Incorporating Long-Term Streamflow Forecasting into the Cascade Regional Yield Simulation Model

Amie Myers¹ and Richard N. Palmer ²

¹Research Assistant, Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington, 98195-2700; PH 206-616-1775; acmyers@u.washington.edu
²Professor, Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington, 98195-2700; PH 206-685-2658; palmer@u.washington.edu

Abstract

This paper describes the use of long-term streamflow forecasts for improved reservoir operations. The forecasts make use of climate conditions (El Niño Southern Oscillation and Pacific Decadal Oscillation) to derive operating policies that increase flows for fish while maintaining water supply reliability. The impacts on historical instream flows and reservoir storage volumes of six climate conditions as a function of PDO and ENSO are investigated. Four simulation experiments are performed using current instream flow requirements and three alternatives, including increasing instream flows by 10% and 25%, and a variable trigger based upon climate conditions and reservoir storage volume. Performance is based upon impacts to reliability and ability to meet increased instream flow targets. This study demonstrates that PDO-ENSO conditions can be used to develop reservoir operating policies that provide more flows for fish with little impact on system reliability.

Background

Seattle, Washington is located in the Pacific Northwest, a region known for its abundance of rainfall and mild climate. However, the region is facing the dual challenge of increasing municipal and industrial (M&I) demand for water and increased concerns about maintaining healthy stream habitat for fish. Seattle and its adjacent suburbs depend primarily upon surface water for M&I uses. Seattle's water supply is subject to considerable hydrologic uncertainty, increasing the vulnerability of water supply in the region. Storage capacities are small relative to streamflow and M&I demands. At maximum conservation storage, demands can only be met for approximately four months. Another important component of this vulnerability may be attributed to climate variability. Due to the 1999 listing of Chinook Salmon as an endangered species, vulnerability has become a key issue for planners. Water resource managers must continue to balance the needs of people with potential ecological impacts.

This study investigates the potential for using long-term streamflow forecasts associated with climate variability to aid in the prediction of seasonal stream flows. Currently, Seattle Public Utilities (SPU) meets instream flow requirements on the South Fork Tolt River as well as flow targets set for the Cedar River. Pending approval of the Cedar River Habitat Conservation Plan in April 2000, Seattle will be required to meet new instream flow requirements on the Cedar River. Historically, instream flows have easily met the targets during wet seasons (November through May). During lower flow seasons (June through September) maintaining these targets becomes more difficult. Reservoir operators must be sure that storage volumes will meet M&I
demands while satisfying instream flow requirements. During this period of time it is more likely that releases for instream flows will closely track minimum requirements. This reduction in releases becomes problematic when instream flow requirements describe a minimum necessary flow for habitat instead of the amount of flow needed to maintain optimal conditions. As demands increase through the years, instream flow releases may approach the instream flow requirements (Nelligan-Doran, Palmer and Reese 1999). Providing reservoir operators with knowledge about expected flows can increase reservoir operations flexibility and performance.

SPU currently operates two reservoirs to meet the demands of SPU customers as well as the needs of 26 wholesale water suppliers within the Seattle metro area. The Cedar and South Fork Tolt Rivers supply water to more than 1.2 million residents in the region. The Cedar River Watershed is approximately 90,500 square acres and the South Fork Tolt watershed is approximately 12,600 square acres. During the winter season, flood control dominates reservoir operations. At the beginning of the water year (October 1st), the reservoirs are drafted to a flood operations elevation. Releases are made for water supply and to meet fish flow targets. After the fall rains begin in earnest (November), SPU's primary concern typically is flood operation as sufficient water exists for all other purposes. In the spring, the reservoirs are refilled, storing snowmelt runoff between March and June. Ideally, on June 1st, the reservoirs are full. This storage and the lower seasonal summer inflows are used to meet summer M&I demands, which are at their yearly highest, as well as providing habitat needs downstream (City of Seattle 1998).

