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Stream flow and Losses of the Colorado River in the Southern Colorado Plateau

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Exploring uncertainty in quantifying stream flow and losses of the Colorado River in the southern Colorado Plateau, including Lake Powell, the Grand Canyon, and Lake Mead

Photo courtesy Michael Collier

Executive Summary:

A confounding uncertainty for predicting stream flow and losses in anticipation of renegotiation of the *2007 Interim Guidelines for Lower Basin Shortages* concerns the accuracy and precision of those data. Several key gages that are not used in CRSS and are not considered part of the standard network of gages used to manage the Colorado River offer critical insight into understanding future watershed conditions:

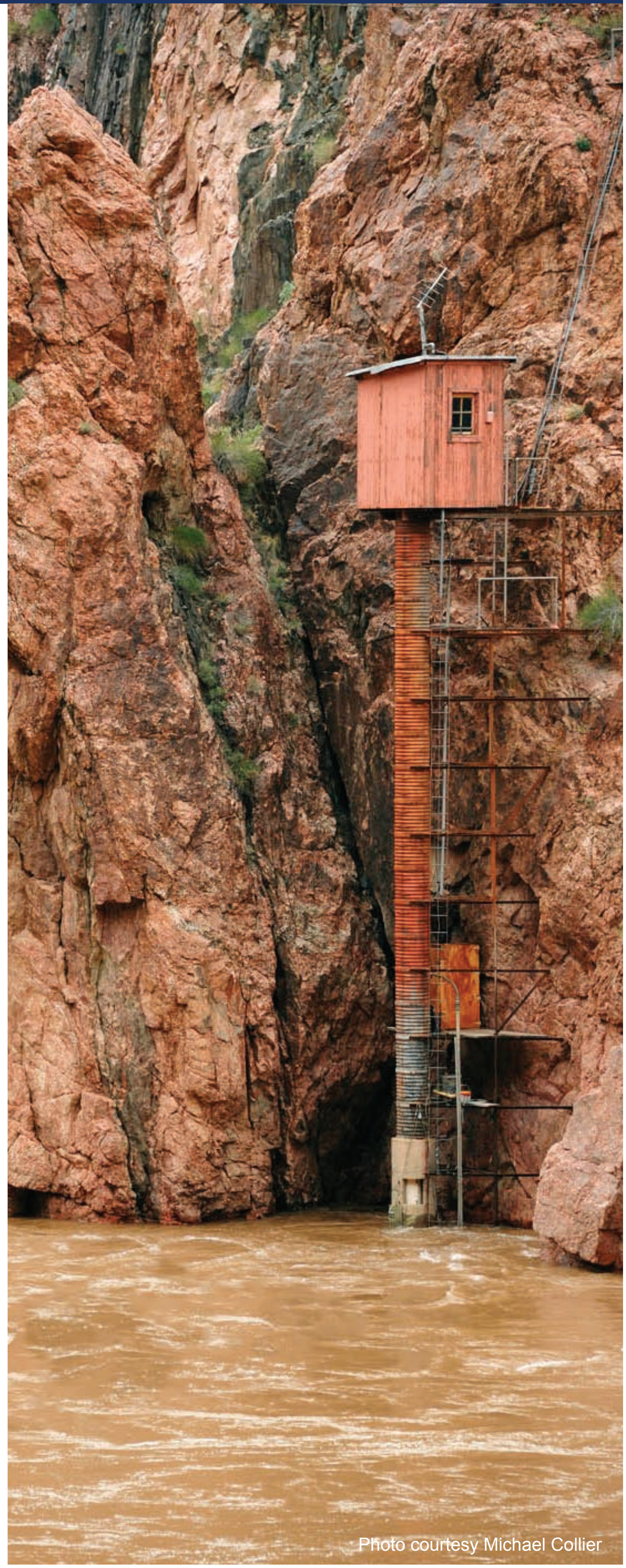
- Colorado River at Potash (USGS gage 09185600), because data from this gage reduces the ungaged drainage area to Lake Powell by 1,306 mi^2.
- Green River at Mineral Bottom (USGS gage 09328920), because data from this gage eliminates the need to estimate the contribution of inflow from the San Rafael River.
- Little Colorado River above mouth near Desert View (USGS gage 09402300), because spring flow into the Little Colorado River downstream from Cameron contributes ~20% of all inflows (~170,000 af/yr) to the Colorado River between Lees Ferry and Lake Mead that arise within the Grand Canyon.
- Colorado River above Diamond Creek (USGS gage 09404200), because this gage allows quantification of inflows to the Colorado River in the east-central and west-central Grand Canyon that are between 300,000 and 400,000 af/yr. Funding should be provided to USGS to improve the accuracy of reported annual flow at this gage, because these flows represent 99% of the inflows to Lake Mead.

We encourage continued efforts by the USGS to establish a gage on the Colorado River at Hite. Such a gage would allow direct measurement of all inflows from the upper Colorado and Green Rivers into Lake Powell.

There should be renewed study of the magnitude of seepage around Glen Canyon Dam that reenters the Colorado River upstream from Lees Ferry, including ground water modeling. Measurements since 2005 indicate that ~150,000 af/yr seeps around the dam.

We suggest maintaining the long-term program to measure evaporation from Lake Mead and make the present experimental program at Lake Powell a permanent monitoring program. Total, or gross, evaporation should be regularly reported for both reservoirs, because that is the actual amount of water lost to the atmosphere.

We suggest initiating studies to quantify bank storage at Lakes Mead and Powell. Bank storage estimates from 1962 to 2012 by Myers (2013) were very different from the bank storage estimates reported in the Natural Flow and Salt Data base.



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There is a need for clarification of the different types of data in Reclamation's Natural Flow and Salt Data base, because the reported natural intervening flow of some segments are actually accounting artifacts associated with the uncertainty in reservoir water budgets.

Water uses and losses, as described in Reclamation water accounting reports should be reported to no more than four significant figures.

Similar analysis of the uncertainty about stream flow measurements, other hydrologic processes, and water budgets should be conducted between Hoover Dam and the North International Boundary (NIB). The water distribution system downstream from Hoover Dam is complex, and the losses associated with irrigated agriculture, evapotranspiration from riparian forests, and evaporation from reservoirs have significant uncertainty. Inflows from the Bill Williams and Gila Rivers may be poorly known.

Hydrologic data concerning streamflow and losses of the Colorado River should be made available in a simple and easily accessible database. Reclamation's new Hydrologic Database is a great improvement because it centralizes data availability.

Acknowledgments

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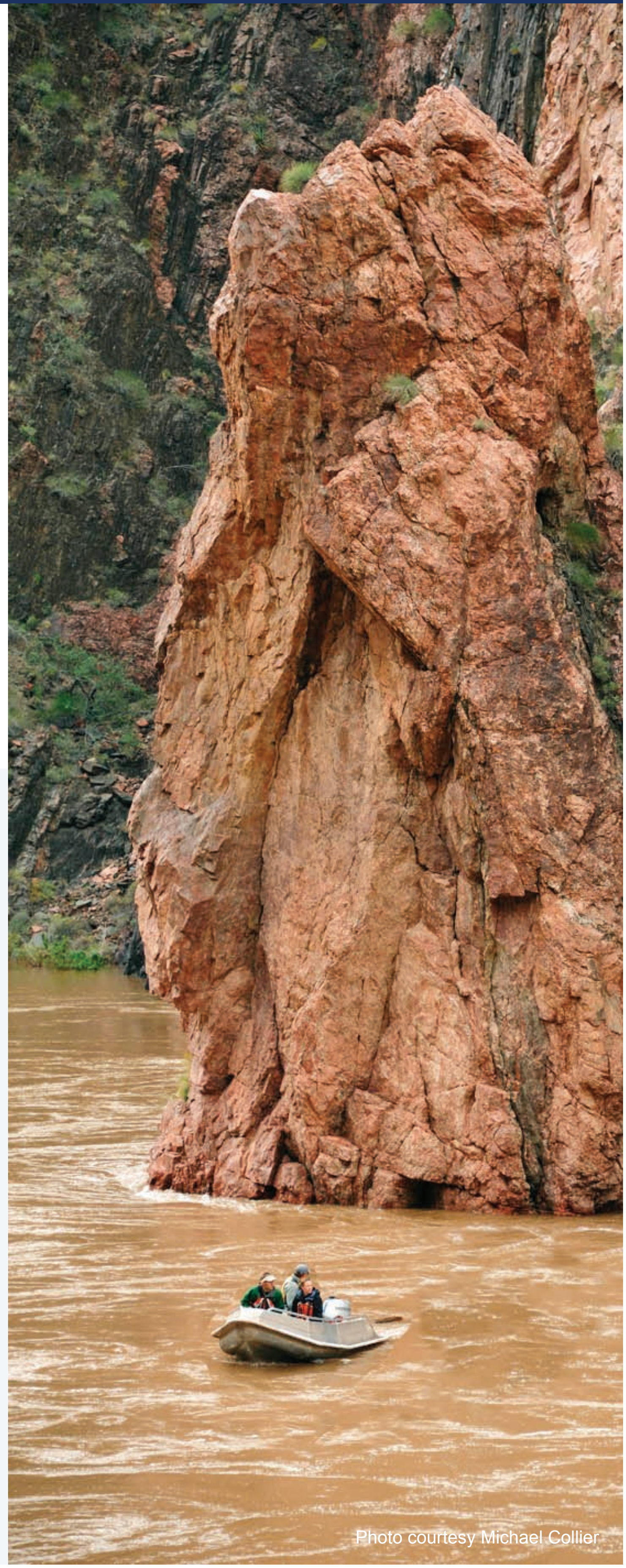

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This publication is part of a series of white papers from the Future of the Colorado River Project. Also included in the series:

White Paper 1. Fill Mead First – A Technical Assessment
Outlines a plan that would establish Lake Mead reservoir as the primary water storage facility of the main-stem Colorado River and would relegate Lake Powell reservoir to a secondary water storage facility to be used only when Lake Mead is full.

White Paper 2. Water Resource Modeling of the Colorado River: Present and Future Strategies
Explores alternative management strategies for the Colorado River that might provide benefit to water-supply users and to river ecosystems.

White Paper 3. Managing the Colorado River for an Uncertain Future
Distinguishes four levels of decision-making uncertainty and suggest tools and resources to manage the different levels.

White Paper 4. The Future Hydrology of the Colorado River Basin
Summarizes the current understanding of future hydrology from the perspective of how that understanding can be incorporated into CRSS and other river planning models.

