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Distinguishing human and climate influences on the Columbia River: changes in the disturbance processes

PRADEEP K. NAIK[1] **& DAVID A. JAY**[2]

1 *Agricultural Engineering and Water Resources, Ministry of Municipality Affairs and Urban Planning, PO Box 31126, Kingdom of Bahrain*
pradeep.naik@water.net.in

2 *Department of Civil and Environmental Engineering, Portland State University, PO Box 751, Portland, Oregon 97207, USA*

Abstract This paper distinguishes human and climate influences on the Columbia River streamflow disturbance regime, examines how this disturbance regime has changed over the last 150 years, and discusses downstream impacts. Flow management and withdrawal have greatly curtailed exceedence of the natural bankfull level of approx. 20 000 $m^3 s^{-1}$. The frequency distribution of Columbia River flow has also changed. Sediment transport is positively correlated with streamflow standard deviation, and has been greatly reduced by flow regulation. Three kinds of spring freshet styles have been identified; there are also four kinds of winter freshets. Flow regulation and regional climate warming have changed freshet styles and reduced their maximum spring intensities. Downstream effects of hydrological alterations include increased salinity intrusion length, loss of shallow water habitat area during the freshet season, increased tides throughout most of the year, and a decrease in area of the Columbia River offshore plume during spring and summer. Although climate changes and variations have played a substantial role in changing the hydrological disturbance regime, their influence is still less than that of human manipulation of the flow cycle.

Key words Columbia River; climate impact; human impact; freshet style; salmonid; overbank flow; disturbance frequency; flow regulation; reservoir manipulation; irrigation depletion

INTRODUCTION

Columbia River Basin (Fig. 1) hydrology has changed due to both human and climate influences (Sherwood *et al.*, 1990; Hamlet & Lettenmaier, 1999; Jay & Naik, 2002; Naik & Jay, 2005). Naik & Jay (2010, 2011) separated anthropogenic and climate impacts on the Columbia River mean flow and sediment transport regimes. We show here that direct human manipulation of river flow through flood control, water withdrawal and hydropower generation, has been the largest single source of disturbance to the physical processes in the system. Still, climate fluctuations and other human activities, such as navigational development, diking and filling, and changes in land use (especially timber harvest), are individually important and interact with river flow manipulation. The hydrological factors discussed here affect not only the river, but also the estuary and the coastal ocean. Moving in a seaward direction, the effects of hydrological alterations on the river are fairly well defined, those on the estuary are becoming clearer, and those on the coastal ocean are quite uncertain.

The Cascade Mountains divide the Columbia River drainage basin into two parts: (1) a Western Sub-basin and (2) an Interior Sub-basin covering ~92% of the total drainage east of the Cascade Range. Understanding the response of the Columbia River Basin to human influences and climate perturbations requires attention to the diverse properties of its sub-basins. There is, for example, wide variability in the percentage flow from the various parts of the basin during the spring freshet and over the water year. The West sub-basin (~8% of basin area, 24% of total flow at the mouth) is very wet. The Canadian part of the Interior sub-basin also has a high runoff production per unit area – Canada accounts for ~50% of the flow at The Dalles (that measures 95% of the flow of the Interior sub-basin), but has only 25% of the total surface area of the Interior sub-basin. The Snake River is relatively dry, with ~40% of the Interior sub-basin surface area, but only 30% of the total flow at The Dalles. In very high flow years, half or more of the streamflow at Dalles is derived from Canada. During the largest known freshet (1894), for example, the peak flow at Grand Coulee was ~20 500 $m^3 s^{-1}$ compared to a maximum flow at The Dalles of 34 800 $m^3 s^{-1}$ and at Beaver of ~39 400 $m^3 s^{-1}$. The Canadian contribution to the spring freshet has

