Status Report

Work to Date on the Development of the VARQ Flood Control Operation at Libby Dam and Hungry Horse Dam

January 1999

Section 1

The Effects of VARQ at Libby and Hungry Horse On Columbia River System Flood Control

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Prepared by

U.S. Army Corps of Engineers
Northwestern Division
North Pacific Region
P.O. Box 2870
Portland, Oregon 97208-2870

Principal Engineers: Bruce Glabau and Russ Morrow
Water Management Division, (503) 808-3950

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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.

3. Kootenai River Flood Control Study, Analysis of Local Impacts of the Proposed VARQ Flood Control Plan. Seattle District, Corps of Engineers. January 1998.

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6. Simulated Runoff Forecasts for the Period 1929-1978. Contracts DACW57-84-0070 and DACW57-86-M-1391. Prepared by Kuehl and Moffitt. July 1986.

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1. INTRODUCTION

This report describes the impact to the Columbia River system flood control operation resulting from modifying the flood control requirements at Libby and Hungry Horse. This modified flood control regulation is called VARQ and was designed to improve the multi-purpose operation of the reservoirs by defining a more flexible flood control operation. Columbia River water management activities have changed dramatically since the listing of Snake River salmon (1991,1992,1994) and Kootenai River white sturgeon (1994) under the Endangered Species Act. The National Marine Fisheries Service and the U.S. Fish and Wildlife Service issued Biological Opinions which described operations for flow augmentation resulting in releases of water from Libby and Hungry Horse during the annual reservoir refill period far in excess of that envisioned in the current flood control plans. This fishery operation has reduced the likelihood and frequency of refill. To address this imbalance, the Corps of Engineers developed the VARQ flood control procedure which reduces system flood control space required at Libby and Hungry Horse and allows outflows during refill to vary based on the water supply forecast. VARQ can accommodate the higher releases required for endangered species while maintaining current flood protection and improving the ability to refill the reservoirs.

VARQ was first introduced as a possible alternative to the current flood control operation for Libby and Hungry Horse 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 completed by the Seattle District and is documented in Kootenai River Flood Control Study, Analysis of Local Impacts of the Proposed VARQ Flood Control Plan, January 1998.

This report covers only the VARQ system flood control evaluation and its affect on Grand Coulee. It is structured in the following manner. Chapter 2 describes the historical background and general nature of the Columbia River system flood control operation. Chapters 3 and 4 describe the analysis procedure and the results of the evaluation of system flood control, respectively. Chapter 5 describes the affect VARQ has on the Grand Coulee flood control operation, and lastly, Chapter 6 contains a summary of the analysis.

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. 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 approximately 25 maf (13 maf for primary flood control), which more than doubled the previously existing storage capability of the system (Table 1). 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-Feet)	Additional On-Call Flood Control Space (Acre-Feet)
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. To date, the Canadian Entity has not requested implementation of the 4.08/3.6 maf Mica/Arrow flood control drafts.

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 should be 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 to non-damaging levels the stages at all potential flood damage areas while insuring with a high level of confidence that storage projects are refilled at the end of the spring runoff. Flood damage areas are shown in Table 2. The Columbia River at The Dalles, Oregon, is used as the main 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.

Table 2. Flood Damage Areas

CONTROL POINT	RIVER REACH	ZERO DAMAGE	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 feet	1,774.0 feet
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 feet	2894.5 feet
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 feet	2,065.0 feet
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

The first and overriding assumption 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.

Also, it was assumed that the influence of the Willamette River on the nature of the stage-frequency relationship in the Portland/Vancouver harbor is insignificant 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, were developed for regulation of these large Columbia Basin-wide spring snowmelt events.

3.2 Selection of Years for Evaluation

The 50-year record, 1929-1978, was selected as the study period for the flood control evaluation. This period of record has been extensively used in hydropower and water management planning studies and the data is well documented. In this 50-year period four significant spring floods occurred, 1948, 1956, 1972, and 1974. The 1948 unregulated peak flow ranks as the second highest peak flow at The Dalles since records began in 1848. The unregulated peak flows of 1972 and 1974 rival the third highest peak flow of record.

3.3 Simulated Water Supply Forecasts

Simulated water supply volume forecasts for the 1929-1978 period were used in the development of seasonal flood control requirements for the hydro-regulations. The simulated forecasts were developed in the late 1980's and are called the Kuehl-Moffitt Simulated Runoff Forecasts. They consist of first of the month, January through July, water supply forecasts for each year in the 1929-1978 period. The runoff forecasts were simulated using actual water supply forecasting procedures that are used in operational forecasting and were statistically corrected for long term bias. 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 Libby and Hungry Horse. 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). This procedure is intended to reduce the April 30 system flood control draft without compromising system flood control. The releases from these projects during refill (post-April 30) would be increased as the inflow volume runoff forecast to each project decreased. If water that is normally stored during the refill 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 (125 percent of the 1961-1990 average at Libby and near 130 percent at Hungry Horse), then the VARQ operation emulates the standard flood control regulation with similar storage space requirements and outflows during refill. This feature of VARQ is depicted in Table 3 for a variety of water supply forecast levels.

Table 3. Comparison of the Flood Control Draft at Libby and Hungry Horse.

		Apr30 FC Draft 80% of Normal Runoff		Apr30 FC Draft 100% of Normal Runoff		Apr30 FC Draft 120% of Normal Runoff		Apr30 FC Draft 130% of Normal Runoff	
		(kaf)	(ft)	(kaf)	(ft)	(kaf)	(ft)	(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	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 space that can realistically be reached by April 30. The values are calculated using average monthly inflows for January through April.

3.5 Modeling Procedure

FCOP guidelines for operating reservoirs for system flood control 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.
- 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 took priority over the draft of Duncan when outflows were required to be reduced to adhere to the International Joint Commission criteria for the operation of Kootenay Lake.

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 and Grand Coulee, thereby providing a modeling process that limits subjectivity and the introduction of bias. The modeling was conducted using a daily time step.

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

The 1928-1978 hydro-regulations were evaluated to determine the differences in flow at Birchbank, BC and The Dalles, OR between the Base Case and VARQ simulations. These are key system flood control points on the Columbia River. The results of this analysis are shown in Table 4. Base Case represents the current FCOP regulation with the standard flood control procedures. Monthly averages are shown for the January through July time frame. Table 4 demonstrates how the VARQ operation at Libby and Hungry Horse reshapes the flow, less during the winter drawdown period and more during the spring runoff, as compared to the Base Case operation. A graphical depiction of the differences in the Base Case and VARQ hydro-regulations is shown in Figure 8.

Table 4. Distribution of Simulated Flow at Key Points on the Columbia River.

