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Estimation of Columbia River virgin flow: 1879 to 1928

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Abstract:

The Columbia River is a major source of and conduit for Pacific Northwest economic activity, and is one of the more heavily modified rivers in North America. Understanding human and climate-induced changes in its hydrologic properties is, therefore, vital. Long streamflow records are essential to determining how runoff has changed over time, and Columbia River daily streamflow record at The Dalles began in 1878. To understand and separate anthropogenic and climate effects, however, it is also necessary to have a basin-scale estimate of virgin or naturalized flow. The United States Geological Survey 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 has estimated the monthly averaged virgin 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 early years, i.e. for the period 1879–1928. In addition, to allow hindcasting of a virgin flow sediment transport for the system, a daily virgin flow index with realistic higher moments and spectral properties has been calculated. Examination of the virgin flow record shows that climate change since the late 19th century has decreased annual average flow volume by >7%; irrigation depletion has reduced the flow by another ∼7%. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS Columbia River; flow estimation; virgin flow; flow regulation effects; irrigation depletion effects

INTRODUCTION

We develop a method here for estimation of the virgin or naturalized flow for the Columbia River. The Columbia is the largest river on the Pacific Coast of North America and is the third largest in the USA in terms of runoff. It drains an area of 660 480 km^2 and has a mean annual flow of 6970 m^3 s^{-1}; it encompasses parts of two Canadian provinces and seven US states (Figure 1). Human intervention along its course has resulted in extensive physical, chemical, hydrological, and biological modifications of its fluvial and estuarine ecosystems.

The principal drivers of the ecosystem alterations include rapid population growth and consequent exploitation of the natural resources. Important modifications include construction of 28 main-stem and tributary dams for hydroelectric power generation, water withdrawal for irrigation, waste discharges (point and non-point), deforestation, loss of marginal wetlands, and navigational development. Although construction of major dams began in 1906, system-wide management of the flow began only *ca* 1970 (Sherwood *et al*., 1990; Simenstad *et al*., 1992; Kukulka and Jay, 2003). The effects of climate change, flow regulation and water withdrawals have caused an ∼15% reduction in average flow, a >40% reduction of spring freshet peak flows, an increase in flows in late summer, fall and winter, and an increase in water temperature over the past 120 years (1879–2000; Bottom *et al*., 2001). Hydrologic model results from Matheussen *et al*. (2000) suggest that deforestation may have accelerated spring snowmelt (increasing April to June flows) and increased annual average runoff by 1–2% through decreased evapotranspiration.

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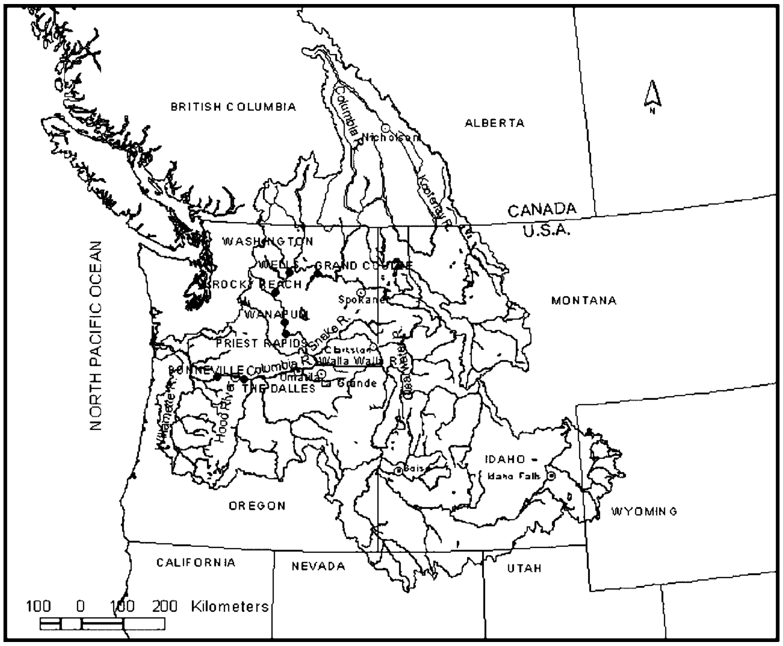

Figure 1. The Columbia River basin. The Cascade Range divides the basin into eastern and western sub-basins. Major dams and gauging stations are shown

Climate has also played a role in changing the hydrology of the Columbia River basin (Redmond and Koch, 1991; Mantua, 1996; Hamlet and Lettenmaier, 1999; Miles *et al.*, 2000). However, most analyses of climate effects in the Columbia River have been based on observed flows, which are heavily altered by irrigation depletion and flow regulation. Climate effects on seasonality of the flow and timing and volume of freshets can, however, only be determined from analyses of the virgin flow. Thus, it is vital to have estimates of virgin Columbia River flow to provide a historical perspective of the water resources development, to define the anthropogenic and climate influences separately, and for hindcasting sediment transport under natural conditions.

HYDROLOGIC BACKGROUND

The flow record of the Columbia River at The Dalles is of special interest, because it is the longest continuous daily record on the Pacific Coast of North America. Annual peak flows were recorded beginning in 1858, and daily US Geological Survey (USGS) flow observations began in June 1878 (Henshaw and Dean, 1915). The changes in the hydrologic cycle over the last 125 years are evident (Figure 2). These changes reflect human and climatic influences. Therefore, it is desirable to correct for the human alterations in order to isolate the impacts of climate change.

The accuracy of early flow estimates is naturally a concern in forming such estimates. Indeed, random errors may have been higher in the early days than is the case at present. Such random errors are also, however, of relatively minor importance given the opportunity to average over decadal periods in making flow comparisons. Systematic errors are a greater concern. Although the USGS has not published formal uncertainty estimates for The Dalles gauge, the gauge is located in a bedrock reach, where the rating curve is stable over time. The gauging location has, however, moved over time. Thus, it was at Umatilla for 6 months in 1878 and at The Dalles (1879–81) for 2 years. It was moved ~100 km downstream to Cascade Locks

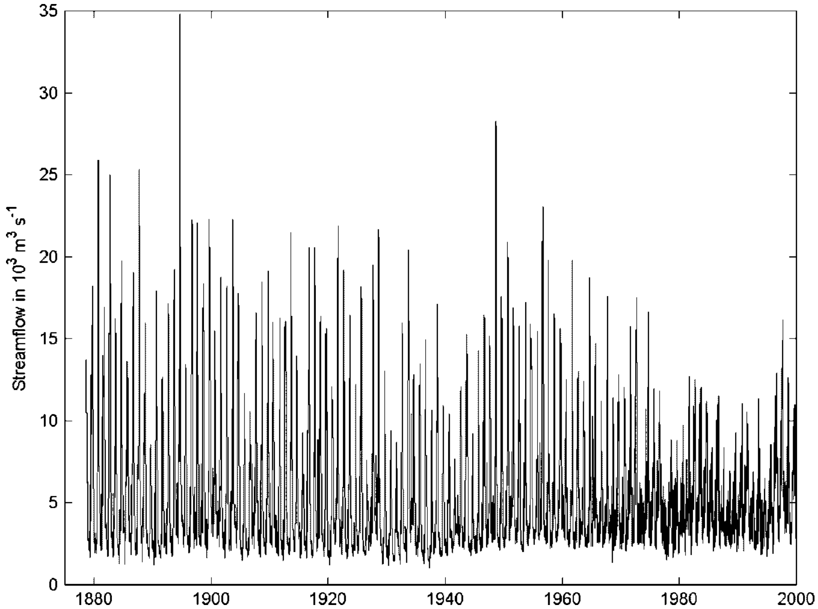

Figure 2. Daily observed Columbia River flow at The Dalles, 1878–1999

until 1892, another largely bedrock reach (Wells, 1958). In 1992, the USGS station was moved back to The Dalles. The US Weather Bureau, however, maintained the gauge at Cascade Locks until 1928, allowing ample opportunity for inter-calibration of the records for the two stations.