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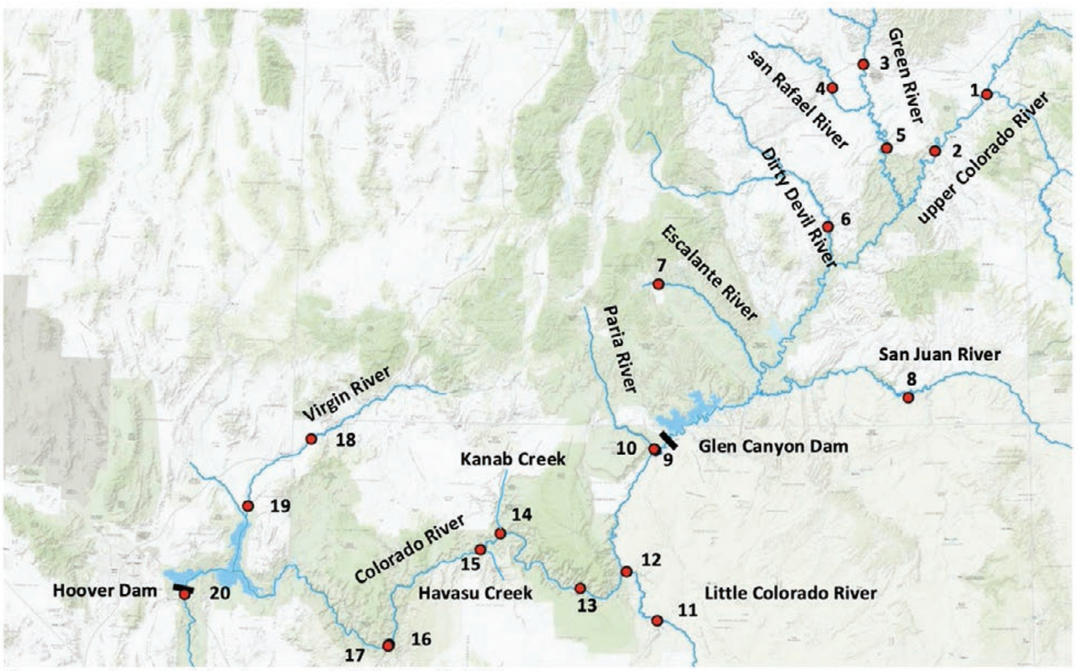
Introduction

Renegotiation of the 2007 Interim Guidelines for Lower Basin Shortages (Hereafter, Interim Guidelines) (Reclamation, 2007a) unavoidably necessitates immersion in numbers. How much snowmelt runoff will come from the Rocky Mountains? How much rain will fall during the season of the North American monsoon? How much stream flow will pass Lee Ferry? How much water will be lost to evapotranspiration by irrigated agriculture? How much water will be exported from the Colorado River basin? How much water will evaporate from Lake Mead and Lake Powell?

There is great uncertainty in predicting these numbers decades into the future, but there are techniques and strategies designed for developing policies and guidelines that can be adapted to future uncertainty (Wang, Rosenberg et al., 2020). An additional confounding uncertainty concerns the accuracy and precision of the data used to manage today's river and its reservoirs. Although managers have long been aware of some of the deficiencies and uncertainties in some of these data, there was no urgency in resolving them, because surplus conditions existed. In the present era of shortage, water managers are likely to require more data of greater accuracy. Although it may not be possible to reduce all uncertainty, effective water-supply negotiation and river management are best served if Colorado River stakeholders are mindful that ***some key aspects of the modern hydrology of the river are imprecisely known.***

We ask, ***what is the uncertainty in quantifying stream flow and losses of the Colorado River in the southern Colorado Plateau, including Lake Powell, the Grand Canyon, and Lake Mead?*** These two reservoirs are the largest in the United States, and their operations are coordinated by rules described in the Interim Guidelines. Releases from Lake Powell have significant ecological impacts on the 255 miles of the Colorado River between the two reservoirs that are primarily within the Grand Canyon. Inflow to Lake Powell comes from the three headwater branches of the river network – the upper Colorado, Green, and San Juan Rivers (Fig. 1).



Gages and annual (water year) data availability

1. Colorado River near Cisco, 09180500 (1914-2019)
2. Colorado River at Potash, 09185600 (2016-2019)
3. Green River at Green River, 09315000 (1895-2019)
4. san Rafael River Near Green River, 09328500 (1910-2019)
5. Green River at Mineral Bottom, 09328920 (2015-2019)
6. Dirty Devil River above Poison Spring Wash near Hanksville, 09333500 (1949-2019)
7. Escalante River near Escalante, 09337500 (1943-2019)
8. San Juan River near Bluff, 09379500 (1916-2019)
9. Colorado River at Lees Ferry, 09380000 (1922-2019)
10. Paria River at Lees Ferry, 09382000 (1924-2019)
11. Little Colorado River nr Cameron, 09402000 (1948-2018)
12. Little Colorado River nr Desert View, 09402300 (2004-2019)
13. Colorado River nr Grand Canyon, 09402500 (1923-2019)
14. Kanab Creek near Supai, 09403850 (2011-2019)
15. Havasu Creek near Supai, 09404115 (1996-2019)
16. Colorado River near Peach Springs, 09404200 (1990-2019)
17. Diamond Creek near Peach Springs, 09404208 (1994-2019)
18. Virgin River at Littlefield, 09415000 (1930-2019)
19. Virgin River near Overton, 09415250 (2007-2018)
20. Colorado River Below Hoover Dam, 09421500 (1935-2017)

Figure 1. Map showing stream-flow gages and data availability. Each number corresponds to a gage whose official USGS number is listed, along with the period of availability of annual flow data.

Most of the outflow from Lake Mead occurs by releases through Hoover Dam. Between the region of primary inflows to Lake Powell and the releases from Hoover Dam, other significant hydrologic processes occur that include precipitation, small tributary inflows, exchange of water between the reservoirs and the surrounding bedrock, evaporation from the reservoirs, and withdrawals from the reservoirs. Calculation of "what goes in and what goes out" of this part of the Colorado River provides an illustration of how precisely and accurately we understand the various components of the water supply of the Colorado River.

Accuracy and precision of reservoir release data

In science and engineering, accuracy is the proximity of a measurement to the true value, sometimes expressed as a range of uncertainty, such as $\pm$ 5% or $\pm$ 1,000 acre feet (af). Precision is the resolution of the representation, typically defined by the number of significant figures or significant digits (Fig. 2). In some situations, the number of significant figures also represents the accuracy of reported values, because the number of significant figures reflects the resolution to which we can measure the phenomena accurately. The margin of error is understood to be one-half the value of the last significant digit. For example, if the reported value of the annual release from Lake Powell was 9,001,000 af, this number has 4 significant figures and a margin of error of 500 af[1]. In this case, the precision of this reported release would be higher if this value had been reported with more significant figures, such as 9,001,396 af. However, the more precise number is not necessarily more accurate. It is impossible to know the true value of most numbers used in hydrology, but we can evaluate the accuracy of some numbers by comparing complementary or overlapping measurements. We can also evaluate accuracy of numbers by constructing water budgets that account for all inflows and all outflows. Balancing this kind of budget is similar to balancing our check books. If our check book doesn't balance, then our deposits or our expenses are not accurate. If a water budget doesn't balance, then we know some of numbers concerning inflows or outflows are inaccurate at the specified level of precision.

Reclamation directly measures releases from Lake Powell and Lake Mead and reports monthly releases from each reservoir in its 24-Month Study (Operation Plan for Colorado River System Reservoirs, available at https://www.usbr.gov/lc/region/g4000/24mo/index.html) that is issued every month. These data are also reported in Reclamation's annual water accounting reports (Colorado River Accounting and Water Use Report: Arizona, California, Nevada, available at https://www.usbr.gov/lc/region/g4000/wtracct.html). Monthly release data are also reported at Reclamation's new Hydrologic Database (available at https://www.usbr.gov/uc/water/hydrodata/reservoir_data/site_map.html). As described below, monthly reservoir release data from these sources do not always agree.

Between 1997 and 2005, releases from Lake Powell were based on rating relations for the turbines at the Glen Canyon Dam powerplant and rating relations for the river outlet works used to bypass water around the powerplant. In 2005, acoustic velocity meters were installed in the powerplant penstocks to measure releases from the dam. At Hoover dam, acoustic velocity meters have measured reservoir release since 1990. We assume that the accuracy of these data is +1%.

1 In science and engineering, this number would be written as 9.001 x 10^6 af, and the number of significant digits would be easily determined. We do not use scientific notation in this paper, because this style of scientific writing is not commonly used in water supply, policy, or legal literature.

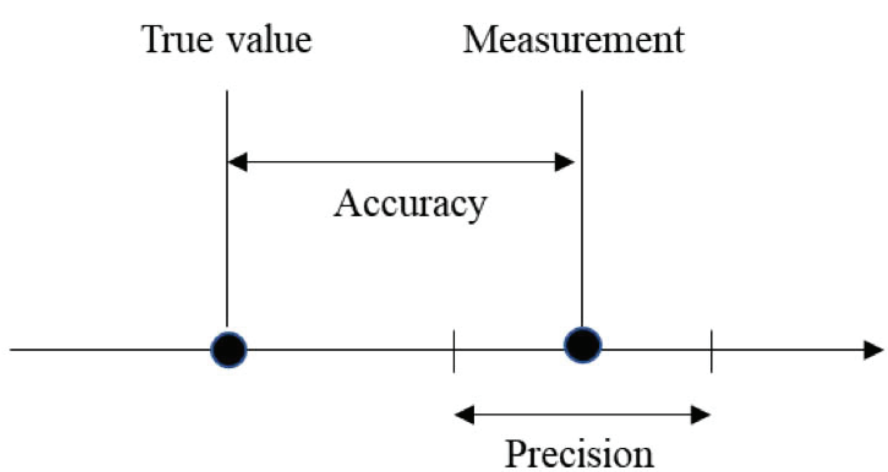


Figure 2. Illustration of the concepts of precision and accuracy.

Table 1. Precision of published monthly dam release in Water Accounting Reports, 24-Month Study reports and the Hydrologic Database

	Prior to 1997, in 2000 and 2001, and between 2003 to 2006	In 1998, 1999, and 2002	Since 2013 and between 2007 to 2010	Since 2010	Since 1963
Water Accounting Reports	to the nearest 100 af (4 significant figures)	to the nearest 1,000 af (3 or 4 significant figures)	to the nearest 1 af (6 or 7 significant figures).	-	-
24-Month Study reports	-	-	-	to the nearest 1,000 af (3 or 4 significant figures)	-
Reclamation Hydrologic Database					to the nearest 0.1 af or 1 af when release is less than 1 maf; to the nearest 1 af or 10 af when release is greater than 1 maf

In the past, there was less urgency to understand the precision and accuracy of the data, because there was a relative surplus in the water supply. Since 2000 and beginning of the millennium drought (Salehabadi, Tarboton et al., 2020), there is an increasing need to understand the accuracy of the data. The precision to which data have been reported in the past have differed by data source and year (Table 1). In the analyses described below, we report all data concerning reservoir releases and Colorado River flow to 4 significant figures, and we report all tributary flow data to 3 significant figures, consistent with USGS reporting standards. We analyse the appropriateness of that level of precision in describing stream flow and reservoir losses.

Analysis of data demonstrating seepage around Glen Canyon Dam

The U.S. Geological Survey (USGS) has measured stream flow 15 miles downstream from Glen Canyon Dam (USGS gage 09380000, Colorado River at Lees Ferry; gage number 9 in Fig. 1) since 1922 (Topping et al., 2003). This gage is approximately one mile upstream from Lee Ferry that is defined by the 1922 Compact as located one mile downstream from the Paria River confluence. Monthly mean flow data are reported by the USGS in cubic feet per second (ft^3/s) to 4 significant figures, and these data are reported at the USGS National Water Information System website (available at https://waterdata.usgs.gov/nwis). Reclamation's annual water accounting reports summarize Lake Powell release data for calendar years (CY), and USGS data are summarized by WY. To facilitate comparison, we converted USGS data in ft^3/s to af[2], and we converted CY to WY.

2 1 ft^3/s for 1 day = 1.98347 af for a day; leap years were explicitly considered

Comparison of the Lake Powell release data with the USGS data at Lees Ferry since 2005 demonstrate that ***a significant amount of water seeps around Glen Canyon Dam and enters the Colorado River upstream from Lees Ferry***. We assume that the uncertainty in these data is + 1% because of the use of acoustic velocity meters at the dam since 2005 and because of the rigorous gaging program at Lees Ferry. Our analysis demonstrates that there is discrepancy in the reported reservoir release data in CY 2011 and CY 2012, but other monthly reservoir release data generally agree. The average annual increase in stream flow between Glen Canyon Dam and Lees Ferry is ~150,000 af/yr between WY2005 and WY2019 based on the data of the 24-Month Study and the Hydrologic Database (Fig. 3). This value is approximately the same as the average increase in flow based on the annual accounting reports if the data for CY2011 and CY2012 are ignored (Fig. 4). This value is 1.7% of the average annual reported release from Lake Powell during this period.

