

## **Progress Report**

# **Historic Habitat Opportunities and Food-Web Linkages of Juvenile Salmon in the Columbia River Estuary and Their Implications for Managing River Flows and Restoring Estuarine Habitat**

## **Physical Sciences Component**

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## Table of Contents

Item	Page
Executive Summary	5
Introduction	7
Task 1	7
The interaction of Tides, River Flow and Coastal Forcing	7
Methods	13
Results	14
Task 2	21
The Historical Flood Regime	21
Methods	21
Results	21
Tasks 3-5	24
Hydrologic Change and its Causes	24
Methods	25
Results	27
Publications Associated with the Project	41
References	41



## Executive Summary

Long-term changes and fluctuations in river flow, water properties, tides, and sediment transport in the Columbia River and its estuary have had a profound effect on Columbia River salmonids and their habitat. Understanding the river-flow, temperature, tidal, and sediment-supply regimes of the Lower Columbia River (LCR) and how they interact with habitat is, therefore, critical to development of system management and restoration strategies. It is also useful to separate management and climate impacts on hydrologic properties and habitat. This contract, part of a larger project led by the National Oceanic and Atmospheric Administration (NOAA), consists of three work elements, one with five tasks. The first work element relates to reconstruction of historic conditions in a broad sense. The second and third elements consist, respectively, of participation in project-wide integration efforts, and reporting. This report focuses on the five tasks within the historic reconstruction work element. It in part satisfies the reporting requirement, and it forms the basis for our participation in the project integration effort.

The first task consists of several topics related to historic changes in river stage and tide. Within this task, the chart datum levels of 14 historic bathymetric surveys completed before definition of Columbia River Datum (CRD) were related to CRD, to enable analysis of these surveys by other project scientists. We have also modeled tidal datums and properties (lower low water or LLW, higher high water or HHW, mean water level or MWL, and greater diurnal tidal range or GDTR) as a function of river flow and tidal range at Astoria. These calculations have been carried for 10 year intervals (1940-date) for 21 stations, though most stations have data for only a few time intervals. Longer-term analyses involve the records at Astoria (1925-date) and Vancouver (1902-date). Water levels for any given river flow have decreased substantially (0.3-1.8 m, depending on river flow and tidal range), and tidal ranges have increased considerably (by a factor of 1.5 to 4 for most river-flow levels) since the 1900-1940 period at most stations, with the largest percentage changes occurring at upriver stations. These changes have been caused by a combination of changes in channel roughness, shape and alignment, changes in coastal tides, and (possibly) bed degradation. Tides are growing throughout the Northeast Pacific, and Astoria (Tongue Pt) has one of the most rapid rates of increase in tidal range in the entire Eastern Pacific, about 0.3m per century. More than half of this change appears to result from changes within the system, the rest from larger scale changes in coastal tides. Regression models of HHW have been used to estimate daily shallow water habitat (SWHA) available in a ~25mile long reach of the system from Eagle Cliff to Kalama for 1925-2004 under four different scenarios (the four possible combinations of diked/undiked and observed flow/ virgin flow). More than 70% of the habitat in this reach has been lost (modern conditions vs. virgin flow with not dikes). In contrast, however, to the reach between Skamokawa and Beaver, selective dike removal (instead of a combination of dike removal and flow restoration) would suffice to increase spring SWHA.

The second task consists of reconstruction of the hydrologic cycle before 1878, based on historic documents and inversion of tidal data collected before the onset of the historic flow record in 1878. We have a complete list of freshet times and peak flows for 1858-1877, and scattered freshet information for 1841-1857. Based on tidal data, we have reconstructed the annual flow cycles for 1870 and 1871; other time periods between 1854 and 1867 are under analysis.

The three remaining tasks relate to post-1878 hydrologic conditions (flows, sediment supply and water temperature), and separation of the human and climate influences thereon. Estimated observed (sometimes routed), adjusted (corrected for reservoir manipulation) and virgin (corrected also for irrigation diversion) flows for 1878-2004 have been compiled for the Columbia River at The Dalles and Beaver, and for the Willamette River at Portland. Sediment transports for the observed, adjusted and virgin flows have been calculated for 1878-2004 for the Columbia River at Vancouver and Beaver, for the Willamette River at Portland, and for other west-side tributaries seaward of Vancouver. For Vancouver and Portland, it has been possible to estimate sand transport (including gravel), fine sediment transport and total load. Only total load can be estimated at Beaver, and only fine sediment transport can be determined for the west-side tributaries, except for the post-1980 period influenced by the 1980 eruption of Mt St. Helens. Changes in flows and sediment transport due to flow regulation, irrigation diversion, and climate have been estimated. The total decrease in flow at The Dalles between 1878-1899 and 1970-2004 is about 19%, about half of this due to climate change. The loss of total load at Vancouver between these two time periods appears to be about 60%, most due to human reduction of peak spring freshet flows. The loss of sand supply has been more severe, likely >70%.

The incidence of overbank flow has greatly decreased due primarily to flow regulation. Major flow events ( $>24,000 \text{ m}^3 \text{ s}^{-1}$ ) have occurred only five times since 1900. This is a sharp contrast to the second half of the 19<sup>th</sup> century, when flows  $>24,000 \text{ m}^3 \text{ s}^{-1}$  appear to have occurred in 15 years over the 56 yr period between 1844 and 1899. Freshet shape has also changed – modern freshets would be (absent flow regulation) much more sharply peaked than was historically the case, likely as a result of more rapid spring snow melt. Without flow regulation and diversion, modern freshets would sometimes be as large as those before 1900, even though average flows have decreased. Three-year extreme high and low flow periods (triads) were also identified. Most (9 of 10 at The Dalles and 8 of 10 at Beaver) of the highest observed flow triads occurred before 1900. This percentage is reduced to 5 of ten at both stations for virgin flow. All of the 10 most extreme three-year low-flow triads have, with the sole exception of 1890, occurred since 1925, regardless of whether the observed or virgin flow is considered. The two driest three-year triads and five of the 10 driest triads occurred between 1925 and 1941. The remaining dry triads (except 1890) occurred between 1978 and 2002.

Analyses of the 1938-date Bonneville Dam water temperature record, flow and air temperature data back to 1891 suggest that water temperatures are now 1.9-3°C warmer than historically for the months of May to December, potentially affecting both outbound juvenile salmonids and returning adults. Reservoir manipulations account for more than half of the total change in water temperatures. Climate change accounts for 0.6-1°C of warming during the months of June to October.

## **Introduction**

Long-term changes and fluctuations in river flow, water properties, temperature, tides, and sediment transport in the Columbia River and its estuary have had a profound effect on Columbia River salmonids and their habitat. These alterations have been caused both directly by human influences and indirectly by natural processes related to climate and the coastal ocean. Human alterations include the hydropower system (the largest single factor), irrigation withdrawal, navigational development, diking and filling, and changes in land use throughout the basin. These human alterations interact with each other and are difficult to separate from the influence of climate. Climate processes include a long-term increase in temperature, a decrease (relative to the 19<sup>th</sup> Century) in flow, and fluctuations in flow related to the Pacific Decadal Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO) cycle. Long-term changes in the Eastern Pacific Ocean (both human and natural) have changed the tidal regime of the system. Understanding the river-flow, temperature, tidal, and sediment-supply regimes in the Columbia River and how they interact with habitat is critical to development of system management strategies, including the maintenance and restoration of shallow water habitats used by juvenile salmon. It is also vital to separate the impacts of climate and management.

Attempts to restore salmon habitat in the Columbia River tidal-fluvial regime require that the interaction of basic physical processes (e.g., river flow, tides, and sediment input) with habitat be defined. It is also important to define and model the trajectory of physical changes over the last 150 yrs, and determine how this has influenced salmonids, salmonid habitat, and the tidal-fluvial ecosystem as a whole. We use, therefore, available data, new data analysis methods, and models to determine: 1) how changes in river flow, temperature, and the tidal regime and sediment input affect habitat, and 2) how these changes are related to climate and human alterations. Work for five tasks has been carried out, as described below.

## **Task 1: Analyze Historic Changes in River Stage and Tides**

### The interaction of Tides, River Flow and Coastal Forcing

River flow controls juvenile salmonid habitat availability and character directly by altering river stage, and indirectly by influencing tidal range and salinity. Tidal range affects juvenile salmonid habitat location and availability during juvenile migration through the lower river and estuary. Changes in coastal tides and alterations of seasonality and strength of the annual river flow cycle (especially changes in volume and timing of the spring freshet) mean that the annual cycle of tidal range has changed since construction of the hydropower system. The net result is that habitat for juvenile salmonids has been displaced in time (season) and space (distance from the river channel). Habitat availability reaches a maximum earlier in the season than historically and habitat is available only at lower elevations (and decreased in extent) by the reduction in river stage in spring. Its character has changed because of the displacement, because tidal range during spring has increased, and because the new habitat is at elevations more strongly affected by tides. The 40-45% decrease in spring freshet flow (Naik and Jay, 2005, Bottom et al., 2005) has also limited the availability of shallow water habitat (SWHA) by increasing salinity intrusion – Chawla et al. (2009) suggest that salinity intrusion length in the Columbia varies approximately with the inverse square root of river flow. Our analyses focus, however, on the tidal river landward of Tongue Pt, where salinity intrusion is typically absent during high-flow periods, regardless of flow regulation. We also focus on tidal-fluvial interactions.

The physical processes involved in tidal-fluvial interactions can be described as follows. Tidal conditions throughout the system are affected by the amplitude of the tides entering the system from the coastal ocean. Coastal tides have been growing throughout the NE Pacific in recent decades (Jay, 2009). Coastal conditions are, however, not the only determinant of tidal ranges in the system. Tidal wave propagation and river outflow within the Lower Columbia River (LCR) are both strongly influenced by friction at the river bed. Bed friction varies with the square of total velocity (river flow plus tidal flow). The stronger that friction, the more quickly the tidal wave is damped as it propagates upriver, and the greater the slope needed to discharge the river flow; i.e., the higher the river stage. The total friction or drag at the bed is also related to bed roughness and channel shape. It is, therefore, affected by navigation channel development, changes in the sediment budget (e.g., trapping of sediment behind dams and sand removal), and natural changes in channel configuration. The factors investigated in this part of the program include: historic datum levels, historic decreases in river stage and shallow water habitat area (SWHA) related to flow reduction, a decrease in stage for any given flow related to decreased bed friction, and increased tidal range throughout the system (the latter related both to reduced friction and changing coastal processes).

## Methods

### *a) Tidal-fluvial interactions*

Innovative use of existing tidal analysis methods and development of new methods has allows us to: (1) understand how tides and river flow interact, (2) deal with challenges presented the historic data set, (3) separate local anthropogenic effects on tides from those related to changes in coastal tides, (4) model changes in shallow water habitat, and (5) hindcast river flow. Tidal and water level analyses have been carried out using four methods:

1) Wavelet tidal analysis (Jay and Flinchem, 1997, 1999, Flinchem and Jay, 2000): Kukulka and Jay (2003a) used a wavelet filter bank tuned to the frequencies of the tidal species (e.g., diurnal and semidiurnal) to optimally extract information concerning the modulation of tides by river flow. This approach has been further used to hindcast pre-1878 river flows (see Task 2).

2) Extraction of datum levels: Because of the emphasis on habitat and datum levels, recent work has used multiple linear regression analyses to extract datum levels (Lower Low Water or LLW, Mean Water level or MWL, and or Higher High Water HHW) and Greater Diurnal Tidal Range (GDTR) as a function of river flow and other external forcing. Separate analyses are carried out for overlapping 10 year periods, allowing the historic evolution of the tidal datums and tidal range to be determined. While it would be desirable to use shorter time periods for these analyses, to search for sharp changes in tidal properties, this is not possible because of the limited dynamic range of river flow periods of <10yrs. The analysis is further complicated (after 1970) by flow regulation – very high events are rare since 1970, and it is difficult to obtain a satisfactory dynamic flow range using even 10-year increments. Two types of regression models were used. Both were based on those developed by Kukulka and Jay (2003a), but with some modification based on experience. The first form was designed for simplicity and robustness against change in the dynamic range of river flow. The equations used were:

$$LLW = a_0 + a_1 Q_{TD} + a_2 Q_{WR} + a_3 \left( \frac{T_{R,Astoria}^2}{Q^{0.5}} \right) \quad (1)$$



$$HHW = b_0 + b_1 Q_{TD} + b_2 Q_{WR} + b_3 \left( \frac{T_{R,Astoria}^2}{Q^{1.5}} \right) \quad (2)$$

$$MWL = c_0 + c_1 Q_{TD} + c_2 Q_{WR} + c_3 \left( \frac{T_{R,Astoria}^2}{Q^{1.333}} \right) \quad (3)$$

$$\log_{10} \left[ \frac{T_{R,Vancouver}}{T_{R,Astoria}} \right] = d_0 + d_1 Q_{TD} + d_2 Q_{WR} + d_3 \left( \frac{T_{R,Astoria}^2}{Q^{0.5}} \right) \quad (4)$$

Where:

$Q_{TD}$	= River flow at The Dalles in 1000s of m <sup>3</sup> /sec
$Q_{WR}$	= River flow at The Dalles in 1000s of m <sup>3</sup> /sec
$T_R$	= Greater diurnal range (m)
$a_0$ to $a_3$	= Model parameters for each station

The coefficients (the  $a_i$  to  $d_i$ ,  $i=1,4$ ) in (1) to (4) were determined by regression to best fit the observations over successive 10-yr periods, with a different set of coefficients determined for each time period. Two departures from “standard” multiple linear regression were employed. First, a Robust inversion was used. A Robust regression iteratively down-weights outliers to achieve a more certain result with tighter confidence limits. A second set of weights were also used. Very high and low river flows (and very small or large tidal ranges) are rare, but these points are very important in determining the behavior of tidal datum levels for very high and low flows, which is necessary here. Data points were accordingly weighted relative to the inverse square root of their frequency of occurrence (in river-flow and tidal range space). This weighting was applied along with the Robust re-weighting, so that the total weight on each data point was the product of the river-flow/range weight with the Robust weight.

Because of their robustness against changes in dynamic range of flow, the models shown in (1) to (4) were used for historical comparison across time periods. More complex models (with additional powers of river flow) were used to optimize accuracy of the flow predictions over the full range of river flows. These models are closer to the system dynamics, but are more strongly affected by changes in flow dynamic range. Because this latter set of models optimizes the representation of tidal properties within any given time period, they were used for SWHA analyses. Regardless of which sort of model was used, the regressions described the data quite well. The weighted  $R^2$  values for regressions of LLW, HHW and MWL using (1) to (4) were almost always  $>0.9$ , with many values between  $0.95 < R^2 < 0.99$ . Models of GDTR were less successful, typically with  $0.65 < R^2 < 0.85$ .

