Hydrologic Analysis of Upper Columbia Alternative Flood Control and Fish Operations On Columbia River System including the VARQ Flood Control Plan at Libby and Hungry Horse Projects

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

REFERENCES

1. Columbia River System Operation Review, Final Environmental Impact Statement, Appendix E, Flood Control. November 1995.

2. Columbia River Basin System Flood Control Review, Preliminary Analysis Report. North Pacific Division, Corps of Engineers, February 1997.

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1. INTRODUCTION

The Corps is preparing an Environmental Assessment (EA) and an Environmental Impact Statement (EIS) for the VARQ flood control plan at Libby and Hungry Horse Projects in response to the National Marine Fisheries Service and U.S. Fish and Wildlife Service 2000 Biological Opinions. The Biological Opinions recommend VARQ as a possible flood control operating strategy for both Libby and Hungry Horse Projects with the intention to benefit sturgeon, bull trout, salmon, and steelhead stocks listed as threatened or endangered in the Columbia River Basin. This report was prepared by Corps of Engineers, Northwestern Division, Water Management Division, Hydrologic Engineering Branch to assess the hydrologic impacts of this flood control strategy to the Columbia River. The EA will aid in VARQ implementation for Libby Project in January 2003. VARQ flood control at Hungry Horse Project has been implemented based on previous studies.

VARQ was first introduced as a screening alternative to the current flood control operation for Libby and Hungry Horse Projects in the Columbia River System Operation Review, November 1995 (SOR). The SOR Flood Control Work Group concluded that the VARQ procedure had promise and further refinements could lead to its implementation. A more detailed analysis was conducted for the Columbia River Basin System Flood Control Review, February 1997. Results from the evaluation of system flood control were encouraging; however, more work was needed to identify the impacts to providing local flood protection for the Kootenai River and its effect on meeting fishery and refill objectives. This work was conducted by the Seattle District and is documented in Kootenai River Flood Control Study Analysis of Impacts of the Proposed VARQ Flood Control Plan and Local Effects of the Proposed VARQ Flood Control Plan at Hungry Horse Dam, Montana 1998. An updated flood control analysis is now being done by Seattle District for the Kootenai and Flathead Systems for the EA and EIS.

The 1998 Supplemental Biological Opinion called for a status report on work to date on VARQ. The Corps of Engineers published the Status Report in January 1999. The report summarized work to date on the development of VARQ. The work was performed by two Corps offices including Northwestern Division for system flood control work and hydropower analysis, and Seattle District for work on local impacts and effects of VARQ.

This report describes the system flood control impacts of implementing VARQ on the Columbia River system and impacts of other Upper Columbia River Alternative Flood Control and Fishery operations. This includes additional outflow (25 and 35 kcfs) at Libby Project onto the Columbia River system, and fishery operations at both Hungry Horse and Libby Projects. Fishery operations at Libby and Hungry Horse projects pertain to the varied fish species of salmon, bull trout and sturgeon that have been listed as Threatened or Endangered in the Columbia River Basin. Upper Columbia alternative operations are explained in more detail in the Local Effects of Alternative Operations at Hungry Horse and Libby Dam: Hydrologic Study for the Upper Columbia, September 2002.

2. CURRENT FLOOD CONTROL PLAN

2.1 Historical Perspective

On September 16, 1964, the U.S. and Canada ratified the Columbia River Treaty, which formed the basis for major hydropower and flood control-related developments on the Columbia River system. There are two parties to the agreement, the U.S. and Canadian entities. Under terms of the Treaty, four major water storage projects were built: Mica, Arrow, and Duncan in Canada, and Libby in the U.S. The combined active storage of these projects is about 25 million acre-ft (maf), and includes 13 maf for primary flood control. This more than doubled the previously existing storage capability of the system. Table 1 denotes major elements of this flood control system, and Figure 1 provides a general depiction of location for these projects. This action led to the development of the Columbia River Treaty Flood Control Plan (FCOP) completed in draft form in 1968, and finalized in 1972. This plan provides the basis for the current Columbia River system flood control operation.

Table 1. Major Elements of the Columbia River Flood Control System.

Project	Primary Flood Control Space (Acre-Ft)	Additional On-Call Flood Control Space (Acre-Ft)
Mica	2,080,000	9,920,000
Arrow	5,100,000	2,000,000
Duncan	1,270,000	77,000
Libby	4,960,000	
Hungry Horse	2,980,000	
Grand Coulee	5,185,000	
Dworshak	2,016,000	
Brownlee	975,300	
John Day	535,000	
TOTAL	25,101,300	11,997,000

In 1995 the Corps completed an analysis of a proposal to change the maximum flood control drafts at Mica and Arrow, Summary Report, Proposed Reallocation of Flood Control Space, Mica and Arrow Reservoirs. The Canadian Entity proposed changing Mica's space allocation from 2.08 maf to 4.08 maf and Arrow's from 5.1 maf to 3.6 maf. The Corps concluded that the changes in the maximum drafts at Mica and Arrow would not adversely affect system flood control as measured at The Dalles, nor adversely affect flood control at Birchbank.

In 1998 the Corps submitted a revised FCOP to the Columbia River Treaty Operating Committee for review. The revised FCOP clarifies general operating procedures, contains updated statistics, and introduces a formal process to exchange flood control space between Arrow and Mica. This plan was finalized in 1999.

2.2. Current Flood Control Criteria

The basic objective of the Columbia River system flood control operation is to regulate reservoirs to reduce damages to the lowest level possible for stages at all potential flood damage areas while ensuring with a high level of confidence that storage projects are refilled at the end of the spring runoff. Table 2 denotes major flood damage areas in the Columbia River Basin. The Columbia River at The Dalles, Oregon, is used as the main system control point in the FCOP. Storage in upstream reservoirs to meet flood control objectives at this point generally will result in adequate control at the locations mentioned in Table 2. Throughout this document, all elevations are in feet in reference to the National Geodetic Vertical Datum, or NGVD.

Table 2. Flood Damage Areas in the Columbia River Basin.

CONTROL POINT	RIVER REACH`	EXCEEDANCE FLOW OR STAGE FOR MINIMAL DAMAGE	EXCEEDANCE FLOW OR STAGE FOR MAJOR DAMAGE
Flow at Columbia River at Birchbank, BC	Columbia River from below the confluence of Arrow Lakes and Brilliant Dam to the U.S. border	225,000 cfs	280,000 cfs
Stage at Kootenai River at Bonners Ferry, ID	Kootenai River from Libby Dam to and including Bonners Ferry	1,764.0 ft	1,774.0 ft
Flow at Flathead River at Columbia Falls, MT	Flathead River from Columbia Falls, MT to Flathead Lake	52,000 cfs	82,800 cfs
Stage at Flathead Lake at Somers, MT	Flathead Lake shoreline	2893.1 ft	2894.5 ft
Flow at Flathead River nr Polson, MT	Flathead River from Kerr Dam to Thompson Falls Dam	28,000 cfs	80,000 cfs
Stage at Pend Oreille Lake nr Hope, ID	Lake Pend Oreille shoreline	2,062.5 ft	2,065.0 ft
Flow at Pend Oreille River at Newport, WA	Pend Oreille River from Albeni Falls Dam to the Columbia River	100,000 cfs	120,000 cfs
Flow at Clearwater River at Spalding, ID	Clearwater River from Dworshak Dam to the Snake River and then to the Columbia River	112,000 cfs	129,300 cfs
Flow at Columbia River at The Dalles, OR	Columbia River between Bonneville Dam (river mile 145) and river mile 40	450,000 cfs	750,000 cfs

Source: Columbia River System Operation Review, Final Environmental Impact Statement, Appendix E, November 1995, and Seattle District correspondence.

3. ANALYSIS PROCEDURE

3.1 General Assumptions

System Flood Control

The first and overriding assumption for the system flood control impacts in this evaluation is that it was a flood control-only analysis; all prescribed drafts at the storage projects were for flood control purposes. During the regulation of the historical events, project operations were guided strictly by FCOP and by the International Joint Commission's order regarding Kootenay Lake. On-call storage provisions were left unchanged. Two alternatives were modeled based exclusively on system flood control. The alternatives are:

Standard Flood Control (**Standard FC** also known as Base-CRT63)
VARQ flood control (**VARQ FC**)

For the purposes of this report, Standard FC, Base, or Base-CRT63 all refer to Standard Flood Control. Additional storage space associated with possible power drafts was not taken into consideration for Standard FC hydro-regulations. A discussion of Standard FC is contained in the document Review of Flood Control, Columbia River Basin. Columbia River and Tributaries Study, CRT-63. North Pacific Division, Corps of Engineers. June 1991.

Upper Columbia River Fish Operations

The assumption for the system impacts of Upper Columbia River alternative fish operations, as described earlier, is that the entire system will be operated to system flood control, and Hungry Horse and Libby Projects will also be modeled to Upper Columbia River fishery requirements. For Libby Project, the current maximum powerhouse outflow of 25 kcfs will be modeled, as well as additional outflow (35 kcfs). The additional outflow, above maximum, is to be used only during fishery requirements for sturgeon. Hungry Horse and Libby will be operated to Upper Columbia River fishery requirements as long as system flood control is not violated.   Four alternatives based on Upper Columbia River fishery operations and different outflows were modeled. The four alternatives denoted in parentheses are based on the following parameters:

Standard FC + Upper Columbia Fish flows + 25 kcfs Libby Qmax (**Standard FC 25**)
VARQ FC + Upper Columbia Fish flows + 25 kcfs Libby Qmax (**VARQ FC 25**)
Standard FC + Upper Columbia Fish flows + 35 kcfs Libby Qmax (**Standard FC 35**)
VARQ FC + Upper Columbia Fish flows + 35 kcfs Libby Qmax (**VARQ FC 35**)

Additionally, for both the system flood control and different outflow alternatives, it was assumed that the influence of the Willamette River on the nature of the stage-frequency relationship in the Portland/Vancouver harbor is insubstantial for the spring runoff season. The Willamette River contributes a relatively minor amount to spring time flooding on the Columbia River. During the winter, the Willamette River is a major contributor to flood events in the Portland/Vancouver harbor. Flooding from the Willamette River is generated from excessive rainfall and augmented at times by rain on snow conditions. However, spring runoff on the Columbia River is mainly from melting of the winter snow pack, and the FCOP, including the operation of Libby and Hungry Horse Projects, was developed for regulation of these large Columbia Basin-wide spring snowmelt events.

3.2 Selection of Years for Evaluation

System Flood Control

The 60-year record, 1929-1989, was selected as the period of study for system flood control evaluation. This period of record has been extensively used in hydropower and water management planning studies and the data are well documented. In this 60-year period four substantial spring floods occurred, 1948, 1956, 1972, and 1974. The 1948 unregulated peak flow ranks as the second highest peak flow for Columbia River at The Dalles since records began in 1848. The unregulated peak flows of 1972 and 1974 approximately tie for the third highest peak flow of record.

Upper Columbia River Fish Operations

Ten years were selected for study of system impacts of Upper Columbia River Fish operations based on their potential to influence stages at Bonner Ferry, Idaho, or flood control draft at Grand Coulee Dam. In addition to this, understanding how forecast error or early/delayed spring freshets might compound effects at Bonners Ferry or Grand Coulee was also important. To address these issues, the criteria below were developed to select the ten years.

Each of the ten years met all of the following three criteria:

1. The VARQ flood control draft points had to be different from the standard flood control draft point. During high forecast years (greater than 125%) the VARQ FC and Standard FC draft targets are identical for the months of January through April. Therefore, the April-August Libby inflow forecast volume (issued in May) need to be less than 8.0 maf.

2. The volume forecast had to be large enough so that sturgeon volumes would be provided. Therefore, the April-August Libby inflow forecast volumes (issued in May) needed to be greater than 4.8 maf.

3. The maximum stage at Bonners Ferry for the VARQ FC only simulations had to be between 1757 and 1765 ft. The low end of this range was selected as 1757 ft because agricultural impacts begin to occur at that river stage. The high end of 1765 ft was selected because previous modeling suggested that the VARQ and Standard FC

frequency curves converge for large water years when the stage at Bonners Ferry exceeds 1764 ft.

Each of the ten years also met at least one of the following criteria:

4. The forecast representing the April-August Libby inflow volume (as issued in May) had to be over-forecasted by at least 1 maf or under-forecasted by at least 1 maf. This way, the impact of a “mis-forecast” could be assessed.

5. The Initial Controlled Flow at The Dalles had to be reached early enough so that refill was initiated in April (considered early), or late enough so that refill did not begin until after 15 May (considered normal to later than normal).

6. The average June flows at The Dalles had to be greater than 625 kcfs – thereby indicating a large, late freshet.

7. In the flood control-only simulations, the draft at Grand Coulee Dam had to be at least four ft deeper with VARQ FC than with Standard FC.

Sixty-one years (1929-1989) were narrowed down to 10 by using the above criteria. However, even though 1942 met the screening criteria, it was not chosen because it was a low volume year with minimal flood control draft at Grand Coulee Dam and an initial controlled flow less than 220 kcfs. It was replaced by 1948, a year that is particularly interesting because of its record high runoff. The 10 selected years were 1933, 1948, 1949, 1955, 1968, 1971,1975, 1981, 1986, and 1989.

3.3 Water Supply Forecasts

The water supply forecasts used for this study are a combination of modeled and actual water supply volume forecasts for the 1929-1989 period. These forecasts were used in the development of seasonal flood control requirements for the hydro-regulations. The forecasts did not change for system flood control or Upper Columbia River Alternative operations analyses. The modeled forecasts were developed in the late 1980’s and are called the Kuehl-Moffitt Simulated Runoff Forecasts. The forecasts consist of first of the month, January through July, water supply forecasts for each year in the 1929-1982 period. The runoff forecasts were modeled using actual water supply forecasting procedures that are used in operational forecasting and were statistically corrected for long-term bias. Actual water supply forecasts were used for the final seven-year period 1983-1989. The use of forecast data in the hydro-regulations, as opposed to observed volumetric runoff, adds the element of uncertainty that is experienced in real-time water management and is a more rigorous test of the system flood control operation.

3.4 VARQ Flood Control Requirements

Storage reservation diagrams (SRD) define the amount of space that is necessary from US and Canadian projects for system flood control. Needed flood control space is based on seasonal volumetric water supply forecasts. The storage space at each project is held vacant until storing is required for flood control and reservoir refill. Figures 2 through 5 show the Standard and VARQ SRDs for both Libby and Hungry Horse Projects. The standard SRDs are part of the FCOP and are based on the concept that outflows from Libby and Hungry Horse during the refill period are at their minimum level. On the other hand, the VARQ SRD is designed around the concept of allowing outflows to vary during refill based on the water supply forecast (Figures 6 and 7) beginning on 1 May. This procedure is intended to reduce the April 30 system flood control draft without compromising system flood control. The outflows after 1 May can be adjusted due to over drafting or under drafting flood control storage. Please note that the outflows are a computed minimum average flow. Flows can also be adjusted due to a updated runoff forecast or due to local flood control requirements.

For example, the releases from these projects during refill (post-April 30) would be increased as the inflow volume runoff forecast to each project decreased. The outflows will also be adjusted during the final stages of refill to avoid overfilling and unwanted spill. Please see Appendix A for a thorough step by step application of the VARQ flood control procedure to include re-computation of project outflows after 1 May.

Regarding refill, if water that is normally stored during that period is instead passed through the project, then the amount of space needed in the project is reduced. Therefore, the April 30 draft requirement, as specified by the SRD, is reduced in lower runoff years. In years where the inflow volume runoff forecast is high (at or above 125 percent of the 1961-1990 average at Libby and at or above 130 percent at Hungry Horse), then the VARQ FC operation is not applied since it directly emulates or copies the Standard FC regulation with similar storage space requirements and outflows during refill. Table 3 depicts this feature of VARQ for a variety of water supply forecast levels in thousands of acre-ft (kaf).

Table 3. Comparison of FC Drafts at Libby and Hungry Horse Projects.

		Apr30 FC Draft 80% of Normal Runoff (kaf)	(ft)	Apr30 FC Draft 100% of Normal Runoff (kaf)	(ft)	Apr30 FC Draft 120% of Normal Runoff (kaf)	(ft)	Apr30 FC Draft 130% of Normal Runoff (kaf)	(ft)
LIB \1	**Standard FC**	1983	2413.2	3816	2347.6	4980	2287	4980	2287
	VARQ FC	521 (1860)	2447.7 (2414.8)	2291	2402.7	4298	2325.6	4980	2287
	Difference	1462 (123)	34.5 (1.6)	1525	55.1	682	38.6	0	0
HGH	**Standard FC**	893	3521.3	1229	3504.6	1611	3483.2	1802	3471.4
	VARQ FC	485	3539.8	836	3524.0	1475	3491.2	1793	3472
	Difference	408	18.5	393	19.4	136	8	9	0.6

\1 Libby has a fixed 2,000 kaf December 31 flood control draft requirement. The values in parenthesis are estimates of the storage space that can realistically be reached by April 30, and are related both to volume and hydrograph-shape. The values are calculated using average monthly inflows for January through April. For the period April-August, the 1961-1990 average runoff for Libby Project is 6376.8 kaf.
\2 The 1961-1990 average May-September runoff for Hungry Horse Project is 1834.6 kaf.