The seepage around Glen Canyon Dam can be observed in springs along the canyon walls and was confirmed by ground-water measurements and modelling by Thomas (1986) (Fig. 5). ***The amount of seepage is significant, and is a transfer of water from the Upper Basin to the downstream river. The amount of this transfer, ~150,000 af/yr, is half of the Nevada's annual consumptive use.***

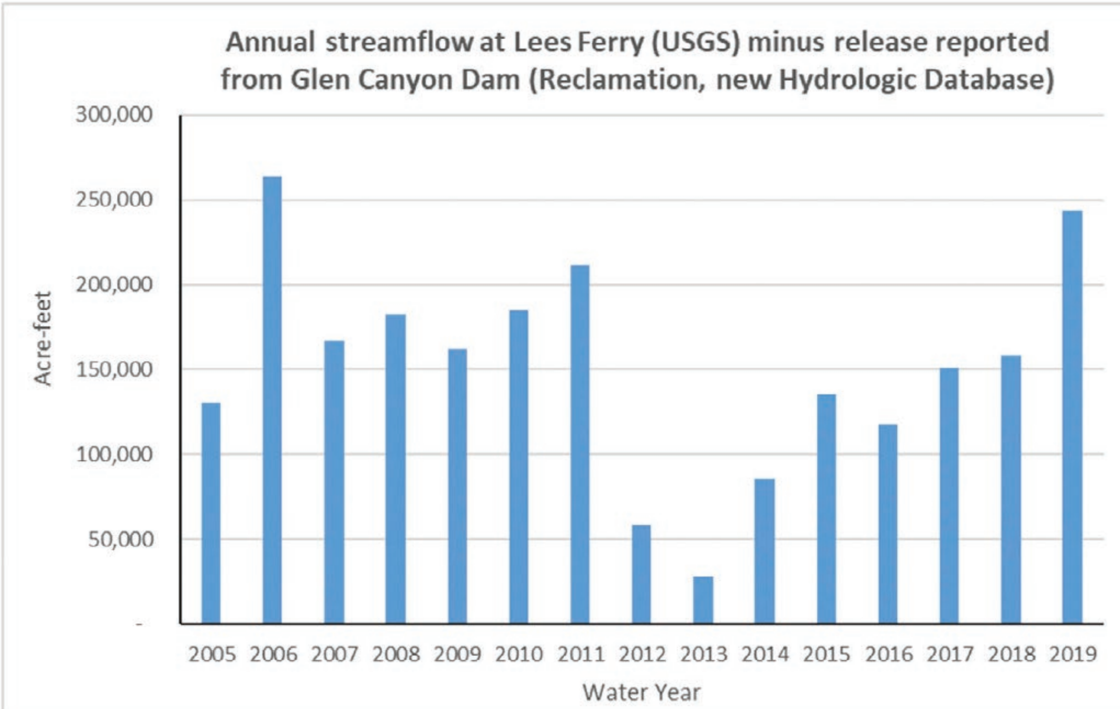


Figure 3. Graph showing difference between annual release from Lake Powell reported by Reclamation (24 Month Study and Hydrologic Database) and annual streamflow at Lees Ferry reported by the USGS since 2005.

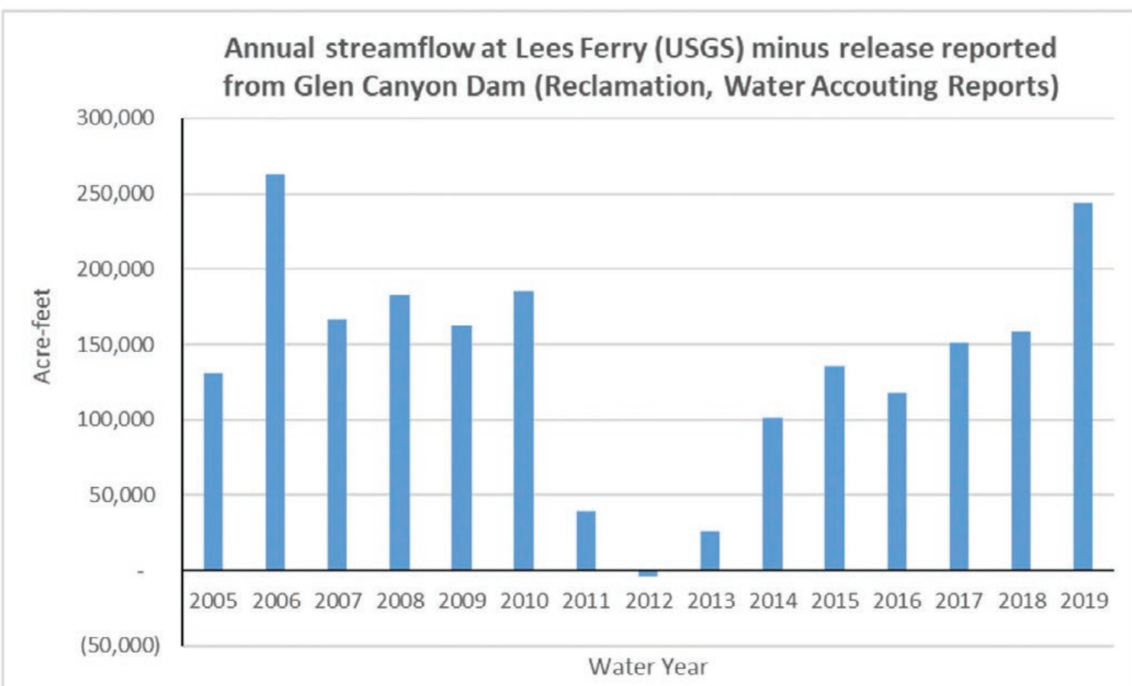


Figure 4. Graph showing difference between annual release from Lake Powell reported by Reclamation (Water Accounting Reports) and annual streamflow at Lees Ferry reported by the USGS since 2005.

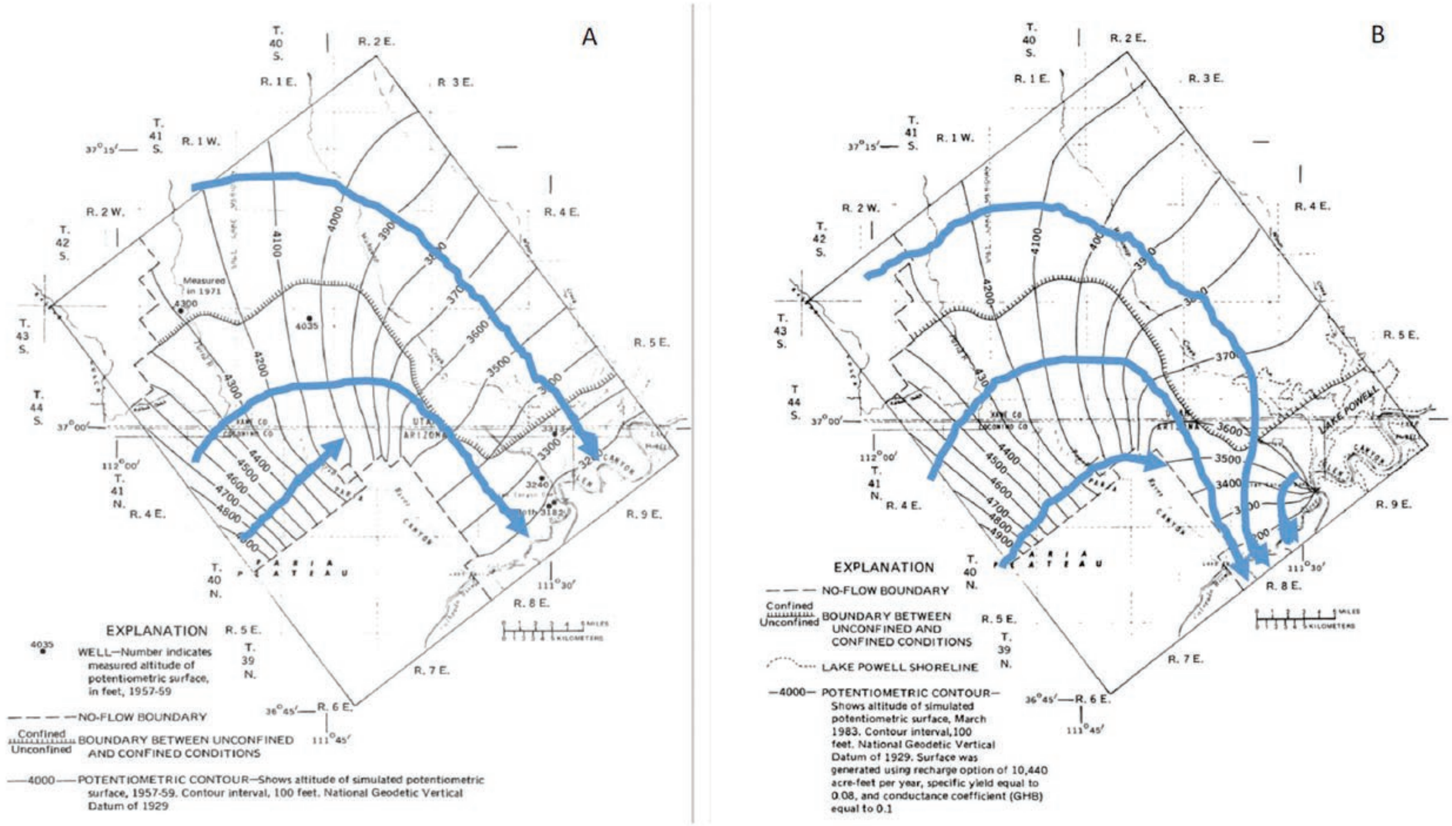


Figure 5. Maps showing estimated equilibrium potentiometric surface and ground-water flow paths (blue arrows) that existed (A) before construction of Glen Canyon Dam and (B) in March 1983. (adapted from Thomas, 1986, figures 10 and 13).

Intervening Inflows to the Colorado River downstream from Lees Ferry

Effective management of the Colorado River in the future also necessitates understanding the amount and sources of significant intervening inflows between Lees Ferry and Lake Mead. These intervening inflows can be quantified by calculating the difference between flow measurements made at different gages within the Grand Canyon. Some of the inflow comes from two tributaries with large watersheds whose headwaters are beyond the Grand Canyon – the Paria River and the Little Colorado River. Inflows from the Paria (USGS gage 09382000; Paria River at Lees Ferry; drainage area 1,410 mi^2; gage number 10 in Fig. 1) and Little Colorado River (USGS gage 09402000; Little Colorado River near Cameron; drainage area 26,459 mi^2; gage number 11 in Fig. 1) have been measured since 1924 and 1947, respectively. Additional sources of inflow are from large springs within the Grand Canyon that either flow directly into the Colorado River or sustain perennial flow in tributaries such as the lower Little Colorado River, Bright Angel Creek, Shinumo Creek, Tapeats Creek, Deer Creek, Kanab Creek, and lower Havasu Creek. Flow of these springs in the future may be diminished if climate change leads to decreasing precipitation over the high plateaus surrounding the Grand Canyon and by ground-water development associated with municipal use and/or mining.