	January (cfs)	February (cfs)	March (cfs)	April (cfs)	May (cfs)	June (cfs)
Columbia River at Birchbank, BC						
VARQ FC	65,600	65,400	59,500	43,900	101,800	135,300
Standard FC	73,700	67,100	60,800	41,500	98,300	130,200
Difference	-8,100	-1,700	-1,300	2,400	3,500	5,100
Columbia River at The Dalles, OR						
VARQ FC	149,800	175,900	202,700	240,300	324,600	330,300
Standard FC	158,000	179,100	207,500	240,600	317,700	321,400
Difference	-8,200	-3,200	-4,700	-300	6,900	8,900

Note: All flows are monthly averages from the 1928-1978 flood control hydro-regulations.

4.2 Discharge-Frequency at Birchbank, BC

The results of the frequency analysis for the flows on the Columbia River at Birchbank, BC are shown in Table 5 and graphically depicted in Figure 9. The chance that a flood level flow of 225,000 cfs will be equaled or exceeded in a given year is six percent for the Base Case hydro-regulations and seven percent for VARQ. The Base Case and VARQ frequency curves begin to converge in the neighborhood of one-percent exceedance. This feature reflects the gradual merging of the VARQ and standard flood control procedures for above normal runoff conditions at Libby. In the Base Case hydro-regulations, a flood flow of 225,000 cfs was exceeded three times during the 1928-1978 period. In the VARQ hydro-regulations, flooding occurred five times.

Table 5. Peak 1-Day Discharge Frequency Analysis at Birchbank, BC.

Exceedance Frequency (%)	Base Case (cfs)	VARQ (cfs)	Difference (cfs)
99	111,000	117,000	6,000
50	166,000	172,000	6,000
20	196,000	201,000	5,000
10	214,000	219,000	5,000
2	252,000	255,000	3,000
1	268,000	269,000	1000
.5	283,000	283,000	0
.2	303,000	303,000	0

4.3 Discharge-Frequency Analysis at The Dalles

The results of the frequency analysis at The Dalles are shown in Table 6 and Figure 10. For comparison, the unregulated frequency curve is also depicted. It is readily apparent that the effects of VARQ at The Dalles are negligible. The chance that a flood level flow of 450,000 cfs will be equaled or exceeded in a given year increases from forty percent for Base Case to forty-three percent for VARQ. The Base Case and VARQ frequency curves converge in the neighborhood of one-percent exceedance. This feature reflects the gradual merging of VARQ and standard flood control procedures at both Libby and Hungry Horse for above normal runoff conditions.

Table 6. Peak 1-Day Discharge Frequency Analysis at The Dalles, OR.

Exceedance Frequency (%)	Base Case (cfs)	VARQ (cfs)	Difference (cfs)
99	214,000	215,000	1,000
90	295,000	302,000	7,000
70	366,000	376,000	10,000
50	422,000	432,000	10,000
20	520,000	530,000	10,000
10	577,000	585,000	8,000
2	683,000	684,000	1,000
1	722,000	722,000	0
.5	759,000	759,000	0
.2	805,000	805,000	0

4.4 Flow Duration Analysis at The Dalles, Or.

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. The 50-year average of these values for Base Case and VARQ are depicted in Figure 11. As the curves show, there is a slight increase in mean flow for the VARQ operation, less than 10,000 cfs for each duration, which has a negligible impact on system flood control.

4.5 Hydro-Regulations of Historic Floods

Figures 12 and 13 demonstrate the effects of VARQ on the distribution of flows at The Dalles for two notable floods, 1948 and 1974. The flood of 1948 is significant 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. The flood of 1974 is significant because its January-July and April-August runoff volume exceeds all years in the 1929-1978 study period and its unregulated peak is second only to 1948. For both years, there is very little difference at The Dalles between the Base Case and VARQ hydro-regulations. This is due in large part to the similarity of the VARQ and standard FCOP flood control operations 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 at The Dalles.

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

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 14 is the stage frequency curve for Vancouver, WA. The effects of VARQ are small, only 0.2 feet difference on average for the 1929-1978 hydro-regulations. The chance that a stage of 16 feet (flood stage) will be equaled or exceeded in a given year increases from 44 percent for Base Case to 46 percent for VARQ. Again, the frequency curves converge, in this case, as exceedance levels approach five percent.

5. **VARQ EFFECTS AT GRAND COULEE**

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 impact the flood control draft requirements at Grand Coulee by reducing the amount of available upstream storage space on May 1. This has the effect of increasing the flood control draft at Grand Coulee in normal to below normal years as measured at The Dalles, OR. The difference in the April 30 Grand Coulee draft requirements for a variety of runoff conditions are shown in Table 7. 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 caused by implementing VARQ at Libby, the following section shows the difference caused by implementing VARQ at Hungry Horse, and the last section depicts the difference in draft required by implementing VARQ at both Libby and Hungry Horse. It is important to understand that the difference in flood control draft at Grand Coulee does not equal the net change in draft at Libby and Hungry Horse caused by VARQ. This feature can be seen be examining the difference in storage drafts for Libby and Hungry Horse shown in Table 3 and the differences at Grand Coulee shown in Table 7. For example, the VARQ procedure at Libby causes 1525 kaf less draft than the standard flood control procedure for a 100 percent runoff forecast (Table 3), whereas the difference at Grand Coulee is only 183 kaf of extra draft (Table 7). Grand Coulee compensates 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 in proportion to the available upstream storage capacity at the other projects.

Table 7. Comparison of Flood Control Draft at Grand Coulee.

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 Grand Coulee Reservoir Elevations

The results of the Base Case and VARQ hydro-regulations were compared to determine the general effect of VARQ on Grand Coulee reservoir elevations. Monthly average elevations for the January through July period are shown in Table 8. In general, the average monthly elevations for the VARQ simulations for the 1928-1978 period are slightly lower, less than one foot, between February and June than the standard flood control simulations. The maximum difference occurs in the month of May where the average elevation for the VARQ simulations was 0.7 feet lower. This is less than one percent of the reservoir space available for flood control regulation between elevation 1208 (minimum pool) and 1290 feet (full pool). May is the first month of refill following the flood control evacuation that ends on April 30. The average difference of the April 30 elevation at Grand Coulee in the Base Case and VARQ 50-year reservoir simulations was 1.2 feet and the maximum difference was 7.7 feet.

Table 8. Average Monthly Differences in Grand Coulee Reservoir Elevations.

Operational Scenario	January (feet)	February (feet)	March (feet)	April (feet)	May (feet)	June (feet)	July (feet)
Standard FC	1290.0	1289.4	1278.4	1253.9	1246.1	1269.5	1288.3
VARQ FC	1290.0	1289.3	1278.2	1253.5	1245.4	1268.9	1288.3
Difference	0	0.1	0.2	0.4	0.7	0.6	0
% of FC space (1208-1290 ft)	0	0.1	0.2	0.5	0.8	0.7	0

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

An elevation-frequency analysis was conducted to evaluate the effect of VARQ on Grand Coulee minimum reservoir elevations. The results are shown in Table 9 and graphically depicted in Figure 15. This relationship represents the frequency of the maximum flood control draft (minimum reservoir elevation) achieved during the winter period for each year in the 1928-1978 Base Case and VARQ hydro-regulations. The maximum difference in frequency occurs in requiring a draft to elevation 1220 feet, where the chance this elevation will be reached in a given year increases from 20 percent for Base Case to 30 percent for VARQ. This is mainly a function of the shape of Grand Coulee's storage reservation diagram, which limits the flood control draft to elevation 1220 feet for parameter values between 80,000 and 95,000 kaf. The frequency curves converge below elevation 1220 feet reflecting the merging of the VARQ and standard flood control procedures at Libby and Hungry Horse for above normal runoff conditions which eliminates any differences in flood control requirements at Grand Coulee. The frequency curves also converge at elevation 1283.3 feet. This demonstrates how the VARQ operation does not impact flood control space requirements at Grand Coulee for well below normal seasonal runoff conditions in the Columbia Basin.

