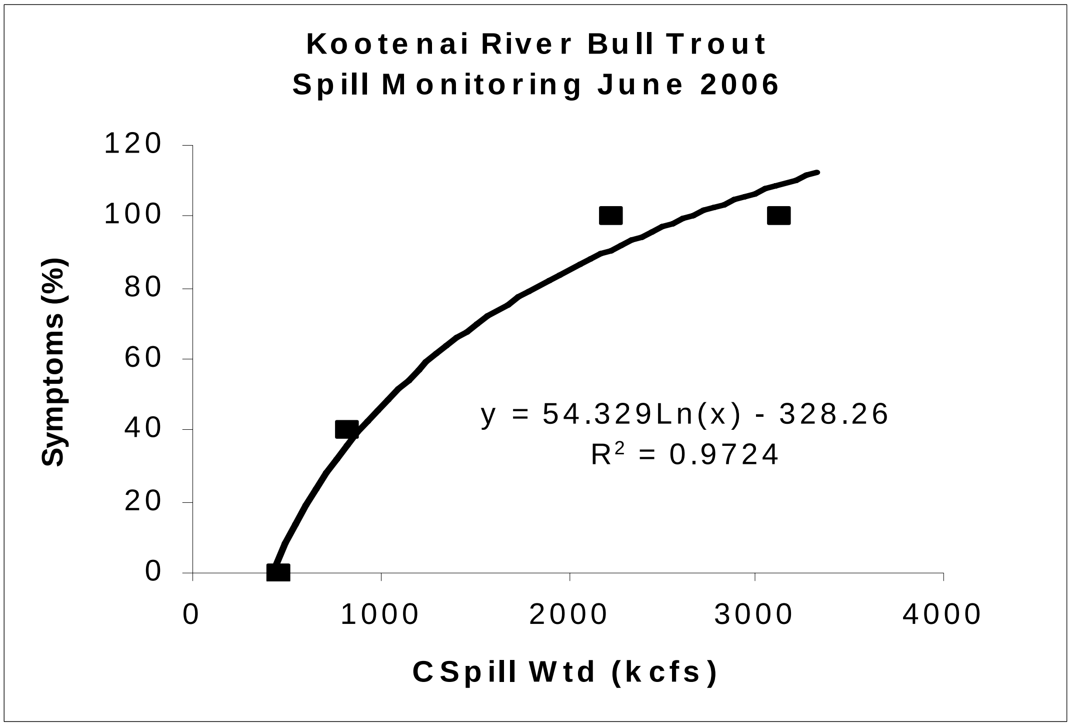


Figure 11. Comparison of spill exposure indexes (CSpill and CSpillWtd, from Dunnigan 2003) in relation to the percent of rainbow trout with gas bubble trauma.



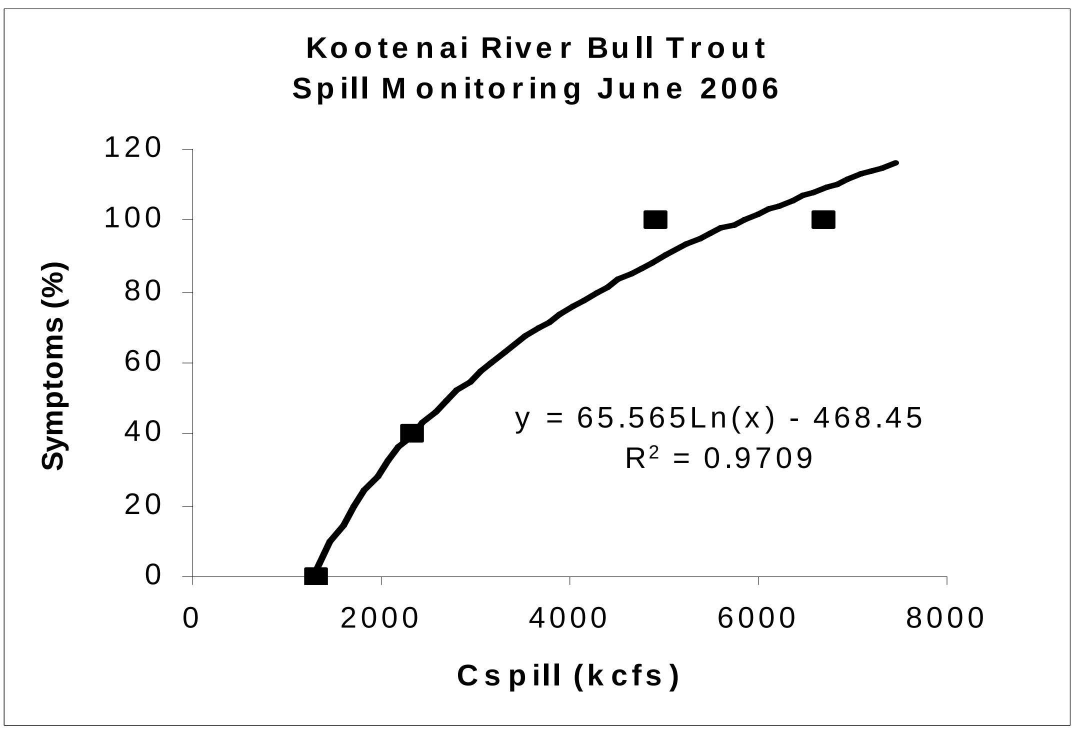
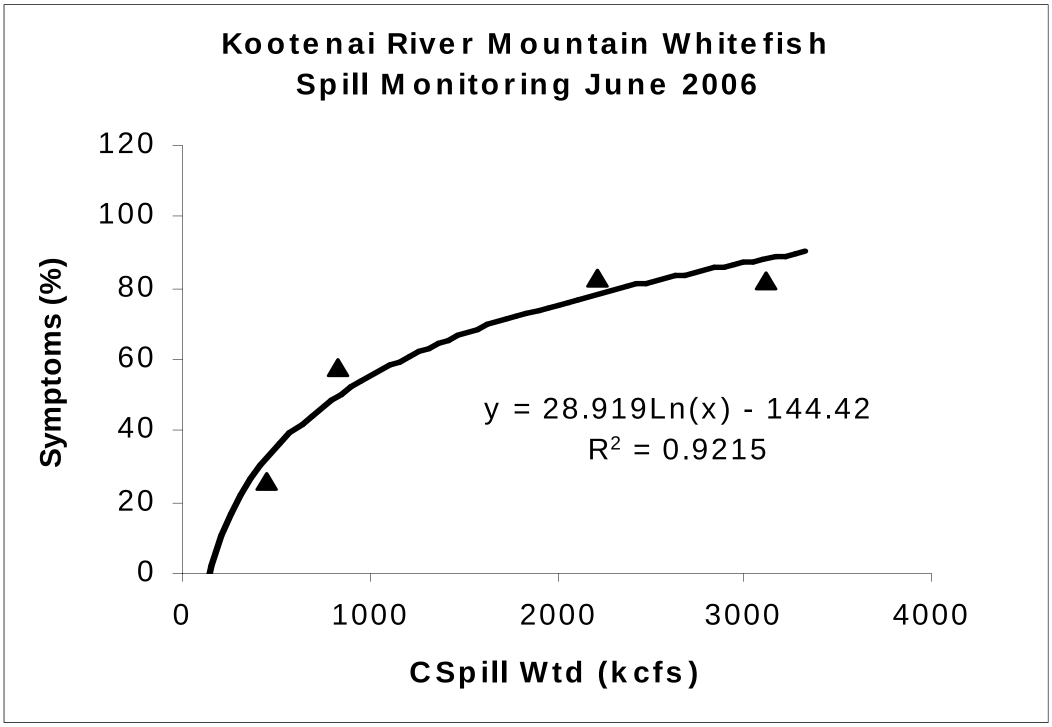


Figure 12. Comparison of spill exposure indexes (Cspill and Cspill WTD, from Dunnigan 2003) in relation to the percent of bull trout with gas bubble trauma.



