# LOW WATER PLANNING IN THE COLUMBIA RIVER BASIN

**Thomas Chisholm, Hydraulic Engineer, U. S. Army Corps of Engineers, Northwestern Division, Portland, OR, tom.a.chisholm@usace.army.mil**

## INTRODUCTION

Storage reservoirs even out variation in river flow. A chief benefit of this function is more reliable supplies of both hydropower and water. For reservoirs that supply power and water perhaps the most basic design question is: how much reservoir capacity is required given natural flow and demand.

In 1961 United States President Dwight Eisenhower and Canadian Prime Minister John Diefenbaker signed the Columbia River Treaty. The Treaty's preamble states: "Recognizing that the greatest benefit to each country can be secured by cooperative measures for hydroelectric power generation and flood control, which will make possible other benefits as well." Thus, the Treaty focuses on flood control and hydropower. During low water conditions attention focuses on hydropower over flood control. Although in many rivers water supply is the primary objective in the Columbia River Treaty it falls into "other benefits". However, attention to ecological processes, which value water supply, has increased since the signing of the Treaty.

The Treaty and its annexes provide guidelines for developing project operating plans and apportioning benefits. Both operating plans and benefit calculations use the critical period concept. Article I of the Treaty entitled Interpretation includes:

(d) "**critical stream flow period**" means the period, beginning with the initial release of stored water from full reservoir conditions and ending with the reservoirs empty, when the water available from reservoir releases plus the natural stream flow is capable of producing the least amount of hydroelectric power in meeting system load requirements.

## CRITICAL PERIOD DEVELOPMENT

**Critical Period Concept:** Considering that Treaty ratification occurred in 1961, the Treaty used methods existing in 1961. In 1961 computers were in their infancy. The concept of critical period arose in water supply engineering. In the water supply context critical period has the same definition as in the Treaty but with water substituted for hydroelectric power. The critical period concept is applied when calculating reservoir capacity required to meet demand and also the demand that a reservoir of a given capacity can meet. The concept may have arisen before the name critical period. Oguz and Bayazit (1991) describe statistical properties of the water supply critical period. They credit Hall, Askew and Yeh (1969) with inventing the concept of critical period, clearly not the case. However, Hall, Askew and Yeh include a modest bibliography and do not cite papers that describe critical periods, but they imply the technique was in use. Like Oguz and Bayazit this author has not located literature with critical period in the title prior to Hall Askew and Yeh's paper. Also, all literature on critical period analysis located by this author treat water supply not hydropower.

Klemes' papers (1979 1984) expound on historical development of the reservoir sizing problem. The seminal paper in this field is Rippl (1883) who proposed the mass curve method. This technique plots a time series of cumulative inflow. The maximum deviations of the plot below a straight line with a slope at the demand for water allow calculation of reservoir size required to support the demand. The time period covered by the line used to size the reservoir is the critical period. The graphical nature of this method made it appealing prior to the advent of computers.

A similar method, which Klemes (1984) credits to Varlet (1923), requires plotting two mass curves separated by the reservoir capacity. This method is commonly called the stretched string method. The yield of the reservoir is the flattest line that extends from the bottom line to the top line. The extent of this line is the critical period. The intuitiveness and graphical nature of this method made it appealing prior to the advent of computers. The author is not aware of this method being applied to the power problem. However, it is conceivable that it was used in analysis leading to development of the Treaty.

**Power:** The hydropower generation equation is

$$P = e\rho g h Q \tag{1}$$

Where P denotes power, e nondimensional efficiency, ρ density of fluid, g acceleration of gravity, h hydraulic head, and Q volume flow rate. Metric units yield generation in Watts. Efficiency depends on dam and generator physical properties in addition to flow rate and head. Because operating conditions continually vary, long term planning uses average values.

Assuming head scales linearly with impounded volume, V, and generating flow is the sum of inflow, I, and change of impounded volume dV/dt yields

$$P = e\rho g\ aV(\frac{dV}{dt} + I) \tag{2}$$

This equation indicates that maximizing system generation when decreasing reservoir content primarily requires retaining maximum head in projects that have the highest Q. If two reservoirs, denoted by subscripts one and two, are in series with inflow to the upstream reservoir, generation as the reservoirs draft from full to empty is:

$$G = e\rho g \int_0^T aV_1 \left(\frac{dV_1}{dt} + I\right) + bV_2 \left(\frac{dV_1}{dt} + \frac{dV_2}{dt} + I\right) \mathrm{dt} \tag{3}$$

The critical period definition includes drafting reservoirs from full to empty. Its power interpretation requires retaining volume in projects that make the largest contribution to head. Note that in many cases inflow originates from an upstream project. Typically headwater projects have lower inflows so drafting them first maximizes generation. As equation 3 illustrates, the downstream project passes all the outflow from the upstream project plus draft

from the downstream project. As power demand continues to require draft, reduced head reduces generation per unit of water. This requires ever-increasing draft to meet generation targets.