Table 9. Elevation-Frequency Relationship at Grand Coulee.

Percent Chance of Non-Exceedance (%)	Base Case (feet)	VARQ (feet)	Difference (feet)
99	1283.3	1283.3	0
80	1269.5	1267.9	1.6
60	1238.7	1236.3	2.4
40	1225.9	1224.9	1.0
30	1221.2	1220.2	1.0
20	1220.2	1220.2	0
10	1216.5	1216.5	0
2	1208	1208	0
1	1208	1208	0
.5	1208	1208	0
.2	1208	1208	0

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

A duration analysis was conducted to evaluate the effect the VARQ operation has on the Grand Coulee reservoir elevation over time. The results are shown in Figure 16. The time span covers both the winter drawdown period and the spring refill season, January through June. Daily elevation data from the Base Case and VARQ hydro-regulations were used in the analysis. It is apparent from Figure 12 that VARQ at Libby and Hungry Horse influence the overall duration of the evacuation and refill of the reservoir only slightly, in the neighborhood of a one to two percent increase in time for elevations between 1220 and 1290 feet (full pool). This represents about two to four days, on average, to the winter evacuation and spring refill cycle of the reservoir. There is no effect between elevation 1208 (minimum pool) and 1220 feet.

6. SUMMARY AND CONCLUSIONS

VARQ flood control procedures were developed to improve the multi-purpose regulation of Libby and Hungry Horse. In contrast to the current flood control procedures, VARQ requires less system flood control space to be made available in each reservoir prior to spring runoff and allows outflows during refill to vary based on the water supply forecast. Normally, VARQ outflows will be higher than those required by the current procedures. Full system hydro-regulations for the 1928-1978 period were conducted to evaluate the impact VARQ has on system flood control. The results of this analysis are summarized below:

- The VARQ operation at Libby increases the frequency of flooding on the Columbia River at Birchbank, BC. from an exceedance level of six percent for Base Case to seven percent for VARQ. The frequency curves converge in the neighborhood of one-percent exceedance.

- The VARQ operation at Libby and Hungry Horse causes a small change in flow at the Dalles during the winter drawdown and spring runoff season. During the spring runoff, VARQ adds less than 10,000 cfs, on average, to the flow at The Dalles for duration of flow between one and 120 days. Libby provides about 60 percent of the extra flow while Hungry Horse provides 40 percent.

- The impact to flood control at The Dalles, Oregon, is negligible. The chance that a flood level flow of 450,000 cfs increases from 40 percent for Base Case to 43 percent for VARQ. The frequency curves converge in the neighborhood of one-percent exceedance.

- The impact to flooding in the Portland/Vancouver harbor is negligible. As at The Dalles, the effects of VARQ are small, averaging only 0.2 feet in peak stage for the 1929-1978 hydro-regulations. The chance that a stage of 16 feet (flood stage) will be equaled or exceeded in a given year increases from 44 percent for Base Case to 46 percent for VARQ. Again, the frequency curves converge, in this case as exceedance levels approach five percent.

- VARQ procedures trigger additional flood control draft at Grand Coulee for normal to below normal runoff conditions at The Dalles than the standard flood control procedure. The additional space required at Grand Coulee is only a portion of the reduced flood control space at Libby and Hungry Horse caused by VARQ. In the simulations, VARQ drafted less than one foot deeper, on average, than the standard flood control procedure for the months February through June. The maximum average difference was 0.7 feet in May. The average April 30 elevation was 1.2 feet lower in the VARQ simulations and the maximum difference was 7.7 feet. 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 adds about two to four more days to the annual flood control evacuation and refill cycle of the reservoir.

- 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.

- By design, VARQ requires less storage space at the beginning of spring runoff and increases spring and summer flows. Under-forecasting seasonal water supply volume can lead to higher than desired outflows, possibly at damaging levels. In addition, less storage space reduces operating flexibility during refill to control excessive spill.

FIGURES

Figure 1. Columbia River Basin Map.

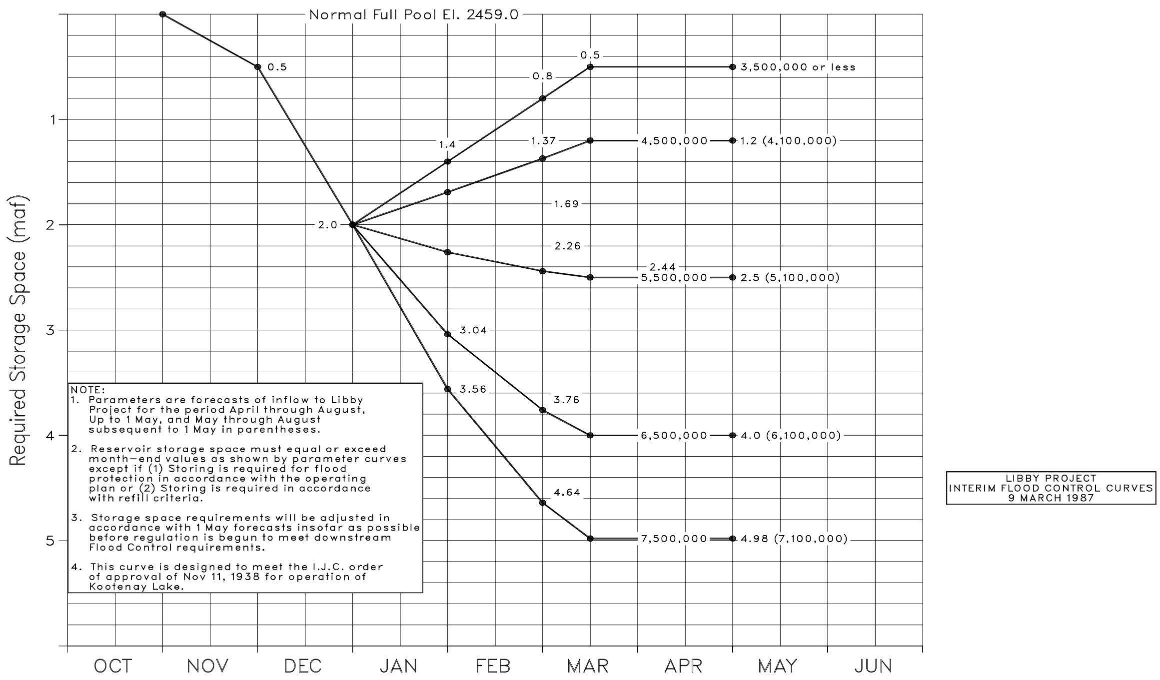

Figure 2. FCOP Storage Reservation Diagram at Libby Dam.

