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ESTIMATION OF THE COLUMBIA RIVER VIRGIN FLOW (1879-1928)

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ABSTRACT

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 United States today. Understanding human and climate-induced changes in its hydrologic 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 1978. However, the observed daily flow does not alone provide enough information to understand or separate anthropogenic and climate effects. It is necessary also to have an estimate of virgin flow of the river to provide a historical perspective of water resources development, separate anthropogenic and climate effects, and 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 for 1879-1999 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 1929-89. We 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. In addition, a filtered version of the daily observed flows were combined with monthly virgin flow corrections to obtain estimates

of daily virgin flows with realistic higher moments and spectral properties. Examination of the virgin flow record shows that climate change since late 19th century has caused a decrease of >7% in its annual average flow volume. The decrease in flow due to irrigation diversion during the same period is also ~7%. 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, effecting significant interannual transfers of flows for the first time.

INTRODUCTION

The Columbia River is the largest river on the Pacific Coast of North America and the second largest in the United States (Simenstad et al., 1990). It drains an area of 660,480 km^2, encompassing parts of two Canadian provinces and seven states in the US (Figure 1). Human intervention along its course has resulted in physical, chemical, hydrological, and biological modifications of its fluvial and estuarine ecosystems. The principal drivers of the physical modifications include rapid population growth and consequent exploitation of the natural resources. Factors that have contributed significantly toward these modifications include construction for hydroelectric power generation of 28 main-stem and tributary dams, water withdrawal for irrigation, waste discharges (point and non-point), deforestation, diking and filling of shallow water and intertidal areas, and navigational development. Although construction of major dams began in 1906, system-wide management of the flow began only about 1970. The cumulative effects of climate change, flow regulation and water withdrawals have caused a ~17% reduction in average flow, a ~44% reduction of spring freshet peak flows, an increase in flows in late summer, fall and winter, and an increase in water temperature (Bottom et al., 2001).

Climate has played an important role in changing the flow hydrology of the Columbia River basin (Redmond and Koch, 1991; Mantua, 1996; Hamlet and Lettenmaier, 1999; Miles et al., 2000). However, analysis of climate effects on the Columbia and other western rivers have been based to date on the basis of the observed flow data, without regard to irrigation depletion and flow regulation. Obviously, human factors influence long-term trends in the observed annual average flow and strongly effect the seasonality of the flow. Climate effects on seasonality of the flow and timing and volume of freshets can only be determined from analyses of the virgin flow. Thus, it is imperative to have estimates of virgin (or naturalized) flow of the Columbia River in order to provide a historical perspective of the water resources development, separate the anthropogenic and climate influences, and to compare present water use patterns with those of the past decades. Finally, virgin flows are also necessary for hindcasting the sediment transport under natural conditions.

The Columbia River at The Dalles has the longest continuous flow record of any river on the Pacific Coast of North America. Observations began in 1858 (Henshaw and Dean, 1915). However, until 1878, only the annual peak flows were recorded. United State Geological Survey (USGS) flow records are available on daily basis since June 1878 (Figure 2). In order to estimate the effects of storage changes due to flow regulation in the upstream reservoirs, the USGS has made corrections to the observed flows at The Dalles (L. Hubbard, USGS, Portland, personal communication, 1999). These adjusted flows are available on a monthly basis for water years 1879 to 1999. These are the flows that would have occurred if dams were in place but not operated for the period of record. Adjusted flows eliminate, therefore, the effects of flow regulation, reservoir manipulation, and evaporation.

Bonneville Power Administration (BPA) (1993) has estimated the monthly "natural" or "virgin" flow of the Columbia River at The Dalles for 1929-89. These represent the monthly averaged flows that would have occurred if there were no white settlements (M. Newsom, US Bureau of Reclamation, personal communication, 2000). In other words, these are the flows adjusted to eliminate all effects of development including irrigation depletion, flow regulation, reservoir manipulation and evaporation (USBR, 1999). The difference between the virgin flow and the observed flow gives the total change in flow, due both to flow regulation and irrigation depletion. In the present contribution, virgin flow for the Columbia River at The Dalles has been estimated for the missing years, i.e., for the period 1879-1928. We have also estimated a daily virgin flow index for the period 1879-1989, for analysis of changes in sediment transport.

