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New water accounting reveals why the Colorado River no longer reaches the sea

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Persistent overuse of water supplies from the Colorado River during recent decades has substantially depleted large storage reservoirs and triggered mandatory cutbacks in water use. The river holds critical importance to more than 40 million people and more than two million hectares of cropland. Therefore, a full accounting of where the river's water goes en route to its delta is necessary. Detailed knowledge of how and where the river's water is used can aid design of strategies and plans for bringing water use into balance with available supplies. Here we apply authoritative primary data sources and modeled crop and riparian/wetland evapotranspiration estimates to compile a water budget based on average consumptive water use during 2000–2019. Overall water consumption includes both direct human uses in the municipal, commercial, industrial, and agricultural sectors, as well as indirect water losses to reservoir evaporation and water consumed through riparian/wetland evapotranspiration. Irrigated agriculture is responsible for 74% of direct human uses and 52% of overall water consumption. Water consumed for agriculture amounts to three times all other direct uses combined. Cattle feed crops including alfalfa and other grass hays account for 46% of all direct water consumption.

Barely a trickle of water is left of the iconic Colorado River of the American Southwest as it approaches its outlet in the Gulf of California in Mexico after watering many cities and farms along its 2330-kilometer course. There were a few years in the 1980s in which enormous snowfall in the Rocky Mountains produced a deluge of spring snowmelt runoff capable of escaping full capture for human uses, but for most of the past 60 years the river's water has been fully consumed before reaching its delta[1,2]. In fact, the river was overconsumed (i.e., total annual water consumption exceeding runoff supplies) in 16 of 21 years during 2000–2020[3], requiring large withdrawals of water stored in Lake Mead and Lake Powell to accommodate the deficits. An average annual overdraft of 10% during this period[2] caused these reservoirs– the two largest in the US – to drop to three-quarters empty by the end of 2022[4], triggering urgent policy decisions on where to cut consumption.

Despite the river's importance to more than 40 million people and more than two million hectares (>5 million acres) of cropland—producing most of the vegetable produce for American and Canadian plates in wintertime and also feeding many additional people worldwide via exports—a full sectoral and crop-specific accounting of where all that water goes en route to its delta has never been attempted, until now. Detailed knowledge of how and where the river's water is used can aid design of strategies and plans for bringing water use into balance with available supplies.

There are interesting historical reasons to explain why this full water budget accounting has not been accomplished previously, beginning a full century ago when the apportionment of rights to use the river's water within the United States was inscribed into the Colorado River Compact of 1922[5]. That Compact was ambiguous and confusing in its allocation of water inflowing to the Colorado River from the Gila River basin in New Mexico and Arizona[6], even though it accounts for 24% of the drainage area of the Colorado River Basin (Fig. 1). Because of intense disagreements over the rights to the Gila and other tributaries entering the Colorado River

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Fig. 1 | Map of the Colorado River Basin (CRB). The physical boundary of the Colorado River Basin is outlined in black. Hatched areas outside of the basin boundary receive Colorado River water via inter-basin transfers (also known as 'exports'). The Gila River basin is situated in the far southern portion of the CRB in Arizona, New Mexico, and Mexico. Map courtesy of Center for Colorado River Studies, Utah State University.

downstream of the Grand Canyon, the Compact negotiators decided to leave the allocation of those waters rights to a later time so that the Compact could proceed[6]. Arizona's formal rights to the Gila and other Arizona tributaries were finally affirmed in a US Supreme Court decision in 1963 that also specified the volumes of Colorado River water allocated to California, Arizona, and Nevada[7]. Because the rights to the Gila's waters lie outside of the Compact allocations, the Gila has not been included in formal accounting of the Colorado River Basin water budget to date[8]. Additionally, the Compact did not specify how much water Mexico—at the river's downstream end—should receive. Mexico's share of the river was not formalized until 22 years later, in the 1944 international treaty on "Utilization of the Waters of the Colorado and Tijuana Rivers and of the Rio Grande" (1944 Water Treaty)[9]. As a result of these political circumstances, full accounting for direct water consumption at the sectoral level—in which water use is accounted according to categories such as municipal, industrial, commercial, or agricultural uses—has not previously been compiled for the Gila River basin's water, and sectoral accounting for Mexico was not published until 2023[10].

The US Bureau of Reclamation ("Reclamation")—which owns and operates massive water infrastructure in the Colorado River Basin—has served as the primary accountant of Colorado River water. In 2012, the agency produced a "Colorado River Basin Water Supply and Demand

Study"[8] that accounted for both the sectoral uses of water within the basin's physical boundaries within the US as well as river water exported outside of the basin (Fig. 1). But Reclamation did not attempt to account for water generated from the Gila River basin because of that sub-basin's exclusion from the Colorado River Compact, and it did not attempt to explain how water crossing the border into Mexico is used. The agency estimated riparian vegetation evapotranspiration for the lower Colorado River but not the remainder of the extensive river system. Richter et al.[11] published a water budget for the Colorado River that included sectoral and crop-specific water consumption but it too did not include water used in Mexico, nor reservoir evaporation or riparian evapotranspiration, and it did not account for water exported outside of the Colorado River Basin's physical boundary as illustrated in Fig. 1. Given that nearly one-fifth (19%) of the river's water is exported from the basin or used in Mexico, and that the Gila is a major tributary to the Colorado, this incomplete accounting has led to inaccuracies and misinterpretations of "where the Colorado River's water goes" and has created uncertainty in discussions based on the numbers. This paper provides fuller accounting of the fate of all river water during 2000–2019, including averaged annual consumption in each of the sub-basins including exports, consumption in major sectors of the economy, consumption in the production of specific types of crops, and water consumed by reservoir evaporation and riparian/wetland evapotranspiration.

Rising awareness of water overuse and prolonged drought has driven intensifying dialog among the seven US states sharing the basin's waters as well as between the United States, Mexico, and 30 tribal nations within the US. Since 2000, six legal agreements affecting the US states and two international agreements with Mexico have had the effect of reducing water use from the Colorado River[7]:

- In 2001, the US Secretary of the Interior issued a set of "Interim Surplus Guidelines" to reduce California's water use by 14% to bring the state within its allocation as determined in the 1963 US Supreme Court case mentioned previously. A subsequent "Quantification Settlement Agreement" executed in 2003 spelled out details about how California was going to achieve the targeted reduction.
- In 2007, the US Secretary of the Interior adopted a set of "Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead" that reduced water deliveries to Arizona and Nevada when Lake Mead drops to specified levels, with increasing cutbacks as levels decline.
- In 2012, the US and Mexican federal governments signed an addendum to the 1944 Water Treaty known as Minute 319 that reduced deliveries to Mexico as Lake Mead elevations fall.
- In 2017, the US and Mexican federal governments established a "Binational Water Scarcity Contingency Plan" as part of Minute 323 that provides for deeper cuts in deliveries to Mexico under specified low reservoir elevations in Lake Mead.i
- In 2019, the three Lower Basin states and the US Secretary of the Interior agreed to commitments under the "Lower Basin Drought Contingency Plan" that further reduced water deliveries beyond the levels set in 2007 and added specifications for deeper cuts as Lake Mead drops to levels lower than anticipated in the 2007 Guidelines.
- In 2023, the states of California, Arizona and Nevada committed to further reductions in water use through the year 2026[12].

