STRATECON INC.

December 20, 2022

VIA EMAIL (CRinterimops@usbr.gov)

Reclamation 2007 Interim Guidelines
SEIS Project Manager
Upper Colorado Basin Region
125 South State Street
Suite 8100
Salt Lake City, Utah 84138

RE: Stratecon Comments on Bureau of Reclamation's Preparation of a Supplemental Environmental Impact Statement to December 2007 Record of Decision on Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead ("2007 Interim Guidelines")

Dear SEIS Program Manager:

On behalf of *Stratecon Inc*, I appreciate the opportunity to provide input into the above captioned matter.

Stratecon is a strategic planning and economic consulting firm specializing in water resources with more than four decades experience in negotiating water transfers, developing privately-fund water projects, professional due diligence, and expert testimony on the economics of public policy and legal matters throughout the western United States and Mexico. Stratecon has been involved in Colorado River matters since the mid-1990s, most prominently as an economic advisor to the Imperial Irrigation District ("IID") from 1996-2010 on quantification of IID's Priority 3 right, as well as negotiation of IID's historic agreement with the San Diego County Water Authority, the Quantification Settlement Agreement, and dozens of inter-related agreements executed on October 10, 2003. Stratecon continues to provide advisory services to clients in the Colorado River Basin and elsewhere. For additional information, visit Stratecon's website www.stratwater.com.

The comments presented below are solely Stratecon's perspective on the urgent challenges facing the Colorado River Basin. The suggestions presented below do not necessarily reflect the opinions or positions of any of Stratecon's past, current, or future clients. On the use of language, I use "I" and "Stratecon" interchangeably when discussing the information, analysis, and suggestions presented below. Statements involving "we" state perspectives about the collective interests in the Colorado River Basin, including the Republic of Mexico.

Prelude

The current circumstances on the Colorado River are clearly dire and unsustainable. "Staying the course" is not viable. How did we get ourselves into this mess? How do we dig ourselves out? What new tools may the Bureau of Reclamation ("Reclamation") use to navigate our situation? The discussion below shares Stratecon's perspective on these questions.[1]

Despite the bleakness of our current situation, I remain optimistic about the future of the Colorado River Basin. On the technical side, I have interacted with Reclamation technical staff over the years and always encountered dedicated, competent, and open-minded professionals. There has been an impressive evolution over the decades in the thoroughness of Reclamation's tools. As discussed below, today's challenges are an opportunity for further development.

On the policy side, the Colorado River Basin has a history of innovating to address daunting problems. The California 4.4 Plan and Quantification Settlement Agreement come to mind. We tried to "run the table" with the 2007 Interim Guidelines, Minute 323, and the 2019 Drought Contingency Plan ("DCP"). We stumbled. Time to get back to work.

How Did We Get into This Mess?

Understanding how we got into this mess is the first step towards redemption. Stratecon's diagnosis: hubris and failed risk management.