3.5 Modeling Procedure

System Flood Control

FCOP guidelines for operating reservoirs for the system flood control analysis were followed in performing the hydro-regulations. Key components of this operation include:

- Drafting Libby, Duncan, Mica, Arrow, Hungry Horse, Grand Coulee, Dworshak and Brownlee in accordance with their flood control storage reservation diagrams.
- Developing control flow targets at The Dalles to trigger system refill and minimize flooding in the lower Columbia River.
- Using flood control refill curves to guide reservoir refill.
- To the extent possible, operating Libby, Dworshak and Hungry Horse to meet local flood control objectives.
- Adhering to the International Joint Commission criteria for the operation of Kootenay Lake, which affects the operation of Libby and Duncan.
- Refilling Arrow and Grand Coulee in accordance with the procedure as defined in Charts 3 and 6 of the FCOP.

In addition to these principles of operation, the evacuation of Libby takes priority over the draft of Duncan when outflows must be reduced to adhere to the International Joint Commission criteria for the operation of Kootenay Lake.

Upper Columbia River Fish Operations

The following guidelines for modeling Upper Columbia River Fish Operations to analyze hydrologic effects to the system were followed in performing the hydro-regulations. The guidelines include operating for system flood control and the following Upper Columbia Fishery operations.

- Libby Project is operated primarily to meet downstream flood control objectives. As a secondary objective, Libby is also operated to meet sturgeon volumes (if required) in May or June, to meet bull trout minimum flow requirements in June, July, and August, and to draft to elevation 2439 ft by 31 August for salmon flow augmentation. Libby overflows of 25 and 35 kcfs respectively were also modeled.
- Hungry Horse Project is operated primarily to meet downstream flood control objectives. As a secondary objective, Hungry Horse is also operated to meet minimum flow requirements out of the project or at Columbia Falls, whichever was the greater, and to draft to elevation 3540 ft by 31 August for salmon flow augmentation.

This subject is explained in greater detail in Local Effects of Alternative Operations at Hungry Horse and Libby Dam: Hydrologic Study for the Upper Columbia, September 2002.

The modeling of the reservoir system was conducted using the Corps' SSARR and AUTOREG programs. AUTOREG follows the FCOP procedures for developing the controlled flow targets at The Dalles and refilling Arrow (Hugh Keenleyside) and Grand Coulee, thereby ensuring consistent application of the FCOP. The modeling was conducted using a daily time step.

The hydro-regulation model runs performed for this assessment were developed with relatively strict modeling guidance. The water supply forecasting technique used in the models was consistent for the 1929 through 1982 period, and was slightly updated to a new technique for the historic years of 1983 through 1989.

The forward-looking weather and forecast approach used by the modelers was somewhat limited. The modelers attempted to prepare operations scenarios during the historic period of record that may have been likely to occur. Although the actual hydrograph for each historic water year is well known to modelers, they tried to develop operations as if they had no knowledge of the weather and resultant hydrograph in any year.

In development of scenarios with fish flows, a rigid operational template of outflow was developed. The increase of outflow from Libby Dam began on a fixed date, depending on the magnitude of the water year. In actual operation, adaptive management might cause fish flow operations that may begin earlier, or later, than those developed for the fish flow template. Real-time adaptive management allows for flexibility in the operation of Libby Dam to better meet multi-purpose needs.

Because of the short forward-looking weather forecast and the rigid fish flow template used by the modeler, some of the model output results may be skewed to demonstrate more risk under VARQ FC than Standard FC. In real-time adaptive management some high risk may be somewhat reduced by use of operational flexibility that could not be injected into these scenarios.

3.6 Statistical Analysis

The standard procedures set forth in Bulletin 17B of the Water Resources Council Guidelines for Developing Flood Flow Frequency were used to perform a statistical analysis of the results of the hydro-regulations.

4. RESULTS OF FULL SYSTEM REGULATION

4.1 Summary of System Hydro-Regulations

System Flood Control

The 1928-1989 hydro-regulations were evaluated to determine the differences in flow at Birchbank, BC and The Dalles, OR between the two alternatives, Standard FC and VARQ FC simulations. These are key system flood control points on the Columbia River. Table 4 shows the results of this analysis. Standard FC represents the current FCOP regulation with the Standard FC procedures. Monthly averages are shown for January through August. Table 4 demonstrates how the VARQ FC operation at Libby and Hungry Horse Projects would reshape the flow, less during the winter drawdown period and more during the spring runoff, as compared to the Standard FC operation. Figure 8 provides a graphical depiction of the differences in Standard FC and VARQ FC hydro-regulations for those two downstream locations.

Table 4. Distribution of Modeled Flow at Key Points on the Columbia River for Standard FC and VARQ FC Operations.

	January (cfs)	February (cfs)	March (cfs)	April (cfs)	May (cfs)	June (cfs)	July (cfs)	August (cfs)
Columbia River at Birchbank, BC								
VARQ FC	59,500	59,200	56,800	45,700	98,900	127,200	116,900	88,500
Standard FC	66,500	62,100	58,300	45,600	95,000	120,900	116,000	88,400
Difference	-7,000	-2,900	-1,500	100	3,900	6,300	900	100
Columbia River at The Dalles, OR								
VARQ FC	142,600	170,200	210,100	235,700	316,800	317,200	197,600	129,400
Standard FC	150,000	175,100	211,800	236,700	313,800	309,400	195,800	129,200
Difference	-7,400	-4,900	-1,700	-1,000	3,000	7,800	1,800	200

Note: All flows are monthly averages from the 1928-1989 flood control hydro-regulations.

Upper Columbia River Fishery Operations

Hydro-regulations were evaluated for the 10 years selected for analysis of fishery operations. The hydro-regulations utilized the guidelines for modeling Upper Columbia River Alternative operations to determine the differences in monthly average flow at Birchbank and The Dalles between Standard FC and VARQ FC simulations. Four alternatives were modeled based on flood control (Standard FC and VARQ FC) and additional outflows at Libby (25 and 35 kcfs respectively). Tables 5 and 6 denote the results of this analysis for additional outflow at Libby Project. However, these tables cannot be compared directly to Table 4 since only ten years were selected for analysis of fishery operations. The averages are denoted for January through August. However, Table 5 (VARQ FC 25 and Standard FC 25) and Table 6 (VARQ FC 35 and Standard FC 35) could be used for comparison purposes. This approach could be used for other tables in the report comparing different fishery flows.

Both tables demonstrate how VARQ FC operation at Libby and Hungry Horse Projects combined with Upper Columbia River fish operations would reshape the flow, less during the winter drawdown period and more during the spring runoff, as compared to Standard FC operation. For the fish flow alternatives (25 kcfs and 35 kcfs), there is only a small difference in monthly average flows at Birchbank or The Dalles. Figures 9 and 10 provide a graphical depiction of differences in monthly average flows for Standard FC and VARQ FC hydro-regulations with fish flows at Libby Project.

Table 5. Distribution of Modeled Flow at Key Points on the Columbia River for Upper Columbia River Fishery Operations with 25 kcfs Overflow for Fish at Libby.

	Jan (cfs)	Feb (cfs)	March (cfs)	April (cfs)	May (cfs)	June (cfs)	July (cfs)	August (cfs)
Columbia River at Birchbank, BC								
VARQ FC 25	62,800	61,300	59,900	46,000	98,900	140,400	124,200	104,000
Standard FC 25	71,700	64,900	62,400	46,800	94,800	137,400	121,400	101,900
Difference	-8,900	-3,600	-2,500	-800	4,100	3,000	2,800	2,100
Columbia River at The Dalles, OR								
VARQ FC 25	145,800	175,600	229,200	233,900	326,300	378,200	221,500	154,200
Standard FC 25	155,100	181,100	230,300	235,400	324,600	372,200	218,800	152,100
Difference	-9,300	-5,500	-1,100	-1,500	1,700	6,000	2,700	2,100

Note: All flows are monthly averages from the 1928-1989 flood control hydro-regulations.

Table 6. Distribution of Modeled Flow at Key Points on the Columbia River for Upper Columbia River Fishery Operations, with 35 kcfs Overflow for Fish at Libby.

	Jan (cfs)	Feb (cfs)	March (cfs)	April (cfs)	May (cfs)	June (cfs)	July (cfs)	August (cfs)
Columbia River at Birchbank, BC								
VARQ FC 35	62,800	61,300	59,900	46,000	99,100	141,000	123,600	103,900
Standard FC 35	71,700	64,900	62,400	46,800	94,900	138,200	120,800	101,600
Difference	-8,900	-3,600	-2,500	-800	4,200	2,800	2,800	2,300
Columbia River at The Dalles, OR								
VARQ FC 35	145,800	175,600	229,200	234,000	326,300	378,200	221,500	154,100
Standard FC 35	155,100	181,100	230,200	235,500	325,000	372,500	218,800	151,800
Difference	-9,300	-5,500	-1,000	-1,500	1,300	5,700	2,700	2,300

Note: All flows are monthly averages from the 1928-1989 flood control hydro-regulations.

4.2 Discharge-Frequency Analysis at Birchbank, BC

System Flood Control

The results of the frequency analysis for flow on the Columbia River at Birchbank, BC are shown in Table 7 and graphically depicted in Figure 11. The probability that a flood flow of 225,000 cfs will be equaled or exceeded in a given year is six percent for the Standard FC and seven percent for VARQ FC hydro-regulations. The frequency curves for Standard FC and VARQ FC begin to converge in the neighborhood of one-percent exceedance. This feature reflects the gradual merging of VARQ FC and Standard FC procedures for above normal runoff conditions at Libby. In the modeling for Standard FC hydro-regulations, a flood flow of 225,000 cfs (six percent-chance-exceedance) was exceeded only once during the 1928-1989 period. That flood flow on June 1948 was calculated at 240,000 cfs. In the VARQ FC hydro-regulations, a flood flow of 225,000 cfs (seven percent exceedance) was exceeded two times during the same period. The first flood flow on June 1948 was calculated at 254,900 cfs, while the second flood flow on July 1954 was calculated at 226,100 cfs.

Table 7. Peak 1-Day Discharge Frequency Analysis at Birchbank for Standard FC and VARQ FC.

Exceedance Frequency (%)	Standard FC (cfs)	VARQ FC (cfs)	Difference (cfs)
99	93,600	95,100	1,500
50	162,500	167,000	4,500
20	191,900	199,100	7,200
10	208,400	217,600	9,200
2	239,000	242,000	3,000
1	250,000	251,000	1000
0.5	261,000	261,000	0
0.2	274,000	274,000	0

Upper Columbia River Fishery Operations

Tables 8 and 9 denote peak 1-day discharges for the selected ten years at Birchbank based on Upper Columbia River fishery operations at Hungry Horse and Libby Projects, and also 25 kcfs and 35 kcfs fish flows at Libby Project, respectively. Current powerhouse capacity at Libby is 25 kcfs, and 35 kcfs represents 10 kcfs of additional outflow at Libby. For the ten years selected for analysis of fishery operations, VARQ FC 25 compared to Standard FC 25 shows a difference to Birchbank of the peak 1-day flow of 16,000 cfs for 1948 and 18,800 cfs for 1986. For the ten selected years, VARQ FC 35 compared to Standard FC 35 shows a difference to Birchbank of the peak 1-day flow of 14,400 cfs in 1948 and 16,800 cfs in 1968.

Table 8. Peak 1-Day Discharges (cfs) at Birchbank for Upper Columbia River Fishery Operations with 25 kcfs Overflow for Fish at Libby.

	1933	1948	1949	1955	1968	1971	1975	1981	1986	1989
VARQ FC 25	201,900	254,900	121,200	207,400	186,400	190,100	177,200	183,900	172,400	137,600
Standard FC 25	199,900	238,900	115,600	209,900	186,300	183,500	173,700	183,000	191,200	130,000
Difference	2,000	16,000	5,600	-2,500	100	6,600	3,500	900	-18,800	7,600

Table 9. Peak 1-Day Discharges (cfs) at Birchbank for Upper Columbia River Fishery Operations with 35 kcfs Overflow for Fish at Libby.

	1933	1948	1949	1955	1968	1971	1975	1981	1986	1989
VARQ FC 35	203,100	254,900	121,200	207,400	186,400	190,100	177,200	183,900	172,400	137,600
Standard FC 35	201,400	240,500	122,900	209,800	203,200	187,500	178,000	181,900	177,900	130,000
Difference	1,700	14,400	-1,700	-2,400	-16,800	2,600	-800	2,000	-5,500	7,600

4.3 Discharge-Frequency Analysis at The Dalles

System Flood Control

The results of the frequency analysis for flow on the Columbia River at The Dalles, OR are shown in Table 10 and graphically depicted in Figure 12. For comparison, the unregulated frequency curve is also depicted in Figure 12. The use of VARQ at The Dalles shows a 2 percent increase in peak 1-day discharge. The chance that a flood level flow of 450,000 cfs would be equaled or exceeded in a given year increases from forty percent for Standard FC to forty-three percent for VARQ FC. The Standard FC and VARQ FC frequency curves converge in the neighborhood of one-percent exceedance. This feature reflects the gradual merging of VARQ and Standard FC procedures at both Libby and Hungry Horse Projects for above-normal runoff conditions.

Table 10. Peak 1-Day Discharge Frequency Analysis at The Dalles for Standard FC and VARQ FC.

Exceedance Frequency (%)	Standard FC (cfs)	VARQ FC (cfs)	Difference (cfs)
99	205,000	211,000	6,000
90	286,000	292,000	6,000
70	351,000	360,000	9,000
50	401,000	411,000	10,000
20	490,000	501,000	11,000
10	541,000	550,000	9,000
2	635,000	639,000	4,000
1	670,000	670,000	0
0.5	703,000	703,000	0
0.2	743,000	743,000	0

Upper Columbia River Fishery Operations

Tables 11 and 12 respectively denote peak 1-day discharges at The Dalles for the ten years selected for analysis of fishery operations. The tables are based on Upper Columbia River fishery operations at Hungry Horse and Libby Projects, and also 25 kcfs and 35 kcfs additional fish flows at Libby Project, respectively. For the ten selected years, VARQ FC 25 compared to Standard FC 25 at The Dalles would result in a peak 1-day flow increase of 13,800 cfs in 1948 and 8,800 cfs in 1981. For the same ten years, VARQ FC 35 compared to Standard FC 35 at The Dalles would result in a peak 1-day flow increase of 9,000 cfs in 1948 and 11,300 cfs in 1981.

Table 11. Peak 1-Day Discharges (cfs) at The Dalles for Upper Columbia River Fishery Operations with 25 kcfs Overflow for Fish at Libby.

	1933	1948	1949	1955	1968	1971	1975	1981	1986	1989
VARQ FC 25	458,100	775,100	409,900	405,400	365,500	549,200	488,700	399,200	434,500	383,700
Standard FC 25	453,800	761,300	403,900	406,800	359,400	541,300	481,000	390,400	425,800	376,200
Difference	4,300	13,800	6,000	-1,400	6,100	7,900	7,700	8,800	8,700	7,500

Table 12. Peak 1-Day Discharges (cfs) at The Dalles for Upper Columbia River Fishery Operations with 35 kcfs Overflow for Fish at Libby.

	1933	1948	1949	1955	1968	1971	1975	1981	1986	1989
VARQ FC 35	459,600	775,100	411,400	406,800	366,200	548,000	489,800	401,200	434,500	384,000
Standard FC 35	455,400	766,100	403,200	406,100	359,800	541,800	483,400	389,900	434,300	375,400
Difference	4,200	9,000	8,200	700	6,400	6,200	6,400	11,300	200	8,600

4.4 Flow Duration Analysis at The Dalles.

System Flood Control

A volume duration analysis was conducted to look into the impacts to flow over time at The Dalles. Time periods from one day through 120 days were selected for the analysis. Flow values represent the highest running-mean flow for a specific duration in a given year. Figure 13 depicts the 60-year average of these values for Standard FC and VARQ FC, and for reference purposes also unregulated flows. As shown on the curves, there would be a slight increase in mean flow for the VARQ FC operation, less than 10,000 cfs for each increment.

Upper Columbia River Fishery Operations

Tables 13 and 14 respectively denote flow duration information at The Dalles based on Upper Columbia River fishery operations at Hungry Horse and Libby Projects, and also 25 kcfs and 35 kcfs fish flows at Libby Project, respectively. The information in both tables is based on the ten years selected for analysis of fishery operations from the record 1929-1989. Both tables show the flow duration impacts at The Dalles due to VARQ FC operations, when Upper Columbia River fishery flows and additional outflow at Libby Project are held constant.

Table 13. Flow Duration Analysis at The Dalles for Upper Columbia River Fishery Operations with 25 kcfs Overflow for Fish at Libby Project.

Percent Equaled or Exceeded (%)	Standard FC 25 (cfs)	VARQ FC 25 (cfs)	Difference (cfs)
99	84,000	84,000	0
90	97,000	97,000	0
70	121,000	119,000	-2,000
50	156,000	153,000	-3,000
20	270,000	271,000	1,000
10	345,000	348,000	3,000
2	476,000	480,000	4,000
1	520,000	524,000	4,000
0.5	597,000	618,000	21,000
0.2	690,000	697,000	7,000

Table 14. Flow Duration Analysis at The Dalles for Upper Columbia River Fishery Operations with 35 kcfs Overflow for Fish at Libby Project.