Modern flows of the four tributaries have been affected by increasing upstream consumptive uses and/or by decreasing watershed runoff caused by a changing climate. For example, the average total annual flow of the Little Colorado River near Cameron between 1996 and 2015 was 96,000 af/yr, which was 53% less than the average total annual flow (205,000 af/yr) between 1965 to 1995. Dean and Topping, (2019) explained that this decrease was caused by evaporation from upstream reservoirs and stock ponds, consumptive water uses caused by irrigated agriculture and trans-basin diversions from the Little Colorado River basin. Approximately 6,000 af/yr of water is diverted from C.C. Cragin Dam to the Salt River, and the cumulative amount of exported water since 1965 has been equivalent to ~4% of the total annual flow of the Little Colorado River during same time period. Other studies examined the causes of decreasing runoff on other tributaries (Hereford, 1984, 1986, 2002; Graf et al, 1991; Hereford and Webb, 1992).

Quantification of intervening inflows is made by analyzing flow data at gages within the Grand Canyon. The oldest gage operated within the Grand Canyon is located 87 miles downstream from Lees Ferry and has operated since 1923

(USGS gage 09042500, Colorado River near Grand Canyon; draining area 137,641 mi^2; gage number 13 in Fig. 1). Additional gages in the Grand Canyon were established in the mid-1980s as part of Reclamation's Glen Canyon Environmental Studies program, and continuous operation of these gages began in the early 1990s, funded by the Glen Canyon Dam Adaptive Management Program. The most important of these recently established gages is the one in the western Grand Canyon (USGS gage 09404200; Colorado River above Diamond Creek near Peach Springs, established in 1990; gage number 16 in Fig. 1), approximately 240 river miles downstream from Glen Canyon Dam. The upstream end of Lake Mead at full pool is only 15 miles downstream from this gage. ***The measurements above Dimond Creek allow direct calculation of the total inflows of tributaries and springs in the east-central and west-central Grand Canyon.***

Another gage that greatly advances understanding of the sources of intervening inflows is the gage near the mouth of the Little Colorado River (USGS gage 09402300; Little Colorado River near Desert View; drainage area 26,972 mi^2; gage number 12 in Fig. 1). The difference between measured flow at the gage near Cameron and the Desert View gage primarily represents inflow from large springs near the mouth of this tributary that maintain perennial flow, even though the additional increase in drainage basin area between the two gages is relatively small. We assumed that all flow measured at the gage near the mouth of Kanab Creek (USGS gage 09403850; Kanab Creek above the mouth near Supai; drainage area 2367 mi^2; gage number 14 in Fig. 1) comes from spring flow within Grand Canyon, because most upstream water is used for irrigated agriculture. We assumed that all flow measured at the gage near the mouth of Havasu Creek (USGS gage 09404115; Havasu Creek above the mouth near Supai; drainage area 3020 mi^2; gage number 15 in Fig. 1) comes from spring flow within Grand Canyon, although a small amount is actually surface flow that occurs during the season of the North American monsoon (Melis et al. 1996).

The amount of intervening inflow in the upstream 87 miles of the Grand Canyon that does not come from the Paria River or from the large Little Colorado River watershed beyond the Grand Canyon and upstream from Cameron can be calculated by:

$$Q_{LFtoGC} = Q_{GC} - Q_{LF} - Q_{LCR\_Cam} - Q_{Paria} \qquad (1)$$

where Q_{LFtoGC} represents intervening inflow between the Grand Canyon gage and the Lees Ferry gage, Q_{GC} represents streamflow measured at the Grand Canyon gage (USGS gage 09042500), Q_{LF} represents streamflow measured at Lees Ferry (USGS gage 09380000), Q_{LCR_Cam} represents streamflow of the Little Colorado River measured near Cameron (USGS gage 09402000) and Q_{Paria} represents streamflow of Paria River measured at Less Ferry (USGS gage 09382000).

The amount of intervening inflow to 153 miles downstream from the Grand Canyon gage was calculated by:

$$Q_{GCtoDC} = Q_{DC} - Q_{GC} \qquad (2)$$

where Q_{GCtoDC} represents intervening inflow between the gage above Diamond Creek and the Grand Canyon gage, Q_{DC} represents streamflow of Colorado River above Diamond Creek (USGS gage 09404200) and represents Q_{GC} streamflow measured at Grand Canyon gage (USGS gage 09042500).

Between 1990 and 2018, reservoir releases averaged 9.175 maf/yr, and the reported average annual flow at Lees Ferry was 9.270 maf/yr. Intervening inflows between Lees Ferry and the Diamond Creek gage during this period averaged 768,000 af/yr, of which 17% (133,000 af/yr) came from the large watersheds of the Paria and Little Colorado Rivers beyond the Grand Canyon, and 83% (on average 635,000 af/yr) came from ground-water sources within the Grand Canyon (Fig. 6). ***Thus, ground-water inflows to the Colorado River that arose within the Grand Canyon were significant, and averaged 635,000 af/yr between WY1990 and WY2018 (Table 2).***

Photo courtesy Michael Collier

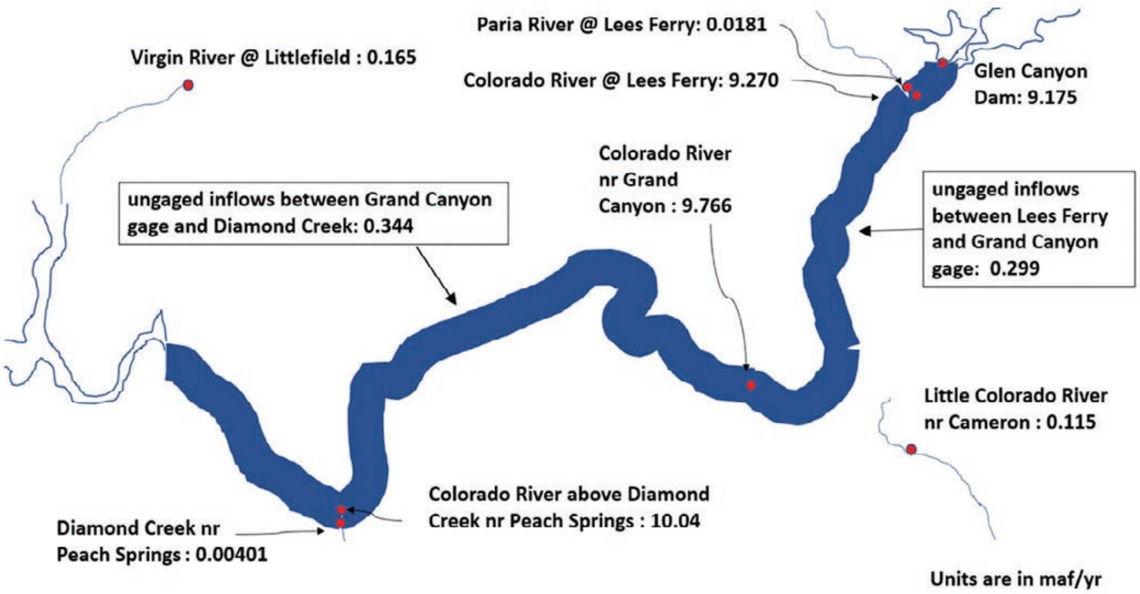


Figure 6. Diagram showing average annual flows between Glen Canyon Dam and Lake Mead between 1990 and 2018. See Table 2 for data and sources. The width of each line is proportional to that river's annual flow.

Table 2. Average annual flows between Lake Powell and Hoover Dam between 1990 and 2018.

Measurement location	Reporting agency	USGS gage number	Gage number in Figure 1	Average total annual flow (maf/yr)
Glen Canyon Dam releases	Reclamation	-	-	9.175
Colorado River at Lees Ferry	USGS	09380000	9	9.270
Paria River at Lees Ferry	USGS	09382000	10	0.0181
Little Colorado River nr Cameron	USGS	09402000	11	0.115
Ungaged inflows to Colorado River within Grand Canyon (Lees Ferry to Grand Canyon gage) [1]	-	-	-	0.299
Colorado River nr Grand Canyon[1]	USGS	09402500	13	9.766
Ungaged inflows to Colorado River within Grand Canyon (Grand Canyon gage to Diamond Creek) [1]	-	-	-	0.344
Total ungaged inflows (Lees Ferry to Diamond Creek)	-	-	-	0.768
Total ungaged inflows that arise within Grand Canyon (Lees Ferry to Diamond Creek)	-	-	-	0.635
Colorado River nr Peach Springs	USGS	09404200	16	10.04
Diamond Creek nr Peach Springs [2]	USGS	09404208	17	0.00401
Virgin River @ Littlefield	USGS	09415000	18	0.165
Hoover Dam releases	Reclamation	-	-	9.530

[1] Does not include WY1993-1995

[2] Annual flows not reported in WY1990-1993

Annual flow data collected between 2007 and 2018 allow a more precise estimate of the sources of intervening inflow, because these data quantify more of those sources of intervening flows (Fig. 7). Between those years, ~99% of the gaged inflow to Lake Mead came from the Colorado River, based on measurements of the Colorado River above Diamond Creek (Table 3). Of the total delivered to Lake Mead by the Colorado River, ~92% was released from the Glen Canyon Dam or seep around the dam, and 8% came from tributaries and springs within the Grand Canyon or from the Paria or Little Colorado Rivers. Sources of intervening inflow from within the Grand Canyon, including inflows into the lower Little Colorado River, contributed an average of 710,000 af/yr, and only 114,000 af/yr came from the Paria River or from the Little Colorado River upstream from the Cameron gage. Approximately 48% of intervening inflows entered the Colorado River further downstream. Most of the intervening inflow upstream from the Grand Canyon gage came from the springs in the lower Little Colorado River Canyon (on average 172,000 af/yr) and from ungaged springs and ungaged tributaries elsewhere (on average 146,000 af/yr). Downstream from the Grand Canyon gage, Kanab and Havasu Creek contributed a very small amount of inflow. ***Thus, gaging measurements between 2007 and 2018 suggest that most of the intervening inflows came from spring sources within the Grand Canyon that directly drain to the Colorado River or its perennial tributaries. Springs in the lower part of the Little Colorado River canyon are a large source of water. Calculation of the magnitude of these inflows is only possible, because there are gages of the Little Colorado River at its mouth and of the Colorado River above Diamond Creek.***

