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River management response to multi-decade changes in timing of reservoir inflows, Columbia River Basin, USA

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Abstract

Around the world, long-term changes in the timing and magnitude of streamflow are testing the ability of large managed water resource systems constructed in the 20th century to continue to meet objectives in the 21st century. Streamflow records for unregulated rivers upstream of reservoirs can be combined with records downstream of reservoirs using a paired-watershed framework and concepts of water resource system performance to assess how reservoir management has responded to long-term change. Using publicly available data, this study quantified how the intra-annual timing of inflows and outflows of 25 major reservoirs has shifted, how management has responded, and how this has influenced reliability and vulnerability of the water resource system in the 668,000 km^2 Columbia River basin from 1950 to 2012. Reservoir inflows increased slightly in early spring and declined in late spring to early fall, but reservoir outflows increased in late summer from 1950 to 2012. Average inflows to reservoirs in the low flow period exceeded outflows in the1950s, but inflows are now less than outflows. Reservoirs have increased hedging, that is, they have stored more water during the spring, in order to meet the widening gap between inflows and outflows during the summer low flow period. For a given level of reliability (the fraction of time flow targets were met), vulnerability (the maximum departure from the flow target) was greater during periods with lower than average inflows. Thus, the water management system in this large river basin has adjusted to multi-decade trends of declining inflows, but vulnerability, that is, the potential for excess releases in spring and shortfalls in summer, has increased. This study demonstrates the value of combining publicly available historical data on streamflow with concepts from paired-watershed analyses and metrics of water resource performance to detect, evaluate, and manage water resource systems in large river basins.

KEYWORDS

climate and vegetation change, hedging, historical streamflow records, large river basin water management, non-stationarity, reference watersheds, reservoir management

1 | INTRODUCTION

Management of water resources on the time scale of many decades across large bioclimatically variable river basins is challenging, as management objectives and the environment evolve. Gradual environmental change, such as climate change and land cover change, test the reliability of engineered water resource systems and their vulnerability to failure (Schewe et al., 2014; Srinivasan, Lambin, Gorelick, Thompson, & Rozelle, 2012). Dried lakes in central Asia, the result of decades of unsustainable water resource management, are powerful symbols of such failures (Alborzi et al., 2018). Non-stationary conditions pose challenges for water management (Milly et al., 2008). A key question is how river basin management can continue to meet multiple objectives in the face of gradual change (Lehner et al., 2011).

Many factors have gradually changed the timing of water inputs to river basin water resource systems over multiple decades. These include climate change (e.g., Cayan, Kammerdiener, Dettinger, Caprio, & Peterson, 2001), disturbance by wildfire and insects (Goeking & Tarboton, 2020), and forest management (Jones & Post, 2004). Model simulations indicate that in the northwestern United States climate change will increase rain, decrease snow, and shift high flows to earlier in the year, increasing flooding and reducing flows in the dry season (Elsner et al., 2010; Hamlet et al., 2013). Simulations indicate that long-term changes in the timing of inflows will degrade water management system performance around the world (Palmer et al., 2008). However, few studies have quantified how these changes have altered the intra-annual timing of inflows and outflows to reservoirs.

Models also suggest that in response to changes in timing of inflows, reservoirs managed for flood control and low flow supplementation will store more water to compensate for decreases in summer inflows (Payne, Wood, Hamlet, Palmer, & Lettenmaier, 2004). When reservoir storage volume falls below a certain level, reservoir managers use "hedging" to reduce releases and conserve water (Shih & Revelle, 1994). Optimization models indicate that an increase in hedging may enable water systems to adjust to increased drought (Adeloye & Soundharajan, 2019; Chang et al., 2019). Yet little is known about how reservoir operations have responded to multi-decadal shifts in the timing of inflows to reservoirs.

Water resources system performance can be assessed based on how often the system meets operational flow targets (reliability), and how significant the consequences of failure may be (vulnerability) (Hashimoto, Stedinger, & Loucks, 1982). As a system's ability to meet flow targets declines, the magnitude of departures from flow targets increases (Moy, Cohon, & ReVelle, 1986). It is unclear how reliability and vulnerability have changed over multiple decades in large managed river basins.

We address these three long-term, large-scale watershed management challenges of the 21st century using water resources data, concepts, and methods developed in the 20th century: long-term monitoring of streamflow; paired-watershed experiments; and metrics for assessing water resource system performance. Long-term streamflow records have been collected upstream of reservoirs in reference watersheds, where streamflow is unregulated, as well as downstream of reservoirs, reflecting regulation, and these records are publicly available in the United States (Hirsch & Fisher, 2014). The paired-watershed approach quantifies the effect of an experimental manipulation on streamflow and has been extended to detect effects of long-term change between pairs of non-stationary watersheds (Jones & Grant, 1996; Jones & Post, 2004; Perry & Jones, 2017). The paired-watershed approach can be extended to quantify how reservoir management has responded to long-term change, in cases where reservoirs have a reference gage upstream and a gage downstream of the dam. Paired long-term records of reservoir inflows and outflows also can be evaluated to quantify changes in reservoir reliability and vulnerability.

This study combines these approaches to examine how 60 years of changes in inflows to reservoirs, and the accompanying adjustments in reservoir management, have affected reliability and vulnerability of water resources in the 668,000 km^2 Columbia River Basin in the northwestern United States. We asked:

1. How have the timing and magnitude of inflows to reservoirs changed since 1950?
2. How have reservoir outflows responded to changes in inflows?
3. How have these changes affected reliability and vulnerability of the system?

2 | MATERIALS AND METHODS

2.1 | Study site and data

This study was conducted in the Columbia River Basin (CRB) (668,000 km^2) which drains parts of Canada and the United States (Figure 1). It is the largest river on the Pacific Coast of the Americas by flow volume, and formerly had large runs of native anadromous salmon. The CRB basin is bioclimatically diverse, spanning wet and dry

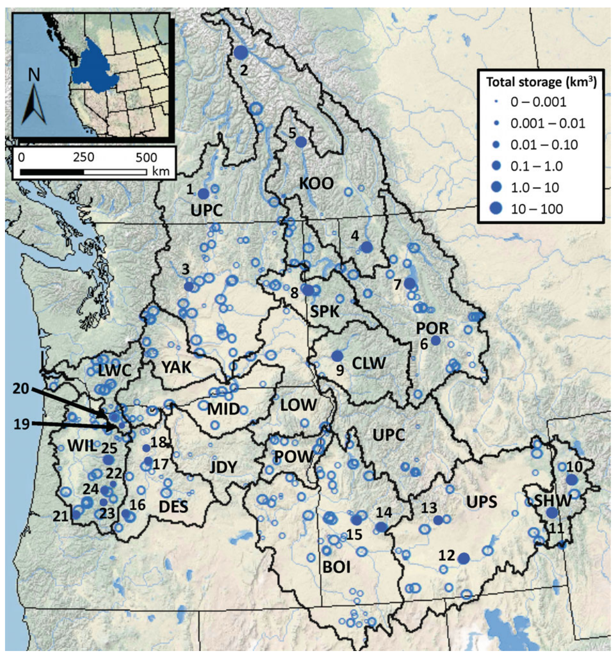

FIGURE 1 The study was conducted in the Columbia River Basin. Twenty-five reservoirs (solid circles) were selected (open circles). Symbol size indicates reservoir storage capacity. Study reservoirs had a matched record of streamflow since 1950 (or when the reservoir went into operation) at both above-dam and below-dam gages. Study reservoirs are on main tributaries in 10 of the sub-basins of the Columbia River. Numeric labels correspond to the gage pair number and dam reported in tables and figures. Pairs 1 to 15 are relatively dry, snow-dominated interior basins with low annual flow, while pairs 16 to 25 are relatively wet, rain and transient snow-dominated basins draining the Cascade Range (Tables 1 and 2)

areas and rain- and snow-dominated hydrographs (Tables S1–S3 in Data S1). Wet winters and dry summers produce strong seasonal variability in streamflow. Since the 1950s, intensive water management in the form of an extensive network of >60 large dams on major tributaries has modified streamflow to provide hydropower generation, flood protection, irrigation, recreation, water supply, and habitat for endangered fish species.

Data were obtained from multiple publicly available sources, described in Data S1. 25 of the 60 major reservoirs in the CRB have matching daily streamflow records upstream and downstream of a reservoir for the period of study (1950 to 2012) (Table 1, Figure 2, Figure S1 in Data S1). Above-dam gages are USGS reference gages (Falcone, 2011) in unregulated streams. Although they are much smaller than the watersheds below dams, they represent inflows to reservoirs unaffected by management, that is, the "reference" in each pair. Below-dam gages are regulated rivers; they represent the outflows or releases from reservoirs, and below-dam streamflow reflects the "treatment" in each pair. Hereafter we use

TABLE 1 Twenty-five sites in this study, where matched records were available at an unregulated basin ("above dam") and a gage downstream of the reservoir ("below dam")

		Drainage area (km[b])			Mean annual flow (mm)		
Pair	Dam	Above dam	Below dam	%	Above dam	Below dam	%
1	Okanagan Lake Dam	112	5,980	2	184	86	216
2	Mica Dam	298	11,790	3	1,522	1,459	104
3	Chelan Dam	831	2,415	34	1,565	778	201
4	Libby Dam	420	23,271	2	368	410	90
5	Duncan Dam	1,330	4,080	33	1,479	1,248	119
6	Milltown Dam	2,939	15,592	19	894	176	509
7	Kerr Dam	1715	16,726	10	620	628	99
8	Post Falls Dam	2,679	10,162	26	795	565	141
9	Dworshak Dam	3,355	20,665	16	913	615	148
10	Jackson Lake Dam	404	1964	21	592	662	89
11	Palisades Dam[a]	8,867	13,424	66	446	431	103
12	Minidoka Dam	1,060	48,830	2	15	121	13
13	Little Wood River Dam	646	802	81	197	180	109
14	Anderson Ranch Dam	1,660	2,533	66	404	343	118
15	Lucky Peak Dam[b]	2,154	6,959	31	514	353	146
16	Crane Prairie Dam	39	671	6	1,437	296	485
17	Pelton Dam	818	20,857	4	1,691	202	836
18	Warm Springs Dam	277	1,362	20	504	280	180
19	Bull Run Dam 1	21	278	8	2,395	1952	123
20	Bull Run Dam 2[c]	60	1,118	5	2,183	1850	118
21	Cottage Grove Dam	185	275	67	1,009	860	117
22	Trail Bridge Dam	237	480	49	1725	1868	92
23	Cougar Dam	414	540	77	1,365	1,416	96
24	Blue River Dam	62	228	27	1774	1783	99
25	Detroit Dam	273	1,171	23	1929	1799	107
	Average	1,234	8,487	28	1,061	814	178
	SD	1865	11,284	25	679	646	177
	min	21	228	2	15	86	13
	max	8,867	48,830	81	2,395	1952	836

Note: % = above dam value as percent of below dam value.
[a]Palisades Dam is downstream of Jackson Lake Dam, whose watershed is 15% of the Palisades Dam watershed area (or 22% of the discharge at Palisades Dam).
[b]The below-dam gage at Lucky Peak Dam also includes flow from a tributary that drains the Anderson Lake Dam; the Anderson Lake watershed is 36% of the drainage area and 35% of the discharge of the gage downstream of Lucky Peak reservoir.
[c]The below-dam gage at Bull Run Dam2 also includes flow from a tributary whose drainage area includes the Bull Run dams above the gage downstream of Bull Run Dam1; this drainage area is 29% of the drainage area and 25% of the discharge of the gage downstream of Bull Run Dam2.