Hubris

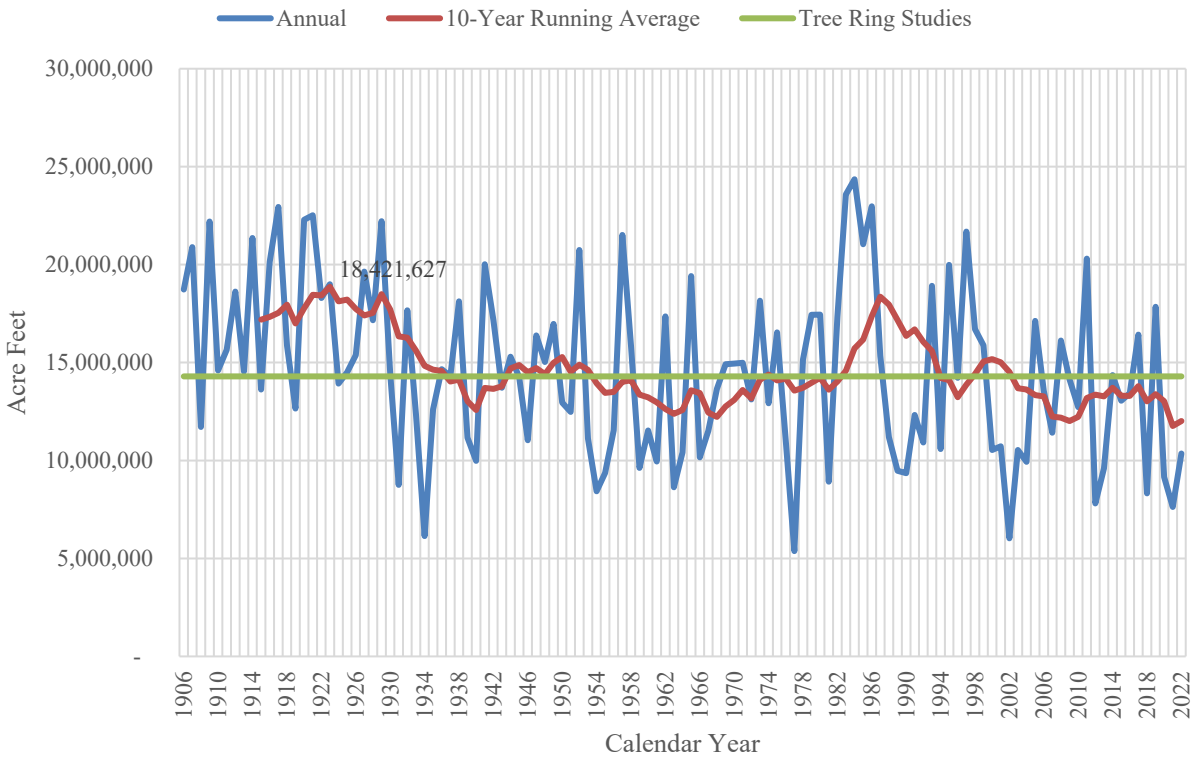
At least thirty years ago, a debate was starting between those who look in the "rear view mirror" versus those who look through the "windshield." The Rear View Mirror Brigade was content to rely upon historical data on the natural flow of the Colorado River since 1906 as an indicator of the future. The Windshield Brigade asked what are the implications if the 20th Century was a "wet century" and the natural flow of the Colorado River returned to the levels estimated by Tree Ring studies? At that time in the mid-1990s, the debate was whether the long-term average annual natural flow of the Colorado River was 15.0 million acre-feet or 13.5 million acre-feet.

Looking at data from alternative viewpoints is informative (see Figure 1 for Bureau of Reclamation data). For the period 1906-1922, the 10-year running average in 1922 was 18.4 million acre-feet. Ironically, the 1922 Compact divided 15.0 million acre-feet per year equally between the Upper and Lower Basin, the 1944 Treaty provided the Republic of Mexico with 1.5 million acre-feet per year, and up to 2.0 million-acre-feet per year is lost to evaporation and system

[1] The discussion below is based upon and supplements two recent Stratecon blog posts: "The Colorado River in Disarray" August 19, 2022, https://hydrowonk.com/blog/2022/08/19/the-colorado-river-in-disarray/ and "On Evaporation and System Losses on the Colorado River" November 22, 2022, https://hydrowonk.com/blog/2022/11/22/on-evaporation-and-system-losses-in-the-colorado-river-basin/.

losses (according to the Bureau of Reclamation's 2012 *Colorado River Basin Water Demand and Supply Study,* Figure 7, p. SR ("Study Report")-25).

Figure 1
Natural Flow of Colorado River at Lees Ferry



The Colorado River's natural flows since 1922 stubbornly show a convergence toward long-term conditions. Recent Tree Ring studies put the long-term average natural flow of the Colorado River at 14.3 million acre-feet per year (see Attachment A). Since the Great Depression, the 10-year running average of the annual natural flow of the Colorado River has hovered at or below 14.3 million acre-feet, except during the 1980s. During those years, the United States delivered "excess flows" to the Republic of Mexico when historic floods overran water storage on the Colorado River. Pending the arrival of the next historic flood (once every fifty or hundred years?), the average annual natural flow of the Colorado River will fluctuate around 14.3 million acre-feet, or less depending on the impact of climate change.