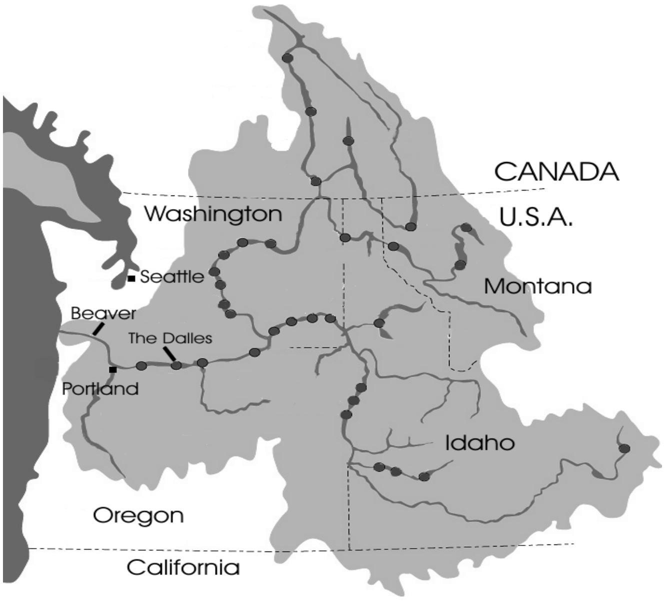

Fig. 1 The Columbia River basin; the Interior basin is east of The Dalles (after US Army Corps of Engineers).

been declining since 1970 due to the large residence time of the dams in Canada. These dams are very effective in changing the seasonality of the flow in the Upper Columbia, which in turn affects streamflow in the entire mainstem (Naik & Jay, 2010).

RESULTS

1 **Disturbance frequency** The magnitude and frequency of disturbance to the Columbia River system is important to the survival of salmonids. The historical bankfull flow level was approx. 20 000 $m^3 s^{-1}$ for the Columbia mainstem below Vancouver; modern bankfull level has now been set by the standard project flood level of ~24 000 $m^3 s^{-1}$ for the lower river. Some overbank flows did occur in many years before 1900, but now flow regulation (after 1970) and water withdrawal have made overbank flows (above 24 000 $m^3 s^{-1}$) rare, with significant events occurring only five times since 1948. With regard to the incidence of overbank flow now, climate is a secondary factor. Even during cold PDO (Pacific Decadal Oscillation) phases, overbank flow is now rare; it was totally absent during the warm phase of 1977–1995 (Fig. 2).

2 **Habitat availability** Reduction in overbank flows in the lower Columbia River due to decrease in maximum flow levels, disposal of dredged material, and diking/flood protection measures, have resulted in the reduction of shallow water habitat availability/opportunity during the freshet season, when juvenile salmonid densities are high, by limiting flow out over the historic flood plain and into areas that were previously forested swamp or other types of seasonal wetland.

3 **River flow frequency distribution** High frequency variations associated with power peaking have been greatly augmented by the dam system, whereas low-frequency flow variations with periods of between ~2 years and 6 months have been substantially suppressed. Also, the diurnal tidal signal in the river has been perturbed by the daily power peaking cycle (Fig. 3).

4 **Spring freshet styles** The flow cycle is different each year, but three recurring patterns of spring freshets have been identified: (a) a large winter snow pack without exceptional spring rain, (b) a normal winter snow pack followed by a very wet spring, and (c) a large winter snow pack combined with heavy spring rains. The largest known freshet that occurred in 1894 was of type (c), and the second largest freshet that occurred in 1948 was of type (b).