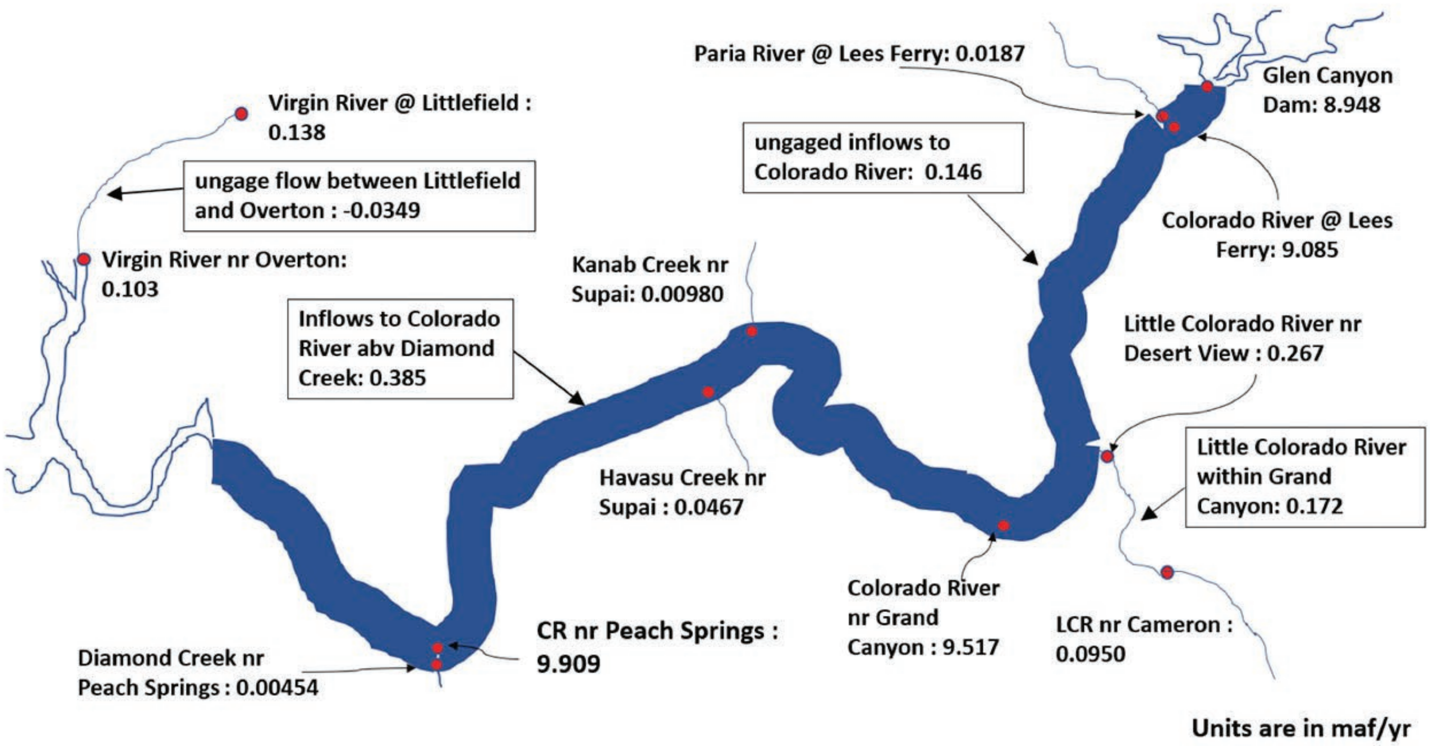


Figure 7. Diagram showing average annual flows between Lake Powell and Hoover Dam between 2007 and 2018. See Table 3 for data and sources. The width of each line is proportional to that river's annual flow.

Table 3. Average annual flows between Lake Powell and Hoover Dam between 2007 and 2018.

Measurement location	Agency	USGS gage number	Gage number in Figure 1	Average total annual flow (maf/yr)	Total gains between Lees Ferry and indicated location (maf/yr)	Percentage of all gains from indicated source
Glen Canyon Dam releases	Reclamation	-	-	8.948	-	-
Colorado River at Lees Ferry	USGS	09380000	9	9.085	-	-
Paria River at Lees Ferry	USGS	09382000	10	0.0187	-	2%
Little Colorado River nr Cameron	USGS	09402000	11	0.0950	-	12%
Little Colorado River nr Desert View	USGS	09402300	12	0.267	-	-
Little Colorado River within Grand Canyon	-	-	-	0.172	-	21%
Ungaged inflows to Colorado River, not including Paria or Little Colorado River	-	-	-	0.146	-	18%
Colorado River nr Grand Canyon	USGS	09402500	13	9.517	0.432	-
Kanab Creek nr Supai	USGS	09403850	14	0.00980	-	-
Havasu Creek nr Supai	USGS	09404115	15	0.0467	-	-
Inflows to Colorado River abv Diamond Creek, including Kanab and Havasu Creeks	-	-	-	0.392	-	48%
Colorado River nr Peach Springs	USGS	09404200	16	9.909	0.824	-
Diamond Creek nr Peach Springs	USGS	09404208	17	0.00454	-	-
Virgin River @ Littlefield	USGS	09415000	18	0.138	-	-
Ungaged inflows to Virgin River blw Littlefield	-	-	-	-0.0349	-	-
Virgin River nr Overton	USGS	09415250	19	0.103	-	-
Hoover Dam releases	Reclamation	-	-	9.323	-	-

A Water Budget for Lake Mead

We constructed a water budget of Lake Mead between March 2010 and February 2015, because detailed measurements of evaporation were made during that period (Moreo and Swancar, 2013; Moreo, 2015). Inflows to Lake Mead measured above Diamond Creek averaged 10.13 maf/yr during this period (Table 4). Gaged inflows from Diamond Creek and the Virgin River were insignificant.

Anning (2002) estimated the uncertainty of annual flow measurements at gaging stations in the Lower Basin and found that the standard error of estimated total annual flow was less than 1% for three mainstem gages with stable gaging conditions (below Davis Dam, below Parker Dam, and above Imperial Dam). In contrast, uncertainty for remote streams with unstable gaging conditions, such as the Gila River near Dome and the Bill Williams River, was between + 3% to 12% and between ± 2% to 4%, respectively.

We assumed that the uncertainty of estimates of annual flow of the Colorado River above Dimond Creek is ±2%. Based on this assumption, the uncertainty of annual flows of the Colorado River upstream from Diamond Creek for the study period was~ 405,000 af/yr, which is greater than the average annual consumptive use by the state of Nevada during the same period. The uncertainty associated with measuring stream flow of small tributaries matters little to the overall water budget, because those flows are very small. If one assumes uncertainties of ± 3% to 5%, none of the uncertainties associated with inflow from small tributaries exceed 15,000 af/yr.

Approximately 92% of the outflows from Lake Mead occurred by Hoover Dam releases (Fig. 8 and Table 5). Between 1935 and 2017, the USGS reported data for a gage immediately downstream from Hoover Dam (USGS gage 09421500, Colorado River below Hoover Dam). Since at least 2006, the reported mean daily data and the computed monthly and annual data were those provided to the USGS by Reclamation, whose measurements has been based on acoustic velocity meters since the 1990s. We assumed the uncertainty in those data to be within ± 1%.

In order to evaluate whether the reported inflows equalled the reported outflows, we considered the uncertainties associated with each measurement and standard arithmetic procedure for maintaining the correct significant figures in calculations. Water withdrawn from Lake Mead by the Southern Nevada Water Authority is precisely measured, because it represents Nevada's consumptive uses and losses that are reported in the annual water accounting reports. The water accounting reports quantify the amount of water diverted from Lake Mead and the amount of water returned to Lake Mead in Las Vegas Wash. Nevada's consumptive uses of Lake Mead are the difference between these two measurements. We assumed 2% uncertainty for the estimate of Nevada's consumptive uses primarily because of uncertainty in estimating the return flows in Las Vegas Wash.

Table 4. Annual reservoir releases and streamflow in the Grand Canyon region between March 2010 and February 2015

Period	3/2010 to 2/2011 (maf/yr)	3/2011 to 2/2012 (maf/yr)	3/2012 to 2/2013 (maf/yr)	3/2013 to 2/2014 (maf/vr)	3/2014 to 2/2015 (maf/vr)	Average (maf/vr)
Glen Canyon Dam releases	8.604	13.19	8.112	7.980	7.992	9.175
Colorado River @ Lees Ferry	8.770	13.36	8.145	8.025	8.126	9.285
Paria River @ Lees Ferry	0.0256	0.0139	0.0162	0.0259	0.0196	0.0202
Little Colorado River nr Cameron	0.201	0.0430	0.0649	0.123	0.0489	0.0961
Ungaged inflows abv Grand Canyon gage, not including Paria or Little Colorado River	0.293	0.334	0.300	0.324	0.317	0.314
Colorado River nr Grand Canyon	9.289	13.750	8.525	8.498	8.512	9.715
Ungaged inflows	0.443	0.370	0.416	0.505	0.363	0.419
Colorado River abv Diamond Creek nr Peach Springs	9.732	14.12	8.941	9.003	8.875	10.13
Diamond Creek nr Peach Springs	0.00618	0.00399	0.00358	0.00452	0.00504	0.00466
Virgin River nr Overton	0.200	0.208	0.0810	0.0738	0.0790	0.128
Hoover Dam releases	9.591	9.522	9.153	9.443	9.724	9.487

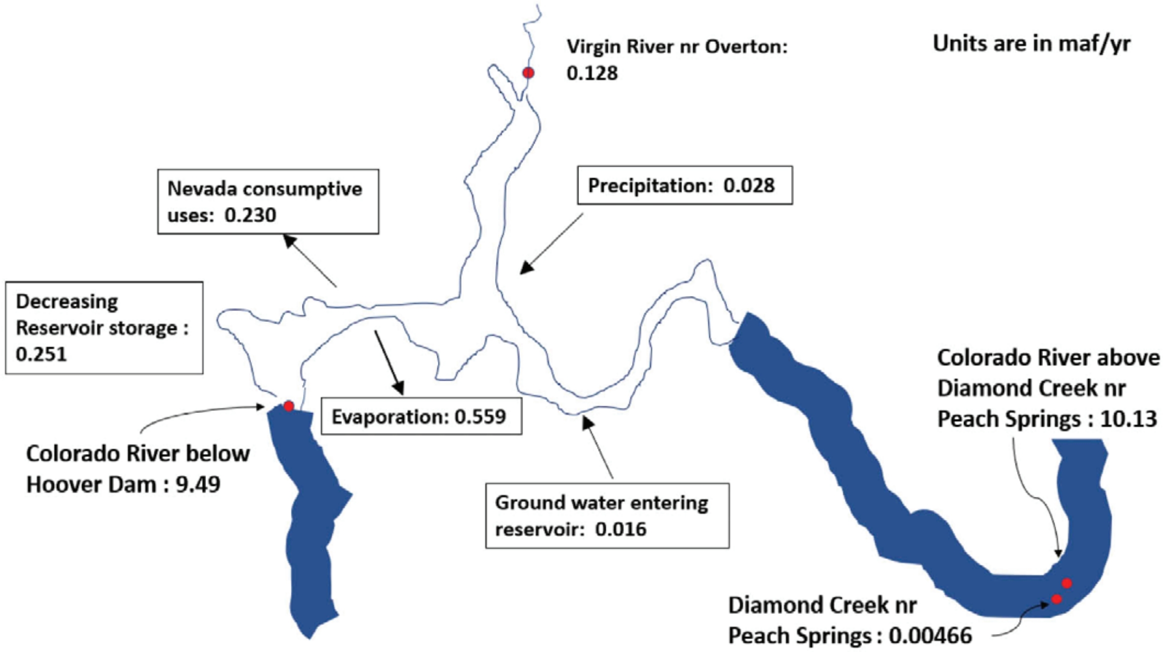


Figure 8. Water budget components for Lake Mead between March 2010 and February 2015. The width of each line is proportional to that river's annual flow.

Table 5. A water budget for Lake Mead between March 2010 and February 2015

Item	Reported value (maf/yr)	Uncertainty (minimum value) (maf/yr)	Uncertainty (maximum value) (maf/yr)	Assumed uncertainty (±)
Inputs				
Colorado River above Diamond Creek near Peach Springs	10.13	9.93	10.33	2%
Diamond Creek near Peach Springs	0.00466	0.00443	0.00489	5%
Virgin River above Lake Mead near Overton	0.128	0.122	0.134	5%
Gage inflows	**10.26**	**10.05**	**10.47**	-
Precipitation	0.028	0.025	0.031	10%
Ground water entering reservoir (bank storage)	0.016	0.014	0.018	15%
Gage inflows and other inputs	**10.31**	**10.09**	**10.52**	-
Change in reservoir storage	0.251	0.246	0.256	2%
Total inflows and other inputs, including change in storage	**10.56**	**10.34**	**10.78**	-
Outputs				
Colorado River below Hoover Dam	9.49	9.40	9.58	1%
Nevada consumptive uses[1]	0.230	0.225	0.235	2%
Evaporation	0.559	0.539	0.580	-
All outflows including losses	**10.28**	**10.16**	**10.40**	-

[1] Total withdrawals minus return flow from Las Vegas Wash

During the study period, evaporation was measured by Moreo and Swancar (2013) and Moreo (2015) using the energy-balance-corrected, eddy covariance method. They determined that the most probable values of the annual evaporation rate were between 5.7 ft/yr and 6.8 ft/yr in the different years of their study. These evaporation data are considered state-of-the-science. We multiplied the most probable monthly evaporation rates, as well as the likely minimum and maximum monthly evaporation rates, of each month by the average reservoir surface area of each month to determine the minimum, most probable, and maximum monthly evaporation from Lake Mead.

