DISTINGUISHING HUMAN AND CLIMATE-INDUCED CONTRIBUTIONS TO THE COLUMBIA RIVER HYDROLOGY

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SUMMARY

Most hydrologic trends result from a combination of climatic and human influences, and analyses of hydrologic changes often do not differentiate these factors, despite the obvious relevance of this distinction. Here, we separate human and climate influences on the Columbia River hydrologic cycle and sediment discharge. Human influences include water withdrawal for irrigation, flow regulation, reservoir manipulation, mining and deforestation. The Columbia's streamflow and sediment discharge are strongly correlated with large-scale climate patterns, particularly the ENSO (El Niño Southern Oscillation) and PDO (Pacific Decadal Oscillation). The mean annual average Columbia River virgin flow at The Dalles has decreased ~16.5%, 8-9% due to climate change and 7-8% due to water withdrawal for irrigation. Climate impacts on the sediment discharge are larger than on streamflow because sediment discharge increases more than linearly with flow. Total sediment and sand transports have decreased >50% and >70% respectively, only a fraction of which is due to climate change. Changes in the timing of maximum flows from sub-basins, as influenced by flow regulation and irrigation withdrawal, determine freshet timing and play a larger role in determining the maximum flow and sediment transport levels. 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 11%; the decreases due to water withdrawal and flow regulation are about 12% and 26% respectively. The peak freshet flow now occurs two to four weeks earlier than before 1900.

INTRODUCTION

Runoff integrates changes in hydrologic characteristics over a large area and is a particularly valuable indicator of climate change (USGCRP, 2000). Considerable efforts have been made in the past two decades to evaluate climate impacts on the individual rivers. The hydrological cycle in most of these systems has significant human influences, and no clear separation has actually been made between these two vital components. The present study summarizes the effects of anthropogenic and climate-induced changes in the Columbia River hydrological processes over the last 150 years, 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 hydrologic cycle should assist in policy analyses and formulation of strategies for future management, particularly with reference to the Columbia's endangered salmon runs.

Fig.1: The Columbia River basin showing the mainstem reservoirs (after the US Corps of Engineers).

The Columbia River, with an average flow of 7300 m^3s^{-1} at the mouth, is the largest river on the Pacific Coast of North America and the fourth largest in the United States in terms of runoff (Kammerer, 1990). It drains an area of 660 500 km^2, encompassing parts of two Canadian provinces and seven US states (Fig. 1). Columbia River flows are strongly correlated with large-scale climate patterns, principally the ENSO (El Niño Southern Oscillation) and PDO (Pacific Decadal Oscillation). 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. Streamflows have fluctuated considerably over the period of instrumental records, and the socio-economic, physical, and biological significance of this variability is great. Sediment discharge in the Columbia varies non-linearly with flow, and fluctuations in the sediment discharges are larger than those in streamflow.

Sediment transport and deposition have direct implications for reservoir sedimentation, changes in channel bed elevation and flood frequency, maintenance of in-channel structures and navigation systems, aquatic food-web functioning, transport of contaminants etc. (Meade et al., 1990). 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., 2007). On the other hand, man-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. Our objective in this paper is not to estimate the contribution of each of these human activities in enhancing/limiting sediment supply to the Columbia River, but to differentiate their net effect on sediment supply from those imposed by climate change.

Columbia River mainstem flow and sediment transport, both of which are climate dependent, affect salmonids in numerous ways (Bottom et al., 2005). Salmon responds directly to hydrographic factors (temperature, salinity, turbidity) controlled or influenced by river flow and to current velocities set in part by river flow. The multiple aspects of salmonid dependence on hydrologic properties mean that it is vital to document changes in the Columbia River hydrologic processes over historic time. Especially important to downstream migrant salmonids are changes in the magnitude and timing of the spring freshet and associated sediment transport. Intelligent formulation of future management options requires that human and climate-induced impacts on the historical record be separated as clearly as possible. This study has, therefore, special relevance to the Columbia River endangered salmonids.