CLIMATE AND GENERAL HYDROLOGY

It is important to put The Dalles flow record in its geographic context. The north-south trending Cascade Mountain Range divides the Columbia River basin into two distinct parts: (1) the Western sub-basin covering an area of 46,650 km^2, with the Willamette River as the largest drainage, and (2) an Interior sub-basin covering an area of about 613,830 km^2, east of the Cascade Ranges (including the Snake and the Upper Columbia as the principal drainages). The western sub-basin has a maritime climate. Daily mean temperature varies from 1.5^{o}C in the winter to 24^{o}C in the summer. The

Interior sub-basin shows marked temperature fluctuations. Temperature varies between less than $0^{o}C$ in the winter to more than $38^{o}C$ in the summer. Akin (1991) describes the climate of this part of the basin as belonging to Middle Latitude Steppe type. Annual precipitation of the Columbia River basin decreases from west to east. It varies from >2550 mm yr^{-1} in the coastal region to <250 mm yr^{-1} for the Snake River basin and the Columbia plateau.

The precipitation distribution is reflected in the flow distribution. Although the coastal sub-basin covers only about 7% of the basin area, it contributes about one quarter of the total flow at the mouth. Runoff in Coastal sub-basin occurs mostly from winter precipitation during the months of November through March. In the Interior sub-basin, on the contrary, runoff is mainly due to the spring snowmelt during the months of April through July. The measured flow at The Dalles accounts for about 97% of the total Interior sub-basin flow. Because of the large surface area of the Interior sub-basin, it encompasses substantial climate variations. For example, the Canadian portion of the sub-basin contributes about 52% of the flow at The Dalles from only about 23% of the surface area above The Dalles. In contrast, the Snake River is a relatively dry area with 43% of the sub-basin but only 28% flow contribution at The Dalles (Table 1).

IRRIGATION DEPLETION AND VIRGIN FLOW

Historical Setting

Agriculture has historically been a major source of economic activity in the Columbia River basin. Many parts of the Interior sub-basin are, however, semi-arid and require irrigation during the growing season. Probably the earliest irrigation was carried out by the missionaries who settled in the Walla Walla and the Clearwater River drainages prior to 1840 (Simons, 1953) (Figure 3). The early settlers were able to divert water from tributary streams to adjacent lands with little effort. Still, in 1860, human population was very thin and there was only 9 km^2 of land under irrigation. The period between 1860 and 1880 saw an influx of settlers because of the booming mining and cattle raising activities in the Pacific Northwest. During this time railroads were constructed bringing additional settlers and expanding the markets for farm products. In 1870 there were about 130,000 people living in Washington, Oregon and Idaho and approximately 197 km^2 of land were being irrigated in the Columbia River basin above the Dalles (Simons, 1953). By 1880, the population was about 400,000, about 230% higher than the previous decade. Also, the year 1880 marked the completion of the transcontinental rail connections between the Great Lakes region and the ocean ports of the Pacific Northwest. New markets were opened for the products of the farmlands, mines, and forests, and larger irrigation projects were undertaken in the Snake and Yakima River valleys. Between 1880 and 1890, the population increased by 170 percent. From a total of 9 km^2 in 1860, the irrigated area increased to 2098 km^2 in 1890.

Population growth became sluggish during the decade 1890-1900 in part because of the devastating 1894 flood, the most severe flood in the Pacific Northwest since white settlement. However, this flood did not have a great impact on the growth of irrigated area. Irrigation canals were constructed during the period 1884-1896, and by 1910, the irrigated area had increased to 9198 km^2. It reached 13,458 km^2 in 1920 (Figure 3), and the first irrigation districts were created. The increase in irrigation after 1900 marked the onset of major alteration of the river system and established irrigated agriculture as an important part of the Pacific Northwest economy. Thus, the year 1900 marks the end of period during which observed Columbia River flows approximate the virgin flows. This division is also convenient because the 19th and 20th century climate regimes were rather different.