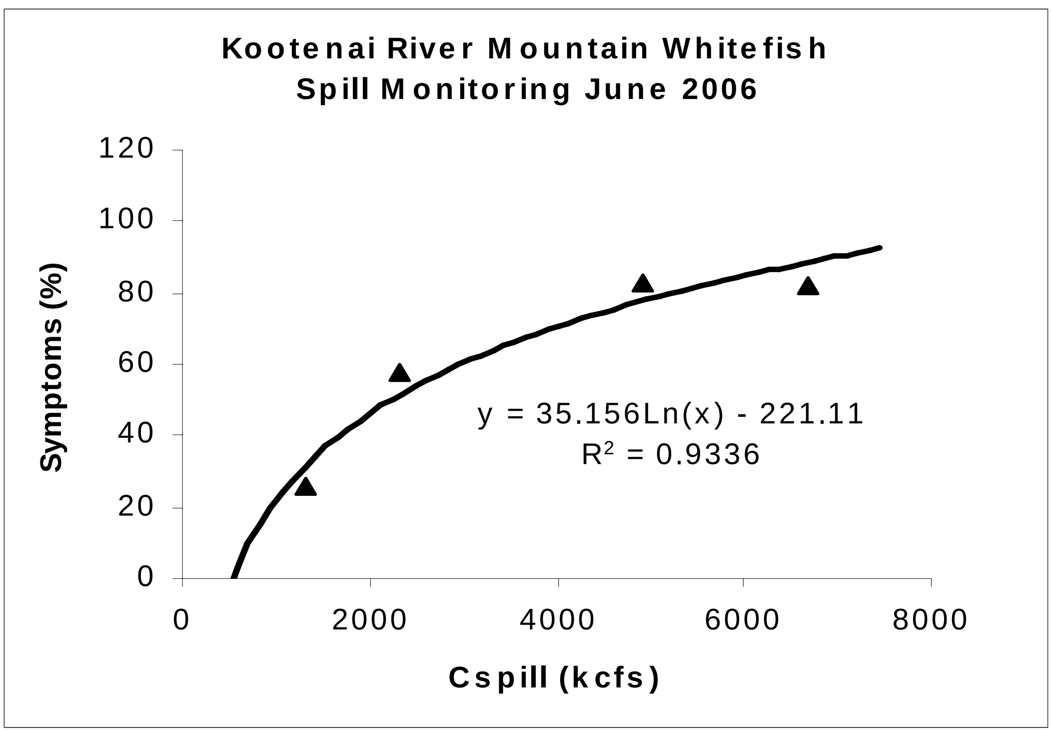
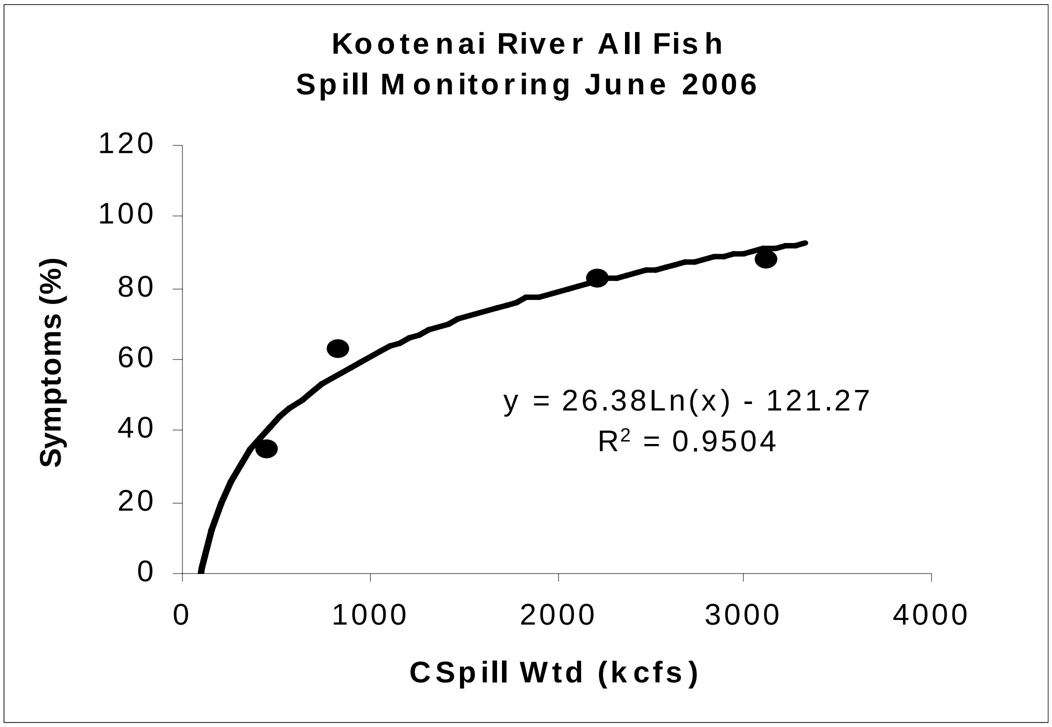


Figure 13. Comparison of spill exposure indexes (Cspill and Cspill WTD, from Dunnigan 2003) in relation to the percent of mountain whitefish with gas bubble trauma.



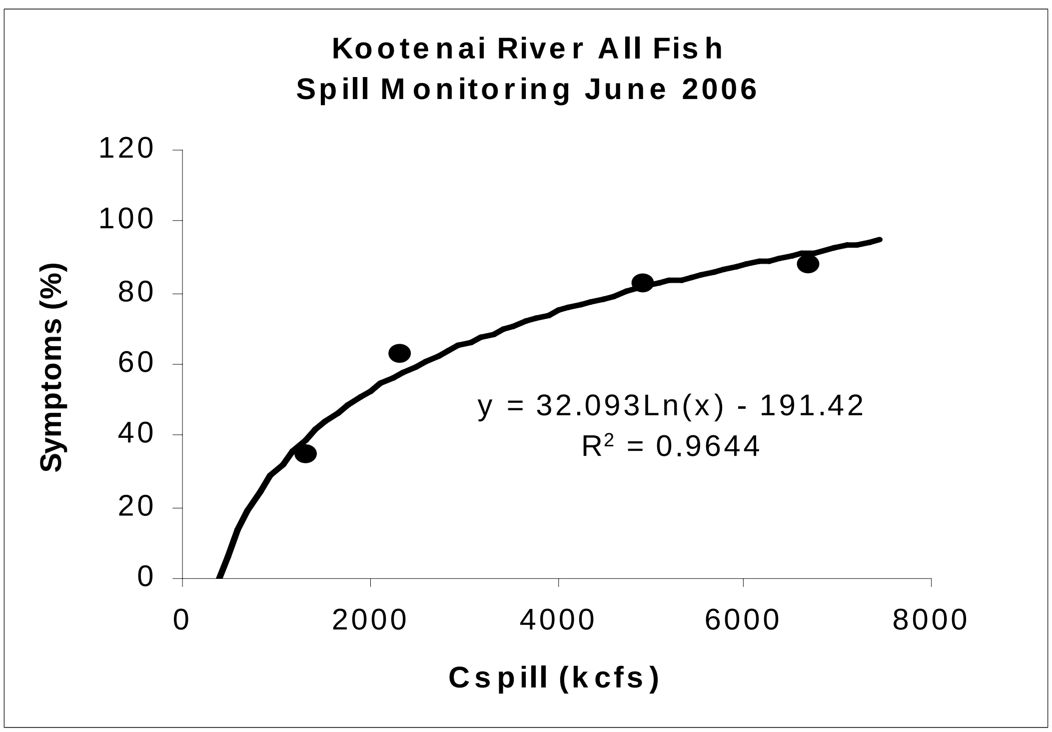


Figure 14. Comparison of spill exposure indexes (Cspill and Cspill WTD, from Dunnigan 2003) in relation to the percent of all fishes with gas bubble trauma.

Fish Population Estimates

Bull trout

We conducted five bull trout population estimates in the Libby Dam Tailrace (LDT) section on the Kootenai River. Population estimates and associated 95% confidence intervals were calculated after each period (Table 3). The three population estimates for 2004 and 2005 ranged from 906 to 1,068, with each varying by less then 10% compared to the mean for 2004 and 2005 (945). We observed a substantial reduction in the estimated number of bull trout present at this section in 2006, with only an estimated 176 bull trout present at this site (Table 3). It should be noted that this reduction occurred prior to the spill event in June 2006. The estimated number of bull trout present at this site in 2007 was 417 bull trout. MFWP suspects that many of the bull trout residing in this section of the Kootenai River may have originated upstream of Libby Dam, and have been either entrained or passed over the spillway. Fish genetics (DNA markers) will be used to investigate this hypothesis during summer 2007.

The mean length of bull trout present at the LDT section in April increased each year from 2004 to 2006. However, only the 2004/2006 year-by-year comparisons were significant ($\alpha = 0.05$; Table 4). The estimated mean length decreased from 692 mm in 2006 to 655mm in 2007. These observations are also consistent with the working hypothesis that many of the bull trout residing below Libby Dam originated upstream of the dam.

Table 3. The sampling dates for the number of adult bull trout marked, recaptured, and the estimated total population and number of fish per mile in the Libby Dam Tailrace section of the Kootenai River, 95 percent confidence intervals (CI) are presented in parentheses.

Dates	**Bull Trout Marked**	**Bull Trout Recaptured**	**Total Population Estimate (95 % CI)**	**Bull Trout per Mile (95 % CI)**
April 8,15, 21 & 22, 2004	109	13	918 (511 – 1,326)	262 (146 – 379)
August 18 & 19, 2004	28	11	906 (494 – 1,318)	259 (144 – 374)
April 20 & 21, 2005	38	13	1,012 (608 – 1,415)	289 (177 – 401)
April 11, 12, 18 & 19, 2006	19	5	176 (73 – 279)	50 (21-80)
April 30, May 1, 7 & 8, 2007	37	4	417 (120 - 714)	119 (34 – 204)

Table 4. The mean total length, standard deviation, range and results from the analysis of variance and multiple comparison test to determine yearly differences of bull trout captured during April 2004-2007 at the Libby Dam Tailrace section of the Kootenai River.

Year	**Mean Total Length (mm)**	**Standard Deviation**	**Range**	**Significantly Different than**
2004	648.9	113.3	343-861	2006
2005	677.1	129.7	388-903	none
2006	692.3	105.2	425-870	2004
2007	655.1	137.0	308-875	none

Oncorhychus spp.

Numbers of *Oncorhynchus* spp. in the Rereg section were stable at about 150 to 250 fish per thousand feet from 2001 to 2006 (Figure 15). The majority of fish are less than 250 mm in total length (Table 5). In 2007, a large increase in fish less than 200 millimeters was observed, likely due to a strong year class in 2005. This caused a large increase in the total number of fish, from and average of 189 fish (2001-2006) to 432 fish in 2007. *Oncorhychus* spp. greater than 300mm increased slightly in the Spring 2007 estimate but was still within the range observed during the 2001 through 2006 estimates. Had displacement of fish occurred, we would have likely seen a decrease in some length categories. No evidence of downstream fish displacement was detected in the Rereg section of the Kootenai.