RESULTS

The Columbia is not an especially turbid river, and its annual average sediment discharge (~12 M tons $year^{-1}$) is exceeded by several western US rivers. Major changes over the last 150 years in the Columbia River mainstem hydrological processes have resulted primarily from human alteration to the system and secondarily from climate processes. The primary climate, human and hydrologic factors influencing and altering the Columbia River hydrology have been:

(1). Climate Change: The period from ca. 1850-1900 appears to have been significantly cooler and wetter than present conditions. For example, 9 of the 13 strongest known freshets in the system occurred between 1858 and 1900, even after human manipulation of the flow is accounted for.

(2). Climate Cycles: The ENSO and PDO exert a strong influence on the Columbia River hydrology. 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 114 (±8)% of normal during cold-PDO/La Niña years, whereas it is only 87 (±7)% during warm-PDO/El Niño years (Fig. 2). The corresponding figures for the Willamette River, representing the western sub-basin, are 120 (±13) and 83 (±10)%.

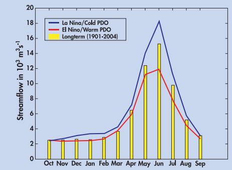

Fig. 2. Response of the Columbia River virgin flow at The Dalles to combined ENSO and PDO effects (1901-2004).

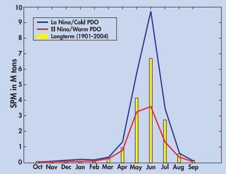

Fig. 3: Response of the Columbia River hindcast virgin total sediment load to ENSO and PDO effects (1901-2004).

(3). Climate Effects on Sediment: Flow fluctuations are amplified by fluvial sediment transport, because sediment transport varies more than linearly with flow. El Niño years in the warm PDO phase typically exhibit a very low sediment transport [10.2 M (±2.1) tons in the Columbia and 1.25 (±0.6) M tons in the Willamette] while in the La Niña/cold PDO combination, the SPM transport increases to more than two times than that of the El Niño/warm PDO years [22.3 (±4.3) M tons for the Columbia and 3.62 (±1.6) M tons for the Willamette] (Fig. 3). Climate effects on sand transport are even stronger than those on total load.

(4). Annual Average Flow at The Dalles: The mean annual average flow of the Columbia River at The Dalles has decreased about 16.5% from 6320 m^3s^{-1} (1879-1899 estimated natural or virgin flow) to 5270 m^3s^{-1} (1945-2004 observed flow) (Fig. 4). We estimate that a 8.4% decrease is due to climate change, and 7.5% is due to irrigation depletion.

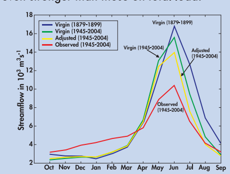

Fig. 4: Comparison of observed, adjusted and virgin flows of the Columbia River at The Dalles for 1945-2004 with virgin flow for 1879-1899.

(5). Spring Freshet Properties: Spring-freshet properties have been much more highly altered than the mean flow. The average virgin flow for the spring-freshet season (May-July) was ~13 610 m^3s^{-1} before 1900. This has decreased by 6550 m^3s^{-1} (48%) to 7060 m^3s^{-1}, with most of this reduction (~25.8%) due to flow regulation, 11.6% due to irrigation depletion, and 10.7% due to climate change. Thus, freshet-season flow at The Dalles is now only 138% of the present (reduced) mean flow, while it was 215% 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.

(6). 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^3s^{-1} (1858-1899) to 10 600 m^3s^{-1} (1970-2004), a decrease of 45%. This is a change from 358 to 166% of the mean flow.

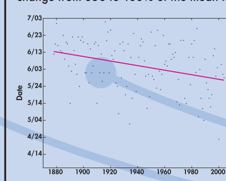

Fig. 5: Peak freshet flows of the Columbia River at The Dalles (1879-2000) as a function of year-day.

(7). Spring Freshet Timing: 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 (Fig. 5). The shape of the hydrograph has also changed, however, and the change in the phase of the wavelet annual cycle indicates a shift of about one month (mid-June to mid-May).

