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Simulating the Law of the River

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ABSTRACT

With the Colorado River Compact of 1922 as its foundation, the evolving body of compacts, treaties, federal and state statutes, court decisions and decrees, contracts, and regulations known as the "Law of the River" governs the apportionment and use of the waters of the Colorado River. Since the ratification of the 1922 Compact, models, simple and complex, have been developed and used to understand what the Law of the River means to water availability in the basin, at spatial resolution ranging from sub-basins to diversion structures. This article summarizes the Law of the River and provides an overview of the history of system-level modeling of the Colorado River, sometimes called "big-river modeling". In its current state, this article focuses on modeling that addresses the legal availability of water to the Upper Division states in the Colorado River Basin.

This is a working document. The Law of the River and modeling tools, practices and studies continue to evolve, as will our understanding of past modeling practices, and this manuscript will be updated from time to time to reflect that evolution.

Concerns that consumptive use in the Upper Division states might be limited by the obligations imposed on them by Articles III(c) and Article III(d) of the Colorado River Compact seem first to have been raised publicly to state or federal officials in a 1953 report by Raymond Hill (Hill, 1953) to the Colorado Water Conservation Board, acknowledged by the Board in 1955 (CWCB, 1955) and reiterated by Hill in a 1961 report to the Attorney General of California (Hill, 1961). This concern was stated more prominently by Royce J. Tipton in his report of 1965 for the Colorado Water Conservation Board (Tipton, 1965a) and his statement to Congress in the same year on behalf of the Upper Colorado River Commission (Tipton, 1965b).

These concerns were an undercurrent in water management policy debates over the following decades. From time to time a controversy would arise that would bring "Compact issues" to the surface for a while, but when the Millennium Drought (Wheeler, et al., 2022) set itself on the Colorado River Basin beginning in 2000, and particularly after a very dry 2002, concerns about the legal availability of water in the Upper Division states came to top of mind among officials, water managers and water users in those states.

On January 25, 2001, in what can only be viewed as singularly ironic timing, the Bureau of Reclamation published notice in the Federal Register "…of the availability of the Final Environmental Impact Statement (FEIS) on the proposed adoption of specific criteria under which surplus water conditions will be determined in the Lower Colorado River Basin during the next 15 years" (Interior, 2001). Not only did no surplus waters arrive during those 15 years, but storage in the mainstem reservoirs, Lake Powell and Lake Mead, plunged to the lowest levels seen since they were filled and in 2005 Reclamation began the process that in 2008 would result in the issuance of Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead ("Interim Guidelines", Interior, 2005, 2008). There is no longer a link to the Interim Surplus Guidelines on Reclamation's Colorado River web page.

Unlike the attitude of optimism and denial that prevailed among the negotiators of the Colorado River Compact (Kuhn and Fleck, 2019), Reclamation, the Upper Division states and scientists confronted the reality they faced but could not describe with much certainty in a large body of studies that while they differed in details expressed a single theme—we should expect drier conditions in the Colorado River indefinitely.

The Interim Guidelines expire in 2026 and at this writing Reclamation is two years into a process to develop "Post-2026 Operational Guidelines and Strategies for Lake Powell and Lake Mead" (Interior, 2022). It is fair to say that this is not going well, but it is also fair to say that no one could have expected anything else. The facts are stark—this is not a positive-sum game, there is no way to make the pie higher--there will be winners and losers here. And, on top of this, the inescapable but highly uncertain effects of climate change add yet another layer of complexity.

Models have been central to navigating the growing complexity of developing policy and management practices for the Colorado River. Understanding the motivations for their development and their evolution will at least satisfy curiosity and may provide insight that can improve future modeling efforts. This article summarizes the Law of the River and provides an brief and preliminary history of system-level modeling of the Colorado River. In its current state, this article focuses on modeling that addresses the legal availability of water to the Upper Division states in the Colorado River Basin.