Instream flow requirements exist on the Cedar and Tolt Rivers. On the Cedar River, new requirements will be implemented when SPU implements its new Habitat Conservation Plan. This plan was initiated by SPU in response to the potential Endangered Species Act listing of Chinook Salmon (Chinook salmon were listed March 1999). The 1988 Tolt Settlement Agreement sets instream flow requirements along the South Fork Tolt River. This agreement was between Seattle City Light, regulatory agencies, and the Tulalip tribe as part of Federal Energy Regulatory Commission licensing at that time.

Long-Term Forecasts Using Climate Variability

Climate variability describes regular climate patterns with discernable characteristics. These patterns may be identified by time scale (months to decades) and impacts. Northwestern hydrology and ecology are believed to be impacted by two patterns in particular, the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997). The ENSO has a time scale of two to four years. ENSO oscillates between warm (El Niño), cool (La Niña), and moderate phases. The El Niño phase is associated with above average temperatures during the winter and spring seasons and lower than average precipitation in Seattle. La Niña can be associated with the reverse conditions: cooler winter and spring temperatures, and higher than average rainfalls. ENSO forecasts can now be made a year in advance.

PDO phases are associated with warm and cool phases, with similar temperature and rainfall characteristics as those corresponding to ENSO. During the 20th century, PDO phases have extended two to three decades. Cool PDO regimes prevailed from 1890-1924 and from 1947-1976, while warm PDO regimes occurred from 1925-1946 and 1977 until at least the mid 1990s.
Hamlet and Lettenmaier (1999) investigated long-term forecasts in the Columbia River Basin based upon historical data and climate variability conditions. Their study indicated that instream flows reflect PDO-ENSO conditions, especially during periods of time when the two oscillations are in sync (Cool, La Niña and Warm El Niño). Long-term forecasts using PDO-ENSO conditions can be made up to a year in advance by using ENSO forecasts and assuming PDO conditions are the same as the current year. This method becomes difficult to apply during shifts between PDO phases, which currently can only be noted after they occur (Hamlet and Lettenmaier 1999).

During most years Seattle's water supply is very reliable, providing water in excess of municipal demands and fish requirements. During the late summer an excess volume of water typically exists prior to the reservoir refill season. This volume (noted here as slackwater) represents the amount of water that is available but not used during the critical season. Increasing the power of long-term streamflow forecasts may provide the opportunity to use slackwater volume to enhance fish flows downstream during above average flow years. The use of slackwater could have significant benefits for instream flows as well as municipal water supplies if used properly (Reese, Palmer and Nelligan-Doran 2000). The goal of incorporating long-term forecasts into reservoir operating policies is to increase operational flexibility and the ability to maximize the water made available to fish when they need it most, without reducing M&I reliabilities.

**CRYSTAL Model Framework**

The Cascade Regional Yield Simulation Model (CRYSTAL) was developed by researchers at the University of Washington with the cooperation of water supply agencies in the area (Nelligan-Doran, Palmer and Reese 1999, Reese, Palmer and Nelligan-Doran 2000). This model is a significant part of the University of Washington's Puget Sound Regional Synthesis Model (PRISM) Project. PRISM is a multi-disciplinary campus effort to model human impacts on the Puget Sound and to determine ways in which to better manage its natural resources. CRYSTAL simulates demands, instream releases, and water supply operations for the Puget Sound Region, focusing on the water supplies of Everett, Seattle, and Tacoma. This model utilizes 63 years of historical gauge data and incorporates current operations associated with the water supplies to produce probabilistic results demonstrating the reliability of these systems, the ability to meet future demands, and the impacts operational changes have on the systems. In this study, CRYSTAL is used as the modeling framework to evaluate the value of ENSO-PDO forecasts.

**Characterization of System with Respect to PDO-ENSO Conditions**

This study investigates the impacts, if any, PDO-ENSO conditions have upon the system with respect to streamflow, reservoir storage, and fish flows. Six climate variability conditions, based upon one of two PDO phases and one of three ENSO phases, were used to study this: Cool, La Niña; Cool, Moderate; Cool, El Niño; Warm, La Niña; Warm, Moderate; and Warm, El Niño.