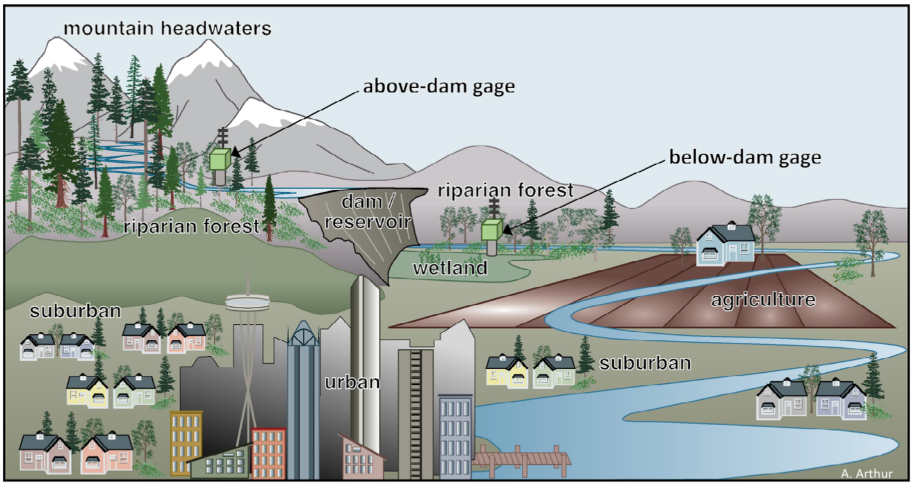

FIGURE 2 An illustration of long-term streamflow gaging above and below reservoirs in the Columbia River basin

TABLE 2 Location, date of construction, management objectives, and normal storage of reservoirs in this study

Pair	Dam	Sub-basin		S/P	Date	Obj	Stor (km^3)	Source
1	Okanagan Lake	Upper Columbia	UPC	BC	1958	F,S,R	26.21	1
2	Mica	Upper Columbia	UPC	BC	1973	H,F	40.70	4
3	Chelan	Upper Columbia	UPC	WA	1927	H,R	1.31	2
4	Libby	Kootenay	KOO	MT	1975	H,F,R	7.43	3
5	Duncan	Kootenay	KOO	BC	1967	F,G	1.73	3
6	Milltown	Pend Oreille	POR	MT	1908	H	NA	5
7	Kerr	Pend Oreille	POR	MT	1938	H,R	1.50	3
8	Post Falls	Spokane	SPK	ID	1908	I,H	0.29	2
9	Dworshak	Clearwater	CLW	ID	1973	H,F,R	4.39	2
10	Jackson Lake	Snake Headwaters	SHW	WY	1916	I,F,R	1.04	2
11	Palisades	Snake Headwaters	SHW	ID	1957	I,H,F,R	1.75	2
12	Minidoka	Upper Snake	UPS	ID	1906	I,H,F,R	0.27	2
13	Little Wood River	Upper Snake	UPS	ID	1939	I,F,R	0.04	2
14	Anderson Ranch	Middle Snake - Boise	BOI	ID	1950	I,F,R,H	0.62	2
15	Lucky Peak	Mid Snake - Boise	BOI	ID	1955	F,R,I	0.38	2
16	Crane Prairie	Deschutes	DES	OR	1940	I,R	0.08	2
17	Pelton	Deschutes	DES	OR	1958	H	0.05	2
18	Warm Springs	Deschutes	DES	OR	1919	H	0.21	6
19	Bull Run 1	Lower Columbia	LWC	OR	1928	S	0.04	2
20	Bull Run 2	Lower Columbia	LWC	OR	1928	S	0.03	2
21	Cottage Grove	Willamette	WIL	OR	1942	F,I,R	0.06	2
22	Trail Bridge	Willamette	WIL	OR	1963	H	0.00	2
23	Cougar	Willamette	WIL	OR	1964	H,F	0.27	2
24	Blue River	Willamette	WIL	OR	1968	F,R	0.11	2
25	Detroit	Willamette	WIL	OR	1953	H,F,R	0.56	2

Abbreviations: Date, date of initiation or reservoir operation; F, Flood control; G, reregulation, H, hydropower, I, irrigation; Obj, management objective; R, recreation, S, Water supply; S/P, state/province; Stor, total storage.

Source: 1. http://www.env.gov.bc.ca/wat/wq/studies/oklimnology.pdf.

2. National Atlas of Dams, http://nid.usace.army.mil/cm_apex/f?p=838:5:0::NO.

3. Wikipedia.

4. Atlas of Canada - Dams, http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/0c78d7fe-100b-5937-b74e-7590a03a6244.html.

5. Milltown Dam was declared a Superfund Site in 1981. The dam was breached and drained starting in 1996 (USEPA 2016). Trends were computed for the period up to 1996.

6. https://www.usbr.gov/projects/index.php?id=85.

the terms "above-dam" and "inflows" and "below-dam" and "outflows."

The 25 reservoirs are located between the unregulated headwaters and the highly regulated portions of the CRB river network (Figure 2). They are located on 22 different tributaries, in rain, snow, and glacier-influenced portions of the basin. They represent more than one-third of the major reservoirs in the Columbia River system. The pairs are numbered by location in the basin, from the north (Canada) to the northeast and east (WA, MT), southeast (ID, WY), and finally the south (OR) (Table 2). Pairs 1 to 15 are relatively dry, snow-dominated interior basins with low annual flow, while pairs 16 to 25 are relatively wet, rain and transient snow-dominated basins draining the Cascade Range (Tables 1 and 2). Pairs with lower numbers have the largest reservoir capacities and drainage areas in the study, while pairs with higher numbers have relatively small capacity (Table 2). In 22 of 25 cases the below-dam gages are influenced by upstream water management at only one reservoir; in three cases the below-dam gages are influenced by two or more reservoirs (Table 1).

20 of 25 pairs are managed for multiple objectives, by 10 US and Canadian entities. 15 reservoirs are managed for flood control, 15 for hydropower, 15 for recreation, and nine for irrigation (Tables 2 and 3, Figure 3). Pairs with lower numbers (1 to 8) are mostly managed by utilities (government, industry, tribes), while pairs in the middle third (9 to 16) are mostly managed by the USBOR, and pairs in the last third (17–25) are mostly managed by utilities, municipal water bureaus, and the USACE (Table 3). Thirteen of the reservoirs went into operation between 1906 and 1950, and the remainder went into operation between 1950 and 1973 (Table 2). Matched records from the above-dam and below-dam gages were available for 62-year periods for 12 pairs, and for >36 years at all pairs (Table 3). Climate and vegetation changed over the study period in the above-dam basins. Young forests, regenerated after fire or forest harvest, represent substantial portions of the area of above-dam basins (Table S4 in Data S1).

2.2 | Trend analyses to detect shifts in intra-annual timing of inflows and outflows from reservoirs

Trends in streamflow were calculated to determine how the timing of streamflow has shifted within the year over multiple decades above

TABLE 3 Above-dam and below-dam gages and periods of analysis used in this study

Pair	Dam	Above-dam Gage 1 ID	Below-dam Gage ID	Period of analysis	Owner
1	Okanagan Lake	08NM174	08NM050	1958–2012	BC Hydro
2	Mica	08NC004	Mica Outflow	1973–2012	BC Hydro
3	Chelan	12451000	12452500	1977–2012	Chelan County
4	Libby	08NF001	12301933	1975–2012	USACE
5	Duncan	08NH119	08NH118	1967–2012	BC Hydro
6	Milltown[a]	12358500	12340500	1950–2012	Northwestern Energy
7	Kerr	12370000	12372000	1950–2012	People of Montana and Salish/Kootenai Tribe
8	Post Falls[a]	12414500	12419000	1950–2012	Washington Water Power Company
9	Dworshak	13340600	13341050	1973–2012	USACE
10	Jackson Lake	13011500	13011000	1950–2012	USBOR
11	Palisades	13022500	13032500	1957–2012	USBOR
12	Minidoka	13078000	13081500	1950–2012	USBOR
13	Little Wood River	13147900	13148500	1950–2012	USBOR
14	Anderson Ranch	13186000	13190500	1950–2012	USBOR
15	Lucky Peak	13185000	13202000	1955–2012	USACE
16	Crane Prairie	14050500	14054000	1950–2012	USBOR
17	Pelton	14091500	14092500	1958–2012	Portland General Electric
18	Warm Springs	14095500	14097100	1950–2012	USBOR
19	Bull Run 1	14138800	14140000	1950–2012	City of Portland
20	Bull Run 2	14141500	14142500	1950–2012	City of Portland
21	Cottage Grove	14152500	14153500	1950–2012	USACE
22	Trail Bridge	14158500	14158850	1963–2012	Eugene Water & Electric Board
23	Cougar	14159200	14159500	1964–2012	USACE
24	Blue River	14161500	14162200	1968–2012	USACE
25	Detroit	14179000	14181500	1953–2012	USACE

Abbreviations: BC Hydro, British Columbia Hydro; USACE, US Army Corps of Engineers; USBOR, US Bureau of Reclamation.
[a]This dam had >1 above-dam gage; we used the gage which had the longest record and least amount of land cover change.