With each of the above agreements, overall water consumption has been reduced but many scientists assert that these reductions still fall substantially short of balancing consumptive use with 21st century water supplies[2,13]. With all of these agreements—excepting the Interim Surplus Guidelines of 2001—set to expire in 2026, management of the Colorado River's binational water supply is now at a crucial point, emphasizing the need for comprehensive water budget accounting.

Results

Our tabulation of the Colorado River's full water consumption budget (Table 1) provides accounting for all *direct* human uses of water as either agricultural or MCI (municipal, commercial, industrial), as well as *indirect* losses of water to reservoir evaporation and evapotranspiration from riparian or wetland vegetation including in the Salton Sea and in a wetland in Mexico (Cienega de Santa Clara) that receives agricultural return flows from irrigated areas in Arizona. We explicitly note that all estimates represent *consumptive use*, resulting from the subtraction of return flows from total water withdrawals. Table 2 provides a summary based only on direct human uses and does not include indirect consumption of water. We have provided Tables 1 and 2 in English units in our Supplementary Information as Tables SI-1 and SI-2. We have lumped municipal, commercial, and industrial (MCI) uses together because these sub-categories of consumption are not consistently differentiated within official water delivery data for cities utilizing Colorado River water. More detail on urban water use by cities dependent on the river is available in Richter[14], among other studies.

We differentiated water consumption geographically using the 'accounting units' mapped in Fig. 2, which are based on the Colorado River Basin map as revised by Schmidt[15]; importantly, these accounting units align spatially with Reclamation's accounting systems for the Upper Basin and Lower Basin as described in our Methods, thereby enabling readers accustomed to Reclamation's water-use reports to easily comprehend our accounting. We have also accounted for all water consumed within the Colorado River Basin boundaries as well as water exported via inter-basin transfers. Water exported outside of the basin includes 47 individual inter-basin transfer systems (i.e., canals, pipelines, pumps) that in aggregate export ~12% of the river's water. We note that the Imperial Irrigation District of southern California is often counted as a recipient of exported water, but we have followed the rationale of Schmidt[15] by including it as an interior part of the Lower Basin even though it receives its Colorado River water via the All American Canal (Fig. 2).

These results confirm previous findings that irrigated agriculture is the dominant consumer of Colorado River water. Irrigated agriculture accounts for 52% of overall consumption (Table 1; Figs. 3 and 4) and 74% of direct human consumption (Table 2) of water from the Colorado River Basin. As highlighted in Richter et al. [11], cattle-feed crops (alfalfa and other hay) are the dominant water-consuming crops dependent upon irrigation water from the basin (Tables 1 and 2; Figs. 3 and 4). Those crops account for 32% of all water consumed from the basin, 46% of all direct water consumption, and 62% of all agricultural water consumed (Table 1; Fig. 3). The percentage of water consumed by irrigated crops is greatest in Mexico, where they account for 86% of all direct human uses (Table 2) and 80% of total water consumed (Table 1). Cattle-feed crops consume 90% of all water used by irrigated agriculture within the Upper Basin, where the consumed volume associated with these cattle-feed crops amounts to more than three times what is consumed for municipal, commercial, or industrial uses combined.

Another important finding is that a substantial volume of water (19%) is consumed in supporting the natural environment through riparian and wetland vegetation evapotranspiration along river courses. This analysis—made possible because of recent mapping of riparian vegetation in the Colorado River Basin[16]—is an important addition to the water budget of the Colorado River Basin, given that the only previous accounting for riparian vegetation consumption has limited to the mainstem of the Colorado River below Hoover Dam and does not include vegetation upstream of Hoover Dam nor vegetation along tributary rivers[17]. Given that many of these habitats and associated species have been lost or became imperiled due to river flow depletion[18]—including the river's vast delta ecosystem in Mexico—an ecologically sustainable approach to water management would need to allow more water to remain in the river system to support riparian and aquatic ecosystems. Additionally, 11% of all water consumed in the Colorado River Basin is lost through evaporation from reservoirs.

It is also important to note a fairly high degree of inter-annual variability in each sector of water use; for example, the range of values portrayed for the four water budget sectors shown in Fig. 5 equates to 24–47% of their 20-year averages. Also notable is a decrease in water consumed in the Lower

Table 1 | Water consumption by all water uses

	UPPER BASIN		EXPORTS - UPPER BASIN		TOTAL UPPER BASIN		LOWER BASIN (w/o GILA)		EXPORTS - LOWER BASIN		TOTAL LOWER BASIN		GILA BASIN		MEXICO		MEXICO - EXPORTS		TOTAL MEXICO		TOTAL COLORADO RIVER	
	Water consumed	% of total unit	Water consumed	% of total unit	Water consumed	% of total unit	Water consumed	% of total unit	Water consumed	% of total unit	Water consumed	% of total unit	Water consumed	% of total unit	Water consumed	% of total unit	Water consumed	% of total unit	Water consumed	% of total unit	Water consumed	% of total consumption
Municipal, Commercial & Industrial	317.18	5%	657.30	71%	974.49	13%	1407.70	13%	1214.00	78%	2621.70	21%	522.52	24%			252.28	100%	252	13%	4371	18%
Irrigated agriculture	3246.29	50%	266.67	29%	3512.96	48%	6265.52	59%	344.55	22%	6610.06	54%	725.55	34%	1598.83	91%			1599	80%	12,447	52%
Alfalfa	2077.63	64%	136	51%	2213.63	30%	3195.41	51%	151.60	44%	3347.01	27%	391.80	54%	416	26%			416	21%	6368	27%
Other Hay	908.96	28%	24	9%	932.96	13%	501.24	8%	41.35	12%	542.59	4%	21.77	3%	16	1%			16	1%	1513	6%
Almonds									0.03	0.01%	0.03	0.0003%									0.1	0.0003%
Barley			3	1%	2.67	0.04%							21.77	3%							24	0.1%
Corn	129.85	4%	75	28%	204.52	3%	12.53	0.2%	1.03	0.3%	13.56	0.1%	21.77	3%							240	1%
Cotton							250.62	4%	1.03	0.3%	251.65	2%	181.39	25%	288	18%			288	14%	721	3%
Dry Beans	32.46	1%	3	1%	35.13	0.5%							1.45	0.2%							37	0.2%
Grapes									2.27	1%											2	0.01%
Oats	32.46	1%	1	0.3%	33.26	0.5%	12.53	0.2%	0.69	0.2%	13.22	0.1%	7.26	1%							54	0.2%
Oranges							56.39	0.9%	3.45	1%	59.84	0.5%	0.73	0.1%							61	0.3%
Pecans													14.51	2%							15	0.1%
Potatoes							6.27	0.1%	0.34	0.1%	6.61	0.1%	0.73	0.1%							7	0.03%
Sorghum			1	0.3%	0.80	0.0001							7.26	1%	64	4%			64	3%	72	0.3%
Sugarbeets			11	4%	10.67	0.001	125.31	2%	13.78	4%	139.09	1%									150	1%
Sweet Corn							18.80	0.3%	1.03	0.3%	19.83	0.2%									20	0.1%
Wheat (durum, spring, winter)	64.93	2%	11	4%	75.59	1.0%	375.93	6%	20.67	6%	396.60	3%	58.04	8%	799	50%			799	40%	1330	6%
Other							1503.72	24%	89.58	26%	1593.31	13%			32	2%			32	2%	1625	6.8%
Reservoir Evaporation	1139.67	18%			1139.67	15%	1234.65	12%			1234.65	10%	154.19	7%							2529	11%
Lake Powell	764.14	12%			764.14	10%															764	3%
Lake Mead							728.68	7%			728.68	6%									729	3%
Riparian & Wetland ET	1757.32	27%			1757.32	24%	1752.74	16%			1752.74	14%	742.52	35%	149.51	9%			150	7%	4402	19%
GRAND TOTALS	**6460.47**		**923.97**		**7384.44**		**10,660.60**		**1558.54**		**12,219.15**		**2144.78**		**1748**		**252**		**2001**		**23,749**	
PERCENTAGE	**27%**		**4%**		**31%**		**45%**		**7%**		**51%**		**9%**		**7%**		**1%**		**8%**		**100%**	