Percent Equaled or Exceeded (%)	Standard FC 35 (cfs)	VARQ FC 35 (cfs)	Difference (cfs)
99	84,000	84,000	0
90	97,000	97,000	0
70	120,000	119,000	-1,000
50	156,000	153,000	-3,000
20	271,000	271,000	0
10	346,000	348,000	2,000
2	476,000	480,000	4,000
1	520,000	524,000	4,000
0.5	597,000	618,000	21,000
0.2	690,000	697,000	7,000

4.5 System Hydro-Regulation of Historic Floods

Figures 14 and 15 demonstrate respectively the effects of VARQ on the distribution of flows at The Dalles for two notable floods, 1948 and 1974. The flood of 1948 is substantial not only because it has the highest unregulated peak since 1868, but also because it involved a large water supply forecast error and the resulting floodwaters destroyed the city of Vanport, Oregon, located downstream of Portland. The flood of 1974 is substantial because its January-July and April-August runoff volume would exceed all years in the 1929-1989-study period and its unregulated peak is second only to 1948. For both years, there is very little difference at The Dalles between the Standard FC and VARQ FC hydro-regulations. This is due in large part to the similarity of flood control operations for VARQ and Standard FC alternatives for above normal runoff conditions. The re-regulating effects of Grand Coulee and the natural attenuation of flow also contribute to minimize the influence of VARQ FC at The Dalles. For comparison, the unregulated flow hydrographs are also depicted in Figures 14 and 15 for the 1948 and 1974 floods respectively.

4.6 Results of System Hydro-Regulations at Vancouver, WA.

System Flood Control

Although not determined from sophisticated hydraulic modeling, the effect of VARQ in the Portland/Vancouver harbor can be estimated using the SSARR model. SSARR uses a simple stage-discharge rating table derived from historical flows. Figure 16 is the stage frequency curve for Vancouver, WA. The effects of VARQ show a difference of 0.2 ft on average for the 1929-1989 hydro-regulations. The chance that a stage of 16 ft (flood stage) would be equaled or exceeded in a given year increases from 44 percent for Standard FC to 46 percent for VARQ. Again, the frequency curves converge, in this case, as exceedance probabilities approach five percent.

Upper Columbia River Fishery Operations

Tables 15 and 16 respectively denote peak 1-day elevations at Vancouver based on Upper Columbia River fishery operations at Hungry Horse and Libby Projects, and also 25 kcfs and 35 kcfs fish flows at Libby Project, respectively. The information in both tables is based on the ten years selected for analysis of fishery operations from the period of record 1929-1989. VARQ FC 25 as compared to Standard FC 25 at Vancouver shows a peak 1-day stage increase of 0.43 ft that would occur in 1948. The average absolute difference for all values is about 0.3 ft.

VARQ FC 35 as compared to Standard FC 35 at Vancouver shows a peak 1-day stage increase of 0.40-ft that would have occurred in 1981; which corresponds to a small freshet on the Columbia River. The average absolute difference for all values is about 0.2 ft.

Table 15. Peak 1-Day Elevations (ft) at Vancouver for Upper Columbia River Fishery Operations with 25 kcfs Overflow for Fish at Libby Project.

	1933	1948	1949	1955	1968	1971	1975	1981	1986	1989
VARQ FC 25	14.97	25.08	13.29	13.12	12.16	18.20	16.17	12.56	14.19	12.13
Standard FC 25	14.86	24.67	13.05	13.19	11.97	17.97	15.87	12.23	13.86	11.82
Difference	0.11	0.43	0.24	-0.07	0.19	0.23	0.30	0.33	0.33	0.31

Table 16. Peak 1-Day Elevations (ft) at Vancouver for Upper Columbia Fishery Operations with 35 kcfs Overflow for Fish at Libby Project.

	1933	1948	1949	1955	1968	1971	1975	1981	1986	1989
VARQ FC 35	15.07	25.08	13.33	13.17	12.16	18.20	16.21	12.61	14.19	12.13
Standard FC 35	14.90	24.80	13.03	13.18	11.97	17.97	15.96	12.21	14.19	11.82
Difference	0.17	0.28	0.30	-0.01	0.19	0.23	0.25	0.40	0	0.31

5. VARQ EFFECTS AT GRAND COULEE PROJECT

5.1 Grand Coulee Flood Control Draft

The Grand Coulee flood control draft requirement is a function of the expected April-August unregulated runoff at The Dalles and the storage space upstream of The Dalles that is available on May 1. Upstream storage space is composed of space at Mica, Arrow, Libby, Duncan, Hungry Horse, Kerr, Noxon, Albeni Falls, Dworshak, Brownlee and John Day. The unregulated April-August runoff at The Dalles is adjusted downward for the total amount of upstream storage available on May 1 at these projects. The adjusted runoff is then used with the Grand Coulee SRD to determine the flood control draft requirement.

5.2 General Effects of VARQ at Grand Coulee

VARQ at Libby and Hungry Horse Projects would impact the flood control draft requirements at Grand Coulee by reducing the amount of available upstream storage space on May 1. This would have the effect of increasing the flood control draft at Grand Coulee Project in normal to below-normal years as measured at The Dalles, OR. The differences in the April 30 Grand Coulee Project draft requirements for a variety of runoff conditions are shown in Table 17. Data for this table are hypothetical and were derived by assuming a uniform water supply forecast across the basin. Three separate calculations were made. The first shows the difference in draft at Grand Coulee Project caused by implementing VARQ at Libby Project, the following section shows the difference caused by implementing VARQ at Hungry Horse Project, and the last section depicts the difference in draft required by implementing VARQ at both Libby and Hungry Horse Projects.

It is important to understand that the difference in flood control draft at Grand Coulee Project would not equal the net change in draft at Libby and Hungry Horse Projects caused by VARQ. This feature can be seen be examining the difference in storage drafts for Libby and Hungry Horse Projects shown in Table 3 and the differences at Grand Coulee Project shown in Table 17. For example, the VARQ procedure at Libby Project causes 1525 kaf less draft than the Standard FC procedure for a 100 percent of average runoff forecast (Table 3), whereas the difference at Grand Coulee Project would be only 183 kaf of extra draft (Table 17). Grand Coulee Project would compensate for only a portion of the change in required space. This is due to the nature of the storage reservation diagrams (slope of the rule curves) and the limited amount of total flood control space in Grand Coulee Project in proportion to the available upstream storage capacity at the other projects.

Table 17. Comparison of Flood Control Drafts at Grand Coulee Dam for Standard FC versus VARQ FC.

Operational Scenario	Grand Coulee Apr30 FC Draft for 70% of Normal Runoff at The Dalles, OR		Grand Coulee Apr30 FC Draft for 80% of Normal Runoff at The Dalles, OR		Grand Coulee Apr30 FC Draft for 90% of Normal Runoff at The Dalles, OR		Grand Coulee Apr30 FC Draft for 100% of Normal Runoff at The Dalles, OR		Grand Coulee Apr30 FC Draft for 110% of Normal Runoff at The Dalles, OR	
	(kaf)	(ft)	(kaf)	(ft)	(kaf)	(ft)	(kaf)	(ft)	(kaf)	(ft)
Standard FC	537	1283.3	1699	1267.6	3041	1247.6	4119	1229.4	4600	1220.2
VARQ at LIB	537	1283.3	1739	1267.1	3260	1244.3	4302	1226	4600	1220.2
Difference	0	0	40	0.5	219	3.3	183	3.4	0	0
Standard FC	537	1283.3	1699	1267.6	3041	1247.6	4119	1229.4	4600	1220.2
VARQ at HGH	537	1283.3	1830	1265.8	3125	1246.3	4166	1228.5	4600	1220.2
Difference	0	0	131	1.8	84	1.3	47	0.9	0	0
Standard FC	537	1283.3	1699	1267.6	3041	1247.6	4119	1229.4	4600	1220.2
VARQ at LIB & HGH	537	1283.3	1869	1265.2	3344	1242.8	4349	1225.5	4600	1220.2
Difference	0	0	170	2.4	303	4.8	230	3.9	0	0

5.3 Hydro-Regulation Results: Differences in Elevations for Grand Coulee Project

System Flood Control

The results of the Standard FC and VARQ FC hydro-regulations were compared to determine the general effect of VARQ on Grand Coulee reservoir elevations. Monthly average elevations for the January through August period are shown in Table 18. In general, the average monthly elevations for the VARQ FC simulations for the period 1929-1989 are lower between April and May than the Standard FC simulations. The maximum differences occur in the months April and May where the average elevation for the VARQ simulations was 1.5 ft lower. This is less than two percent of the reservoir space available for flood control regulation between elevation 1208 (minimum pool) and 1290 ft (full pool). May is the first month of refill following the flood control evacuation that ends on April 30. Based on the 60-year reservoir simulations, the mean difference of the April elevations at Grand Coulee Project in the Standard FC and VARQ FC would be 1.5 ft and the maximum difference would be 6.3 ft.

Table 18. Mean Differences in Monthly Mean Elevations for Grand Coulee for Standard FC and VARQ FC.

Operational Scenario	January (ft)	February (ft)	March (ft)	April (ft)	May (ft)	June (ft)	July (ft)	August (ft)
Standard FC	1290.0	1288.5	1275.2	1253.2	1248.2	1273.1	1289.2	1290.0
VARQ FC	1290.0	1288.5	1274.5	1251.7	1246.7	1273.4	1289.3	1290.0
Mean Difference	0	0	0.7	1.5	1.5	0.3	0.1	0.0
% of FC space (1208-1290 ft)	0	0	1.1	1.8	1.8	0.4	0.2	0.0

Upper Columbia River Fishery Operations

Tables 19 and 20 respectively denote mean differences in monthly mean pool elevations at Lake Roosevelt (Grand Coulee Dam) based on Upper Columbia River fishery operations at Hungry Horse and Libby Projects, and also 25 kcfs and 35 kcfs fish flows at Libby Project. The information in both tables is based on the ten years selected for analysis of fishery operations from the period of record 1929-1989, and hence cannot be compared directly to the 60-year data base in Table 18. VARQ FC 25 compared to Standard FC 25 would have differences in pool elevation for the months March through May. The maximum differences occur in the months April and May where the average elevation for the VARQ simulations was respectively 3.4 and 3.3 ft lower. This is about four percent of the reservoir space available for flood control regulation between elevation 1208 (minimum pool) and 1290 ft (full pool). Table 20 provides similar results for VARQ FC 35 compared to Standard FC 35.

Table 19. Mean Differences in Monthly Mean Elevations for Grand Coulee for Upper Columbia Fishery Operations with 25 kcfs Overflow for Fish at Libby Dam.

Operational Scenario	Jan (ft)	Feb (ft)	March (ft)	April (ft)	May (ft)	June (ft)	July (ft)	August (ft)
Standard FC 25	1290.0	1288.9	1274.4	1249.3	1242.4	1273.2	1289.2	1290.0
VARQ FC 25	1290.0	1288.9	1273.0	1245.9	1239.1	1272.5	1289.1	1290.0
Mean Difference	0	0	1.4	3.4	3.3	0.7	0.1	0.0
% of space (1208-1290 ft)	0	0	1.9	4.5	3.9	0.9	0.2	0.0

Table 20. Mean Differences in Monthly Mean Elevations for Grand Coulee Project for Upper Columbia Fishery Operations with 35 kcfs Overflow for Fish at Libby Dam.

Operational Scenario	Jan (ft)	Feb (ft)	March (ft)	April (ft)	May (ft)	June (ft)	July (ft)	August (ft)
Standard FC 35	1290.0	1288.9	1274.3	1249.3	1242.3	1273.3	1289.2	1290.0
VARQ FC 35	1290.0	1288.9	1273.0	1245.9	1239.1	1272.8	1289.2	1290.0
Mean Difference	0	0	1.3	3.4	3.2	0.5	0	0.0
% of space (1208-1290 ft)	0	0	1.8	4.5	3.7	0.7	0	0.0

5.4 Hydro-Regulation Results: Elevation-Frequency Relationship at Grand Coulee

System Flood Control

An elevation-frequency analysis was conducted to evaluate the effects of VARQ FC on Grand Coulee minimum reservoir elevations. The results are shown in Table 21 and graphically depicted in Figure 17. This relationship represents the frequency of the maximum flood control draft (minimum reservoir elevation) achieved during the winter period for each year in the 1928-1989 Standard FC and VARQ FC hydro-regulations. The maximum difference in frequency occurs when requiring a draft to elevation 1220 ft, where the chance this elevation will be reached in a given year increases from 20 percent for Standard FC to 30 percent for VARQ FC. Simply put this means that on average elevation 1220 ft would be reached 30 percent utilizing VARQ FC at Hungry Horse and Libby Projects versus 20 percent for a Standard FC operation. This is mainly a function of the shape of Grand Coulee's storage reservation diagram, which limits the flood control draft to elevation 1220 ft for parameter values (runoff at The Dalles adjusted for upstream storage space) between 80,000 and 95,000 kaf. The frequency curves converge below elevation 1220 ft reflecting the merging of the VARQ FC and Standard FC procedures at Libby and Hungry Horse Projects for above-normal runoff conditions which would eliminate any differences in flood control requirements at Grand Coulee Project. The frequency curves also would converge at elevation 1283.3 ft.

Table 21. Elevation-Frequency Relationship at Grand Coulee Project for Standard FC and VARQ FC.

Percent Chance of Non-Exceedance (%)	Standard FC (ft)	VARQ FC (ft)	Difference (ft)
99	1283.3	1283.3	0
80	1275.9	1274.1	1.8
60	1244.5	1240.2	4.3
40	1230.1	1226.5	3.6
30	1220.3	1220.2	0.1
20	1220.2	1220.2	0
10	1216.7	1216.7	0
2	1208	1208	0
1	1208	1208	0
0.5	1208	1208	0
0.2	1208	1208	0

Upper Columbia River Fishery Operations

Tables 22 and 23 respectively denote the maximum flood control draft as defined by minimum 1-day pool elevations at Lake Roosevelt (Grand Coulee Dam) based on Upper Columbia River fishery operations at Hungry Horse and Libby Projects, and also 25 kcfs and 35 kcfs fish flow at Libby Project, respectively. The information in both tables is based on the ten years selected for analysis of fishery operations from the period of record 1929-1989, and hence cannot be compared directly to the 60-year data base in Table 21. It is important to note that Tables 22 and 23 are based on individual years compared where Table 21 presents a statistical analysis of all 60 years. Therefore results between VARQ FC and Standard FC and fish flow alternatives cannot be compared directly. Table 22 shows that VARQ FC 25 would result in greater drafts than Standard FC 25 for eight of the ten years studied for system impacts of Upper Columbia River fishery operations. For 1981, the minimum pool elevation would reach 8.0 ft lower for VARQ FC 25 than for Standard FC 25. Table 23 denotes nearly identical results for 35 kcfs outflow at Libby Project.

Table 22. Minimum 1-Day Pool Elevations (ft) at Grand Coulee Project for Upper Columbia Fishery Operations with 25 kcfs Overflow for Fish at Libby Project.

	1933	1948	1949	1955	1968	1971	1975	1981	1986	1989
VARQ FC 25	1220.2	1220.2	1225.6	1258.3	1242.0	1212.6	1220.2	1256.5	1239.6	1229.9
Standard FC 25	1220.2	1222.1	1232.1	1263.1	1244.4	1216.2	1220.2	1264.5	1245.0	1234.5
Difference	0	-1.9	-6.5	-4.8	-2.4	-3.6	0	-8.0	-5.4	-4.6

Table 23. Minimum 1-Day Pool Elevations (ft) at Grand Coulee Project for Upper Columbia Fishery Operations with 35 kcfs Overflow for Fish at Libby Project.

	1933	1948	1949	1955	1968	1971	1975	1981	1986	1989
VARQ FC 35	1220.2	1220.2	1225.6	1258.3	1242.0	1212.6	1220.2	1256.5	1239.6	1229.9
Standard FC 35	1220.2	1222.1	1232.1	1263.1	1244.4	1216.2	1220.2	1264.5	1245.0	1234.5
Difference	0	-1.9	-6.5	-4.8	-2.4	-3.6	0	-8.0	-5.4	-4.6

5.5 Hydro-Regulation Results: Duration Analysis of Grand Coulee Reservoir Elevation

System Flood Control

A duration analysis was conducted to evaluate the effect that VARQ FC operation would have on the Grand Coulee reservoir elevation over time. Figure 18 denotes the results of this duration analysis. The time span covers both the winter drawdown period and the spring refill season, January through August. Daily elevation data from the Standard FC and VARQ FC hydro-regulations were used in the analysis. Figure 18 shows the inputs that VARQ FC at Libby and Hungry Horse Projects have on evacuation and refill of the reservoir, which is in the neighborhood of a one to two percent increase in time for elevations between 1220 and 1290 ft (full pool). This represents about two to four days, on average, to the winter evacuation and spring refill cycle of the reservoir. There would be no effect between elevation 1208 (minimum pool) and 1220 ft.

5.6 Hydro-Regulation Results: Retention Time Analysis for Grand Coulee Reservoir

System Flood Control

Additionally, an analysis of retention time for water in Grand Coulee Reservoir was made for all six alternatives. Table 24 denotes the results for Standard FC and VARQ FC. The retention time is a function of both project outflow and storage above minimum pool elevation (1208 ft for Grand Coulee Project). Specifically, it is calculated by dividing monthly average storage in acre-ft by monthly average outflow in ft^3/s. To obtain retention in days, 0.504 multiplies this number. Retention time would be 6 days for May due to high project outflows and minimum pool elevations. The reverse is true for September where the retention time would be 46 days due to low project outflows and full pool elevation. The retention time for VARQ FC compared to Standard FC would be about 0.5 days less for June due to the lower pool level at Grand Coulee Project associated with VARQ FC operations during the spring refill season.

Table 24. Average Retention Time in Days for Water at Grand Coulee Project for Standard FC and VARQ FC.

Operational Scenario	April (days)	May (days)	June (days)	July (days)	August (days)	Sept (days)
Standard FC	9.77	6.44	11.73	19.07	27.34	46.25
VARQ FC	9.47	6.05	11.26	18.85	27.30	46.22
Difference	0.30	0.39	0.47	0.22	0.04	0.03

Upper Columbia River Fishery Operations

Tables 25 and 26 respectively denote the results for Standard FC and VARQ FC based on Upper Columbia River fishery operations at Hungry Horse and Libby Projects, and fish flows of 25 kcfs and 35 kcfs at Libby Project. The information in both tables is based on the ten years selected for analysis of fishery operations from the period 1929-1989, and hence cannot be compared directly to Table 24. Retention times for Tables 25 and 26 would be very similar, and uniformly denote less retention time for VARQ flood control operations.