History confirms the view of the "Windshield Brigade." The magnitude and duration of any drought should be measured by how annual natural flow compares to 14.3 million acre-feet. Reclamation must abandon reliance on historical data for forecasting future hydrologic conditions. Will the impact of climate change make the hydrologic circumstances in the future even more severe than suggested by tree-ring studies? Undoubtedly. The discussion below "New Tools" presents suggestions.

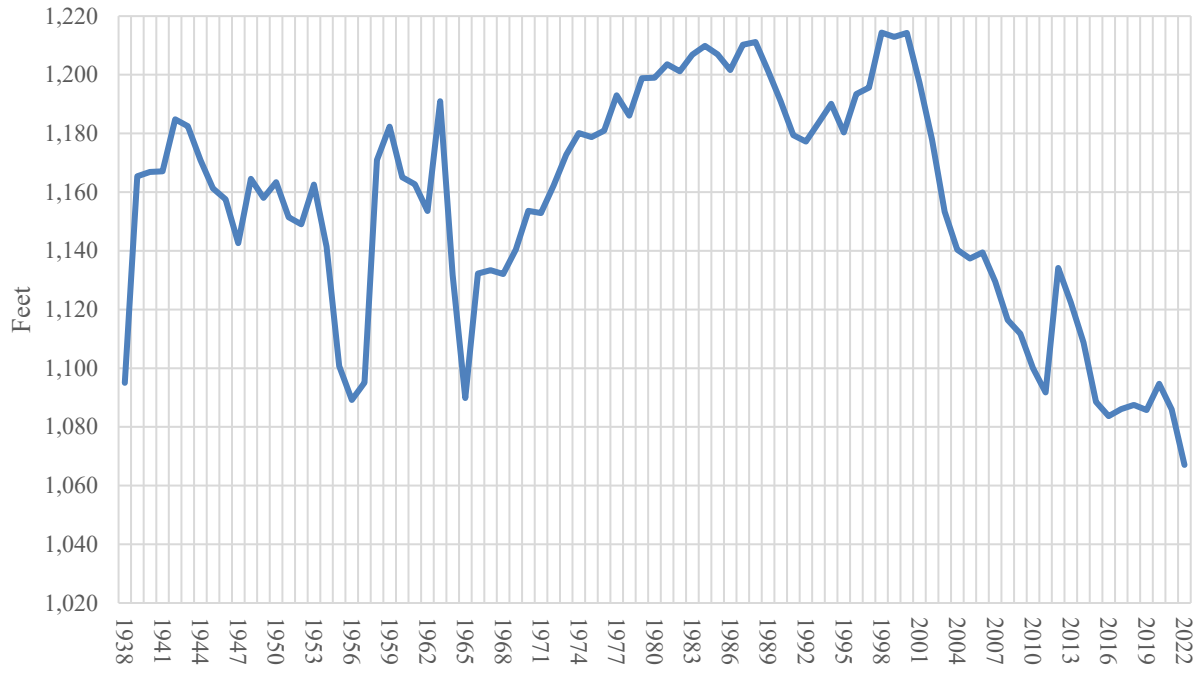
Our challenge today reflects the consequences of "deferred action." The historic floods of the 1980s proved to be a distraction from the needed acknowledgment that the Colorado River was over-appropriated. This perception may have found solace in the three high flow years in the mid-1990s. Fooled by randomness.

Our challenges today have two dimensions: (1) the decline of average annual natural flows of the Colorado River to long-term conditions, and (2) drought conditions reflected by the amount annual natural flows of the Colorado River fall below long-term conditions. Can we declare an end to the Rear View Mirror Brigade era? In Stratecon's opinion, yes.