The regression analyses of tidal properties carried out are summarized in Table 1. The discrete regression model coefficients provided values at 21 stations at 5-10 yr intervals from 1940 to 2004, with many gaps. Continuous coefficient values were, however, needed for SWHA analyses. Several spatial and temporal interpolation methods were used to estimate missing values for use in SWHA analyses. The resulting coefficients allow stage calculation from rivermile (RM)-18 to 143 at 1 mile increments with annual changes to the coefficient values from 1940 to 2004. Using these coefficients, historic tidal data at Astoria, and river flow at Beaver Army Terminal daily tidal properties was calculated for RM-18 to 143 from 1925 to 2004 using (1) to (4). Because Astoria (Tongue Pt) tidal data were available continuously from 1925-date and it was de-

sirable to consider the warm-PDO period from ca. 1926-1946 in the analysis, tidal properties typical of 1940-1943 were assumed also to be valid for 1925-1939.

**Table 1:** Inventory of Modeled Tidal Data

Nominal Period Central Date Station:	1940-1943 1941.9	1970's 1976.5	1980's 1985.5	1990's 1995.5	2000's 2004	RM
Hammond			X			8
Ft Stevens	X					8.1
Astoria (Tongue Pt)	X	X	X	X	X	13
Altoona	X		X			24
Skamokawa	X		X	X	X	33.7
Cathlamet	X					37.3
Wauna	X	X	X	X	X	41.6
Eagle Cliff	X					51.1
Beaver			X	X	X	54.1
Stella	X					56.2
Longview	X		X	X	X	66.3
Rainier			X			67.5
Kalama	X					75.4
Columbia City		X	X			84
St Helens	X		X	X	X	86.1
Willowbar	X					95
Kelly Pt	X					101
Vancouver	X		X	X	X	106.3
Ellsworth	X					112.1
Washougal	X		X			123.1
Warrendale	X		X			142.6

3) Robust harmonic analysis (Leffler and Jay, 2009): In conjunction with other funded research, we have improved standard harmonic analysis to allow extraction of tidal characteristics from noisy tidal records with gaps. The improvement is accomplished by changing the traditional least-squares minimization of harmonic analysis to a more flexible (Robust) minimization that iteratively down-weights the noisier parts of the record. This type of analysis was used in detecting bad data and evaluating the effects of record length on the accuracy of derived tidal parameters. It was particularly useful in analyses of pre-1900 tidal data, which were noisy.

4) Mean water level (MWL) based on daily water level data: Recently we were able to recover an elevation data set (1 point per day) for Vancouver for 1902-1971. Joined with more detailed data available since late 1972, this allowed us to reconstruct historic changes in MWL at Vancouver for 1902-2008. Water level data were collected at Vancouver only once daily before 1972 (except for hourly data 1940-42). Fortunately, the protocol of collecting a single value daily at a fixed time randomizes the tidal phase over a ~29d period (one tidal month). Over a period of several years, the daily data will sample random tidal phases over the range of river flow levels.

Thus, even with daily sampling, MWL can be determined as a function of flow, given sufficient averaging time. These daily data do not allow estimation of LLW, HHW or GDTR.

#### *b) Regional Tidal Evolution*

Tidal properties are changing quite rapidly throughout the Lower Columbia River (LCR), a symptom associated in part with navigational development. There is, however, also a regional component to tidal evolution. This has been evaluated for all long term tide stations along the eastern Pacific Coast (Jay, 2009), with support from other projects, funded primarily the National Science Foundation. To determine the long-term evolution of the major diurnal ( $K_1$ ) and semidiurnal ( $M_2$ ) constituents, the hourly tidal time series for each station were convolved with filters tuned to the appropriate frequencies; this yields an amplitude and phase for each constituent for each time period; 3-yr windows were used to ensure isolation of the frequencies. The hourly astronomical tidal potential for each station was analyzed in the same manner. Yearly values of admittance (complex ratio of tidal response to astronomical forcing) for the two frequencies were determined and resolved into an amplitude ratio and a phase difference. A trend in admittance amplitude was converted to a trend in amplitude, and the results interpreted. This work has also been partially supported by the Oregon Transportation Research and Education Consortium (OTREC). Results will be presented in Jay et al. (2009, in preparation).

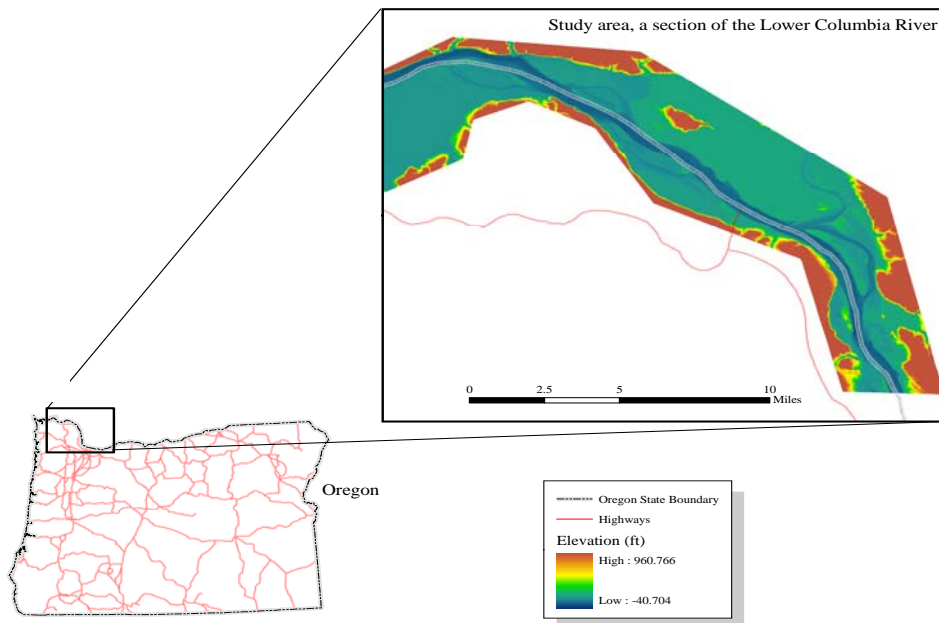
#### *c) Analyses of Historic Datum Levels*

Jointly with work funded by the US Army Engineers Portland District, we have analyzed datum levels for 14 historic bathymetric surveys (H-sheets) from the US Coast and Geodetic Survey (USC&GS). This work employs all available information on the H-sheets and other historic documentation. It appears that most 19<sup>th</sup> Century surveys above about Skamokawa were referenced to a datum similar to the present CRD (Columbia River Datum), but about 0.2-0.3m higher. It is interesting that they were able, with very limited tidal data and rudimentary surveying techniques, to do as well as they did in setting up this datum level.

#### *d) Shallow Water Habitat Area (SWHA) Analyses*

SWHA was defined for a variety of flow and tidal scenarios for a reach upriver of that considered by Kukulka and Jay (2003a,b). The study area was a 25-mile reach from Eagle Cliff to just below Kalama. It consists of both sections with narrow entrenched topography and reaches with broad floodplains (Figure 1). The elevation data used was a 10m resolution digital elevation model (DEM) created from LiDAR flown in 2005 by the Puget Sound LiDAR Consortium and bathymetry data compiled by the University of Washington. The inundated area was defined, the LiDAR data were processed to remove the erroneous returns resulting from LiDAR striking the water surface, bathymetric and LiDAR data were merged, and gaps between the bathymetric and LiDAR data were interpolated. The resulting 10m DEM was used as the basis for further work. Digital ortho-photo quadrangles (DOQ) were used to assist in defining shoreline features.

The 25-mile reach was divided into 1 rivermile (1 RM) sub-reaches. Two sets of shape-files were used to delineate these sub-reaches and to locate the levee-protected areas. The Lower Columbia River Estuary Partnership provided shapefiles containing levee linework and polygons representing flood protected areas. Both the line work and polygons were approximate representations of levee and protected area locations, but were sufficiently accurate for this analysis.



**Figure 1:** The study area for Shallow-Water Habitat Area study reach from Eagle Cliff (at left) to near Kalama (lower right). The state line is shown as dotted.

Describing the quantity of available SWHA and relating it to the stage of the river was accomplished through the calculation of hypsometric curves for each sub-reach. The hypsometric curve is a graph that relates the river stage to inundated area. The relationship was derived for two different elevation models to represent the diked (modern) and undiked (historic) conditions. This approach allows for quick computation of SWHA, relative to use of the full hydrodynamic equations. However, it does not account for the topographical connectivity of areas behind levees. This issue is dealt with by calculating the hypsometric curve for the diked condition by “filling” levee-protected areas to the minimum dike elevation.

The levee protected scenario required manipulation of the original DEM to numerically prevent flooding of the protected areas except for river stage conditions where the levees would be overtopped. This was accomplished by increasing the height value of the protected area raster cells to that of the overtopping height of the respective levees. When flooding is calculated using this manipulated DEM the results reflect behavior expected of a levee protected reach. This solution involved editing the levee polygons, defining an overtopping height for each levee, and processing the original DEM to reflect the developed conditions. After this processing, the 1-RM sub-reaches were aggregated into four larger sub-reaches for each development scenario, each with a different hypsometric curve shape (e.g., floodplain vs. entrenched). The defined relationship between river stage and SWH provides a concise numerical depiction of reach flooding, given specific tide and river flow conditions.

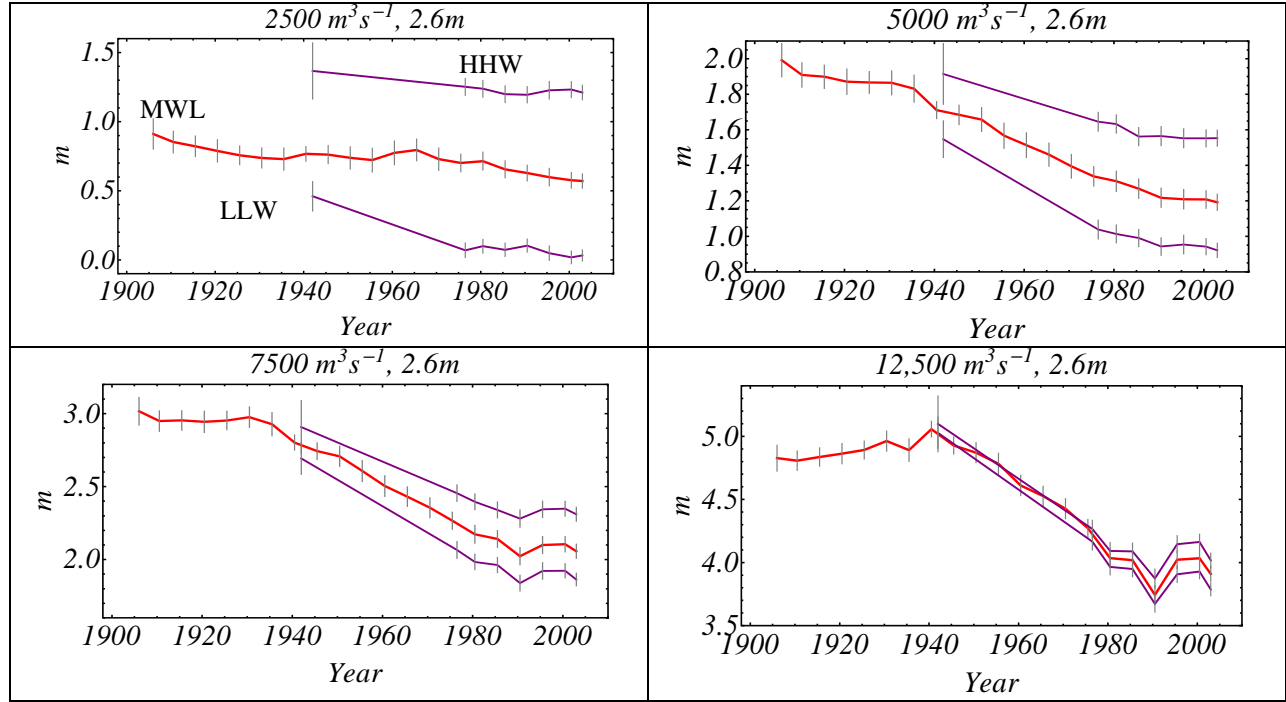
This work was in part supported by the US Army Engineers, Portland District.