The 19th century record for The Dalles was recognized as important and reviewed for accuracy before construction of Bonneville Dam (Henshaw and Dean, 1910). They rate the record as 'fair' for 1878–84, but excellent thereafter. Examination of USGS Portland District files indicates that it was reviewed again during preparation of a flood report for the 1948 flood (the second largest freshet in the last 150 years; Paulsen, 1949), and the details reported in Wells (1958) probably come from the 1948–49 review.

The great magnitude of some of the 19th century freshets is also attested to by independent stage measurements at Vancouver, WA (~70 km seaward of The Dalles) for most years since 1876 by the US Weather Bureau and the US Army Engineers. We believe, therefore, that the observed flow record at The Dalles provides a sound basis for investigation of hydrologic change in the Pacific Northwest.

To estimate the effects of reservoir manipulation, flow regulation and evaporation, the USGS has made monthly corrections to the observed flows at The Dalles for 1878–1999 (Orem, 1968; L. Hubbard, USGS Portland, personal communication, 1999). The 'adjusted flow' (observed flow plus monthly corrections) is the flow that would have occurred if dams were in place but not operated for the period of record. Bonneville Power Administration (BPA) (1993) has estimated the monthly 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). Thus, these flows add a correction for irrigation withdrawal and return to the adjusted flow (USBR, 1999). The lack of a virgin flow estimate for the period before 1929, however, limits the analyses that may be carried out. Thus, we present here estimates of virgin flow for the Columbia River at The Dalles for the period 1879–1928. A daily virgin flow index for the period 1879–1989, necessary for analyses of changes in sediment transport, has also been calculated.

Individual monthly virgin and adjusted flow estimates are susceptible to random errors of perhaps 5–20%. There are, however, no known systematic biases to either estimate, and the two are independent. Also, our virgin flow estimates are largely unaffected by changes in land use and deforestation. Matheussen *et al.* (2000) suggest that these factors have altered flow seasonality by changing monthly flows by 5–10%. These changes would, however, have been compensated by reservoir flow adjustments. Their modelled changes in annual average flow appear to be O(1–2%), small relative to current irrigation depletion and the net change in flow over time. Therefore, our estimates should provide (for 1879–1928) a reliable basis for understanding long-term human and climate impacts on Columbia River hydrology.

CLIMATE AND HYDROLOGY

It is important to put The Dalles flow record in a geographic context. The north–south-trending Cascade Mountain Range divides the Columbia River basin into two parts: (1) a Western sub-basin covering 46 650 km^2, with the Willamette River as the largest drainage; (2) an Interior sub-basin (area of 613 830 km^2) east of the Cascade Range. The latter includes the Snake River and the Upper Columbia as principal drainages; 97% of the total Interior sub-basin flow is gauged at The Dalles. The Western sub-basin has a maritime climate, and the Interior sub-basin exhibits a Middle Latitude Steppe climate with marked daily and seasonal temperature fluctuations (Akin, 1991). Annual precipitation of the Columbia River basin decreases west to east, from >2550 mm $year^{-1}$ in the coastal region to <250 mm $year^{-1}$ over the Snake River basin and the Columbia plateau.

The precipitation distribution is reflected in tributary flow volumes. Although the Western sub-basin covers only 7% of the basin area, it contributes ∼25% of the total flow at the mouth. Runoff in the Western sub-basin occurs mostly from winter precipitation, November to March. On the contrary, in the Interior sub-basin the runoff occurs during the spring snowmelt, April through to July. Because of the large drainage area of the Interior sub-basin, it encompasses substantial precipitation variations. Thus, the Canadian portion of the Interior sub-basin contributes ∼52% of the flow at The Dalles from only 23% of the drainage area above The Dalles. In contrast, the Snake River basin is relatively dry, with 43% of the sub-basin but only ∼28% flow contribution at The Dalles (Table I).

IRRIGATION DEPLETION AND VIRGIN FLOW

Historical setting

Irrigated agriculture has historically been a major source of economic activity in the Columbia River basin. The first irrigation was carried out by the missionaries who settled in the Walla Walla and the Clearwater River drainages prior to 1840 (Simons, 1953). Early settlers were able to divert water from tributary streams to adjacent lands with little effort. Still, in 1860, the human population was very sparse and there was only 9 km^2 of land under irrigation (Figure 3). The 1860–80 period saw an influx of settlers because of the booming

Table I. Annual mean flow and catchment area ratios of selected Columbia River gauging stations with respect to The Dalles[a]

Gauging station	Mean flow ratio	Catchment area ratio
Arrow	0·21	0·06
Birchbank	0·39	0·14
International boundary	0·54	0·25
Grand Coulee	0·60	0·32
Ice Harbor	0·28	0·46

[a] Arrow and Birchbank flow data courtesy of Environment Canada. Flow data for US stations from the USGS.

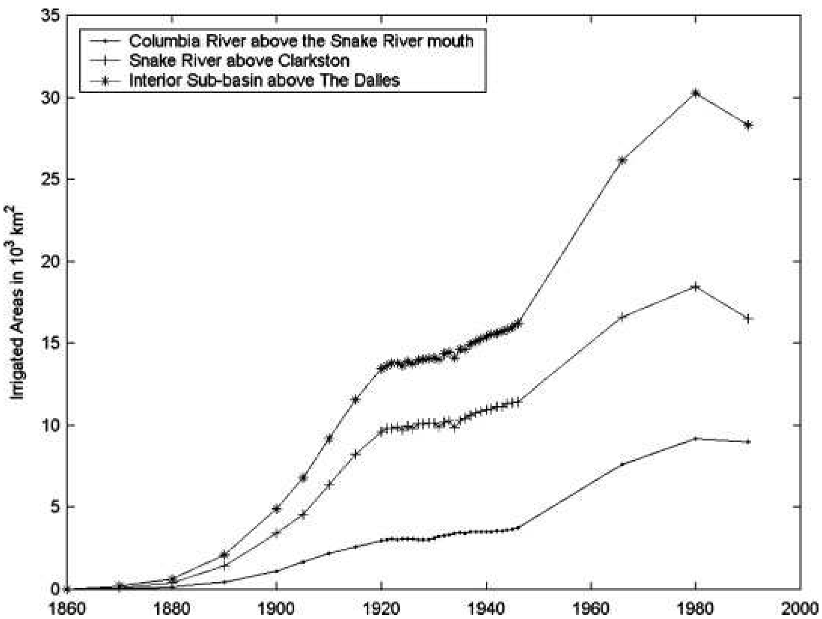

Figure 3. Irrigated area in the Columbia River basin, 1860–1989

mining and cattle-raising activities in the Pacific Northwest. 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 ~200 km^2 of land was being irrigated above The Dalles (Simons, 1953). By 1880, the population had increased to 400 000, and there was ~800 km^2 of irrigated agriculture. Also in 1880, a transcontinental rail connection was completed between Chicago and the ocean ports of the Pacific Northwest. This opened new markets for the products of the farmlands, mines, and forests. Larger irrigation projects were then undertaken in the Snake and Yakima River valleys. Between 1880 and 1890, the population increased by 170% and the irrigated lands to ~2100 km^2.