Calculating power critical periods using current technology is an optimization problem. But when the Treaty was developed USACOE (1981) describes it as "trial and error." While the principles in the previous paragraph guide an operation, gradient solvers (Fletcher 1987) often struggle because in complex hydrosystems the problem is very nonlinear. Conditions where projects spill are particularly challenging because if discharge is greater than turbine capacity there is no gradient in generation until flow decreases below maximum turbine capability. However, a successfull solution describes a system operation that is useful for planning.

**Treaty:** The Treaty determines Columbia River Basin hydro operation using a procedure called the Treaty Storage Regulation (TSR). This calculates an operation which meets operational constraints and at least critical period power. Constraints include those described in the Flood Control Operating Plan (2003) along with physical ones. The wide variety of operational constraints serving fish and environmental concerns are not addressed by the TSR because they did not exist when the Treaty was signed. Some are addressed by supplemental agreements negotiated between the United States and Canadian Entities.

The TSR plans an operation which guarantees critical period generation unless water is unavailable. If reservoirs are empty generation becomes limited by inflow. The Treaty uses 30 years of water record from 1929 -1960 as its period of record. With the Treaty based on 30 years of record and Mica Dam completed in 1973 the dams have been in operation for longer than the period of record. Analysis performed by Hicks and Baldrica (1970) using synthetic records give a return period of 385 years for the 1929-1932 critical period. USACOE (1981) refers to a reanalysis performed by the University of Washington which reduces this return period to 164 years. One would think that the long return period of the critical period in the Treaty's period of record would avoid ever drafting reservoirs to empty. But the TSR called for drafting reservoirs to empty in 2001. However Treaty language that allows operation as agreed to by the parties allows ad hoc hedging, which is described in the next section, in actual operations.

**Treaty Assumptions:** The delivery vs. availability diagram has long been used to describe reservoir operation. Draper and Lund (2004) explain its use but did not invent it. The flat section of line in the unhedged case between 10 and 20 on the horizontal axis shows operations when the reservoir is between full and empty and meets demand for water. To the left, passing inflow plus drafting available water cannot meet demand so the reservoir drafts to empty then passes inflow. To the right of the flat line the reservoir is full so it passes inflow. Both the left and right are undesirable situations. To the left water demand is not met and to the right the reservoir cannot make any contribution to flood reduction.

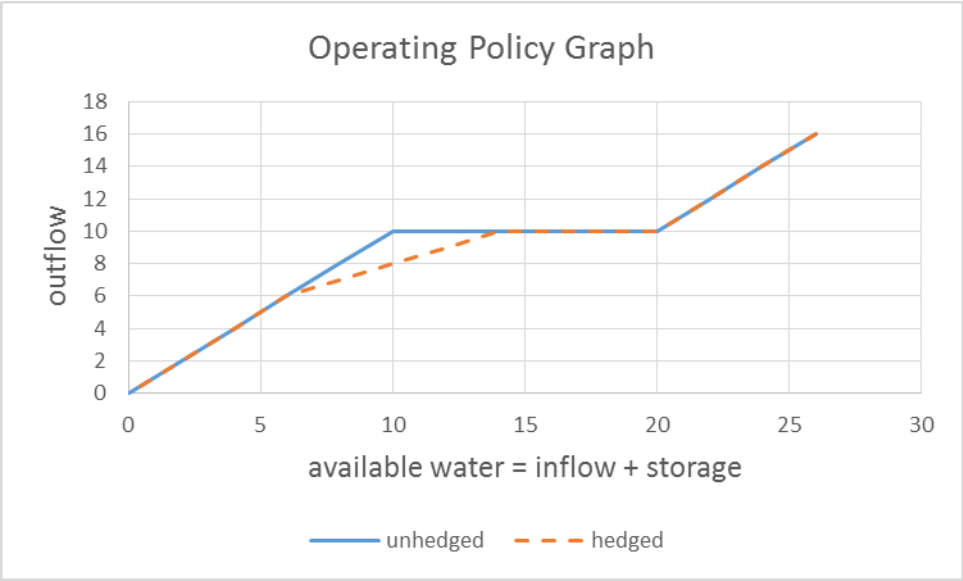


Figure 1 Effect of hedging on outflow.