## Results

### *a) The interaction of tides and river flow*

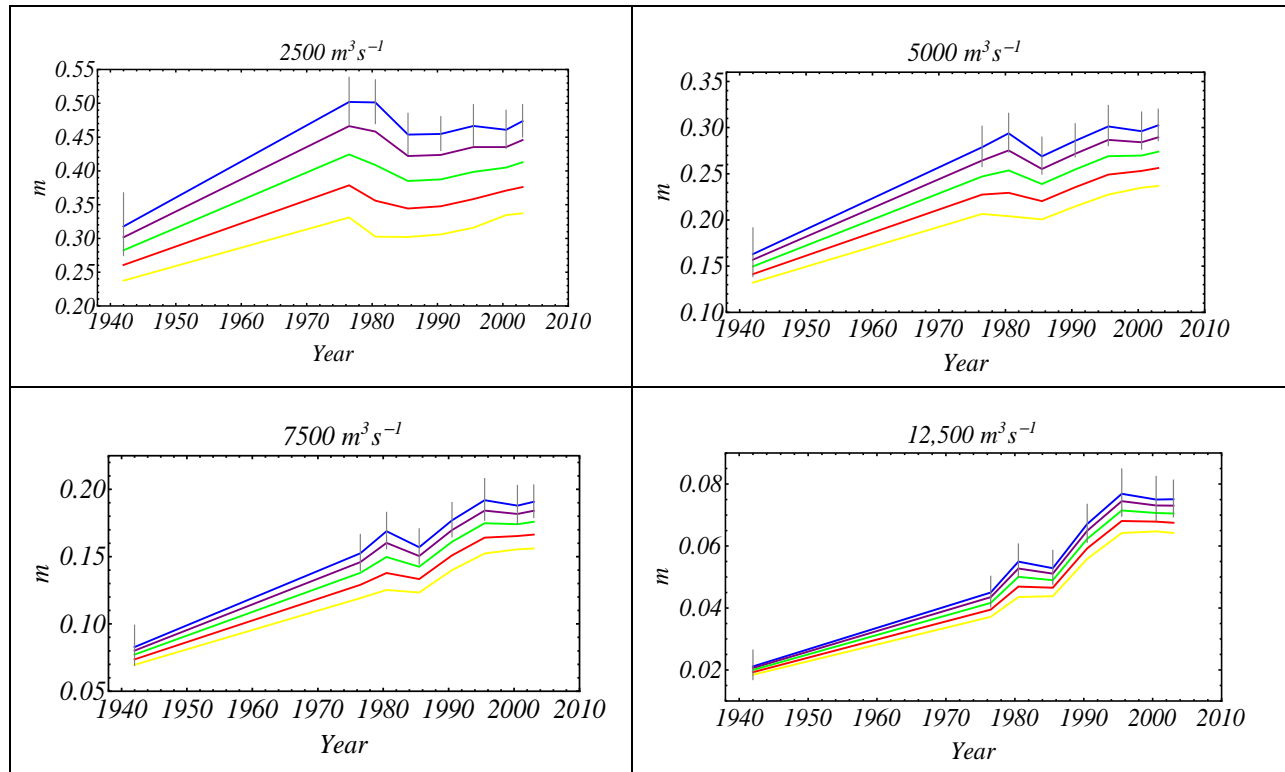
We have analyzed historical changes in tidal datum levels for all major Columbia River stations from ca. 1940-date (Table 1) and for Vancouver 1902-date. Presented here (Figure 2) are results for Vancouver, for which an almost continuous record is available since 1902 for MWL. HHW and LLW values are available from 1940-1943 and 1972-date. The time evolution of each of these datum levels is presented for four different river flow levels,  $Q_R = 2500, 5000, 7500$  and  $12,500 \text{ m}^3 \text{ s}^{-1}$ , each for a tidal range of 2.6m at Astoria, which represents an average between neap and spring conditions. MWL has dropped almost monotonically since ca. 1900-1940 for flow levels between 2500 and  $7500 \text{ m}^3 \text{ s}^{-1}$ . The decrease in MWL from maximum values has been ~0.4, 0.8, 1, and 1.1m, respectively for the four flow levels shown in Figure 2. Larger decreases are hindcast for the highest modeled flows (not shown), e.g. 1.3-1.5 for flows of  $15\text{-}20,000 \text{ m}^3 \text{ s}^{-1}$ . There is also a maximum in MWL ca. 1930-1940 for the flow levels of  $10\text{-}20,000 \text{ m}^3 \text{ s}^{-1}$ , possible because of the installation of pile dikes during the 1930s. Tidal ranges, the vertical distance between HHW and LLW, has increased for all flow levels, as further discussed below. At the lowest flow level modeled ( $Q_R = 2000 \text{ m}^3 \text{ s}^{-1}$ ; not shown) MWL and LLW have decreased from a maximum in the 1960s, but HHW has increased in recent years, reflecting an increase in tidal range GDTR (HHW-LLW). The LLW decrease of ~0.4m since 1940 for  $Q_R = 2000 \text{ m}^3 \text{ s}^{-1}$  is most relevant for navigation, because low water levels limit the draft at which loaded ships may sail. The HHW decrease of 1.5-1.8m since 1940 for very high river flow is most relevant for SWHA, because decreases in HHW limit inundation of SWHA during the spring season.

Historical changes in Vancouver GDTR are shown in Figure 3, for four different river flow levels,  $Q_R = 2500, 5000, 7500$  and  $12,500 \text{ m}^3 \text{ s}^{-1}$ . Each panel in Figure 3 represents results of five different forcing tidal ranges at Astoria, ranging from 1.6m (a very weak neap tide) to 3.6m (a very strong spring tide). Tidal ranges have generally increased for all flow levels, by a factor of ~1.5-4, with the largest percentage increases for the highest flows. The lower two flow levels suggest that larger tidal ranges prevailed in the 1970s than at present. Tidal ranges for all flow levels suggest a recent decrease in the rate of change, with the highest flow levels showing the most recent decreases in the rate of change. Figure 2 suggest (comparing the LLW and HHW curves) that tidal range is actually still increasing. How can these divergent results be reconciled? The error bars are substantially wider for GDTR than they are for LLW and HHW, in part because the data are noisier. The greater noise in the GDTR results from the fact that noise in either LLW or HHW affects GDTR, so that there are more noisy GDTR data points. Thus, it appears likely that tidal range is still increasing at Vancouver; this idea is consistent with less detailed data at other stations.



**Figure 2:** Hindcasts of MWL, LLW and HHW at Vancouver at 5-10 yr intervals for four flow levels, 2500, 5000, 7500 and 12,500  $\text{m}^3\text{s}^{-1}$ . MWL is hindcast for 1902-date, LLW and HHW for 1940-date. These are based on regression analyses of overlapping 10 yr periods; 95% confidence limits are shown for each time period (vertical bars), and the confidence limits are located at the center time for each analysis period. Note that there are no HHW and LLW data available between 1943 and 1972.

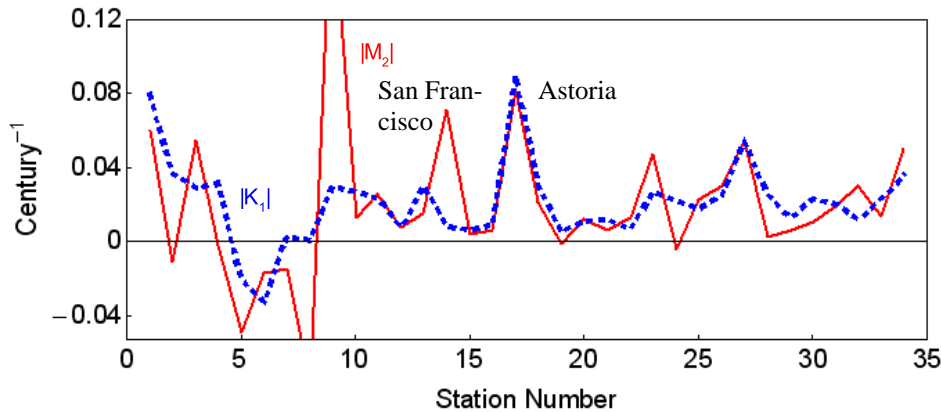
One significant caution in interpreting results of the regression model presented in Figures 2 and 3 should be mentioned. While the model is based on hydrodynamic reasoning, realistic results can only be expected for conditions represented within the historic record. The results are “accurate” in that they describe the available data, as suggested by the 95% confidence limits shown in each figure. Such statistical measures reflect, however, only the effects of random errors in the data, not systematic effects. There has, for example, been a decrease in the incidence of very low-flow days  $<2000 \text{ m}^3\text{s}^{-1}$  at The Dalles. Such conditions occurred frequently before 1940, but only rarely since. The number of high flow days (flow  $>12,500 \text{ m}^3\text{s}^{-1}$ ) has decreased drastically since ca. 1970 due to flow regulation. Variations in the dynamic range in flow between time periods – e.g., there were no high flows between 1986 and 1995 whereas flows were quite high from 1996-1999 – may affect model predictions even in the absence of actual changes in hydrodynamic properties in the system. Thus, the model is most reliable for flows between 2500 and 12,500  $\text{m}^3\text{s}^{-1}$  (because all time periods have flows in this range) and the most believable changes are those that endure over several decades. To put this in more concrete terms, the long-term decreases shown in MWL and LLW for all flow levels is robust; i.e., similar results can be achieved by a variety of methods. However, the minimum for MWL, LLW and HHW ca. 1990 for flows above 10,000  $\text{m}^3\text{s}^{-1}$  may be an artifact – there were no high flows during the 1986 to 1995 analysis period.



**Figure 3:** Hindcasts of tidal range at Vancouver at 5-10 yr intervals for four flow levels, 2500, 5000, 7500 and 12,500  $m^3 s^{-1}$  for 1940-date. In each panel, the curves represent tidal range at Vancouver for Astoria tidal ranges of (top to bottom) 3.6, 3.1, 2.6, 2.1 and 1.6m, respectively. Hindcasts are based on regression analyses of overlapping 10 yr periods; 95% confidence limits are shown for each time period (vertical bars on the top line in each panel), and the confidence limits are located at the center time for each analysis period. Note that there are no range data available between 1943 and 1972.

#### b) Regional Tidal Evolution

Astoria has, aside from stations in Mexico and Central America with noisy records, one of the highest rates of increase in relative tidal range amongst all long-term stations along the Eastern Pacific Coast. Only Queen Charlotte City has a higher rate. Shown in Figure 4 is the relative rate of change (absolute rate of change in mm/century divided by amplitude in mm) for the dominant diurnal ( $K_1$ ) and semidiurnal ( $M_2$ ) constituents. The tidal range is related to the sum of twice the  $K_1$  and  $M_2$  amplitudes (but is also influenced by overtides that are small at Astoria). Based on the record for Astoria for 1925-date, the rate of increase at Astoria is about  $0.3m \text{ century}^{-1}$  (1ft  $\text{century}^{-1}$ ), or  $\sim 16\% \text{ century}^{-1}$ . Less complete data suggest that the rate is even larger at Wauna, especially in relative terms. The Northern California and Oregon Coasts from San Francisco to Astoria are, in general, a “hot spot” for increasing tidal range. Comparing the Astoria data to shorter records for South Beach (Newport Bay) and Charleston (Coos Bay) not shown in Figure 4, it appears that roughly half the rate of change at Astoria is due to estuarine and fluvial alterations, and about half due to changes in coastal tides. Figure 4 includes only stations with length of records or LOR > 44yrs, thus excluding South Beach and Charleston. Such long records are needed to eliminate the effects of the 18.6 cycle in tidal range.



**Figure 4:** The relative rate of tidal evolution (evolution rate over amplitude for each constituent) of stations from Chile (at left) to Alaska (at right); Astoria and San Francisco are indicated (From Jay, 2009).

### c) Analyses of Historic Datum Levels

Analyses of historic habitat being carried out by University of Washington require that datum levels for historic hydrographic surveys (H-Sheets) conducted by the US Coast and Geodetic Survey (now the National Ocean Service or NOS) and US Army Engineers be established and evaluated for accuracy. Internal comparisons for each sheet, analyses of information provided by groups of sheets in adjacent areas, and other documentary evidence provided by NOS and the US Army Engineers, Portland District and NE Pacific Region have been used to estimate a datum for each of 16 surveys, and to evaluate as far as possible the internal consistency of the results achieved. It is not only important to establish what datum level was used (and its apparent relationship to CRD or Columbia River Datum), but whether the values used are plausible (or affected by substantial systematic errors.) The best opportunity to evaluate the consistency and quality of the 19<sup>th</sup> Century is provided by the near-simultaneous occupation of nine stations from Cathlamet to Warrendale in September 1877 (Table 1).

Table 2 shows datum estimates for the nine stations occupied in September 1877. There is a general pattern (with the exception of St Helens) that the established datum was 0.2-0.3 m above CRD. The most definite result is provided by Vancouver, where a river gauge was established in 1876 and has been maintained since that time. No datum was established at Warrendale based on the 1877 observations (even though the station was maintained for almost a month), because the tide was too small and irregular, presumably due to fluctuations in river flow. The reason for the discordant result St Helens is unclear. However, the first major dredging and pile dike construction in the lower river was on the St Helens bar starting in 1877. It may be, therefore, that the hydraulics of this reach changed considerably between 1877 and establishment of CRD in 1912. It should also be noted that, for stations below Rainier, a correction was made for the effects of the strong 1877 El Niño, as noted in Table 2. This correction was based on NOS records for the old Astoria gauge in use from 1853 to the 1880s, climate indices, and the effect of El Niño on contemporary tides. The correction applied is -0.15m at Cathlamet and decreases to zero at Rainier and points landward. The rationale for this decrease is that ocean effects on datum levels should decrease landward, as the base level of the river rises away from the ocean. If this assumption is not made (i.e., no El Niño correction is applied), then the 1877 datum rises relative to CRD as the ocean is approached. This seems unlikely, since water level fluctuations due to



river flow are smaller at more seaward stations. This should have resulted in estimate by NOS of a datum level closer to CRD at the more seaward stations. Overall, the results suggest that the quality of the work carried out was quite impressive considering the difficult working conditions.

**Table 2:** Datum Analysis, Based on September 1877

Station	H-Sheet <sup>1</sup>	Sheet Datum on CRD <sup>2</sup> , m	El Niño Factor <sup>3</sup> , m
Cathlamet	H-1335	0.23	-0.15
Eagle Cliff	H-1336	0.28	-0.1
Oak Point	H-1336, H1368	0.28	-0.1
Rinearson	H-1368	0.29	-0.05
Rainier	H-1369a	0.25	0
Kalama	H-1369b	0.25	0
St Helens	H1524, H-1711	0.14	0
Vancouver	CL 102-5	0.24	0
Warrendale	H-2574	none	0

<sup>1</sup> The H-Sheet designation indicates the sheet for which the datum was used. In some cases, this was 10-25 years after the 1877 datum determination.

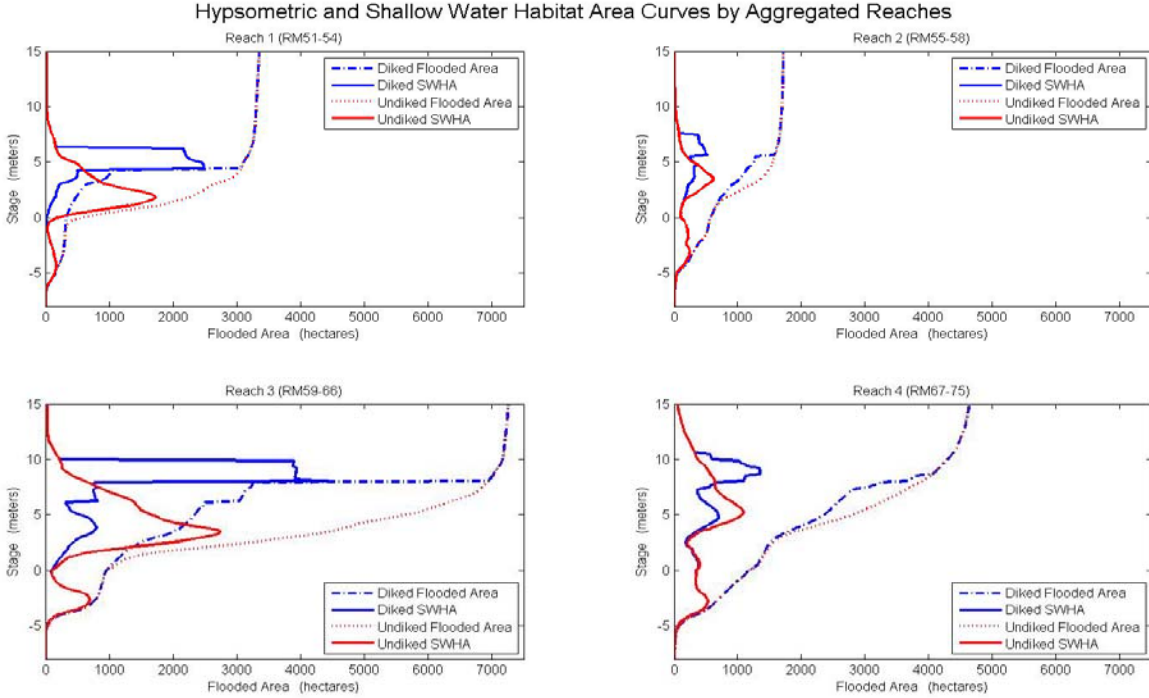
<sup>2</sup> A positive value indicates that the datum level is above CRD.