Historical streamflows for both the Tolt and Cedar Rivers during June-September (a critical period due to low streamflows) are categorized with respect to climate variability conditions that prevailed during summer months. Figure 1 presents the total streamflows during June through
September for each year of historical data. These figures were generated following the procedure described by Hamlet and Lettenmaier (1999). The horizontal lines depict the average instream flow for the given climate condition and the average flow for the rest of the data. Point data portray the total instream flow during the period of interest for each year. Points falling into the climate conditions are in bright blue. Table 1 presents the percentage of historical data in each condition that falls into the categories of high flows, average flows, and low flows. Low flows were defined as flows with a greater than 75% probability of occurrence. Flows with less than 25% probability of occurring were defined as high flows. The flows plus or minus 25% from the average were considered to be average flows. This table demonstrates that for all climate conditions except for Cool, La Niña, flows will most likely fall into the average range. For PDO-Cool conditions, if flows are outside of average conditions, they will most likely fall into the higher than average flow category. For PDO-Warm conditions, flows outside of average will fall into the low flow category.

**Table 1. Streamflows by PDO-ENSO Conditions.**

<table>
<thead>
<tr>
<th>PDO Phase, ENSO Phase</th>
<th>Cool, La Niña</th>
<th>Cool, Moderate</th>
<th>Cool, El Niño</th>
<th>Warm, La Niña</th>
<th>Warm, Moderate</th>
<th>Warm, El Niño</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Flows</td>
<td>42%</td>
<td>30%</td>
<td>25%</td>
<td>0%</td>
<td>20%</td>
<td>8%</td>
</tr>
<tr>
<td>Average Flows</td>
<td>42%</td>
<td>50%</td>
<td>50%</td>
<td>73%</td>
<td>60%</td>
<td>67%</td>
</tr>
<tr>
<td>Low Flows</td>
<td>16%</td>
<td>20%</td>
<td>20%</td>
<td>27%</td>
<td>20%</td>
<td>25%</td>
</tr>
</tbody>
</table>

Reservoir storage conditions were generated on a weekly time step using the CRYSTAL model. The reservoir storage data were generated with instream flow requirements that were unvaried from year to year (no adjustments for low flow years as would normally happen) as well as no allowable dead storage. This system description was used to demonstrate the influence of climate conditions upon reservoir storage without allowing the system to fail or switch to critical instream flows, which would ease demands upon the reservoirs in low flow conditions. Figure 2 presents the average of the total reservoir storage (Cedar and Tolt reservoir) for each condition during drawdown as well as average total storage. This figure indicates that for Cool, La Niña and Cool, Moderate, the reservoir remains filled for a longer period of time. During these two climate conditions, drawdown ends at a storage volume higher than average, as well. During average Warm, El Niño conditions, the reservoir is never full and is well below average storage. Other climate conditions closely track average storage conditions, with the exception of Warm, Moderate, which remains below average until a minimum storage is reached, after which there is a steep increase in storage. Figure 2 demonstrates that the categorization of flows based on PDO-ENSO is useful in describing storage characteristics. If climate conditions are Warm, El Niño, it is very probably that reservoir storage will be below average. If climate conditions are Cool, La Niña and Cool, Moderate, then reservoir storage will most likely be above average.

**Operating Policies**

The CRYSTAL model was used to test operating policies associated with fish flows, with one policy being triggered based on climate conditions and reservoir storage. Simulation 1 modeled
Figure 1. Graphs of June-September Combined Cedar River and South Fork Tolt Streamflows. Each graph presents the average instream flow for the given PDO-ENSO condition as well as the average of the rest of inflows.
operations using instream flow requirements proposed in the Cedar River HCP. Simulations 2 and 3 modeled operations using the HCP instream flow requirements, increased by 10% and 25%, respectively. Simulation 4 uses the HCP instream flow requirements, which were then varied with respect to PDO-ENSO conditions and reservoir storage volume. This regime was specifically developed to explore the feasibility of using PDO-ENSO conditions to improve operations. This simulation includes a triggering process that determines instream flows based upon PDO-ENSO and current amount of supply available. Table 2 presents the instream flow regimes for each simulation.