Table 25. Average Retention Time in Days for Water at Grand Coulee Project for Upper Columbia Fishery Operations with 25 kcfs Overflow for Fish at Libby Project.

Operational Scenario	April (days)	May (days)	June (days)	July (days)	August (days)	Sept (days)
Standard FC 25	8.66	5.36	9.86	17.30	22.53	46.61
VARQ FC 25	7.85	4.72	9.45	16.96	22.13	46.33
Difference	0.81	0.64	0.41	0.34	0.40	0.28

Table 26. Average Retention Time in Days for Water at Grand Coulee Project for Upper Columbia Fishery Operations with 35 kcfs Overflow for Fish at Libby Project.

Operational Scenario	April (days)	May (days)	June (days)	July (days)	August (days)	Sept (days)
Standard FC 35	8.66	5.33	9.87	17.31	22.59	46.63
VARQ FC 35	7.84	4.72	9.49	17.01	22.16	46.30
Difference	0.82	0.61	0.38	0.30	0.43	0.33

6. SUMMARY AND CONCLUSIONS

VARQ FC was developed to improve the multi-purpose regulation of Libby and Hungry Horse Projects. In contrast to Standard FC, VARQ FC requires less system flood control space to be made available for both projects prior to spring runoff and allows outflows during refill to vary based on the water supply forecast. Normally, VARQ FC outflows will be higher than those required by the current procedures. Full system hydro-regulations for the period 1928-1989 were conducted to evaluate the impact VARQ FC has on system flood control. The results of this analysis are summarized below:

- System Flood Control: The VARQ FC operation at Libby would slightly increase the frequency of flooding on the Columbia River at Birchbank, BC, from an exceedance level of six percent for Standard FC to seven percent for VARQ FC. The frequency curves converge in the neighborhood of one-percent exceedance. For June, the monthly average flow would increase by about 6,300 cfs, from 120,900 cfs to 127,200 cfs that corresponds to a difference of about 5 percent.

- Upper Columbia Fishery Operations: For the ten years selected for analysis of fishery operations, both VARQ FC 25 and FC 35 at Birchbank and The Dalles would reshape the monthly average flow, less during the winter drawdown period and more during the spring runoff period, compared to Standard FC 25 and FC 35, respectively.

- Upper Columbia Fishery Operations: VARQ FC 25 compared to Standard FC 25 would increase peak 1-day discharges at Birchbank for nine of ten study years, and decrease in the remaining year. The average absolute difference was about 3.5 percent. However, VARQ FC 35 compared to Standard FC 35 would increase peak 1-day discharges at Birchbank for only five of ten years, and decrease in the remaining five years. The average absolute difference was about 2.9 percent.

- System Flood Control: The VARQ operation at Libby and Hungry Horse Projects would cause a small change in flow at The Dalles during the winter drawdown and spring runoff season. During the spring runoff, VARQ would add less than 10,000 cfs, on average, to the flow at The Dalles for duration of flow between one and 120 days. Libby would provide about 60 percent of the extra flow while Hungry Horse would provide 40 percent.

- System Flood Control: The chance that a flood level flow of 450,000 cfs at The Dalles, Oregon (exceedance flow for minimal damage) increases from 40 percent for Standard FC to 43 percent for VARQ FC. The frequency curves converge in the neighborhood of one-percent exceedance.

- Upper Columbia Fishery Operations: VARQ FC 25 compared to Standard FC 25 would increase peak 1-day discharges at The Dalles for nine of ten study years, and decrease for the remaining year. The average absolute difference was about 1.6 percent. VARQ FC 35 compared to Standard FC 35 would increase peak 1-day discharges at The Dalles for all ten years. The average absolute difference was about 1.4 percent.

- Upper Columbia Fishery Operations: VARQ FC 25 compared to Standard FC 25, and also VARQ FC 35 compared to Standard FC 35, show minimal differences at The Dalles. For the 0.5%-chance-exceedance event, however, VARQ FC 25 and VARQ FC 35 would increase the discharge at The Dalles by 21,000 cfs.

- System Flood Control: The impact to flooding in the Portland/Vancouver harbor from VARQ averages about 0.2 ft in peak stage for the 1929-1989 hydro-regulations. The chance that a stage of 16 ft (flood stage) would be equaled or exceeded in a given year increases from 44 percent for Standard FC to 46 percent for VARQ FC. Again, the modeled frequency curves converge, in this case as exceedance levels approach five percent.

- Upper Columbia Fishery Operations: VARQ FC 25 compared to Standard FC 25 would increase peak 1-day elevations at Vancouver for nine of ten study years, and decrease for the remaining year. The average absolute difference for all values was about 0.3 ft. VARQ FC 35 compared to Standard FC 35 would increase peak 1-day discharges at The Dalles for eight of ten study years, and not change for the remaining two years. The average absolute difference for all values was about 0.2 ft.

- System Flood Control: VARQ FC procedures would trigger additional flood control draft at Grand Coulee for normal to below normal runoff conditions at The Dalles compared to the Standard FC procedure. The additional space required at Grand Coulee is only a portion of the reduced flood control space at Libby and Hungry Horse Projects caused by VARQ. In the simulations, VARQ FC drafted less than one foot deeper, on average, than the Standard FC procedure for the months February through June. The average April 30 elevation was 1.5 ft lower in the VARQ simulations and the maximum difference was 6.3 ft. The frequency of drafting deeper increased by a few percent for most elevations with a maximum increase of about 10 percent for elevation 1220. On average, the VARQ operation would add about two to four more days to the annual flood control evacuation and refill cycle of the reservoir.

- Upper Columbia Fishery Operations: VARQ FC 25 compared to Standard FC 25 would draft Grand Coulee Dam deeper for five months between March and July. The maximum difference in average monthly elevations is for the month of April when VARQ FC 25 would be 3.4 ft deeper than Standard FC 25. VARQ FC 35 compared to Standard FC 35 would also draft Grand Coulee Dam deeper between March and June. VARQ FC 35 compared to Standard FC 35 would provide nearly the same results.

- System Flood Control: VARQ FC compared to Standard FC would yield a fifty percent exceedance value difference of about 4 ft in minimum 1-day pool elevations for 60 years of record. VARQ FC 25 compared to Standard FC 25 for individual years would also have lower minimum 1-day pool elevations at Grand Coulee Dam for eight of ten study years, with the maximum difference at 8.0 ft. VARQ FC 35 compared to Standard FC 35 provides the same results. It is important to note that comparisons between VARQ FC and Standard FC to the fish flow alternatives cannot be compared directly.

- System Flood Control: For retention time of water at Grand Coulee Reservoir, VARQ FC compared to Standard FC would have less retention time for all months between April and September. The greatest difference is about 0.5-day for June.

- Upper Columbia Fishery Operations: For VARQ FC 25 compared to Standard FC 25, the retention time would be reduced even further for the same months, with the greatest difference at 0.8-days for April. VARQ FC 35 compared to Standard FC 35 provides nearly the same results.

- System Flood Control: Generally, VARQ at Libby and Hungry Horse impact system flood control almost equally. Therefore, if VARQ were adopted at Libby only, the effect at Grand Coulee, The Dalles, and the Portland/Vancouver harbor would decrease by about 50 percent from the hydro-regulation results shown in this report.

- System Flood Control: By design, VARQ requires less storage space at the beginning of spring runoff and would increase spring and summer flows. Under-forecasting seasonal water supply volume could lead to higher than desired outflows, possibly at damaging levels. In addition, less storage space would reduce operating flexibility during refill to control excessive spill.

FIGURES

Figure 1. Columbia River Basin Map Showing Federal and Non-Federal Dams.

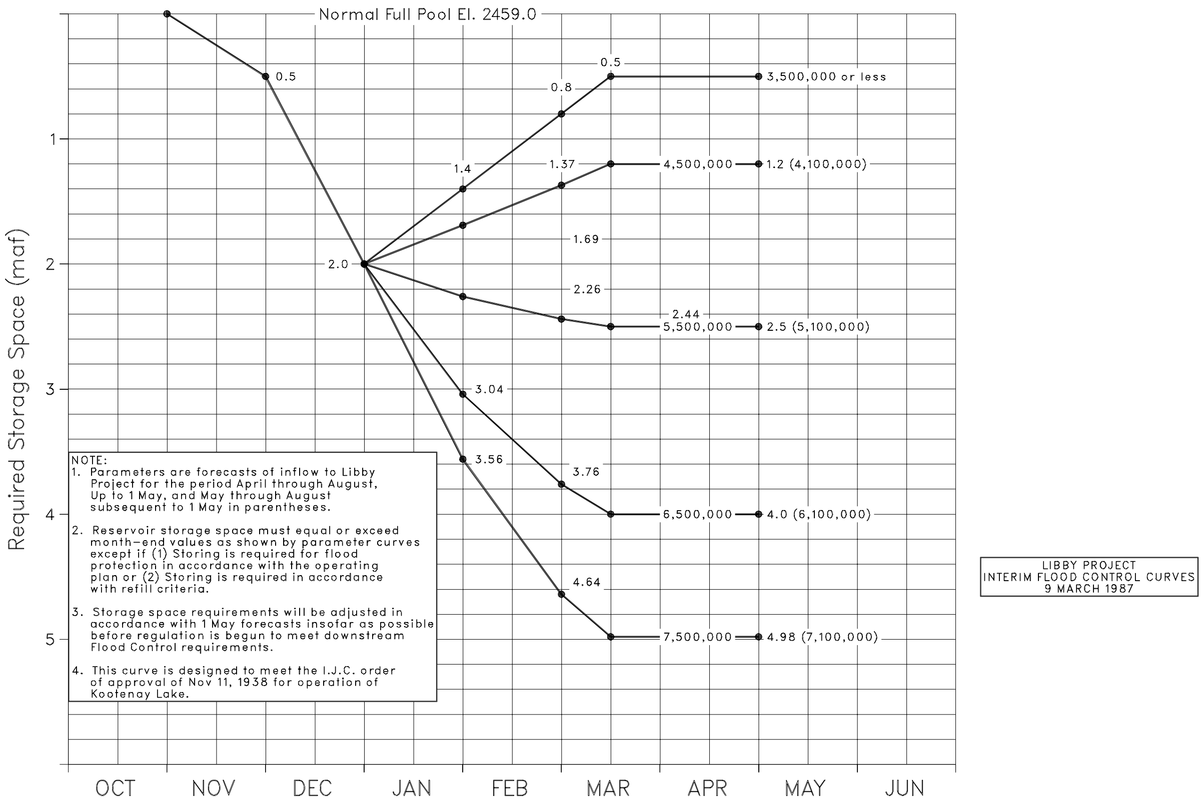

Figure 2. Columbia River Treaty Flood Control Operating Plan Storage Reservation Diagram at Libby Dam.

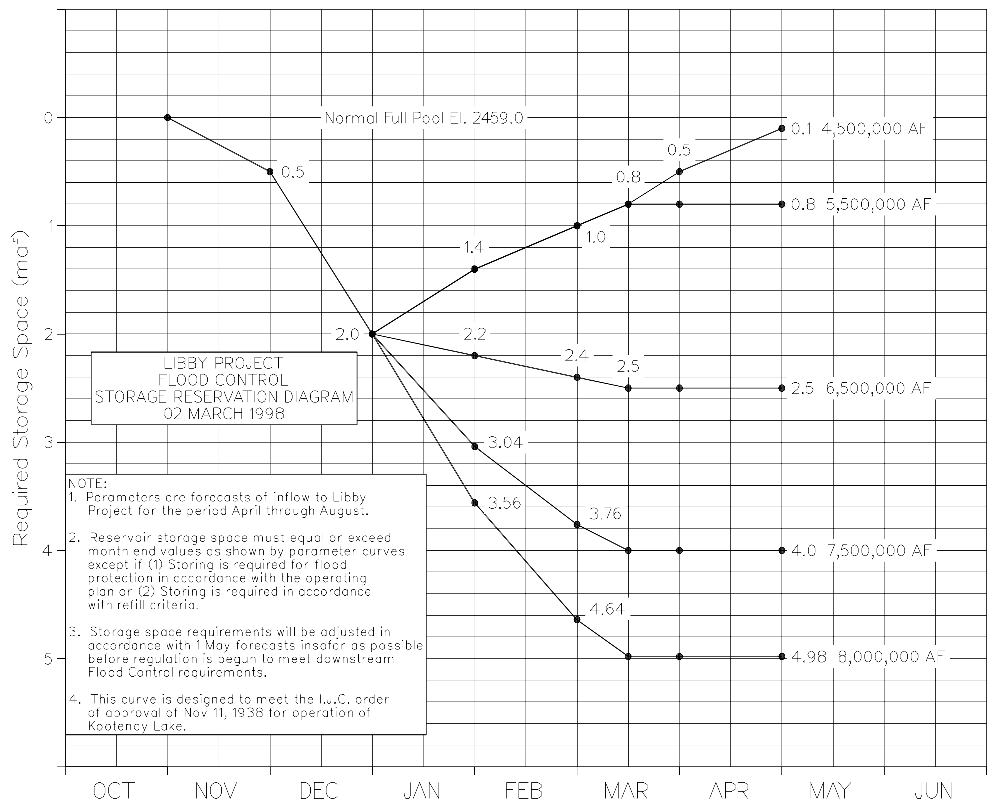

Figure 3. Draft VARQ Storage Reservation Diagram at Libby Dam.

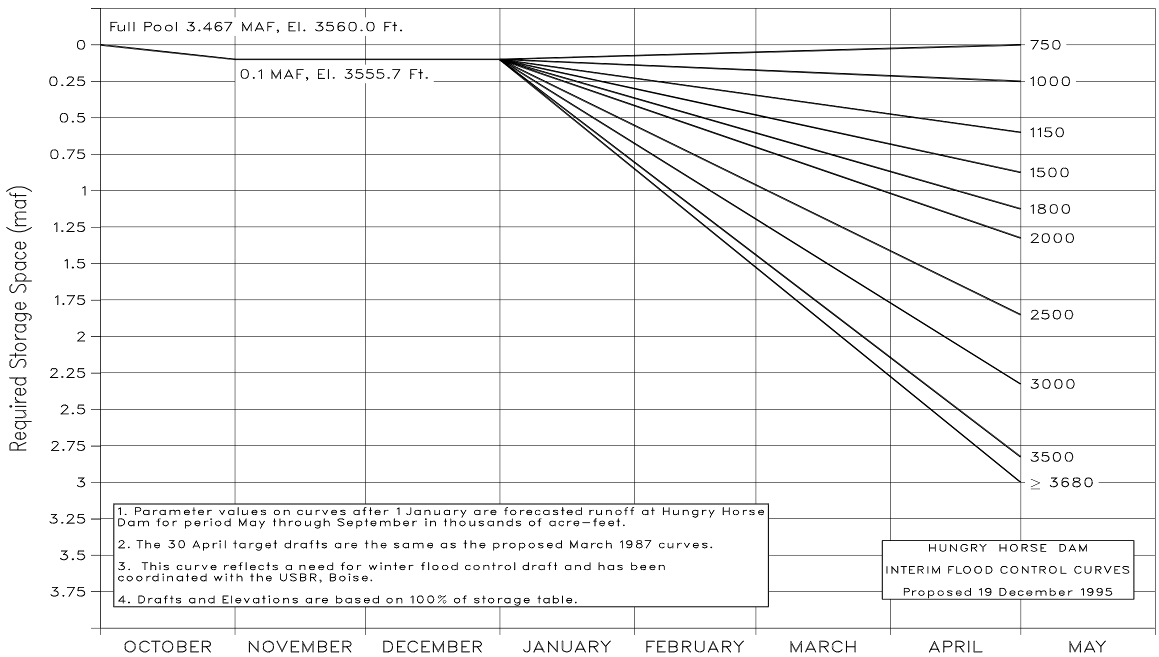

Figure 4. CRT63 Storage Reservation Diagram at Hungry Horse Dam.