Failed Risk Management

Since the turn of this century, the elevation of Lake Mead has been in free fall (see Figure 2). Before the year 2000, the elevation of Lake Mead increased with unprecedented flood flows in the 1980s (see above). Starting in 2000, the elevation of Lake Mead has been steadily falling, only interrupted by high natural flows in the 2010-2013 period (fooled again by randomness). After this "bubble," the march of declining Lake Mead elevation continues.

Figure 2
January Elevation of Lake Mead



The federal government and the Upper and Lower Basin parties recognized that the era of ubiquitous Colorado River water was ending. The adoption of the 2007 Interim Guidelines was the first step. Shortages were not triggered for years. Natural inflows above 20 million acre-feet happened in 2011 (see Figure 1). Starting in 2016, however, the elevation of Lake Mead hovered

less than 10 feet above the 1,075-foot trigger for declaring a shortage under the 2007 Interim Guidelines.

With the cutbacks in the 2007 guidelines looking insufficient to manage the declining elevation of Lake Mead, the United States and the Republic of Mexico negotiated the 2019 DCP allocating curtailments in Colorado River water supplies depending on the elevation of Lake Mead (see Table 1). Arizona, Nevada, and Mexico, respectively, agreed to cutbacks of 192,000 acre-feet, 8,000 acre-feet and 41,000 acre-feet before a shortage declaration is triggered (unless the elevation of Lake Mead exceeds 1,090 feet).

Table 1
Curtailment of Colorado River Water for Lower Basin States and Republic of Mexico Under Drought Contingency Plan (acre feet)

Lake Mead Elevation (Below)	*Arizona*	*California*	*Nevada*	*Mexico*	*Total*
1,090 Feet	192,000		8,000	41,000	241,000
1,075 Feet	512,000		21,000	80,000	613,000
1,050 Feet	592,000		25,000	104,000	721,000
1,045 Feet	640,000	200,000	27,000	146,000	1,013,000
1,025 Feet	720,000	350,000	30,000	275,000	1,375,000

For the first time in history, Reclamation declared a shortage for 2022 on the Colorado River as the expected elevation of Lake Mead fell below 1,075 feet but remained above 1,050 feet. While the current circumstances seem like a drought, the risk of curtailments extend beyond a "temporary" drought cycle. In fact, since storage at Lake Mead commenced in 1938, the Bureau of Reclamation's estimates of the annual natural flow of Colorado River at Lees Ferry averaged 14.0 million acre-feet, or 0.3 million acre-feet below the long-term average from a Tree Ring Study.

The Bureau's June 2022 announcement about the need for immediate curtailments beyond those under the 2019 DCP is a testament that current tools of risk management are inadequate. What went wrong? Two interrelated flaws.

First, the focus on expected elevations ignores the underlying risk of hydrology. There is a material risk that the actual elevation will fall below the expected elevation. Especially if there are underlying trends in hydrology, whether or not captured by the model used to forecast future

hydrologic conditions, curtailments are delayed at the expense of more severe challenges in future years (witness the free fall in Lake Mead's elevation).

Stratecon participated in a study commissioned by California's Department of Water Resources to provide a retrospective assessment of the operation of California's 1991 Drought Water Bank. During discussions with former Director, David Kennedy, he shared that he regretted not curtailing State Water Project deliveries in the late 1980s in the face of emerging dry conditions so that California had more water in storage for water deliveries during California's 1991 drought. *A series of small earlier curtailments to reduce a larger curtailment later can indeed be a sound economic bargain*. Instead, California drew down water storage to avoid curtailments from assumed temporary drought conditions and increased its vulnerability to more severe water shortages as dry conditions ran longer than presumed. Without a firm understanding of the underlying risk of future hydrologic conditions, imprudent decisions are inevitable.

Second, the focus on only "next year's" elevation ignores potential dynamics driving future water supply availability. Especially if there is a run of "dry/drought years" (see below), curtailments should be made earlier to maintain storage to address a succession of future dry years. Otherwise, not only will one not take advantage of Mr. Kennedy's bargain, but there will also be a growing risk of reservoir elevations falling to minimum power pools and marching toward dead pool elevations.