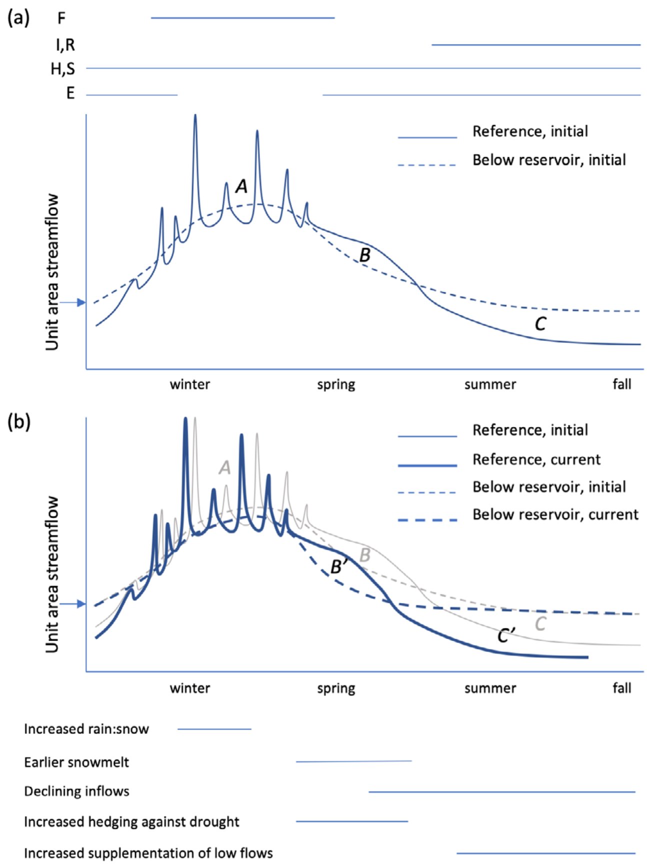

FIGURE 3 Reservoirs in the Columbia River basin are managed for multiple objectives, which vary over the year (top panel); changes in reservoir inflows may have changed reservoir management (bottom panel). Top panel: Reservoirs are managed for flood control (F) in winter and spring; irrigation (I) and recreation (R) in summer, hydropower (H) and municipal water supply (S) year-round, and in recent years, environmental flows for fish (E). Management mitigates flood peaks in winter and spring (A), stores water in late spring (B), and supplements low flows in summer (C). Bottom panel: Over multiple decades, peak inflows to the system may have shifted earlier in the year, and summer low flows may have declined (heavy solid line), possibly leading to increased hedging (B′) and increased low flow supplementation (C′)

and below dams (Figure 3). Trends of unit-area mean daily flow were calculated for each day of the year for the period of record at each above-dam and below-dam gage (n = 992,070 observations) (e.g., Déry et al., 2009; Hatcher & Jones, 2013). Trends also were calculated over the period of record for inflows and outflows in the low flow period (May through October) and for precipitation by month.

Trends were estimated using the Mann-Kendall non-parametric trend test (Helsel & Hirsch, 2002; McLeod, 2011) paired with estimation of trend slope using Sen's slope estimator with $p < .05$ (Sen, 1968; Theil, 1950; zyp R package in Bronaugh & Werner, 2013). Prior analyses demonstrated that trend slopes from Mann-Kendall trend tests and from linear regression of log-transformed streamflow data were equivalent; regression residuals were not autocorrelated; and wavelet analysis confirmed that trends were independent of climate cycles (Hammond, 2014; Hatcher & Jones, 2013). Trend analyses included the period since the reservoir began operation; paired record lengths ranged from 35 to 62 years (mean 54.4 ± 9.5 years) (Table 3).

Slopes of trends below dams were designated as s_1 and slopes of trends above dams were designated as s_2. Days with significantly positive (blue) and negative (red) values of s_1 and s_2 and the mean daily flow for the first and last decade of the record, were plotted by day of year at each pair of above-dam and below-dam gages (Figure 4). Values of s_1 and s_2 were plotted by day of year for each above-dam and below-dam pair (Figure S4 in Data S1) and for the average of all pairs (Figure 5). The numbers of days with significantly positive or negative values of s_1 and s_2 were counted and summed by day of year and summed for three periods: the entire year, the early snowmelt period, and the low-flow period, for each of the 25 pairs and all pairs combined (Figure 6, Data S1). Trends in precipitation were plotted by month (Figure S3 in Data S1). Reservoir inflows, outflows, and the average of the difference (inflows − outflows) for all 25 pairs were plotted by year (Figure 7).

2.3 | Paired-watershed analysis to detect changes in reservoir management

In a standard paired-watershed analysis, streamflow is monitored at two watersheds over a pre-treatment period, and then one of the watersheds is subjected to a treatment (such as forest harvest), while the other is left undisturbed as a control. The effect of the treatment on streamflow is then determined as:

$$\ln(\text{effect}) = \ln(t_a/c_a) - \ln(t_b/c_b), \tag{1}$$

where ln is the natural logarithm, t_b, t_a = streamflow in the treated watershed before (t_b) and after (t_a) the treatment, and c_b, c_a = streamflow in the control watershed before (c_b) and after (c_a) the treatment (Eberhardt & Thomas, 1991; Jones & Grant, 1996). This equation is valid when streamflow at either or both watersheds is non-stationary, and when the treatment is gradual or sudden (Figure S2 in Data S1).

We adopted the paired-watershed analysis to detect long-term changes in reservoir management. In this case, the "control" is the inflows to the reservoir from the unregulated above-dam watershed, and the "treatment" is the outflows at the below-dam gage (e.g., Figure 2). The terms in Equation (1) can be re-arranged to express the effect of the treatment over time as a difference in rates of change at the treated and control watersheds (details in Data S1):

$$\ln(\text{effect})/T = [\ln(t_a) - \ln(t_b)]/T - [\ln(c_a) - \ln(c_b)]/T, \tag{2}$$

where T is time. The first term in Equation (2) is the slope of the trend in below-dam streamflow (i.e., s_1), and the second term is the slope of the trend in above-dam streamflow (i.e., s_2, see Section 2.2). In other words, the effect of long-term shifts in reservoir management can be determined as the rate of change of streamflow at the below-dam gage minus the change in streamflow at the above-dam gage:

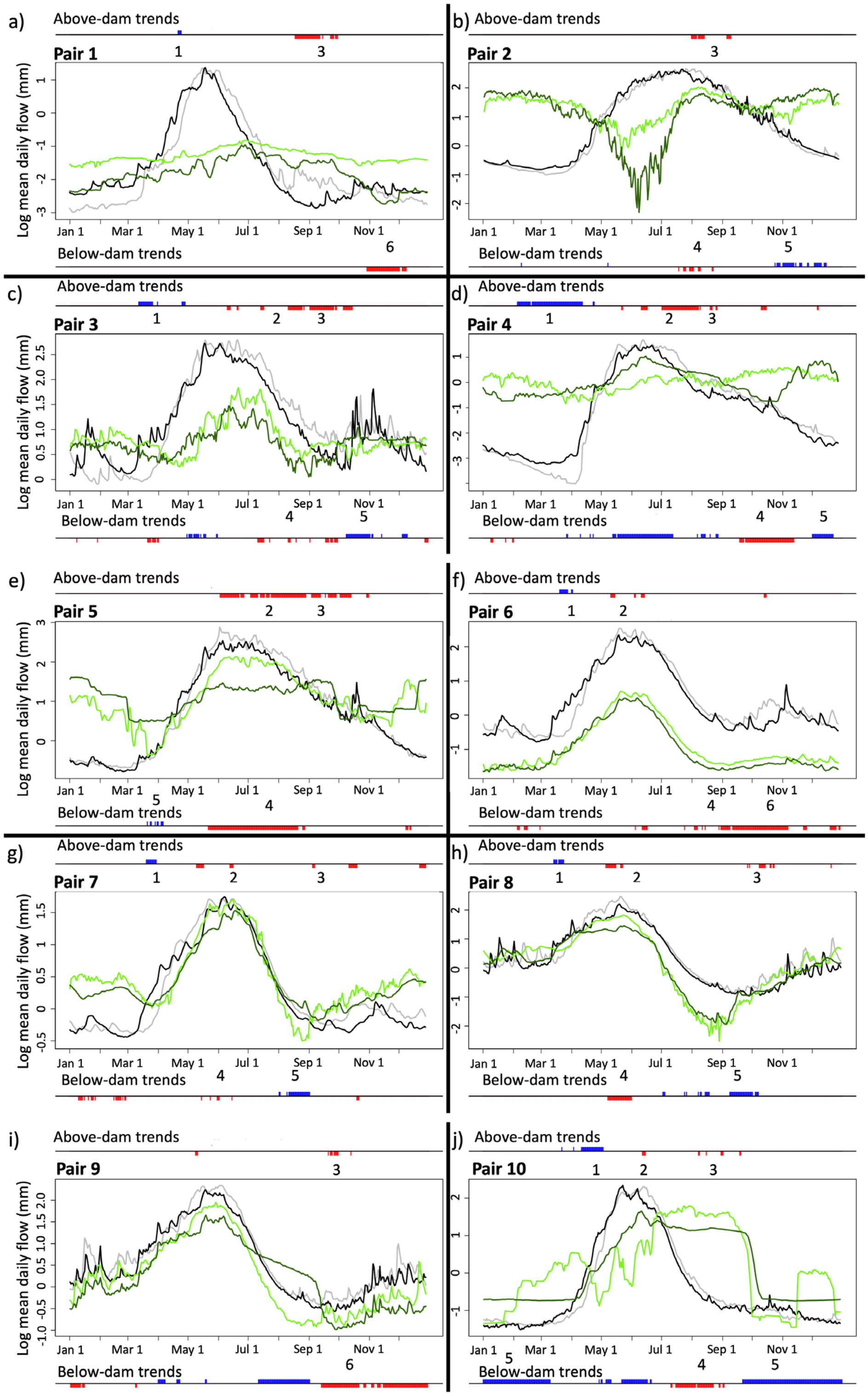

FIGURE 4 Shifts in timing of inflows and outflows from reservoirs based on 25 pairs of above-dam and below-dam gages (a–y) in the Columbia River basin over the period 1950–2012 reflect adjustment of reservoir operation to accommodate changes in inflows. Reservoir operations are shown by the relationship between inflows (mean daily flow at the above-dam gage, grey and black lines) and outflows (mean daily flow at the below-dam gage, pale dark green lines), for the first decade of operation (grey and pale green lines) and the most recent decade (black and dark green lines). Relationships between inflows and outflows reveal three forms of reservoir management: flood control (A), storage of water in spring (B), and low flow supplementation in summer (C). Long-term shifts in timing of flow is shown by days with significant positive trends in daily streamflow over the period of record (blue bars) and days with significant negative trends over the period of record (red bars), for gages above dams (inflows, above the graph, s_2) and gages below dams (outflows, below the graph, s_1). Trends in flow timing above dams (inflows) include: 1 = increasing rain or early snowmelt inflows to reservoir; 2 = declining snowmelt freshet; and 3 = declining inflows in the low-flow period. Trends in flow timing below dams include: 4 = declining reservoir outflows during the snowmelt period (increased "hedging"; 5 = increased reservoir outflows in the low-flow period; 6 = decreased reservoir outflows in the low-flow period (see summary in Table 4). Reservoir outflows in the first decade of reservoir operation (pale green line) were used as operational flow targets to calculate reliability and vulnerability