Subsequent to 1920, the increase in irrigated lands was gradual. A shift from the wet conditions (before 1890 to ~1924) to the following dry period of ~1925-46 (Mantua et al., 1997) also had a substantial effect on irrigation developments. Most of the storage reserves were found inadequate to cope with such conditions. Additional irrigation projects were more expensive to develop, water supplies were less accessible and pumping was often required. These factors greatly restricted further irrigation expansion, especially during the depression of the 1930s.

Further river development was driven by the vision of cheap hydropower as the key to regional economic development. The period between 1930 and 1950 saw an initiation and construction of small to large-sized surface water reservoirs, including the Bonneville (initiated in 1933, completed in 1944) and the Grand Coulee Projects (authorized in 1935, completed in 1954). Until mid 1940s, about 70% of the irrigated areas of the Columbia River basin above The Dalles were found in the Snake River basin, while about 23% were above the mouth of the Snake River basin. The remainder (about 7%) were between the mouth of the Snake River basin and The Dalles (Figure 3). With the commencement of the construction of Priest Rapids dam in 1956, Rocky Reach dam in 1957, Wanapum in 1959 and Wells in 1963, the irrigated areas in the middle reaches of the Columbia River rose quickly. The reach between the Snake River mouth and The Dalles also saw a rapid irrigation development in the sixties.

By 1970, irrigated area reached essentially its current level. Also, about this time, a number of large reservoirs were completed. These reservoirs were high in the basin and had longer residence times than those earlier mainstem dams (Simenstad et al., 1992). This in addition to the river management system allowed the Interior sub-basin flows to be managed in an integrated manner. This resulted in substantial interannual transfer of flow, especially in the 1972-77 period of highly variable flow – a novelty in the system. The period between 1960 and 1980 saw some growth in irrigation development. However, the relatively dry climate period after 1977, combined with the flow regulation and the desire to restore salmon runs, especially in the Snake River basin, caused some decline in irrigation after 1980.

Virgin Flow Calculation and Validation

Simon (1953) estimates the area under irrigation and the corresponding annual irrigation depletion along the Columbia River from 1860 to 1946. His estimates are for every ten years for 1860-1900 period, for every five years for 1900-1920 period and on annual basis for the subsequent years up to 1946. Based on his data, irrigated areas were interpolated on an annual basis for the period 1860-1919 (Figure 3). Simons (1953) also estimated irrigation depletion estimates on annual basis, but these estimates do not in any way determine the monthly virgin flow. Also, they do not take into account variations in precipitation during the irrigation season. Therefore, the monthly adjusted flow provided by USGS since 1879, monthly virgin flows provided by BPA for 1929-89, precipitation data (1878-1989), and the interpolated irrigated areas data for 1860-1919 were used for estimation of the monthly virgin flows for the 1879-1928 time period.

The difference between the published estimates of monthly virgin and adjusted flows for 1929 to 1989 gives a monthly depletion due to irrigation for this period. When the monthly depletion values are divided by the area under irrigation for the corresponding years, an estimate of monthly depletion per unit area is obtained. These monthly values averaged over the 1929-46 period define the average annual cycle of depletion (Fig. 4). Irrigation depletion, however, also depends on weather, the crops under irrigation, and their water requirements for growth. Changes in cropping pattern are dependent on the change in climate over a period of years and alteration to the existing irrigation systems. Such changes are usually gradual. Therefore, the cycle of depletion defined for a particular year can be grouped with the preceding or the succeeding years in close proximity.