The hedged line in Figure 1 shows water delivery curtailment before the reservoir drafts to empty. This increases probability of a curtailment but reduces probability of a very severe curtailment. The balance between avoiding curtailments and avoiding empty reservoirs has received attention in the literature recently. For example, Google Scholar indicates J. W. Labadie's (2004) article "Optimal Operation of Multireservior Systems State of the Art Review" has been cited 728 times. Many of these articles apply modern optimization techniques to optimizing reservoir operations. The Treaty makes no attempt to hedge. Hedging theory was developed prior to negotiation of the Treaty. One of the seminal works in optimization, Little (1954), applied dynamic programming to operation of the Columbia River dams. Perhaps the Treaty developers were aware that the unusually dry period in the period of record led to conservative operations.

## COLUMBIA RIVER CRITICAL PERIOD

**Low Water Periods:** Calculating periods of lowest average unregulated inflow of various lengths provides insight. The unregulated flows used for planning in the Columbia River Basin are the modified flows published by the Bonneville Power Administration (2011). These modified flows are essentially flow that would exist if dams did not exist but irrigation withdrawals occurred at 2010 levels. Using modified flows and a spreadsheet one can calculate consecutive rolling averages of increasing lengths. For example, a column of three month averages contains averages of August through October, September through November, October through December and so on until all data are used. Columns going across contain progressively longer periods August through October, August through November, etc. Each column has a minimum value. These minimum values increase as longer periods are averaged. Figure 2 shows periods of lowest average unregulated flow at The Dalles for periods between one and 76

months. Most periods of lowest average flow add one month to the preceding shorter period. However, periods sometimes jump years away. For example the smallest ten month average extends from July 1936 to April 1937, the smallest 11 month average extends from July 1936 to May 1937, but the smallest 12 month average extends from December 1976 to November 1977.

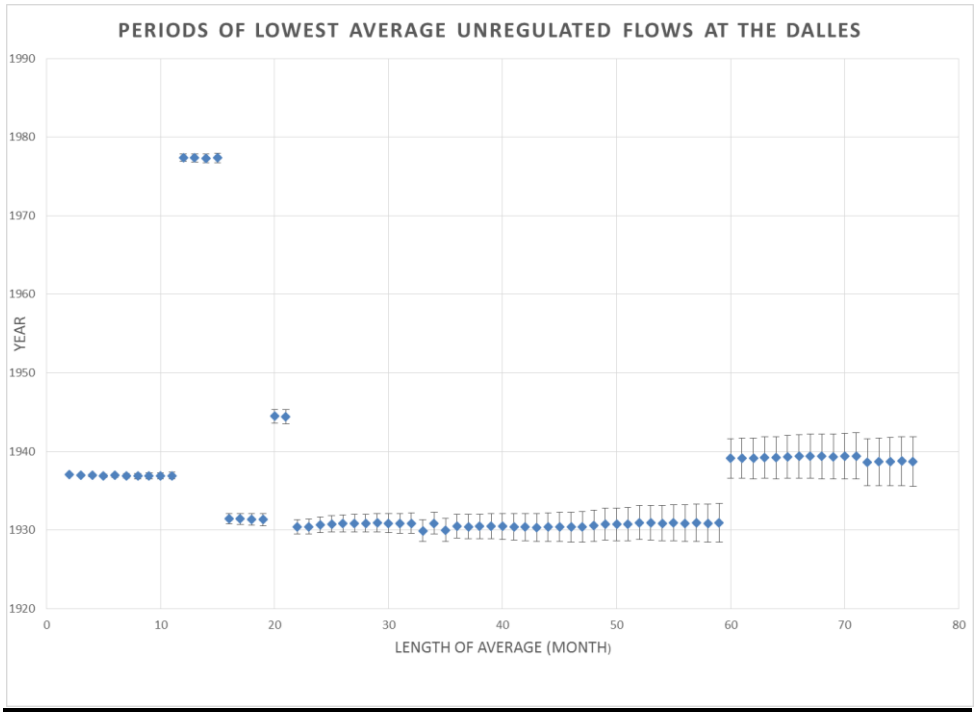


Figure 2 Periods of lowest unregulated flows at The Dalles

**Water Supply Critical Period:** To include effects of reservoir drafting in critical periods, reservoir content is divided by the number of months averaged and added to the average flow values described in the previous section. Longer periods have reservoir content divided by a larger period length yielding a smaller result. Smaller storage content also yields a smaller value. Over longer periods average reservoir contribution decreases but average stream flow increases. There exists a time where the sum of these two competing effects result in a minimum value. This is the critical period flow. Figure 3 shows average critical period flow with drafting for some storage levels. The periodicity of the plot arises from the seasonality of flow. Higher flow occurs during spring snow melt and lower flow occurs in fall and winter.