This is a working document. The Law of the River and modeling practices continue to evolve, as will our understanding of past modeling practices, and this manuscript will be updated from time to time to reflect that evolution.

1. Colorado River Basin

The Colorado River basin drains approximately 243,000 square miles contained within the states of Colorado, Wyoming, Utah, New Mexico, Nevada, Arizona, California, and parts of the Mexican states of Baja, California and Sonora. The river is highly regulated by a total reservoir storage capacity approximately equal to four times the river's average annual flow. Figure 1 shows the geographical extent of the Colorado River basin, the seven basin states, and the major rivers and reservoirs in the basin.

The basin is divided both geographically and legally at Lee Ferry, just downstream of the point where the river crosses the Arizona-Utah border. The Upper Basin includes lands in the states of Colorado, New Mexico, Utah, and Wyoming, and a small amount of land in Arizona. The Upper Basin is the principal source of inflow into the Colorado River system. The Lower Basin includes lands in the states of Arizona, California, Nevada and New Mexico. A lesser amount of inflow occurs in the Lower Basin, principally via the Little Colorado, Virgin, Bill Williams and Gila Rivers.

Many reservoirs alter the natural flow of the Colorado River. The two principal reservoirs, Lake Powell and Lake Mead, provide over 50 million acre-feet (maf) of storage. There are thousands of reservoirs in the Upper Basin, above Lake Powell, but only slightly more than 60 with capacities above 4,000 acre-feet. Water is diverted from the river at hundreds of relatively small diversion points in the Upper Basin.

1.1. Hydrology

An extensive record of streamflows and reconstructed natural flows exists for the Colorado River. Since the 1970s this record has been supplemented by long reconstructions of prehistoric flows and, since the 1990s, by ensembles of time series of projected flows affected by projected future climate conditions.

The natural flows in the basin are highly irregular in occurrence. While the virgin flow at Lee Ferry has averaged 15.1 million acre-feet annually over its measured period of record, annual natural flows exceeding 23 maf and less than 7 maf have been observed. Over 70% of the annual natural flow occurs in the months of May, June, and July. Flows have been recorded for less than 100 years at most points on the river.

1.2. Water Use

Water is diverted from the river at hundreds of relatively small diversion points in the Upper Basin, almost all of which operate under a state water right. The Lower Basin diversions tend to be larger and considerably fewer in number. Major diversion structures in the Lower Basin include the Colorado River Aqueduct which delivers water to the Los Angeles basin, the Havasu Pumping Plant/Central Arizona Project Canal which supplies the Central Arizona Project, the Colorado River Indian Reservation Main Canal in Arizona's Parker Valley, the Palo Verde Canal which diverts water to the Palo Verde Irrigation District of California, the All American Canal System bringing water to the Imperial and Coachella Valleys of California and the Yuma Project in California and Arizona, and the Gila Main Gravity Canal which serves the Gila project in Arizona. Below the international boundary, Morelos Dam diverts water for irrigation in Sonora, Mexico. All of the mainstem diversions are supplied by releases from Lake Mead, and benefit from storage in Lake Powell.

2. The Law of the River

The Colorado River system is managed and operated in accordance with the "Law of the River", which consists of compacts, treaties, federal and state statutes, court decisions and decrees, contracts, and regulations. See Wilbur and Ely (1933), Wilbur and Ely (1948), Nathanson (1978), MacDonnell, et al. (1995), and Verburg (2010). A comprehensive review of the Law of the River is provided by MacDonnell (2021a) and convenient digital compilation of source documents is at Weisheit (2019).

The Colorado River Compact (CRC, 1922) and the Upper Colorado River Basin Compact (UCRBC, 1948), the principal elements of the Law of the River, set constraints on consumptive use of water in the Upper Basin of the Colorado River. A water treaty with Mexico (1944) created a federal obligation to deliver water from the Colorado River system at the international border.