Population growth was sluggish from 1890 to 1900, in part because of the devastating 1894 flood, the largest spring freshet since white settlement. However, this flood did not inhibit the growth of irrigation. Irrigation canals were constructed from 1884 to 1896, and by 1910 the irrigated lands had increased to 9200 km^2 (Figure 3). Irrigated area reached ~1350 km^2 in 1920 when the first irrigation districts were created. The rapid increase in irrigation after 1900 marked the onset of major alteration of the mainstem hydrology and established irrigated agriculture as an important part of the Pacific Northwest economy. Thus, 1900 marks the end of an era during which the observed and virgin Columbia River flows differed by ~1% (mean 1879–1990 observed flow: 6271 $m^3 s^{-1}$; virgin flow: 6321 $m^3 s^{-1}$). This division is also convenient because the 19th and 20th century climate regimes were rather different.

After 1920, the increase in irrigated lands was gradual. A shift from the wet conditions (about 1880 to 1924) to a following dry period ~1925–46 (Mantua *et al.*, 1997), likely the driest since at least 1800, also had a substantial effect on irrigation developments. Many storage reserves were found inadequate to cope with such dry conditions, new 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 a vision of cheap hydropower as the key to regional economic development. The 1930–50 period saw construction of the first mainstem dams, including Bonneville Dam (initiated in 1933, completed in 1944) and the Grand Coulee Projects (initiated in 1935, completed in 1954). Until the mid 1940s, about 70% of the irrigated land of the Columbia River basin above The Dalles was found in the Snake River basin, and about 23% was above the mouth of the Snake River. The remainder (about 7%) was between the mouth of the Snake 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 1960s. The 1970s saw some growth in irrigation development. However, the relatively dry years after 1977, combined with the flow regulation and the desire to restore salmon runs, caused some decline in irrigation after 1980, especially in the Snake River basin.

By 1973, all of the large storage reservoirs (both US and Canadian) were completed. Several major reservoirs were high in the basin and had longer residence times than earlier mainstem dams (Simenstad *et al*., 1992). These longer water residence times made integrated management of Interior sub-basin flows possible. Integrated management then resulted in substantial interannual transfer of flow, especially in the 1972–77 period of highly variable flow—a novelty in the system.

Virgin flow calculation and validation

Simons (1953) estimated irrigated area and the corresponding annual irrigation depletion in the Interior sub-basin from 1860 to 1946. His estimates are decadal for 1860–1900, bi-decadal for 1900–20, and yearly after 1920 (Figure 3). Based on his data, irrigated areas were interpolated annually for 1860–1919. Simons (1953) also estimated annual irrigation depletion, but these estimates do not suffice to 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 the USGS since 1879, monthly virgin flows provided by BPA for 1929–89, precipitation data (1878–1989), and the interpolated irrigated areas for 1879–1919 were used for estimation of the monthly virgin flows for the 1879–1928 period.

The difference between the published estimates of monthly virgin and adjusted flows (1929 to 1989) gives a monthly depletion due to irrigation for this period. Division by the area under irrigation for the corresponding year (1929–46) yields an estimate of monthly depletion per unit area for each year. These monthly values (averaged over 1929–46) yield an average monthly cycle of depletion (Figure 4). Irrigation depletion, however, also depends on weather, and the water requirements of the crops irrigated. Cropping patterns also respond, but only gradually, to climate change, economic cycles, and irrigation technology. Therefore, the cycle of depletion defined for a particular year can be grouped with the preceding or the succeeding years.

Investigation of the annual irrigation cycles 1929–46 suggests that the annual cycles of depletion for 1929–33 (a period with one very wet and several rather dry years) be averaged to define a depletion cycle that is assumed typical also of the period prior to 1929 and could be tested against the remainder of the 1929–46 period. 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, for example, that less water was used before 1900 due to the wetter climate and absence of irrigation canal networks. 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 the 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 year period suggests that the random error involved in assuming the 1929–33 depletion cycle valid for the period 1879–1928 is likely small.

Irrigation in the Columbia Basin prior to 1945 was mostly accomplished by diverting water from small dams constructed across streams and rivers, with minimal pumping. Because of the simple technologies available, it is unlikely that changes in the cropping pattern over the 1879–1933 period would have caused radical changes in water use. Thus, for 1879–1928, the monthly depletion rate R (m^3 s^{-1} km^{-2}) was multiplied by

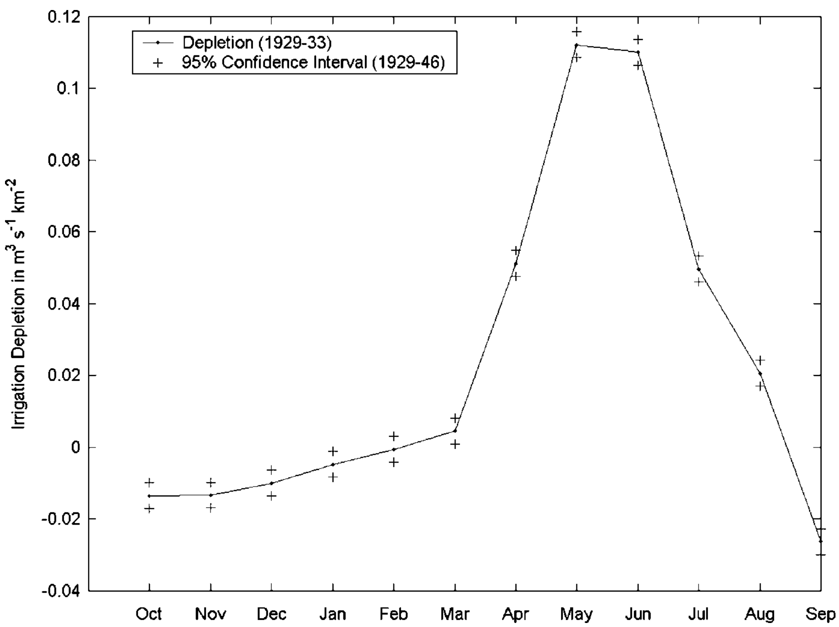

Figure 4. The 1929–33 irrigation depletion cycle with uncertainty range (±95% confidence interval) for 1929–46

the total area under irrigation in a year A (km^2) for every year to obtain an initial estimate of the monthly depletion ($m^3\ s^{-1}$) in that year.

However, it was suspected that R might also be affected by the monthly precipitation. Regression analysis of R against monthly rainfall volume for 1929–46 shows that R declined slightly with increased rainfall during the peak irrigation season (April–July). This relationship, however, reversed during the late summer (September) and early fall (October) periods, when the return flows exceed the depletion. To account for these changes in depletion with respect to the variations in rainfall, a correction factor (CF) was defined:

$$\mathrm{CF} = \frac{ap^* + b}{(a\overline{p} + b)} \quad (1)$$

where a is the slope of the monthly depletion versus the precipitation curve, p^* is the monthly volume of precipitation received by the area, $\overline{p}$ is calendar-month averaged precipitation for 1929–46, and b is the intercept of the regression. The empirical formula thus obtained for estimation of the monthly depletion is

$$\text{Depletion} = \frac{AR}{\mathrm{CF}} \quad (2)$$

Divisional precipitation data (1895–2000), obtained from the Western Regional Climate Center and summarized in Table II, were used for estimating the monthly Interior sub-basin precipitation. Only precipitation data east of the Cascades in the states of Oregon, Washington, Idaho, Wyoming, and Montana were considered. Before the middle of the 20th 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 US portion, the area lying in northwestern Montana and northern Idaho is largely mountainous with little agriculture. Therefore, these areas have been excluded from the above rainfall correction.