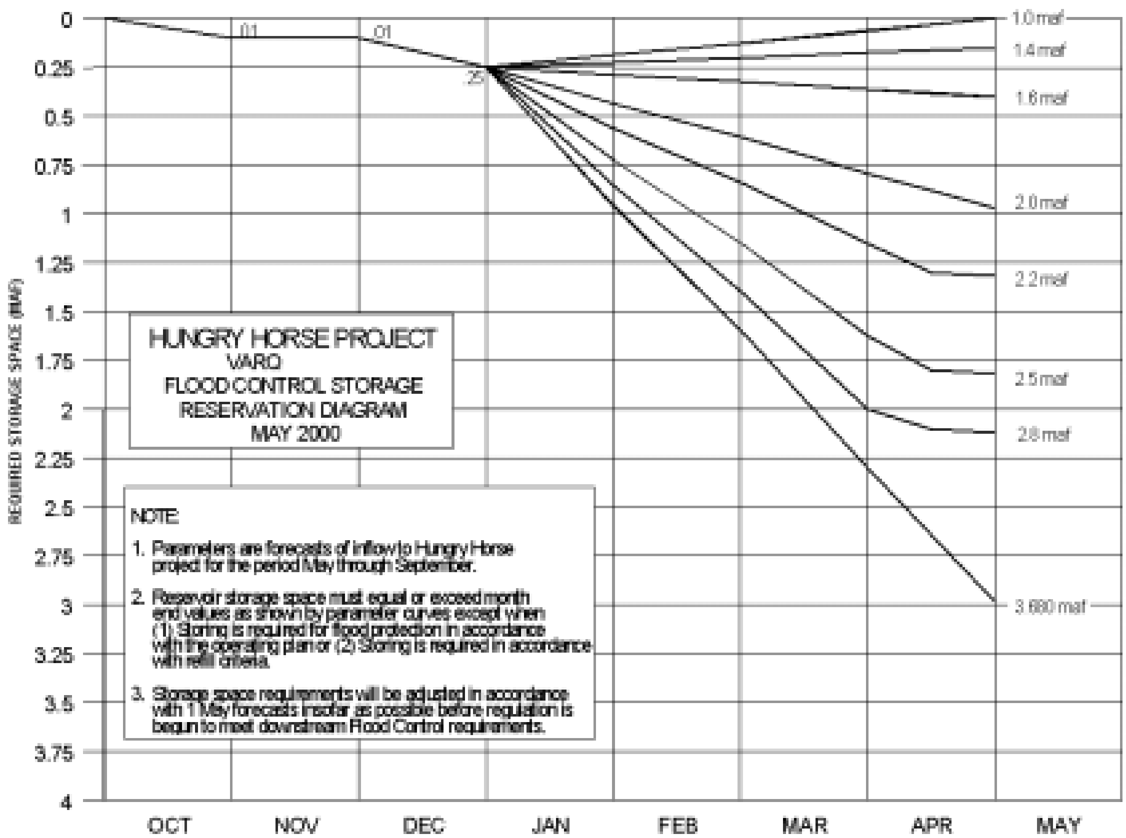

Figure 5. VARQ Storage Reservation Diagram at Hungry Horse Dam.

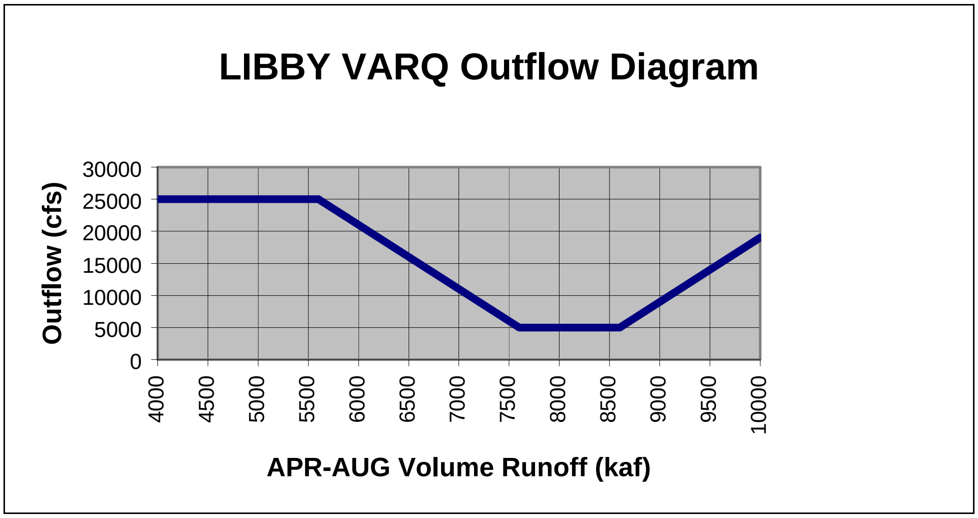

Figure 6. VARQ Minimum Average Outflows at Libby Project.

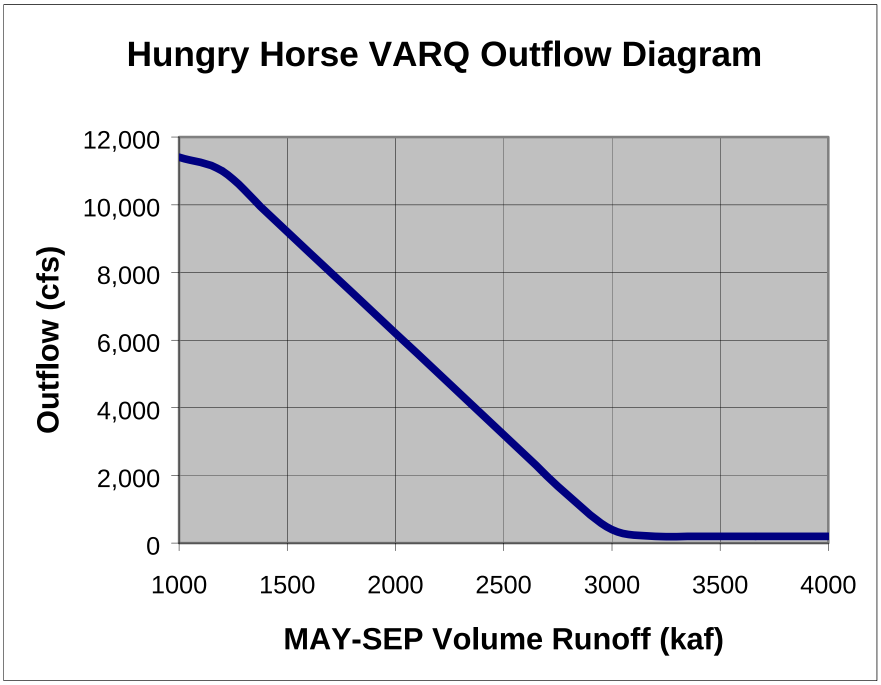

Figure 7. VARQ Minimum Average Outflows at Hungry Horse Project.

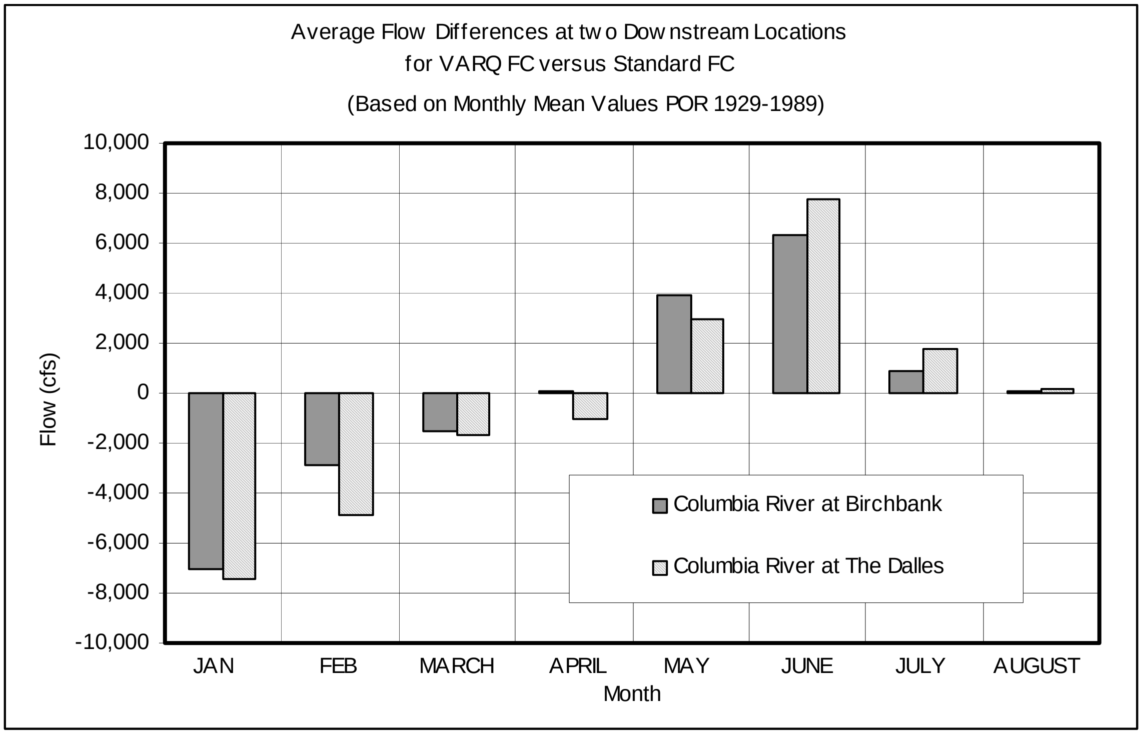

Figure 8. System Hydro-Regulation Results for Standard FC and VARQ FC.

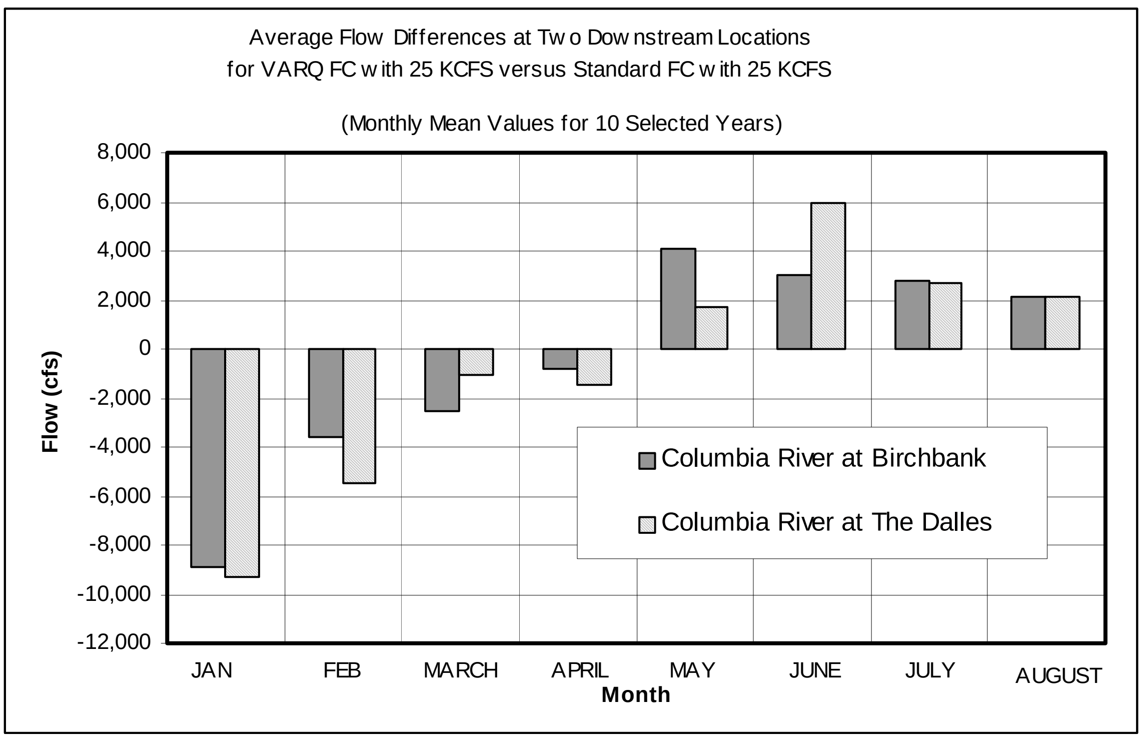

Figure 9. System Hydro-Regulation Results for Upper Columbia Fishery Operations with 25 kcfs Overflow for Fish at Libby Project.

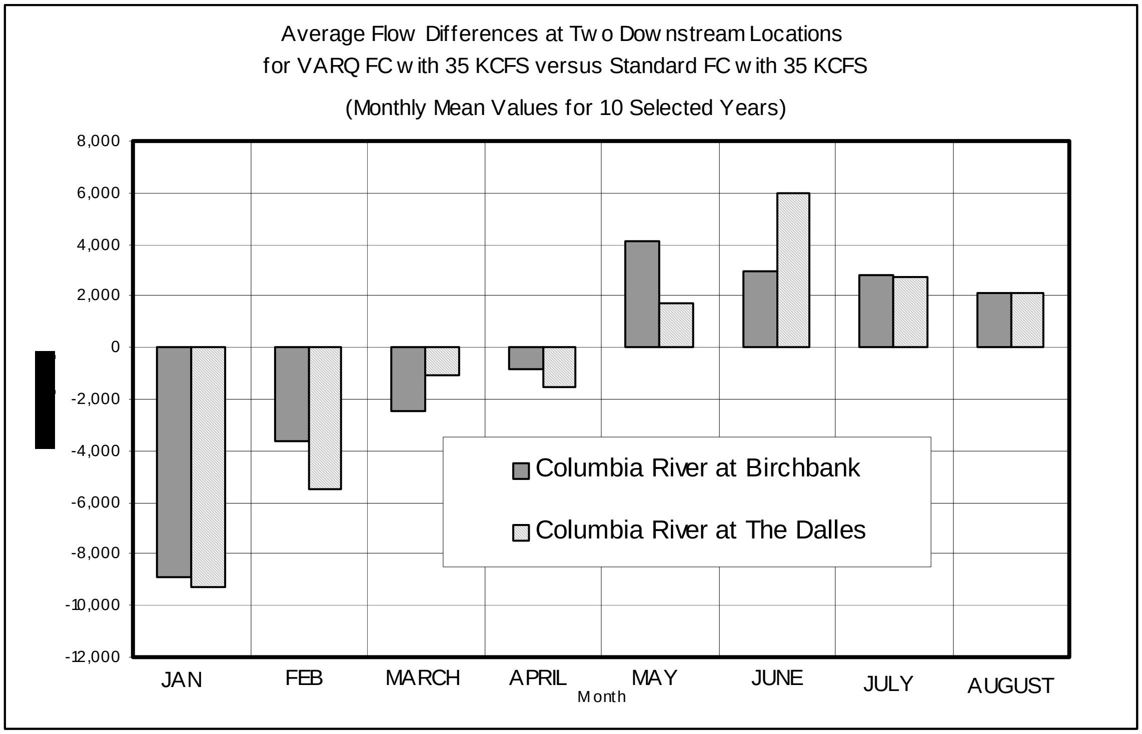

Figure 10. System Hydro-Regulation Results for Upper Columbia Fishery Operations with 35 kcfs Overflow for Fish at Libby Project.

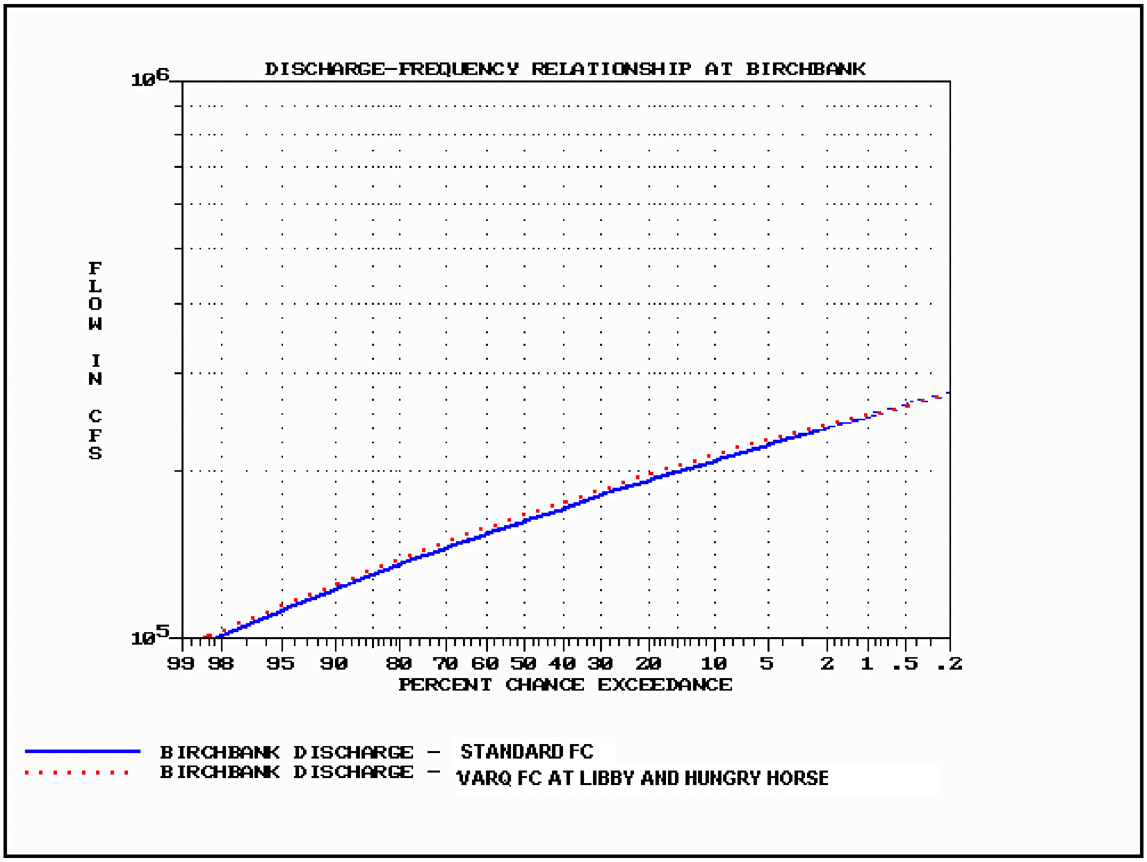

Figure 11. Peak Discharge-Frequency Relationship at Birchbank for Standard FC and VARQ FC.