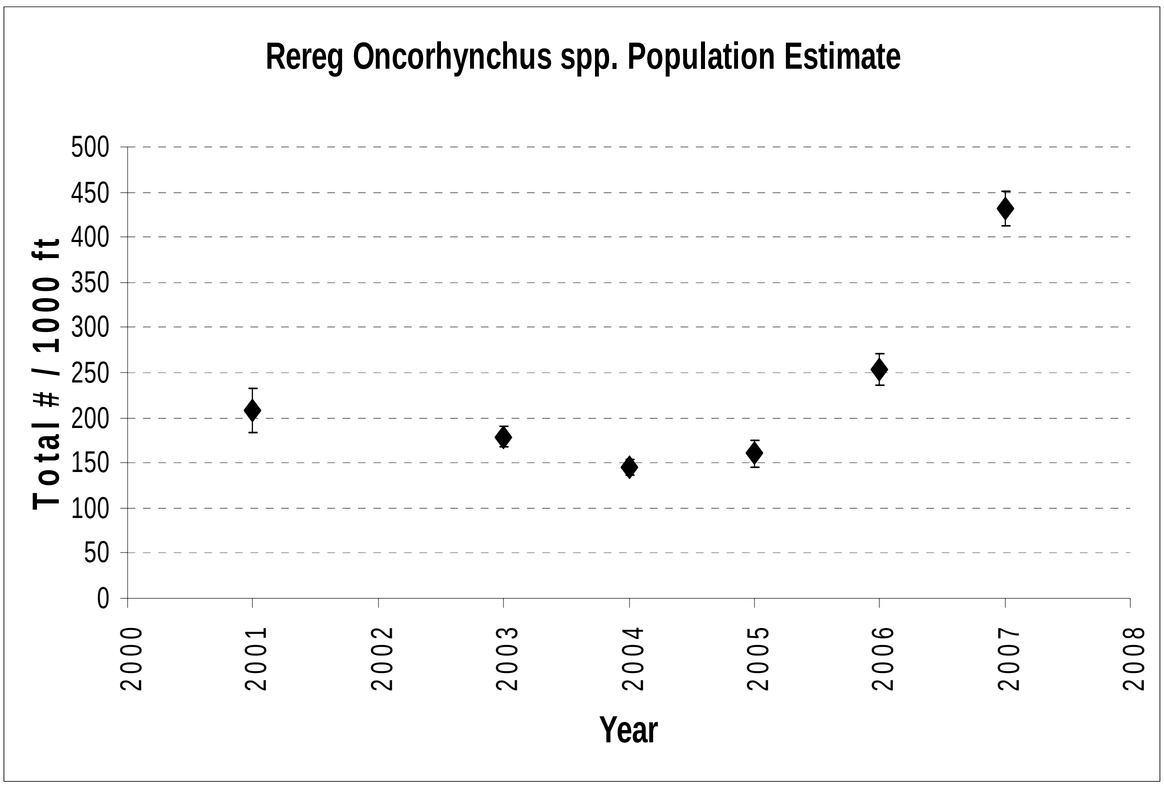


Figure 15. Total number of fish (*Oncorhychus* spp.) per thousand feet in the Rereg section approximately 8 miles downstream of Libby Dam from 2001-2007 using mark-recapture techniques and partial log-likelihood estimator methods. No population estimate was completed in 2002 due to high water. An * indicates a lumped estimate for that length group and longer length groups and the error bars represent 1 standard deviation.

Table 5. Number of fish (*Oncorhychus* spp.) per thousand feet by length category in the Rereg section approximately 8 miles downstream of Libby Dam from 2001-2007 using mark-recapture techniques and partial log-likelihood estimator methods. No population estimate was completed in 2002 due to high water. An * indicates a lumped estimate for fish equal to or greater than the length category shown.

	Year						
Length Category (mm)	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
0-24	0.0		0.0	0.0	0.0	0.0	0.0
25-49	0.0		0.0	0.0	0.0	0.0	0.0
50-74	0.0		0.0	0.0	0.0	0.0	0.0
75-99	0.0		0.0	1.0	0.0	0.0	0.0
100-124	4.0		8.0	19.0	0.0	15.0	26.0
125-149	36.0		1.0	18.0	3.0	16.0	24.0
150-174	38.0		35.0	8.0	4.0	16.0	79.0
175-199	49.0		40.0	17.0	14.0	37.0	99.0
200-224	23.0		50.0	25.0	20.0	55.0	80.0
225-249	20.0		22.0	16.0	27.0	37.0	36.0
250-274	2.0		8.0	10.0	25.0	25.0	26.0
275-299	4.0		4.0	7.0	19.0	18.0	19.0
300-324	10.0		2.0	10.0	17.0	19.0	17.0
325-349	10.0		2.0	14.0*	31.0*	16.0*	16.0
350-374	5.0		7.0*				10.0*
375-399	3.0						
400-424	4.0*						
425-449							
450-474							
475-499							
500-524							
Total	208		179	145	160	254	432

The Flower-Pipe section ranged from 50 to 200 fish per thousand feet in the late 1970's and early 1980's (Figure 16). Numbers of fish averaged about 400 per thousand feet from the mid 1980's thorough 2006 with peaks up to nearly 800 fish per thousand feet. Many of these fish were less than 250 mm TL (Table 6). The Flower-Pipe section increased from an average of 410 fish (2003-2005) up to more than 800 fish in 2006. Peaks near 800 fish per thousand feet also occurred in 2002 and 1997, likely indicating one strong year class. Fish greater than 300 mm increased slightly in 2006 in the Flower-Pipe section, but there was no corresponding decrease in the upstream Rereg section of the Kootenai River, lending additional evidence that little downstream displacement occurred during the spill event.

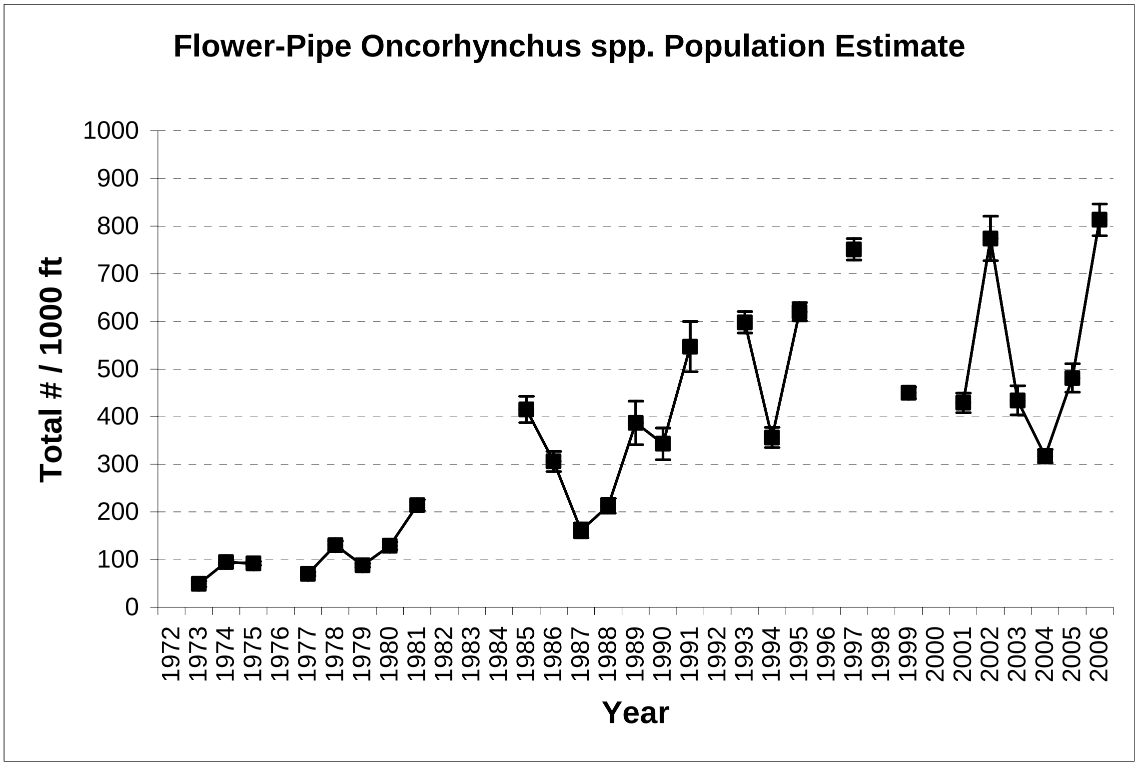


Figure 16. Total number of fish (*Oncorhychus* spp.) per thousand feet in the Flower-Pipe section approximately 18 miles downstream of Libby Dam using mark-recapture techniques and partial log-likelihood estimator methods. Error bars represent 1 standard deviation.

Table 6. Number of fish (*Oncorhychus* spp.) per thousand feet by millimeter group in the Flower-Pipe from 1995-2006 section approximately 18 miles downstream of Libby Dam using mark-recapture techniques and partial log-likelihood estimator methods. No population estimate was completed in 2002 due to high water. An * indicates a lumped estimate for that length group and longer length groups. No population estimates were completed in 1996, 1998, and 2000.