Investigation of the annual cycles for 1929-46 period suggested that the annual cycles of depletion for the five year period 1929-33 be averaged to define a depletion cycle that was assumed to be typical also of the period prior to 1929 (Figure 4). This assumption is subject to uncertainty in relation to both short-term variability in depletion and longer-term variability in climate that cannot readily be estimated. It is possible that systematically less water was needed during the wetter climate period that prevailed for most of the 1860-1928 period. Fortunately, irrigated areas were small before 1900, and errors in our estimates scale according to irrigated area. However, to estimate the uncertainty (related to random variations) involved in application of the 1929-33 irrigation depletion cycle to earlier periods, the depletion rates by month were compared with 95% confidence interval of the depletion rates for the corresponding months for the 1929-46 period. As shown in Figure 4, the narrow margin in the monthly depletion rates for the 18 years period suggests that the random error involved in assuming the 1929-33 depletion cycle valid for the period 1879-1928 is likely small.

Irrigation during the late 19^{th} century and early 20^{th} centuries, including the period 1929-33, was mostly accomplished by diversion of water by construction of small dams across the streams and rivers. Because of the simple technologies available, it is unlikely that changes in the cropping pattern during the 1879-1933 period would have caused radical changes in water use. Thus, for the period 1879-1928, the monthly depletion rate R (in m^3 s^{-1} km^{-2}) (estimated from the average 1929-33 depletion cycle) was multiplied by the total area under irrigation A (in km^2) in a year for every year to obtain an initial estimate of the monthly depletion (in m^3 s^{-1}) in that year.

However, monthly rate of irrigation depletion is affected by the monthly volume of precipitation received by the area. Regression analysis of the monthly depletion rate with the monthly volume of rainfall for the period of 1929-46 shows that monthly rate of depletion declined slightly with increased rainfall during the peak irrigation season (April-July) (Figure 5a). This relationship, however, reverses during the late summer (August) and early fall (September) periods when the return flows exceed the depletion (Figure 5b). To account for these changes in depletion with respect to the variations in rainfall, a multiplicative correction factor (CF) was defined:

$$CF = (ap^* + b)/(a\overline{p} + b) \qquad (1)$$

where

a = slope of the monthly depletion vs. the precipitation curve (cf Fig. 5),

p^* = monthly volume of precipitation received by the area,

$\overline{p}$ = Calendar-month averaged precipitation for 1929-46, and

b = intercept of the regression (cf. Fig. 5).

The empirical formulae thus obtained for estimation of the monthly depletion is:

$$Depletion = A * R * CF \text{.....................................} (2)$$

The Divisional precipitation data (1895-2000) obtained from the Western Regional Climate Center, Nevada, were used for estimating the total monthly precipitation received by the Interior sub-basin. Precipitation data east of the Cascades in the states of Oregon, Washington, Idaho, Wyoming, and Montana were only considered. Before the middle of the 19th century, irrigated area in the Columbia River basin above the International Boundary in Canada was very small (<100 km^2) (Simons, 1953). Also, in the United States portion, the area lying in northwestern Montana and northern Idaho is largely mountainous. Therefore, these areas have been excluded from the above rainfall correction.

Precipitation data for the Interior sub-basin before 1895 were scarce. For Washington State, Spokane was the only available station with monthly data since 1881. For Oregon State, data were available for Umatilla for 1877-83 and 1893-94, and for La Grande for June 1886-1894. In the state of Idaho, Boise and Idaho Falls had precipitation data available for 1878-94 and 1881-83 respectively. No pre-1895 precipitation data were, however, found for the portions in Wyoming and Montana. For the period 1895-1910, Umatilla and La Grande have correlation coefficients of 0.65 and 0.56 respectively with the total precipitation received in Oregon State in the Interior sub-basin. Umatilla was assumed to be representing the southern part of the Columbia River basin in the Oregon State for the period 1878-83 and La Grande for the period 1884-94. To fill gaps between 1884 and May 1886 and between September 1888 to March 1889 in the La Grande data, precipitation data from Hood River was used. Hood River precipitation, available since 1884, is significantly correlated (correlation coefficient 0.56) with the La Grande data for the period 1886-1910. Umatilla and Spokane precipitation data are highly correlated (ccof. 0.78 for 1893-1910). Therefore, for the period 1878-80, Spokane precipitation was hindcast using the precipitation at Umatilla. The precipitation data at Umatilla and La Grande were converted to MCM (million cubic meters) using the surface area of the Oregon portion. Spokane precipitation data were treated similarly with respect to the precipitation in Washington State in the Interior sub-basin.