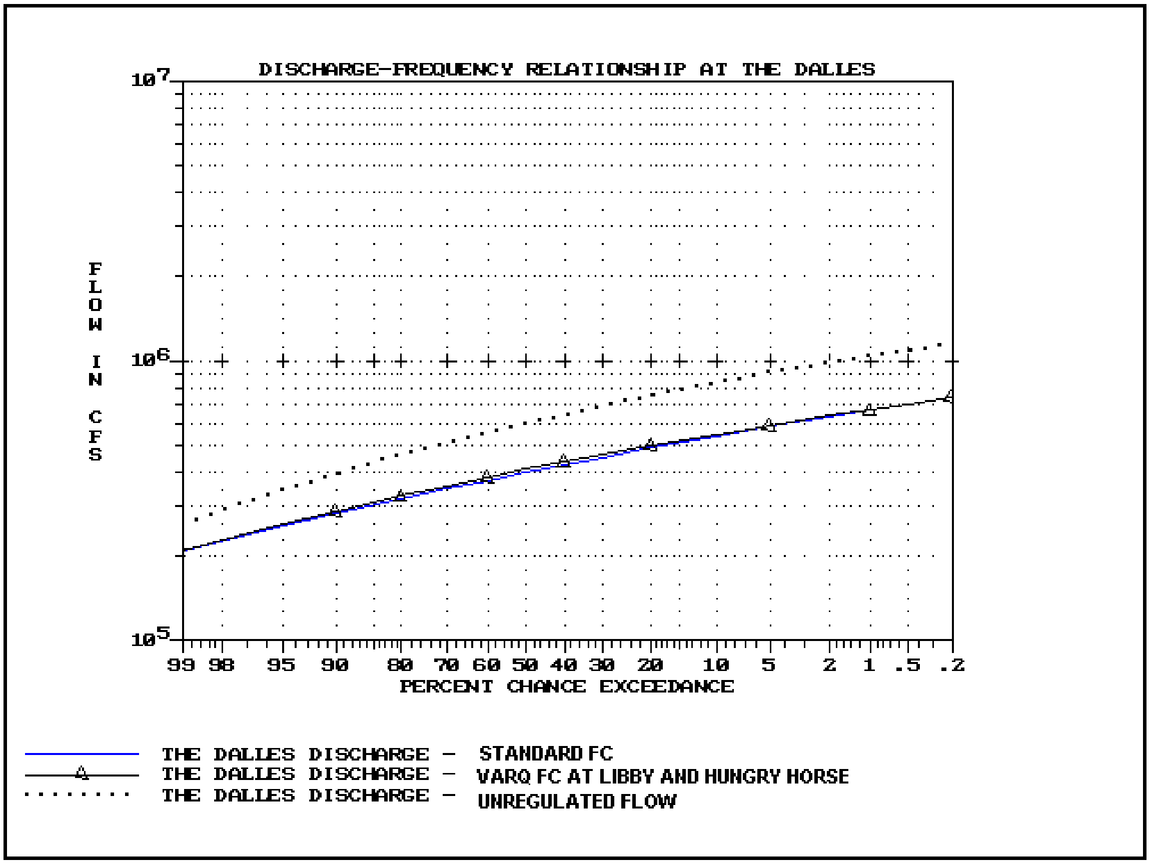

Figure 12. Peak Discharge-Frequency at The Dalles for Standard FC, VARQ FC, and Unregulated Flow.

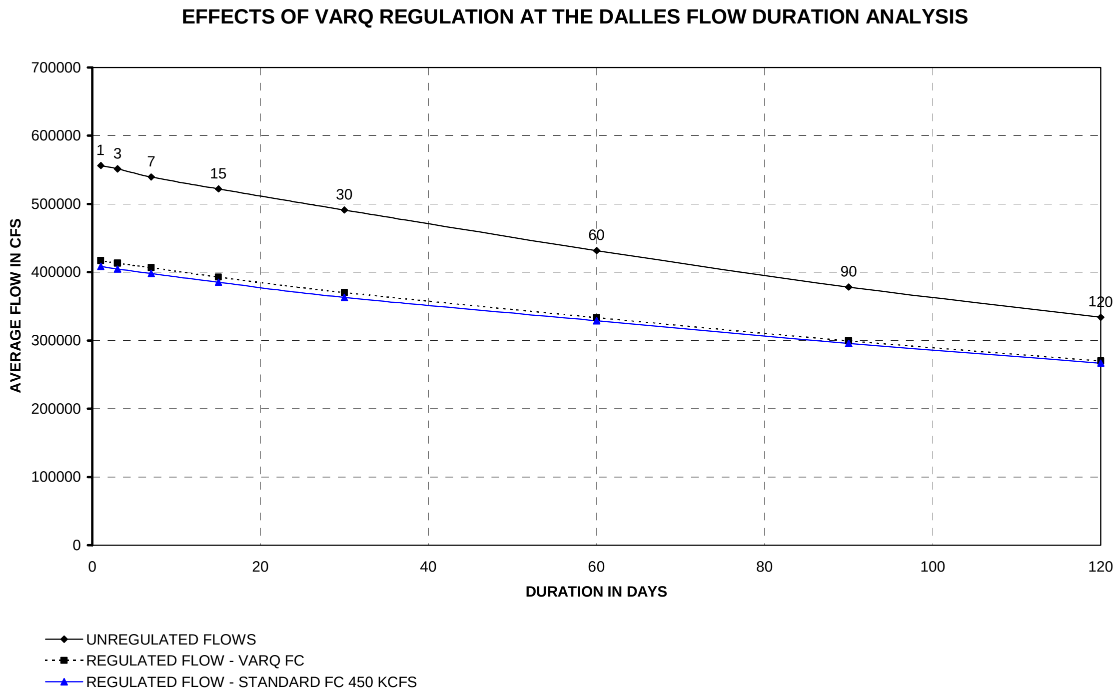

Figure 13. Flow Duration Analysis at The Dalles for Standard FC, VARQ FC, and Unregulated Flow.

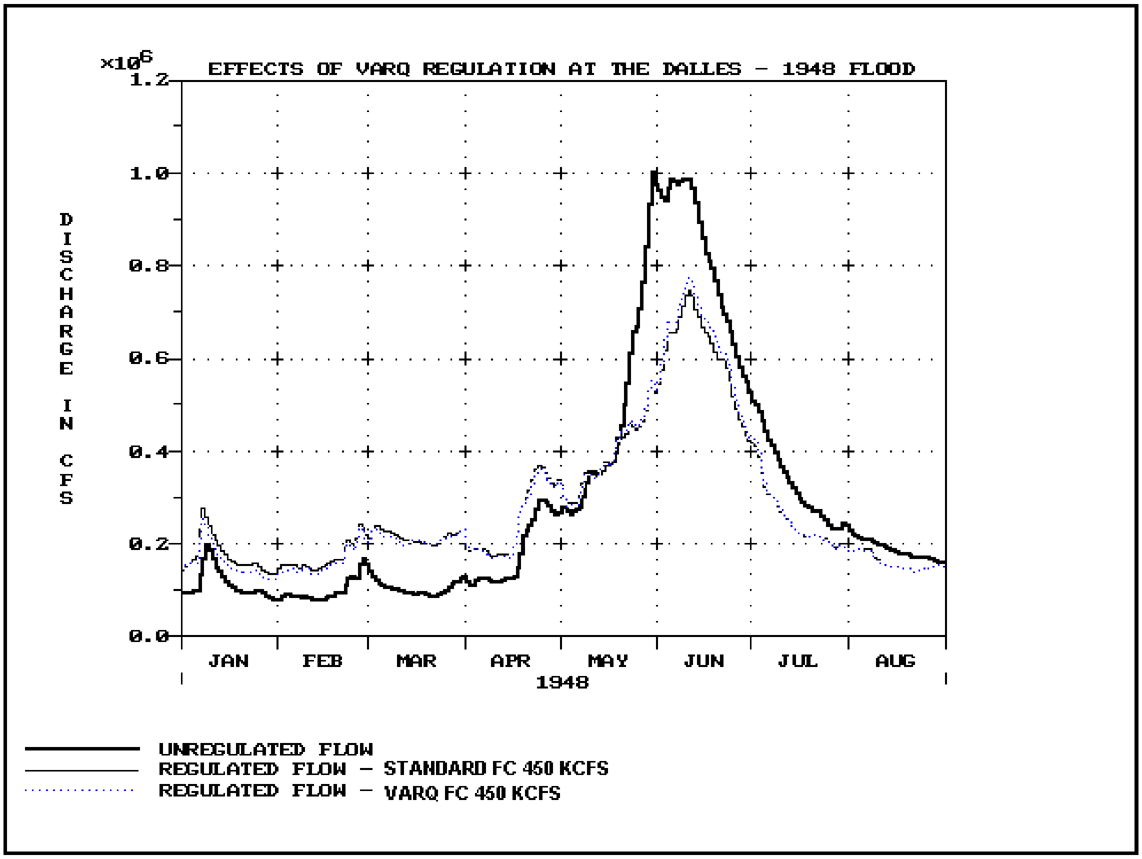

Figure 14. 1948 Flood Hydrographs at The Dalles for Standard FC, VARQ FC, and Unregulated Flow.

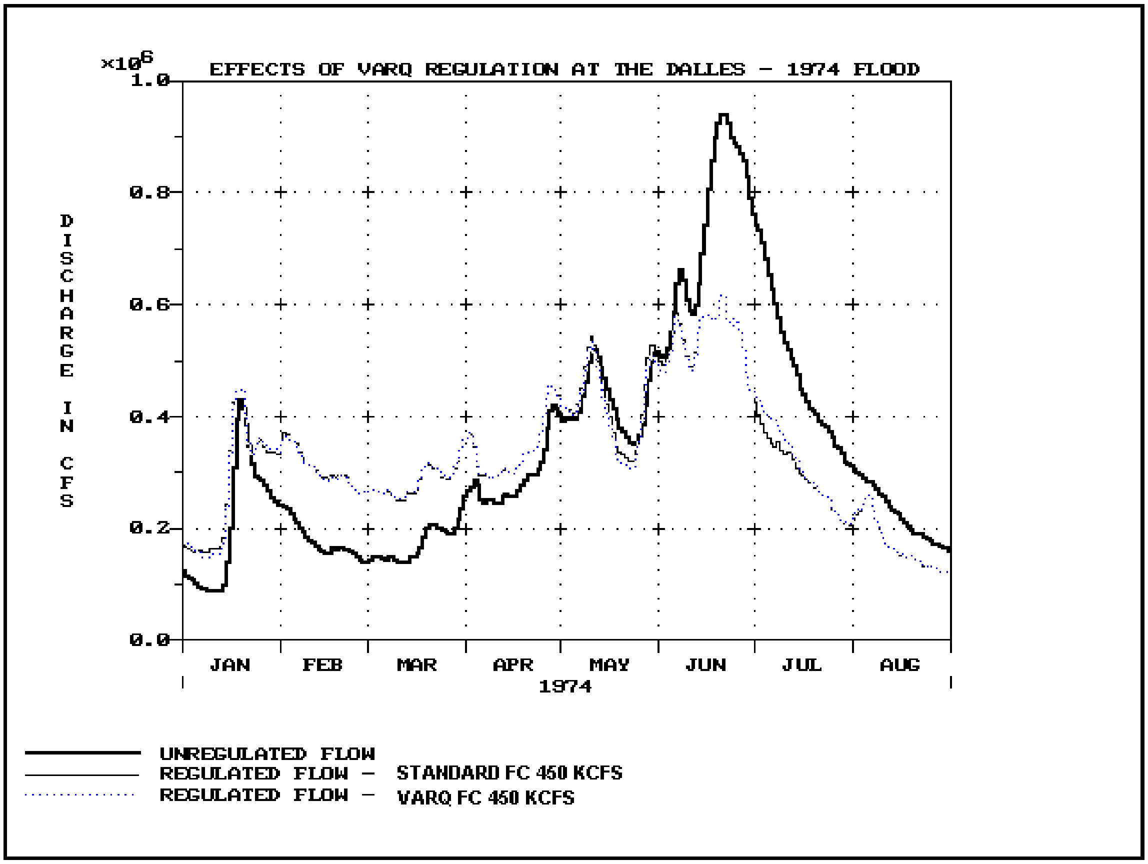

Figure 15. 1974 Flood Hydrographs at The Dalles for Standard FC, VARQ FC, and Unregulated Flow.

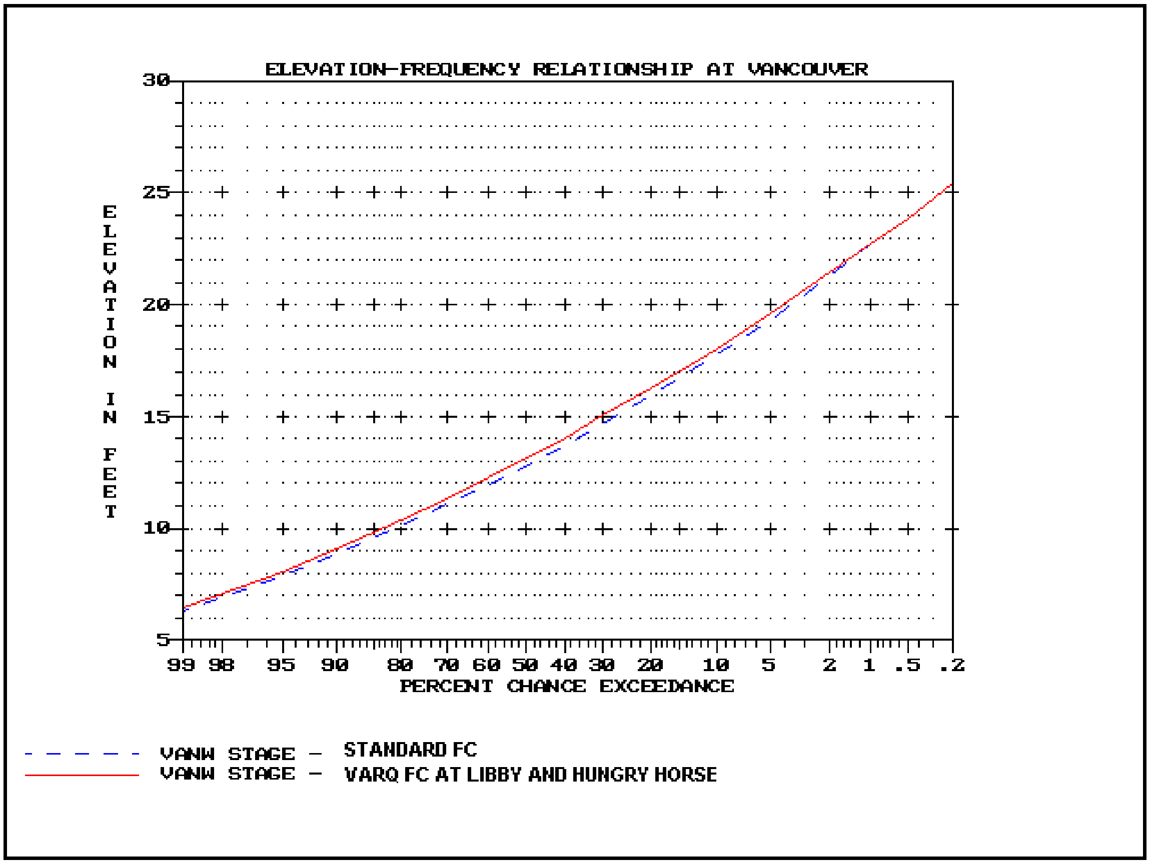

Figure 16. Stage-Frequency Curves at Vancouver for Standard FC and VARQ FC.

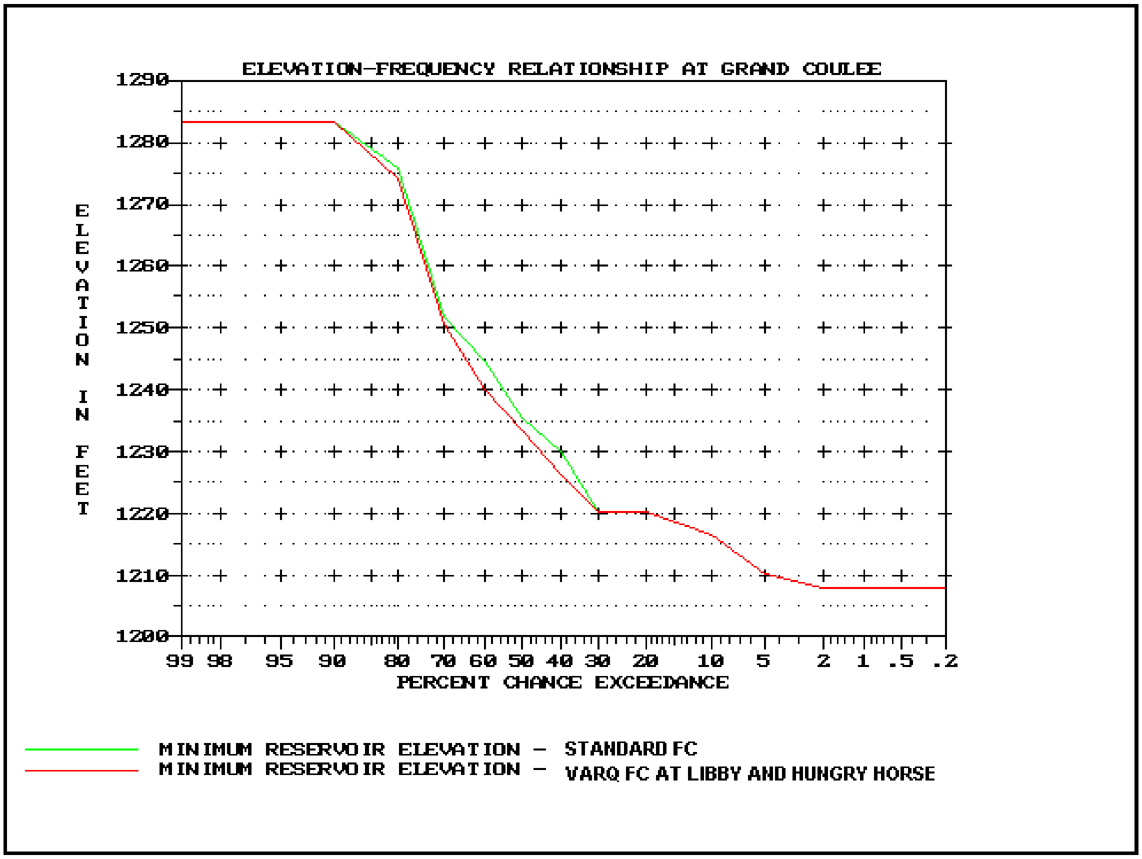

Figure 17. Elevation-Frequency Curves at Grand Coulee Project for Standard FC and VARQ FC.