For the 5 years considered here, evaporation losses were ~559,000 af/yr and were 5.4% of the total outflows and losses from Lake Mead. ***Evaporation losses from Lake Mead were more than twice the consumptive uses by the state of Nevada***. Nevada's consumptive uses of Lake Mead were approximately 230,000 af/yr and were only 2.2% of the total outflows and losses from the reservoir.

A water budget also includes the increases or decreases in reservoir volume. Between March 2010 and February 2015, Lake Mead decreased in reservoir storage by ~1.254 maf, although water storage increased for a few months during CY 2011 when inflow was large. The net change in reservoir storage between the beginning and end of the study period augmented the inflows, thereby sustaining the outflows.

Bank storage is the amount of water exchanged with the surrounding ground-water system (Harbeck et al, 1958; Langbein, 1960; Wiele et al, 2009). Water enters the surrounding geologic deposits when the reservoir increases in storage, and water enters the reservoir from the surrounding deposits when reservoir elevation declines. Bank storage is very difficult to measure and was estimated by Reclamation to be 6.5% of the change in reservoir storage (Reclamation, 1985). We assumed this value in our water budget. We estimated the monthly precipitation over Lake Mead by reviewing monthly maps of precipitation (available at https://water.weather.gov/precip/index.php) and multiplying that value by the reservoir surface area to determine total inputs of precipitation.

Between March 2010 and February 2015, gaged surface-water inflows were 10.26 maf/yr, and ***the range of uncertainty*** (10.05 to 10.47 maf/yr) ***was dominated by our assumption about the uncertainty in the estimated inflow of the Colorado River***. Ground-water inflow and precipitation were very small inputs between March 2010 and February 2015, and their contribution did not significantly affect the total estimated inflows. The sum of these inflows was 10.31 maf/yr (10.09 to 10.52 maf/yr). The estimated total outflows were approximately the same and were 10.28 maf/yr (10.16 to 10.40 maf/yr). Total outflows were caused by release from Hoover Dam (9.49 maf/yr; 9.40 to 9.58 maf/yr), and the uncertainty of this release, even though assumed to be only 1%, was much larger than the uncertainty of the other outflows. Although the inflows are approximately equal to the outflows, the water budget for Lake Mead during this period is not physically reasonable, because Lake Mead storage decreased at a rate of 0.251 maf/yr (0.246 to 0.256 maf/yr) during the same period. The decrease in Lake Mead storage was an additional source of water that supported the outflows, and the sum of the inflows plus the decrease in storage should equal the outflows. Addition of the loss in storage to the measured flows results in an estimate of 10.56 maf/yr (10.34 to 10.78 maf/yr) that should equal the total estimated outflows. For the study period, ***average total annual inflows (including gage inflow, precipitation, ground water entering reservoir) plus the change in reservoir storage exceeded the total outflows (Hoover Dam releases, net Nevada withdrawals, and evaporation) by 280,000 af/yr during this 5-year period, approximately equal to the annual consumptive uses of Nevada.*** If one considers the uncertainty in the different values that comprise the water budget, then the ranges of uncertainty of total inputs and outputs overlap. In other words, ***the water budget only makes physical sense if one accepts that the uncertainty of measurements of the various inflows and outflows that is ±200,000 af/yr. The most significant source of uncertainty with budget component volumes is likely to be the measured inflows from the Colorado River at the gage upstream from Diamond Creek, suggesting that the flow above Diamond Creek may be biased to represent more flow than is actually the case.***

How the Natural Flow Data Base and CRSS consider the hydrology of the southern Colorado Plateau

Natural flows are the estimated natural runoff of the Colorado River that would have occurred without consumptive uses and losses caused by irrigated agriculture, municipal or industrial uses, trans-basin diversions, reservoir storage, or reservoir operations. In the Upper Basin, natural flows are estimated for 20 gage locations and reported in Reclamation's Natural Flow and Salt Data base (available at [https://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html)](https://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html). There are 9 gage locations in the Lower Basin, but none of those reported data are true natural flows that meet the definition above. Data for four Lower Basin tributaries (Paria, Little Colorado, Virgin, and Bill Williams) are actual flow, as measured and reported by the USGS, and reflect upstream consumptive uses and losses. No data are reported for Gila River. Data for the three mainstem gages are a combination of estimated upstream, mainstem natural flows plus the actual measured inputs from these tributaries. Data from the 29 gage sites, as well as the calculated amount of intervening flow that enters between the gages are used for the planning and

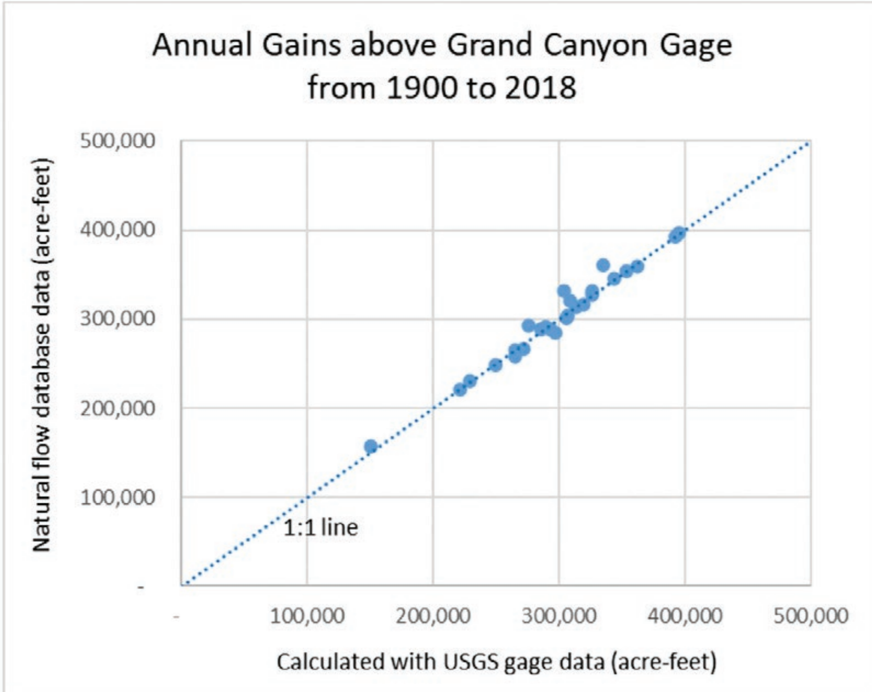


Figure 9. Graph showing annual intervening flows between Lees Ferry and the Grand Canyon gage calculated from USGS gaging data and reported by Reclamation in the Natural Flow Data base.

management of the Colorado River using Colorado River Simulation System (CRSS).

We compared natural flow data reported for intervening flows between Lees Ferry and Lake Mead with the measured gains calculated from the difference between upstream and downstream measurements at the USGS gages for 1990 to 2018. As described in a preceding section, intervening flows upstream from the Grand Canyon gage were calculated using equation (1). Although the reported natural flows at Lees Ferry and Grand Canyon significantly differ from the actual flows, the intervening flows reported by Reclamation and calculated from USGS gaging data are consistent with one another (Fig. 9).

We made a similar comparison of estimated intervening flows downstream from the Grand Canyon gage between 2007 and 2018. Reclamation reports the sum of intervening flows in the east-central and west-central Grand Canyon, the Virgin River, and minor tributaries to Lake Mead. We compared these annual data with the annual intervening flow calculated from the difference between the reported annual flow of the Colorado River above Diamond Creek and the reported flow at the Grand Canyon gage using equation (2). We added this value to the calculated difference between measured flow of the Virgin River at Littlefield and near Overton. The estimated intervening flows calculated from the USGS gaging data was always higher than the intervening flows reported in the Natural Flow Data base from WY 2007 to WY 2018 (Fig. 10), and the actual intervening inflows exceeded those reported in the Natural Flows database averaged 260,000 af/yr. In fact, there are some years in which the reported intervening flows in the Natural Flow Data base are negative numbers, which is a physical impossibility. The measured annual intervening flows in the east-central and west-central Grand Canyon averaged 344,000 af/yr (Table 2). The primary reason for that the intervening inflows estimated in the Natural Flow database are too small is that these intervening flows are an accounting artifact that balances the uncertainty in measuring other hydrologic processes that are part of Lake Mead's water budget. ***The intervening flows between Lees Ferry and the Grand Canyon gage reported by Reclamation in the Natural Flow Data base are a true estimate of actual intervening flows. However, the intervening flows between the Grand Canyon gage and Hoover Dam reported in the Natural Flow Data base are not a true estimate and are an accounting artifact.***

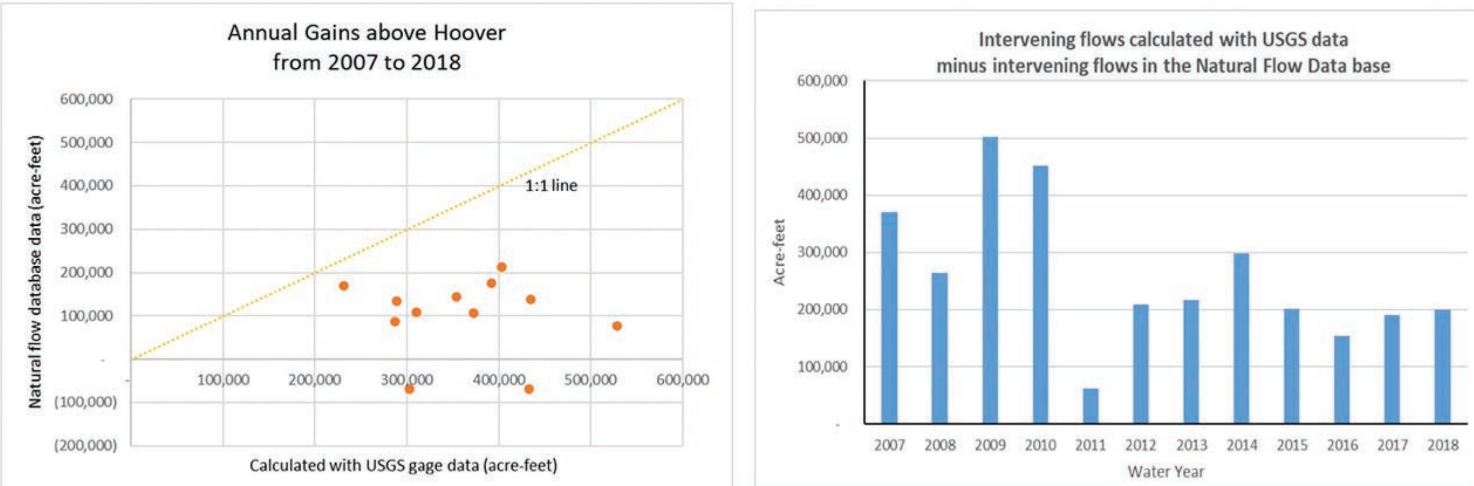


Figure 10. Graph showing annual intervening flows between the Grand Canyon gage and Hoover Dam calculated from USGS gaging data and reported by Reclamation in the Natural Flow Data base.

A Water Budget for Lake Powell

The components of a water budget for Lake Powell are less well understood than for Lake Mead and the uncertainties are greater. The stream-flow measurement sites are more numerous and further upstream from the reservoir than is the case for Lake Mead. However, the uncertainty associated with ungaged inflows is less at Lake Powell, because the drainage area of ungaged inflows to Lake Powell is less than to Lake Mead. The area draining to Lake Powell that is downstream from all of these gages is 10,255 mi^2, and is less than the 13,986 mi^2 of ungaged watershed that drain to Lake Mead.