	Year								
Length Group (mm)	**1995**	**1997**	**1999**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
0-24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25-49	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
50-74	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
75-99	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100-124	3.0	1.0	30.0	27.0	0.0	2.0	2.0	1.0	5.0
125-149	10.0	19.0	92.0	87.0	33.0	14.0	2.0	6.0	55.0
150-174	30.0	110.0	108.0	99.0	252.0	36.0	23.0	47.0	162.0
175-199	110.0	242.0	55.0	69.0	264.0	126.0	34.0	135.0	269.0
200-224	197.0	207.0	35.0	58.0	143.0	108.0	69.0	137.0	171.0
225-249	152.0	80.0	29.0	33.0	46.0	58.0	86.0	65.0	54.0
250-274	64.0	30.0	37.0	19.0	18.0	46.0	53.0	31.0	32.0
275-299	17.0	20.0	30.0	13.0	9.0	26.0	20.0	26.0	19.0
300-324	15.0	18.0	19.0	9.0	4.0	11.0	12.0	19.0	16.0
325-349	13.0	20.0	7.0	15.0	2.0	8.0	16.0	14.0	29.0
350-374	6.0		10.0		5.0				
375-399									
400-424									
425-449									
450-474									
475-499									
500-524									
Total	**620**	**751**	**450**	**427**	**774**	**434**	**317**	**481**	**813**

Downstream Fish Displacement

We examined 131 rainbow and/or cutthroat trout in the Flower Pipe section in October 2006, and none were PIT tagged. Based on the maximum detectible limit using the binomial distribution function, we concluded that displacement from the upstream Rereg or LDT sections may have been as high as 4.0 - 4.5% with a 5% chance of detecting this rate given our sample size. We also did not observe any PIT tagged rainbow and/or cutthroat trout that were originally marked in the LDT section in 2006 when we conducted the population estimate at the Rereg section in April 2007. However, downstream displacement at this site may have been as high as 2.5-3.0% with a 5% chance of detecting this rate given our sample size of 157 fish. Based on our results, there is no evidence to suggest that downstream displacement of rainbow and/or cutthroat trout from the LDT or Rereg sections occurred as a result from the spill event at Libby Dam in 2006.

We PIT tagged 274 bull trout in the LDT section in the spring of 2004, and recaptured 14 of these fish in the spring of 2005, for a recapture rate of 5.1%. In spring of 2005, we PIT tagged 52 bull trout at this site and recaptured 2 of those fish the following spring in 2006, for an annual recapture rate of 3.8%. The mean annual recapture rate for these two pre-spill years was 4.45%. In the spring of 2006, prior to the spill event, we PIT tagged 66 bull trout in the LDT section, and recaptured 3 of those fish in the spring of 2007 (pos-spill), for an annual recapture rate of 4.5%. Based on this information, we have no evidence to suggest that downstream displacement of bull trout from the LDT section resulted from the spill event of 2006 at Libby Dam.

Growth of Bull trout, Rainbow Trout, and Westslope Cutthroat Trout

There were no significant differences detected in growth ($g \cdot day^{-1}$, $mm \cdot day^{-1}$), mean length, and mean weight of recaptured bull trout between the no spill and spill treatments (Tables 7 and 8). *Oncorhychus* spp. in the spill grew significantly less (0.047$mm \cdot day^{-1}$) than the no spill fish (0.099 $mm \cdot day^{-1}$; $p = 0.048$) even though the mean length was not significantly different ($p = 0.337$) between the groups (Tables 7 and 8) indicating that spill may have affected growth in terms of body length. There were no differences in the growth ($g \cdot day^{-1}$) or mean weight of recaptured rainbow/cutthroat trout between the no spill and spill treatment groups.

Table 7. Analysis of Variance results for the average growth ($g \cdot day^{-1}$, $mm \cdot day^{-1}$) of no spill and spill groups of recaptured bull trout and *Oncorhychus* spp. below Libby Dam. An asterisk indicates a significant difference between no spill and spill treatments at an alpha level of 0.05.

Fish species	**Treatment**	**Growth Metric**	**Sample Size**	**Mean**	**Variance**	**P-value**	**Power (1-β)**
Bull trout							
	No spill	$mm \cdot day^{-1}$	45	0.137	0.018	0.431	0.122
	Spill	$mm \cdot day^{-1}$	6	0.185	0.034		
	No spill	$g \cdot day^{-1}$	37	3.079	9.157	0.877	0.053
	Spill	$g \cdot day^{-1}$	6	2.880	3.285		
Oncorhychus spp.							
	No spill	$mm \cdot day^{-1}$	9	0.099	0.012	0.048*	0.510
	Spill	$mm \cdot day^{-1}$	24	0.047	0.002		
	No spill	$g \cdot day^{-1}$	8	0.185	0.052	0.514	0.098
	Spill	$g \cdot day^{-1}$	23	0.264	0.095		

Table 8. Mean length (mm) and weight (g) of recaptured bull trout and *Oncorhychus* spp. used for growth calculations for no spill and spill treatment fish. An asterisk indicates a significant difference between no spill and spill treatments at an alpha level of 0.05.

Fish Species	**Treatment**	**Metric**	**Sample Size**	**Mean**	**Variance**	**P-value**	**Power (1-β)**
Bull trout							
	No spill	Length	45	731	7230	0.268	0.196
	Spill	Length	6	689	10094		
	No spill	Weight	37	4677	3907994	0.705	0.066
	Spill	Weight	6	4348	3474147		
Oncorhychus spp.							
	No spill	Length	9	389	6701	0.337	0.157
	Spill	Length	24	368	1592		
	No spill	Weight	8	552	165297	0.527	0.095
	Spill	Weight	23	485	36383		

2006 Operations

The United States Fish and Wildlife Service (USFWS) 2006 Biological Opinion (BiOp) recommended spill up to 10 kcfs in excess of maximum turbine capacity at Libby Dam for up to 14 days during late May or early June. Their rationale was that higher river stage, increased depth and water velocities in the vicinity of Bonners Ferry, Idaho, would aid the upstream migration of adult white sturgeon. This experimental flow was designed to increase river depths to help adults migrate upstream of Bonners Ferry, where river substrate size and water velocities are suitable for spawning. The planned spill operation was opposed by Montana because spill causes the Kootenai River to become supersaturated with gas in excess of the state water quality standard (110 percent saturation). Spill plunges atmospheric gas deep below the surface where water pressure forces gas into solution, which can harm aquatic life. Monitoring results during the spill test of 2002 demonstrated that gas saturation exceeded 110 percent when less than 2 kcfs or more was released through the spillway. Although Montana Department of Environmental Quality (MDEQ) agreed to the scheduled spill test in 2002, they could not grant a variance to the gas standard because Montana adopted the federal Clean Water Act in its entirety, so the requested variance would violate both the federal and state laws. Soon after the scheduled spill test began in 2002, an unforeseen precipitation event caused an uncontrolled spill. Gas saturation increased to 126 percent and gas bubble trauma (GBT) was observed in trout and whitefish (Dunnigan 2003). Therefore in 2006, The State of Montana joined a lawsuit to prevent spill and avoid GBT in bull trout and other resident fish associated with spillway operations at Libby Dam.

Montana and the Kootenai Tribe of Idaho collaborated to prevent spill, and recommended an alternative operating strategy to benefit the endangered white sturgeon. Rather than spill water and risk ecological damage to the Kootenai River, high river flows could be achieved by releasing maximum turbine capacity during the peak of low elevation runoff from unregulated streams downstream of Libby Dam. This “stacked” flow strategy allowed researchers to assess the response of migrating white sturgeon to high river flows without using the spillway. Montana recommended that the USFWS focus on sturgeon reproduction in two phases, spawning and incubation. During the sturgeon spawning migration, a recommendation was made that high flows be created, by coordinating discharge from Libby Dam with low elevation runoff below Libby Dam, when water temperatures were appropriate. Montana stated that until it can be shown that migrating adult sturgeon travel further upstream in response to high river flow, experiments should focus on the known bottleneck for reproduction, post-spawning incubation and early life survival. These lifecycle phases correspond with the natural reduction in river flow after the spring runoff peaks. Montana recommended a gradual flow reduction after the spring freshet to mimic the pre-dam condition, stabile, gradually declining flows during the biologically productive summer and fall months, and using the selective withdrawal device to manage water temperatures for optimal incubation conditions. Montana also supported plans to physically modify the river channel in the braided reach above Bonners Ferry as soon as possible to increase depth and turbulent velocity.

Libby Dam has also been operated to augment flow in the Columbia River during spring and summer to aid anadromous fish migrations. The NOAA-Fisheries 2005 BiOp attempts to refill Koocanusa Reservoir during spring runoff, and then drafts the pool to 20 feet below full pool (2459 ft msl –20 ft = 2439 ft) by the end of August. This strategy provides 6 to 8 kcfs greater discharge in the Columbia River (Technical Management Team notes) in an attempt to achieve a 200 kcfs flow target at McNary Dam. Montana endorsed the Northwest Power and Conservation Council's mainstem amendment operation that reduces this summertime reservoir draft to 10 feet below full pool (except in the driest 20th percentile drought years when the reservoir can be drafted up to 20 feet from full pool). Montana cautioned operators to avoid a sudden flow reduction after the spring freshet and before summer flow augmentation (called the "double peak" operation). Flow reductions "reset" the river benthos to the lower river stage. Biological productivity ends when river substrate becomes dry. When river sediments become inundated, the substrate must remain wet for nearly a month and a half before benthic biomass fully recovers. Montana requested that gradually declining flows extend through September to optimize Montana's short growing season. Biological production in Koocanusa Reservoir and Kootenai River is greatest from late June through September (Marotz et al. 1996).

Montana recommended operating the reservoir to fill more gradually based on a "sliding refill date", which refills earlier in dry years and later in wet years to avoid uncontrolled spill. Gradually filling and drafting the reservoir optimizes biological productivity in the reservoir. The reservoir drawdown zone or "varial zone", like the river, is biologically unproductive until shorelines are inundated for a sufficient duration to become biologically productive. Maintaining the reservoir elevation near full pool increases fish food availability in the reservoir. The large volume and surface area benefits production of phytoplankton, zooplankton, and benthic insects. A large surface area increases the amount of terrestrial insects from the shoreline that fall on the water surface. Stomach content analysis showed that insectivorous fish (e.g., juvenile bull trout, rainbow, westslope cutthroat and mountain whitefish) shift their diet from aquatic insects in spring to terrestrial insects during summer and fall. Fewer insects are deposited on the reservoir surface when water recedes from shoreline vegetation (May et al. 1988; Chisholm et al. 1989; Marotz et al 1996).