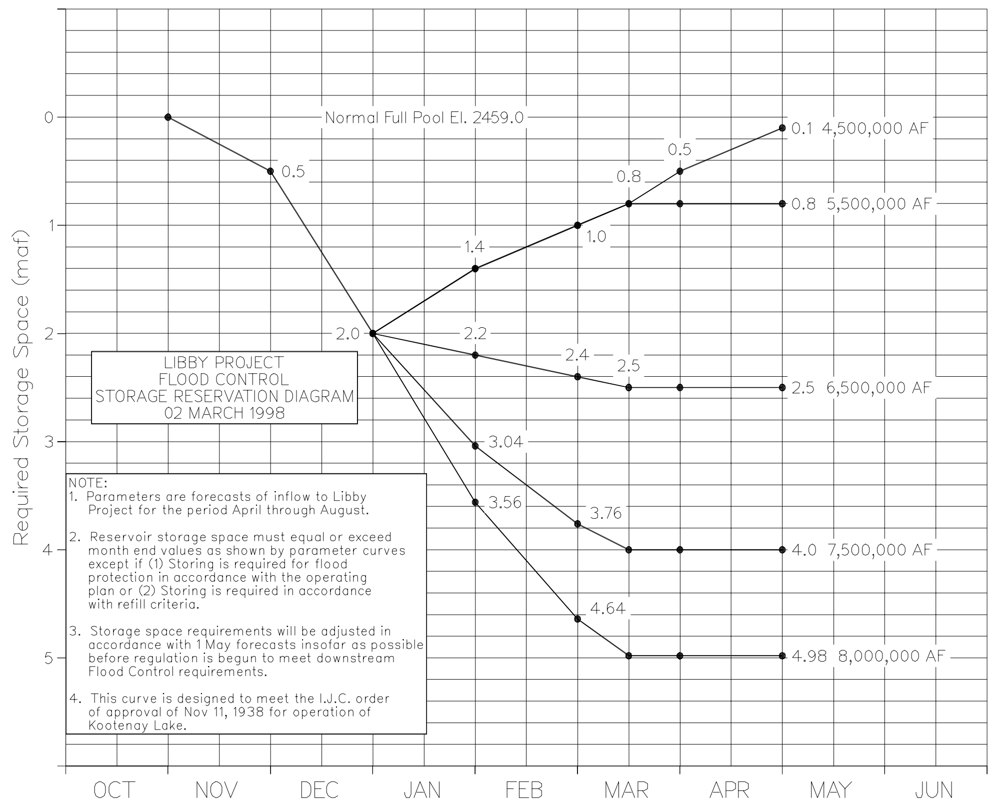

Figure 3. VARQ Storage Reservation Diagram at Libby Dam. (Revised Libby VARQ Storage Reservation Diagram. Changes to original 22 Sep 1994 SRD were made in response to comments from Seattle District. The end of January point on the 6.5 Maf rule curve was lowered by 200 acre-feet and the curves for a forecast of 4.5 Maf or less were combined and straightened.)

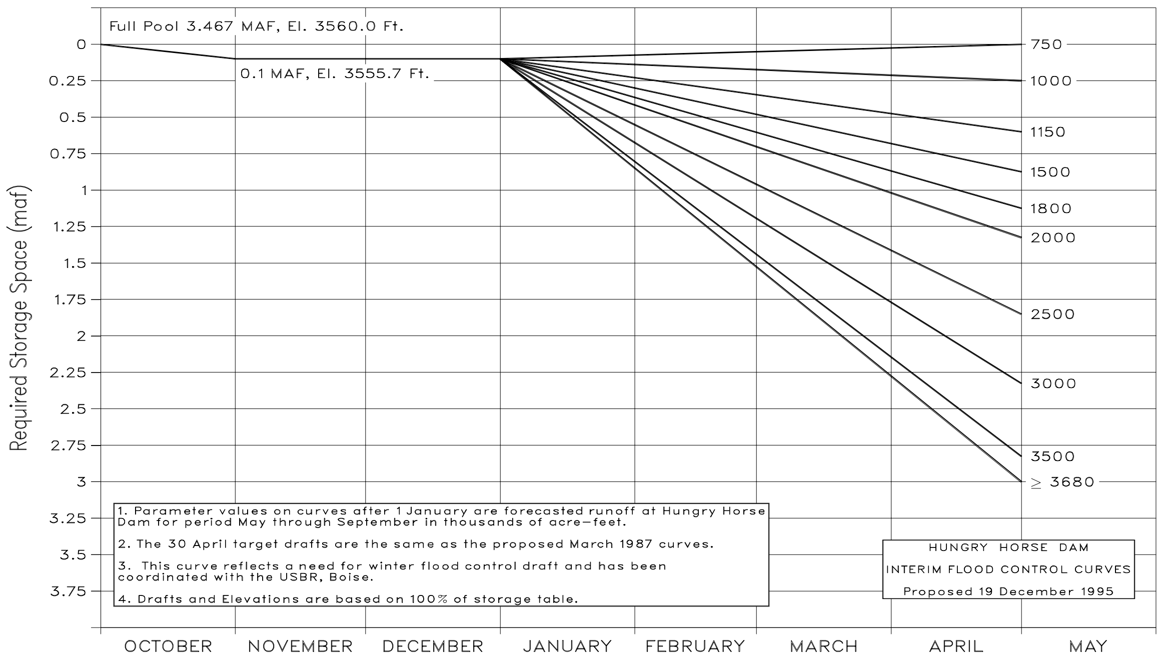

Figure 4. FCOP Storage Reservation Diagram at Hungry Horse Dam.