<sup>3</sup> A negative correction indicates that the datum report in column 3 was lowered by the indicated amount.

### *c) Shallow-Water Habitat Area (SWHA) Analyses*

Kukula and Jay (2003a,b) reported calculation of shallow water habitat area (SWHA) for the Skamokawa to Beaver Reach for four scenarios: virgin flow and no dikes, virgin flow with dikes, actual flow without dikes, and actual flow with dikes in place. All scenarios were analyzed using 1980-2000 tides. A revision of this work has been carried out, using much improved (LiDAR) floodplain topography and an awareness of the rapid evolution of tides. The reach under analysis at present extends from Eagle Cliff (RM-51) to just below Kalama (RM-75). While the regression analysis of tidal datum levels summarized in Table 1 would allow us to carry out SWHA analyses for the entire reach from Tongue Pt (RM-18) to Warrendale (RM-143), merged bathymetry and corrected LiDAR topography are only available for RM-51 to RM-75. When corrected LiDAR topographic data for other reaches are made available, we will be able to analyze other parts of the system. Thus, we cannot, at this time, update the earlier calculations by Kukulka and Jay for the Beaver to Skamokawa reach.

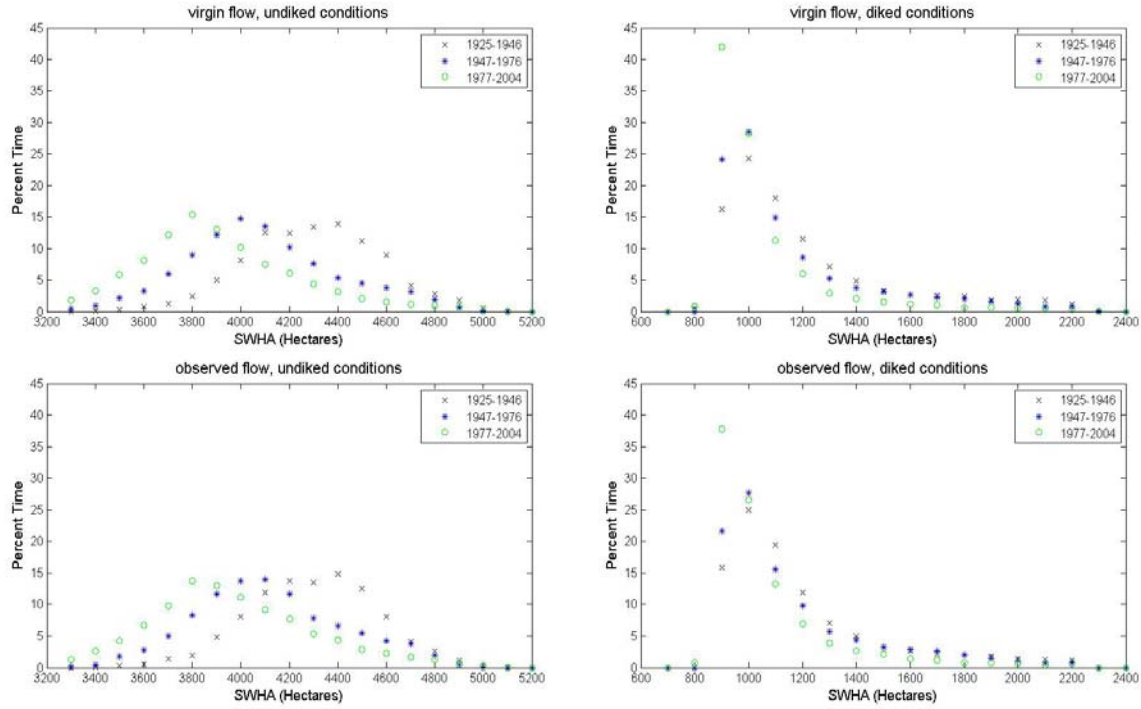
The Eagle Cliff to Kalama reach was, as noted above, divided into four sub-reaches for analysis. Figures 5 shows hypsometric and SWHA vs. height curves, with and without dikes, for the four sub-reaches. Diking raises the elevation required to inundate a significant amount of SWHA in all four sub-reaches, the difference being most pronounced in sub-reaches 1 and 3, and smallest in sub-reach 4. Also in sub-reaches 1 and 3, the consistent height of dikes establishes an effective floor for inundation at ~4m (at Beaver Army Terminal) and ~8m (the Longview area), respectively. This presumably reflects the high level of development under protection in these two sub-reaches. The other two sub-reaches have less consistent dike heights. For comparison between reaches, we analyze the same four scenarios as Kukulka and Jay (2003a,b). We analyze, however, the effects on SWHA over a longer period (1925-2004 vs. 1974-1998) to allow consideration of climate effects, (warm and cold PDO periods) and changing flow management.



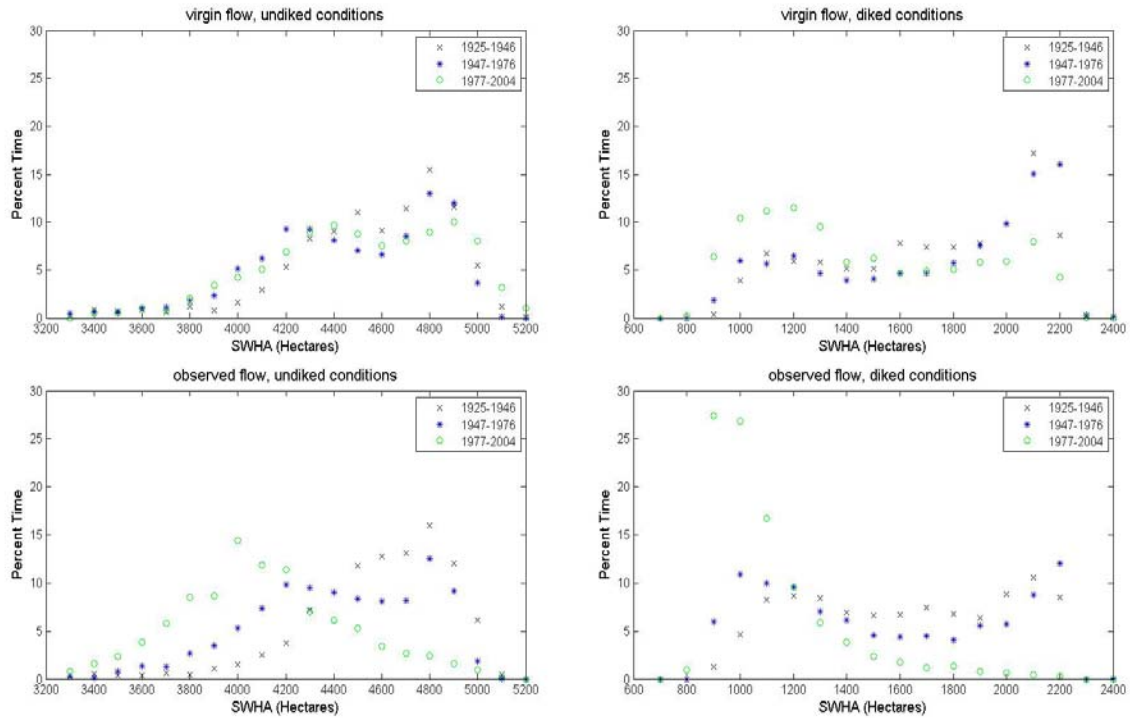
**Figure 5:** Sub-reach hypsometric and SWHA vs. elevation curves for the Beaver to Kalama reach, for diked and undiked topography.

We present here, for comparison with Kukulka and Jay (2003a,b), summary results for the four scenarios defined above for the freshet (May to July) and non-freshet (August to April) seasons. Average non-freshet season SWHA (Figure 6a) and average freshet season SWHA (Figure 6b) are shown (as percent occurrence of various levels SWHA) for three time periods (1925-1946, 1947-1976, and 1977-2004). The years 1925-1946 was a warm-PDO period with little flow regulation, moderate flow diversion, and variable flows, quite low in some years. The years 1947-1976 cover a cold-PDO (Pacific Decadal Oscillation) period with moderate to high flow regulation and diversion, and consistently high virgin flows. The 1977-2004 period represents the present management regime of high flow regulation and diversion. It has variable PDO (mostly warm PDO 1977-1995, then cold PDO or mixed from 1996). Figure 6a and b were compiled using the maximum SWHA (based on the estimated daily HHW for each sub-reach) for each day in the 1925-2004 period. Figure 6a was compiled using all days during the months August-April. Figure 6b was compiled using only days during the May-July freshet period.

The 1977-2004 period has the lowest percentage occurrence of large values of SWHA for all scenarios in both Figures 6a and 6b. This is not surprisingly, given the long-term reduction in flow documented below. It is initially non-intuitive that, for undiked conditions (with both observed and virgin flows), the 1925-1946 period shows higher peak SWHA values than the 1947-1976 period, even though mean flows were higher during the 1947-1976 period. This is because very high flows inundate large parts of the flood plain with more than 2m of water, and SWHA is defined as areas with between 0.1 and 2m of inundation. This situation occurred much more often after 1946 than during 1925-1946.



**Figure 6a:** Percentage occurrence of SWHA for three climate periods based on all non-freshet season (August to April) days in the 1925-2004 period; see text for details.



**Figure 6b:** Percentage occurrence of SWHA for three climate periods based on all freshet-season (May-July) days in the 1925-2004 period; see text for details.

**Table 3:** Summary of Average SWHA for Three PDO and Management Periods, for the Freshet and Non-Freshet Seasons

<b>Freshet Season</b>	<b>1925-1946</b>	<b>1925-1946</b>	<b>1947-1976</b>	<b>1947-1976</b>	<b>1977-2004</b>	<b>1977-2004</b>
(May-July)	Hectares	%	Hectares	%	Hectares	%
Virgin Flow, Undiked	4570	100 <sup>1</sup>	4450	97	4552	100
Observed Flow, Undiked	4634	101	4454	97	4146	91
Virgin Flow, Diked	1769	39	1853	41	1520	33
Observed Flow, Diked	1671	37	1604	35	1151	25
<b>Non-Freshet Season</b>	<b>1925-1946</b>	<b>1925-1946</b>	<b>1947-1976</b>	<b>1947-1976</b>	<b>1977-2004</b>	<b>1977-2004</b>
(August-April)	Hectares	%	Hectares	%	Hectares	%
Virgin Flow, Undiked	4347	100	4329	100	3945	91
Observed Flow, Undiked	4350	100	4166	96	4014	92
Virgin Flow, Diked	1253	29	1257	29	1093	25
Observed Flow, Diked	1240	29	1244	29	1118	26

<sup>1</sup> The SWHA for the virgin flow/undiked scenario for 1925-1946 is taken as 100%.

Average SWHA properties (by area in hectares, as a percentage of 1925-1946 SWHA for the virgin flow/undiked scenario) are shown in Table 3, for both the freshet and non-freshet seasons. It is again evident that the very high flow period 1947-1976 has slightly less SWHA than other periods in the virgin flow/undiked scenario. In fact, the observed flow/undiked scenario for 1925-1946 also has slightly more SWHA than the virgin flow in both seasons. The contrast between natural (virgin flow/undiked scenario) and modern (observed flow/diked scenario) are considerably starker than in Kukula and Jay (2003a,b). Fully 75% of the original SWHA has been lost during the freshet season (74% for the non-freshet season), and most of the increased loss (relative to the Skamokawa-to-Beaver reach) is associated with diking. Flow regulation plays a comparable role as in the Skamokawa-to-Beaver reach. There is one encouraging difference – there is little redundancy between diking and flow regulation in the reduction in SWHA. Thus, in this reach, some restoration of SWHA can occur without substantial changes in the flow regime. This does NOT mean that there is no redundant flood control. It means that with reduced flows, floodplain areas too deeply covered under natural conditions to count as SWHA, which must be inundated to <2m. Finally, during the non-freshet season roughly the same amount of SWHA is available with and without flow regulation. This SWHA will be in different locations for the two scenarios, however. Water elevations are higher in absence of flow regulation, the higher the flow, the higher SWHA extends up into the floodplain. As flows increase, some initially flooded SWHA areas become too deeply (>2m) covered to be included as SWHA, shifting SWHA away from the channel.

Full results of our SWHA analysis will be presented in Meagher et al. (2009, in preparation).

## Task 2: Estimate Columbia River Flows Before 1878

### The Historical Flood Regime

The instrumental hydrologic record for the Columbia River begins with daily flow observations at The Dalles in 1878. Observations were also begun at this time at Albany on the Willamette River, but there are many gaps in the Albany record up to 1893. By 1878, irrigation, agriculture, logging, and mining were already beginning to change hydrologic properties, and the climate warming after the “little ice age” that extended up to about 1850. It is, therefore, desirable to learn as much as possible regarding Columbia River hydrology before 1878. The ideal would be to extend the daily flow record back to ca. 1850, but this is not been possible. We have been able to extend knowledge of spring freshets back to 1841 (with gaps), and to estimate the daily flow for 1870-1871, to examine the annual flow cycle.

### Methods

Two approaches have been used to extend the hydrologic record back before 1878: a) compilation and analyses of historical records, and b) a form of inverse analysis that determines river flow from tidal properties. The first approach allows us to extend knowledge of peak freshet flow and timing back to the 1840s, the second allows analysis of the annual flow cycle for selected years, for which tidal data available.