Article II of the CRC defines the Colorado River System and divides it into the Upper Basin and the Lower Basin. Lee Ferry, a point on the Colorado River main stem one mile below the mouth of the Paria River, divides the two basins. Article II also partitioned the states into the Upper Division (Colorado, New Mexico, Utah, and Wyoming) and the Lower Division (Arizona, California and Nevada). Arizona includes a small portion of the Upper Basin while New Mexico and Utah include small areas of the Lower Basin. One million acre-feet is 1.2 billion cubic meters.

Article III(a) of the CRC apportions to each basin 7.5 maf per year of consumptive use of the waters of the Colorado River System. Article III(b) grants an additional apportionment of 1 maf per year of consumptive use to the Lower Basin.

The Mexican Water Treaty of 1944 established a federal obligation to deliver 1.5 maf of water per year to Mexico. Article III(c) of the CRC sets out terms by which that treaty obligation would be shared between the

Upper Division and the Lower Division--some portion of that federal delivery obligation may be the responsibility of the States of the Upper Division (Kenney, 2012b).

Article III(d) of the CRC sets out the terms of an obligation on the states of the Upper Division not to cause the 10-year cumulative flow at Lee Ferry to be depleted below 75 maf. This requirement is not without controversy (Kenney, 2012a; Kuhn, 2007; MacDonnell, 2021b). This flow obligation will likely be the most significant legal constraint on consumptive use in the Upper Basin. The framers of the Compact expected that annual natural flows at Lee Ferry would typically substantially exceed 16 maf, which would satisfy the 10-year cumulative flow obligation in Article III(d), allow the Upper Basin to consume 7.5 maf under Article III(a) and to contribute one half of the treaty obligation to Mexico under Article III(c), and leave a surplus, but that expectation is now understood to have been optimistic (Kuhn and Fleck, 2019).

Article VIII of the CRC exempts Present Perfected Rights (PPRs) in the Upper Basin from the apportionment and obligations set out in Article III. PPRs are state water rights that were perfected before the execution of the Compact. Though there is controversy about their definition, most authorities define these as rights perfected before November 24th, 1922, the date the CRC was signed. The effect of protection of PPRs is to provide a reliable minimum supply of water in the Upper Division, but the tradeoff is that curtailment spells will be extended.

Article III of the UCRBC apportions water from the Colorado River to the states in the Upper Basin. Arizona, a Lower Division state, was allocated a fixed amount of 50,000 acre-feet (af) or 62 million cubic meters (mcm). Water was apportioned among the Upper Division states according to percentage shares, reflecting the recognition, in the 26 years that had passed since the formulation of the CRC, that future Colorado River flows would likely be insufficient to supply the Upper Basin with its full Article III(a) apportionment (Kenney, 2012a).

The CRC apportioned water between the Upper and Lower Basins but established the Article III(d) non-depletion requirement as an obligation of the Upper Division. The UCRBC sets out rules for the curtailment of consumptive use in the states of the Upper Division. Water use in the Upper Basin in Arizona and water use in the Lower Basin in New Mexico and Utah are not subject to curtailment.

In general terms, if the flow at Lee Ferry falls below the obligations set out in Article III(c) and Article III(d)--however those may eventually be interpreted--consumptive use in the Upper Division states must be curtailed to the degree necessary to offset any flow shortfall, except that Present Perfected Rights are not subject to curtailment (Article IV, UCRBC, 1948). Herein, the term “curtailment” is used to refer to the concept of a cutback required by the combined action of Article III(c) and Article III(d) of the CRC and Article IV of the UCRBC, and a particular such cutback. Curtailment is also used here to refer to the amount by which Upper Division consumptive use demand must be reduced in any year to comply with those constraints. Short of unpredictable outcomes from litigation by the Lower Basin, these curtailments would be coordinated by the Upper Colorado River Commission, even prospectively, and implemented by the states.