Today's emergency on the Colorado River is a legacy of failed risk management.

How Did We Get Ourselves Out of This Mess?

Stratecon recommends a three-part plan: prudent risk management, respect for the Law of the River and the priority system, and develop decentralized, transparent markets for trading water among Colorado River water users.

Prudent Risk Management

Prudent risk management is based on how best to achieve a defined objective in the face of underlying hydrologic uncertainty and economic conditions. This requires understanding (i) how decision rules impact the likelihood of achieving objectives, and (ii) balancing the cost versus the benefits of achieving the objective.

A simple example can illustrate prudent risk management. Suppose an objective is to minimize the risk that a reservoir elevation falls below the minimum power pool. For a beginning reservoir elevation, one can calculate the probability that the elevation falls below the minimum power pool given the underlying uncertainty of future hydrologic conditions assuming no curtailments. If the risk (i.e., probability) is unacceptable, then impose curtailments until the risk (*e.g.*, probability of the reservoir elevation falling below the minimum power pool) becomes acceptable. Given that there are runs of dry/drought conditions in successive years, one must

consider the implications of a curtailment in the current year on the risk of falling below the minimum power pool next year and in successive future years given the underlying uncertainty about future hydrologic conditions.

A comprehensive risk management strategy is a time profile of curtailments (both timing and magnitudes) that provides an acceptable time profile of the risk of elevations falling below the minimum power pool over time, given the time profile of the underlying uncertainty of current and future hydrologic conditions and the economic costs of curtailments today versus the economic cost of reservoir elevations falling below the minimum power pool in the future.

A comprehensive risk management strategy will adapt with new information about hydrologic conditions. A prudent risk management strategy would have the terms and conditions of curtailment changing over time. Give the Colorado River Basins states and the Republic of Mexico their due when they moved to the 2019 DCP. By June 2022, Reclamation concluded that that plan is not sufficient. Stratecon supports Reclamation's conclusion.

Does comprehensive risk management sound complex? This is simply an exercise in stochastic dynamic programming. This tool has revolutionized golf by changing how PGA/LPGA compiles statistics and how players select targets (see *Every Shot Counts: Using the Revolutionary Strokes Gained Approach to Improve Your Golf Performance and Strategy*, Mark Broadie). (I have implemented the approach and reduced my handicap by 25%!) Golfers can change how they think about and improve their game. Can Reclamation and the Colorado River Basin up their game?

Follow the Law of the River and the Priority System

Since the 1990s, when the Grand Canyon Trust commissioned a Stratecon study of the implications of river flows following tree ring studies, I have been a member of the Windshield Brigade. Therefore, I agree with the perspective that the expectations of the 1922 Colorado River Compact are unlikely to be realized.

The status quo ante of the Law of the River and the priority system anchors negotiations of how to respond to today's challenges. Concessions would involve "trades" among the parties where interests with senior priorities under the Law of the River would "concede" water to interests with junior priorities. To reach a consensus, the junior priorities must provide mutually agreeable compensation to senior priorities. This sounds like water trading within the context of the Law of the River and the priority system of water rights.

The alternative would be regulatory intervention to "force reallocations" with terms determined by regulatory fiat and conflict. The inevitable outcome is litigation and water resource management failure. Given the urgency of current circumstances on the Colorado River, Stratecon

doubts that litigation lotteries are the best venues for timely improvement of water resource management on the Colorado River.

Jumping into the abyss of regulatory intervention and litigation lotteries would have adverse consequences for the long-term management of the Colorado River. In addition to reallocating currently available Colorado River water, meeting the long-term water demands of the Colorado River Basin should include development of "new water." Responsible federal water policy must consider the impact on the economic incentives to create new water as one addresses the current allocation of the dwindling supplies of Colorado River water.

Develop Decentralized and Transparent Markets for Trading Available Colorado River Water

Voluntary reductions of the use of Colorado River water by users of senior water rights can assist Reclamation achieve its objective of reducing Colorado River water by more than the curtailments under the 2019 DCP. Voluntary reductions can also assist junior water right holders by providing an offset of the curtailments under the 2019 DCP.