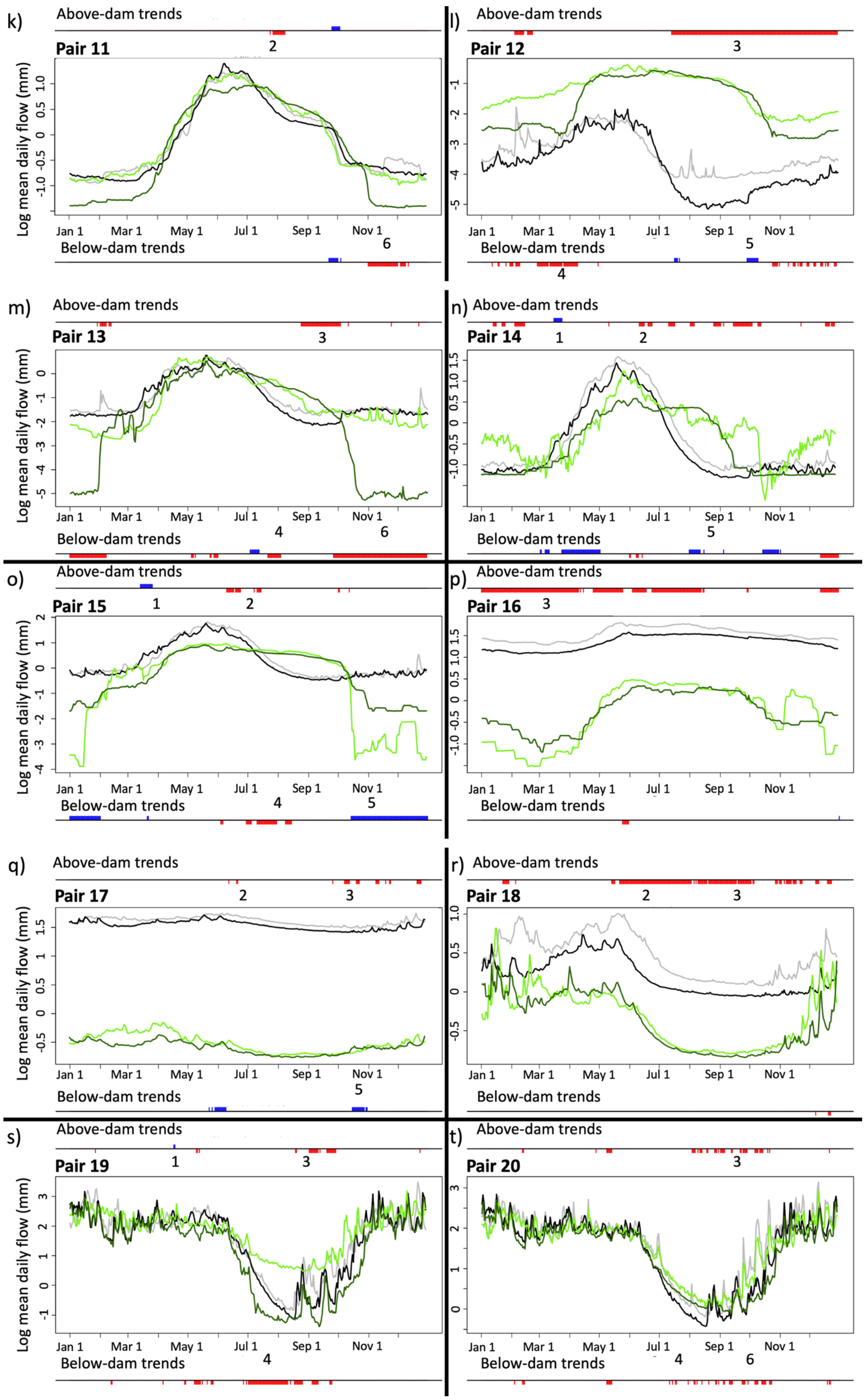

FIGURE 4 (Continued)

$$\ln(\text{effect}/T) = s_1 - s_2. \tag{3}$$

The change in reservoir management, that is, $(s_1 - s_2)$, was plotted by day of year for each above-dam and below-dam pair (Figure S4 in Data S1) and for the basin as a whole (Figure 5).

2.4 | Reliability and vulnerability

Reservoir reliability and vulnerability (e.g., Hashimoto et al., 1982; Moy et al., 1986) were estimated for each day of the record at all below-dam gages. Operational targets, that is, daily flow levels, are

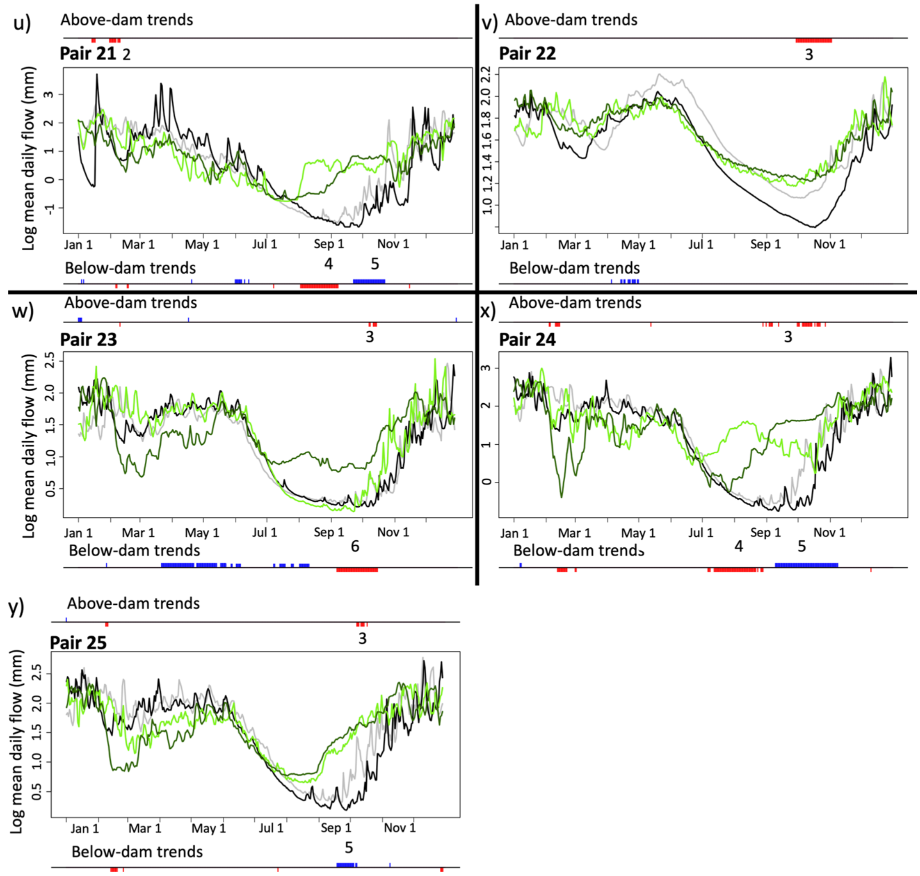

FIGURE 4 (Continued)

established in the first decade of operation of a reservoir. We therefore defined the target flow as the average daily flow during the first decade of reservoir operation. The flow target was expressed in terms of an anomaly, that is, the difference relative to the long-term mean flow on that day. These daily flow targets were used as the basis to calculate reliability and vulnerability over the subsequent decades at each reservoir.

Reliability (r_{mt}) was defined as the frequency of success in meeting targets, that is, the fraction of days when flow targets were met, for each month *m* of each year *t* for each below-dam gage. Flow targets were considered to be met for summer months (May through October) when the observed daily flow exceeded the target flow, because during this period reservoir releases primarily supplement low flows. Flow targets were considered to be met for winter months when the observed daily flow was less than the target flow, because during this period reservoirs hold back water to prevent downstream flooding. Vulnerability (v_{mt}) was defined as the magnitude of departure of flow from the target for each month *m* in each year *t* in the record for each below-dam gage. Vulnerability was calculated as the largest negative departure from the flow target during the period when reservoirs primarily supplement low flows (May to October) and the largest positive departure from the flow target during the period when reservoirs hold back water to prevent downstream flooding (November to April). Vulnerability was expressed as a percent of the mean daily flow during the first decade of record (see details in Data S1).

To test how inflows to reservoirs affect reliability and vulnerability, values of r_{mt} and v_{mt} were subdivided into categories of dry (below normal), wet (above normal), and normal inflows to the reservoir. Each month *m* in each year *t* in the record at each reservoir was categorized as dry (below normal, $q_{6mt} < -0.5$ mm), normal ($-0.5 < q_{6mt} < 0.5$ mm), or wet (above-normal, $q_{6mt} > 0.5$ mm), based on the average inflow to each reservoir for the prior 6 months (q_{6mt}). Values of vulnerability (monthly flow anomaly) were plotted as a function of reliability (fraction of time target met) by inflow category (dry, normal, wet) for summer and winter periods (Figure 8).

3 | RESULTS

Comparison of inflow and outflow hydrographs reveals the effects of reservoir management on streamflow in the CRB (Figures 4 and 5). Average precipitation varies five-fold among months (Figure 5a). Average monthly streamflow at reference watersheds above dams is lagged relative to precipitation inputs in part due to snow accumulation and melt in the watersheds draining to reference gages. Average monthly streamflow below dams is further lagged and reduced, because reservoirs store water during the snowmelt freshet (February to July) and supplement low flows in late summer (July to October, depending on location).