The principal reservoir in the Upper Basin is Lake Powell, with a current active capacity of 20.3 maf, impounded behind Glen Canyon Dam, about 18 river miles above Lee Ferry. Construction of Glen Canyon Dam, which closed in 1963, added another layer to the Law of the River in the form of operating rules: Long-range Operating Criteria (LROC, Interior, 1970) formulated under the Colorado River Basin Project Act (1968), as subsequently updated (Verburg, 2010). The provision in the LROC for a “minimum objective release” is most relevant here. The minimum objective release (“MOR”) was set at 8.23 maf, consisting of the annualized value of the Article III(d) obligation (7.5 maf), plus one-half of the federal obligation to Mexico (0.75 maf), less the average annual flow of the Paria River (0.02 maf) that enters the Colorado River between Glen Canyon Dam and the compact point at Lee Ferry.

In 2005, motivated by several years of drought and declining storage in the major reservoirs on the River, the Department of Interior began an effort to develop what became the Interim Guidelines, issued in 2008 (Interior, 2005, 2008). Among other things, the Interim Guidelines provide for coordinated operations at Lake Powell and Lake Mead, based on levels in the two reservoirs, intended to "minimize shortages in the Lower Basin and avoid the risk of curtailments in the Upper Basin". The Interim Guidelines established four operating tiers in Lake Powell and three operating tiers in Lake Mead. When Lake Powell is in the lower three tiers, annual releases can range from 7.0 maf to 9.5 maf, depending on the state of Lake Mead. When Lake Powell is in the upper, "Equalization Tier" releases greater than 9.5 maf could occur to equalize storage in the two reservoirs or to avoid spills. The Interim Guidelines expire in 2026 and negotiations are underway to formulate their replacement. If these negotiations are unsuccessful operations may subsequently be controlled again by the LROC (Kuhn, 2024).

What might be the future interpretation of each of the elements of the Law of the River, and how they may be implemented, is broadly contentious and their precise nature will only be resolved by negotiation or prolonged litigation, or both (Robison & Kenney, 2012; MacDonnell, 2021b).

3. Simulating the Colorado River System

Perhaps the earliest model studies on the Colorado River were attempts to estimate the future amount of water available for a planned large reservoir below the Grand Canyon that eventually was constructed at Black Canyon as Hoover Dam. The earliest studies, involving very simple model approaches, were done using an incremental approach, adding expected future depletions to the record of observed flows. In these studies, past flows had to be normalized to account for the growth of consumptive use over time. More studies of this type were done in the following decades.

The origin and any records of the first reservoir models used on the Colorado River are lost to time, but some operational model was likely used to manage flood control at Lake Mead. These were certainly hand calculations done as part of an annual operating plan.

1.3. Colorado River Storage Project Operation Model

The Colorado River Storage Project Act of 1956 (CRSPA, 1956) authorized the construction of Glen Canyon, Flaming Gorge, Navajo and Curecanti dams, along with other participating projects. Glen Canyon Dam and Navajo Dam were closed in 1963, Flaming Gorge Dam was closed in 1964 and Curecanti (Blue Mesa) Dam was closed in 1966. With these reservoirs now in place Reclamation had to consider the best way to operate an integrated system of reservoirs in the Upper Basin on a year-to-year basis, with the principal objective of maximizing hydropower production, the revenues from which were a substantial source of funding for developing additional water supply projects in the Upper Basin. These studies were done at the offices of Reclamation's Upper Colorado Basin Region in Salt Lake City, Utah using large paper spreadsheets. In 1964, Michael Clinton, at the Region, began converting the paper spreadsheets to FORTRAN computer code, and those codes became the operational model for the Colorado River Storage Project. (Clinton, 2024)

Section 602(a) of the Colorado River Basin Project Act (CRBPA, 1968) directed the Secretary of the Interior to propose and adopt "criteria for the coordinated long-range operation" of the Colorado River reservoirs constructed and operated by the Department of the Interior, known as the Long-Range Operating Criteria (LROC; Interior, 1970). The LROC, in turn, directed the Secretary to develop and transmit annually a report "describing the actual operation under the adopted criteria for the preceding compact water year and the projected plan of operation for the current year", known as the Annual Operating Plan (AOP). The first of these, issued in April 1970 provided a review of actual operations in 1969 and a plan for operations through March 1972. Exhibits IV, V and VI of the