Reclamation has two alternatives. Place continued reliance on closed door negotiations among representatives of junior water users and senior water right users. Given Stratecon's experience in water transactions, closing the deal involves bridging the gap between divergent valuations of buyers versus sellers as well as assuring that pricing negotiated by representatives of users of senior water rights secures the necessary participation to generate promised volumes of conserved water.

Alternatively, Reclamation can use decentralized decision-making and create a platform running double-sided auctions and let water users set the price through buyer bids and seller offers.[2] The platform must be based on transparent rules regarding eligibility for participation, with records of water rights and water use linked to the Reclamation's contracts and operational data. In other words, there must have substantial "back-end" infrastructure to assure that trading will, in fact, improve water resource management.

Auctions make potential buyers and potential sellers think hard about their price bids and price asks. At the close of the auction, buyers who bid too low prices will suffer the economic consequences of water shortages because they did not acquire new water. Responsible buyers would think hard about the economic costs of avoided water shortages. Sellers who asked for too

[2] A double-sided auction sets the price where the quantity of bids at the price (or higher) equals the quantity of offers at the price (or lower). Successful buyers pay the price they bid (or lower). Successful sellers receive the price they bidder (or higher).

high prices will lose the opportunity to secure economic gain. Responsible sellers will think hard about what price it makes sense to conserve water.

Reclamation should have oversight but not operational control of the marketplace, which should be vested in a third party. Why? Because Reclamation itself may be an acquirer of water to increase reservoir levels. In addition to water users, other eligible buyers could be power or environmental interests who purchase water for dedication to increase storage and flows on the Colorado River. Eligibility criteria should recognize state law regarding the entities who control water rights.

In effect, the auction will discover "who is in and who is out" of addressing the challenges on the Colorado River. To the extent Reclamation is using funds from the Inflation Reduction Act to induce voluntary reductions in the use of Colorado River water, Reclamation could submit bids for acquiring conserved water to increase storage on the Colorado River in a competitive marketplace. Third party administration of double-sided auctions can provide sellers assurance that Reclamation has addressed its conflict of interest of being a buyer of water (who understandably seeks low prices) while maintaining that senior water right owners reduce their use of Colorado River water for the benefit of the entire Colorado River Basin.