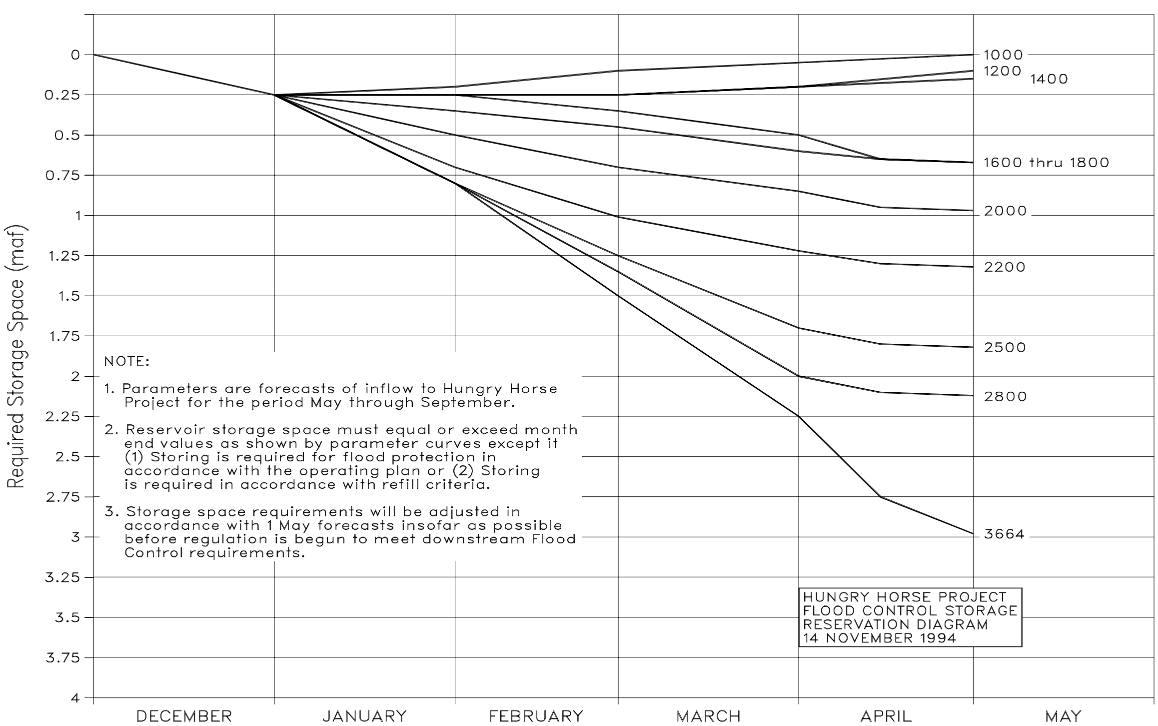

Figure 5. VARQ Storage Reservation Diagram at Hungry Horse Dam.

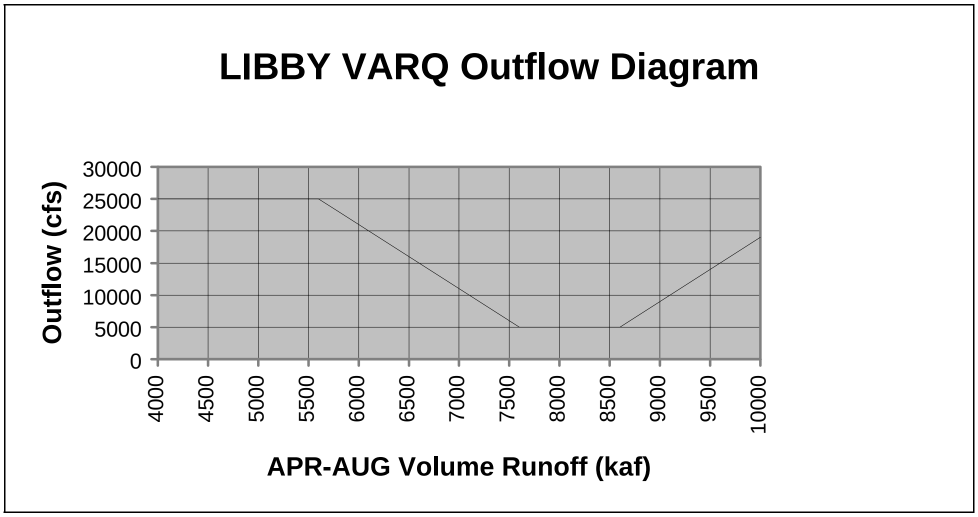

Figure 6. VARQ Outflows at Libby

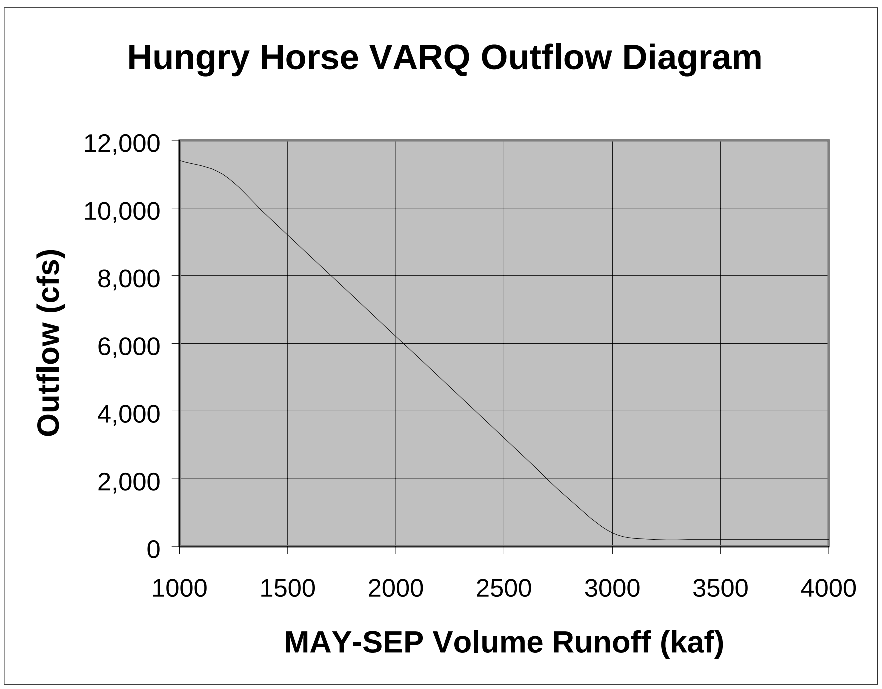

Figure 7. VARQ Outflows at Hungry Horse

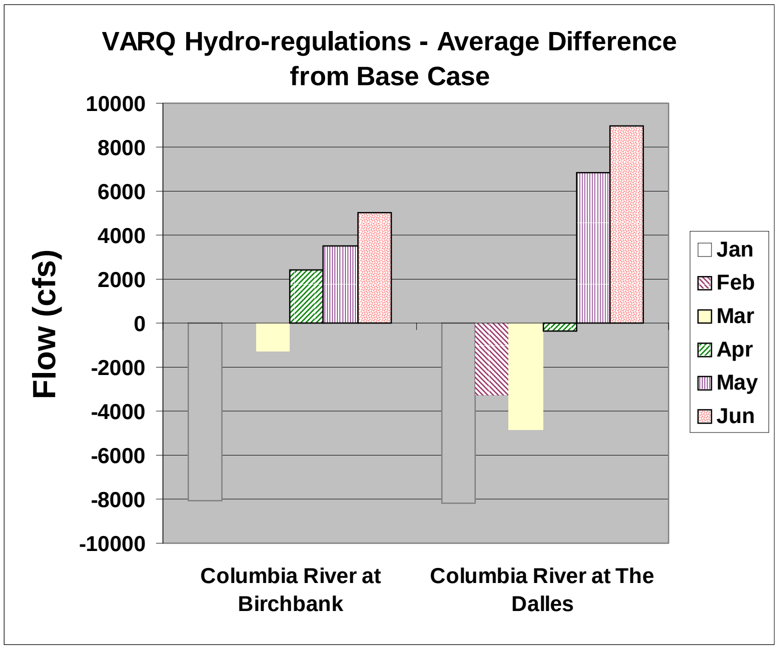

Figure 8. System Hydro-Regulation Results.