1970 AOP are computer outputs, presumably produced from codes that evolved from Clinton's work in 1964. (Reclamation, 1970)

By 1969, computer codes, presumably also derived from Clinton's original operational simulations, had been developed to simulate conditions over an annual time-series of natural flows for planning purposes. The first known application of this new code was in the 1969 Report of the Committee on Probabilities and Test Studies to the Task Force on Operating Criteria for the Colorado River (Reclamation, 1969). This report provided analyses that were used to support development of the LROC and appear to have provided estimates of water availability in support of the effort to authorize and build the Central Arizona Project.

1.4. Colorado River Simulation Model

It is likely that the simulation codes used in the 1969 report and the codes used for operations and for development of the 1970 AOP were maintained separately, and each evolved over time. It appears that until 1977, the planning simulations were based on an annual time series of virgin or natural flows. In a 1977 letter to Gordon Jacoby, R. Keith Higginson, Commissioner of Reclamation states that Reclamation was at that time developing monthly natural flow data. (Higginson, 1977) This refinement ushered in the modern, formal era of simulation of the Colorado River System.

As described in Reclamation (1984) Reclamation at that time maintained two datasets of flows at Lees Ferry, the annual virgin flows and the monthly CRSS natural flows. The virgin flows are undepleted (but not unregulated) flows while the natural flows are undepleted and unregulated flows. Modeling of the sort done in the 1969 report (and in all subsequent system modeling on the Colorado River) are best done using natural flows because understanding the effect of different reservoir operating policies is central to those analyses, so it is likely that at least an annual natural flow data set had been developed by the time of the 1969 study. Based on Higginson (1977) these were likely disaggregated to monthly flows around 1977.

The Colorado River Simulation Model (CRSM) was a monthly simulation of the Colorado River system, written in FORTRAN. These codes were mature by 1983, when the author first obtained a copy. By that time the CRSM code had been incorporated into the Colorado River Simulation System (CRSS), which included, in addition to the CRSM code, several data-management, input and output codes. By 1988, CRSS and CRSM had been formalized and were used and maintained on an ongoing basis. (Schuster, 1987, 1988a, 1988b). The CRSS natural flows had by this time been disaggregated to 29 inflow points throughout the Colorado River Basin.

1.5. Colorado River Network Model

William B. Lord and Associates (WBLA), and its successor Hydrosphere Resource Consultants, developed and maintained models of the Colorado River system between 1984 and 1996. The first of these models was implemented using the MODSIM variant of a network approach for simulation, SIMYLD, developed by Martin (1972). This model was used to simulate the fate of the incremental increase in streamflow arising from specific prescriptions for forest management, by apportioning that increase to uses and losses throughout the basin in accord with legal constraints including the Colorado River Compact (Harding, et al., 1986). Based on that experience, WBLA developed the Colorado River Network (CORN) model code that better facilitated data management and added substantial new simulation capabilities along with enhanced ease of use. CORN was used for several studies of the economics of water apportionments in the Colorado River and an early study of the impact of climate change on the river system (Brown et al. 1988, 1990).

The most notable application of the CORN model was in the Severe and Sustained Drought Project where the CORN model was used to simulate the impacts of a severe and sustained drought (Harding, et al., 1995); to evaluate potential institutional responses to an SSD, including reverse equalization, salinity reduction, minimum flow requirements and temporary suspension of the Article III(d) Lee Ferry flow obligation (Sangoyomi et al., 1995); and to evaluate the effectiveness of those responses (Lord et al., 1995).

The CORN model was maintained until the introduction of the new RiverWare version of CRSS in 1996.