New Reclamation Tools

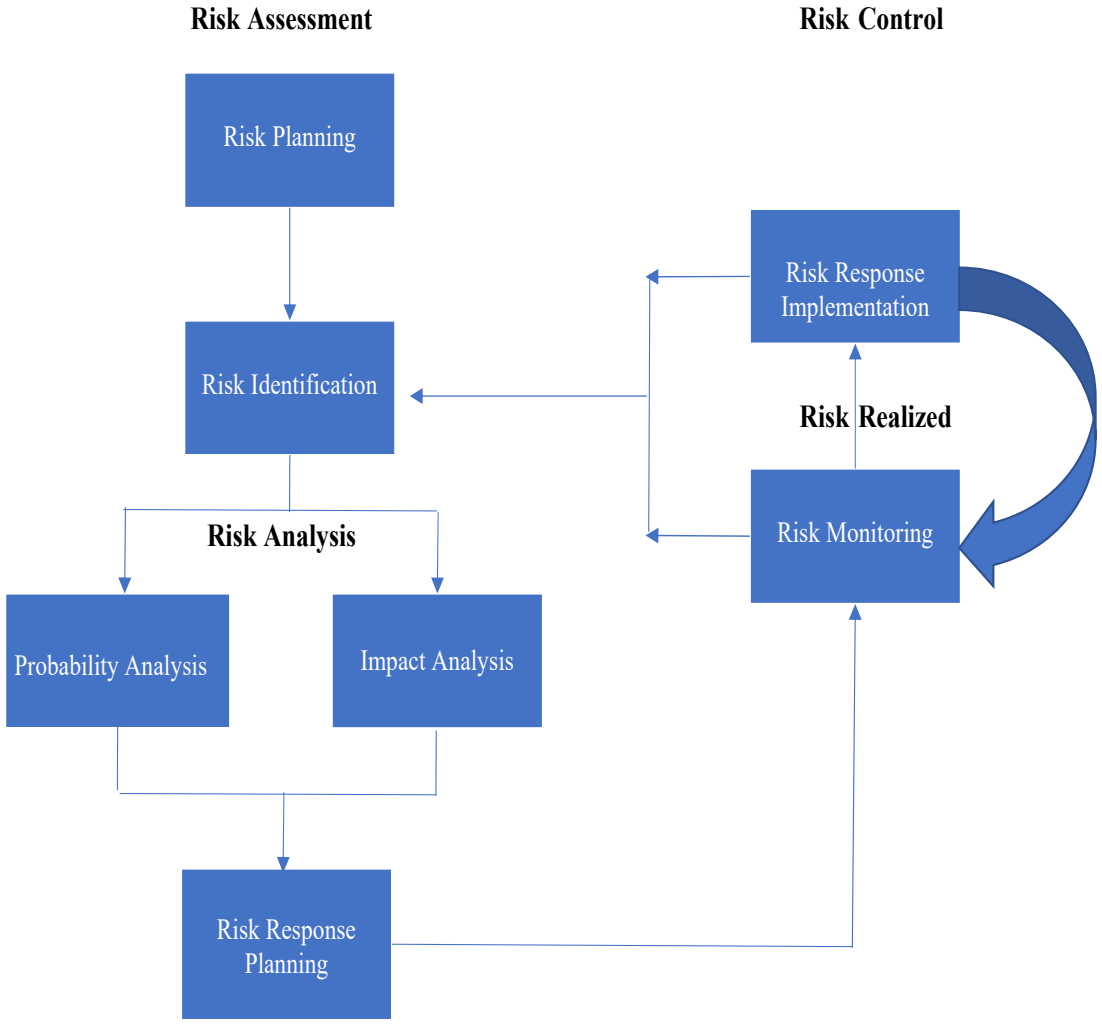
Stratecon's recommended actions requires Reclamation to develop new tools for prudent risk management, for forecasting the amount and variability in future natural flows on the Colorado River, and for addressing evaporation and system losses.

Prudent Risk Management

Uncertainty about future circumstances is inevitable. Predictions should be based on the best available information and analysis. How actual outcomes compare with predictions provides the opportunity for learning.

Risk Assessment and Control Framework provides a context for Reclamation decision-making (see Figure 3). Risk planning involves identification of the risk factors impacting outcomes. Risk Analysis examines the probability and impact of the risk factors. Risk planning identifies the tools used to manage realized risks. Monitoring outcomes is essential to implement risk responses. Lessons learned feedbacks to improved risk identification.

Figure 3
Risk Assessment and Control Framework



The process is related to concepts of "adaptative management" employed in the water industry and machine learning.[3] Plans have implicit, often unrecognized risks about future circumstances." Putting strategic into planning means thinking critically about fundamental assumptions and asking what the potential is for the future to look differently than the past. Provide a clear statement of the problem or hypothesis to be explored. Test hypotheses.

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[3] "The Machine Learning Primer" by Kimberly Nevada (https://www.sas.com/content/dam/SAS/en_us/doc/whitepaper1/machine-learning-primer-108796.pdf,. Machine learning studies data to detect patterns to:

- predict likely outcomes based on identified patterns
- identify unknown patterns and relationships
- detect anomalous or unexpected outcomes

The key decision for Reclamation is deciding what are the acceptable risks for Lake Powell and Lake Mead falling to minimum power pool and dead pool elevations. As discussed above, the issue is about the time profile of these risks. What is the acceptable balance between incurring the economic cost of curtailments in Colorado River water to increase storage in Lake Powell and Lake Mead, versus the future economic costs of elevations falling below minimum power pools or dead pool elevations in future years. In the end, there must be a balancing of risks.