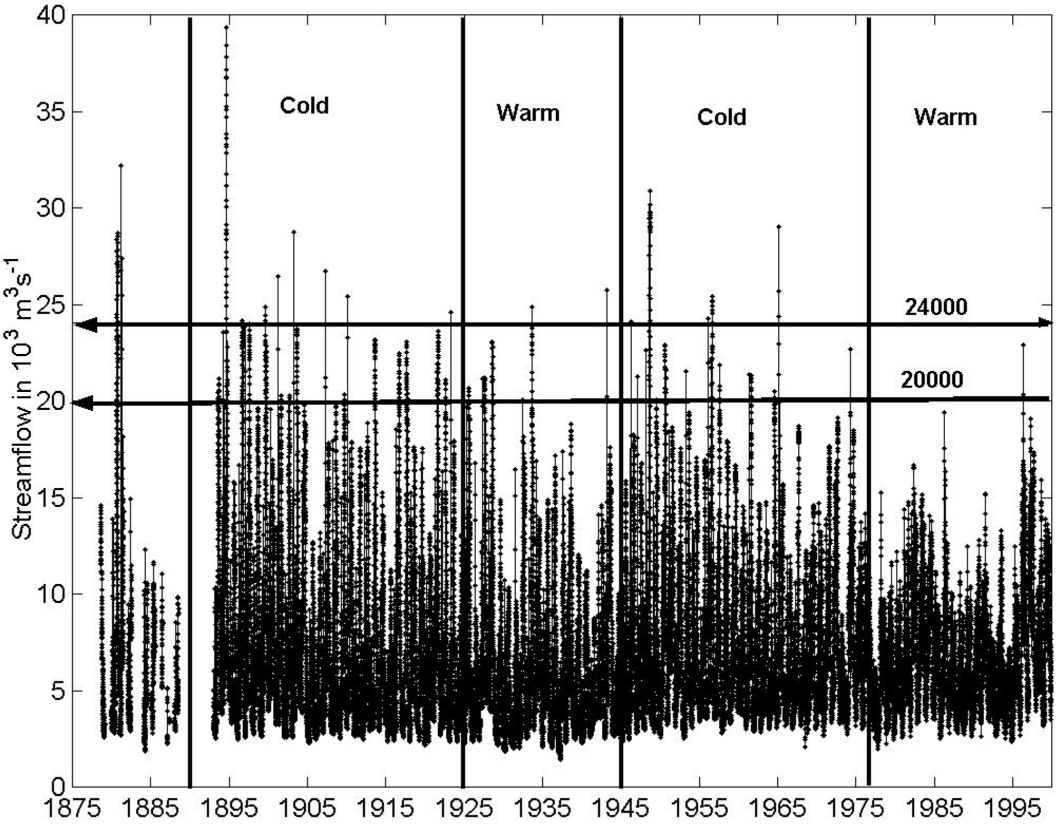

Fig. 2 Overbank flows exceeding 20 000 m^3 s^{-1} and 24 000 m^3 s^{-1} in cold and warm PDO phases in the Columbia River at Beaver.

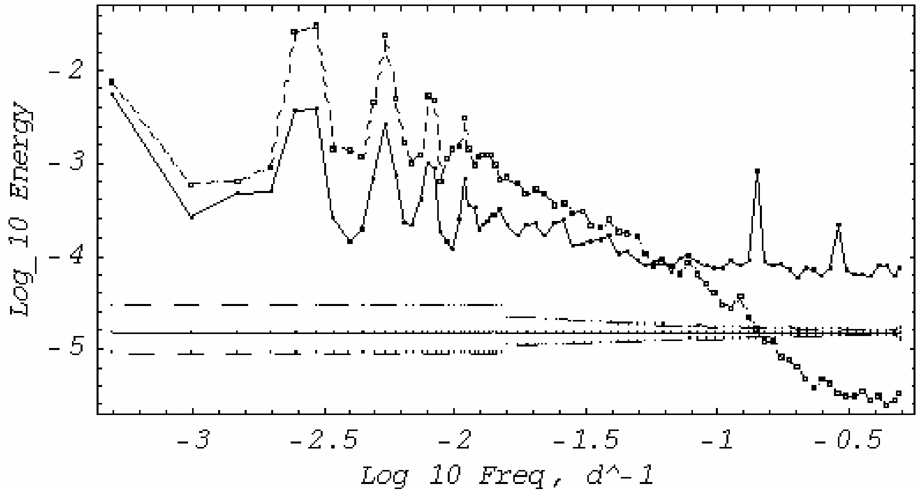

Fig. 3 Power spectra of The Dalles observed daily flow 1878–1910 and 1970–1999. The peaks at 1 year and 6, 4, and 3 months, clearly visible in the 1878–1910 record, have been greatly reduced by flow regulation and irrigation depletion. The power peaking cycle has added energy to the system at frequencies above ~20 days, but especially at 7 and 3.5 days. Also shown are 95% confidence limits.