Modern, state-of-the-science measurements of evaporation are not available at Lake Powell, although a new program of eddy covariance measurements of evaporation is presently underway. The uncertainty in reported outflows from Lake Powell was discussed in a preceding section. Reservoir releases have been more precisely measured since 2005 when acoustic velocity meters were installed in the Glen Canyon Dam powerplant. Exchange of water with the surrounding bedrock was studied by Blanchard (1986) and Thomas (1986) and estimated by Myers (2013). Here, we describe the components of a water budget for WY2016 to WY2019 that incorporates annual flow data from new gages on the Colorado and Green Rivers.

Inflows to Lake Powell

The Colorado River has been measured since 1913 (USGS gage 09180500, Colorado River near Cisco; drainage area 24,100 mi^2; gage number 1 in Fig. 1), and the gage measures flow from most of the watershed including the Dolores River. A new gage was established around 46 miles downstream at Potash Road near Moab, UT in 2014 (USGS gage 09185600, Colorado River at Potash; 25,406 mi^2; gage number 2 in Fig. 1), and this new site reduces the uncertainty associated with ungaged inflows to a small degree. Annual flow data are available for this site beginning in WY2016. The measured flow at Potash was 4.411 maf/yr between WY 2016 and WY2019 and was 41,000 af/yr higher than the flow measured flow at Cisco (Table 6). The uncertainty in estimating annual flow is evident in comparison of the Cisco and Potash data, because reported annual flow at Potash is not always higher than at Cisco. For example, in WY2019, annual flow at Potash was 10,000 af/yr less than at Cisco, which is unlikely.

Stream flow of the Green River has been measured since 1894 (USGS gage 09315000; Green River at Green River, UT; drainage area 44,850 mi^2; gage number 3 in Fig. 1), and flow at this site comes from the two headwater branches of the river system – the upper Green River and the Yampa River – as well as other tributaries. Since 2014, a gage ~68 river miles further downstream and just north from Canyonlands National Park (USGS gage 09328920, Green River at Mineral Bottom near Canyonlands National Park, drainage area 48,560 mi^2; gage number 5 in Fig. 1) has measured flow. This gage is downstream from the San Rafael River and therefore eliminates the need to estimate inflows from this large tributary. The reported flow at Mineral Bottom was 4.110 maf/yr (Table 6) between WY2016 and WY2019 and was 36,000 af/yr higher than the measured flow at the Green River gage. The reduction in uncertainty associated with estimating inflows from the San Rafael River is illustrated by the fact that the reported flow at Mineral Bottom for this period was 30,000 af/yr less than the sum of the measured flow at the Green River gage and the long-term gage on the San Rafael (USGS gage 09328500, san Rafael near Green River, drainage area 1628 mi^2; gage number 4 in Fig. 1). This discrepancy might be associated with measurement uncertainty, because the San Rafael gage is remote and has an unstable

Table 6. Annual streamflow to Lake Powell between October 2015 and September 2019

Gage	Source	USGS gage number	Gage number in Figure 1	WY2016 (maf/yr)	WY2017 (maf/yr)	WY2018 (maf/yr)	WY2019 (maf/yr)	Average (maf/yr)
Colorado River near Cisco	USGS	09180500	1	4.538	4.676	2.511	5.753	4.369
Colorado River at Potash	USGS	09185600	2	4.572	4.811	2.518	5.743	4.411
Green River at Green River	USGS	09135000	3	3.977	5.074	2.941	4.305	4.074
San Rafael River near Green River	USGS	09328500	4	0.0293	0.0958	0.0134	0.127	0.066
Green River at Mineral Bottom	USGS	09328920	5	3.996	5.161	2.872	4.410	4.110
Dirty Devil River above Poison Springs Wash near Hanksville	USGS	09333500	6	0.0795	0.0598	0.0380	0.0739	0.0628
Escalante River near Escalante	USGS	09337500	7	0.0052	0.0050	0.0019	0.0060	0.0045
San Juan River near Bluff	USGS	09379500	8	1.246	1.423	0.4818	1.327	1.119
Glen Canyon Dam release	Reclamation	-	-	9.000	9.000	9.000	9.001	9.000
Colorado River at Lees Ferry	USGS	09380000	9	9.118	9.151	9.158	9.245	9.168

rating relation (Fortney, 2015), but there are many losses as the San Rafael River crosses the San Rafael Desert downstream from the gage, and loss of flow might be real.

The San Juan River has been measured at the community of Mexican Hat (USGS gage 09379500; San Juan River near Bluff; drainage area 23,000 mi^2; gage number 8 in Fig. 1) since November 1914, and the annual stream flow was 1.119 maf/yr between WY2016 and WY2019. Other measured inflows to Lake Powell are from the Dirty Devil River (USGS gage 09333500, Dirty Devil River above Poison Spring Wash near Hanksville; drainage area 4159 mi^2; gage number 6 in Fig. 1) and the Escalante River (USGS gage 09337500; Escalante River near Escalante; drainage area 320 mi^2; gage number 7 in Fig. 1) that have been measured since 1948 and 1942, respectively. Myers (2013) attempted to estimate the ungaged inflow to Lake Powell, but we could not replicate his analysis or results and therefore, did not consider these contributions in our analysis.

Water Budget Analysis for Lake Powell

We calculated the water budget of Lake Powell for WY2016 through WY2019. Although this period is relatively short, reported annual flow data of the Colorado River at Potash are only available for this period. During the study period, Reclamation reported that it released 9.000 maf/yr from Glen Canyon Dam, and the USGS reported that the average annual flow of the Colorado River at Lees Ferry was 9.168 maf/yr (Fig. 11 and Table 7). As described in a preceding section, this increase in flow between these two measurement points probably reflects the magnitude of seepage around Glen Canyon Dam, though the accuracy and appropriate precision of the seepage in unknown.

Between WY2016 and WY2019, 99% of the inflow to Lake Powell came from the upper Colorado, Green, and San Juan Rivers (Table 6). Between WY2016 and WY2019, the annual average flow from the Dirty Devil and Escalante Rivers was 66,000 af/yr and 5,000 af/yr, respectively. Total inflow to Lake Powell from all gaged streams averaged 9.711 maf/yr over the study period (Table 7). On average, the upper Colorado River, measured at Potash, contributed the largest amount -- 4.411 maf/yr – and the Green River contributed slightly less – 4.110 maf/yr. Inflow from the San Juan River averaged 1.119 maf/yr. We considered the uncertainty of reported annual flow of each of the headwater branch gages to be 2%, and we considered the uncertainty of the Dirty Devil and Escalante River data to be 5%

The precipitation rate was assumed to be equal to the historical Lake Powell precipitation rates estimated in the U.S. Climate Data base (available at https://www.usclimatedata.com/climate/lake-powell/utah/united-states/usut0284), and missing data were estimated from regional precipitation maps of the National Weather Service (available at https://water.weather.gov/precip/index.php). Monthly precipitation was calculated by multiplying the precipitation rate by the average reservoir surface area of each month. The uncertainty of precipitation was assumed to be 10%. Bank storage is difficult to estimate, and we assumed change in bank storage equalled 8% of change in Lake Powell storage, which is consistent with the assumption used by Reclamation (Reclamation, 1985). Extrapolation of Thomas' (1986) modelling results suggests that seepage away from a full Lake Powell would be between 30,000 and 50,000 af/yr, and Lake Powell was never

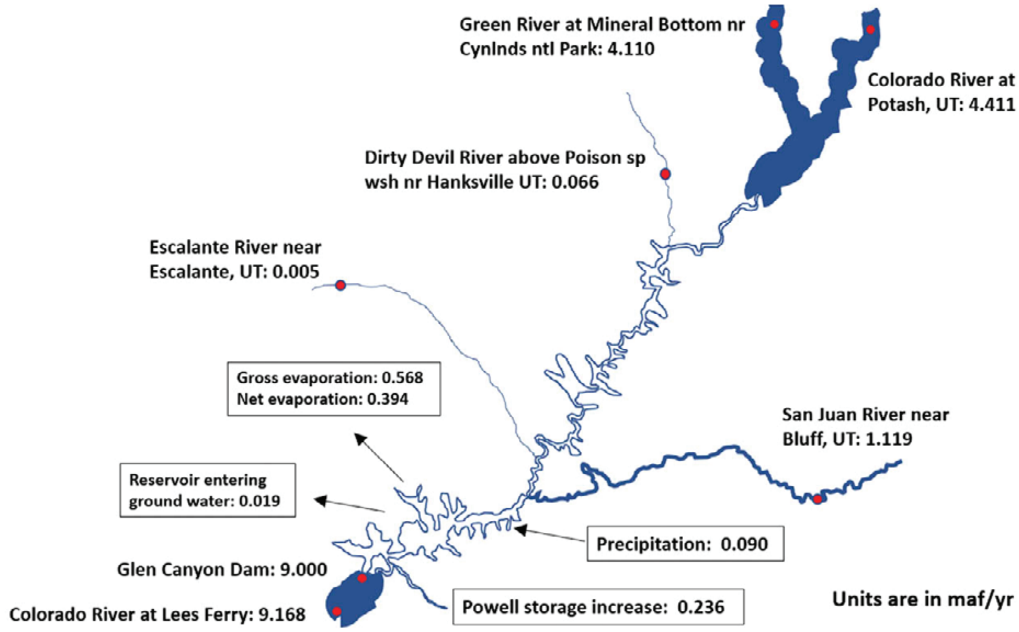


Figure 11. Water budget components for Lake Powell between October 2015 and September 2019. The width of each line is proportional to that river's annual flow.

Table 7. A water budget for Lake Powell between October 2015 and September 2019

Item	Averaged Reported (maf/yr)	Uncertainty range (min) (maf/yr)	Uncertainty range (max) (maf/yr)	Assumed uncertainty (±)
Inputs				
Green River at Mineral Bottom nr Cynlnds ntl Park	4.110	4.028	4.192	2%
Colorado River at Potash, UT	4.411	4.323	4.499	2%
Dirty Devil River above Poison sp wsh nr Hanksville UT	0.066	0.063	0.069	5%
Escalante River near Escalante, UT	0.005	0.005	0.005	5%
San Juan River near Bluff, UT	1.119	1.097	1.141	2%
Total inflow	**9.711**	**9.515**	**9.907**	-
Precipitation	0.090	0.081	0.099	10%
All inputs	**9.801**	**9.596**	**10.01**	-
Outputs				
Glen Canyon Dam releases	9.000	8.910	9.090	1%
Colorado River at Lees Ferry, AZ	9.168	9.076	9.260	1%
Gross evaporation	0.568	0.408	0.775	-
Net evaporation	0.394	0.296	0.493	25%
Reservoir water entering Ground water (bank storage)	0.019	0.016	0.022	15%
Powell storage increases	0.236	0.234	0.238	1%
Total outflow calculated as Lees Ferry flow and gross evaporation	**9.991**	**9.735**	**10.30**	-
Total outflow calculated as Glen Canyon Dam releases and net evaporation	**9.649**	**9.455**	**9.843**	-

full during our study period. The change of reservoir storage during the study period was small. Using Reclamation's bank storage rate, we estimate that the total loss of water into bank storage was only 19,000 af/yr.

Unlike Lake Mead, state-of-the-art measurements of evaporation from Lake Powell are not available. We used evaporation rates estimated by Reclamation (1986), originally calculated for the period 1965-1979. These estimates were based on the mass transfer method, and the annual rates for the original study period ranged from 4.1 to 7.8 ft/yr. We multiplied the average monthly evaporation rate reported by Reclamation (1986), as well as the lowest rate for each month and the highest rate for each month, to define the most probable, minimum, and maximum gross evaporation rate. We multiplied these rates by the average reservoir surface area of each month between WY2016 and WY2019 to determine the most probable gross evaporation from Lake Powell, as well as the range of uncertainty.