Boise and Idaho Falls data are well-correlated (ccof. 0.50) for the period 1895-1910. Therefore, for the period from 1883 to 1894, Idaho Falls precipitation was hindcast with respect to the Boise precipitation. Idaho Falls precipitation was assumed to be valid for the adjoining portions of Wyoming also. There is a good correlation (ccof: 0.62) between the precipitation around Boise and northwestern portion of Montana. Therefore, on the basis of the precipitation around Boise, Montana precipitation were hindcast for the period 1878-94. The precipitation data of Boise were converted to MCM using the surface area of the western parts of Idaho. Similarly, the Idaho Falls precipitation data were converted to MCM using the combined area of the eastern part of Idaho and the Wyoming portion. Montana precipitation was similarly treated with respect to the geographical area of the Montana portion of the Columbia River basin. To obtain the total monthly volumes of precipitation received in the Columbia River basin, the monthly precipitation in the states of Washington, Oregon, Idaho, Wyoming, and Montana were summed by month.

In application of (1) and (2), A was changed for each year, and p* was changed for every month for the period 1879-1928, while a, b and R are functions of calendar month. The monthly depletion values (Figure 6) thus obtained were added to the corresponding monthly adjusted flows to obtain the virgin flows for each month for the period 1879-1928. The monthly virgin flow derived by this method matches closely (standard error = 281 $m^3\ s^{-1}$) with the BPA derived virgin flow derived when compared for the period 1929-46 (Figure 7). Table 2 and Figure 8a show the virgin flow for the entire period of 1879-1928.While it is possible that percentage errors in estimation of irrigation depletion increase as (1) and (2) are extrapolated to the period before 1900, the relative and absolute errors in virgin flow should decrease, because irrigation was small prior to 1900.

A daily virgin flow index was also estimated for the 1879-1989 period. The monthly irrigation depletion estimates were spline interpolated to daily and added to the daily observed flows to obtain the daily virgin flow index. After 1940, the daily virgin flow index was low-passed filtered to remove effects of the weekly hydropower peaking cycle. The resulting daily estimates of virgin flow are shown in Figure 8b.

We term this estimate an index, because the true daily virgin flow is not recoverable. Still, it is useful to have an estimate with realistic spectral properties and higher moments. One of the primary reasons for estimating a daily virgin flow index is to allow hindcasting of a virgin flow sediment transport for the system, based on observations carried out by the USGS during the 1960s (Haushild et al., 1973, and http://webserver.cr.usgs.gov/sediment/). Analyses of these observations suggest that daily total sediment transport (total load) varies a power n of the daily virgin flow, $n \cong 2.5$. Sand transport varies with $n \cong 3.5$ (cf Haushild et al., 1966). Because of the strongly non-linear relationship between the river flow and the sediment transport, monthly average flows cannot be used to hindcast sediment transport. The non-linear relationship between river flow and sediment transport also means that most sediment transport occurs during relatively short periods of very high flow. Thus, realistic estimates of peak flows are needed.

We have used two statistical tests to demonstrate that our virgin flow index has the correct statistical properties so that the estimated virgin sediment transport will not be inaccurate due to underestimation of the variances of the virgin flow. The two tests are:

- A comparison of the higher moments (standard deviation, skewness and kurtosis) of the estimated virgin flow (1940-1989) with those of the observed flow (1878-1910), in Figure 9a,b and Table 3.
- A comparison of the power spectra of the estimated virgin flow (1940-1989) and the observed flow (1878-1910), in Figure 10.

These time periods were chosen to verify the appropriateness of the filter used to eliminate hydropower peaking cycles that affect the observed data after ca. 1940. There are, moreover, no meaningful differences between moments of the observed and virgin flows before 1910. Differences in spectra between the observed and virgin flows before 1910 are within the 95% confidence limits on the spectra.