5 Winter freshet styles There are also four types of winter freshets, based on the source of streamflow: (a) primarily Western sub-basin with extensive snowmelt, (b) Interior and Western sub-basins, (c) primarily Interior sub-basin, and (d) primarily Western sub-basin without extensive

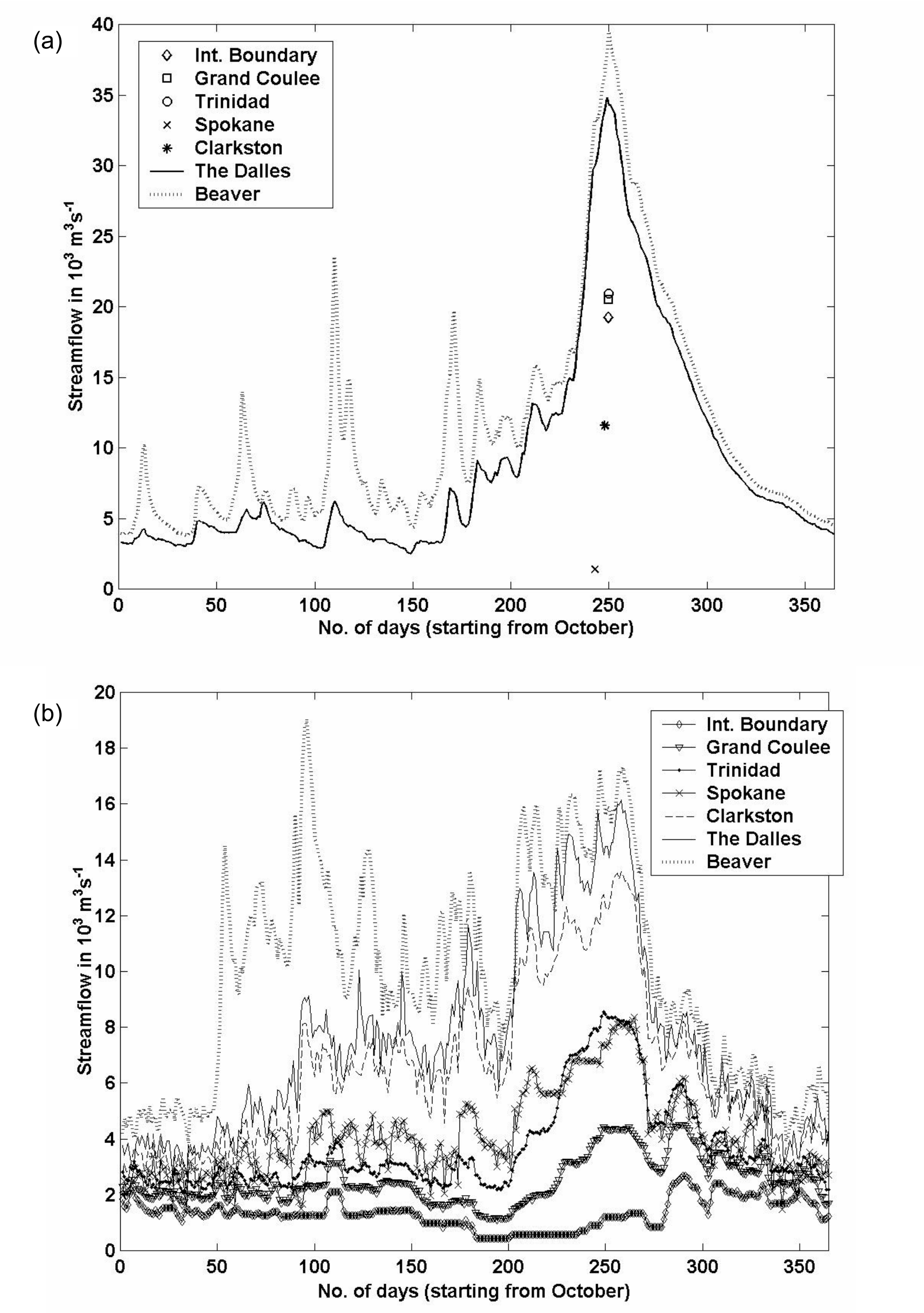

Fig. 4 (a) An example of a significant winter snowmelt event occurring before a major spring freshet (1894 water year); (b) an example of flow regulation decreasing spring freshet magnitude and increasing flows during the rest of the year (1997 water year); and (see opposite) (c) comparison of flow hydrographs for two low-flow years of the Columbia River at The Dalles (1926 and 1977). Regulation and power peaking effects are so prominent in 1977 that there is little annual cycle; unregulated flows in 1926 show a distinct, but attenuated, annual cycle.