Hydrographs at 20 of the 25 reservoirs show evidence of management to reduce high flows during winter and spring (A in Figures 3

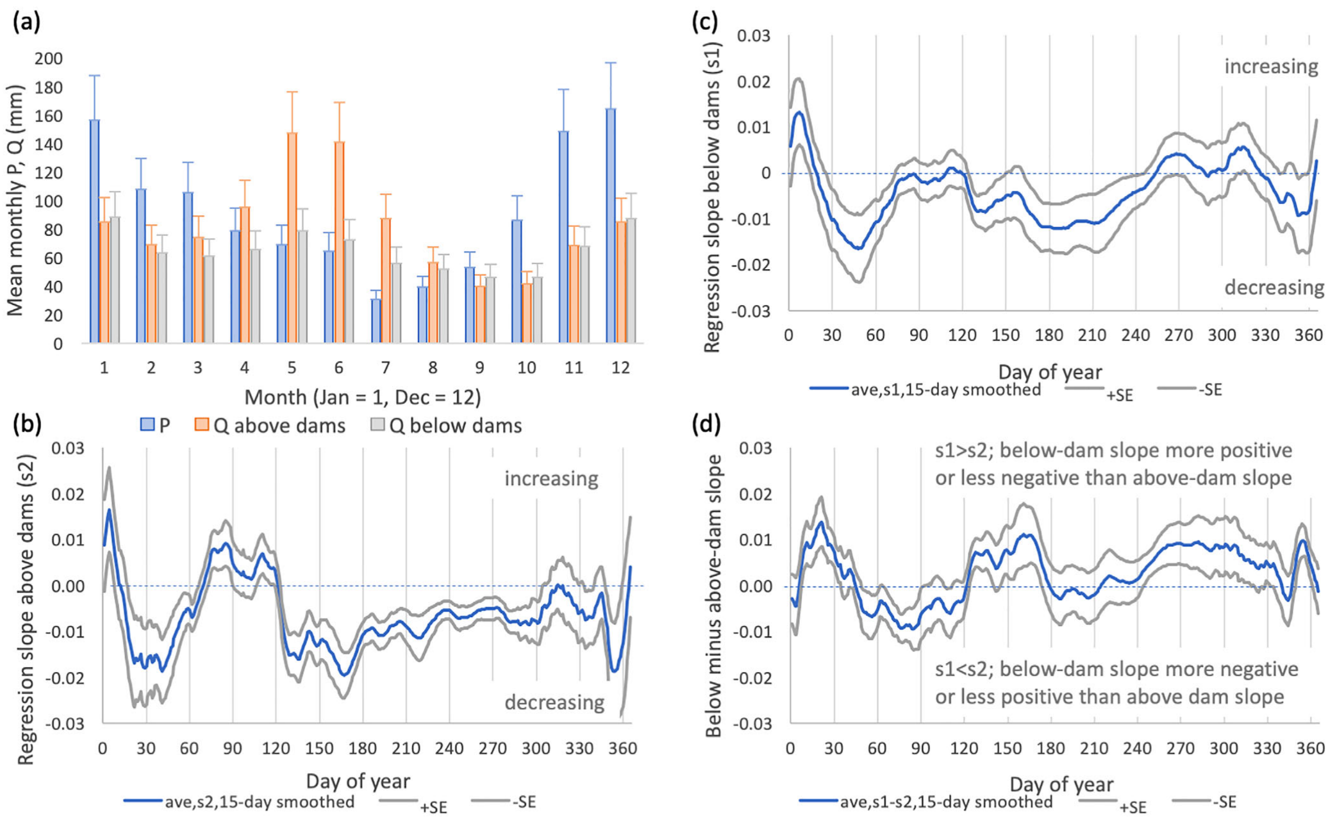

FIGURE 5 The changing relationship between above-dam and below dam streamflow at 25 reservoirs in the Columbia River Basin reveals how the intra-annual timing of inflows to reservoirs has changed and how reservoir management has responded over the period 1950 to 2012. (a) Basin-wide reservoir management shifts the intra-annual timing of streamflow as shown by mean monthly precipitation (P) and streamflow (Q) above dams and streamflow below dams over the period 1950 to 2012; (b) Average (n = 25) rates of change of daily streamflow above dams over multiple decades (s_2) have declined except in March, November, and December; (c) Average (n = 25) rates of change of daily streamflow below dams over multiple decades (s_1) also have declined except in March, April, and September to December; (d) Average (n = 25) difference in rates of change of daily streamflow below minus above dams over multiple decades (s_1 - s_2) reveal increased hedging in mid-February to April, and increased flow supplementation in May to October. Values are smoothed with a 15-day window

and 4, Table 4). Fourteen of these reservoirs have a flood control objective, and five have a hydropower objective (Table 2). Springtime hydrographs at 19 of the reservoirs show evidence of net storage of water during the latter part of the high flow period ("hedging") (B in Figures 3 and 4, Table 4). The summer hydrographs at all reservoirs practicing hedging show evidence of low flow supplementation. Summer hydrographs at 21 reservoirs indicate low flow supplementation (C in Figures 3 and 4, Table 4). Nineteen of the reservoirs managed to supplement low flows have hydropower, recreation, and/or irrigation objectives, and two have water supply objectives (Table 2).

3.1 | Long-term shifts in intra-annual timing of inflows and outflows to reservoirs

Intra-annual timing of reservoir inflows shifted over the period of study (1950–2012). High flows shifted earlier in the year at 11 above-dam gages (noted as 1 in Figure 4, Table 4), and spring/early summer streamflow declined at 13 above-dam gages (noted as 2 in Figure 4, Table 4) (see also Tables S1–S4 in Data S1). Trends of earlier intra-annual timing of high flows predominated in snow-dominated sub-basins, such as the upper Columbia, Kootenay, Pend Oreille, Spokane, Snake headwaters, and Boise (Figure 1, Table 2). Streamflow declined significantly from 1950 to 2012 during the dry (low-flow) part of the year at 22 of 25 above-dam gages (noted as 3 in Figure 4 and Table 4). These changes have occurred despite a lack of significant long-term trends in precipitation (Figure S3 in Data S1).

Intra-annual timing of reservoir outflows also shifted over the period of study (1950–2012), but less than for inflows. Hedging (i.e., increased storage during the transition from high to low flows) increased at 17 below-dam gages over the study period (noted as 4 in Figure 4, Table 4). At 14 below-dam gages where hedging increased significantly, reservoir releases during the low-flow period also increased significantly from 1950 to 2012 (noted as 5 in Figure 4, Table 4; see also Tables S1–S4 in Data S1). Reservoir outflows during the low-flow period increased in sub-basins throughout the CRB (Table 4). From 1950 to 2012, reservoir outflows declined during the low-flow period at only seven below-dam gages (noted as 6 in Figure 4 and Table 4).

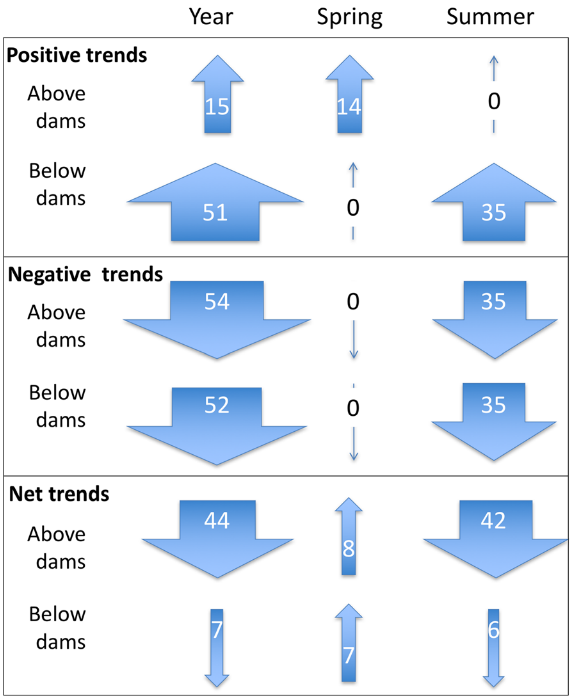

FIGURE 6 Trends in daily streamflow from 1950 to 2012 above and below 25 major reservoirs in the Columbia River Basin were significantly positive three times more frequently below dams than above dams (51 vs. 15 days), while trends were significantly negative with equal frequency above and below dams (54 vs. 52 days). Significant positive trends above dams occurred in spring (March, n = 14 days) and significant positive trends above dams occurred only in summer (May to October, n = 35 days). Numbers of significant net trends in summer were seven times more frequent above dams than below dams (42 vs. 6 days) (see Data S1)

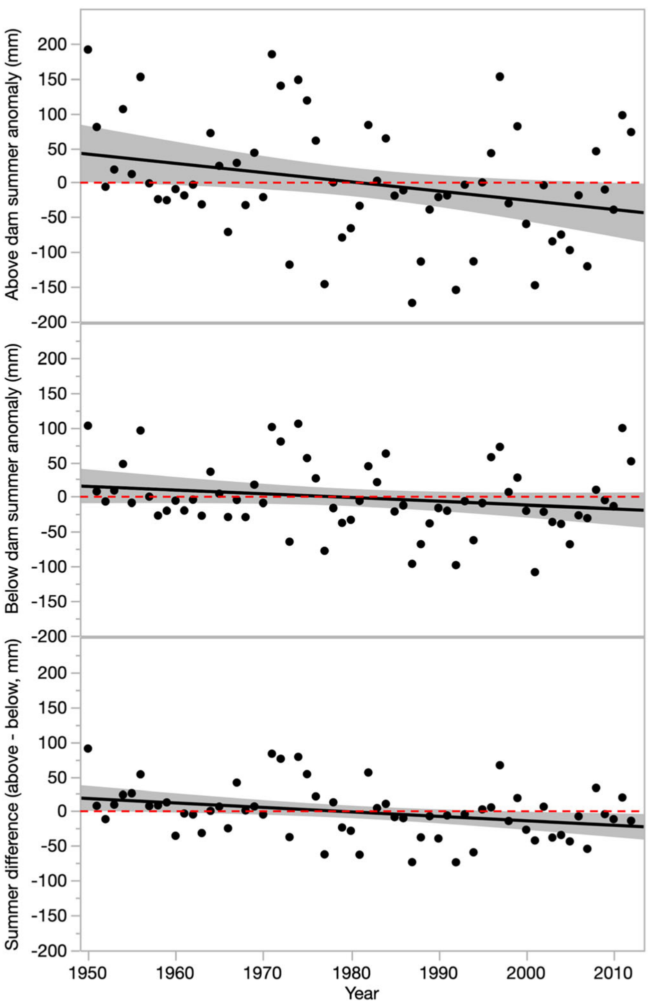

FIGURE 7 Average streamflow (May to October) throughout the Columbia River Basin over the period 1950 to 2012 has declined at above-dam gages (a) and below-dam gages (b), and inflows have declined more rapidly than outflows, based on the median difference at each pair of above and below-dam gages (c). This trend implies that there has been a gradual shift from reservoir surplus (inflows > outflows) to deficit (inflows < outflows) during the May to October period from 1950 to 2012. This trend also implies that when reservoirs initiated operation, inflows on average during May to October were more than sufficient to meet flow targets from May to October, whereas now reservoirs are relying on water stored prior to May 1 in order to meet flow targets in the May to October period

3.2 | Reservoir management has shifted to compensate for changing inflows

Average slopes of regressions for daily streamflow (1950–2012) above and below 25 reservoirs in the CRB reveal a shift in the timing of flows above dams and slightly different shifts below dams (Figure 5b–d, Figure S4 in Data S1). Over the study period (1950–2012), daily streamflow has declined in mid-January to mid-March, and May through October at reference gages above dams (s_2), and in mid-January to mid-March and May through August at gages below dams (s_1). Daily streamflow has increased in January, March, and April at reference gages above dams (s_2), and in January at gages below dams (s_1). The average differences in slopes of regressions for daily streamflow (1950–2012) below minus above dams ($s_1 - s_2$) reveals changes in reservoir management. Over the study period (1950–2012), daily streamflow in late February and March has increased less at gages below dams than above dams, indicating that reservoirs are increasing storage of water being released by earlier snowmelt (i.e., reservoirs have increased hedging). Daily streamflow in May and June, and September to November has increased more at gages below dams than at gages above dams, indicating increased flow supplementation (Figure 5d). The numbers of significant positive and negative trends show the same result, indicating long-term increases in storage in reservoirs in the spring and long-term increases in reservoir releases in the summer low-flow period (Figure 6, Table S5 in Data S1).