Water budget accounting for Colorado River including all direct human uses as well as indirect losses to reservoir evaporation and riparian and wetland evapotranspiration. All estimates based on 2000–2019 averages unless otherwise noted in Methods section. All units in million cubic meters per year.

Table 2 | Water consumption for direct human uses

	UPPER BASIN		EXPORTS - UPPER BASIN		TOTAL UPPER BASIN		LOWER BASIN (w/o GILA)		EXPORTS - LOWER BASIN		TOTAL LOWER BASIN		GILA BASIN		MEXICO		MEXICO - EXPORTS		TOTAL MEXICO		TOTAL COLORADO RIVER	
	Water consumed	% of total unit	Water consumed	% of total unit	Water consumed	% of total unit	Water consumed	% of total unit	Water consumed	% of total unit	Water consumed	% of total unit	Water consumed	% of total unit	Water consumed	% of total unit	Water consumed	% of total unit	Water consumed	% of total unit	Water consumed	% of direct human consumption
Municipal, Commercial & Industrial	317.18	9%	657.30	71%	974.49	22%	1407.70	18%	1214.00	78%	2621.70	28%	522.52	42%		0%	252.28	100%	252.28	14%	4118.71	25%
Irrigated agriculture	3246.29	91%	266.67	29%	3512.96	78%	6265.52	82%	344.55	22%	6610.06	72%	725.55	58%	1598.83	100%			1598.83	86%	12,447.41	75%
Alfalfa	2077.63	64%	136.00	51%	2213.63	49%	3195.41	51%	151.60	44%	3347.01	36%	391.80	54%	415.70	26%			415.70	22%	6368.13	38%
Other Hay	908.96	28%	24.00	9%	932.96	21%	501.24	8%	41.35	12%	542.59	6%	21.77	3%	15.99	1%			15.99	1%	1513.30	9%
Almonds									0.34	0.1%	0.34	0%									0.34	0.002%
Barley			2.67	1%	2.67	0.1%	-						21.77	3%							24.43	0.1%
Corn	129.85	4%	74.67	28%	204.52	5%	12.53	0.2%	1.03	0.3%	13.56	0.1%	21.77	3%							239.85	1%
Cotton							250.62	4%	1.03	0.3%	251.65	3%	181.39	25%	287.79	18%			287.79	16%	720.83	4%
Dry Beans	32.46	1%	2.67	1%	35.13	1%	-						1.45	0.2%							36.58	0.2%
Grapes							125.31	2%	10.34	3%	135.65	1%									135.65	1%
Oats	32.46	1%	0.80	0.3%	33.26	1%	12.53	0.2%	0.69	0.2%	13.22	0.1%	7.26	1%							53.74	0.3%
Oranges							56.39	0.9%	3.45	1%	59.84	1%	0.73	0.1%							60.56	0.4%
Pecans													14.51	2%							14.51	0.1%
Potatoes							6.27	0.1%	0.34	0.1%	6.61	0.1%	0.73	0.1%							7.34	0.04%
Sorghum			0.80	0.3%									7.26	1%	63.95	4%			63.95	3%	71.21	0.4%
Sugarbeets			10.67	4%			125.31	2%	13.78	4%	139.09	2%									139.09	1%
Sweet Corn							18.80	0.3%	1.72	0.5%	20.52	0.2%									20.52	0.1%
Wheat (durum, spring, winter)	64.93	2%	10.67	4%	75.59	2%	375.93	6%	20.67	6%	396.60	4%	58.04	8%	799.42	50%			799.42	43%	1329.66	8%
Other crops & unaccounted							1503.72	24%	103.36	30%	1607.09	17%			31.98	2%			31.98	2%	1639.06	10%
GRAND TOTALS	**3563.48**		**923.97**		**4487.45**		**7673.22**		**1558.54**		**9231.76**		**1248.07**		**1,598.83**		**252.28**		**1,851.11**		**16,566.11**	
PERCENTAGE	**22%**		**6%**		**27%**		**46%**		**9%**		**56%**		**8%**		**10%**		**2%**		**11%**		**100%**	

Water budget accounting for Colorado River including only direct human uses for municipal, commercial, industrial, and agricultural uses. All estimates based on 2000–2019 averages unless otherwise noted in Methods section. All units in million cubic meters per year.

Fig. 2 | Spatial delineation of accounting units. The water budget estimates presented in Tables 1 and 2 are summarized for each of the seven "accounting units" displayed here.

Basin between the years 2000 and 2019 for both the MCI (−38%) and agricultural sectors (−15%), which can in part be attributed to the policy agreements summarized previously that have mandated water-use reductions.

Discussion

The water accounting in Richter et al.[11] received a great deal of media attention including a front-page story in the New York Times[19]. These stories focused primarily on our conclusion that more than half (53%) of water consumed in the Colorado River Basin was attributable to cattle-feed crops (alfalfa and other hays) supporting beef and dairy production. However, that tabulation of the river's water budget had notable shortcomings, as discussed previously. In this more complete accounting that includes Colorado River water exported outside of the basin's physical boundary as well as indirect water consumption, we find that irrigated agriculture consumes half (52%) of all Colorado River Basin water, and the portion of direct consumption going to cattle-feed crops dropped from 53% as reported in Richter et al.[11] to 46% in this revised analysis.