Precipitation data for the Interior sub-basin before 1895 are scarce. For Washington, Spokane (monthly data from 1881) is the only pre-1900 station. For Oregon, data are available from Umatilla for 1877–83 and

Table II. Rainfall data before 1895 and their use

State	Data available	Filling of gaps	Correlation coefficients	Data representation
Oregon	Umatila 1877–83, La Grande 6/1886–94, Hood River 1884–94	La Grande 1884–5/86, 9/1888–3/89 from Hood River	0·56 La Grande vs Hood River, 1886–1910	Umatilla 1878–83, La Grande 1884–94
Washington	Spokane 1881–94	Spokane 1978–80 from Umatilla	0·78 Umatilla vs Spokane, 1893–1910	Spokane 1878–94
Idaho	Boise 1878–94, Idaho Falls 1881–83	Idaho Falls 1978–80 and 1883–94 from Boise	0·50 Boise vs Idaho Falls, 1895–1910	Boise 1878–94, Idaho Falls 1878–94
Montana	No data; Boise 1878–94 data used	NW Montana 1878–94 from Boise data	0·62 NW Montana vs Boise, 1895–1910	Boise 1878–94
Wyoming	No data; Idaho Falls 1881–83 data used	Idaho Falls 1978–80 and 1883–94 from Boise data	0·50 Idaho Falls vs Boise, 1895–1910	Idaho Falls 1878–94

1893–94, and from La Grande, 1886–94. In Idaho, Boise and Idaho Falls precipitation data are available for 1878–94 and 1881–83 respectively. No pre-1895 precipitation data were found for the relevant portions of Wyoming and Montana. For 1895–1910, Umatilla and La Grande have correlation coefficients of 0·79 with each other and 0·65 and 0·56 respectively with the total precipitation received in the Oregon part of the Interior sub-basin. Umatilla was assumed to represent the part of the Columbia River basin in Oregon for 1878–83; La Grande was used for 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, ∼30 km downriver from The Dalles, 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 (correlation coefficient of 0·78 for 1893–1910). Therefore, for the period 1878–80, Spokane precipitation was hindcast using the precipitation at Umatilla.

Boise and Idaho Falls data are significantly correlated (correlation coefficient: 0·50) for the period 1895–1910. Therefore, for the period from 1883 to 1894, Idaho Falls precipitation was hindcast using the Boise record. Idaho Falls precipitation was also assumed to be valid for the adjoining portions of Wyoming. There is a good correlation (correlation coefficient: 0·62) between the Boise precipitation and the climate division data for the northwestern portion of Montana. Therefore, on the basis of the Boise precipitation, Montana precipitation was hindcast for the period 1878–94. Long-term average ($\overline{p}$) monthly Interior sub-basin precipitation and deviations therefrom (p^*) were determined by summing the monthly values for the four states.

Virgin flows were then estimated using Equations (1) and (2). In application of these equations, A was tabulated yearly and p^* varies by month (1879–1928), whereas a, b and R are functions of calendar month. The monthly depletion values thus obtained were added to the corresponding monthly adjusted flows to obtain the virgin flows for each month for the period 1879–1928 (Table III); the trend toward increasing irrigation depleting over time is evident (Figure 5). Our virgin flows closely match (standard error: 281 $m^3\ s^{-1}$) the BPA-derived virgin flows for the period 1929–46 (Figure 6). Figure 7 shows the annual virgin flow for the period 1879–1928. While it is possible that percentage errors in estimation of irrigation depletion increase as Equations (1) and (2) are extrapolated to the period before 1900, the relative and absolute errors in virgin flow should decrease, because irrigated area was very small prior to 1900.

Daily virgin flow index

It is also useful to have a virgin flow estimate that may be used to hindcast a virgin-flow sediment transport for the system, on the basis of sediment transport data collected by the USGS during the 1960s (Haushild *et al*., 1973; http://webserver.cr.usgs.gov/sediment/). These data suggest that daily total sediment transport (total load) follows a power law, with the daily virgin flow varying with $n \cong 2\cdot5$ and sand transport varying

Table III. Estimated monthly virgin flow of the Columbia River at The Dalles for water years 1879–1928

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1879	2534	2356	2568	1864	2468	5126	10 221	11 253	17 379	14 205	7794	4344
1880	3105	2409	2411	2790	2185	2131	4307	11 507	19 816	22 472	10 935	5587
1881	3698	2934	2280	3028	5971	6257	10 967	12 128	15 529	12 232	6919	3972
1882	3100	3159	2436	2218	1887	2709	6540	9595	21 872	13 539	7461	4224
1883	3097	2659	3417	2464	2476	5041	5626	11 549	15 204	11 281	5736	3541
1884	2553	2089	2068	2030	2035	2977	5797	11 552	18 481	11 457	7238	4672
1885	3747	3805	2273	2640	4641	5353	7380	10 685	12 732	9681	5770	4355
1886	3435	2897	2900	2614	5038	3458	5990	9830	16 465	10 000	5714	3502
1887	2410	1952	2119	2804	2132	4988	7408	12 105	23 077	16 630	8207	4799
1888	3205	2808	2792	1970	4075	3403	5420	10 432	14 833	9649	6060	4284
1889	2861	2612	2400	1888	1803	2519	4400	7460	7775	5273	4257	2678
1890	2446	2163	1808	1451	3311	3408	5522	16 081	12 601	9330	5532	3368
1891	2491	2166	1942	1860	1771	2096	3976	9931	12 181	8774	5850	3674
1892	2466	3022	2801	1757	2066	3605	4467	8792	15 678	12 777	5998	4036
1893	3104	2742	2404	2207	2318	2023	4999	12 823	17 186	13 299	7784	4175
1894	3407	3977	4662	4101	3218	4628	9312	16 812	28 686	15 806	7733	4873
1895	3715	3805	3190	2883	2661	3382	5304	11 069	11 107	10 015	5903	3565
1896	2687	2176	2096	2552	2621	3808	5303	8084	19 589	18 265	7311	4346
1897	2476	3399	4574	3265	3481	3106	8639	18 087	15 722	10 723	6029	3774
1898	2691	3169	3951	3225	4158	4177	5876	12 410	17 508	11 503	6795	3934
1899	2696	2305	1883	2782	2772	3020	5664	9281	18 512	17 604	8762	5340
1900	3889	3613	4392	4715	3552	5313	7955	13 336	12 132	9386	5386	3720
1901	3148	3468	3848	3640	3452	5314	4919	12 736	15 137	9883	6306	3601
1902	2355	2300	2559	2511	2858	3138	4324	10 796	15 749	11 792	6650	3388

(*continued overleaf*)

Table III. (*Continued*)