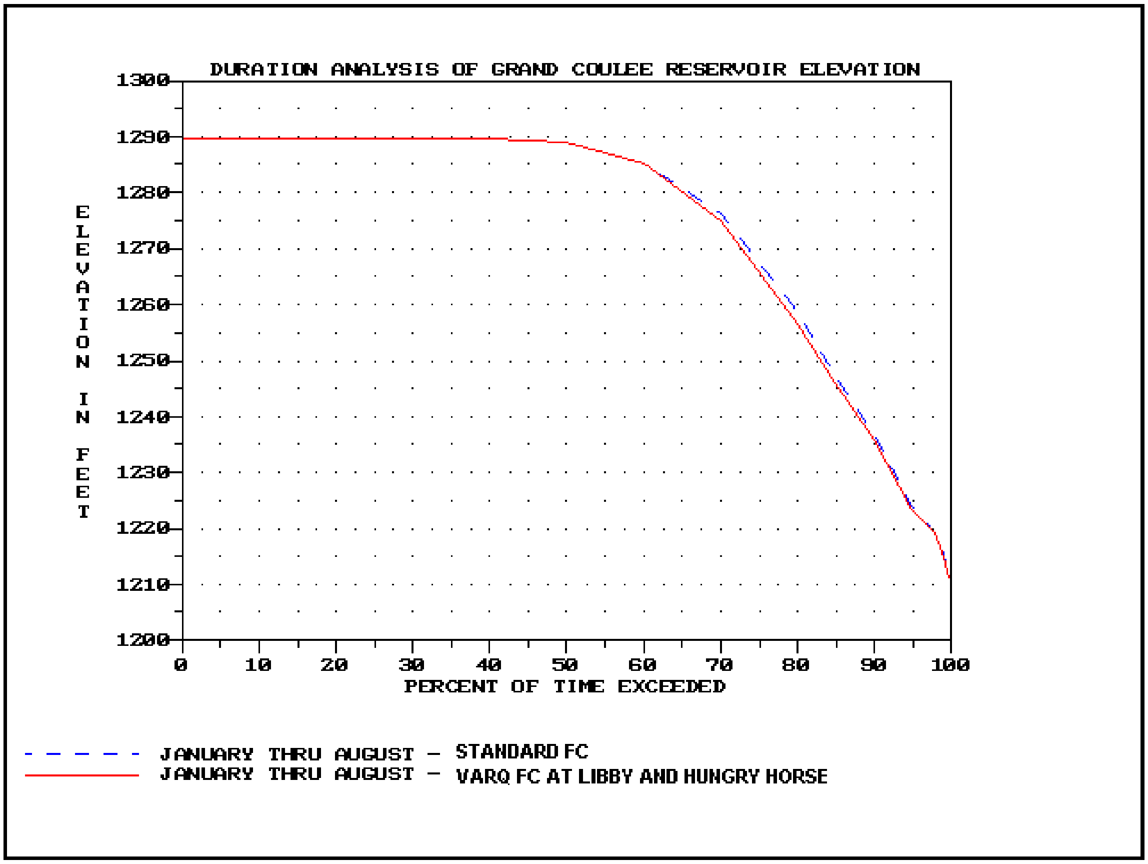

Figure 18. Elevation-Duration Curves at Grand Coulee Project for Standard FC and VARQ FC.

Appendix A

VARQ Operating Procedures

A.1. **INTRODUCTION**. This appendix contains a description of the rules that govern the VARQ procedure at Libby and Hungry Horse Dams. Examples of the VARQ operation are presented.

A.2. **GENERAL RULES**. The general rules that govern the VARQ flood control procedure are listed below.

Rule 1. Storage Reservation Diagrams. Storage reservation diagrams (SRD) for Libby and Hungry Horse (Figures A-1 and A-2, respectively) guide the evacuation of space for flood control. Required space is a function of the April-August runoff forecast at Libby and the May-September forecast at Hungry Horse. Following evacuation (after May 1) the projects are required to maintain this space until the initiation of refill. During evacuation and up until the initiation of refill, outflows should be limited to hydraulic capacity of the powerhouse to the best extent possible. However, situations such as the loss of hydraulic capacity or rapidly changing forecasts may require spill to meet flood control requirements.

Rule 2. Initiation of Refill. Initiation of refill is determined by the operating procedures for system flood control on the lower Columbia River. These procedures are described in Columbia River Treaty, Flood Control Operating Plan, October 1972. At Libby and Hungry Horse, refill is initiated approximately ten days prior to when streamflow forecasts of unregulated flow are projected to exceed the Initial Control Flow (ICF) at The Dalles, Oregon. This criteria applies most of the time: however, if the reservoir intersects with its flood control refill curve (FCRC) prior to ICF being reached, then refill is initiated at that time. The FCRC is a refill curve that fills the reservoir with 95 percent confidence at minimum outflow.

Rule 3. Initial VARQ Outflow. Use Figure A-3 and A-4 to determine an initial VARQ outflow for Libby and Hungry Horse, respectively.

Rule 4. Adjusting VARQ Outflows for Delta Storage. Adjust the initial VARQ outflows, if necessary, to compensate for any storage difference between the actual May 1 reservoir level and the space required for flood control. This difference can reflect under or over-drafted conditions (Delta). This is done in the following manner:

Estimate the duration of the system flood control operation (Duration) using Figure A-5. Select the appropriate curve based on the level of the latest projected control flow at The Dalles (ICF). From the selected curve determine the flood control duration using the April-August runoff forecast for The Dalles.

Compute the VARQ storage adjustment:

ADJSTO = [Delta(kaf) x 0.5(ksfd/kaf)] / Duration(days)

Compute the new VARQ outflow:

VARQ(new) = VARQ(initial) + ADJSTO

If the runoff forecast at The Dalles is less than 85 million acre-ft, it is likely that system flood control of any substantial duration will not be necessary for the lower Columbia River. Use streamflow forecasts to adjust VARQ outflows, if necessary, to compensate for any storage difference between the actual May 1 reservoir level and the space required for flood control. Reduce the VARQ outflows as necessary to provide protection against local flooding and to improve the likelihood of refill.

Rule 5. Adjusting VARQ Outflows for Prior VARQ Releases.

VARQ releases are seasonal in nature, generated using seasonal runoff forecasts. This rule accounts for the difference in outflows released since the initiation of refill and the new VARQ outflows developed using the updated runoff forecast:

ADJDUR = [VARQ(new) – VARQ(prior)] x [Prior Release(days) / [New Duration(days) – Prior Release(days)]]

Compute final VARQ outflow:

VARQ(final) = VARQ(new) + ADJDUR

Rule 6. Inflows Less Than VARQ Outflows. At the initiation of refill, if inflows are less than the VARQ outflow, pass inflow until inflows rise to the VARQ level. Thereafter, if inflows drop below the VARQ outflow, pass inflow until they rise again to the VARQ level.

Rule 7. Updating VARQ Outflows During Refill Season. Update VARQ outflows throughout the refill season, May through June, as new runoff forecasts are developed. Use streamflow forecasts to evaluate the performance of the VARQ outflows in meeting system and local flood control objectives. Reduce VARQ outflows if necessary to provide protection from local flooding. Return to VARQ outflows once local flooding is over.

Rule 8. Final Stages of Refill. Adjust VARQ outflows during the final stages of refill to avoid overfilling and unwanted spill. Use streamflow forecasts and engineering judgement to select the appropriate outflows.

Optional Fish/Spill Adjustments. For Libby Dam regulation, Seattle District has proposed making an additional adjustment to lower the likelihood of spill during refill. This adjustment is a function of the runoff forecast at Libby and would be added directly onto VARQ outflows that are computed for flood control (Rules 3,4, and 5). This is an optional adjustment made after evaluating the volume and distribution of the projected runoff and the likelihood of future spill based on the level of the reservoir and condition of the powerplant.

A.3. **LIBBY DAM EXAMPLE.**

Water Year: 1997
Condition: High runoff, 7852 kaf for Apr-Aug, 123% of 1961-1990 normal.
Figure A-6 shows the daily reservoir operation.

January 1 – April 30:

Ops: Evacuation of flood control space.

April Apr-Aug Runoff Forecast for Libby	7610 kaf
Rule 1. Flood Control Space Requirement (Figure A-1)	4215 kaf
Flood Control Elevation	2329.6 ft
Observed Space	3902.8 kaf
Observed Pool Elevation	2343.8 ft
April Apr-Aug Runoff Forecast for The Dalles	125 maf
Initial Control Flow at The Dalles	494 kcfs

May 1:

Ops: Operate in accordance with IJC criteria for Kootenay Lake and continue to draft to flood control requirements, if possible.

May 2:

Ops: Refill begins (Rule 2). IFC is reached in unregulated streamflow forecast ten days out on May 11.

Rule 3. Initial VARQ Outflow (Figure A-3)	5.0 kcfs
Rule 4. Delta Storage (4215-3902.8=312.2)	312.2 kaf
Rule 4. Duration (Figure A-5)	63 days
Rule 4. Delta Storage Adjustment (312.2*.504)/63=2.5	2.5 kcfs
Rule 4. Final VARQ Outflow (5+2.5=7.5)	7.5 kcfs

May 9:

Ops: May runoff forecast issued. Determine lookback adjustment to flood control space requirement for May 1 and, if necessary, adjust VARQ outflows.

May Apr-Aug Runoff Forecast for Libby	7665 kaf
Rule 1. May 1 Flood Control Space Requirement (Figure A-1)	4323 kaf
May 1 Flood Control Elevation	2324.4 ft
Rule 3. Initial VARQ Outflow (Figure A-3)	5.0 kcfs
Rule 4. Delta Storage (4323-3902.8=420.2)	420.2 kaf
May Apr-Aug Runoff Forecast for The Dalles	130 maf
Initial Control Flow at The Dalles	518 kcfs
Rule 4. New Duration (Figure A-5)	67 days
Rule 4. VARQ Storage Adjustment (420.2*0.504)/67=3.16	3.16 kcfs
Rule 4. New VARQ Outflow (5.0+3.16=8.16)	8.16 kcfs
Rule 5. Prior Release Duration	7 days
Rule 5. Duration Adjustment (8.16-7.50)*(7/(67-7))=0.08	0.08 kcfs
Rule 5. Final VARQ Outflow (8.16+0.08=8.24)	8.24 kcfs

May 15 – 18:

Ops: Reduce outflows to minimum for local flood control at Bonners Ferry (Rule 7).

May 19 – June 7:

Ops: Resume VARQ outflows of 8.24 kcfs.

June 8 – 14:

Ops: June runoff forecast issued. Use new runoff forecast and latest streamflow forecast to adjust VARQ outflow. Determine regulation that provides protection against flooding and limits unnecessary spill.

June Apr-Aug WSF for Libby	7840 kaf
Rule 1. May 1 Lookback Flood Control Space Requirement	4666 kaf
Rule 3. Initial VARQ Outflow (Figure A-3)	5.0 kcfs
Rule 4. Delta Storage (4666.4-3902.8=763.6)	763.6 kaf
June Apr-Aug WSF for The Dalles	136 maf
Initial Control Flow at The Dalles	530 kcfs
Rule 4. New Duration (Figure A-5)	68 days
Rule 4. VARQ Storage Adjustment (763.6 x 0.504)/68=5.66	5.66 kcfs
Rule 4. New VARQ Outflow (5.0+5.66=10.66)	10.66 kcfs
Rule 5. Prior Release Duration	37 days
Rule 5. VARQ Duration Adjustment (10.66-Average Previous VARQ Outflows)*(37/(68-37))=3.60	3.60 kcfs
Rule 5. Final VARQ Outflow (10.66+3.60=14.26)	14.26 kcfs

June 21 – 30:

Ops: VARQ outflows adjusted during the final stages of refill to avoid overfilling and unwanted spill (Rule 8). Outflows selected using streamflow forecasts and engineering judgement.

A.4. **HUNGRY HORSE EXAMPLE**.

Water Year: 1997
Condition: High runoff year, 2932 kaf, 153% of the 1961-1990 normal.
Figure A-7 shows the daily reservoir operation.

January 1 – April 30:

Ops: Evacuation of flood control space.

April May-Sep Runoff Forecast for Hungry Horse	2371 kaf
Rule 1. Flood Control Space Requirement (Figure A-2)	2049 kaf
Flood Control Elevation	3445.6 ft
Observed Space	2049 kaf
Observed Pool Elevation	3445.6 ft
April Apr-Aug Runoff Forecast for The Dalles	125 maf
Initial Control Flow at The Dalles	494 kcfs

May 1:

Ops: Maintain Pool at 3445.6 ft until initiation of refill.

May 2:

Ops: Refill begins (Rule 2). IFC is reached in unregulated streamflow forecast ten days out on May 11.

Rule 3. Initial VARQ Outflow (Figure A-4)	1.78 kcfs
Rule 4. Delta Storage (2049–2049=0)	0 kaf
Rule 4. Duration (Figure A-5)	63 days
Rule 4. VARQ Delta Storage Adjustment	0 kcfs
Rule 4. Final VARQ Outflow (1.78+0=1.78)	1.78 kcfs

May 9:

Ops: May runoff forecast issued. Determine lookback adjustment to flood control space requirement for May 1 and, if necessary, adjust VARQ outflows.

May May-Sep Runoff Forecast for Hungry Horse	2861 kaf

Rule 1. May 1 Flood Control Space Requirement (Figure A-2)	2179 kaf
May 1 Flood Control Elevation	3424.5 ft
Rule 3. Initial VARQ Outflow (Figure A-4)	0.99 kcfs
Rule 4. Delta Storage (2179–2049=130)	130 kaf
May Apr-Aug Runoff Forecast for The Dalles	130 maf
Initial Control Flow at The Dalles	518 kcfs
Rule 4. New Duration (Figure A-5)	67 days
Rule 4. VARQ Storage Adjustment (130*0.504)/67=0.98	0.98 kcfs
Rule 4. New VARQ Outflow (0.99+0.98=1.97)	1.97 kcfs
Rule 5. Prior Release Duration	7 days
Rule 5. Duration Adjustment (1.97-1.78)*(7/(67-7))=0.02	0.02 kcfs
Rule 5. Final VARQ Outflow (1.97+0.02=1.99)	1.99 kcfs

<u>May 16 – 18:</u>

Ops: Reduce outflows to minimum for local flood control at Columbia Falls (Rule 7).

<u>May 19 – 31:</u>

Ops: Resume VARQ outflows of 1.99 kcfs.

<u>June 1 –2:</u>

Ops: Reduce outflows to minimum for local flood control at Columbia Falls (Rule 7).

<u>June 3 – 7:</u>

Ops: Resume VARQ outflows of 1.99 kcfs.

<u>June 8 – 14:</u>

Ops: June runoff forecast issued. Use new runoff forecast and latest streamflow forecast to adjust VARQ outflow. Determine regulation that provides protection against flooding and limits unnecessary spill.

June May-Sep WSF for Hungry Horse	2901 kaf
Rule 1. May 1 Lookback Flood Control Space Requirement	2221 kaf
Rule 3. Initial VARQ Outflow (Figure A-4)	0.75 kcfs
Rule 4. Delta Storage (2221-2049=172)	172 kaf
June Apr-Aug WSF for The Dalles	136 maf
Initial Control Flow at The Dalles	530 kcfs
Rule 4. New Duration (Figure A-5)	68 days
Rule 4. VARQ Storage Adjustment (172 x 0.504)/68=1.28	1.28 kcfs
Rule 4. New VARQ Outflow (0.75+1.28=2.03)	2.03 kcfs
Rule 5. Prior Release Duration	37 days
Rule 5. VARQ Duration Adjustment (2.03-Average Previous VARQ Outflows)*(37/(68-37))=0.39	0.39 kcfs
Rule 5. Final VARQ Outflow (2.03+0.39=2.42)	2.42 kcfs

June 15 – 30:

Ops: VARQ outflows adjusted during the final stages of refill to avoid overfilling and unwanted spill (Rule 8). Outflows selected using streamflow forecasts and engineering judgement.