1.6. Hydrologic Determinations, 1967 – 2007

Public Law 87-483 (1962) that authorizes the Navajo Indian Irrigation Project and San Juan-Chama Project, requires, before any long-term contracts for delivery of water from Navajo Reservoir be entered into, that the Secretary of the Interior shall determine "…by hydrologic investigations that sufficient water to fulfill said contract is reasonably likely to be available for use in the State of New Mexico during the term thereof under the allocations made in articles III and XIV of the Upper Colorado River Basin compact…" and submit such determination to Congress.

The first such "hydrologic determination" was made in December 1963 and submitted to Congress in November, 1967 (Reclamation, 1984). Further hydrologic determinations were conducted by the Bureau of Reclamation in 1984, 1987, 1988 and 2007.

1.6.1. 1984 Hydrologic Determination

The 1984 hydrologic determination (Reclamation, 1984) utilized two approaches to determine the amount of consumptive use that could occur in the Upper Basin given the historical hydrology and the constraints imposed by the CRC, the "formula method" (a mass-balance analysis) and the "model method" (using CRSM). Both approaches used an assumption that the annualized total obligation at Lee Ferry was 8.25 maf. Reclamation adopted this assumption "to avoid a critical compact interpretation".

In this study, Reclamation describes the flow obligation as at Lee Ferry, but the analyses are carried out based on flows at Lees Ferry. Both the virgin flows and the CRSS natural flows were used in this analysis. In the case of the natural flows, only the total at Lees Ferry was used in the formula analysis.

The formula method was an analysis of total water availability over the 34-year critical period, 1931-1964, based on average conditions, first based on the virgin flow dataset (all reported numerical precision is as in the report): Reservoirs in the Upper Basin were assumed full in 1931; the volume of available storage in 1931 (26.232 maf) was added to the total volume of virgin or natural flow over the period 1931 through 1964 (465.649 maf) and the result was divided by the length of the critical period (34 years), resulting in an estimated average annual flow at Lees Ferry 13.695 maf. Subtracting the assumed non-depletion obligation at Lee Ferry (8.25 maf) resulting in an estimate for allowable depletions in the Upper Division states of 5.446 maf.

It is important to note that this mass balance includes evaporation from CRSP units, including Lake Powell, in the total consumptive use allowable in the Upper Basin.

In its final determination, Reclamation allowed for a 10 percent shortage to agricultural uses for an overall shortage of 6% to Upper Division water uses, resulting in a determination that 5.8 maf were available for consumptive use in the Upper Division. This result was compared to the results of Tipton (1965a) for validation.

The formula method was automated with a computer code and that was run against both the virgin flow and natural flow datasets. The results for the virgin flow case were unchanged. Applying the formula code to the CRSS natural flow dataset over the same period also gave the same result. However, the most critical period in the CRSS natural flow trace was 1953 through 1977, with a lower average flow, but this was not used in the final determination.

Several "CRSS model runs" were also made to verify the formula result. Presumably this refers to the CRSM, a component of CRSS. The run set up to be consistent with the formula approach and incorporating "tolerable shortages" gave a result of 5.775 maf.

The shortages allowed to Upper Basin consumptive use represent an assumption that water uses in the Upper Division States will be curtailed so this appears to be the first Reclamation study to represent operation of the Article III(c) and Article III(d) obligations.

1.6.2. 1987 Hydrologic Determination

The 1987 Hydrologic Determination (Reclamation, 1987) again employed a mass-balance analysis to determine allowable consumptive use in the Upper Basin. In this analysis, an assumed amount of bank storage is added to the initial storage amount. Yield was determined using the same formulation as in the 1984 Hydrologic Determination except that bank storage was included in the initial reservoir contents. The equation used for the mass-balance analysis is:

$$Yield = ((Q + S(1 + B))/n - Rm)/(1 - s)$$

Where:

Q = streamflow for the critical period
S = surface storage available
B = bank storage coefficient
Rm = minimum release to the lower basin
s = percent basin-wide shortage
n = number of years in the critical period.