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1903	2290	2320	2345	3306	2482	2783	5681	9410	19 972	12 351	6228	4060
1904	4303	3678	3374	2745	2830	4798	9843	15 031	16 462	11 548	5792	3283
1905	2305	1965	1964	1939	1781	3032	4015	6673	10 860	7300	5099	2525
1906	2829	2138	1821	1799	2211	2643	6132	9408	10 193	8203	4881	3060
1907	2494	3811	3423	2913	4542	4755	7048	11 579	15 900	12 563	6633	4372
1908	3161	2375	2434	2170	1882	3365	5631	10 681	16 120	12 101	5922	3197
1909	2427	2369	2096	2275	2900	3096	4631	7568	17 593	12 358	5908	3410
1910	2722	3571	3822	3039	2598	7897	9582	14 867	12 114	7168	4707	2384
1911	2754	3345	3055	2212	2234	3045	4842	9902	15 349	11 162	5481	3125
1912	2254	2091	1847	2306	3113	2358	5776	11 831	15 818	9134	5251	3349
1913	2358	2522	2112	2117	2171	2847	7111	11 923	20 893	11 604	6150	3698
1914	2944	2696	2193	2735	2524	4306	6815	11 787	13 310	9491	4981	2797
1915	2781	3281	2350	2103	2026	2457	5294	8960	8699	6893	5473	3129
1916	2016	2224	2330	1975	3782	5805	8139	12 397	16 374	17 472	7571	4091
1917	2685	2228	1962	1720	1925	2024	5928	12 682	19 672	14 100	6041	3128
1918	2680	2002	3782	5938	3704	3717	6453	11 077	14 744	10 225	5369	3073
1919	2721	2227	1964	2319	2576	3095	6800	10 840	12 599	8715	5080	2727
1920	1844	1689	1693	2308	2185	2268	4141	8593	11 652	11 311	6285	3057
1921	3558	2951	2665	3500	3676	5576	6942	14 434	20 032	10 499	5416	2717
1922	2255	2630	3345	2330	2096	2546	5428	10 856	17 687	8945	4778	2988
1923	2258	1989	1857	3040	2006	2467	5809	10 706	15 997	10 641	5180	3038
1924	2220	1894	1977	1941	3372	2683	3533	9862	9618	6187	3989	2544
1925	1885	2255	2081	2680	4531	3635	8461	14 800	14 824	9602	4962	2625
1926	2189	1841	1954	1983	2585	2821	4638	8479	6485	5299	3272	2238
1927	2234	2708	3295	2739	3463	3447	4952	10 997	18 335	12 040	5715	3993
1928	4189	5637	4952	4212	3405	4821	6513	15 575	15 674	9579	5175	2526

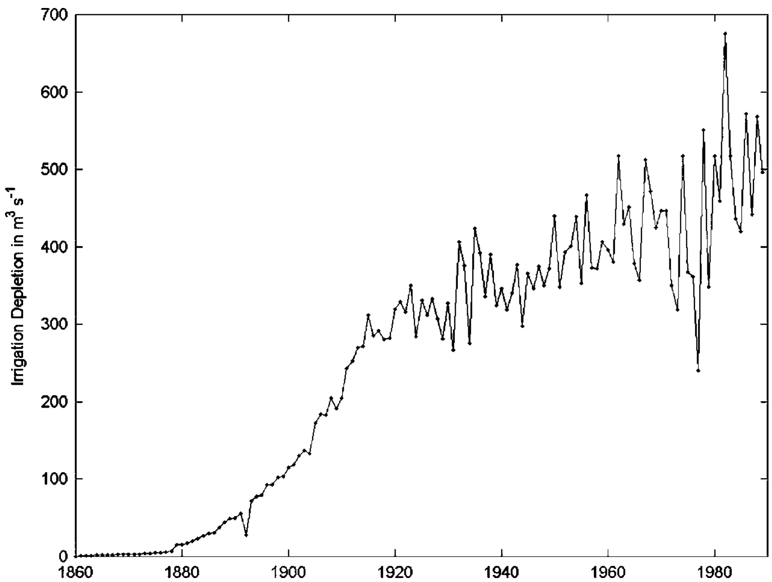

Figure 5. Modelled irrigation depletion for the period 1860–1989

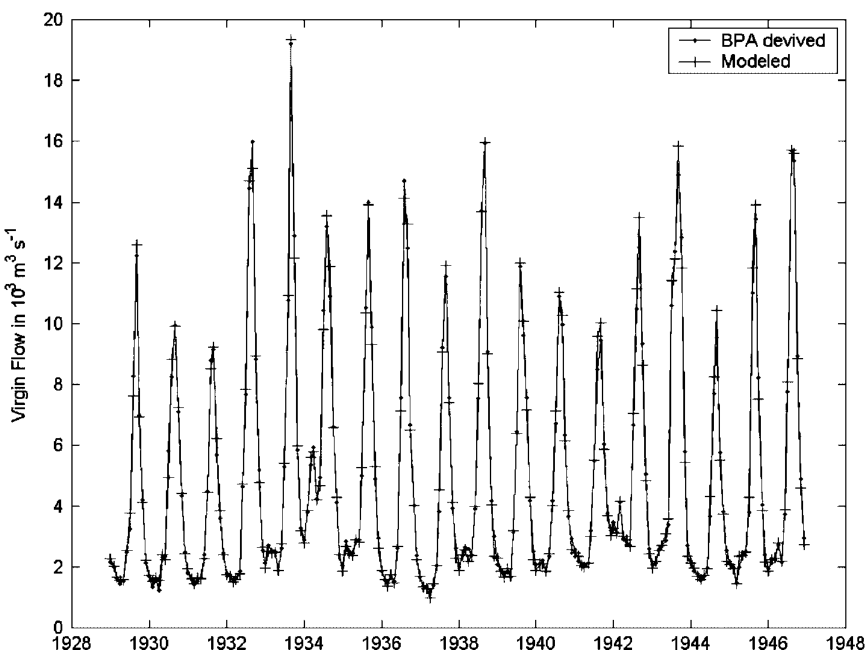

Figure 6. Comparison of BPA-derived virgin flow and the virgin flow derived by the present method for 1929–46

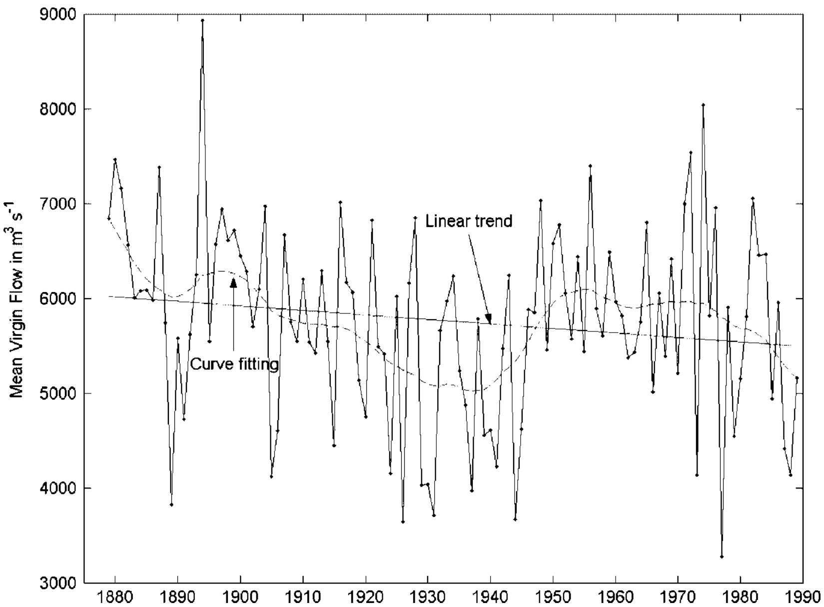

Figure 7. Long-term annual average virgin flow at The Dalles (1879–1989), with linear trend and low-pass filtered

