Separation of climate and anthropogenic influences on Columbia River mean flow and sediment transport

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Abstract Most analyses of hydrologic changes do not differentiate the contributions from climatic and human influences. Here, we separate human and climate influences on the Columbia River mean flow and sediment transport. The mean annual Columbia River virgin (naturalised) flow at The Dalles has decreased ~17%, 8–9% due to climate change and 7–8% due to irrigation water withdrawal. Climate impacts on the sediment discharge are larger than on streamflow because sediment discharge increases more than linearly with flow ($Q_S \sim Q_R^n$, n = ~2.4). Total sediment and sand transports have decreased >50% and >70%, respectively. Flow regulation (since 1970) has decreased peak spring flows by ~45% and increased flow during the rest of the year. The spring freshet flow decrease due to climate change is 8–9%; the decreases due to water withdrawal and flow regulation are about 11–12% and 26–27%, respectively. The peak freshet flow now occurs two to four weeks earlier than before 1900.

Key words climate impact; human impact; climate change; El Niño Southern Oscillation; Pacific Decadal Oscillation; sediment transport; water withdrawal; flow regulation; reservoir manipulation; irrigation depletion

INTRODUCTION

The present study summarizes the effects of anthropogenic and climate-induced changes in the Columbia River's hydrological processes over the last 150 years until the end of the 20th century, and attempts to separate the human and climate influences on the Columbia River mean flow and sediment transport. Separation of these two influences on the hydrological cycle should assist in policy analyses and formulation of strategies for future management, particularly with reference to the Columbia's endangered salmon runs.

The Columbia River has the largest flow (about 7300 $m^3 s^{-1}$) of any river on the Pacific coast of North America. It drains an area of 660 500 km^2, encompassing parts of two Canadian provinces and seven USA states (Fig. 1). Its annual average sediment discharge (~12 M tons $year^{-1}$) is not unusually large, and is exceeded by several other western rivers. In terms of hydrology, the river basin can be divided into western and interior sub-basins by the Cascade Mountain Range. The interior sub-basin (with 92% of the surface area and three-quarters of the flow) is, aside from its Canadian part, relatively arid. Almost all the interior sub-basin flows pass the gauge at The Dalles, which has the longest daily flow record on the West Coast (1878–present). The western sub-basin contains only 8% of the area of the entire Columbia River Basin, but contributes about one-quarter of the flow. The Willamette River is typical of the western sub-basin; the flow record at Albany in the upper reaches extends from 1892 to date.

Columbia River flows are strongly correlated with large-scale climate patterns, principally the ENSO (El Niño Southern Oscillation) and PDO (Pacific Decadal Oscillation) (Hamlet & Lettenmaier, 1999; Jay & Naik, 2000). These climate patterns contribute to the climate variability of the region, while their intensities and frequency of occurrences are also influenced by global climate change (Cayan & Peterson, 1989; Redmond & Koch, 1991; Hamlet & Lettenmaier, 2007). Streamflows have fluctuated considerably over the period of instrumental records, and the socio-economic, physical and biological significance of this variability is great (Miles *et al.*, 2000; Payne *et al.*, 2004; Bottom *et al.*, 2005).

Sediment discharge in the Columbia varies non-linearly with flow, and fluctuations in the sediment discharges are larger than those in streamflow (Jay & Naik, 2000). While accumulation of sediment in aquatic environments is a natural process, some human activities, such as cultivation, forest clearing, mining and construction, have increased erosion rates (Syvitski *et al.*,

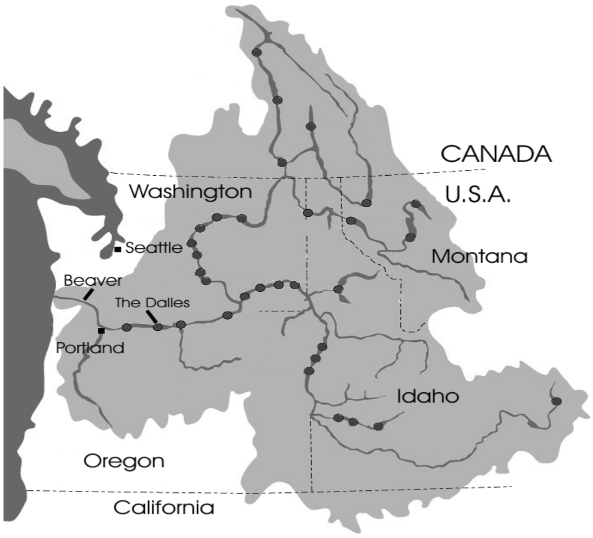

Fig. 1 Columbia River basin with locations of major dams; Interior basin is east of The Dalles. (After US Army Corps of Engineers).