These differences are explained by the fact that we now account for all exported water and also include indirect losses of water to reservoir evaporation and riparian/wetland evapotranspiration in our revised accounting, as well as improvements in our estimation of crop-water consumption. However, the punch line of our 2020 paper does not change fundamentally. Irrigated agriculture is the dominant consumer of water from the Colorado

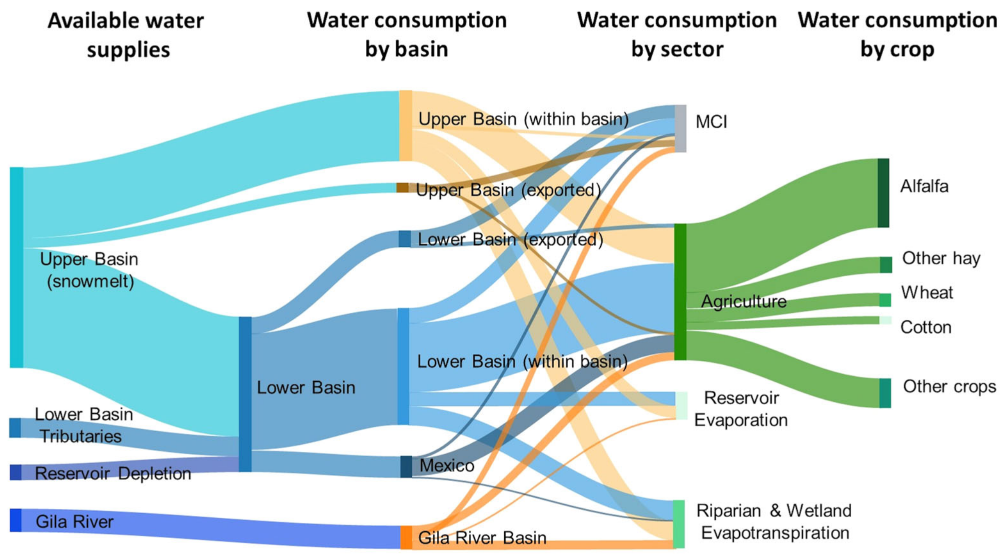

Fig. 3 | Summary of the Colorado River Basin's water supplies (left side) and all water consumed in each sub-basin, in each water-use sector, and by individual crops. All estimates based on 2000–2019 averages. Both agriculture and MCI (municipal, commercial, and industrial) uses are herein referred to as "direct human uses." "Indirect uses" include both reservoir evaporation as well as evapotranspiration by riparian/wetland vegetation.

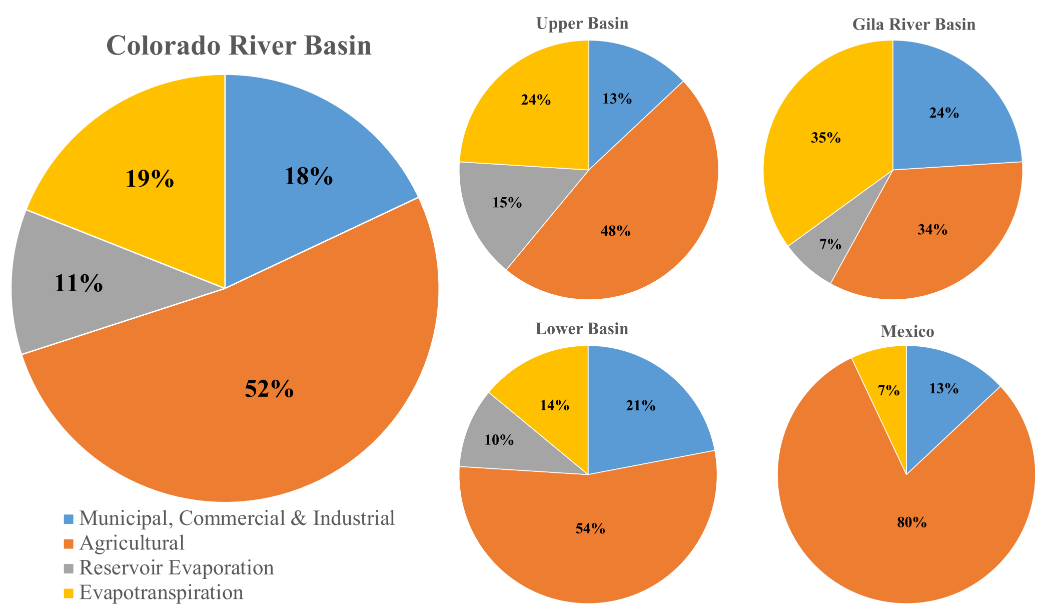

Fig. 4 | Consumptive use of Colorado River water. Water consumed by each sector in the Colorado River Basin and sub-basins (including exports), based on 2000–2019 averages.

River, and 62% of agricultural water consumption goes to alfalfa and grass hay production.

Richter et al.[20] found that alfalfa and grass hay were the largest water consumers in 57% of all sub-basins across the western US, and their production is increasing in many western regions. Alfalfa is favored for its ability to tolerate variable climate conditions, especially its ability to persist under greatly reduced irrigation during droughts and its ability to recover production quickly after full irrigation is resumed, acting as a "shock absorber" for agricultural production under unpredictable drought conditions. The plant is also valued for fixing nitrogen in soils, reducing fertilizer costs. Perhaps most importantly, labor costs are comparatively low because alfalfa is mechanically harvested. Alfalfa is increasing in demand and price as a feed crop in the growing dairy industry of the region[21]. Any efforts to reduce water consumed by alfalfa—either through shifting to alternative lower-water crops or through compensated fallowing[20]—will need to compete with these attributes.

This new accounting provides a more comprehensive and complete understanding of how the Colorado River Basin's water is consumed. During our study period of 2000–2019, an estimated average of 23.7 billion cubic meters (19.3 million acre-feet) of water was consumed each year before reaching its now-dry delta in Mexico. Schmidt et al.[2] have estimated that a reduction in consumptive use in the Upper and Lower Basins of 3–4 billion cubic meters (2.4–3.2 million acre-feet) per year—equivalent to 22–29% of direct use in those basins—will be necessary to stabilize reservoir levels, and an additional reduction of 1–3 billion cubic meters (~811,000–2.4 million acre-feet) per year will likely be needed by 2050 as climate warming continues to reduce runoff in the Colorado River Basin.