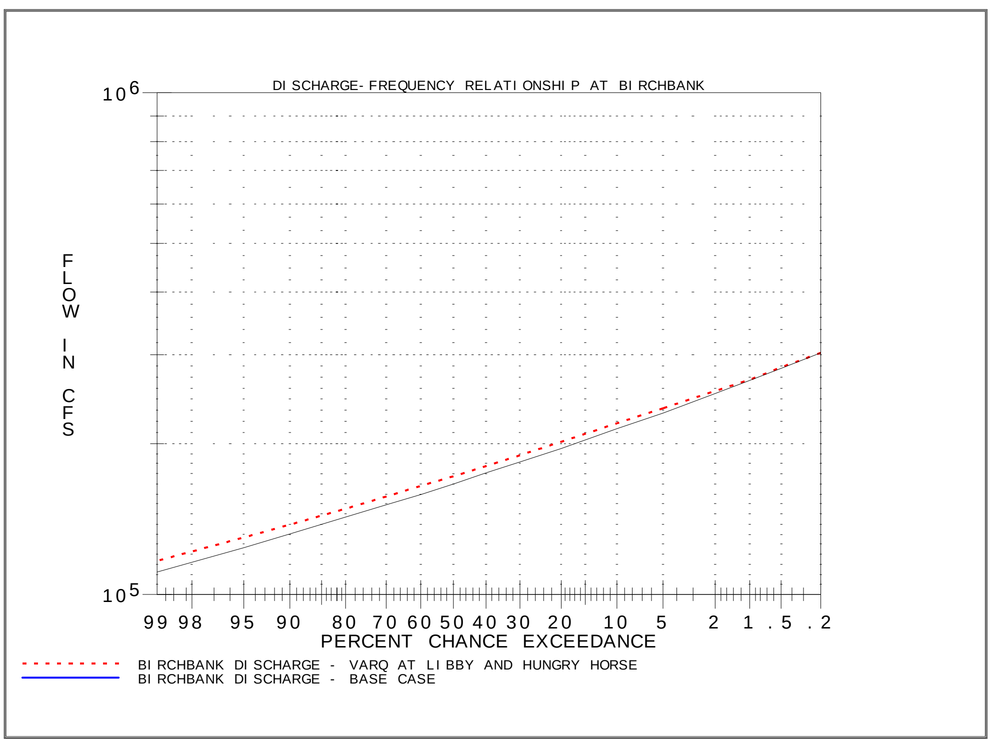

Figure 9. Discharge-Frequency Relationship at Birchbank, BC.

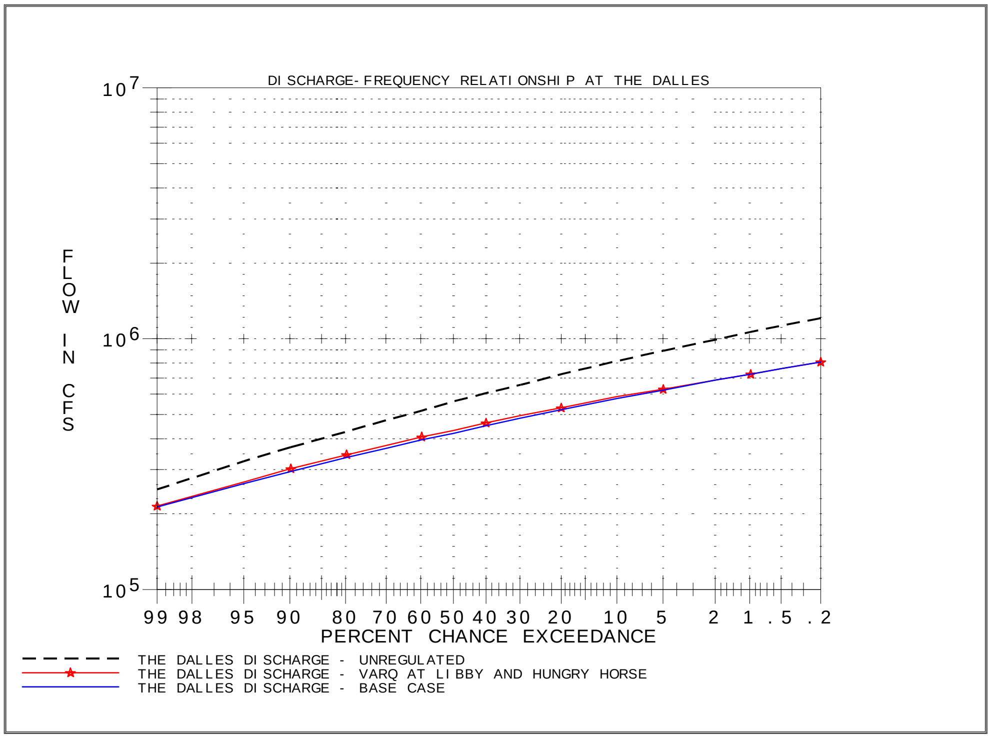

Figure 10. VARQ Peak Discharge Frequency at The Dalles.