Average streamflow (May to October) throughout the Columbia River Basin over the period 1950 to 2012 has declined at above-dam gages and below-dam gages, and inflows have declined more rapidly than outflows (Figure 7). In other words, in the first decade after reservoirs initiated operation, inflows during May to October were more than sufficient to meet flow targets from May to October, whereas

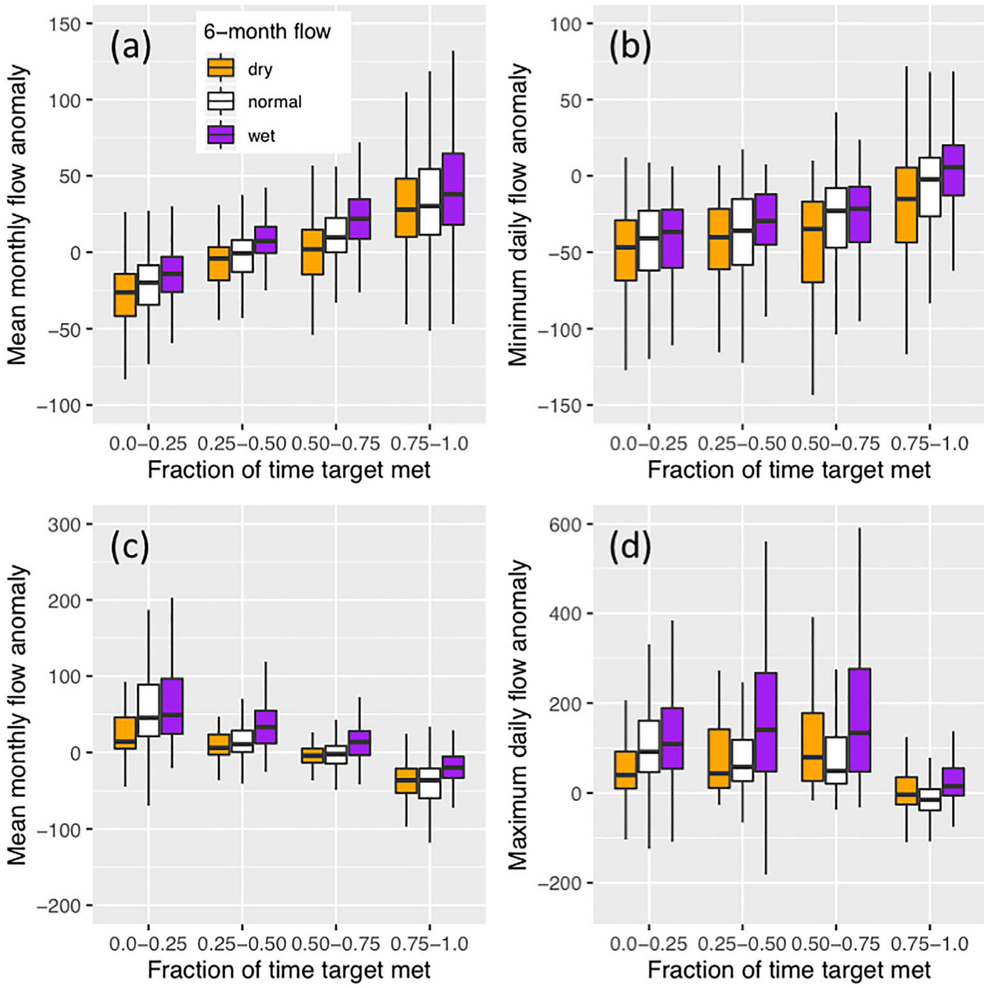

FIGURE 8 Vulnerability was related to reliability and reservoir inflows (dry, normal, wet) during (a,b) summer and (c,d) winter at 25 reservoirs in the Columbia River basin, 1950 to 2012. Reliability (fraction of time flow target is met) and vulnerability (monthly flow anomaly) are defined in the text. Vulnerability in summer (May to October, months 5 to 10), when reservoirs are supplementing low flows, is the deficit relative to flow targets. Vulnerability in winter (November to April, months 11, 12, 1 to 4), when reservoirs are controlling floods, is the amount by which the flow target was exceeded. Reliability and vulnerability are shown for periods defined as dry (below normal), normal, and wet (above normal) based on reservoir inflows over the prior 6 months). Results do not differ by month within the summer or winter periods (Figure S4 in Data S1)

now reservoirs are relying on water stored prior to May 1 in order to meet flow targets in the May to October period.

3.3 | Reliability has been maintained but vulnerability may have increased

Analysis of all historical daily flows from the 25 reservoirs over the period 1950 to 2012 reveals that reservoir vulnerability (the magnitude of departure from flow targets) depends on reliability (how frequently flow targets are met) and on reservoir inflows (Figure 8). During summer months (May to October), mean daily reservoir outflows fell short of targets for low flow supplementation (Y-axis, vulnerability) only in months when flow targets were met less than half the time (X-axis, reliability) (Figure 8a). However, minimum daily reservoir outflows fell short of targets at all levels of reliability (Figure 8b). Over the full period of reservoir operation, minimum daily reservoir outflows during the May to October period ranged from +60% to −150% of the daily flow target (defined as mean daily reservoir outflows of the first decade of reservoir operation), including dry, normal and wet years. The largest (most negative) daily shortfalls occurred during dry periods, which were defined as lower than average reservoir inflows over the preceding 6 months (Figure 8b). In other words, after 6 months of low inflows, summer reservoir storage often was insufficient to meet flow targets, resulting in unusually large shortfalls.

During winter months (November to April), mean daily reservoir outflows exceeded targets (Y-axis, vulnerability) in months when flow targets (for flood control) were met less than half of the time (X-axis, reliability) (Figure 8c). Over the full period of reservoir operation, maximum daily reservoir outflows during winter months ranged from −200% to +600% of the daily flow target including dry, normal and wet years. The largest (most positive) daily maximum flows occurred during wet periods, defined as higher than average reservoir inflows over the preceding 6 months. However, high daily maximum flows also occurred during dry and normal periods, especially in February, March and April (Figure 8d, Figure S5 in Data S1). In other words, independent of prior inflow levels, possibly combined with increased hedging, spring reservoir available storage capacity often was insufficient to capture flows from large storms, resulting in unusually large reservoir spills. This effect may be exacerbated by hedging, which reduces flood storage capacity.

Collectively, analyses of historical records indicate that water management in the Columbia River Basin has responded to

TABLE 4 Summary of effects of reservoir management and trends in streamflow at above-dam and below-dam gages over the period 1950–2012 at 25 reservoirs in the Columbia River basin

				Effects of reservoir management			Trends in reservoir inflows			Trends in reservoir outflows		
Pair	Dam	sub-basin	S/P	A	B	C	1	2	3	4	5	6
1	Okanagan Lake	UPC	BC	x	x	x	x		x			x
2	Mica	UPC	BC	x	x	x	x		x	x	x	
3	Chelan	UPC	WA	x	x	x	x	x	x	x	x	
4	Libby	KOO	MT	x	x	x	x	x	x	x	x	
5	Duncan	KOO	BC	x	x	x		x	x	x	x	
6	Milltown	POR	MT	x			x	x	x	x		x
7	Kerr	POR	MT	x	x	x	x	x	x	x	x	
8	Post Falls	SPK	ID	x	x	x	x	x	x	x	x	
9	Dworshak	CLW	ID	x	x	x			x			x
10	Jackson Lake	SHW	WY	x	x	x	x	x	x	x	x	
11	Palisades	SHW	ID	x	x	x		x			x	x
12	Minidoka	UPS	ID			x			x	x	x	
13	Little Wood River	UPS	ID	x					x	x	*	x
14	Anderson Ranch	BOI	ID	x	x	x	x	x	x	x	x	
15	Lucky Peak	BOI	ID	x	x	x	x	x		x	x	
16	Crane Prairie	DES	OR		x	x			x	*	*	
17	Pelton	DES	OR					x	x		x	
18	Warm Springs	DES	OR	x				x	x			
19	Bull Run 1	LWC	OR	x	x	x	x		x	x		
20	Bull Run 2	LWC	OR		x	x			x	x		x
21	Cottage Grove	WIL	OR	x	x	x		x	*	x	x	
22	Trail Bridge	WIL	OR			x			x			
23	Cougar	WIL	OR	x	x	x			x			x
24	Blue River	WIL	OR	x	x	x			x	x	x	
25	Detroit	WIL	OR	x	x	x			x		x	

Note: Effects of reservoir management (from Figure 3): A = flood control; B = storage; C = lowflow augmentation. Trends in inflows: 1 = increasing rain or early snowmelt; 2 = declining snowmelt freshet; 3 = declines in the lowflow period. Trends in outflows: 4 = declines during the snowmelt period (increased "hedging"); 5 = increases in the lowflow period; 6 = decreases in the lowflow period. * = trend apparent in Figure 4, but was not statistically significant. S/P = US State or Canadian province. Sub-basins are defined in Figure 1 and Table 1. Details of trends are shown in Figure 4.

multi-decade shifts in the timing and magnitude of reservoir inflows. These adjustments have permitted the water management system to continue to meet flow targets, that is, to maintain reliability. However, greater negative departures from flow targets (vulnerability) during dry periods (i.e., lower than normal inflows), combined with multi-decade reductions in reservoir inflows during the dry (low-flow) part of the year suggest that system vulnerability has increased over time.