We hope that this new accounting will add clarity and a useful informational foundation to the public dialog and political negotiations over

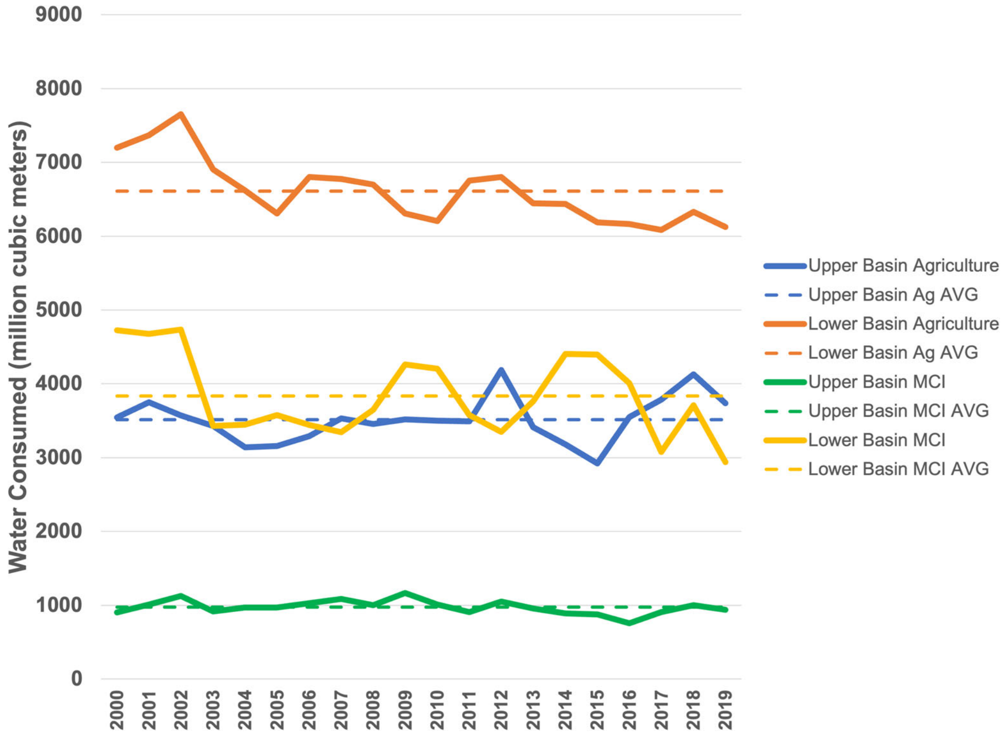

Fig. 5 | Temporal variability in water consumption. Inter-annual variability of water consumption within the Lower and Upper Basins, including water exported from these basins. The average (AVG) values shown are used in the water budgets detailed in Tables 1 and 2.

Colorado River Basin water allocations and cutbacks that are presently underway[2]. Because a persistent drought and intensifying aridification in the region has placed both people and river ecosystems in danger of water shortages in recent decades, knowledge of where the water goes will be essential in the design of policies for bringing the basin into a sustainable water supply-demand balance.

Methods

The data sources and analytical approaches used in this study are summarized below. Unless otherwise noted, all data were assembled for each year from 2000–2019 and then averaged. We acknowledge some inconsistency in the manner in which water consumption is measured or estimated across the various data sources and sectors used in this study, as discussed below, and each of these different approaches entail some degree of inaccuracy or uncertainty. We also note that technical measurement or estimation approaches change over time, and new approaches can yield differing results. For instance, the Upper Colorado River Commission is exploring new approaches for estimating crop evapotranspiration in the Upper Basin[22]. When new estimates become available we will update our water budget accordingly.

MCI and agricultural water consumption

The primary source of data on aggregate MCI (municipal, commercial, and industrial) and agricultural water consumption from the Upper and Lower Basins was the US Bureau of Reclamation. Water consumed from the Upper Basin is published in Reclamation's five-year reports entitled "Colorado River—Upper Basin Consumptive Uses and Losses."[23] These annual data have been compiled into a single spreadsheet used for this study[24]. Because measurements of agricultural diversions and return flows in the Upper Basin are not sufficiently complete to allow direct calculation of consumptive use, theoretical and indirect methods are used as described in the Consumptive Uses and Losses reports[25]. Reclamation performs these estimates for Colorado, Wyoming, and Utah, but the State of New Mexico provides its own estimates that are collaboratively reviewed with Reclamation staff. The consumptive use of water in thermoelectric power generation in the Upper Basin is provided to Reclamation by the power companies managing each generation facility. Reclamation derives estimates of consumptive use for municipal and industrial purposes from the US Geological Survey's reporting series (published every 5 years) titled "Estimated Use of Water in the United States" at an 8-digit watershed scale[26].

Use of shallow alluvial groundwater is included in the water accounting compiled by Reclamation but use of deeper groundwater sources—such as in Mexico and the Gila River Basin—is explicitly excluded in their accounting, and in ours. Reclamation staff involved with water accounting for the Upper and Lower Basins assume that groundwater use counted in their data reports is sourced from aquifers that are hydraulically connected to rivers and streams in the CRB (James Prairie, US Bureau of Reclamation, personal communication, 2023); because of this high connectivity, much of the groundwater being consumed is likely being sourced from river capture as discussed in Jasechko et al.[27] and Wiele et al.[28] and is soon recharged during higher river flows.

Water consumed from the Lower Basin (excluding water supplied by the Gila River Basin) is published in Reclamation's annual reports entitled "Colorado River Accounting and Water Use Report: Arizona, California, and Nevada."[3] These consumptive use data are based on measured deliveries and return flows for each individual water user. These data are either measured by Reclamation or provided to the agency by individual water users, tribes, states, and federal agencies[29]. When not explicitly stated in Reclamation reports, attribution of water volumes to MCI or agricultural uses was based on information obtained from each water user's website, information provided directly by the water user, or information on export water use provided in Siddik et al.[30]. Water use by entities using less than 1.23 million cubic meters (1000 acre-feet) per year on average was allocated to MCI and agricultural uses according to the overall MCI-agricultural percentages calculated within each sub-basin indicated in Tables 1 and 2 for users of greater than 1.23 million cubic meters/year.

Disaggregation of water consumption by sector was particularly important and challenging for the Central Arizona Project given that this canal accounts for 21% of all direct water consumption in the Lower Basin. Reclamation accounts for the volumes of annual diversions into the Central

Arizona Project canal but the structure serves 1071 water delivery subcontracts. We classified every unique Central Arizona Project subcontract delivery between 2000–2019 by its final water use to derive an estimated split between agricultural and MCI uses. Central Arizona Project subcontract delivery data were obtained from the current and archived versions of the project's website summaries in addition to being directly obtained from the agency through a public information request. Subcontract deliveries were classified based on the final end use, including long-term and temporary leases of project water. This accounting also includes the storage of water in groundwater basins for later MCI or agricultural use. Additionally, water allocated to Native American agricultural uses that was subsequently leased to cities was classified as an MCI use.

Data for the Gila River basin was obtained from two sources. The Arizona Department of Water Resources has published data for surface water use in five "Active Management Areas" (AMAs) located in the Gila River basin: Prescott AMA, Phoenix AMA, Pinal AMA, Tucson AMA, and Santa Cruz AMA[31]. The water-use data for these AMAs is compiled from annual reports submitted by each water user (contractor) and then reviewed by the Arizona Department of Water Resources. The AMA water-use data are categorized by purpose of use, facilitating our separation into MCI and agricultural uses. These data are additionally categorized by water source; only surface water sourced from the Gila River hydrologic system was counted (deep groundwater use was not). The AMA data were supplemented with data for the upper Gila River basin provided by the University of Arizona[32]. We have assumed that all water supplied by the Gila River Basin is fully consumed, as the river is almost always completely dry in its lower reaches (less than 1% flows out of the basin into the Colorado River, on average[33]).