snowmelt. All winter freshets, except the fourth type, are generated by rain-on-snow events. The largest known freshets (e.g. 1861, 1881 and 1892) involved both Interior and Western sub-basins. However, the Canadian part of the Interior sub-basin is not generally affected by these floods.

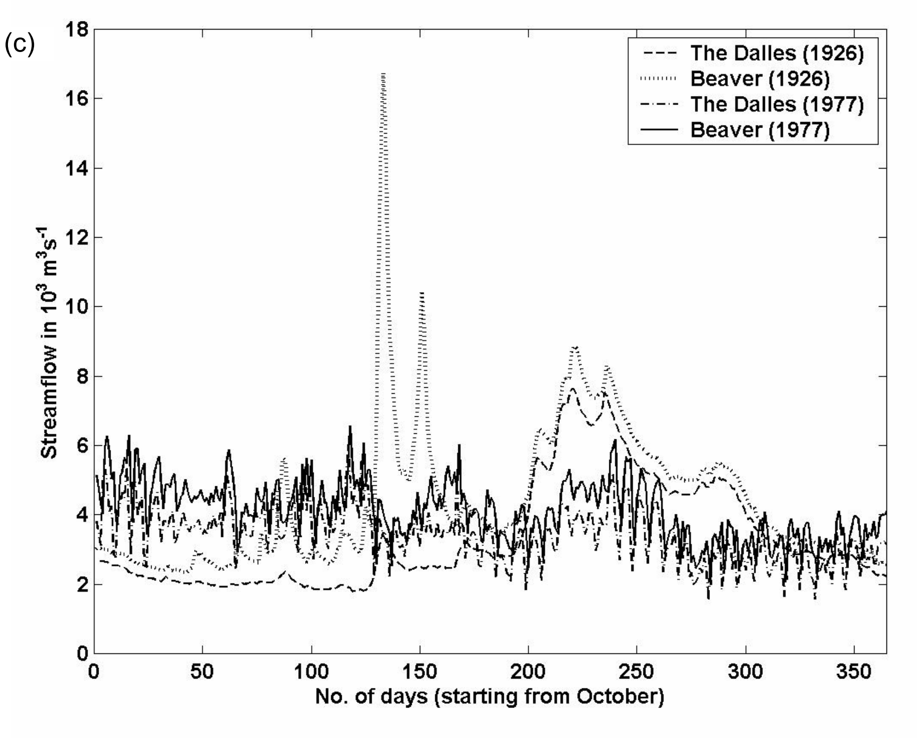

Fig. 4 Continued. (c) see caption opposite.

6 Downstream effects of hydrological alterations Changes in streamflow and sediment transport have exerted an important influence on the Columbia River estuary, but these changes are not yet well understood. Almost totally unknown are the effects of these hydrological changes on the Columbia River buoyant plume in the coastal ocean. Future studies should include the downstream effects of hydrological change by: salinity intrusion and salinity stratification, habitat availability, the fluvial tidal regime, estuarine sediment dynamics, Columbia River plume area, volume, turbidity, and seasonality.