In summary, the daily virgin flow index reproduces the higher moments and spectral properties of the natural flow observed before ~1910. The elimination of power peaking fluctuations (periods < 7d) after 1940 has, however, truncated the frequency spectrum of the estimated daily virgin flow at the high frequency end. Because there is very little energy in this part of the spectrum, this truncation should have very little adverse effect on sediment transport estimates based on the daily virgin flow index. This shifts the sediment hindcast problem to the issue of estimating historical changes in the sediment transport vs. flow relationship, a topic we will discuss elsewhere.

DISCUSSION

The Canadian part of the Columbia River basin, especially above Nicholson, British Columbia has been little affected by irrigation development. By 1946, there was only 100 km^2 of land under irrigation above the International Boundary. Changes due to climate change is difficult to discern at Nicholson due to lack of long-term streamflow data extending back to the 19th century. In the lower reaches at The Dalles, there has been a decrease in annual average virgin flow of >7% between the 1879-1900 and 1946-89 periods (Fig.8a). Differences are also seen in the spring freshet flows, once regulation and irrigation effects are removed. Usually maximum extraction for irrigation takes place in June. The ratio of Nicholson flow to observed flow at The Dalles for June increases over time, reflecting flow diversion between the two locations. Nicholson flow, which was ~2% of the flow at The Dalles during the month of June for the period 1903-70, fluctuates between 3 and 7% and in average 4% during the period 1971-99 (Fig. 11). While there is hardly any change in the June flow of Nicholson and The Dalles virgin flow respectively between the periods 1903-70 (305, 14,981 m^3/s) and 1971-89 (304, 15,229 m^3/s) (Fig. 12a,b), The Dalles June observed flow has significantly decreased (Fig. 12c). The Dalles observed flow was 12,964 $m^3 s^{-1}$ during 1903-70, it was 8,196 $m^3 s^{-1}$ during 1971-89, a drop of 37%. Without a virgin flow estimate for The Dalles, it was not possible to discuss such differences. Virgin flow estimates should also be derived for the Coastal sub-basin, to allow quantification of climate and human changes in the flow regime.

The effects of post-1970 flow regulation are also marked, as can be seen from time series of observed, adjusted, and virgin flows for The Dalles (Fig. 13). The difference between the adjusted flow and the observed flow gives an estimate of flow difference due to regulation, whereas the difference between the virgin flow and the adjusted flow gives an estimate of irrigation depletion. The net effect due to flow regulation and irrigation depletion is derived from the difference between the virgin flow and the observed flow. Climate effects can be estimated by examining changes in the magnitude and timing of the virgin flow over time. The total reduction in the annual average flow (difference between the 1879-99 virgin flow and 1945-89 observed flow) is 960 m^3s^{-1} or 15%, of which ~7.4% is due to climate change, and ~7% is due to irrigation withdrawal. The 1970-89 annual average loss due to water withdrawal for irrigation is 450 m^3s^{-1} or ~7% of the 19th century virgin flow.

Spring is the most critical flow season for juvenile salmonoids, but spring flow has been attenuated more than those during the reminder of the year. Figure 13 separates the effects of flow regulation and irrigation depletion in the Columbia River during the month of June. Until about 1960, irrigation withdrawal was larger than flow regulation. Flow regulation increased dramatically during the late 1960s. After 1970, flow regulation is the dominant human alteration to the June flow. Figure 14 shows the annual depletion due to irrigation and the net annual effects of flow regulation and irrigation depletion for the entire 1879-1989 period. It is evident that flow regulation dominates changes in spring freshet flows. In contrast, the difference between the annual observed and virgin flows is largely determined by irrigation depletion; i.e., flow regulation causes little inter-annual transfer of flow, and evaporation is less than irrigation. In some exceptional years when flows are very high or low (e.g., 1974 and 1977), some inter-annual flow transfer occurs.