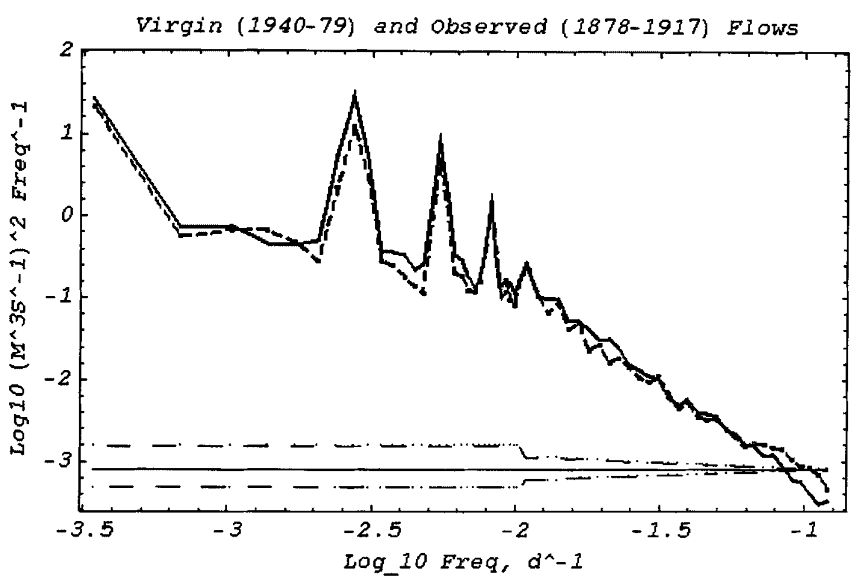

Figure 8. Power spectra of (a) the estimated virgin flow (1940–79; solid line) and (b) the observed flow (1878–1917; dotted line); 95% confidence limits are shown at the bottom

Table IV. Comparison of the moments of virgin flow (1940–89) and observed flow (1878–1910)

Moment	Virgin flow, 1940–89 ($m^3 s^{-1}$)	Observed flow 1878–1910 ($m^3 s^{-1}$)
Mean	5758	6093
Standard deviation	4796	4777
Skewness	1.63	1.67
Kurtosis	5.16	5.79

with $n \cong 3{\cdot}5$. The nonlinear relationship between river flow and sediment transport means that most sediment transport occurs during short periods (of a few days duration) of very high flow, and that monthly average flows cannot be used to hindcast sediment transport. Instead, daily virgin flows estimates are needed that have realistic spectral properties and higher moments. A daily virgin flow index was, therefore, determined for 1879–1989. We term this estimate an 'index' because the true daily virgin flow is not recoverable. To calculate this index, the monthly irrigation depletion estimates were spline interpolated to daily and added to the daily observed flows. After 1940, the daily virgin flow index was low-pass filtered to remove the effects of the weekly hydropower peaking cycle.

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 mis-estimation of the variance of the virgin flow. The first is a comparison (Table IV) of the higher moments (standard deviation, skewness and kurtosis) of the estimated virgin flow (1940–89) with those of the observed flow (1878–1917); there are no meaningful differences. We also compared the power spectra of the estimated virgin flow (1940–79) and the observed flow (1878–1917; Figure 8). Differences between the observed and virgin flow spectra are within the 95% confidence limits on the spectra, except at periods of <1 month, where there is little energy; such differences will have little effect on sediment transport estimates. Having this daily index then shifts the sediment hindcast problem to the issue of determining historical changes in the sediment transport versus flow relationship.

DISCUSSION

The Canadian part of the Columbia River basin, especially above Nicholson, British Columbia, has been little affected by irrigation development and flow regulation. It provides, therefore, a useful comparison with the larger Interior Sub-basin. In the lower reaches at The Dalles, there has been a decrease in annual average virgin flow of >7% between the 1879–99 and 1945–89 periods (Figure 7). The ratio of Nicholson flow to observed flow at The Dalles for June, the usual month of maximum flow alteration, has accordingly increased. Reflecting the growth of human impacts between the two locations, Nicholson June flow has increased from ∼2% of that at The Dalles for 1903–70 to 3–7% (average 4%) during 1971–99 (Figure 9).

There was little change between 1903–70 and 1971–89 Nicholson flow in June (305 $m^3 s^{-1}$ and 304 $m^3 s^{-1}$ respectively). Thus, the altered flow ratio in Figure 9 is almost entirely due to changes in flow at The Dalles, where the observed flow for June has decreased (Figure 10c) from 12 964 $m^3 s^{-1}$ (1903–70) to 8196 $m^3 s^{-1}$ (1971–89), a drop of 37%. If the virgin flow has been calculated correctly, then June virgin flows at The Dalles should also exhibit relatively small changes. In fact there has been a slight (1·2%) increase in virgin flow at The Dalles (14 981 versus 15 229 $m^3 s^{-1}$; Figures 10a and b), which is of the same sign as the increased spring snowmelt predicted by Matheussen *et al*. (2000). Caution is needed in interpreting this result, however, because year-to-year variability is high, and the 1900–89 period does not include an integral number of Pacific decadal oscillation cycles.

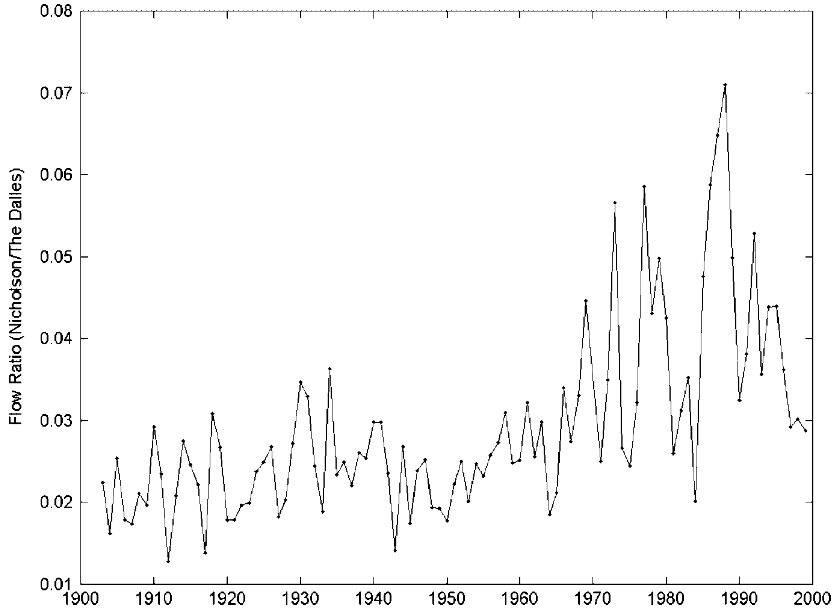

Figure 9. Ratio of the Nicholson and The Dalles flows in June, 1903–99

There are also important seasonal differences in the strength of human impacts. The effects of post-1970 flow regulation are much larger than irrigation depletion during the spring freshet, as can be seen from time series of June observed, adjusted, and virgin flows for The Dalles (Figure 11). On the other hand, interannual flow transfers remain small, except for very high-flow years (like 1972) and very low-flow years (like 1977). Thus, irrigation losses dominate the annual average picture (Figure 12). The 1971–89 annual average loss due to water withdrawal for irrigation is 450 m^3 s^{-1}, or ∼7·4% of the 19th century virgin flow of 6320 m^3 s^{-1}. Without a virgin flow estimate for The Dalles, it would not be possible to discuss such changes.