2007). However, human-made dams and reservoirs often trap at least one-half of the river sediment that flows into them (Xiqing *et al.*, 2005), confounding the problem of evaluating human impacts on riverine sediment transport.

Several studies have been carried out in recent years to identify causes for the decline of the Columbia River salmon populations and to suggest remedial measures (Bottom *et al.*, 2005). Columbia River mainstem flow and sediment transport, both of which are climate dependent, affect salmonids in numerous ways. The multiple aspects of salmonid dependence on hydrological properties mean that it is vital to document changes in the Columbia River hydrological processes over historic time. Intelligent formulation of future management options requires that human and climate-induced impacts on the historical record be separated as cleanly as possible. This study has, therefore, a special relevance to the Columbia River endangered salmonids.

DATA

ENSO events were identified on the basis of the winter averages (October to March) of the Southern Oscillation Index (SOI), obtained from the Climate Research Unit (CRU), University of East Anglia, UK, and the NCEP (National Center for Environmental Prediction), USA. The interdecadal oscillation in the North Pacific Ocean was identified with PDO indices for the period 1901 to 1999 developed by Mantua *et al.* (1997) (http://tao.atmos.washington.edu/pdo). The years characterized by warm (+ve) or cold (–ve) PDO phases were distinguished on the basis of winter values (October to March) of PDO indices.

Three types of streamflow estimates were employed in this study: (1) observed, (2) adjusted, and (3) virgin flows. Observed flows are daily instrumental records available from the US Geological Survey (USGS). Adjusted flows, available on a monthly basis from the USGS, have been corrected to eliminate the effects of flow regulation and reservoir manipulations. Virgin flows, available on monthly basis with the Bonneville Power Administration for 1929–2000 (BPA, 2004) represent the natural flow as it would be without human alteration; i.e. the observed flow corrected for irrigation depletion and return flows, as well as for reservoir manipulation. For the periods 1879–1928, virgin flows were estimated on the basis of the procedure suggested by Naik & Jay (2005). The maximum annual discharge for 1858–1878 was recorded in association with railroad and barge traffic in the Columbia River Gorge (Henshaw & Dean, 1915). A linear regression of 1879–1899 annual mean flow *vs* 1879–1899 annual maximum flow was used to estimate annual mean flow for 1858–1878.

Long-term daily sediment hindcast for the period 1878–1999 was made for the station at Vancouver with respect to both observed and virgin flows at The Dalles. This estimate was on the basis of the SPM (suspended particulate matter) data available at Vancouver for the period 1963–1969. The SPM transport *vs* flow rating curve was developed using a smearing correction (Duan, 1983). Similarly, an SPM hindcast for the Willamette River at Portland was made for the period 1878–1999 on the basis of the available data for 1962–1997. Sand transport estimates associated with the daily observed and virgin flows were made as a fraction of the total sediment transport based on a relationship developed by Haushild *et al*. (1966).

RESULTS

Climate effects have been estimated by examining changes in the magnitude and timing of the virgin flow over time. Comparison of the virgin and adjusted flows has allowed evaluation of the effects of irrigation depletion. The difference between the adjusted and observed flows has quantified the impacts of reservoir manipulations. The total change due to the combination of human and anthropogenic effects has been obtained by comparison of the pre-1900 virgin flows with the contemporary observed flows (Fig. 2). For example, the climatic "present" has been defined as the period since 1945, which encompasses one full Pacific Decadal Oscillation (PDO) cycle plus (perhaps) the beginning of a new cold PDO phase. In terms of flow regulation and irrigation, the post-1970 period is the management "present".

The primary factors influencing and altering Columbia River hydrology and sediment transport are enumerated below:

(a) **Human and climate influences on flow and sediment transport** Major changes over the last 150 years in the Columbia River hydrological processes have resulted primarily from the human alteration to the system and secondarily from the climate processes.

(b) **Climate change** Climate and flow conditions during the last half of the 19th century reflected the end of the "Little Ice Age" from about 1400–1850. This period was significantly cooler