Table 2. Simulation target schemes

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Instream Flow Regimes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flow Requirements designated by Cedar River HCP and Tolt Instream Flow Agreement</td>
</tr>
<tr>
<td>2</td>
<td>All flow requirements are increased by 10%</td>
</tr>
<tr>
<td>3</td>
<td>All flow requirements are increased by 25%</td>
</tr>
</tbody>
</table>
| 4          | Flow requirements are raised according to PDO-ENSO conditions:  
  • Cool, La Niña: 25% increase  
  • Cool, Moderate: 20% increase  
  • Cool, El Niño: 10% increase  
  • Warm, La Niña: 0% increase  
  • Warm, Moderate: 10% increase (becomes 0 if total reservoir storage is less than average during week 37 of the year)  
  • Cool, El Niño: 0% increase |
Results

The comparisons between simulation results were analyzed to determine the impacts each instream flow regime has on fish flows and water supply reliability. Figure 3 depicts annual reliability results of each simulation for M&I water demand projections in 2010, 2020, and 2030. For the demands projected in 2020, each simulation results in 98% to 100% reliability. During Simulation 2, reliability drops to 86% in the year 2030. Reliability anticipated for Simulation 3 declines to 70%. During Simulations 1 and 4, reliabilities remain greater than 90% for the demand of 2030. Under the flow regime in Simulation 4, only one more shortfall occurs than in Simulation 1. This figure indicates that triggering fish flow policies according to climate conditions and storage can mitigate significant losses in reliability due to increased fish flow targets.

Figure 4 presents fish flow results. The graph portrays the fish flows during the summer months generated by each simulation. These flows are the result of averaging the weekly historic flow values generated by CRYSAL and summing them for each month. The units are in cfs/month. During the months of June through October, Simulation 3 results range from 78 cfs to more than 150 cfs larger than the flows provided in the HCP. Simulation 2 range from 29 to 60 cfs greater than flows experienced during Simulation 1. Simulation 4 results are similar to, but less than, simulation 2 results, ranging from 23 to 54 cfs.

Figure 3. Simulation Results: Water Supply Annual Reliability

![Seattle Annual M&I Reliability](image-url)
Conclusions

This study investigates the impacts of PDO-ENSO climate variability patterns upon instream flows and reservoir operations. As expected, PDO-ENSO conditions can indicate when streamflows will vary significantly from the average. During the June-September period, flows tend to be average or less when warm, La Niña conditions occur. This demonstrates that PDO predominates for this climate condition. The three other climate conditions seem to be equally likely to be above or below average streamflows. PDO-ENSO conditions influenced storage volumes in the system as well. When the climate patterns are in sync, storage volumes will be significantly higher than average (Cool, La Niña) or lower than average (Warm, El Niño). Cool PDO conditions produced storage volumes that were overall greater than average storage volumes, and warm PDO conditions produced nearly average or below storage volumes. These results demonstrate that according to historical data, PDO-ENSO conditions do impact Seattle water supply sources.

Four simulation experiments are compared to evaluate the impacts on fish flows. The first of these represents the instream flow requirements soon to be implemented in the Cedar River basing. Simulations 2 and 3 represent increasing instream flows by 10% and 25% regardless of climate conditions. These policies significantly reduced Seattle's ability to provide a reliable water supply under future demands. Increasing fish flows according to the climate conditions associated with each historical year using impacts of PDO-ENSO upon instream flows and storage volumes was successful. Instream flows were increased for more than 65% of the historical years, causing one more shortfall than those that can anticipated using proposed instream flow targets.
The instream flow regimes were then evaluated to determine if their impacts both on system reliability and summer river flows. The 25% increase in fish flows allows the most amount of water to be provided for fish as expected. On average, the fish flows triggered based on climate conditions provide just slightly less flow than the continuous 10% increase in fish flows regime. This demonstrates that the variable flow regime can be successfully used to increase fish flows during the summer with much less stress upon the supply system than a regime which provides fish flows with no consideration of climate conditions or storage volume.

References