Climate effects on annual average flow (perhaps mixed to some degree with changes in runoff due to deforestation) can be estimated by examining changes in the magnitude and seasonality 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^3 s^{-1}, or 15·2%. Thus, the flow reductions due to climate change and irrigation withdrawal are both ∼7·4%; the discrepancy of ∼0·4% comes from the different time periods used to derive these estimates. If (following Matheussen *et al.* (2000)) evapotranspiration has decreased by 1–2%, then the actual climate-induced change in annual average flow is somewhat larger, ∼8–9%.

Finally, it is useful to divide the recent Columbia River flow history into descriptive regimes. Sherwood *et al.* (1990) and Simenstad *et al.* (1992) suggest two such 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, 1900–70, and 1971 onwards. The 19th century is distinguished by a very wet climate, minimal alteration of the hydrologic cycle and annual average flow by irrigation, and an 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 very strong flow regulation but 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 threefold 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

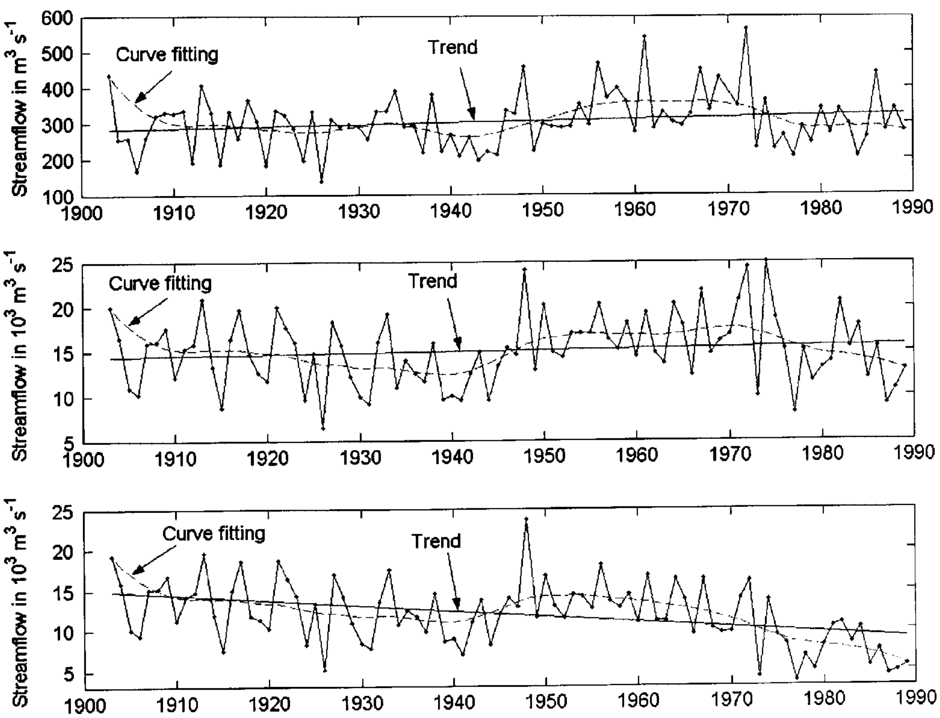

Figure 10. Columbia River flow in June for 1903–89: (a) observed flow at Nicholson; (b) virgin flow at The Dalles; (c) observed flow at The Dalles

other factors (e.g. placer mining) 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 understand the historical changes in sediment transport fully.

SUMMARY AND CONCLUSIONS

Calculation of virgin flow estimates for the Columbia River basin is motivated by the following considerations. 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 and are the dominant factor in historic changes in flow seasonality. However, it is impossible to separate climate and the diverse human influences fully without completing the history of irrigation depletion to form a virgin flow estimate for the entire period of record.

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, which may be normalized by dividing by the area under irrigation for the corresponding years, to obtain an estimate of the annual cycle of depletion per unit area. Based on the examination of the annual depletion cycles defined for 1929–46, the annual cycles for the 5 year period 1929–33 were averaged to define a depletion cycle that was assumed to be typical also of the period 1879–1928 and could be verified against the remainder of the 1929–46 period. The monthly depletion rates defined by this cycle were multiplied by the total area under irrigation for 1879–1928 to obtain an initial estimate of depletion. However, the monthly rate of irrigation depletion is also affected by the actual precipitation for each month, a factor not included in the average depletion cycle.

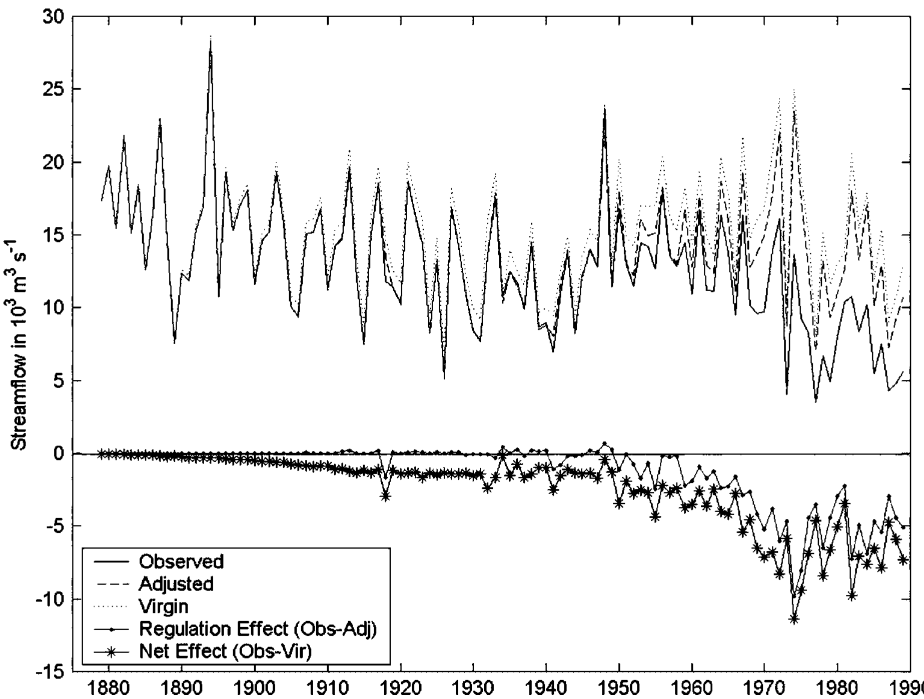

Figure 11. June flow at The Dalles, 1879–1989: the effect of flow regulation and net effect of flow regulation and irrigation depletion

To account for precipitation-related changes in depletion, a correction factor based on observed precipitation was defined for every month during 1878–1928. The monthly depletion values thus obtained were added to the corresponding monthly adjusted flows to obtain the monthly virgin flows for the 1879–1928 time period.