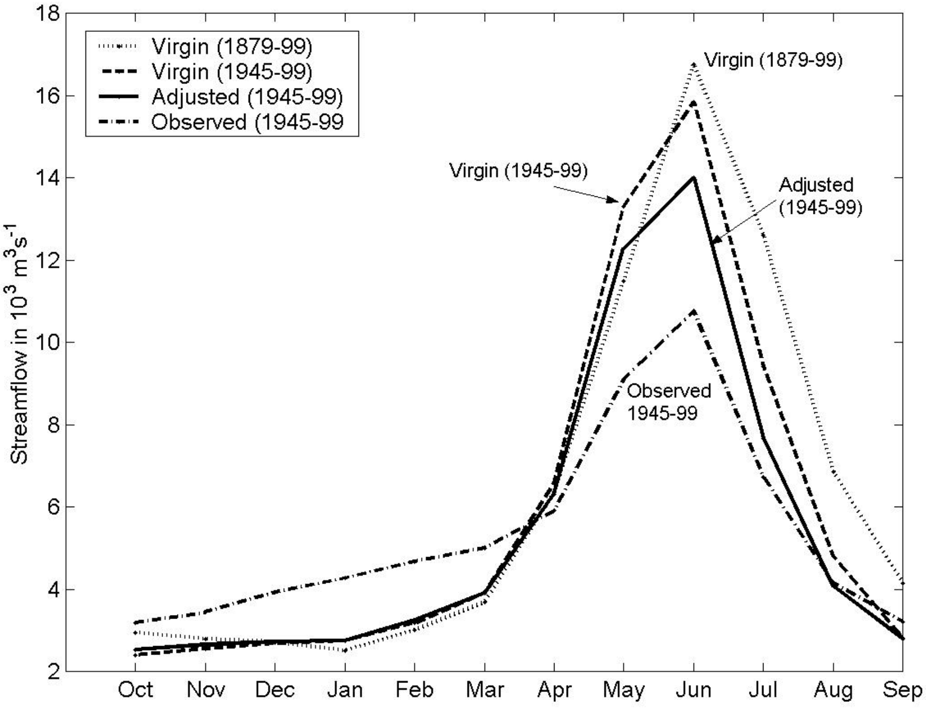

Fig. 2 Comparison of observed, adjusted and virgin flows of the Columbia River for 1945–1999 with virgin flow for 1879–1899.

and wetter than present conditions. For example, 10 of the 14 strongest known freshets in the system occurred between 1849 and 1900, even after human manipulation of the flow is accounted for.

(c) **Climate cycles** Cyclical climate phenomena exert a strong influence on the Columbia River hydrology. Although the history of climate fluctuations in the region during the 19th century is unclear, effects of two cyclical processes were prominent throughout the 20th century:
  (i) The Pacific Decadal Oscillation (PDO) has a cycle that lasts 40–60 years and has likely been active for at least 300 years. Cold-PDO phases (e.g. 1945–1976) are generally associated with high river flows and are favourable for salmonid production in the Pacific Northwest; warm phases (e.g. 1977–1995) are characterized by low river-flows and are less favourable for salmonid production.
  (ii) Indices of the El Niño-Southern Oscillation (ENSO; typically 3–7 years in duration) are also correlated with the Columbia River flow. ENSO cycles affect survival of salmonids in the fluvial, estuarine and ocean environments. Because strong El Niño or La Niña events typically last only 1–2 years, definition of ENSO impacts on salmonids is, however, less clear-cut than is the case with PDO impacts.

(d) **Pacific Decadal/El Niño Southern Oscillation interaction** The PDO and ENSO cycles interact such that El Niño years are most intense during the warm-PDO phase and La Niña years during the cold-PDO phase. The average annual Columbia River flow at The Dalles is 115% of normal during cold-PDO/La Niña years, whereas it is only 87% during warm-PDO/El Niño years. The corresponding figures for the Willamette River are 121 and 82%.

(e) **Climate effects on sediment** Flow fluctuations are amplified by fluvial sediment transport, because sediment transport varies more than linearly with flow. Total sediment load during cold-PDO/La Niña years is more than 200% of that during warm-PDO/El Niño years in both the Columbia and the Willamette Rivers. Climate effects on sand transport are even stronger than those on total load.

(f) **Latitudinal position** The Columbia Basin's climate response is conditioned by its position within a latitudinal band of strong response to both the ENSO and PDO cycles. The flow per unit area is much larger in the western than in the interior sub-basin, and latitudinal differences in the timing of snowmelt influence spring freshet properties. Still, there are only modest variations across the basin in response to ENSO or PDO forcing.

(g) **Annual average flow at The Dalles** Changes in annual mean flow are an important integral measure of system alteration. The mean annual average flow of the Columbia River at The Dalles has decreased about 16.9% from 6320 m^3 s^{-1} (1879–1899 estimated natural or virgin flow) to 5250 m^3 s^{-1} (1970–1999 observed flow). We estimate that a 9% decrease is due to climate change, and ~7.4% is due to irrigation depletion.