#### *a) Compilation and Analyses of Historical Records*

Henshaw and Dean (1915) list spring freshet peak flows for The Dalles, 1858-1877, based on records compiled at Cascade Locks by the Oregon Steam Navigation Company. Unfortunately, no freshet dates are given. These have been determined from contemporary newspaper accounts and other sources. We have also been able to estimate approximate peak flows for the spring freshets of 1841, 1847 and 1853.

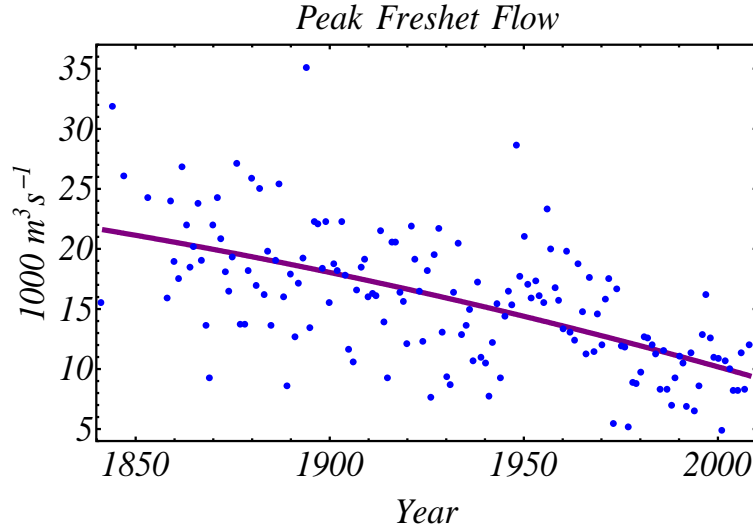
#### *b) Inverse Analysis of Tidal Data*

The tidal-fluvial interactions described under Task 1 provide a method for determining river flow from tidal data. In principle, if the observed tidal range is known at two locations in the river and contemporary tidal conditions are known, then the river flow can be determined for the period of tidal observations. Tidal data (4 daily extrema and one calibration value) are available for much of the 1853-1862 period, with scattered data thereafter. Hourly tidal data are available only for 1870-71, and these are incomplete for 1870. The inverse problem has been solved for the hourly data, 1870-1871, based on a similar analysis for San Francisco Bay, 1858-1931 (Jay et al., 2005). So far, the much sparser data before 1870 have resisted our attempts at inverse analysis – the noise level of the data is too high (given the sparse data) to allow determination of tidal properties over the 7-14d periods that would allow hydrologic estimates. Tidal properties can be estimated over longer periods, but this causes too much averaging of estimated flows.

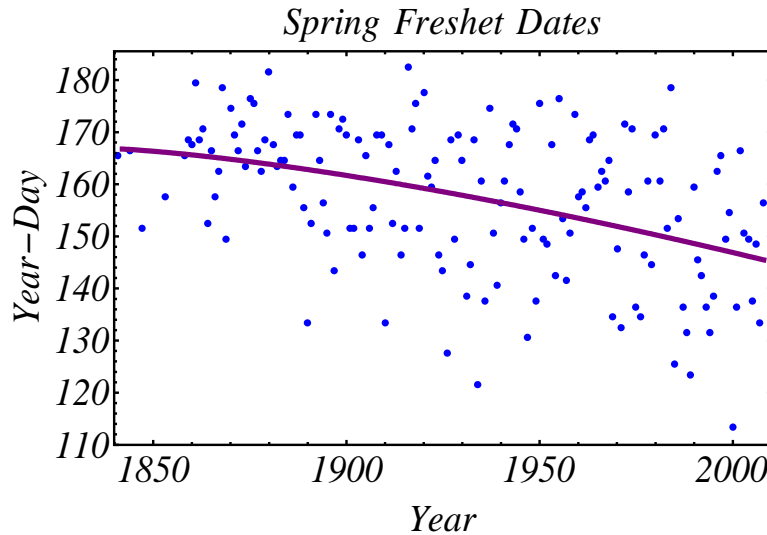
### Results

#### *a) Historical Freshet Dates and Volumes*

Known freshet dates and approximate flows for the 1841-1877 period are tabulated in Table 4, based on our analysis of available documentation. Longer term histories of freshet volumes and dates are provided in Figure 7a,b. It is evident that present peak freshet flows are about half as large as ca. 1860, and that the freshet occurs 15-20 days earlier in the year as in 1860. Figures 7b is consistent with the idea that a slight warming of the climate after ca. 1850 lead to earlier



**Figure 7a:** Peak freshet flows, 1841-2008 and a trend determined by linear regression.



**Figure 7b:** Dates of peak freshet flow as year-day, 1841-2008 and a trend from linear regression.

freshet dates, even before the onset of global warming in the 20<sup>th</sup> Century. Much reduced freshet volumes (Figure 7a) are consistent with the analyses of Bottom et al. (2005), Naik and Jay (2009) and Jay and Naik (2009). In the case of the reduction of peak freshet flow values, flow regulation and irrigation diversion have played a much larger role than climate change. While flow regulation and diversion also affect freshet date, the role of climate has perhaps played a larger role in causing earlier spring freshets than is the case of peak flow values.

#### *b) The Annual Flow Cycle Determined from tidal Analysis*

There are 8760 hrs in a year. More than 8100 hourly tidal observations are available from the Astoria gauge for 1871 (then located in downtown Astoria, not at Tongue Pt). About 5500 observations are available for 1870, with some data missing for each day, and the last days of each

month also missing. Despite these defects in the source data, we have achieved what seems to be a satisfactory inversion of these data to obtain an estimated daily flow (Figure 8). This daily flow provides a smoothed representation of the annual flow cycle on a time scale of several weeks, because of the tidal constituents on which the inversion was based are extracted using overlapping 760 hr analyses. Note that the hindcast flows correspond to the total flow past Astoria, not to the flow at The Dalles.

**Table 4:** Freshet Properties 1841-1877, as Estimated from Historical Documentation: Peak Flow and Date of Peak Flow at The Dalles

Year	Month	Day	$10^3 \text{ ft}^3 \text{ s}^{-1}$	$10^3 \text{ m}^3 \text{ s}^{-1}$
1841	6	?	550	15.6
1844	6	?	1125	31.9
1847	6	1	920	26.1
1853	6	7	856	24.2
1858	6	15	563	15.9
1859	6	18	847	24.0
1860	6	16	668	18.9
1861	6	29	616	17.5
1862	6	18	948	26.8
1863	6	20	777	22.0
1864	6	1	654	18.5
1865	6	16	714	20.2
1866	6	7 or 25	839	9.3
1867	6	11	671	19.0
1868	6	3 or 27	483	13.7
1869	5	30	328	9.3
1870	6	24	777	22
1871	6	19	856	24.2
1872	6	15	737	20.9
1873	6	21	638	18.1
1874	6	13	582	16.5
1875	6	26	684	19.4
1876	6	24	958	27.1
1877	6	16	486	13.8

It is difficult to verify the hindcast in Figure 8, given the absence of instrumental flow data. We can, however, compare the smoothed peak flows in Figure 8 to the peak (one-day) flows for The Dalles in Table 4, taking into account the point that spring freshet flows at Beaver typically exceeded those at The Dalles by  $\sim 2000 \text{ m}^3 \text{ s}^{-1}$  during major 19<sup>th</sup> Century freshets. Table 4 then suggests peak freshet flows at Beaver of  $\sim 24,000$  and  $26,200 \text{ m}^3 \text{ s}^{-1}$  for 1870 and 1871, respectively. The predicted freshet peaks in Figure 8 are  $\sim 19,000$  and  $23,000 \text{ m}^3 \text{ s}^{-1}$  for 1870 and 1871, substantially lower than in Table 4. However, the averaging inherent in methodology used in Figure 8 reduces an LCR freshet of average duration by about 10%, based on analyses of freshets between 1879 and 1900. Taking into account the averaging inherent in the inverse analysis, the predicted peak flow for 1871 is only slightly low, that for 1870 somewhat too low. The correctness of freshet timing can also be checked, and the agreement with Table 4 seems reasonable – the 1871 freshet was later and larger than that in 1870. Newspaper accounts also indicate that there were two freshet peaks in 1870 – one in May and a larger one in mid June; this suggests a freshet of considerable duration. There is a hint of a double freshet for 1870 (with a weak peak in May) in Figure 8, and the 1870 freshet is longer in duration than that in 1871.

The annual fall-season low-flows shown in Figure 8 should also be considered. These are quite high by modern standards,  $7\text{-}9,000 \text{ m}^3 \text{ s}^{-1}$ , with annual minimum flows never dropping to  $6,000 \text{ m}^3 \text{ s}^{-1}$ , even during winter. The most obvious interpretation is that the predicted minimum flows are too high. Such an interpretation is supported by the fact that algorithm is most sensitive at high flows and least sensitive for low flows. On the other hand, analyses of San Francisco bay inflow (1858-1931) suggests that there was a period of substantially higher summer flows in the early 1870s than in later decades. Thus, the meaning and validity of the hindcast in Figure 8 requires further investigation.

### **Task 3: Reconstruction of Hydrologic Properties after 1878**

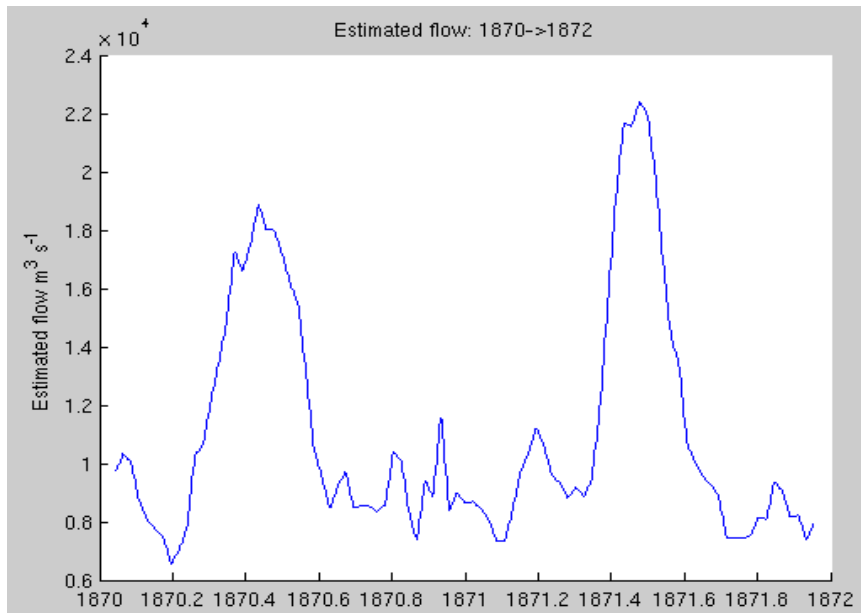
### **Task 4: Reconstruction of Changes in the Sediment Balance since 187**

### **Task 5: Hydrological Effects of Climate Change and Human Activities**

#### Hydrologic Change and its Causes

These three tasks will be discussed together, because any given hydrologic analysis tends to address more than one of them. They are also the subject of three papers submitted in the last year: Naik and Jay (2008, 2009), and Jay and Naik (2009). The work carried out for these tasks includes: new estimates of adjusted and virgin flow for 1878-2004, definition of long-term changes in mean flow and sediment transport since 1878, and analysis of long-term changes in the system's disturbance regime (especially the incidence of overbank flow and the occurrence of very wet and dry periods). Analyses of changes in water temperature at Bonneville Dam since 1938 are the subject of a paper in preparation (Jay et al., 2009). The analysis (reported in Task 1) of variations in SWHA relative to PDO variations also addresses the mission of these three Tasks.





**Figure 8:** Estimated daily river flow for 1870-1871, based on inversion of tidal analysis results.

## Methods

### a) Hydrologic Analyses

Habitat is constructed from sediment, in this system predominantly from mixed sand and silt, the mixture depending on habitat location and exposure to bedstress. A major issue facing the system is the loss of supply caused by reservoir construction and reduction of high flows. This has caused the sand budget to be out of balance – less material is being supplied than is being exported by dredged material disposal (at sea and on land) and export from the estuary to shelf (during high flows). Fine sediments (silt and clay) are also important for their role in water quality (in terms of both toxic content and their effect on oxygen levels in the water column and in the bed), as a detrital food source supporting the estuarine food web, for maintenance of the estuarine turbidity maximum (ETM), and for their contribution to habitat construction.

This part of the research uses data collected by the USGS, Environment Canada, and the U.S. Army Corps of Engineers to understand changes in: (1) seasonality and amount of river flow, (2) the supply of fine and coarse material to the estuary, and (3) long-term changes in flow and sediment transport. Analyses have been carried out as follows; we have: (1) Compiled historical flow data from The Dalles and for western sub-basin tributaries. This included estimating missing flow data for the Willamette at Albany for 1878-1893 (the actual record was only 40% complete). Albany hindcasts used multi-lag correlations between flows and precipitation found using the available flow and precipitation data before 1900. (2) Routed Willamette River flows from Albany and Salem to Portland using the formulation of Orem (1968). (3) Routed flows to Beaver from The Dalles, the Willamette at Portland, and other west-side tributaries using the formulation of Orem (1968). (4) Estimated virgin flows for The Dalles, the Willamette at Portland and Beaver for 1878-date. The methodology and irrigation corrections for these calculations are described in Bureau of Reclamation (1999) and Naik and Jay (2005). (5) Used USGS flow and sediment transport data to develop rating curves for the Columbia at Vancouver and the Willamette at Portland for sand, fines, and total load. Recently, all flow and sediment supply estimates were updated to 2004 (from 1999). The virgin flow methodology is further discussed in

Naik and Jay (2005). Less detained estimates are available at Beaver and for the West-side tributaries (Cowlitz, Lewis, East Fork Lewis, and Kalama). Updating the virgin flow methodology beyond 2004 requires data from several agencies, requested but not yet received.

Sediment transport hindcasts were based on simple power-law rating curves, using data collected 1962-1970 in the Columbia at Vancouver, 1962-1965 in the Willamette at Portland, 1968-1970 at Beaver, and at various times in the West-side tributaries. All hindcasts are based on the assumption that sediment yield has not changed over time due to changes in land use. All exclude the effects of the Mt St Helens eruption. For Vancouver and Portland, results have been provided separately for sand transport, fine sediment transport, and total load, for the observed flow, adjusted flow, and virgin flow (as defined by Bottom et al., 2005 and Naik and Jay, 2005). Due to the diverse data collection methodologies employed by the US Geological Survey at different times and places, not all stations allow prediction of a full suite of parameters. For the west side tributaries only observations of fine sediment are available, whereas for Beaver, only total load was reported.