4 | DISCUSSION

4.1 | River basin management has adapted through increased hedging

In the 21st century, water management systems in large river basins continue to operate under gradually changing conditions, but with a fixed reservoir capacity and management objectives, many of which were established in the mid 20th century. Changes in annual and seasonal hydrographs are expected to challenge water management (Dettinger, Udall, & Georgakakos, 2015). Opinions vary about whether large water management systems will be able to accommodate such changes. Some argue that the use of historical records as the basis for planning, combined with rigid reservoir operating rules, limits adaptation to changing conditions (Hamlet, 2011). Uncertainty surrounding the drivers of change complicates efforts to predict and manage under traditional approaches that assume stationarity (Cosens & Williams, 2012; Milly et al., 2008). Water management systems may lack self-organization and distributed control necessary for adaptation (Pahl-Wostl, 2007). Legal, economic and cultural dependencies on water resource infrastructure provide incentives to preserve, rather than alter, existing infrastructure (Cosens, Gunderson, & Chaffin, 2014).

However, this study found that the Columbia River Basin water management system has adapted to gradually declining inflows. Analysis of historical data shows that the water system has already responded to gradual changes predicted by many simulation models, even without the large changes reflected in future climate model simulations. Over the period 1950–2012, 25 major reservoirs in the CRB continued to meet multiple objectives despite multi-decade changes that advanced the timing and reduced the magnitude of reservoir inflows during the dry (low-flow) period. These findings support assertions that water resource systems have adaptive capacity, because they are malleable and changeable, power is shared among levels of government, and there is redundancy and competition within layers of government (Doyle, 2012). Although the adjustments we observed in reservoir management occurred throughout the CRB, they may have occurred for different reasons in different parts of the basin. Individual regulators may interpret policy guidance in quite different social and environmental settings, producing an appearance of homogeneity in regulatory outcomes at a relatively coarse scale that obscures a high degree of fine-scale heterogeneity (Doyle, Lave, Robertson, & Ferguson, 2013).

Over the period 1950 to 2012, despite multi-decade declines in inflows during the dry (low-flow) part of the year, reservoirs continued to meet flow targets (reliability was maintained) with no long-term increase in the magnitude of departures from flow targets (vulnerability). This has been achieved by increased use of hedging, whereby more water is stored in late spring and early summer in order to meet the widening gap between summer inflows and late summer reservoir flow targets. Multi-decade increases in hedging permitted multi-decade increases in summer streamflow at almost four-fifths of the study reservoirs. Hedging conditioned on seasonal hydrologic forecasts may permit reservoirs to adapt to changing future inflows (Adeloye & Soundharajan, 2019; Chang et al., 2019; Shih & ReVelle, 1994; Steinschneider & Brown, 2012).

4.2 | Possible future increases in system vulnerability

This analysis reveals that multi-decade decreases in reservoir inflows are associated with increased vulnerability (i.e., larger departures from flow targets during the dry, or low-flow, part of the year), as predicted by many studies (e.g., Minville, Brissette, Krau, & Leconte, 2009). In May to October during years with below-average inflows, departures from flow targets were larger (more negative), even when flow targets were met for most or all of the time. In other words, even when reliability was high, vulnerability was greatest during years with low inflows. Despite long-term adjustments of reservoir management, both inflows and outflows have decreased throughout the CRB during the dry (low-flow) half of the year (May to October). May to October inflows have declined more rapidly, and are now less than outflows. In other words, the increased use of hedging has not completely offset the decreases in inflows, and the declining inflows have increased system vulnerability – the magnitude of departures from flow targets.

Future vulnerability of CRB reservoirs likely will depend on reservoir storage capacity, management objectives, and the changing ratio of inflows to outflows (Chang et al., 2013; Patterson & Doyle, 2018). Increased vulnerability may primarily affect reservoirs managed using storage and release to meet multiple objectives, including flood control, hydropower, recreation, irrigation, and water supply. Despite declining late summer inflows, hedging did not increase at reservoirs managed solely for hydropower ("run of the river" reservoirs) (i.e., Pelton, Warm Springs, and Trail Bridge, pairs 17, 18, 22, Figure 4 q,r,v, Tables 2 and 5), countering predictions that hydropower would be affected (Payne et al., 2004). Diversified water sources have enabled some reservoirs managed solely for water supply to meet increased water demand despite declining inflows during the low-flow period (i.e., Bull Run1 and Bull Run2, the municipal water supply for the City of Portland, Oregon, pairs 19 and 20, Figure 4s,t, Tables 2 and 5). For example, the City of Portland has increased groundwater use for summer water supply, a "real-option risk hedging" strategy to diversify water sources during drought (Steinschneider & Brown, 2012).

System vulnerability also may be increased by new objectives, particularly environmental flow requirements for fish (Hand et al., 2018; Payne et al., 2004). In the early 2000s, the US Fish and Wildlife Service, NOAA Fisheries, and the Columbia River Inter-Tribal Fish Commission requested supplemental operations to augment flows to enhance fish passage to meet requirements of US Endangered Species Act Biological Opinions (Columbia River Basin Technical Management Team, 2018; Federal Caucus, 2016). Over the period 1950 to 2012, July to September releases increased (i.e., hedging decreased, counter to the basin-wide trend) at Dworshak (pair 9, Figure 4i) to aid salmon smolt survival during migration to the ocean. In another example, low-flow releases declined at Cougar and increased at neighbouring Blue River (pairs 23 and 24, Figure 4w,x), while a temperature tower was being constructed to enable timing of releases to assist chinook migration and reproduction. These examples indicate that environmental flow requirements may limit system capacity to increase hedging as a strategy to adapt to declining inflows.

Several long-term trends likely will continue to reduce inflows to reservoirs during the low-flow period in the CRB. The shift to earlier snowmelt runoff in snowmelt-dominated basins in the CRB observed in this study is consistent with studies of climate warming effects (e.g., Regonda, Rajagopalan, Clark, & Pitlick, 2005; Stewart, Cayan, & Dettinger, 2005). Low flows also declined in rain-dominated basins, implying that other components of the hydrologic cycle also may be changing. For example, although no significant trends in precipitation were detected in this study, precipitation is changing in response to changing climate (Allan et al., 2020). Warming air temperature may have increased evaporation and snowmelt (Schnorbus, Werner, & Bennett, 2014). In addition, forest management in the latter half of the 20th century increased forest density in the rain- and snow-dominated portions of the CRB (Hessburg, Smith, Salter, Ottmar, & Alvarado, 2000; Johnson & Swanson, 2012; Sachs, Sollins, & Cohen, 1998). Young, dense forests use more water during the dry summer period compared to mature or old-growth forest (Jones &

Post, 2004). A growing body of work indicates that increased intensive forest management in the CRB may have contributed to long-term reductions in low flows (Gronsdahl, Moore, Rosenfeld, McCleary, & Winkler, 2019; T. D. Perry & Jones, 2017; Segura et al., 2020). Insect outbreaks and low-severity wildfire may not produce increases in streamflow that could otherwise mitigate declining trends (Goeking & Tarboton, 2020; Hallema et al., 2018). Further work is needed to investigate how vegetation change and forest management, as well as climate change, affect inflows to reservoirs.

Demand for water also appears unlikely to decline in the CRB. There is little incentive for water conservation or other forms of adaptive behaviour, because the gradual shift in reservoir operations over the period 1950 to 2012 throughout the CRB has obscured emerging water scarcity for downstream water users. Although irrigation has greatly depleted groundwater in some areas of the CRB, there is relatively little adoption of water-saving approaches in agriculture (Perry & Praskievicz, 2017; Richter et al., 2017). Moreover, although municipal water users agree that long-term drought, population growth, and outdoor water use are the most important stressors to urban water systems, there are few incentives for urban water conservation in the CRB (Shandas, Lehman, Larson, Bunn, & Chang, 2015).

5 | CONCLUSIONS

Around the world, long-term changes in the timing and magnitude of streamflow are testing the ability of large managed water resource systems constructed in the 20th century to continue to meet objectives in the 21st century. We demonstrate that where long-term streamflow records exist for unregulated rivers upstream of reservoirs, they can be combined with records downstream of reservoirs using a paired-watershed framework to assess how intra-annual timing of reservoir inflows and outflows has changed over multiple decades, how reservoir management has responded to these long-term changes, and how measures of performance of water resource systems, such as reliability and vulnerability, have responded to changes in reservoir inflows.

In the intensively managed, 668,000 km^2 Columbia River Basin, our analysis of long-term streamflow records reveals that since 1950, the intra-annual timing of inflows and outflows has changed at 25 major reservoirs in the Columbia River Basin water system. Moreover, in response to multi-decade declines in reservoir inflows, reservoir managers have increased hedging in the spring and early summer in order to meet a widening gap between reservoir inflows and water demand in the low-flow period. However, the increased use of hedging has not completely offset multi-decade decreases in inflows. The magnitude of departures from flow targets (vulnerability) is larger during periods when flows are below normal over the prior 6 months. In summary, increased hedging in the spring increases vulnerability because it reduces capacity to meet flood control targets, while multi-decade declines in inflows increase vulnerability because despite increased hedging, reservoir storage, especially in dry years, is inadequate to meet recreation, water supply, irrigation, and hydropower objectives during the summer low flow period.

Results from analyses of historical, publicly available data, such as those presented here, emphasize the need to maintain long-term records at unregulated gages upstream of reservoirs, as well as downstream of reservoirs. This study demonstrates the value of combining publicly available historical data on reservoir inflows and outflows with concepts from paired watershed analyses and metrics of water resource performance to detect, evaluate, and manage water resource systems in large river basins.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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REFERENCES

Adeloye, A. J., & Soundharajan, B. S. (2019). Effect of dynamically varying zone-based hedging policies on the operational performance of surface water reservoirs during climate change. *Geological Society, London, Special Publications*, *488*(1), 277–289.

Alborzi, A., Mirchi, A., Moftakhari, H., Mallakpour, I., Alian, S., Nazemi, A., … Norouzi, H. (2018). Climate-informed environmental inflows to revive a drying lake facing meteorological and anthropogenic droughts. *Environmental Research Letters*, *13*(8), 084010.

Allan, R., Barlow, M., Byrne, M. P., Cherchi, A., Douville, H., Fowler, H. J., … Zolina, O. (2020). Advances in understanding large-scale responses of the water cycle to climate change. *Annals of the New York Academy of Sciences*, *1472*(1), 49–75.

Bronaugh, D., & Werner, A. (2013). *Relative importance of regressors in linear models*, R Package Version 0.10-1.