7 Effects of future climate change Although major changes during the past 150 years in Columbia River hydrological processes have resulted primarily from human manipulation and secondarily from climate, it is still vital to consider how climate will constrain future management options in the river basin, including efforts to restore depleted salmon populations. Climate projections forecast gradual regional warming, possibly accompanied by higher winter precipitation. This may lead to increased incidences of winter freshets and lower natural spring freshet flows. These hydrological changes would aggravate conflicts over water supply during the critical spring freshet period, by decreasing natural flows and increasing water demand.

DISCUSSION

Spring freshets are especially important to downstream migration of juvenile salmons (Bottom *et al.*, 2005). Large freshets can also affect salmonid populations by modifying habitat structure and distribution. On the other hand, water quality and habitat availability may decline during very dry years, effects that are further exacerbated by human alterations like diking and irrigation diversion. Important lessons can be learnt from the flow histories of extreme years because salmon are most severely tested under stressful climatic conditions.

Very large freshets that occurred in the pre-regulation period before 1900 lasted 30–60 days, with the sharpness of the peak governed by the relative timing of snowmelt throughout the basin. Significant snowmelt events occur in many winters before a major spring freshet, e.g. 1862, 1881, 1894, 1948, 1956, 1974 and 1997, reducing the intensity of the following spring freshet (e.g. 1894, Fig. 4(a)) and subsequent summer flows. The occurrence of major freshets even after winter snowmelt events indicates the high magnitude of the snow pack in such years. Flow regulation decreases spring freshet magnitude and increases flows during the rest of year through winter drawdown of reservoirs, filling of the reservoirs during the freshet and de-synchronization of flow peaks throughout the basin. The result is a "spring" freshet in high-flow years like 1996 and 1997 that lasts from January to June (Fig. 4(b)). The effects of human manipulation (especially a weekly power-peaking cycle) are also very prominent during very low flow years like 1977 and 1992. The spring freshet in such years is now an almost totally artificial event. The closest pre-regulation analog to such years (1926) still showed a marked annual cycle, though it was of reduced intensity (Fig. 4(c)).

The Columbia River has historically been a major source of economic activity for the Pacific Northwest, and is one of the more heavily modified rivers in the USA today. Understanding human and climate-induced changes in its hydrological properties is, therefore, a topic of considerable interest. Long streamflow records are essential to determining how runoff has changed over time. Daily streamflow records of the Columbia River at The Dalles dates back to June 1878. However, the observed daily flow does not alone provide enough information to understand or separate anthropogenic and climate effects. It is also necessary to have an estimate of virgin (naturalized) flow of the river to provide a historical perspective of water resources development, to separate anthropogenic and climate effects, and to compare present water use scenarios with those of the past decades. The United State Geological Survey (USGS) has calculated a monthly averaged adjusted river flow at The Dalles since 1879 that accounts for the effects of flow regulation. The Bonneville Power Administration (BPA) has estimated the monthly averaged virgin (or naturalized) flow at The Dalles, i.e. the flow in the absence of both flow regulation and irrigation depletion for 1929–2000 (BPA, 2004). Naik & Jay (2005) have estimated the monthly virgin flow of the Columbia River at The Dalles from records of irrigated area for the missing years, i.e. for the period 1879–1928. Examination of the virgin flow record shows that climate change since the late 19th century has caused a decrease of 8–9% in its annual average flow volume. The decrease in flow due to irrigation diversion during the same period is also 7–8% (Naik & Jay, 2011). Broadly speaking, there are three periods of Columbia River flow management. Before 1900, mainstem dams were absent and flow diversions relatively small. Numerous dams were constructed between 1900 and 1970, and irrigation depletion increased 500%. Since about 1970, river flows have been managed on a system-wide basin, significantly affecting interannual transfers of flows for the first time.

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