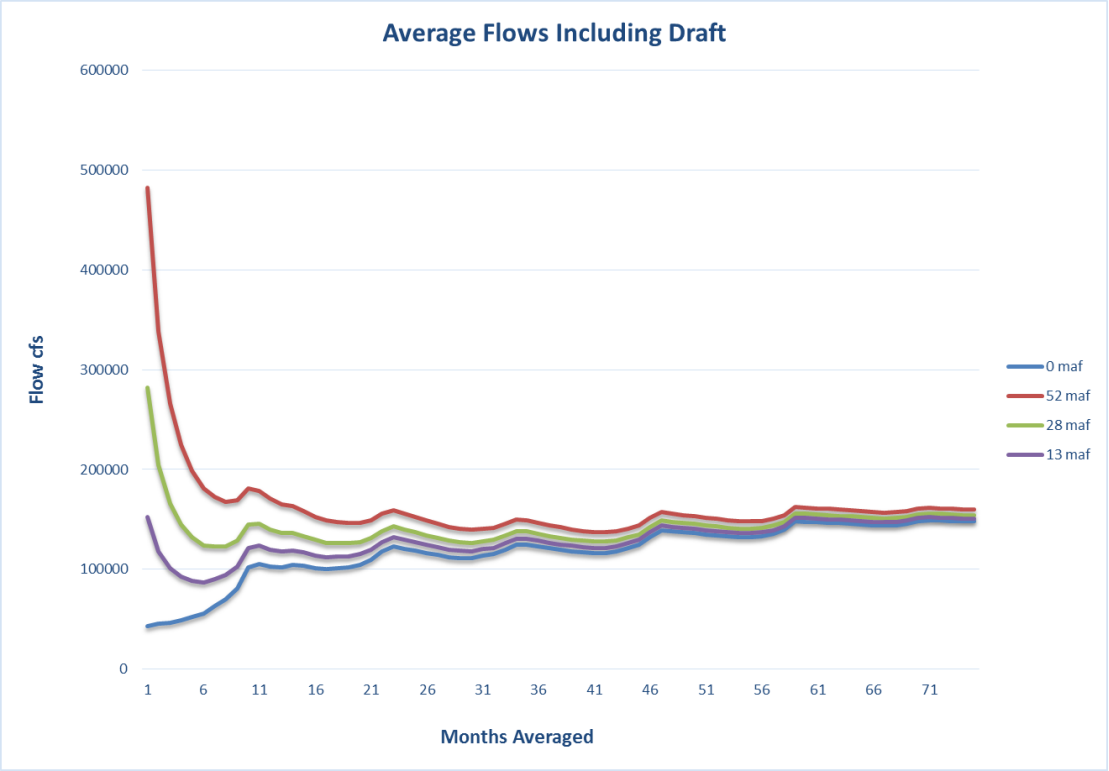


Figure 3 The Dalles average flows with drafting

**<u>Comparison of Water and Power Critical Periods:</u>** Given the complexity of calculating power critical period it is worth examining the difference between power critical periods and water supply critical periods. The power critical periods come from Columbia River Treaty Operating Committee (2013). Table 1 shows time periods are usually quite similar.

Table 1 Power and flow critical periods.

| Storage | Power Critical Period | Water Critical Period |
|---|---|---|
| 52 maf | Aug 1928 Feb 1932 | Sept 1928 – Feb 1932 |
| 28 maf | Sept 1943 April 1945 | Aug 1936 – March 1937 |
| 13 maf | Nov 1936 April 1937 | Sept 1936 – March 1937 |

The power and water critical periods for the 28 maf case appear quite different. However, the two critical periods are eight and 20 months long, respectively. As discussed regarding Figure 3 critical periods with similar values may have lengths differing by 12 months due to the annual shape of flow variation. Figure 2 shows the 20 month flow minimum is near 1945 whereas the eight month minimum is near 1937. Figures 4 and 5 apply the stretched string method to these two periods. The line showing draft in 1945 just barely makes it between the upper and lower lines.