The volume of streamflow, Q, is based on the CRSS natural flow hydrology database; the virgin flow data were not used. The volume of available initial storage, S(1+B), was determined by a set of runs of CRSM. The critical period in the CRSS natural flow trace was the 25 years from 1953 through 1977. Unlike the 1984 analysis, the required minimum release, Rm, was quantified at Lees Ferry to be consistent with the CRSS natural flow data, and was set to 8.23 maf to account for the 0.02 maf contributed by the Paria River between Lees Ferry and the Lee Ferry Compact Point. The mass balance analysis led to a higher result than in 1984, an annual volume of 6.0 maf available for consumptive use in the Upper Basin.

As in the 1984 Hydrologic Determination, this analysis includes evaporation from CRSP units in the estimate of consumptive use in the Upper Basin. However, at one point in the summary and conclusions, Reclamation incorrectly characterizes the "yield" to the Upper Basin in terms of "beneficial use".

Notably, CRSS was used in this study to calculate the probability of different levels of curtailment in the Upper Basin. The probability of a "call" above 0.1 maf was determined to be 0.75 percent. This appears to be the first Reclamation study presenting estimates of simulated curtailments.

1.6.3. 1988 Hydrologic Determination

The 1988 Hydrologic Determination (Reclamation, 1988) is substantially identical to the 1987 Hydrologic Determination.

1.6.4. 2007 Hydrologic Determination

The 2007 Hydrologic Determination (Reclamation, 2007a) incorporated a number of changes from the earlier determinations. An incremental change involved revisions to the CRSS natural flow data to increase some volumes to reflect changes in estimates of historical consumptive use in the Upper Basin. In a significant change, this analysis included storage in both federal and significant non-federal reservoirs in the Upper Basin, under the assumption all storage in the Upper Basin was used to support consumptive use and was available to maintain flows at Lee Ferry. Another important change is that evaporation from CRSP storage units was now treated separately from beneficial uses, so the results in this determination are explicitly stated in terms of Upper Basin beneficial use, which included evaporation from non-CRSP resservoirs. This analysis was made using a simple time-series model of the Upper Basin water balance, most likely implemented in a spreadsheet. The CRSM model was not used in this analysis. Reclamation refers to the 1988 Hydrologic Determination for estimates of risk of curtailment.

The result of this analysis is a determination that allowable beneficial consumptive use in the Upper Basin is 5.79 maf. Adding an estimate of average evaporation from CRSP storage units to this amount gives a total allowable use in the Upper Basin of 6.04 maf, compared to the comparable estimate of 6.0 maf in the 1988 Hydrologic Determination.

1.7. Colorado River Simulation System (CRSS)

Beginning in 1994, Reclamation, in collaboration with the Tennessee Valley Authority and working with the Center for Advanced Decision Support in Water and Environmental Systems, CADSWES, at the University of Colorado, developed RiverWare(tm), a generalized river basin modeling tool. RiverWare was then used to re-implement the simulation logic of CRSM, along with the data management, input, and output capabilities that are native to RiverWare, which replace the corresponding functionality of the old CRSS system codes. CRSS has been used operationally by Reclamation since 1996, and has been adapted into other special-purpose simulation systems, such as the Colorado River Mid-term Modeling System (CRMMS), used for the 24-Month Studies and the Colorado River System 5-Year Probabilistic Projections, and the Mid-term Probabilistic Operations Model (MTOM) which is similar to CRMMS, but can be forced by a large ensemble of inflow traces for probabilistic risk assessments.

CRSS has been central to Reclamation's major Colorado River Basin studies and initiatives since becoming operational, as shown in Table 1.