Data for Mexico were obtained from Hernandez-Cruz et al.[10] based on estimates for 2008–2015. Agricultural demands were estimated from annual reports of irrigated area and water use published by the Ministry of Agriculture and the evapotranspiration estimates of the principal crops published by the National Institute for Forestry, Animal Husbandry, and Agricultural Research of Mexico[10]. The average annual volume of Colorado River water consumption in Mexico estimated by these researchers is within 1% of the cross-border delivery volume estimated by the Bureau of Reclamation for 2000–2019 in its Colorado River Accounting and Water Use Reports[3].

Exported water consumption

Annual average inter-basin transfer volumes for each of 46 canals and pipelines exporting water outside of the Upper Basin were obtained from Reclamation's Consumptive Uses and Losses spreadsheet[34]. Data for the Colorado River Aqueduct in the Lower Basin were obtained from Siddik et al.[30] Data for exported water in Mexico was available from Hernandez-Cruz et al.[10]. We assigned any seepage or evaporation losses from inter-basin transfers to their proportional end uses. All uses of exported water are considered to be consumptive uses with respect to the Colorado River, because none of the water exported out of the basin is returned to the Colorado River Basin.

We relied on data from Siddik et al. (2023) to identify whether the water exported out of the Colorado River Basin was for only MCI or agricultural use. When more than one water use purpose was identified, as well as for all major inter-basin transfers, we used government and inter-basin transfer project websites or information obtained directly from the project operator or water manager to determine the volume of water transferred and the end uses. Major recipients of exported water include the Coachella Valley Water District (California); Metropolitan Water District of Southern California (particularly for San Diego County, California); Northern Colorado Water Conservancy District; City of Denver (Colorado); the Central Utah Project; City of Albuquerque (New Mexico); and the Middle Rio Grande Conservancy District (New Mexico). We did not pursue sectoral water-use information for 17 of the 46 Upper Basin inter-basin transfers due to their relatively low volumes of water transferred by each system (<247,000 cubic meters or 2000 acre-feet), and instead assigned the average MCI or agricultural percentage (72% MCI, 28% agricultural) from all other inter-basin transfers in the Upper Basin. The export volume of these 17 inter-basin transfers sums to 9.76 million cubic meters (7910 acre-feet) per year, equivalent to 1% of the total volume exported from the Upper Basin.

Reservoir evaporation

Evaporation estimates for the Upper Basin and Lower Basin are based upon Reclamation's HydroData repository[35]. Reclamation's evaporation estimates are based on the standardized Penman-Monteith equation as described in the "Lower Colorado River Annual Summaries of Evapotranspiration and Evaporation" reports[17]. The Penman-Monteith estimates are based on pan evaporation measurements. Evaporation estimates for the Salt River Project reservoirs in the Gila River basin were provided by the Salt River Project in Arizona (Charlie Ester, personal communication, 2023).

Another consideration with reservoirs is the volume of water that seeps into the banks or sediments surrounding the reservoir when reservoir levels are high, but then drains back into the reservoir as water levels decline[36]. This has the effect of either exacerbating reservoir losses (consumptive use) or offsetting evaporation when bank seepage flows back into a reservoir. The flow of water into and out of reservoir banks is non-trivial; during 1999–2008, an estimated 247 million cubic meters (200,000 acre-feet) of water drained from the canyon walls surrounding Lake Powell into the reservoir each year, providing additional water supply[36]. However, the annual rate of alternating gains or losses has not been sufficiently measured at any of the basin's reservoirs and therefore is not included in Tables 1 and 2.

Riparian and wetland vegetation evapotranspiration

We exported the total annual evapotranspiration depth at a 30 meter resolution from OpenET[37] using Google Earth Engine from 2016 to 2019 to align with OpenET's data availability starting in 2016. Total annual precipitation depths, sourced from gridMET[38], were resampled to align with the evapotranspiration raster resolution. Subsequently, a conservative estimate of the annual water depth utilized by riparian vegetation from the river was derived by subtracting the annual precipitation raster from the evapotranspiration raster for each year. Positive differentials, indicative of river-derived evapotranspiration, were then multiplied by the riparian vegetation area as identified in the CO-RIP[16] dataset to estimate the total annual volumetric water consumption by riparian vegetation across the Upper, Lower, and Gila River Basins. The annual volumetric water consumption calculated over four years were finally averaged to get riparian vegetation evapotranspiration in the three basins. Because the entire flow of the Colorado River is diverted into the Canal Alimentador Central near the international border, very little riparian evapotranspiration occurs along the river south of the international border in the Mexico basin.

In addition to water consumed by riparian evapotranspiration within the Lower Basin, the Salton Sea receives agricultural drain water from both the Imperial Irrigation District and the Coachella Valley Irrigation District, stormwater drainage from the Coachella Valley, and inflows from the New and Alamo Rivers[39]. Combined inflows to the Sea during 2015–2019 were added to our estimates of riparian/wetland evapotranspiration in the Lower Basin.

Similarly, Mexico receives drainage water from the Wellton–Mohawk bypass drain originating in southern Arizona that empties into the Cienega de Santa Clara (a wetland); this drainage water is included as riparian/wetland evapotranspiration in the Mexico basin.

Crop-specific water consumption

The volumes of total agricultural consumption reported for each sub-basin in Tables 1 and 2 were obtained from the same data sources described above for MCI consumption and exported water. The portion (%) of those agricultural consumption volumes going to each individual crop was then allocated according to percentage estimates of each crop's water consumption in each accounting unit using methods described in Richter et al.[20] and detailed here.