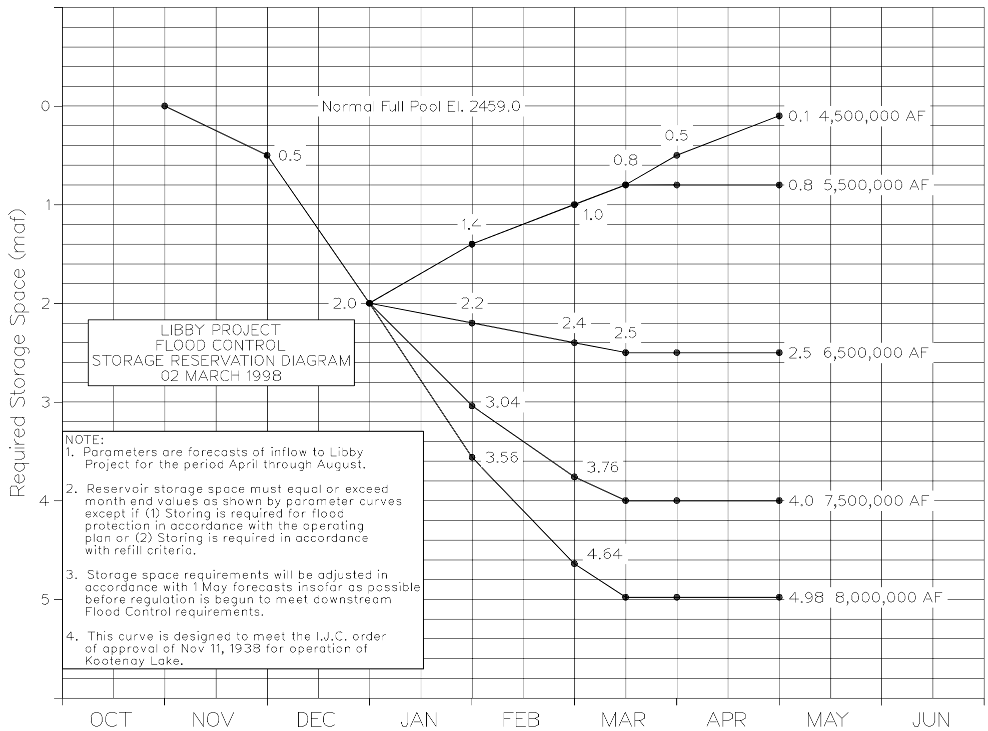

Figure A-1. Draft VARQ Storage Reservation Diagram for Libby Project.

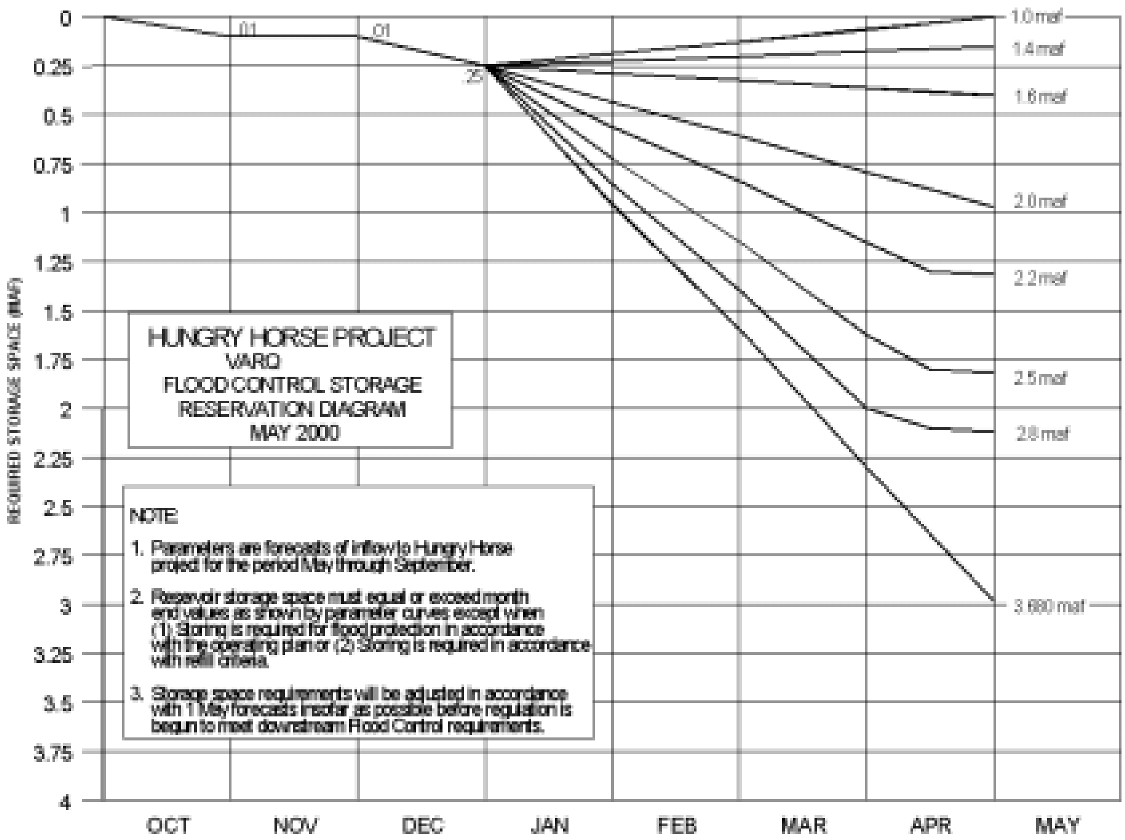

Figure A-2. VARQ Storage Reservation Diagram for Hungry Horse Project.

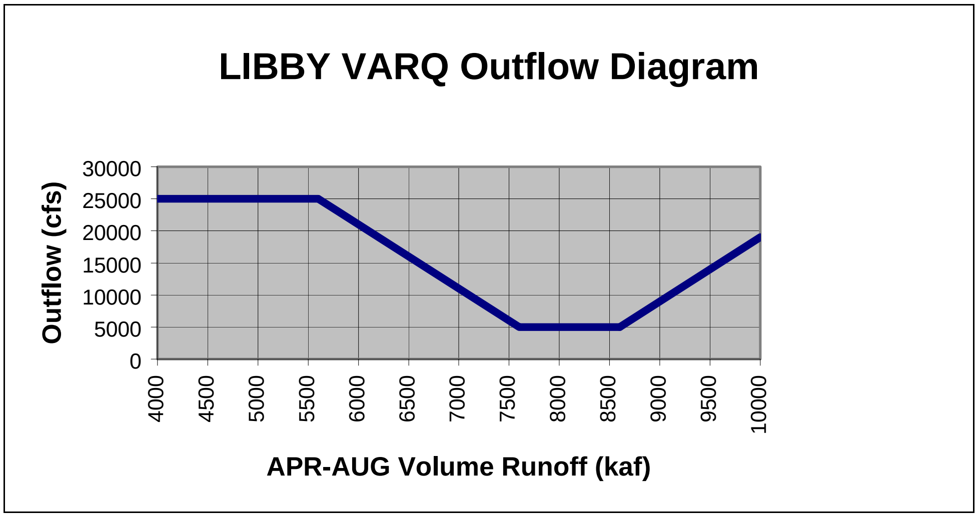

Figure A-3. VARQ Minimum Average Outflows at Libby Project.

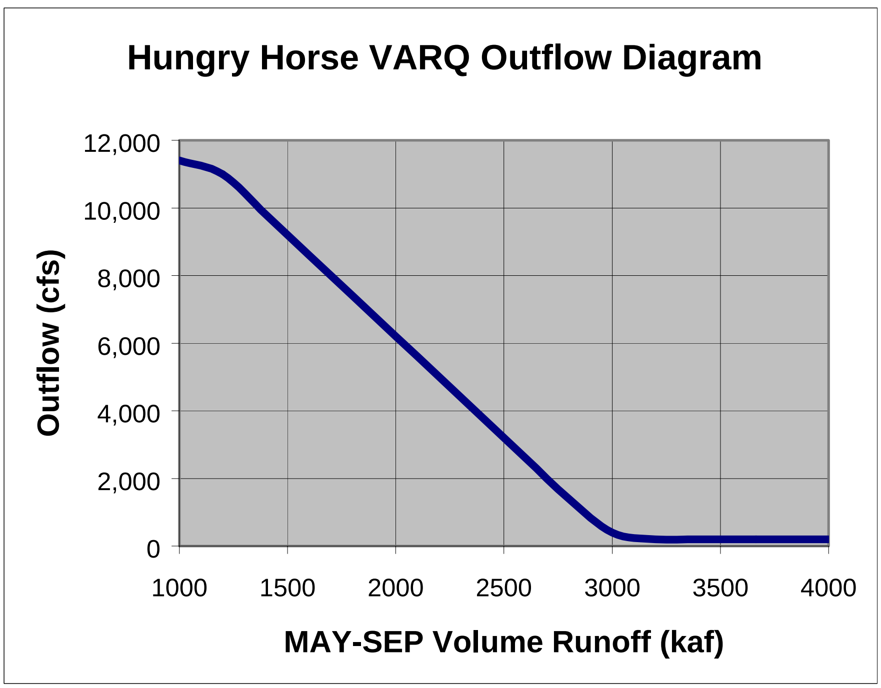

Figure A-4. VARQ Minimum Average Outflows at Hungry Horse Project.

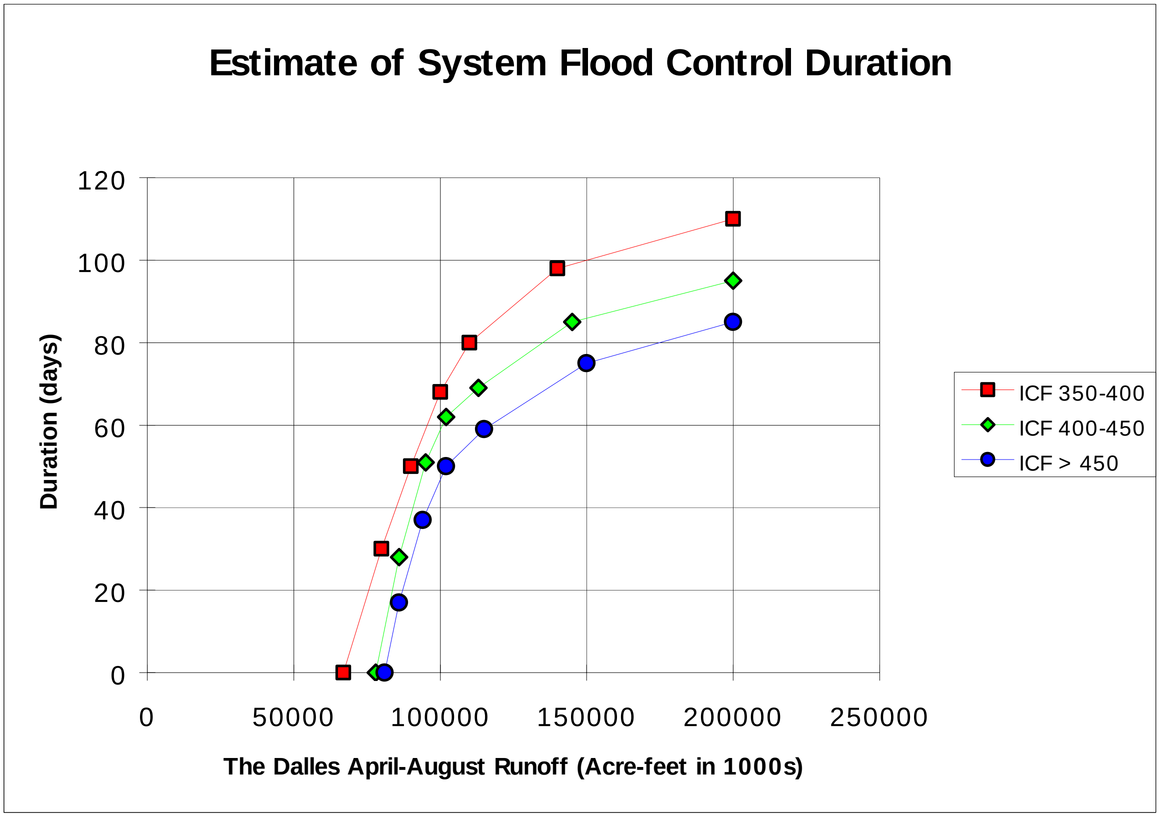

Figure A-5. Estimate of System Flood Control Duration.

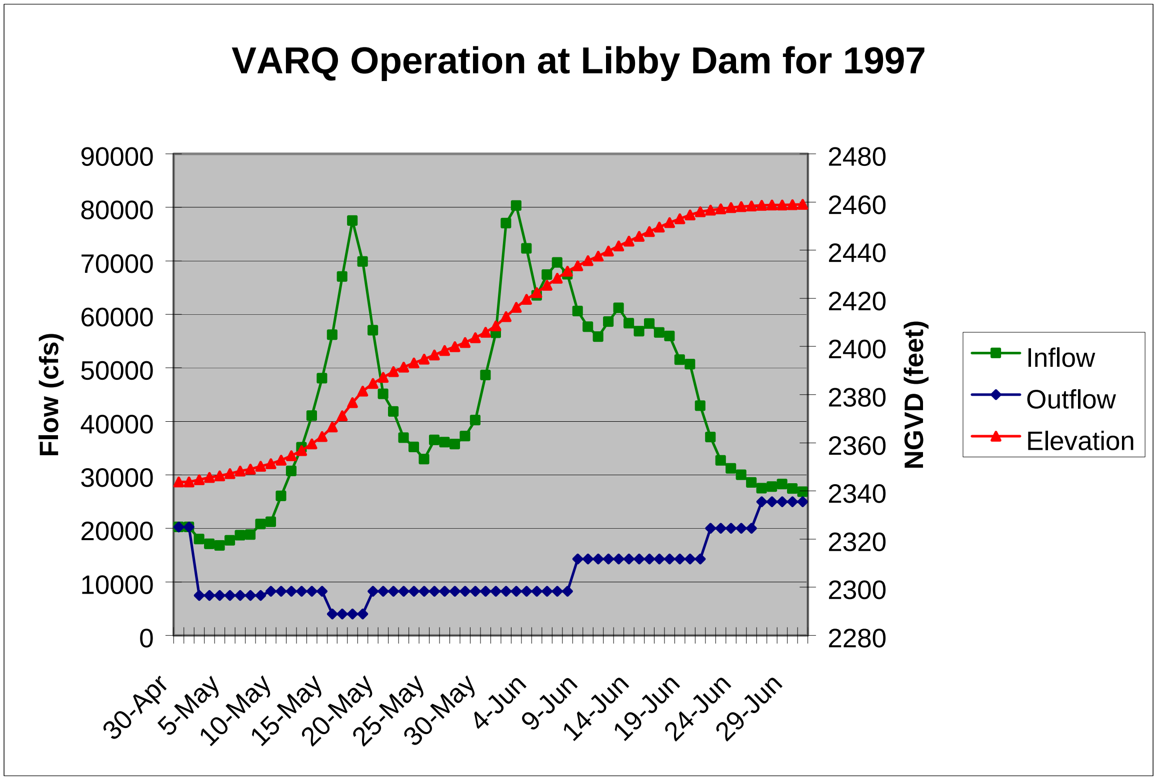

Figure A-6. Example of VARQ Operation at Libby Dam for the Spring of 1997.

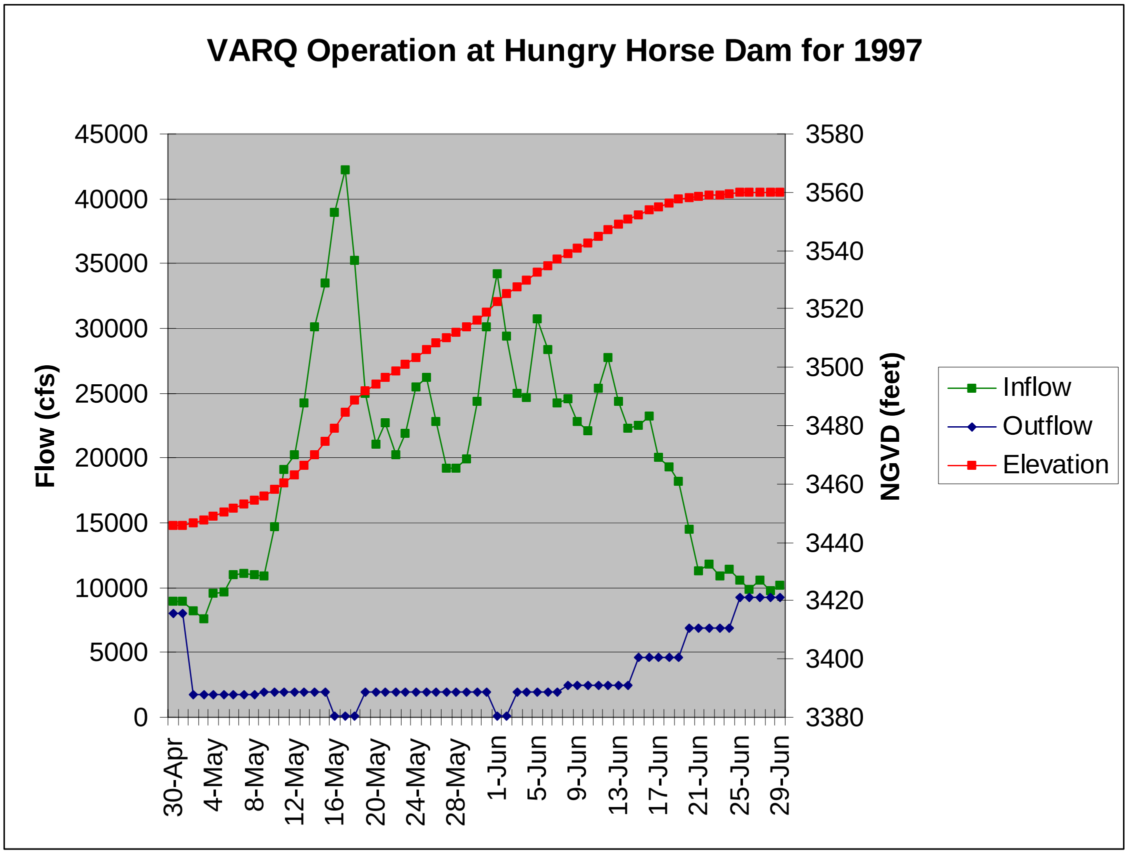

Figure A-7. Example of VARQ Operation at Hungry Horse Project for the Spring 1997.