During 2006, high river flows were achieved by ramping toward full turbine capacity beginning on May 16th. Discharge was maximized until May 19th through May 21 when dam discharges were curtailed to avoid flooding in Bonners Ferry. The white sturgeon operation was scheduled to create a gradual decline in flows after the spring freshet to optimize conditions for incubating sturgeon eggs and early life survival. Unfortunately, evacuated storage was insufficient to contain high reservoir inflows and an uncontrolled spill occurred from June 8th through June 27th. As a result, the timing of spill during 2006 coincided with the white sturgeon incubation phase when natural, historic flows would have been gradually declining.

Methods

The Libby Reservoir Model (LRMOD) was used to perform an incremental analysis of wateryear 2006 (Marotz et al.1996; Marotz and Althen 2005). The model was configured to run annual simulations beginning on the first day of the wateryear, October 1, 2005 and ending on September 30, 2006. Consecutive model simulations operated with no foresight, and used only information that was available to dam operators at the time each monthly inflow forecast became available. For example, the monthly simulation for January used observed, daily inflow and surface elevation data from Oct 1 through Dec 31, and then predicted dam operation through September 30 using the January inflow forecast. For each consecutive annual simulation, the monthly forecast of the inflow volume during the period April 1 through Aug 31 was distributed over time (modulated) using the long-term average inflow shape (Figure 17). Elevation targets for the remainder of the wateryear were "bracketed" using monthly IRC drawdown and refill targets as the lower limit and VARQ storage reservation diagram (SRD) targets as the upper limit. For consecutive months, input data were updated using observed data prior to the date that each inflow forecast became available. The incremental analysis calculated reservoir elevation targets for the end of each month during the remainder of the year and adjusted the targets with each inflow forecast. This modeling strategy provided insight to the decision space available to dam operators as the year progressed.

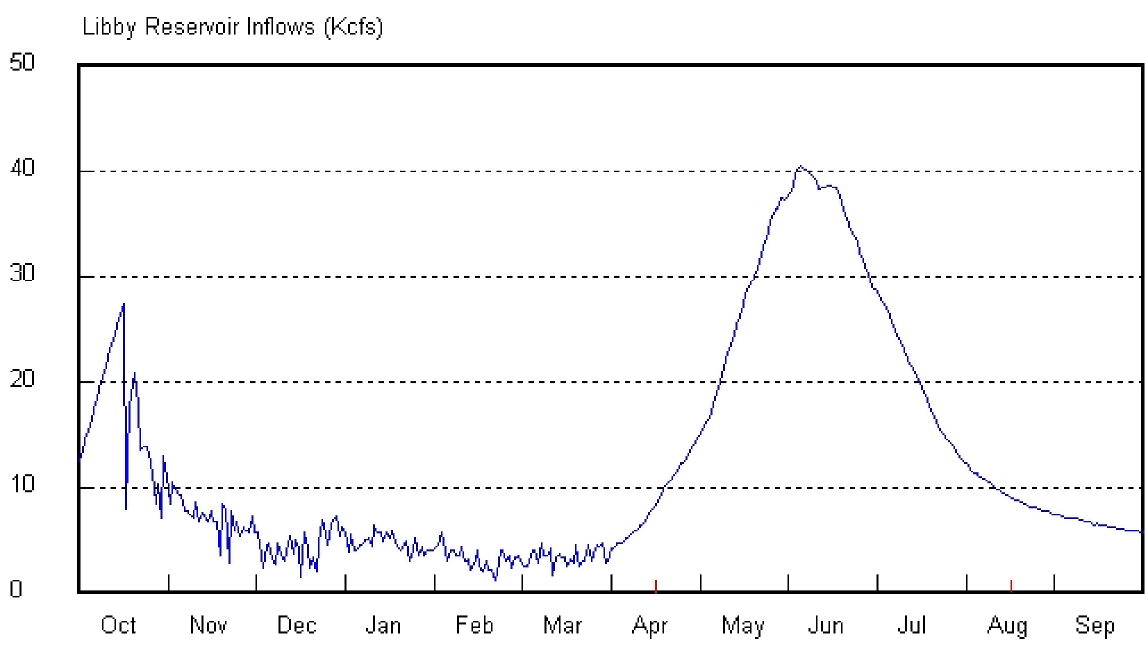


Figure 17. Example of a composite inflow schedule developed using actual data through March 31 and the April inflow forecast, modulated based on the average daily runoff shape (1928-2005). These data were input to LRMOD for the annual simulation using the April inflow forecast. Input data were updated each month January through June based on consecutive inflow forecasts.

Flood control requirements were evaluated downstream of Libby Dam. LRMOD calculates unregulated side flows from tributaries downstream of Libby Dam based on a regression on daily reservoir inflows. The first step is to determine the date of the spring runoff peak into Libby Reservoir (using historic data or estimated from long-term average runoff shape). The wateryear is then divided into three periods, each with a different regression formula:

For the period October 1 through December 6:
$KcfsPH(i) = 0.777 * KcfsIn(i) + 0.05433 * i - 3.774$

where: $KcfsIn(i)$ = inflow into Libby Reservoir (in kcfs) for the i^{th} wateryear date, and
$KcfsPH(i)$ = the estimated flow at Port Hill.

The intercept, inflow term and wateryear date are highly significant ($P \leq 2.34^{-41}$, $P \leq 9.54^{-83}$ and $P \leq 3.34^{-38}$, respectively).

For the period December 7 through the day before the spring peak:
$KcfsPH(i) = 1.1395 * KcfsIn(i) - 0.01651 * (KcfsIn(i))^2 - 0.7187$

The multiple regression uses Libby Reservoir inflow = $KcfsIn(i)$ and inflow-squared $=(KcfsIn(i))^2$ on each day. The intercept is highly significant ($P \leq 4.18^{-9}$) and the linear and squared terms are extremely highly significant ($P \leq 0.0001$, $P \leq 2.1^{-86}$, respectively).

For the period from the spring peak flow through September 30:
$KcfsPH(i) = -0.03461 * KcfsIn(i) + 0.008213 * (KcfsIn(i))^2 + 0.375$

This portion of the wateryear had the poorest fit (Multiple R = 0.67), but was corrected using a separate regression for flows ≤ 40 kcfs for dates surrounding the spring peak:

$KcfsPH(i) = 0.3241 * KcfsIn(i) - 0.3271 * i + 83.42$

This adjustment improved the fit. The intercept ($P \leq 5.48^{-39}$), inflow term ($P \leq 4.45^{-19}$) and wateryear date ($P \leq 1.18^{-42}$) became highly significant. This set of equations reduced the sum of squares on observed values by 51 percent compared to previous versions of LRMOD used to predict flows from unregulated tributaries downstream of Libby Dam.

The estimation of flow at Bonners Ferry, $KcfsBF(i)$ is a polynomial of three terms from the previous equations that estimated flow at Port Hill = $KcfsPH(i)$ on the actual day of interest = i, plus the outflow from Libby Dam on the previous day, $Lqout(i-1)$ (See example in Figure 18):

$KcfsBF(i) = KcfsPH(i) + Lqout(i-1)$.

LRMOD was designed to mimic springtime operations in the USFWS 2002 and 2006 BiOps that were developed using the USACE' hydrology appendix for VARQ flood control (USACE 1999) (Bob Hallock, USFWS email communication 2006). The model incorporates the International Joint Commission (IJC) operating rules for Kootenay Lake and Duncan Reservoir flood control, British Columbia. Flood stage at Bonners Ferry, Idaho was set at elevation 1764 ft msl. The model determined if discharges from Libby Dam must be reduced to avoid violating downstream flood control limits. The model then determined if reservoir elevation targets could be met, or if "trapped storage" prevented operating to the next draft target. This model function allows the user to anticipate when flood control limits might be approached (with some prediction error) so water could be evacuated at other times to meet the draft or refill targets.

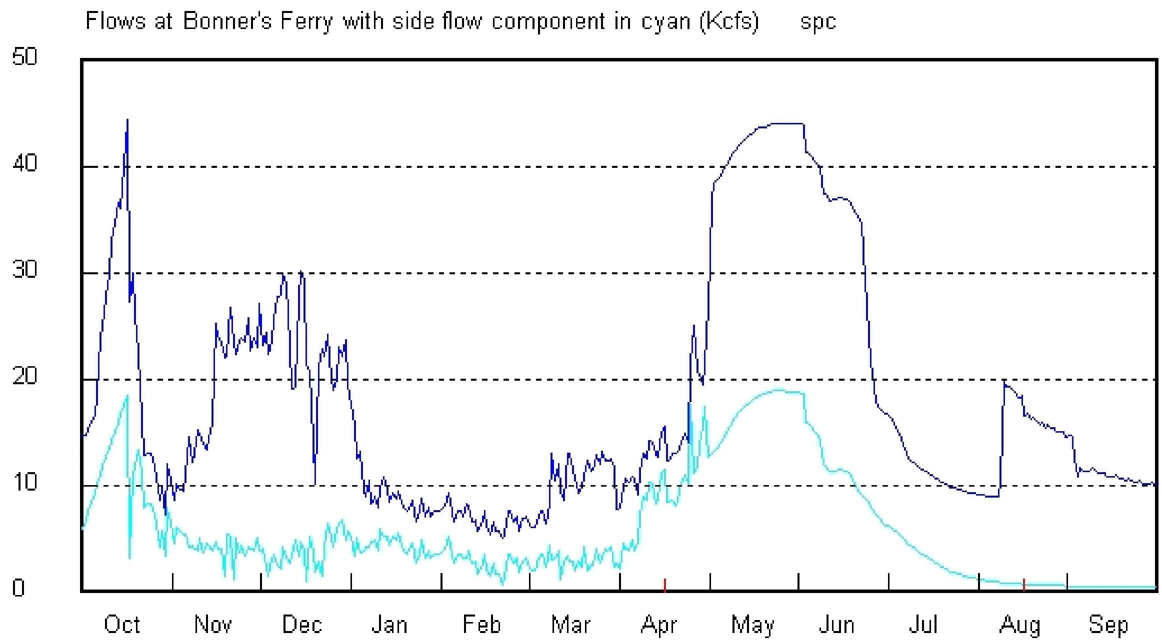


Figure 18. Calculated flow from unregulated tributaries downstream of Libby Dam (cyan, lower line) is added to Libby Dam discharges to estimate combined Kootenai River discharge at Bonners Ferry, Idaho (dark blue). This simulation based on the May forecast was volumetrically accurate, but could not predict the runoff shape in May and June 2006. The “double peak” in August would be smoothed during real time operations.