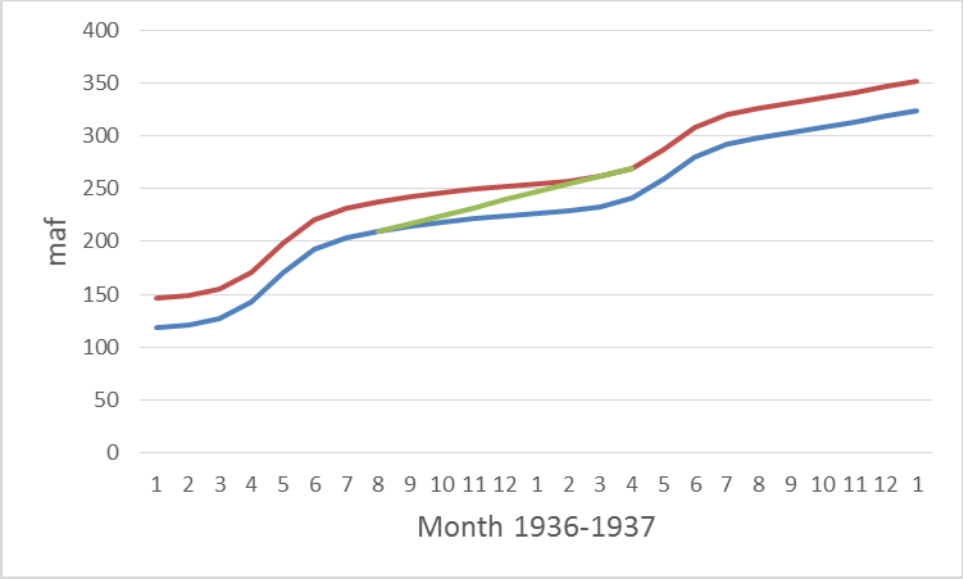


Figure 4 Stretched string approach applied to 1936-1937.

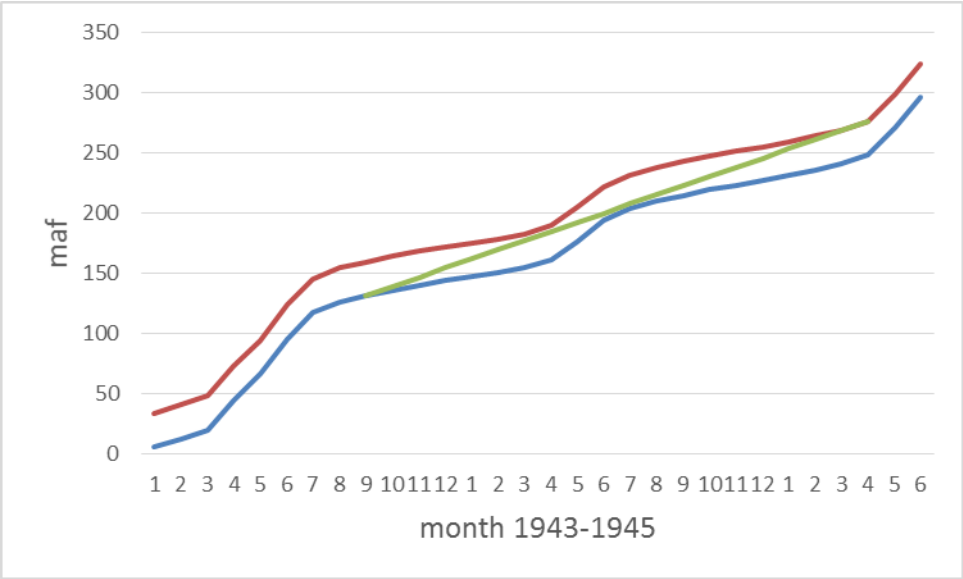


Figure 5 Stretched string approach applied to 1943-1945.

## CONCLUSION

The concept of critical period, the period of minimum flow as a reservoir drafts from full to empty, has a long history in reservoir planning. However, critical period is often referred to by other names in the literature. It has been improved by using a stochastic approach to flows and hedging when low flow conditions exist. The Columbia River Treaty used a straight critical period without either of these improvements. However, the Treaty allows for supplemental agreements between parties, so in practice the United States and Canada often implement these improvements.

Power and water supply critical periods are similar. Power critical period calculations require calculating project operation making these calculations more complicated. Portions of a basins often have different critical periods than the basin as a whole. Consequently, power critical periods depend on where hydrogeneration is located in a basin.

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