This work was carried with support from this project and from US Army Engineers, Portland District. Three papers submitted in the last year: Naik and Jay (2008, 2009), and Jay and Naik (2009).

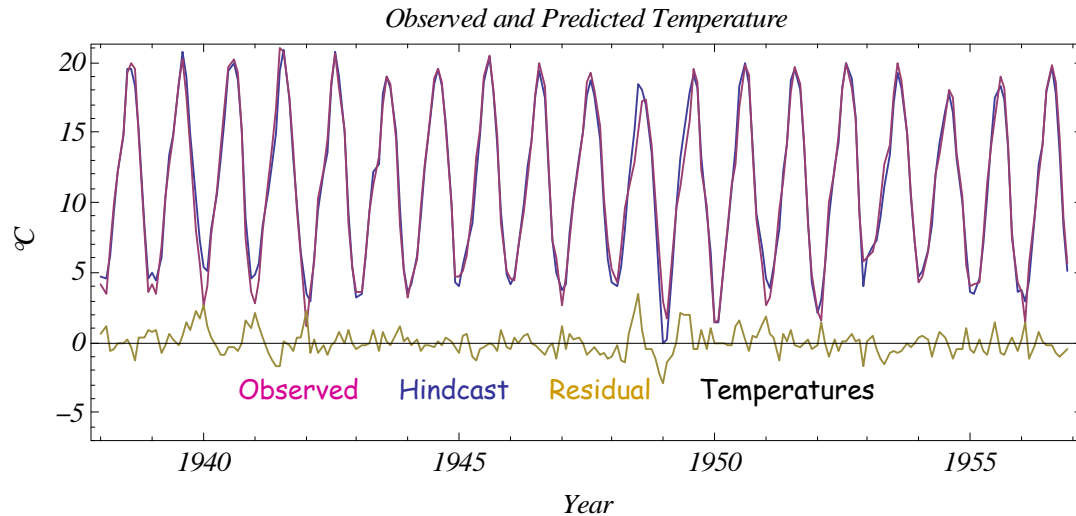
#### b) Long-Term Changes in Water Temperature

The 1937-2002 Bonneville Dam daily scroll-case temperature record has been used in conjunction with atmospheric data (temperature and precipitation, 1890-2003) and river flow records to analyze historical changes in the temperature regime of the river. The 1938-1956 period was used as the base period of the model – this is the part of the Bonneville record that shows the smallest effects of reservoir storage and flow diversion. After 1956, heating from nuclear reactors at Hanford became an important factor in the fluvial heat budget. Gridded air temperature ( $T_A$ ) data (available 1915-2003) were obtained from the Surface Water Modeling group at the University of Washington ([www.hydro.washington.edu/Lettenmaier/Data/gridded/](http://www.hydro.washington.edu/Lettenmaier/Data/gridded/)), the development of which is described by Hamlet and Lettenmaier (2005). The importance of this data set is that it has been carefully corrected for changes in the sensor distribution over time. It was found that monthly and spatially averaged  $T_A$  for large parts of the interior sub-basin were highly correlated with monthly averaged water temperature ( $T_W$ ) at Bonneville Dam, with river flow as an important (but secondary) factor. It was useful, however, to use different regression models for January to June (winter-spring) and July to December (summer-fall) months. These simple regression models accounted for 95% (winter-spring) and 97.5% (summer-fall) of the base-period (1938-1956)  $T_W$ , respectively (Figure 9); there are no obvious biases. The coldest winter months of very cold years are not well hindcast, but April has the highest RMS errors overall. Temperatures during the very high flow of 1948 and subsequent winter of 1948-1949 are also not very well reproduced, but are unique in the time series. Aside from over-prediction of  $T_W$  during the very high flow of 1948 (which had an unusually rapid melting of the snowpack due to heavy rainfall),  $T_W$  during the warmer months are well modeled. The very high flows of 1894 were outside the range of flows for 1938-1956, so present a potential difficulty for hindcasts. Fortunately, flow variability is much less important than  $T_A$  in determining  $T_W$ .

We then hindcast  $T_W$  for a variety of climate and flow scenarios back to 1890. For the 1890-1914 period, it was necessary to determine air temperature conditions from a small number of instru-

mental data, rather than spatially averaged data. To avoid any bias associated with the choice of stations, a regression model was used to determine how the 1915-1927 spatially averaged air temperatures related to values from individual stations. These relationships were then used to model the spatially averaged temperatures for 1890-1914, which in turn were used to drive the  $T_w$  model scenarios.

This work was carried with support from this project and from the US Army Engineers, Portland District. We expect to prepare a paper on this work, in conjunction with D. Bottom, S. Simenstad, and A. Hamlet.



**Figure 9:** Observed and hindcast temperatures for the 1938-1956 base period, and the residual error.

## Results

### a) Results of Hydrologic Analyses

#### 1. Historical changes in flow and sediment input to the estuary.

Table 5 presents observed, adjusted and virgin flows for 1878-1899, 1945-2004, and 1970-2004. These three periods represent, respectively, the historic flow, the present or modern flow (in terms of climate), and the present or modern flow (in terms of management). Results are presented in  $m^3 s^{-1}$  and as percent of the 1879-1899 virgin flow for each location. Tables 5a-c present similar information with respect to sediment transport for the Columbia at Vancouver and Beaver, the Willamette at Portland, and the west-side tributaries; transport are  $10^3$  metric ton  $day^{-1}$ . Sediment transport is broken down in terms of sand transport (including gravel, of any), fines, and total load, except for Beaver, where only total load can be estimated, and the west side tributaries, where only fine sediment transport can be estimated.

The results presented here depart from those in Bottom et al. (2005) in several respects:

- The calculations for up to 2004, instead of 1999. Thus the present climatic regime is assumed to extend from 1945-2004 (not 1945-1999), while the present management regime is assumed to extend from 1970 to 2004 (not 1970-1999). Different averaging is needed to distinguish the two aspects of the present situation, because a relatively long period is needed to cover a repre-

sentative range of PDO and ENSO conditions, whereas the present management regime (in terms of flow regulation and diversion) was not established until ca. 1970.

- We have now estimated adjusted and virgin flows for The Columbia at Beaver and the Willamette at Portland, allowing also corresponding sediment transport estimates.
- Sediment transport results (transport of sand, fines and their sum, the total load) are provided for the Willamette at Portland, as well as for the Columbia at Vancouver. Total load only is presented for Beaver, because we do not have separate results for sand and fines. Only fine sediment transport is presented for the west-side tributaries, because no sand transport data are available, except in the immediate aftermath of the 1980 Mt St. Helens eruption.
- Sand transport at Vancouver has been estimated from a rating curve based on the actual 1962-1963 observations. Previously, it was based on an estimate of percent sand in the total load, an estimate compile by the US Geological Survey (Haushild et al., 1963).

Including the 2000-2004 data causes estimates of modern flow volumes (for both the climate present and management present) to be lower than those in Bottom et al. (2005), reflecting the fact that 2000-2004 was a relatively dry period. For example, the observed flow at The Dalles for 1970-2004 is ~19% lower than in 1878-1899, whereas the previous estimate was a 15-16% decrease. We also see that climate has caused a ~9.6% decrease and irrigation a 7.5% decrease in flow at The Dalles, again slightly larger than previous estimates for modern management period. Irrigation diversion is smaller (~2%) in the Willamette River basin than in the Interior Sub-Basin landward of The Dalles, but climate impacts are very similar (~9%). Flows at Beaver reflect the influence of both the Interior and Coastal Sub-Basins. Because the flow in the Interior Basin is much larger than that from the Coastal Sub-Basin, percentages for Beaver are similar to those at The Dalles. We also note that the Interior Sub-Basin virgin flow was ~78% of the total flow at Beaver before 1900. This percentage has decreased to ~77% at present (1970-2004).

Another very important aspect of historical changes to Columbia River flow cycle relates to the changing shape of the annual spring freshet (Figure 10), as caused both by climate change and human alteration of the system. This analysis uses four time periods: a) 1879-1922 (cold climate but mixed PDO, and relatively unaltered flows), b) 1923-1946 (warm PDO and moderately altered flows), c) 1947-1976 (cold PDO, but a substantially altered flow cycle), and d) 1977-2004 (a contemporary management regime with strongly altered flows and mixed, mostly warm, PDO). Examining a 115 day period around the peak of the spring freshet, it is evident that for observed flow (at the top in Figure 8), the pre-1923 spring freshet was a lengthy affair, with flows above  $6,000 \text{ m}^3 \text{ s}^{-1}$  (at The Dalles) for the entire 115-day freshet period. Freshet flows were somewhat less during the 1923-1946 warm PDO period than in the following cold PDO period, 1947-1976, but still considerably larger than in the present management regime. Nonetheless, there was little change in shape of the observed freshet until the modern (1977-2004) period. Comparing observed flows at The Dalles with those at Beaver it is evident that the Western sub-basin freshet, which typically occurs before the peak of the flow at The Dalles changes the shape of the freshet at Beaver, with higher flows occurring before the freshet peak than after.

Examination of changes in the adjusted and virgin flows shows over time shows some very interesting patterns. Before 1923, flows increased almost linearly to a peak and decreased in the same manner, at both The Dalles and Beaver. The spring freshet has become much more peaked

over time at both locations, with highest flows concentrated in a brief period of <20 d. Without flow regulation and diversion, very high flows would actually have been more common during 1947-1976 than before 1923, and the average freshet peak rather higher. After 1923, there is also a separation of peaks between the Snake River and the mainstem, with the peak Snake River flow occurring 20-25 d before the freshet peak. Given that these changes are prominent in the virgin flow, it appears that climate change, presumably including a more rapid spring snow melt, is the primary cause of the observed changes, however, deforestation may also contribute. To the extent that high flows are beneficial to downstream migrant juvenile salmonids, the concentration of the highest flows in a period of only a few weeks makes the timing of hatchery release more critical – if the flow were not already regulated to reduce peak flows (and spread out) the freshet, then it would likely need to be regulated in most years, to make the freshet longer.

The sediment transport results in Tables 6a-c exhibit several interesting patterns. The average sand transport in the Willamette is quite small relative to that in the mainstem, whereas Willamette fine sediment transport is  $\sim 1/4$  to  $1/3$  of the total Portland plus Vancouver fine sediment transport. Sand transport has been greatly reduced in the mainstem – the sand transport for the modern period (1979-2004) at Vancouver is, for example, estimated to have been reduced to 15% of its historic (<1900) value. Bottom et al. (2005) said that it had been reduced to 30-40% of its historic value. The decrease in this estimate reflects both the different time period and the different estimation methodology. Willamette River sand transport, while quite small, has been much less affected. We cannot separate sand transport at Beaver from the total load results.

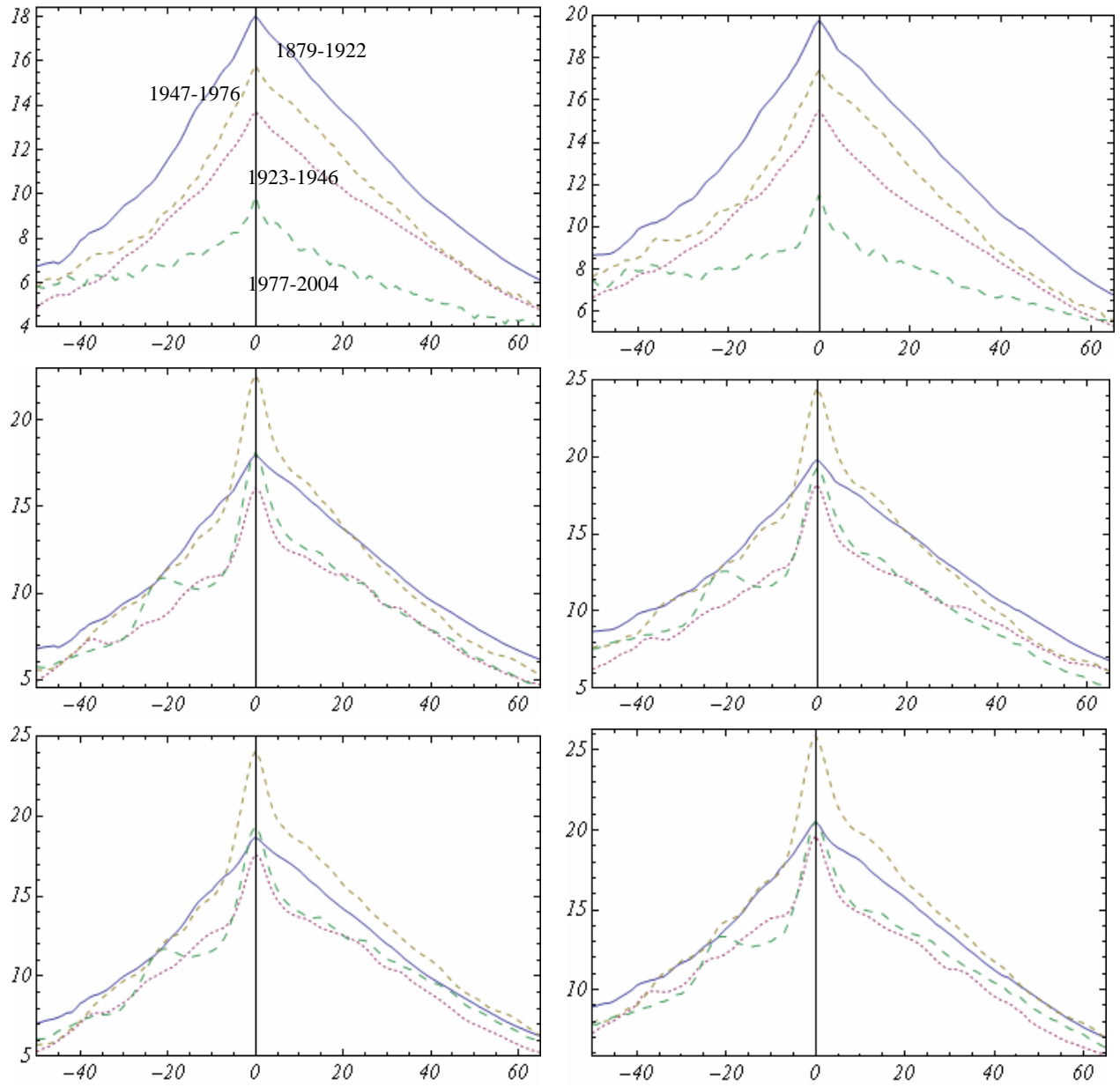
Only fine sediment data have been collected in the West-side tributaries. West-side fine sediment transport is relatively small, possibly because of trapping of sediment in reservoirs, and we have no way estimate historic west-side sand transport. USGS observations, beginning after the Mt St Helens eruption in May 1980 and extending through September 1984 indicate that about  $65 \times 10^6$  metric tons of sand (and coarser material) and  $110 \times 10^6$  metric tons sediment (total load, including all size classes) reached the Columbia River, despite considerable trapping of sand in the Cowlitz and Toutle Rivers. Much of this material was used as fill and did not have any long-term impact on the system, aside from areas filled.