Actual 2006 reservoir elevations were compared to model simulations to learn if spill could have been avoided or reduced using only monthly inflow forecasts and historic data available on the date each monthly forecast became available. Model input files were designed using actual inflow, surface elevation and outflow data for the beginning of the water year prior to each monthly inflow forecast. Monthly runoff volume forecasts of inflow to Koocanusa Reservoir during the period April 1 through August 31 follow the USACE official forecasts for Libby Dam 2006 (Table 9):

Table 9. Monthly wateryear forecasts for Lake Koocanusa above Libby Dam in 2006.

Monthly Forecast	Volume (KAF)	Percent of Normal
January	5553	88.9
February	6301	100.9
March	6409	102.6
April	6131	98.1
May	6179	98.9
June	6766	108.3

Results

Comparison with IRCs

The USACE's VARQ operation differs somewhat from the IRC targets that were designed to limit reservoir drawdown and improve reservoir refill probability, so the IRC operation represents the lower reservoir drawdown limit (Marotz et al. 1996, 1999). Montana views VARQ as a tool that provides flexibility to maintain reservoir elevations higher than the IRCs when it is safe to do so from a flood control perspective. That is, when volume forecasts indicate that the reservoir will not refill until after inflows decline to maximum turbine capacity and spill can be avoided.

During 2006, Libby Reservoir surface elevations remained above the IRC designed for the driest 20th percentile wateryears (Figure 19, top green line) for most of the year (Feb 1 through May 16), and well above the IRC for average years (Figure 19, middle green line). The observed runoff shape could not have been predicted, so the rapid reservoir refill rate during May and early June would have occurred regardless of which flood control operation had been implemented. However, the minimum pool elevation under the IRCs was lower than VARQ, so the amount of evacuated storage was sufficient to contain the inflow volume (Figure 20). Although the IRC strategy targeted reservoir refill in mid July, the actual refill date would likely have occurred earlier in July because warm weather during May resulted in an earlier runoff event that differed from the long-term average runoff shape. If spill had occurred, it would have been a smaller volume, of shorter duration and would have occurred in July instead of June.

Model simulations revealed that Libby Dam discharge volumes during April through mid-May were greater under the IRCs than actually occurred. LRMOD predicted mandatory flow reductions from Libby to avoid conflicts with IJC rules for Kootenay Lake and flood stage at Bonners Ferry, Idaho. Simulations calculate minimum and maximum flow limits for Libby Dam to meet flood constraints in Kootenai watershed (Figure 21). During April and most of May, the maximum flow limits could have physically accommodated higher discharges than were simulated. Libby Dam discharge could therefore have been scheduled during periods when discharge was not restricted to assure that downstream flood control rules were not violated.

In reality, the discharge from Libby Dam had to be reduced from May 19 through May 21, due to "trapped storage" when full powerhouse capacity was not possible, in part because low elevation runoff below Libby Dam was high enough to produce a combined flow approaching flood stage (1764 ft) at Bonners Ferry.

The IJC Board of Control at Kootenay Lake regulates another restriction to Libby Dam discharge. Libby Dam discharge must approximate reservoir inflows until the "commencement of the spring rise" is declared at Kootenay Lake. Once the onset of the spring freshet is officially declared, Libby Dam discharge can be increased to facilitate drafting the pool toward the variable flood control target.

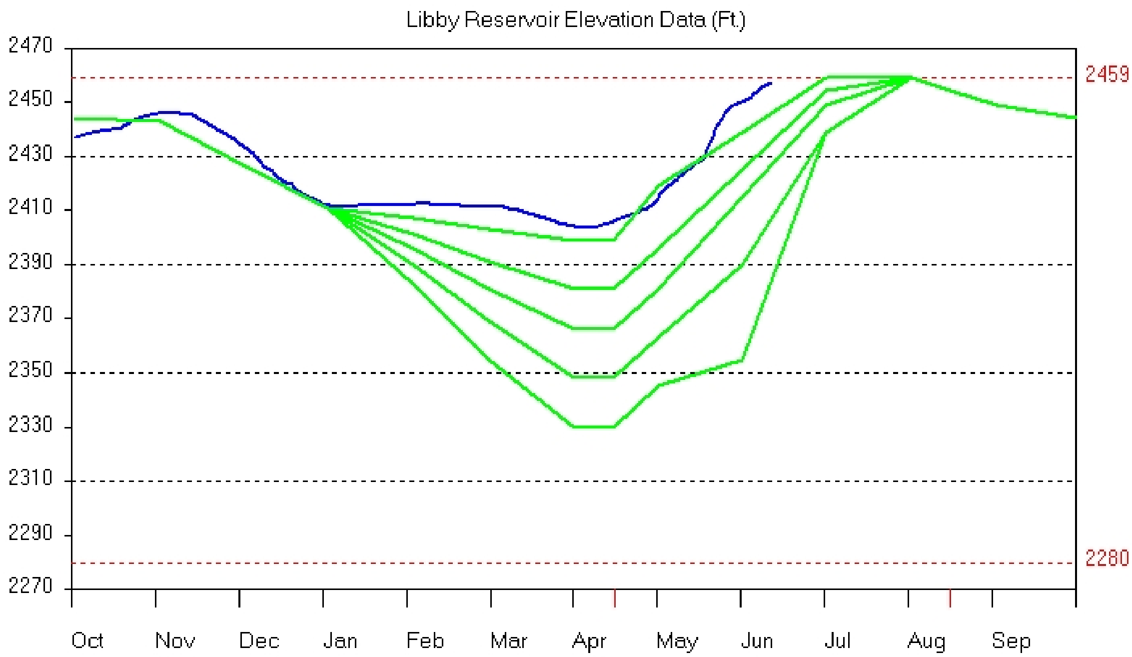


Figure 19. Comparison of actual wateryear 2006 operations (blue) with the Integrated Rule Curves (Marotz et al. 1996, Lmatrix version 2000). This family of IRC curves (green) represent reservoir surface elevations in quintiles of water supply (each 20th percentile of normal inflow volumes) from drought (least reservoir drawdown) to flood conditions (deepest drawdown).

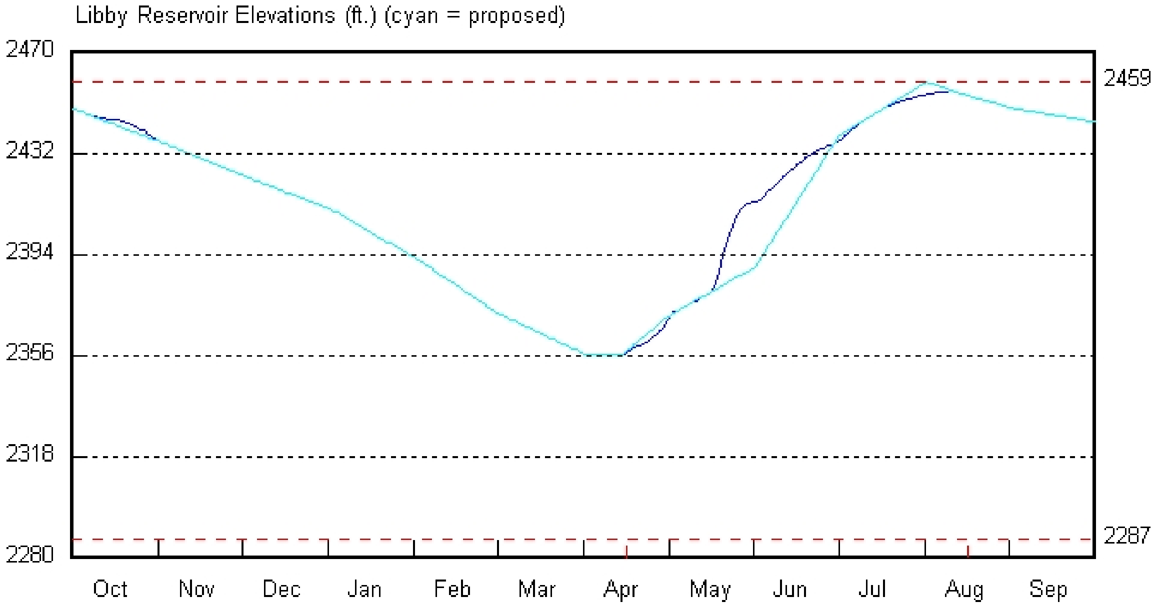


Figure 20. Simulated 2006 Libby Dam operation using Integrated Rule Curves to calculate the end of month draft and refill targets based on monthly inflow forecasts January through June. Reservoir refill was more rapid during May and June (dark blue) than the proposed IRC (cyan) due to unpredicted high runoff during May. Evacuated storage and higher dam discharges were sufficient to prevent spill.