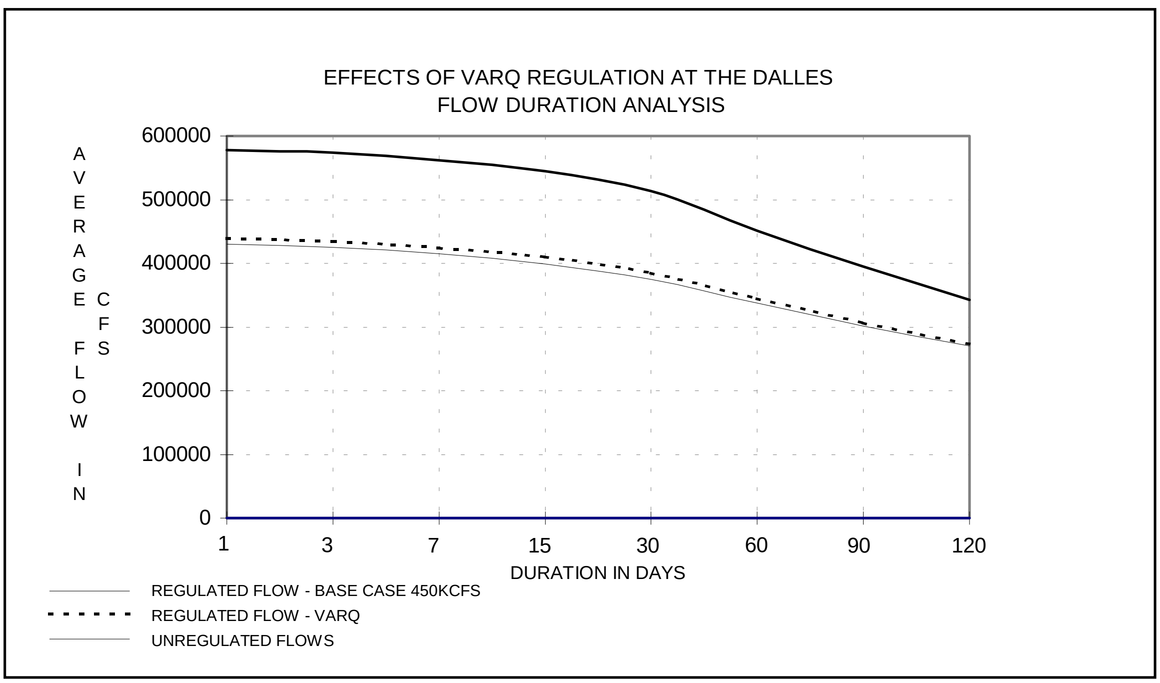

Figure 11. Effects of VARQ Regulation at The Dalles - Flow Duration Analysis.

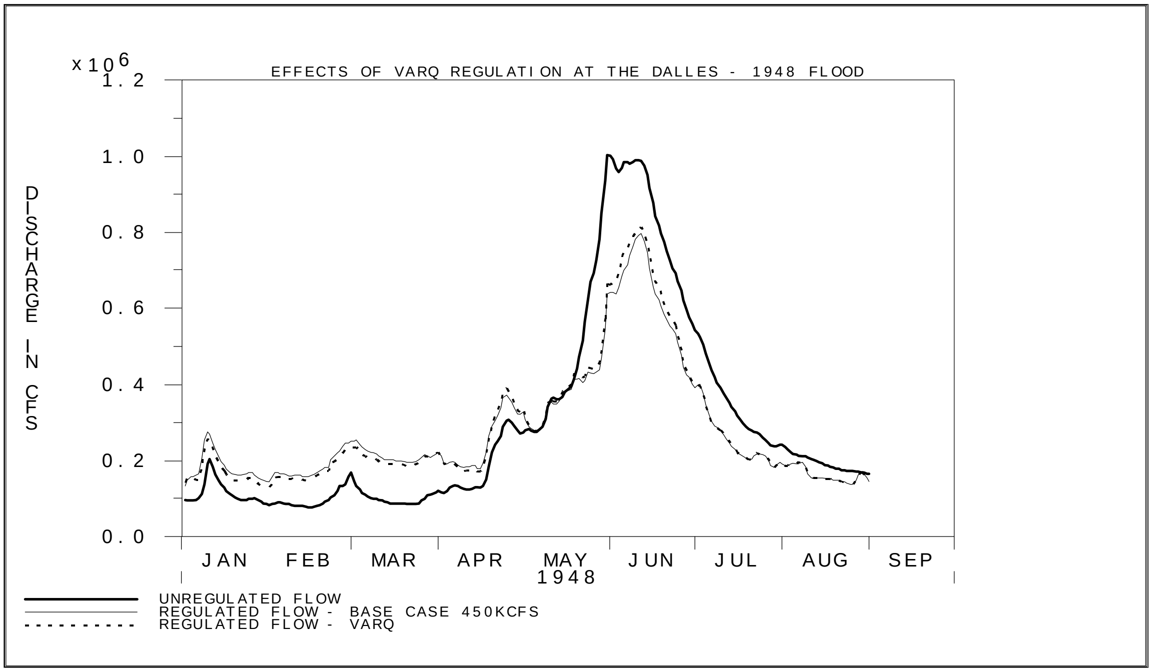

Figure 12. Effects of VARQ Regulation at The Dalles - 1948 Flood.

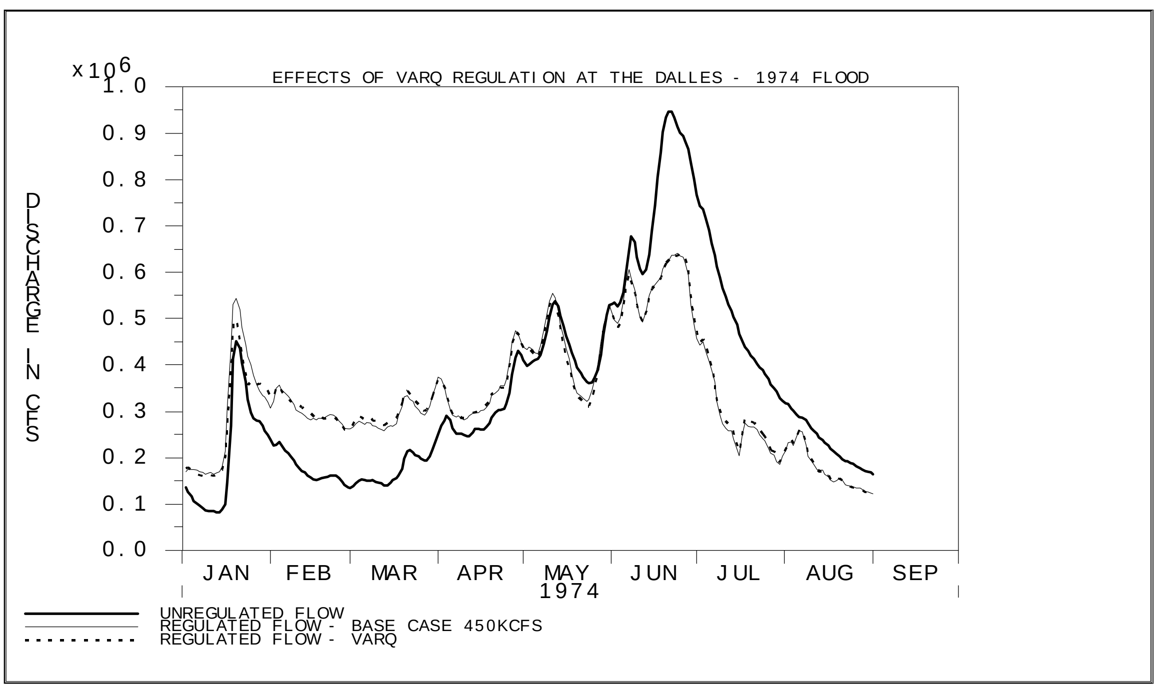

Figure 13. Effects of VARQ Regulation at The Dalles1974 Flood.