Cayan, D. R., Kammerdiener, S. A., Dettinger, M. D., Caprio, J. M., & Peterson, D. H. (2001). Changes in the onset of spring in the western United States. *Bulletin of the American Meteorological Society*, *82*(3), 399–416.

Chang, H., Jung, I. W., Strecker, A., Wise, D., Lafrenz, M., Shandas, V., … Johnson, G. (2013). Water supply, demand, and quality indicators for assessing the spatial distribution of water resource vulnerability in the Columbia River basin. *Atmosphere-Ocean*, *51*(4), 339–356.

Chang, J., Guo, A., Wang, Y., Ha, Y., Zhang, R., Xue, L., & Tu, Z. (2019). Reservoir operations to mitigate drought effects with a hedging policy triggered by the drought prevention limiting water level. *Water Resources Research*, *55*(2), 904–922.

Columbia River Basin Technical Management Team. (2018). Retrieved from http://pweb.crohms.org/tmt/

Cosens, B., Gunderson, L., & Chaffin, B. (2014). The adaptive water governance project: Assessing law, resiliance and governance in regional socio-ecological water systems facing a changing climate. *Idaho Law Review*, *51*, 1.

Cosens, B. A., & Williams, M. K. (2012). Resilience and water governance: Adaptive governance in the Columbia River basin. *Ecology and Society*, *17*(4), 3. http://dx.doi.org/10.5751/ES-04986-170403

Déry, S. J., Stahl, K., Moore, R. D., Whitfield, P. H., Menounos, B., & Burford, J. E. (2009). Detection of runoff timing changes in pluvial, nival, and glacial rivers of western Canada. *Water Resources Research*, *45*(4).W04426.

Dettinger, M., Udall, B., & Georgakakos, A. (2015). Western water and climate change. *Ecological Applications*, *25*(8), 2069–2093.

Doyle, M. W. (2012). America's rivers and the American experiment. *JAWRA Journal of the American Water Resources Association*, *48*(4), 820–837.

Doyle, M. W., Lave, R., Robertson, M. M., & Ferguson, J. (2013). River federalism. *Annals of the Association of American Geographers*, *103*(2), 290–298.

Elsner, M. M., Cuo, L., Voisin, N., Deems, J. S., Hamlet, A. F., Vano, J. A., … Lettenmaier, D. P. (2010). Implications of 21st century climate change for the hydrology of Washington State. *Climatic Change*, *102*(1-2), 225–260.

Falcone, J. A. (2011). *GAGES-II: Geospatial attributes of gages for evaluating streamflow*. Reston, VA: US Geological Survey. Retrieved from https://water.usgs.gov/lookup/getspatial?gagesII_Sept2011

Federal Caucus. (2016). *Biological opinions*. Retrieved from https://www.salmonrecovery.gov/BiologicalOpinions.aspx

Goeking, S. A., & Tarboton, D. G. (2020). Forests and water yield: A synthesis of disturbance effects on streamflow and snowpack in western coniferous forests. *Journal of Forestry*, *118*(2), 172–192.

Gronsdahl, S., Moore, R. D., Rosenfeld, J., McCleary, R., & Winkler, R. (2019). Effects of forestry on summertime low flows and physical fish habitat in snowmelt-dominant headwater catchments of the Pacific Northwest. *Hydrological Processes*, *33*(25), 3152–3168.

Hallema, D. W., Sun, G., Caldwell, P. V., Norman, S. P., Cohen, E. C., Liu, Y., … McNulty, S. G. (2018). Burned forests impact water supplies. *Nature Communications*, *9*(1), 1–8.

Hamlet, A. F. (2011). Assessing water resources adaptive capacity to climate change impacts in the Pacific Northwest Region of North America. *Hydrology and Earth System Sciences*, *15*(5), 1427–1443.

Hamlet, A. F., Elsner, M. M., Mauger, G. S., Lee, S. Y., Tohver, I., & Norheim, R. A. (2013). An overview of the Columbia Basin Climate Change Scenarios Project: Approach, methods, and summary of key results. *Atmosphere-Ocean*, *51*(4), 392–415.

Hammond, J. C. (2014). *Trends in streamflow above and below dams across the Columbia River basin from 1950 to 2012: Assessing sub-basin sensitivity*. (MS thesis). Oregon State University.

Hand, B. K., Flint, C. G., Frissell, C. A., Muhlfeld, C. C., Devlin, S. P., Kennedy, B. P., … Stanford, J. A. (2018). A social–ecological perspective for riverscape management in the Columbia River Basin. *Frontiers in Ecology and the Environment*, *16*(S1), S23–S33.

Hashimoto, T., Stedinger, J. R., & Loucks, D. P. (1982). Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resources Research*, *18*(1), 14–20.

Hatcher, K. L., & Jones, J. A. (2013). Climate and streamflow trends in the Columbia River Basin: Evidence for ecological and engineering resilience to climate change. *Atmosphere-Ocean*, *51*(4), 436–455.

Helsel, D. R., & Hirsch, R. M. (2002). *Statistical methods in water resources techniques of water resources investigations 04-A3* (522 pp.). Reston, VA: U.S. Geological Survey.

Hessburg, P. F., Smith, B. G., Salter, R. B., Ottmar, R. D., & Alvarado, E. (2000). Recent changes (1930s–1990s) in spatial patterns of interior northwest forests, USA. *Forest Ecology and Management*, *136*(1–3), 53–83.

Hirsch, R. M., & Fisher, G. T. (2014). Past, present, and future of water data delivery from the US Geological Survey. *Journal of Contemporary Water Research & Education*, *153*(1), 4–15.

Johnson, K. N., & Swanson, F. J. (2012). Historical context of oldgrowth forests in the Pacific Northwest–policy, practices, and competing worldviews. In T. A. Spies & S. L. Duncan (eds.), *Old growth in a new world: A Pacific Northwest icon reexamined* (pp. 12–28). Washington, DC: Island Press.

Jones, J. A., & Grant, G. E. (1996). Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon. *Water Resources Research*, *32*(4), 959–974.

Jones, J. A., & Post, D. A. (2004). Seasonal and successional streamflow response to forest cutting and regrowth in the northwest and eastern United States. *Water Resources Research*, *40*(5), W05203.

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., … Nilsson, C. (2011). High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment*, *9*(9), 494–502.

McLeod, A. I. (2011). *Kendall: Kendall correlation and trend tests*. R package version 2.2.0.

Milly, P. C., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity is dead: Whither water management? *Science*, *319*(5863), 573–574.

Minville, M., Brissette, F., Krau, S., & Leconte, R. (2009). Adaptation to climate change in the management of a Canadian water-resources system exploited for hydropower. *Water Resources Management*, *23*(14), 2965–2986.

Moy, W. S., Cohon, J. L., & ReVelle, C. S. (1986). A programming model for analysis of the reliability, resilience, and vulnerability of a water supply reservoir. *Water Resources Research*, *22*(4), 489–498.

Pahl-Wostl, C. (2007). Transitions towards adaptive management of water facing climate and global change. *Water Resources Management*, *21*(1), 49–62.

Palmer, M. A., Reidy Liermann, C. A., Nilsson, C., Flörke, M., Alcamo, J., Lake, P. S., & Bond, N. (2008). Climate change and the world's river basins: Anticipating management options. *Frontiers in Ecology and the Environment*, *6*(2), 81–89.

Patterson, L. A., & Doyle, M. W. (2018). A nationwide analysis of US Army Corps of Engineers reservoir performance in meeting operational targets. *JAWRA Journal of the American Water Resources Association*, *54*(2), 543–564.

Payne, J. T., Wood, A. W., Hamlet, A. F., Palmer, R. N., & Lettenmaier, D. P. (2004). Mitigating the effects of climate change on the water resources of the Columbia River basin. *Climatic Change*, *62*(1–3), 233–256.

Perry, D. M., & Praskievicz, S. J. (2017). A new era of big infrastructure? (Re) developing water storage in the US west in the context of climate change and environmental regulation. *Water Alternatives*, *10*(2), 437–454.

Perry, T. D., & Jones, J. A. (2017). Summer streamflow deficits from regenerating Douglas-fir forest in the Pacific Northwest, USA. *Ecohydrology*, *10*(2), e1790.

Regonda, S. K., Rajagopalan, B., Clark, M., & Pitlick, J. (2005). Seasonal cycle shifts in hydroclimatology over the western United States. *Journal of Climate*, *18*(2), 372–384.

Richter, B. D., Brown, J. D., DiBenedetto, R., Gorsky, A., Keenan, E., Madray, C., … Ryu, S. (2017). Opportunities for saving and reallocating agricultural water to alleviate water scarcity. *Water Policy*, *19*(5), 886–907.

Sachs, D. L., Sollins, P., & Cohen, W. B. (1998). Detecting landscape changes in the interior of British Columbia from 1975 to 1992 using satellite imagery. *Canadian Journal of Forest Research*, *28*(1), 23–36.

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N. W., Clark, D. B., … Gosling, S. N. (2014). Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(9), 3245–3250.

Schnorbus, M., Werner, A., & Bennett, K. (2014). Impacts of climate change in three hydrologic regimes in British Columbia, Canada. *Hydrological Processes*, *28*(3), 1170–1189.

Segura, C., Bladon, K. D., Hatten, J. A., Jones, J. A., Hale, V. C., & Ice, G. G. (2020). Long-term effects of forest harvesting on summer low flow deficits in the Coast Range of Oregon. *Journal of Hydrology*, *565*, 124749.

Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, *63*(324), 1379–1389.

Shandas, V., Lehman, R., Larson, K. L., Bunn, J., & Chang, H. (2015). Stressors and strategies for managing urban water scarcity: Perspectives from the field. *Water*, *7*(12), 6775–6787.

Shih, J. S., & ReVelle, C. (1994). Water-supply operations during drought: Continuous hedging rule. *Journal of Water Resources Planning and Management*, *120*(5), 613–629.

Srinivasan, V., Lambin, E. F., Gorelick, S. M., Thompson, B. H., & Rozelle, S. (2012). The nature and causes of the global water crisis: Syndromes from a meta-analysis of coupled human-water studies. *Water Resources Research*, *48*(10), W10516.

Steinschneider, S., & Brown, C. (2012). Dynamic reservoir management with real-option risk hedging as a robust adaptation to nonstationary climate. *Water Resources Research*, *48*(5), W05524.

Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2005). Changes toward earlier streamflow timing across western North America. *Journal of Climate*, *18*(8), 1136–1155.

Theil, H. (1950). A rank-invariant method of linear and polynomial regression analysis. *Mathematica*, *53*, 386–392.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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