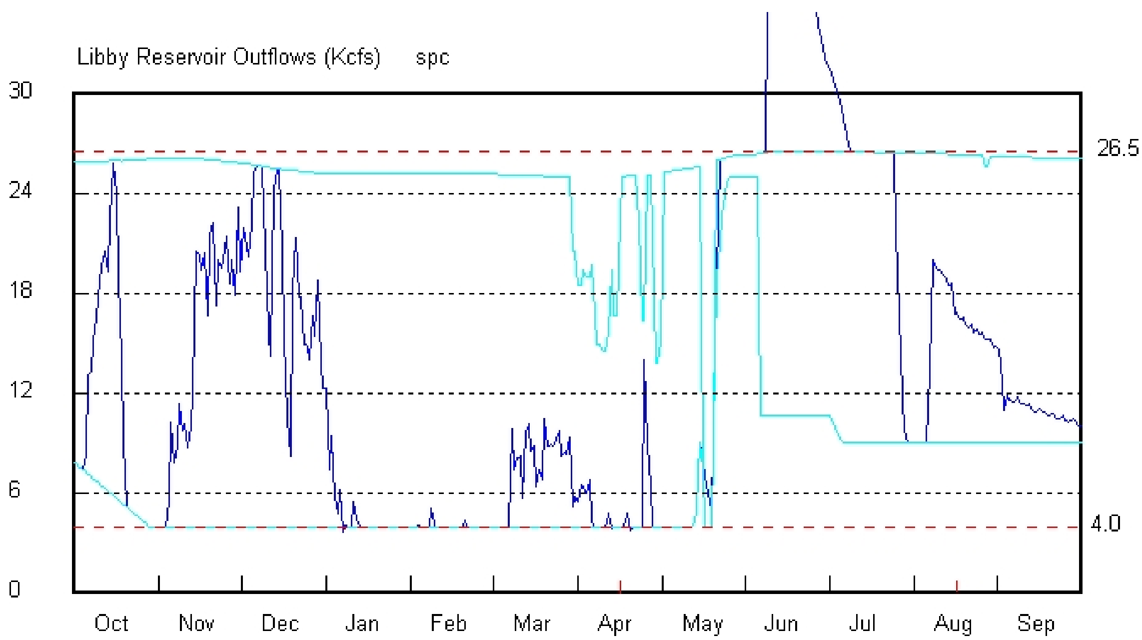


Figure 21. Calculated minimum and maximum flow limits required to meet flood control requirements and white sturgeon tiered flows downstream of Libby Dam 2006 (cyan) compared to actual operations through June 11, three days after spill began (dark blue). The remainder of the year was predicted based on the June forecast and would be smoothed during real time operations.

Comparison of the actual 2006 operation with monthly IRC simulations indicate that upon receiving the Jan 1 forecast, dam discharges would have been reduced to remain at or above the minimum draft curve to avoid a potential reservoir refill failure. When the February inflow forecast became available, predictions indicated that the reservoir would refill. Discharges would therefore be controlled to achieve the end-of-February reservoir elevation target. When the inflow forecast was updated in March, forecasts indicated that the reservoir would refill too soon, before inflows would normally decline to turbine capacity. Discharges would therefore have to be increased to achieve the adjusted draft target and avoid the potential for premature refill and uncontrolled spill. By the time the April forecast became available, model simulations indicated that early refill (high potential for spill) would occur unless dam discharge was increased. There were no downstream constraints preventing increased discharges during the period March 1 through mid-May. The modeled IRC operation released more water prior to mid-May and avoided spill (Figure 22).

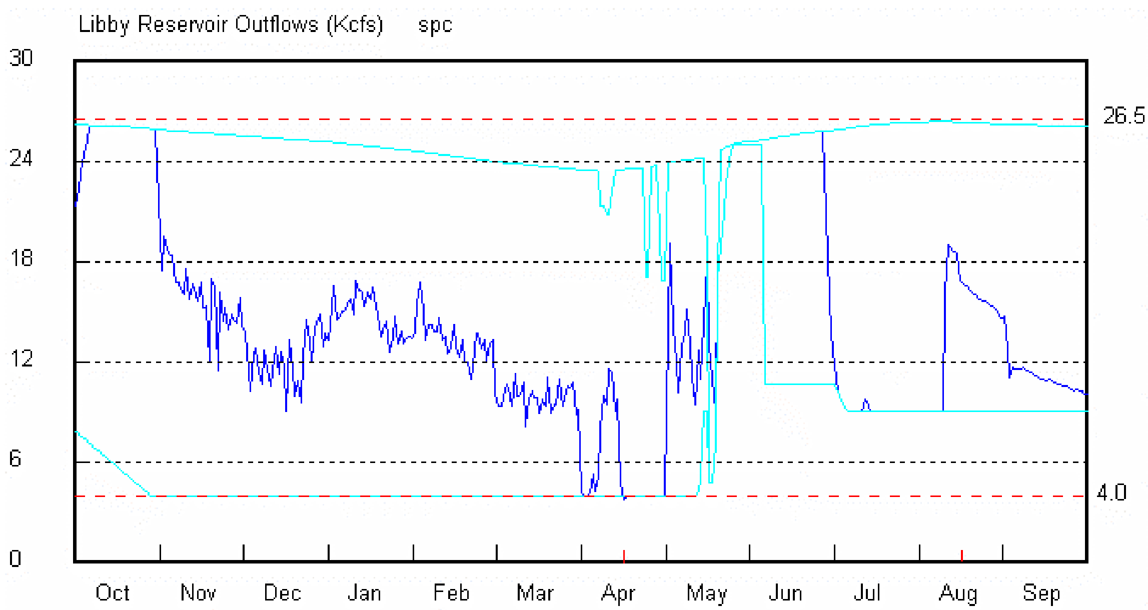


Figure 22. Simulated 2006 Libby Dam discharge schedule under the IRC operation (dark blue). The model simulation was run with no foresight. The upper discharge limits (cyan) required to conform to downstream flood requirements (IJC and Bonners Ferry) would have allowed more discharge during April. Minimum discharge limits (cyan) provide sturgeon tiered flows and stable bull trout summer flows. Discharges after June 11 would have been smoothed during real time operations to create a gradual decline after the spring freshet, and to avoid an unnatural second flow pulse after spring runoff.

Comparison with VARQ

USACE hydraulic branch calculates a preliminary VARQ operation for the Reservoir Control Center that includes such things as the volume runoff forecast, and conditions on Kootenay Lake and Duncan Reservoir. The Reservoir Control Center then modifies the preliminary calculation to fit current reservoir and runoff conditions and makes adjustments for flow requirements for fish species listed under the Endangered Species

Act (ESA). The USACE's VARQ model used a daily time-step over the period October 1947 through September 1999. The reservoir elevation of 2411 was targeted for the end of December to evacuate two Million Acre Feet (2 MAF) by January 1. During January through April, Libby Dam operates to the VARQ Flood Control elevations described by Libby Dam's storage reservation diagram (Figure 23). The VARQ Flood Control elevations are based on monthly volume runoff forecasts for reservoir inflow. After March, Libby Dam discharges generally match reservoir inflow until the flood control curve intersects the refill curve. During 2006, however, discharged were less than inflows during this period. Refill at Libby begins approximately ten days before streamflow forecasts of unregulated flow are projected to the Initial Control Flow (ICF) at The Dalles, Oregon, which varies from year to year. If, however the flood control curve intersects the refill curve, refill normally begins at that time. Discharge from Libby Dam during refill is based on the VARQ Outflow Procedure (USACE 2002, Appendix A-2, Rule 3). However, the USACE also included in their model analysis, sturgeon tiered flows for white sturgeon recovery (USFWS 2006) and summertime flow augmentation for anadromous fish recovery (NOAA-Fisheries 2005). The VARQ instructions require a great deal of operator decision-making that cannot be captured by computer modeling. Forecasting error influences the raw elevational targets based on the VARQ Storage Reservation Diagram (SRD) and subsequent adjustments to Libby Dam discharge required to meet the sturgeon flow targets, refill the pool and avoid spill. While flows were provided for Kootenai River white sturgeon, the VARQ Outflow Procedure was not followed (USACE email 2006). During refill, Libby Dam discharge is normally adjusted based on Rules 4-8 of the VARQ protocol; discharge is reduced if it appears Koocanusa Reservoir will fail to refill, or increased if forecasts indicate the reservoir may fill too early and spill. Models can be used in real time for "flow enveloping", which tracks how much of the forecasted April through August inflow has passed through the dam, and calculates how much of the predicted runoff remains upstream. Following refill, Libby begins drafting to reach elevation 2439 (20 ft below full pool 2459) by the end of August for anadromous fish flow augmentation.