Monthly crop water requirements during 1981–2019 for 13 individual crops, representing 68.8% of total irrigated area in the US in 2019, were estimated using the AquaCrop-OS model (Table SI-3)[40]. For 17 additional crops representing about 25.4% of the total irrigated area, we used a simple crop growth model following Marston et al.[41] as crop parameters needed to run AquaCrop-OS were not available. A list of the crops included in this study is shown in Table SI-3. The crop water requirements used in Richter et al.[11] were based on a simplistic crop growth model, often using seasonal crop coefficients whereas we use AquaCrop-OS[40], a robust crop growth model, to produce more realistic crop growth and crop water estimates for major crops. AquaCrop-OS is an open-source version of the AquaCrop model[42], a crop growth model capable of simulating herbaceous crops. Additionally, we leverage detailed local data unique to the US, including planting dates and subcounty irrigated crop areas, to produce estimates at a finer spatial resolution than the previous study. We obtained crop-specific planting dates from USDA[43] progress data at the state level. For crops that did not have USDA crop progress data, we used data from FAO[44] and CUP+ model[45] for planting dates. We used climate data (precipitation, minimum and maximum air temperature, reference ET) from gridMET[38], soil texture data from ISRIC[46] database and crop parameters from AquaCrop-OS to run the model. The modeled crop water requirement was partitioned into blue and green components following the framework from Hoekestra et al. [47], assuming that blue and green water consumed on a given day is proportional to the amount of green and blue water soil moisture available on that day. When applying a simple crop growth model, daily gridded (2.5 arc minutes) crop-specific evapotranspiration (ETc) was computed by taking the product of reference evapotranspiration (ETo) and crop coefficient (Kc), where ETo was obtained from gridMET. Crop coefficients were calculated using planting dates and crop coefficient curves from FAO and CUP+ model. Kc was set to zero outside of the growing season. We partitioned the daily ETc into blue and green components by following the methods from ref. [41] It is assumed that the crop water demands are met by irrigation whenever it exceeds effective precipitation (the latter calculated using the USDA Soil Conservation Service method (USDA, 1968[48]). We obtained county level harvested area from USDA[43] and disaggregated to sub-county level using Cropland Data Layer (CDL)[49] and Landsat-based National Irrigation Dataset (LANID)[50]. The CDL is an annual raster layer that provides crop-specific land cover data, while the LANID provides irrigation status information. The CDL and LANID raster were multiplied and aggregated to 2.5 arc minutes to match the AquaCrop-OS output. We produced a gridded crop area map by using this resulting product as weights to disaggregate county level area. CDL is unavailable before 2008. Therefore, we used land use data from ref. [51] in combination with average CDL map and county level harvested area to produce gridded crop harvested area. We computed volumetric water consumption by multiplying the crop water requirement depth by the corresponding crop harvested area.

Data availability

All data compiled and analyzed in this study are publicly available as cited and linked in our Methods section. Our compilation of these data is also available from Hydroshare at: http://www.hydroshare.org/resource/2098ae29ae704d9aacfd08e030690392.

Code availability

All model code and software used in this study have been accessed from sources cited in our Methods section. We used AquaCrop-OS (v5.0a), an open source version of AquaCrop crop growth model, to run crop simulations. This model is publicly available at http://www.aquacropos.com/. For estimating riparian evapotranspiration, we used ArcGIS Pro 3.1.3 on the Google Earth Engine. Riparian vegetation distribution maps were sourced from Dryad at https://doi.org/10.5061/dryad.3g55sv8.

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References

1. Stromberg, J. C., Andersen, D. C. & Scott, M. L. Riparian floodplain wetlands of the arid and semiarid southwest In *Wetland Habitats of North America: Ecology and Conservation Concerns*, Chapter 24, pp. 343–356. (University of California Press, 2012). https://www.ucpress.edu/book/9780520271647/wetland-habitats-of-north-america.
2. Schmidt, J. C., Yackulic, C. B. & Kuhn, E. The Colorado River water crisis: Its origin and the future. *WIREs Water* https://doi.org/10.1002/wat2.1672 (2023).
3. *Colorado River Accounting and Water Use Report: Arizona, California, and Nevada. Interior Region 8: Lower Colorado Basin* (US Bureau of Reclamation, 2023). Annual reports available under "Water Accounting Reports" at https://www.usbr.gov/lc/region/g4000/wtracct.html.
4. *Water Operations: Historic Data* (US Bureau of Reclamation, 2023). https://www.usbr.gov/rsvrWater/HistoricalApp.html.
5. Colorado River Compact*, 1922*. US Bureau of Reclamation. https://www.usbr.gov/lc/region/pao/pdfiles/crcompct.pdf.
6. Kuhn, E. & Fleck, J. *Science Be Dammed:How Ignoring Inconvenient Science Drained the Colorado River* (The University of Arizona Press, 2019) https://uapress.arizona.edu/book/science-be-dammed.
7. Castle, A. & Fleck, J. *The Risk of Curtailment under the Colorado River Compact (* https://doi.org/10.2139/ssrn.3483654 (2019).
8. US Bureau of Reclamation. *Colorado River Basin Water Supply and Demand Study: Technical Report C – Water Demand Assessment* https://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Technical%20Report%20C%20-%20Water%20Demand%20Assessment/TR-C-Water_Demand_Assessmemt_FINAL.pdf (2012).
9. *Utilization of the Waters of the Colorado and Tijuana Rivers and of the Rio Grande*. International Treaty between the United States and Mexico, February 3, 1944. (International Boundary and Waters Commission, 1944). https://www.ibwc.gov/wp-content/uploads/2022/11/1944Treaty.pdf.
10. Hernández-Cruz, A. et al. Assessing water management strategies under water scarcity in the Mexican portion of the Colorado River Basin. *J. Water Resour. Plan. Manag.* **149**, 04023042 (2023).
11. Richter, B. D. et al. Water scarcity and fish imperilment driven by beef production. *Nat. Sustain.* **3**, 319–328 (2020).
12. *Biden-Harris Administration announces historic Consensus System Conservation Proposal to protect the Colorado River Basin*. US Department of the Interior, May 22, 2023. https://www.doi.gov/pressreleases/biden-harris-administration-announces-historic-consensus-system-conservation-proposal.
13. Wheeler, K. G. et al. What will it take to stabilize the Colorado River? *Science* **377**, 373–375 (2022).
14. Richter, B. D. Decoupling urban water use from population growth in the Colorado River Basin. *J. Water Plan. Manag.* **149**, 2 (2023).
15. Schmidt, J. C. *Maps Matter: A few suggested changes to the Colorado River basin base map*. Center for Colorado River Studies. (Utah State University, 2022).
16. Woodward, B. D. et al. Co-Rip: A riparian vegetation and corridor extent dataset for Colorado river basin streams and rivers. *ISPRS Int. J. Geo Inform.* **7**, 397 (2018).
17. *Lower Colorado River Annual Summaries of Evapotranspiration and Evaporation*. (US Bureau of Reclamation, Lower Colorado Region, 2023). https://www.usbr.gov/lc/region/g4000/wtracct.html.