(8).Changes in the Willamette River Flow: The virgin annual average Willamette River flow at Portland has decreased from 1080 (±80) m^3s^{-1} for 1879-1899 to 1010 (±70) m^3s^{-1} for 1945-2004 and to 980 (±100) m3s-1 for 1970-2004, decreases of ~6.5% and ~9.3% respectively, due to climate change. Considering 1970-2004 as the present, the total decrease in annual average flow [difference between 19th century virgin flow and 1970-2004 observed flow of 960 (±100) m^3s^{-1}] is 120 m^3s^{-1} or 11.2%. This is apportioned as follows: climate change 9.3% and irrigation depletion 1.9%.

(9). Columbia River Flow at the Head of the Estuary and Mouth: The Columbia River flow at the head of the estuary (1879-1899) was 8130 m^3s^{-1}; it has decreased 16.5% to 6780 m^3s^{-1} for 1970-2004, 8.9% due to climate change and 6.1% due to irrigation depletion (Fig. 6).

(10). Changes in Sediment Transport: The hindcast sediment load associated with the Columbia River virgin flow at The Dalles is 20.5 (±4.4) M tons for 1879-1899 and 16.9 (±2.0) M tons for 1945-2004, a decrease of ~3.6 M tons or ~17.6% due to climate change. The change in sediment transport between 1879-1899 virgin flow and the 1970-2004 observed flow is ~13.2 M tons, a reduction of >60%. The decrease in sand transport is from ~14 M tons in 1879-1899 to 2.1 M in 1970-2004, a reduction of 85%. Most of the reduction in interior sub-basin sediment transport is related to the dam system, especially its reduction of spring freshet flow.

DISCUSSION AND POLICY IMPLICATIONS

Separation of anthropogenic and climate effects on the Columbia River hydrologic processes has been facilitated by definition of three measures of river flow:

- Observed flow - the flow actually observed at a gauge, available on a daily basis for 1878 to present.
- Estimated adjusted flow - the observed flow corrected for reservoir manipulations calculated by the U.S. Geological Survey on a monthly basis for 1878-2004 as per Orem (1968).
- Estimated virgin flow - an estimate of the river 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 manipulations (Bonneville Power Administration, 2004; Naik and Jay, 2005).

Effects of flow regulation and hydropower generation can be judged by comparison of the observed and adjusted flows at The Dalles; the impacts of water withdrawal can be determined from comparison of the adjusted and virgin flows. Climate effects can be estimated by examining changes in the magnitude and timing of the virgin flow over time. The total of all climate and anthropogenic effects can be seen by comparison of the virgin flow before 1900 at The Dalles with the contemporary observed flows. Because of the non-linear dependence of sediment transport on flow, there is no unique decomposition of the changes in sediment transport into human and climate effects. It is evident, however, that climate effects have made only a modest contribution to the total changes to sediment transport over time.

The differences in the time scales of human alteration and climate fluctuations/change can be dealt with by averaging over different time scales. Thus for example, the climatic "present" has been defined as the period since 1945 (Fig. 4), 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" (Fig. 6). The pre-development climate regime is conveniently described in terms of averaging of the data before 1900. In terms of management, there are three periods: a) the nearly unaltered hydrologic 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 hydrologic management.

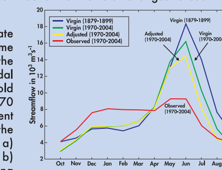

Fig. 6: Comparison of the monthly virgin flow (1879-1899) to the virgin, adjusted and observed flows (1970-2004) of the Columbia River at Beaver.

It is not clear at this time whether the sediment transport throughout 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 landuse) 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 modeling will be needed to fully understand historical changes in sediment transport.

Most river basins around the world suffer from anthropogenic influences, and climate change is a universal phenomenon. To successfully manage a river basin, it is necessary to understand the recent geologic history and the human management trajectory of the system. Furthermore, management strategies based only on streamflow alone may prove sub-optimal. Thus, for example, the flood control and hydropower management strategies used in the Columbia have had unintended impacts on the sediment budget and juvenile salmonids. It is also important (and will become increasingly important in the future) to provide a clear separation between human and climate impacts on the streamflow and sediment transport. This work presents a very simple scheme for analyzing historical changes that can be used in any system with sufficient flow and sediment transport data.

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