Table 1. Colorado River Studies and Initiatives Using CRSS

2001	Interim Surplus Guidelines;
2007	Interim Guidelines for Lower Basin Shortages and Coordinated Operations of Lake Powell and Lake Mead;
2012	Colorado River Basin Water Supply and Demand Study;
2018	Ten Tribes Partnership Tribal Water Study;
2019	Drought Contingency Plans;
2022-present	Colorado River Post 2026 Operations
Ongoing	24-Month Studies;
Ongoing	Annual Operating Plans; and
Ongoing	SECURE Water Act Reports

1.8. Simulation of the Colorado River Compact

Reclamation's CRSM did not simulate operation of the Colorado River Compact and in earlier implementations halted execution if Lake Powell contents reached zero. Later versions of CRSM were used to estimate yields to the Upper Basin, but this was likely done by an iterative process that stopped when Lake Powell volumes were close to zero.

It is unsurprising that Reclamation has not implemented simulation of the Compact. The Secretary of Interior is authorized by the CRSPA to operate the dams and reservoirs in the Upper Basin and is directed in so doing to

"…comply with the applicable provisions of the Colorado River Compact…". The Secretary of the Interior has delegated much of this authority and responsibility to Reclamation. Relations between the Upper Division and Lower Division states were and remain highly contentious and Reclamation is caught right between them, as any simulation of the terms of the Compact would be challenged by parties that perceived it to disfavor them. This situation would not change appreciably until the millennial drought began in 2000 and precipitated development of the 2007 Interim Guidelines.

Reclamation's Hydrologic Determinations in 1984, 1987, 1988 and 2007 described above, simulated some cases where shortages were imposed on Upper Division consumptive uses. CRSM was used to supplement a mass balance analysis in the 1984, 1987 and 1988 Hydrologic Determinations

Studies from outside Reclamation did simulate the operation of the Compact. The earliest appear to be the water balance studies of Hill (1953, 1961) and Tipton (1965). The first simulations of the full system were likely the CORN studies noted above. The first prominent outside study was the Severe and Sustained Drought Project (Harding, et al., 1995). Between 2008 and 2012 the Colorado River Water Availability Study (CRWAS) examined the constraints that the Compact would impose on water availability in Colorado, including under projected climate-impacted water supply and consumptive use conditions. CRWAS intended to use CRSS for these analyses but instead adopted a simpler annual water balance approach based on the 2007 Hydrologic Determination (Reclamation, 2007a). Before adopting the water balance approach, CRWAS modelers had developed a simplified approach in CRSS to quantifying curtailments of consumptive use in the Upper Division states that involved injecting water just above Lee Ferry whenever a shortfall in cumulative flow would have otherwise occurred there. This approach was referred to as "magic water" and has also been referred to as "miracle water" (Harding and Wheeler, 2010).

In developing the 2007 Interim Guidelines, Reclamation for the first time simulated the system against a paleo reconstruction of natural flows (Reclamation, 2007b). That reconstruction included low-flow spells that were more severe than any contained in the historical record, and these led to flow shortfalls at Lee Ferry. Reclamation did not simulate operation of the Compact but rather allowed these flow shortfalls and their consequences in the Lower Basin to occur. This was noted, but not discussed, in the text and shown graphically (Reclamation, 2007b; sections N.3.6 and A.3.1.5).

The 2012 Colorado River Basin Water Demand and Supply Study appears to be the first Reclamation study to represent the operation of the Compact, using the "magic water" approach (Reclamation, 2012b; section 2.4.2 Lee Ferry Deficit). In this study, Reclamation set the Lee Ferry 10-year obligation at 75 maf and did not simulate curtailment of uses in the Upper Division states.

Other models have simulated operation of the Compact: Christensen and Wood (2004) developed a model that was used for research purposes, and Christensen subsequently developed the Colorado River Open-Source Simulation (CROSS) that is available on-line (Weisheit, 2007). A model based on the annual water balance in the 2007 Hydrologic Determination was used by the Colorado River Water Conservation District to estimate the magnitude and frequency of possible future Compact curtailments as part of Phase 1 of its Colorado River Water Bank Feasibility Study (Paulson, 2012) and to conduct a separate assessment of the risk of curtailments.

4. References

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