18. Richter, B. D., Powell, E. M., Lystash, T. & Faggert, M. Protection and restoration of freshwater ecosystems. Chapter 5 in Miller, Kathleen A., Alan F. Hamlet, Douglas S. Kenney, and Kelly T. Redmond (Eds.) *Water Policy and Planning in a Variable and Changing Climate*. (CRC Press - Taylor & Francis Group, 2016).
19. Shao, Elena. "The Colorado River is shrinking. See what's using all the water." *New York Times*, May 22, 2023. https://www.nytimes.com/interactive/2023/05/22/climate/colorado-river-water.html.
20. Richter, B. D., et al. Alleviating water scarcity by optimizing crop mixes. *Nat. Water*. https://doi.org/10.1038/s44221-023-00155-9.
21. Njuki, E. *U.S. dairy productivity increased faster in large farms and across southwestern states*. U.S. Economic Research Service, US Department of Agriculture, March 22, 2022. https://www.ers.usda.gov/amber-waves/2022/march/u-s-dairy-productivity-increased-faster-in-large-farms-and-across-southwestern-states/.
22. Mefford, B. & Prairie J., eds. *Assessing Agricultural Consumptive Use in the Upper Colorado River Basin - Phase III Report* U.S. Bureau of Reclamation and the Upper Colorado River Commission. http://www.ucrcommission.com/reports-studies/ (2022).
23. *Upper Basin Consumptive Uses and Losses* (Bureau of Reclamation). Annual reports available at https://www.usbr.gov/uc/envdocs/plans.html.
24. Bureau of Reclamation. "Consumptive Uses and Losses spreadsheet 1971–2020" Colorado River Basin Natural Flow and Salt Data, Supporting data for consumptive uses and losses computation. https://www.usbr.gov/lc/region/g4000/NaturalFlow/documentation.html.
25. Upper Colorado River Basin Consumptive Uses and Losses Report *2016–2020*. US Department of Interior: Bureau of Reclamation. Five year reports available under "Colorado River-Consumptive Uses and Losses Reports" at https://www.usbr.gov/uc/envdocs/plans.html.
26. *Estimated Use of Water in the United States*. US Department of Interior: US Geological Survey. Reports available every five years at https://www.usgs.gov/mission-areas/water-resources/science/water-use-united-states.
27. Jasechko, S. et al. Widespread potential loss of streamflow into underlying aquifers across the USA. *Nature* **591**, 391–395 (2021).
28. Wiele, S. M., Leake, S. A., Owen-Joyce, S. J. & and McGuire, E. H. *Update of the Accounting Surface* Along the Lower Colorado River US Department of the Interior: US Geological Survey Scientific Investigations Report 2008–5113 (2008).
29. Bruce, B. W., et al. Comparison of U.S. Geological Survey and Bureau of Reclamation water-use reporting in the Colorado River Basin *U.S. Geological Survey Scientific Investigations Report 2018–5021*. https://doi.org/10.3133/sir20185021 (2018).
30. Siddik, M. A. B., Dickson, K. E., Rising, J., Ruddell, B. L. & Marston, L. T. Interbasin water transfers in the United States and Canada. *Sci. Data* **10**, 27 (2023). Data spreadsheet provided by M.A.B. Siddik.
31. *Active Management* Areas: *AMA Annual Supply and Demand Dashboard* (Arizona Department of Water Resources, 2023). https://azwater.gov/ama/ama-data.
32. Lacroix, K. M. et al. *Wet water and paper water in the Upper Gila River Watershed* https://extension.arizona.edu/sites/extension.arizona.edu/files/pubs/az1708-2016_0.pdf The University of Arizona Cooperative Extension, AZ1708. Data spreadsheet provided by A. Hullinger (2016).
33. *Surface-Water Annual Statistics for the Nation: Gila River at Dome, Arizona*. US Geological Survey. Available at https://waterdata.usgs.gov/nwis/annual/?referred_module=sw&site_no=09520500&por_09520500_5810=19975,00060,5810,1905,2024&year_type=C&format=html_table&date_format=YYYY-MM-DD&rdb_compression=file&submitted_form=parameter_selection_list.
34. Consumptive Uses and Losses spreadsheet *1971–2020*. Bureau of Reclamation, Colorado River Basin Natural Flow and Salt Data, Supporting data for consumptive uses and losses computation. https://www.usbr.gov/lc/region/g4000/NaturalFlow/documentation.html.
35. *HydroData: Reservoir Data*. US Bureau of Reclamation. https://www.usbr.gov/uc/water/.
36. Myers, T. Loss rates from Lake Powell and their impact on management of the Colorado River. *J. Am. Water Resour. Assoc.* **49**, 1213–1224 (2013).
37. Melton, F. S. et al. OpenET: filling a critical data gap in water management for the western United States. *J. Am. Water Resour. Assoc.* **58**, 971–994 (2022).
38. Abatzoglou, J. T. Development of gridded surface meteorological data for ecological applications and modelling. *Int. J. Climatol.* **33**, 121–131 (2013).
39. *Salton Sea Management Program: Long-Range Plan Public Draft* (2022). California Natural Resources Agency. https://saltonsea.ca.gov/wp-content/uploads/2022/12/Salton-Sea-Long-Range-Plan-Public-Draft-Dec-2022.pdf.
40. Foster, T. et al. AquaCrop-OS: an open source version of FAO's crop water productivity model. *Agricul. Water Manag.* **181**, 18–22 (2017).
41. Marston, L. T., et al. Reducing water scarcity by improving water productivity in the United States. *Environ. Res. Lett.* **15** https://doi.org/10.1088/1748-9326/ab9d39 (2020).
42. Steduto, P., Hsiao, T. C., Fereres, E. & Raes, D. *Crop yield response to water* (2012). 1028. Rome: Food and Agriculture Organization of the United Nations.
43. USDA, National Agricultural Statistics Service. "Quick Stats." http://quickstats.nass.usda.gov.
44. Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. *FAO Irrigation and drainage paper No. 56* 56, (e156. Food and Agriculture Organization of the United Nations, Rome, 1998).
45. Orange, M. N., Scott Matyac, J. & Snyder, R. L. Consumptive use program (CUP) model. *IV Int. Symp. Irrig. Horticult. Crops* **664**, 461–468 (2003).
46. Hengl, T. et al. SoilGrids250m: Global gridded soil information based on machine learning. *PLoS One* **12**, e0169748 (2017).
47. Hoekstra, A. Y. Green-blue water accounting in a soil water balance. *Adv. Water Resour.* **129**, 112–117 (2019).
48. USDA (US Department of Agriculture). *A Method for Estimating Volume and Rate of Runoff in Small Watersheds*. SCS-TP-149. Washington DC: Soil Conservation Service (1968).
49. Johnson, D. M., & Mueller, R. 2010. "Cropland Data Layer." https://nassgeodata.gmu.edu/CropScape/.
50. Xie, Y., Gibbs, H. K. & Lark, T. J. Landsat-based Irrigation Dataset (LANID): 30m resolution maps of irrigation distribution, frequency, and change for the US, 1997–2017. *Earth Syst. Sci. Data* **13**, 5689–5710 (2021).
51. Sohl, T. et al. Modeled historical land use and land cover for the conterminous United States. *J. Land Use Sci.* **11**, 476–499 (2016).

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Author contributions

B.D.R. designed the study, compiled and analyzed data, wrote the manuscript and supervised co-author contributions. G.L. compiled all crop data, estimated crop evapotranspiration, and prepared figures. S.D. compiled all riparian vegetation data and estimated riparian evapotranspiration. L.S.S. and R.R.R. accessed, compiled, and analyzed data from the Central Arizona Project. D.W. compiled data and prepared figures. A.H.-C. and S.S.-S. compiled and analyzed data for Mexico. J.C.S. compiled and analyzed reservoir evaporation data and edited the manuscript. L.M., B.L.R., and K.F.D. supervised data compilation and analysis and edited the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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