Sherwood et al. (1990) and Simenstad et al. (1992) divide the flow history of the Columbia River into two regimes: a pre-1970 period of weak flow regulation, and a post-1970 period of more active flow management. Examination of the monthly irrigation depletion record from 1860 to date along with the estimated virgin or naturalized flow suggests that the record should be divided into three periods: pre-1900, 1900-1969, and 1970-date. The nineteenth century is distinguished by a very wet climate, minimal alteration of the seasonal flow pattern by irrigation, minimal annual average diversion, and the absence of mainstem dams. Human intervention in the system in the form of dams and irrigation depletion increased rapidly after 1900. The post-1970 period shows strong flow regulation and little net change in irrigation depletion.

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.

SUMMARY AND CONCLUSIONS

Calculation of virgin flow estimates for the Columbia River basin is motivated by the following considerations. The Columbia River hydrology has been affected by both climate and anthropogenic influences. Human factors strongly influence the long-term trend of the observed annual average flow; the situation is worse for the seasonality of the flow. It is impossible to fully separate climate and the diverse human influences without a complete history of irrigation depletion and a virgin flow estimate. In contrast, analyses based on virgin flow allow separation of the long-term climate and anthropogenic influences.

The virgin flow calculation method is as follows. The difference between the published estimates of monthly virgin and adjusted flow (1929-89) gives a monthly depletion due to irrigation. When the monthly depletion values are divided by the area under irrigation for the corresponding years, an estimate of the annual cycle of depletion per unit area is obtained. Based on the examination of the annual depletion cycles defined by the period 1929-46, the annual cycles for the five-year period 1929-33 were averaged to define a depletion cycle that was assumed to be typical also of the period 1879-1928. The monthly depletion rates defined by this cycle were multiplied by the total area under irrigation for the 1879-1928 period to obtain an initial estimate of depletion. However, the monthly rate of irrigation depletion is affected by the actual precipitation for each month, a factor not included in the average depletion cycle. To account for these changes in depletion with respect to the variations in rainfall, a correction factor was defined for every month and multiplied to the corresponding depletion component. The monthly depletion values thus obtained were then added to the corresponding monthly adjusted flows to obtain the monthly virgin flows for the 1879-1928 time period.

One of the primary motivations for estimating virgin flow is to understand historical changes in sediment transport, but sediment load cannot readily be estimated from monthly streamflow. A daily virgin flow index was, therefore, estimated for the

1879-1989 period. The difference between the monthly virgin and monthly observed flows was interpolated and added to the daily observed flows. After 1940, the resultant daily virgin flows were filtered to remove the weekly effects of the hydropower peaking cycles. Comparison of the higher moments (standard deviation, skewness, kurtosis) and power spectra of the estimated virgin flow for 1940-1989 with those of the observed flow for 1878-1910 demonstrate that the daily virgin flow estimate reflect the correct statistical properties. Thus, the virgin flow index provides an appropriate basis for estimation of a virgin sediment transport.

The difference between the adjusted flow and the observed flow gives an estimate of flow difference due to regulation, whereas the difference between the virgin flow and the adjusted flow gives an estimate of irrigation depletion. The net effect due to human manipulation is derived from the difference between the virgin flow and the observed flow. The total reduction in the annual average flow (difference between the 1879-99 virgin flow and 1945-89 observed flow) is 960 m^3s^{-1} or ~15%, of which 7.4% is due to climate change and ~7% is due to irrigation withdrawal. The 1970-89 annual average loss due to water withdrawal for irrigation is 450 m^3s^{-1} or ~7% of the 19^{th} century virgin flow.

Examination of the observed, adjusted and virgin flows suggests that the flow record should be divided into three periods: pre-1900, 1900-1969, and 1970-date. The 19^{th} century is distinguished by minimal alteration of the seasonal flow pattern by irrigation, minimal annual average diversion, and the absence of mainstem dams. Human intervention in the system in the form of dams and irrigation depletion increased rapidly after 1900, and the post-1970 period is marked by strong flow regulation and little net change in irrigation depletion. It is not clear whether the historical sediment transport is susceptible to the same three-fold division.

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