(h) **Spring-freshet properties** Spring-freshet properties have been much more highly altered than the mean flow. The average natural or virgin flow for the spring-freshet season (May–July) was ~13 600 m^3 s^{-1} before 1900. This has decreased by ~6320 m^3 s^{-1} (46.5%) to 7290 m^3 s^{-1}, with most of this reduction (26.5%) due to flow regulation, 11.6% due to irrigation depletion, and 8.4% due to climate change. Thus, freshet-season flow at The Dalles is now only 139% of the present (reduced) mean flow, while it was 217% of the higher 19th-century flow. Flow regulation and the annual irrigation cycle have also increased fall and winter flows, the latter because of pre-release of water before the freshet.

(i) **Maximum daily flow at The Dalles** The observed maximum daily spring freshet flow has been reduced slightly more than freshet season flow, from 19 300 m^3 s^{-1} (1858–1899) to 10 870 m^3 s^{-1} (1970–1999), a decrease of 44%. This is a change from 355% to 200% of the mean flow.

(j) **Spring-freshet timing at The Dalles** The timing of the maximum spring-freshet flow has also changed. Maximum daily spring freshet flow now typically occurs at about water-year

Day 242 (May 29), whereas maximum flow occurred in the 19th century at about water-year Day 256 (June 12), a shift of about two weeks.

(k) **Willamette River hydrology** Changes in the western sub-basin have been similar to those in the interior sub-basin, but are less well documented. The observed annual average Willamette River flow at Albany has decreased from 462 $m^3 s^{-1}$ for 1893–1900 to 394 $m^3 s^{-1}$ for 1970–1999, or 14.8%. Late summer and autumn (August to December) flows have been augmented, whereas, average monthly flows during the January to July periods have decreased.

(l) **Columbia River flow at the mouth** The long-term average flow at the mouth of the Columbia River is 7300 $m^3 s^{-1}$ (1892–1999). The value of the Columbia River flow at the mouth prior to 1900 was ~8530 $m^3 s^{-1}$ and has decreased to ~7080 $m^3 s^{-1}$ (1970–1999).

(m) **Changes in sediment transport** The annual average sediment transport from the interior sub-basin has decreased from about 21 M tons (1858–1878) to ~8 M tons (1970–1999), a reduction of ~60%. We estimate that historical sand transport of over 10 M tons for 1858–1899 has decreased to ~2 M tons, a reduction of ~80%. Most of the reduction in interior sub-basin sediment transport is related to the dam system, especially its reduction of spring freshet flow. In the Willamette River, historical sediment transport for 1893–1903 was approximately 2.4 M tons, compared with only 1.5 M tons for 1970–1999, a reduction of ~35%.

DISCUSSION AND POLICY IMPLICATIONS

Columbia River flow and sediment transport processes have been altered by water withdrawal for irrigation and by construction of 28 large and numerous small dams (Simenstad *et al.*, 1992). Irrigation depletion was small before ~1900, but increased rapidly between 1890 and 1920, and again 1960–1980 (Naik & Jay, 2005). Several dams were constructed with multiple purposes of producing electricity, controlling floods, and facilitating irrigation. Completion of seven large dams high in the basin between 1967 and 1973 more than doubled the storage capacity of the total dam system and provided a considerable increase in storage residence time. These factors identify three periods in terms of hydrological management of the Columbia River: (a) the nearly unaltered hydrological regime that prevailed before 1900, (b) the intermediate phase of irrigation development and dam building from 1900 to 1970, and (c) the contemporary period (after 1970) of highly centralized hydrological management. It is not clear at this time whether the sediment transport throughout the history of the system is susceptible to the same three-fold division. The distinct responses of sand transport (limited by transport capacity and therefore changes in flow) and fine sediment transport (limited by supply and therefore land use) suggest that other factors besides flow regulation, irrigation depletion and climate need to be considered with regard to sediment transport. A combination of analysis of hindcasts and landscape modelling will be needed to fully understand the historical changes in the sediment transport component.

The Canadian part of the Columbia River basin has been little affected by irrigation development and flow regulation. On the other hand, changes in the western sub-basin, such as in the Willamette River, have been similar to those in the interior sub-basin, but are less well documented.

Almost all river basins around the world suffer from anthropogenic influences, and climate change is a universal feature. In order to successfully manage a river basin, it is essential to understand the recent hydrological history and the human management trajectory of the system. Furthermore, management strategies based only on streamflow alone may not be adequate. It is possibly due to these reasons that the flood control and hydropower management strategies used in the Columbia River basin have had unintended impacts on the sediment budget and juvenile salmonids. It is also important, and it will become increasingly important in the future, that a separation between human and climate impacts on the streamflow and sediment transport components is provided as clearly as possible. This paper briefly describes a very simple scheme that can be used in any river system around the world for analysing historical changes.

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