The Beaver total load calculation is poorly constrained for very high flows, because the 1968-1970 observation period did not have any exceptional flows – the highest observed flow was about  $16,000 \text{ m}^3 \text{ s}^{-1}$ . The estimated transports for Beaver depend strongly, therefore, on what form of curve is used to fit the data. The results presented in Table 6c use a power law fit for low flows and a cubic polynomial fit at high flows, which gives higher transport estimates for high flows than the power law. Nonetheless, for the modern observed flows, Beaver transports are substantially lower than the sum of the Vancouver plus Portland transports. This may reflect storage in the channel between Vancouver and Beaver, but it may also indicate that the Beaver transport model is not totally satisfactory.

This work has been described further by Naik and Jay (2008, 2009), and Jay and Naik (2009).

**Table 5:** Columbia and Willamette River Average Observed, Adjusted and Virgin Flows, by Period

Station	1879-1899 $\text{m}^3\text{s}^{-1}$	1945-2004 $\text{m}^3\text{s}^{-1}$	1970-2004 $\text{m}^3\text{s}^{-1}$
Columbia River			
The Dalles Observed	6272	5273	5118
The Dalles Adjusted	6272	5382	5242
The Dalles Virgin	6327	5828	5719
Columbia River			
Beaver Observed	8074	7016	6779
Beaver Adjusted	8074	7122	6906
Beaver Virgin	8122	7585	7404
Willamette River			
Portland Observed	1074	1000	963
Portland Adjusted	1074	1000	965
Portland Virgin	1074	1009	977
	1879-1899 %	1945-2004 %	1970-2004 %
Columbia River			
The Dalles Observed	99.1	83.3	80.9
The Dalles Adjusted	99.1	85.1	82.9
The Dalles Virgin	100.0	92.1	90.4
Columbia River			
Beaver Observed	99.4	86.4	83.5
Beaver Adjusted	99.4	87.7	85.0
Beaver Virgin	100.0	93.4	91.2
Willamette River			
Portland Observed	100.0	93.1	89.6
Portland Adjusted	100.0	93.1	89.9
Portland Virgin	100.0	93.9	91.0



**Figure 10:** At left (top to bottom), average shape of the spring freshet flow ( $\text{m}^3\text{s}^{-1}$ ) for The Dalles observed, adjusted and virgin flows (1878-2004) as a function of day from the peak of the freshet. At right, the same for Beaver. Color scheme, indicated top left, is the same in each panel. Each average freshet shape is compiled over the period indicated from the 50 days before and 65 days after the spring freshet peak for each year.

**Table 6a: Columbia and Willamette River Sand Transport for the Average Observed, Adjusted and Virgin Flows, by Period**

Vancouver	1877-1899	1877-1899		1945-2004	1945-2004		1970-2004	1970-2004	
	$10^3 \text{ m ton d}^{-1}$	$10^6 \text{ m ton yr}^{-1}$		$10^3 \text{ m ton d}^{-1}$	$10^6 \text{ m ton yr}^{-1}$		$10^3 \text{ m ton d}^{-1}$	$10^6 \text{ m ton yr}^{-1}$	
Observed flow	37.3	13.6	100	10.7	3.9	29	5.6	2.0	15
Adjusted flow	35.8	13.1	96	25.4	9.3	68	22	8.0	59
Virgin flow	37.4	13.7	100	34.7	12.7	93	29.8	10.9	80
Portland									
Observed flow	0.67	0.2	100	0.51	0.2	76	0.4	0.1	52
Adjusted flow	0.67	0.2	100	0.75	0.3	112	0.7	0.3	92
Virgin flow	0.67	0.2	100	0.75	0.3	112	0.7	0.3	92
Vancouver+ Portland									
Observed flow	38.0	13.9	100	11.2	4.1	29	6.0	2.2	16
Adjusted flow	36.5	13.3	96	26.2	9.6	69	22.7	8.3	60
Virgin flow	38.1	13.9	100	35.5	12.9	93	30.5	11.1	80



**Table 6b: Columbia and Willamette River Fine Sediment Transport for the Average Observed, Adjusted and Virgin Flows, by Period**

	1877-1899			1945-2004			1970-2004		
Vancouver	10 <sup>3</sup> m ton d <sup>-1</sup>	10 <sup>6</sup> m ton yr <sup>-1</sup>	%	10 <sup>3</sup> m ton d <sup>-1</sup>	10 <sup>6</sup> m ton yr <sup>-1</sup>	%	10 <sup>3</sup> m ton d <sup>-1</sup>	10 <sup>6</sup> m ton yr <sup>-1</sup>	%
Observed flow	19	6.9	103	17.9	6.5	97	18	6.6	97
Adjusted flow	18.4	6.7	99	15.3	5.6	83	15.1	5.5	82
Virgin flow	18.5	6.8	100	16.6	6.1	90	16.8	6.1	91
Portland									
Observed flow	8.8	3.2	100	7.8	2.8	89	6.3	2.3	71
Adjusted flow	8.8	3.2	100	9.4	3.4	107	8.8	3.2	101
Virgin flow	8.8	3.2	100	9.4	3.4	107	8.8	3.2	101
Vancouver+Portland									
Observed flow	27.8	10.1	102	25.7	9.4	94	24.3	8.9	89
Adjusted flow	27.2	9.9	100	24.7	9.0	91	23.9	8.7	88
Virgin flow	27.3	10.0	100	26.0	9.5	95	25.6	9.4	94
West-Side <sup>1</sup> w/o Mt St. Helens									
Observed flow	6.6 x10 <sup>-3</sup>	2.4 x10 <sup>-3</sup>	100	6.6 x10 <sup>-3</sup>	2.4 x10 <sup>-3</sup>	100	6. x10 <sup>-3</sup>	2.2 x10 <sup>-3</sup>	92
Adjusted flow	6.6 x10 <sup>-3</sup>	2.4 x10 <sup>-3</sup>	100	6.8 x10 <sup>-3</sup>	2.5 x10 <sup>-3</sup>	104	6.4 x10 <sup>-3</sup>	2.3 x10 <sup>-3</sup>	96
Virgin flow	6.6 x10 <sup>-3</sup>	2.4 x10 <sup>-3</sup>	100	6.8 x10 <sup>-3</sup>	2.5 x10 <sup>-3</sup>	104	6.4 x10 <sup>-3</sup>	2.3 x10 <sup>-3</sup>	96
West-Side <sup>2</sup> with Mt St. Helens									
Observed flow	6.6 x10 <sup>-3</sup>	2.4 x10 <sup>-3</sup>	100	9.6 x10 <sup>-3</sup>	3.5 x10 <sup>-3</sup>	144	11.1 x10 <sup>-3</sup>	4.1 x10 <sup>-3</sup>	167
Adjusted flow	6.6 x10 <sup>-3</sup>	2.4 x10 <sup>-3</sup>	100	9.6 x10 <sup>-3</sup>	3.5 x10 <sup>-3</sup>	144	11.1 x10 <sup>-3</sup>	4.1 x10 <sup>-3</sup>	167
Virgin flow	6.6 x10 <sup>-3</sup>	2.4 x10 <sup>-3</sup>	100	9.6 x10 <sup>-3</sup>	3.5 x10 <sup>-3</sup>	144	11.1 x10 <sup>-3</sup>	4.1 x10 <sup>-3</sup>	167

<sup>1</sup>. Transports estimated from rating curves developed without using 1980-1988 Colwitz River data.

<sup>2</sup>. Observed transports related to the May 1980 eruption of Mt St. Helens are included for the years 1980-1988.

**Table 6c: Columbia and Willamette River Total Load for the Average Observed, Adjusted and Virgin Flows, by Period**

	1877-1899	1877-1899		1945-2004	1945-2004		1970-2004	1970-2004	
Vancouver	$10^3 \text{ m ton d}^{-1}$	$10^6 \text{ m ton yr}^{-1}$	%	$10^3 \text{ m ton d}^{-1}$	$10^6 \text{ m ton yr}^{-1}$	%	$10^3 \text{ m ton d}^{-1}$	$10^6 \text{ m ton yr}^{-1}$	%
Observed flow	56.3	20.6	101	28.7	10.5	51	23.6	8.6	42
Adjusted flow	54.2	19.8	97	40.7	14.9	73	37.1	13.6	66
Virgin flow	56	20.5	100	51.3	18.7	92	46.7	17.1	83
Portland									
Observed flow	9.45	3.5	100	8.3	3.0	88	6.7	2.4	70
Adjusted flow	9.45	3.5	100	10.2	3.7	108	9.5	3.5	101
Virgin flow	9.45	3.5	100	10.2	3.7	108	9.5	3.5	101
Vancouver+									
Portland									
Observed flow	65.8	24.0	100	37.0	13.5	57	30.3	11.0	46
Adjusted flow	63.7	23.2	97	50.9	18.6	78	46.6	17.0	71
Virgin flow	65.5	23.9	100	61.5	22.5	94	56.2	20.5	86
Beaver									
Observed flow	72.5	26.5	96	25.5	9.3	34	18.05	6.6	24
Adjusted flow	72.4	26.4	96	50.9	18.6	67	43.9	16.0	58
Virgin flow	75.6	27.6	100	68.1	24.9	90	57.3	20.9	76

## 2. Historical Changes in Overbank Flow

We now consider the historical record of major flow events. Floodplain inundation is the primary factor creating the freshet-season SWHA historically utilized by juvenile salmonids. Based on the two-year flow recurrence level for The Dalles (augmented by the typical spring flow level for the west side tributaries before 1900), bankfull flow level before 1900 was  $\sim 20,000 \text{ m}^3 \text{ s}^{-1}$  for the mainstem below Vancouver. Modern bankfull level is set by flood control levies at  $24,000 \text{ m}^3 \text{ s}^{-1}$ . In many years some overbank flow ( $>20,000 \text{ m}^3 \text{ s}^{-1}$ ) occurred before 1900, in winter and/or spring. Overbank flow above the level of present flood protection levees ( $\sim 24,000 \text{ m}^3 \text{ s}^{-1}$ ) was never common and now occurs rarely (Table 7). Major flow events ( $>24,000 \text{ m}^3 \text{ s}^{-1}$ ) have occurred only five times since 1900 – in 1913 (spring), 1948 (spring), 1956 (spring), 1965 (winter), and 1996 (winter) (Data are compiled by water year, October to September, so that the December 1964 flood is assigned to water year 1965). This is a sharp contrast to the second half of the 19<sup>th</sup> century, when flows  $>24,000 \text{ m}^3 \text{ s}^{-1}$  appear to have occurred in 15 years over the 56 yr period between 1844 and 1899, for which we have gauge records or reasonably quantitative contemporary accounts. Exceedence of even the historical bankfull level of  $20,000 \text{ m}^3 \text{ s}^{-1}$  has also been greatly curtailed, primarily by flood control measures and irrigation depletion. Because of flow regulation by numerous mainstem dams, the season when overbank flow is most likely has also shifted from spring to winter.

## 3) The Incidence of Extreme High and Low Flows

Multi-year flow extremes are another important aspect of flow variation, affecting both juvenile salmonids and hydropower production. Table 8a lists the 10 most extreme three-year high-flow periods at The Dalles and at Beaver, for both the observed and virgin flows. Most (9 of 10 at The Dalles and 8 or 10 at Beaver) of the highest observed flow periods occurred before 1900. This percentage is reduced to 5 of ten (at both stations) for virgin flow. The three-year period (triad) centered on 1997 emerges as the wettest in the entire record for The Dalles virgin flow, whereas 1975 is the wettest virgin flow period at Beaver. Thus, despite an approximately 17% decrease in annual average observed flow between the 1879-1899 and 1970-2004 periods, very wet periods can still occur. It is also striking that only one extremely wet triads appeared during the 1947-1976 cold PDO period, despite consistently very large spring freshets and an absence of very low-flow years.

Table 8b shows that all of the 10 most extreme three-year low-flow periods at both The Dalles and Beaver have, with the sole exception of 1890 for The Dalles virgin flow, occurred since 1925, regardless of whether the observed or virgin flow is considered. The two driest three-year periods (triads) and five of the 10 driest triads occurred between 1925 and 1941. The remaining dry triads (except 1890) occurred between 1978 and 2002. The distinction between virgin flow and observed flow is also more important for the extreme high flow triads than for extreme low flows. For the observed flow at The Dalles, for example, the 1997 triad is the only 20<sup>th</sup> Century period to appear in the top 10 wettest three-year periods (in 9<sup>th</sup> place). For virgin flow, four triads in the late 20<sup>th</sup> Century appear in the top 10, and the 1997 triad emerges as the wettest. For the extreme low flows, there is considerable re-ordering between observed and virgin flows, but little change in the triads identified. One way to explain this phenomenon is that, given a well-developed reservoir system after ca. 1970, extreme high-flow periods provide both the motiva-

tion and the water to accomplish significant interannual flow transfers. Low-flow periods may provide motivation for such transfers, but the water is simply not available.