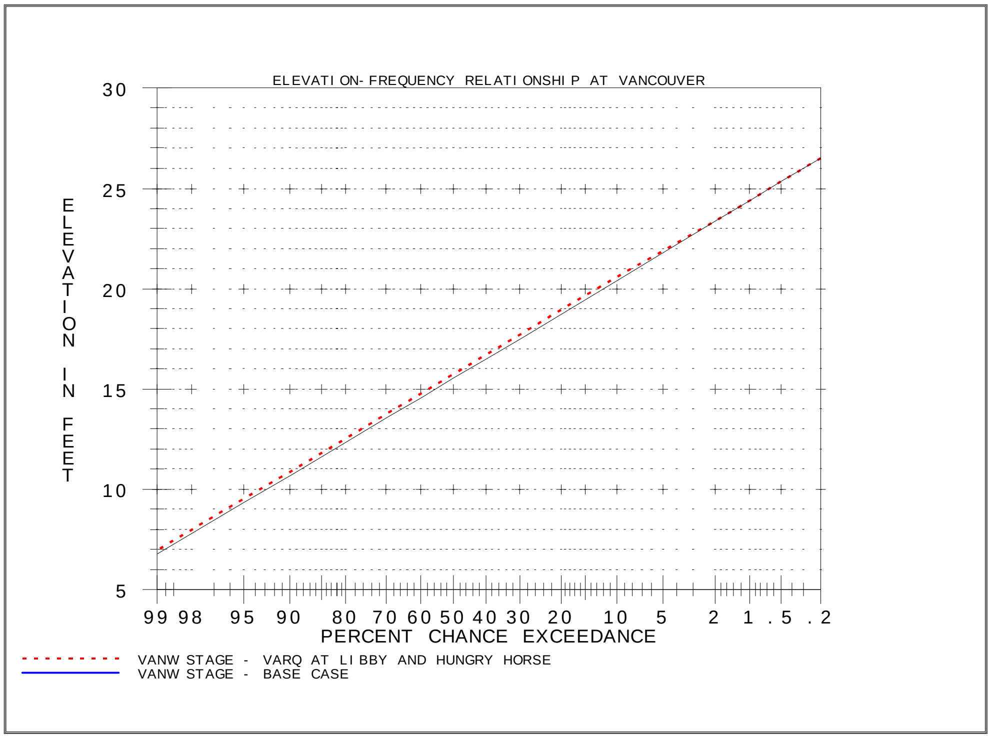

Figure 14. Stage-Frequency Relationship at Vancouver, WA.

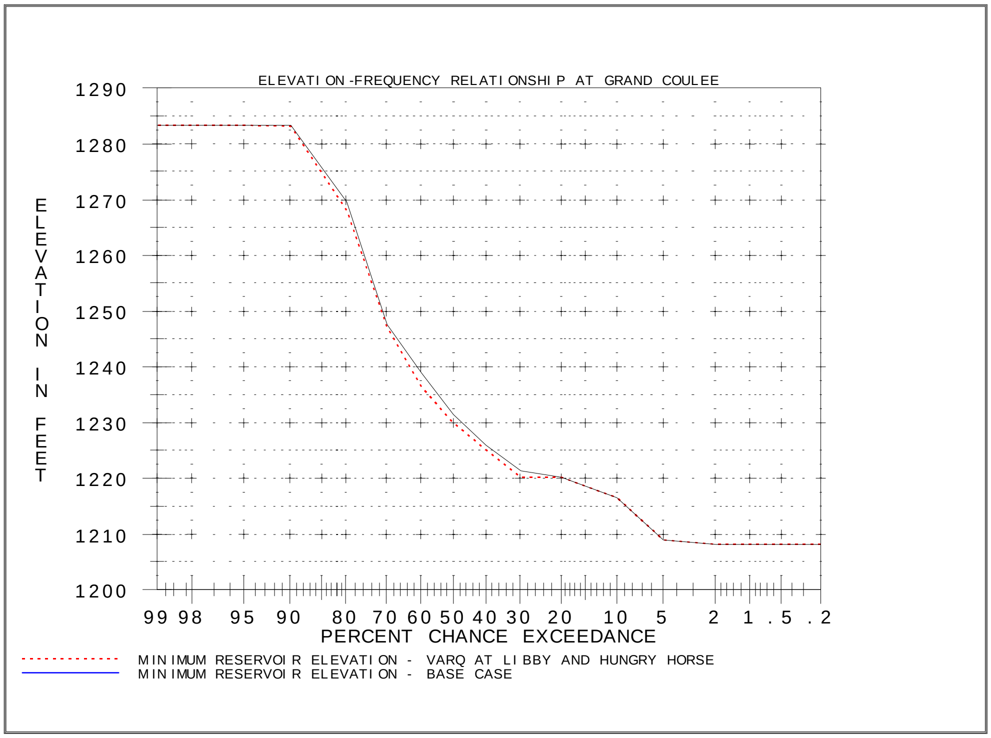

Figure 15. Elevation-Frequency Relationship at Grand Coulee.

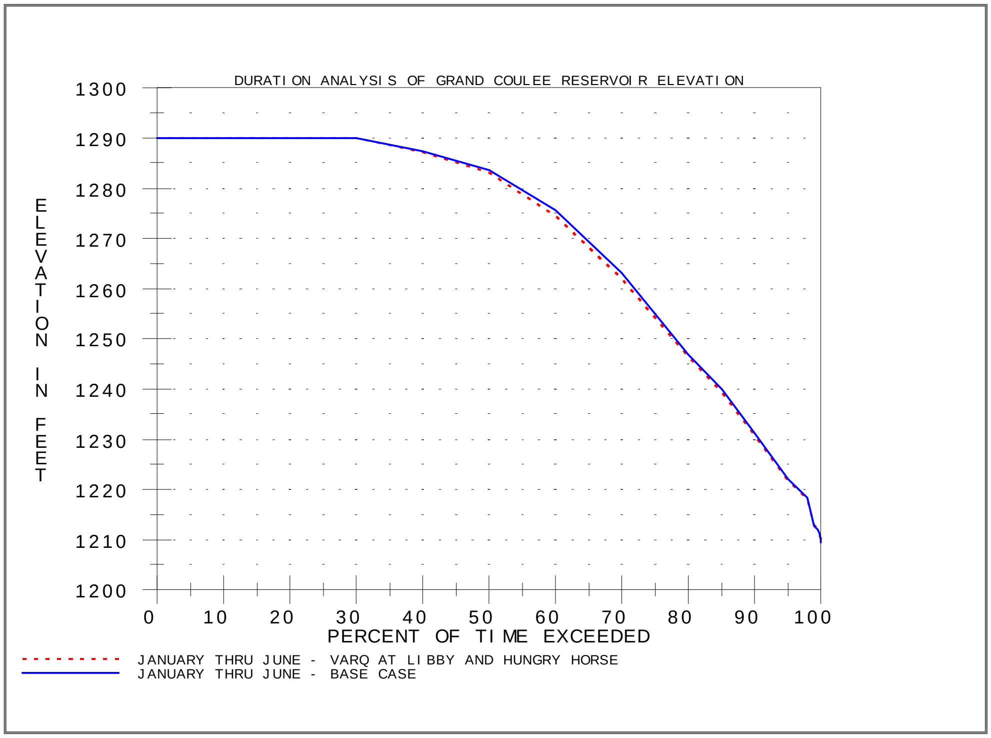

Figure 16. Elevation Duration Analysis at Grand Coulee.