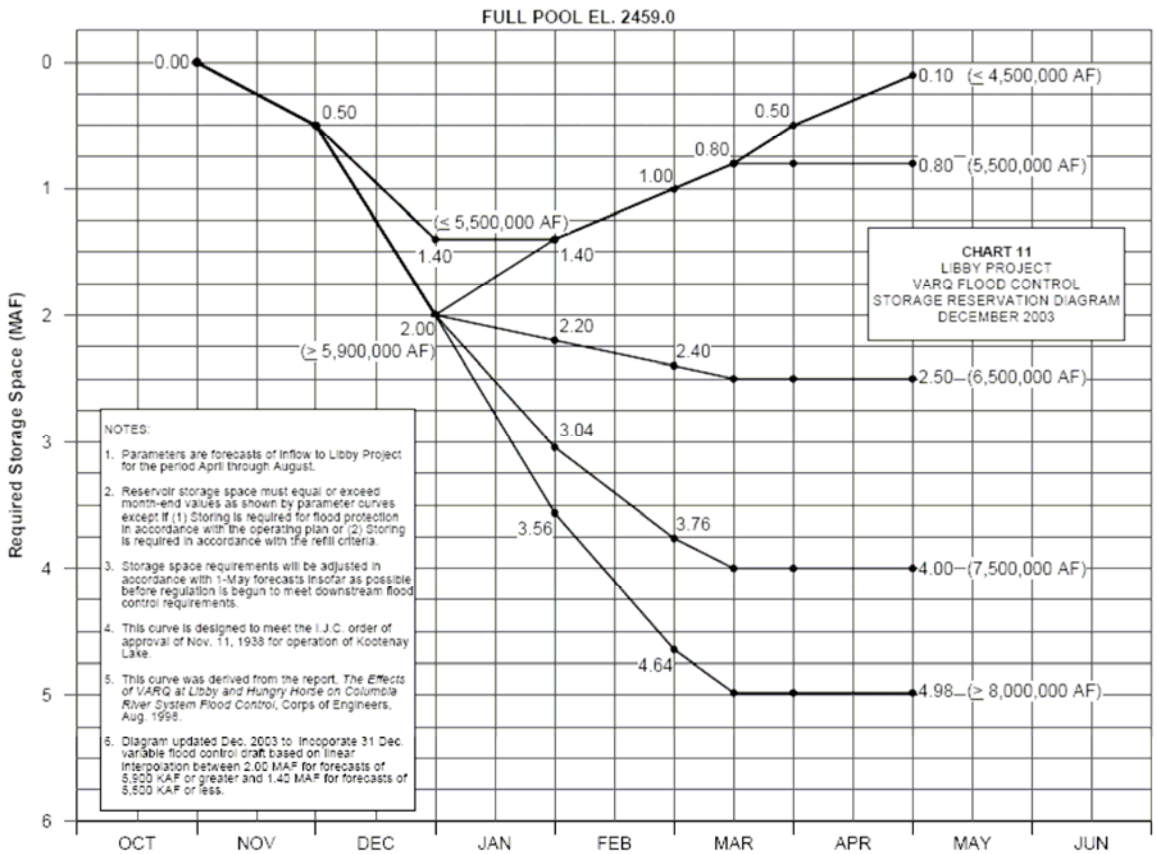


Figure 23. Columbia River Treaty Flood Control Operating Plan Storage Reservation Diagram for Libby Dam (from USACE 2002).

During 2006, the March, April and May inflow forecasts indicated that Libby Reservoir would refill before predicted inflows declined to turbine capacity. Spill must occur if the reservoir fills before inflows decline to maximum turbine capacity (≅24 kcfs). The Initial Control Flow (ICF) at The Dalles occurred in late April, signaling the beginning of spring runoff. Under Rule 2, initiation of refill, the VARQ refill procedure (USACE 2002, Appendix A) could be initiated ten days before ICF at McNary, so by mid April. The commencement of the spring rise was declared on April 9 on Kootenay Lake, British Columbia (Vladimir Plesa, BC Hydro 2006), which allows Libby discharge to exceed the reservoir inflow. Rule 3, the initial VARQ outflow procedure specifies a minimum discharge rate based on the inflow forecast volume (USACE 2002, Appendix A, Figure A-3) to avoid uncontrolled spills. Given the April final inflow forecast of 6131 KAF, Libby Dam discharges should have matched reservoir inflows prior to April 9, and then increased to approximately 20 kcfs by mid April when the spring runoff began. By the May forecast of 6179 KAF, runoff predictions indicated that discharge could have increased. Adjustments may have reduced outflows slightly prior to May 16 when sturgeon releases began to release 1.12 MAF (a Tier 3 wateryear with April through August inflows in the range of 6.0 to 6.7 MAF) (USFWS 2006). In reality, Libby discharges remained at or near minimum flow during the period April 9 through May 14 when discharge began ramping up to full turbine capacity. Discharge records show that after May 16th, the USACE released as much water as they could safely discharge. Evidence suggests that the VARQ adjustment to discharge (VARQ discharge protocol, appendices in the 1999 and 2002 USACE VARQ documents) was not implemented during April and early May. If discharge had been increased in March, April and early May, the spill of 2006 could have been avoided. If discharges remained at or near the minimum flow until May 1, and then increased to maximum turbine capacity, the simulation showed that spill would have occurred for a minimum of 19 days at discharges up to 19.7 kcfs through the spillway (Figure 24). Spill could have been avoided if the VARQ discharge protocol had been initiated by mid-April.

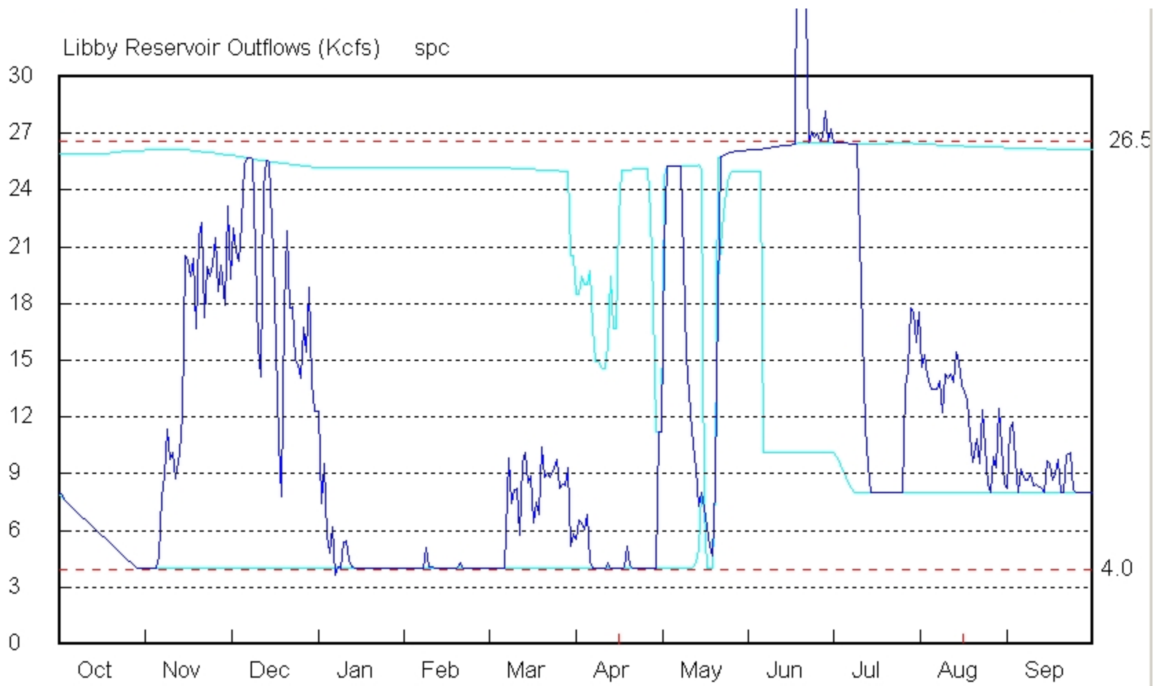


Figure 24. Model simulation of Libby Dam discharges during 2006, configured to increase discharge to maximum turbine capacity beginning May 1. Minimum and maximum flow limits (cyan) conform to the maximum turbine capacity at head, minimum flow limit (4 kcfs), white sturgeon tiered flow, bull trout minimum flow and adjustments required for downstream flood control. Libby Dam discharges (dark blue) show that spill would have occurred in mid to late June for a minimum of 19 days, at a lower volume than actually occurred.

The June 30 refill target in the NOAA-Fisheries' BiOp (2005) also increased the potential for uncontrolled spill. If Libby Reservoir fills on June 30 (or before), spill would occur in approximately 68 percent of all wateryears because inflows exceed turbine capacity after June 30. For this reason, MFWP developed a "sliding refill date" strategy to fill the reservoir later as inflow forecasts increase (early in dry years and late in wet years). In an average year like 2006, reservoir refill should not occur until early to mid July, when inflows decline to turbine capacity or less. If the refill date is based on water supply, spill can be avoided in most years.

Conclusion

Detailed analysis of the 2006 operation presents an opportunity to change some of the current practices, implement VARQ as designed and improve operations in the future. Operation of Libby Dam is difficult because of forecasting error and unpredictable precipitation events. During 2006, uncontrolled spill occurred from June 5 through June 27, mainly due to inflow forecasting error. If the inflow forecast had been more accurate, both the IRC and VARQ would have drafted Koocanusa Reservoir to about 2330 to 2340 feet elevation and spill would not have occurred. Several citizens complained that VARQ flood control caused the spill problem in 2006. Model analyses demonstrated that VARQ could have averted spill or greatly reduced the duration and volume, despite the observed forecasting error. Historic data allow estimation of forecasting error and variability in precipitation for all periods and confidence intervals can be placed around real-time predictions. Despite these tools, inflow forecasting error will likely result in occasional spill events regardless of which flood control or refill strategy is implemented. Conversely, if the reservoir is drafted more deeply to add a margin for error, Libby will fail to refill more often. Nonetheless, if VARQ is implemented as designed, spills will be infrequent (about 2% of the time) and of a low volume and duration, people living along the Kootenai River will witness fewer spill events and fish populations will benefit from lower incidence of GBT and stabilized river flows.

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