**Table 7:** Lower Columbia River: Incidence of Overbank Flow  $>24,000 \text{ m}^3 \text{ s}^{-1}$ , by Water Year

Year	Season	Days Beaver Flow $>24,000 \text{ m}^3 \text{ s}^{-1}$	Max Flow – The Dalles $1000 \text{ m}^3 \text{ s}^{-1}$	Max Flow – Bea- ver $1000 \text{ m}^3 \text{ s}^{-1}$
1844	Spr		$>30^b$	
1847	Spr		$>23.9^a$	
1853	Spr		$>23.9^a$	
1859	Spr		$23.9^b$	
1861	Win			25-35
1862	Spr		$26.8^b$	
1863	Spr		$22.0^b$	
1866	Spr		$23.8^b$	
1870	Spr		$22.0^b$	
1871	Spr		$24.3^b$	
1876	Spr	$\sim 25^d$	$27.1^b$	
1880	Spr	20	$25.9^c$	$28.8^e$
1882	Spr	15	25.0	26.1
1887	Spr	17	25.4	26.3
1894	Spr	34	35.1	38.6
1899	Spr	2	22.3	24.6
1913	Spr	3	21.5	24.4
1948	Spr	23	28.6	30.6
1956	Spr	6	23.3	25.2
1965	Win	3	10.3	28.7
1996	Win	2	10.7	24.5

<sup>a</sup> Contemporary newspaper reports indicate that flows in the springs of 1847 and 1853 were modestly higher than those in 1859.

<sup>b</sup> Henshaw and Dean (1915) provide an annual high flow for The Dalles. 1858-1877. For years before 1878, a flow of  $24,000 \text{ m}^3 \text{ s}^{-1}$  at Beaver is inferred to have occurred, if the maximum flow at The Dalles was  $>22,000 \text{ m}^3 \text{ s}^{-1}$ , assuming a Western Sub-basin flow of  $2000 \text{ m}^3 \text{ s}^{-1}$ . Henshaw and Dean also indicate that a very high flow occurred in 1849. After some investigation, we believe that the correct year for this event was 1844.

<sup>c</sup> From USGS observed flows at The Dalles (1878-date).

<sup>d</sup> From contemporary newspaper accounts for 1876 and 1880.

<sup>e</sup> Beaver flows determined using routed The Dalles flows and estimates of Western Sub-basin flows, after Naik and Jay (2009).

**Table 8a:** Three-Year Extreme High-Flow Periods, Columbia River at The Dalles and at Beaver, 1858-2004.

The Dalles	Observed Flow	The Dalles	Virgin Flow	Beaver	Observed Flow	Beaver	Virgin Flow
Years	$10^3 \text{ m}^3 \text{ s}^{-1}$	Years	$10^3 \text{ m}^3 \text{ s}^{-1}$	Years	$10^3 \text{ m}^3 \text{ s}^{-1}$	Years	$10^3 \text{ m}^3 \text{ s}^{-1}$
1880	7.1	1997	7.2	1880	9.2	1975	9.2
1881	7.0	1880	7.2	1881	9.0	1880	9.2
1895	6.9	1996	7.1	1895	9.0	1997	9.1
1893	6.9	1881	7.1	1893	8.9	1895	9.1
1894	6.8	1895	7.0	1894	8.8	1895	9.1
1863 <sup>a</sup>	6.8	1975	7.0	1997	8.6	1981	9.1
1871	6.8	1893	7.0	1863	8.6	1983	9.0
1862	6.7	1998	6.9	1871	8.6	1893	8.9
1997	6.7	1894	6.9	1998	8.6	1998	8.9
1898	6.8	1983	6.9	1862	8.5	1894	8.8

<sup>a</sup> Annual average flow for the 1858-1878 period was estimated from the one-day high flow for each year, using a regression relationship developed using data from 1879 to 1899 (cf. Naik and Jay, 2009).

**Table 8b:** Three-Year Extreme Low-Flow Periods, Columbia River at The Dalles and at Beaver, 1858-2004.

The Dalles	Observed Flow	The Dalles	Virgin Flow	Beaver	Observed Flow	Beaver	Virgin Flow
Years	$10^3 \text{ m}^3 \text{ s}^{-1}$	Years	$10^3 \text{ m}^3 \text{ s}^{-1}$	Years	$10^3 \text{ m}^3 \text{ s}^{-1}$	Years	$10^3 \text{ m}^3 \text{ s}^{-1}$
1930	3.6	1930	3.9	1930	4.8	1930	5.0
1940	4.0	1940	4.5	1940	5.2	1940	5.7
1993	4.1	1931	4.5	2002	5.4	1931	5.8
2002	4.1	1993	4.6	1993	5.4	2002	5.9
1988	4.1	1925	4.6	1931	5.4	1993	5.9
1931	4.1	1978	4.6	1978	5.5	1978	6.0
1978	4.2	2002	4.6	1988	5.5	1941	6.0
1994	4.3	1988	4.7	1941	5.6	1925	6.1
1925	4.3	1936	4.7	2001	5.6	2001	6.1
1941	4.1	1890	4.7	1925	5.7	1988	6.1

#### *b) Water Temperature Analyses*

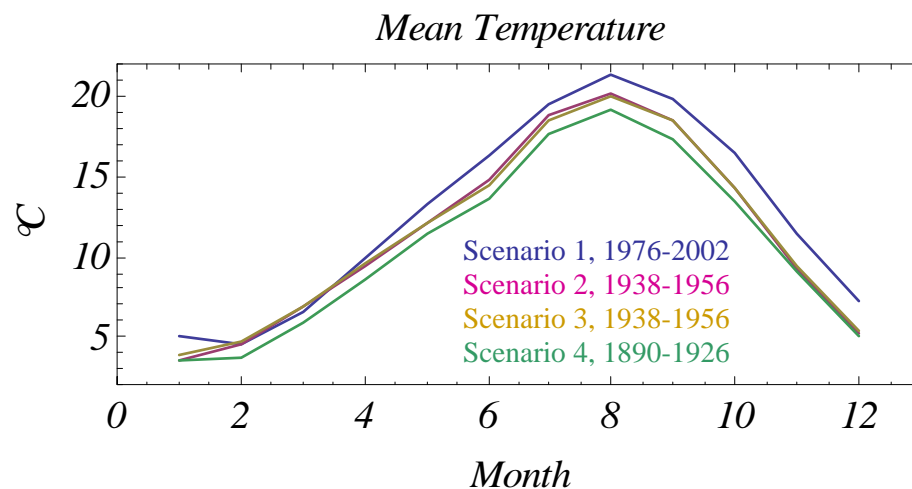
Water temperature trends at Bonneville Dam are indicative of the impact of river basin conditions on water temperatures in the lower river. Four  $T_W$  scenarios were considered:

1. Observed Conditions, 1938-2002: This scenario is simply the  $T_W$  observed during the 1938-2002 period.
2. The base scenario, 1938-2002: The  $T_W$  regression model for this case was based on the flow and  $T_A$  conditions pertaining during the 1938-1956 period. It was considered, in the absence of earlier data, to be representative of unaltered (pre-reservoir) conditions. In fact, both Grand Coulee and Bonneville Dam were in operation for part or all of the period, so some alteration of  $T_W$  by reservoir operations occurred during this period, and a moderate degree of irrigation diversion was also occurring (Naik and Jay, 2005). This model was then used to hindcast  $T_W$  for the entire 1938-2002 period, using the actual (observed)  $T_A$  and flows for each year. This scenario quite closely reproduces Scenario 1 for the base period, 1938-1956.
3. The virgin flow scenario, 1938-2002: This scenario differs from Scenario 2 only in that virgin flows were used (along with the actual, observed  $T_A$  for each year) to hindcast  $T_W$  for the 1890-2002 period.
4. The virgin flow, “cold” scenario, 1890-1926: This scenario differs from Scenarios 2 and 3 in that the  $T_A$  data for 1890-1926 was used along with the virgin flow for each year to hindcast  $T_W$  for the 1890-1926 period.

We can divide the observed 1938-2002 Bonneville Dam temperature record into four periods:

1. The Base Period, 1938-1956: This period represents the  $T_W$  regime under conditions of minimal reservoir manipulations and moderate irrigation depletion. Warm PDO (Pacific Decadal Oscillation) conditions prevailed during the first half of the period (1938-1946), but there was an abrupt change to cold PDO conditions, 1947-1956.
2. The Hanford Period, 1957-1976: This period represents the  $T_W$  regime during a period of growing reservoir manipulation and irrigation diversion, and strong thermal influence by the Hanford reactors. Water temperatures were considerably warmer than during the base period. Cold PDO conditions prevailed during this whole time period; it is convenient to end this period at the end of the cold PDO conditions in 1976.
3. The Reservoir Period, 1977-1996: This period occurs after the reduction of Hanford thermal inputs, but the river continued to warm, due both to warm PDO conditions and associated generally low river flows.
4. The Modern Period, 1997-date: There was a transition to cold PDO conditions with much higher flows during 1996-1998. At about this time also, cold sub-surface waters from Dworshak Dam began to be used to provide cooler temperatures in the Snake River. Although EPA modeling suggests that the effect of the Dworshak outflow disappears by the time the water reaches the Columbia mainstem (M. Soscia, EPA, personal communication), the relationship of  $T_W$  to  $T_A$  and flow changed after 1996. More data will be required to analyze this period.

Perhaps the points of greatest interest are the average  $T_w$  cycles and change thereof for the four scenarios, presented in Figures 11a,b. It appears that historic (Scenario 4, 1890-1926) temperatures did not exceed 19°C in a typical year, even in August (Fig. 6a). Modern temperatures (Scenario 1, 1976-2002) exceed, on average, 19°C for three months (July-September) in a typical year. The causes of the changes in the  $T_w$  cycle can be deduced from Figure 11b. The differences between Scenarios 4 and 1 represent the sum of all effects (heating caused by reservoir storage, heating caused by reduced flows and consequent slower transit of water even without reservoir storage, and climate change). The differences between Scenarios 3 and 1 represent the sum of impacts due to reservoir storage and flow reduction. The differences between Scenarios 2 and 1 represent the differences due to reservoir storage. (These descriptions are approximate because a) the 1938-1956 base period still had some reservoir manipulation and flow diversion, and b) the models do not consider non-linear interactions between factors.)

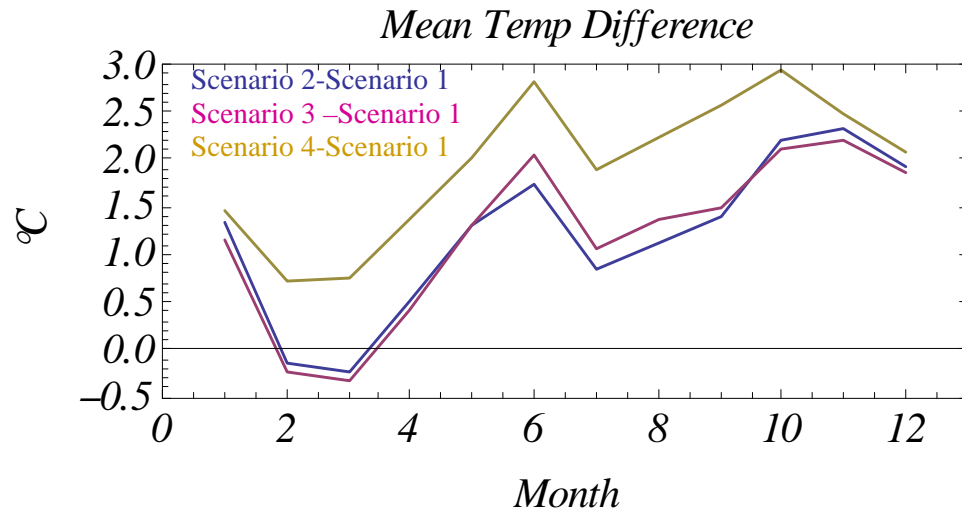


**Figure 11a:** Hindcast average seasonal temperature cycles for January (month 1) to December (month 12). The averaging period over which each scenario is averaged is indicated. See text for details of the scenarios.

Comparison of the scenarios in Figures 11a,b suggest that:

- As a result of all factors together,  $T_w$  is now 1.9-3°C warmer than historically (Scenario 1- Scenario 4) for the months of May to December, potentially affecting both outbound juvenile salmonids and returning adults
- Reservoir manipulations account for more than half of the total change in  $T_w$  (Scenario 1- Scenario 2). During summer and fall, the changes vary from 0.8°C to >2°C in October and November, when the river would cool much more rapidly without reservoir storage.
- Climate change accounts for 0.6-1°C of warming during the months of June to October (difference between Scenario 1- Scenario 3 and Scenario 1- Scenario 4).
- $T_w$  is slightly lower (0.1-0.3°C) in February and March than it would be without reservoir manipulation and flow diversion, but is still warmer than under historic conditions (Scenario 1- Scenario 3 and Scenario 1- Scenario 2).

- The change in volume of flow (without reservoir manipulation) is a relatively small effect (a few tenths of a degree) but not insignificant, especially in combination with the climate change and reservoir manipulation (Scenario 1- Scenario 2 vs. Scenario 1- Scenario 3).



**Figure 11b:** temperature differences between the scenarios presented in Figure 12a.



## **Publications and Presentations Associated with this Project**

### *Peer Reviewed Publications:*

#### Published or In Press

Jay, D. A., 2009, Evolution of tidal amplitudes in the Eastern Pacific Ocean, *Geophys. Res. Lett.* doi:10. 1029/2008GL036185.

Leffler, K. and D. A. Jay, 2009, enhancing tidal harmonic analysis: Robust (hybrid L1/L2) solutions, *Continental Shelf Research* 29, 78-88.

Chawla, A., D. A. Jay, A. M. Baptista, and M. Wilkin, 2009, Seasonal variability and estuary-shelf interactions in circulation dynamics of a river-dominated estuary, *Estuaries and Coasts* 31: 269-288, DOI 10.1007/s12237-007-9022-7.

#### Submitted

Naik, P., and D. A. Jay, 2009, Distinguishing human and climate influences on the Columbia River: changes in mean flow and sediment transport, submitted to *J. Hydrol.*

Jay, D. A., and P. Naik, 2009, Distinguishing human and climate influences on the Columbia River: changes in the disturbance processes, submitted to *Water Resour. Res.*

Naik, P., and D. A. Jay, 2008, Human and climate impacts on Columbia River hydrology and sediment transport, submitted to *J. Riv. Res. Applic.*

#### In Preparation

Jay, D. A., K. Leffler and S. Degens, 2009, Long-Term evolution of Columbia River tides, to be submitted to *ASCE J. Waterw., Port, Coast. Ocean Engin.*

Meagher, L., D. A. Jay and J. Burke, 2009, Long-term changes in shallow water habitat area in the Columbia Tidal River – impacts of management and climate, to be submitted to *Coasts and Estuaries*.

Jay, D. A., S. Simenstad, D. Bottom and A. Hamlet, 2009, Impacts of climate and hydrologic alteration on Columbia River water temperatures, to be submitted to *Coasts and Estuaries*.

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