For purposes of administration of the Colorado River Compact and the Upper Colorado River Compact, Reclamation reports net evaporation from Lake Powell in its semi-decadal Upper Basin water accounting reports (Upper Colorado River Basin Consumptive Uses and Losses Reports, available at https://www.usbr.gov/uc/envdocs/plans.html). Net evaporation is calculated as the gross evaporation minus the estimated evapotranspiration losses that occurred from the Colorado River, its riparian vegetation, and the surrounding hillsides before construction of Glen Canyon Dam. We also calculated the net evaporation from Lake Powell. Reclamation (2007b, Appendix A, Table A-20) reported long-term average annual net evaporation as 3.959 ft/yr, and we assumed the uncertainty of this value to be 25% in our analysis.

When assembled into a water budget, estimated inflows and outflows differ, but the ranges of uncertainty overlap, however there is greater uncertainty in considering this overlap than was the case for Lake Mead. Inflows were on average 9.711 maf/yr (9.515 to 9.907 maf/yr). With the addition of the contribution of estimated precipitation, the total calculated inputs were 9.801 maf/yr (9.596 to 10.01 maf/yr) (blue line, Fig. 12).

As described in a preceding section, there is greater uncertainty in estimating the outflows from Lake Powell, because one can either consider the reported Glen Canyon Dam releases or the reported flow past Lees Ferry. Reported Lees Ferry flow is 168,000 af/yr higher than the reported Glen Canyon Dam releases for this time period, and this increase is presumably due to seepage around the dam.

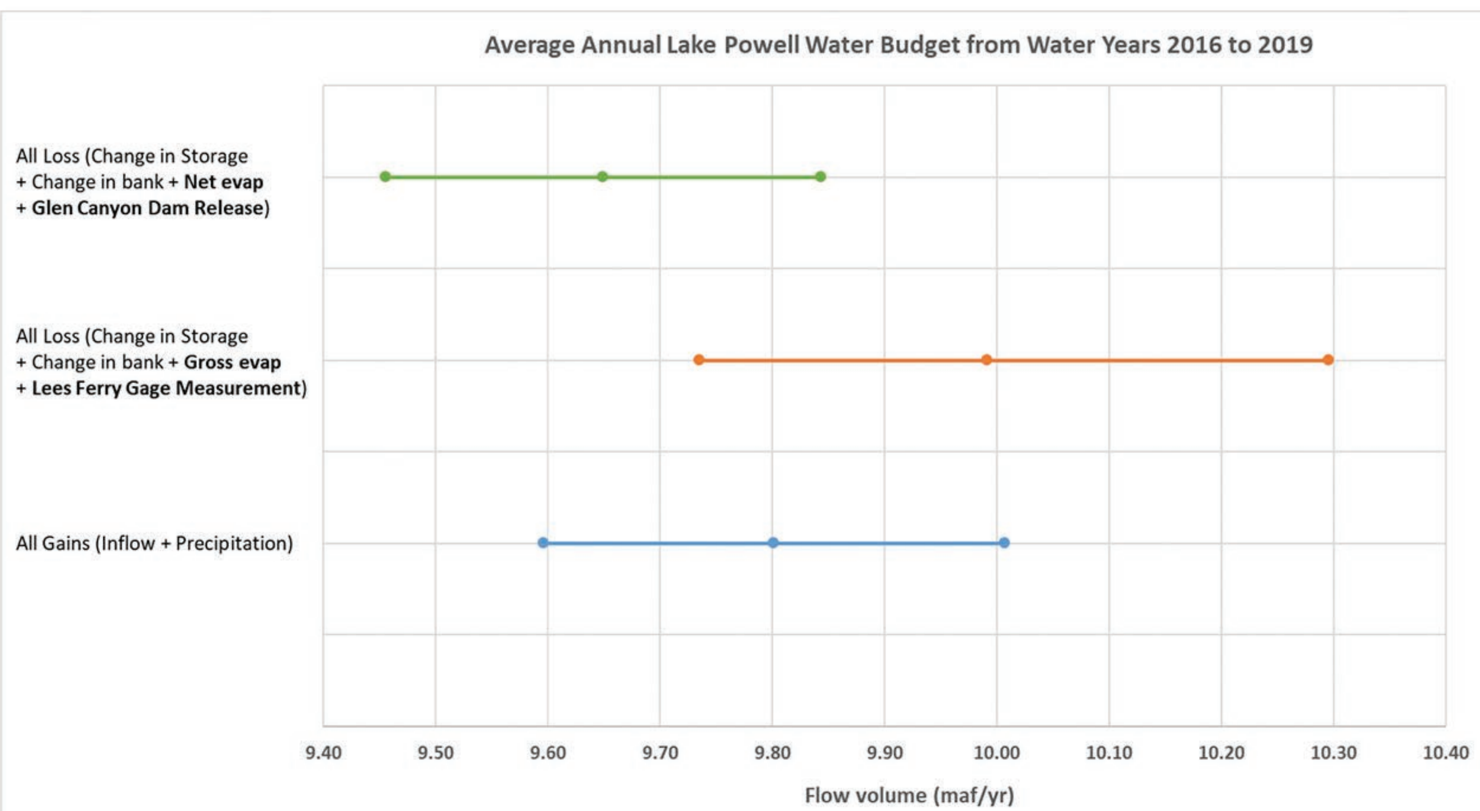


Figure 12. Diagram showing average annual Lake Powell gains and losses with uncertainty range, based on different assumptions that are described in the text.

We estimated that gross evaporation during the study period was 568,000 af/yr (408,000 to 775,000 af/yr) and that the net evaporation was 394,000 af/yr (296,000 to 493,000 af/yr). We also considered the change in reservoir storage and the very small amount of estimated loss of water into the surrounding bedrock in our calculation of outflows and losses from the reservoir.

Larger outflows and losses from Lake Powell would be estimated if the Lees Ferry gaging data and the gross evaporation data were used. Both assumptions are physically reasonable. The sum of these outflows and losses was 9.991 maf/yr (9.735 to 10.30 maf/yr) (orange line, Fig. 12). The largest uncertainty in calculating these outflows and losses was associated with estimation of gross evaporation losses whose range was 367,000 af/yr (Table 7), because gross evaporation rates have not been reported for many decades. Ironically, calculation of outflows and losses based on summing Glen Canyon Dam releases reported by Reclamation and net evaporation reported by Reclamation (2007b) is physically unreasonable but yields an estimated total annual outflows and losses of 9.649 maf/yr (9.455 to 9.843 maf/yr), which is a value more similar to the estimated inflows during the study period (green line, Fig. 12).

Thus, between WY2016 and WY2019, the estimated outflows and losses are more balanced with estimated inflows if one uses the physically unrealistic values of Glen Canyon Dam releases and net evaporation. In any water budget, gross (or total) evaporation should be used, because net evaporation is merely an administrative concept developed to distinguish the increased losses caused by construction of Lake Powell. Thus, ***gross evaporation is the correct concept to employ in water budget calculation, but the data reported by Reclamation (1986) may be too large an estimate of this physical process. On-going studies of evaporation at Lake Powell will hopefully resolve this critical uncertainty.***

Findings and Recommendations

• There are several ***key gages*** that ***are not part of the network of gages used in CRSS and are not considered part of the standard network of gages used to manage the Colorado River.*** However, many of these gages offer critical insight into physical processes essential to understanding future watershed conditions. These gages include:

- ***Colorado River at Potash***, because data from this gage reduces the ungaged drainage area to Lake Powell by 1,306 mi^2.
- ***Green River at Mineral Bottom***, because data from this gage eliminates the need to estimate the contribution of inflow from the San Rafael River.
- ***Little Colorado River above mouth near Desert View***, because spring flow into the Little Colorado River downstream from Cameron contributes ~20% of all inflows (~170,000 af/yr) to the Colorado River between Lees Ferry and Lake Mead that arise within the Grand Canyon.
- ***Colorado River above Diamond Creek***, because this gage allows quantification of inflows to the Colorado River in the east-central and west-central Grand Canyon that are between 300,000 and 400,000 af/yr. ***Funding should be provided to USGS to improve the accuracy of reported annual flow at this gage, because these flows represent 99% of the inflows to Lake Mead.***

• ***Continue efforts by the USGS to establish a gage on the Colorado River at Hite.*** Hite is located at the delta of the Colorado River to Lake Powell. Such a gage would allow direct measurement of all inflows from the upper Colorado and Green Rivers into Lake Powell.

• ***There should be renewed study of the magnitude of inflows to the Colorado River that occur between Glen Canyon Dam and Lees Ferry.*** Measurements since 2005 consistently indicate that flow increases between these two points, and the magnitude of this difference is of the same order as the annual consumptive uses of the state of Nevada. This study should include ground-water modelling of seepage around Glen Canyon Dam and independent analysis of the accuracy of measurements of Glen Canyon Dam releases and gaging at Lees Ferry.

• ***Maintain the long-term program to measure evaporation from Lake Mead and make the present experimental program at Lake Powell a permanent monitoring program.*** Total, or gross, evaporation should be regularly reported for both reservoirs, because that is the actual amount of water lost to the atmosphere.

• ***Initiate studies to quantify bank storage at Lakes Mead and Powell***. In our study, we adopted the assumption used by Reclamation that monthly change of bank storage is a small fraction of monthly change of reservoir storage. Only limited data are available to evaluate this assumption. Bank storage estimates from 1962 to 2012 by Myers (2013) were very different from the bank storage estimates reported in the Natural Flow and Salt Data base.

• ***Clarify the different types of data in Reclamation's Natural Flow and Salt Data base.*** Data reported in this widely used data base include stations where natural flows are estimated and gages where actual measured flow is reported and there is no attempt to estimate natural flows. Natural flows of Lower Basin mainstem gages are calculated based on an amalgamation of natural and actual flow data and are not true natural flow estimates. ***Reported natural intervening flow of some segments are actually accounting artifacts associated with the uncertainty in reservoir water budgets. Users of this data base should be made aware of the inconsistencies among the data reported for each gage and for the intervening flows.***

• ***Water uses and losses, as described in Reclamation water accounting reports for the Upper and Lower Basin, should be reported to no more than 4 significant figures.*** Annual flow volumes of the mainstem Colorado River should not be reported to more than 2 decimal places (i.e., 10.12 maf/yr). The uncertainty in many reported annual flow volumes of the Colorado River in many years is of the order of the nearest 100,000 af/yr.

• ***Similar analysis of the uncertainty about stream flow measurements, other hydrologic processes, and water budgets should be conducted between Hoover Dam and the North International Boundary (NIB).*** Since intervening flows between the Grand Canyon gage and Hoover Dam reported in the Natural Flow Data base are not a true estimate of natural flow (Fig. 10), then natural flows at or downstream from Hoover Dam in the Natural Flow Data base are not true natural flows. The water distribution system downstream from Hoover Dam is complex, and the losses associated with irrigated agriculture, evapotranspiration from riparian forests, and evaporation from reservoirs have significant uncertainty. Inflows from the Bill Williams and Gila Rivers may be poorly known.

• ***Hydrologic data should be centralized and reported in unified unit.*** Many sources of hydrologic data are published in different units (cfs or af) and for different time periods (CY or WY). The numbers don't always agree in the different sources. Some of the data can only be found by people who are very familiar with the available database. ***Reclamation's new Hydrologic Database is a great improvement because it centralizes data availability.***

Data Availability

Data in this paper can be found at https://www.hydroshare.org/resource/cc3eb5b8f36e4e7c9bead6fa8e3a06aa/.

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