Analyses of the observed, adjusted and virgin flows suggest the following conclusions. The total reduction in the annual average flow (difference between the 1879–99 virgin flow and 1945–89 observed flow) is 960 m^3 s^{-1}, or $\sim$15%. Climate change and irrigation withdrawal each account for a reduction of >7% of the 19th century virgin flow. If the hydrologic model results are correct in predicting a 1–2% increase in flow due to deforestation, then the actual climate-change-induced reduction in precipitation has been larger, perhaps 8–9%. These conclusions, vital for understanding changes in the Columbia River management, require knowledge of the virgin flow. At present, we are only able to make virgin flow estimates for the Interior sub-basin, which provides $\sim$75% of the total Columbia River flow to the ocean. Understanding the effects of changes in climate and management on coastal processes requires that virgin flow estimates also be derived for the Coastal sub-basin, which provides the remaining $\sim$25%.

Another motivation for estimating virgin flow is to understand historical changes in sediment transport, but sediment load cannot readily be hindcast from monthly streamflow. A daily virgin flow index was, therefore, estimated for the 1879–1989 period. Comparison of the higher moments (standard deviation, skewness, kurtosis) and power spectra of the estimated virgin flow for 1940–89 with those of the observed flow for 1878–1917 demonstrate that the daily virgin flow estimate has the statistical properties needed for sediment transport hindcasts, though the actual daily virgin flow is not recoverable.

Finally, our analysis suggests that the flow record can be divided into three periods: pre-1900, 1900–70, and 1971 onwards, based on the degree and character of human alteration. It is not clear, however, whether the historical sediment transport is susceptible to the same threefold division.

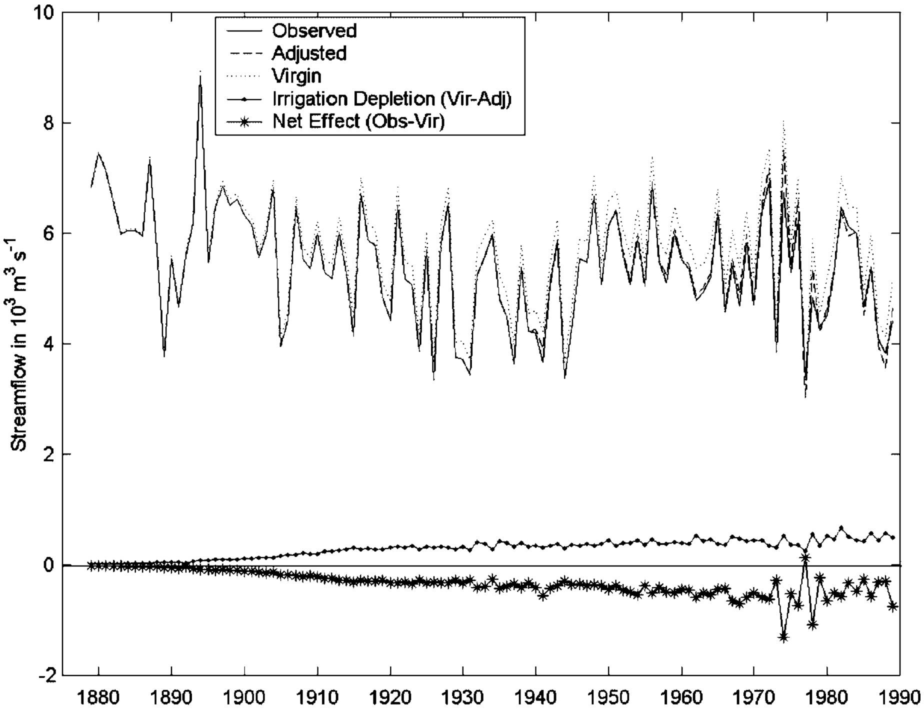

Figure 12. Annual average flow at The Dalles, 1879–1989: the effect of irrigation depletion and net effect of flow regulation and irrigation depletion

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REFERENCES

Akin WE. 1991. *Global Patterns: Climate, Vegetation, Soils*. University of Oklahoma Press: Norman, OK.

Bottom D, Simenstad CA, Baptista AM, Jay DA, Burke J, Jones KK, Casillas E, Schiewe MH. 2001. *Salmon at river's end: the role of the estuary in the decline and recovery of Columbia River salmon*. US National Marine Fisheries Service.

BPA. 1993. *1990 level modified streamflow (1928–1989)*. Bonneville Power Administration, Portland.

Hamlet AF, Lettenmaier DP. 1999. Effects of climate change on hydrology and water resources objectives in the Columbia River basin. *Journal of the American Water Resources Association* **35**: 1597–1624.

Haushild WL, Perkins RW, Stevens HH, Dempster Jr GR, Glenn JL. 1973. *Radionuclide transport in the Pasco to Vancouver, Washington reach of the Columbia River July 1962 to September 1963*. US Geological Survey Open File, Portland, OR.

Haushild WL, Stevens Jr HH, Nelson JL, Dempster Jr GR. 1973. Radionuclides in transport in the Columbia River from Pasco to Vancouver, Washington. *US Geological Survey Professional Papers* **433-N**.

Henshaw FF, Dean HJ. 1915. *Surface Water Supply of Oregon (1878–1910)*. US Geological Survey Water Supply Paper 370. Government Printing Press: Washington, DC; 18–19.

Kukulka T, Jay DA. 2003. Impacts of Columbia River discharge on salmonid habitat II. Changes in shallow-water habitat. *Journal of Geophysical Research* **108**: 3294. DOI: 10·1029/2003JC001829.

Mantua N. 1996. *The relationship between the Columbia River annual flow and the El Niño southern oscillation*. JISAO Project on The Dynamics of Climate Variability, Impacts and Policy Response Strategies for the Pacific Northwest Region.

Mantua NJ, Hare SR, Zhang U, Wallace JM, Francis RC. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* **78**: 1069–1079.

Matheussen BR, Kirshbaum L, Goodman IA, O'Donnell GM, Lettenmaier DP. 2000. Effects of land cover change on streamflow in the interior Columbia River Basin (USA and Canada). *Hydrological Processes* **14**: 867–885.

Miles EL, Snover AK, Hamlet AF, Callahan B, Fluharty D. 2000. Pacific Northwest regional assessment: the impact of climate variability and climate change on the water resources of the Columbia River basin. *Journal of the American Water Resources Association* **36**: 399–420.

Orem HM. 1968. *Discharge in the lower Columbia River Basin, 1928–65*. Circular 550, US Geological Survey, Washington, DC.

Paulsen CG. 1949. *Floods of May–June 1948 in the Columbia River Basin*. Geological Survey Water-Supply Paper 1080. US Geological Survey: Washington, DC.

Redmond KT, Koch RW. 1991. Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices. *Water Resources Research* **27**: 2381–2399.

Sherwood CR, Jay DA, Harvey RB, Hamilton P, Simenstad CA. 1990. Historical changes in the Columbia River estuary. *Progress in Oceanography* **25**: 299–352.

Simenstad CA, Jay DA, Sherwood CR. 1992. Impacts of watershed management on land-margin ecosystems: the Columbia River estuary. In *Watershed Management*, Naiman RJ (ed.). Springer-Verlag: 267–306.

Simons WD. 1953. *Irrigation and Streamflow Depletion in Columbia River Basin Above The Dalles, Oregon*. *US Geological Survey Water-Supply Paper* 1220. Government Printing Press: Washington, DC.

USBR. 1999. *Cumulative hydrologic effects of water development in the Columbia River basin*. US Bureau of Reclamation, Pacific Northwest Region.

Wells JVB. 1958. *Compilation of Records of Surface Waters of the United States Through September 1950*. US Geological Survey Water-Supply Paper 1318. US Government Printing Office: Washington, DC: 187–190.