Forecasting Future Hydrologic Conditions

Given that observed natural flows of the Colorado River have converged to the long-term average of tree ring studies, Stratecon recommends that Reclamation consider a forecast model based on the statistical characteristics of tree ring data. Attachment A presents an illustrative application. Tree ring data suggest that there is a tendency of "runs" of dry and wet years, which have an average expected duration of five years. Given the underlying volatility in annual natural flows from tree ring data, future forecasts should be considered with a dose of humility. Our future includes the prospect of experiencing wide variations in annual hydrologic conditions.

The illustrative model suggests that the challenges on the Colorado River are enduring. Recovery of annual natural flows to even the long-term average of tree ring study, 14.3 million acre-feet, will not likely occur until 2028, with the running average annual flows not likely to occur for another decade. Unless the Colorado River Basin receives a windfall of high flow years soon, which cannot be relied upon long-term, curtailments in the use of Colorado River water are on the table for at least a decade.

As Reclamation invests in monitoring of flows in the Upper and Lower Basin, there is the opportunity to apply machine learning from the "big data" generated by extensive real-time monitoring. From this perspective, Stratecon views Reclamation's current forecast models will ultimately be replaced by the machine learning identifying the best combination of the statistical properties of tree ring data, forecasts from climate change models and other approaches.

Evaporation and System Losses

Stratecon welcomes Reclamation's effort to understand how the Colorado River system, in fact, operates. Reclamation's 2012 *Colorado River Basin Water Demand and Supply Study* did recognize evaporation and system losses. Unfortunately, confronting the implications for management of the Colorado River, especially in the Lower Basin, evidently fell on deaf ears. Fast forward a decade. The emergency on the Colorado River demands that long-standing neglect be placed in the rearview mirror.

There are two parts to the issue. First, what is the scope of Reclamation's scientific investigation? Second, how should Reclamation use scientific information in determining how available water is managed to meet its contractual delivery obligations to water right holders?

Scope of Reclamation's Scientific Investigation

In Stratecon's view, Reclamation scientific investigation has two parts. First, given Reclamation's existing operating policies, what are the evaporative losses reservoirs in the Upper and Lower Basins and the system losses incurred for the delivery of water to water right holders? Regarding the latter, Reclamation should consider a "bottoms up" approach where the calculations focus on the system losses for each delivery contract. While undoubtedly mind-numbing in detail, the investigation could start with a schematic of the sources and destination of water flows from streams into the mainstem, inflows and outflows of reservoirs, and mainstem segments of releases from upstream reservoirs to downstream reservoirs and water users. The findings would provide a schematic of the "Reclamation Network" of how water flows throughout the Upper Basin, down to and through the Lower Basin and ultimately to the Mexico–United States border.

Second, assess how alternative management strategies impact evaporation and system losses. Would moving water storage upstream to higher elevations reduce evaporative losses? Should Reclamation coordinate operating decisions at Lake Powell and Lake Mead with the other smaller reservoirs on the Colorado River? Adoption of more effective management strategies could be part of long-term reform of how Reclamation manages the Colorado River.

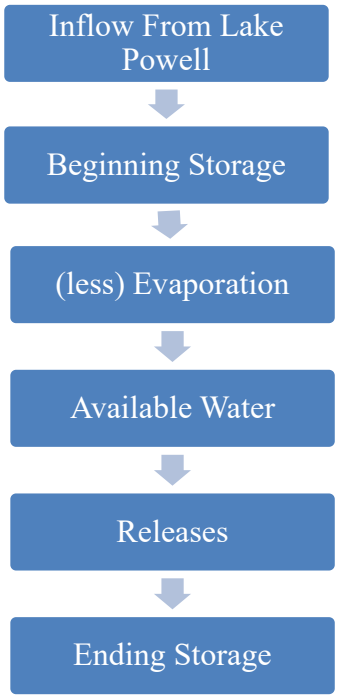
Reclamation's Use of Information in Meeting its Contractual Delivery Obligations

Evaporation impacts the volume of water Reclamation has available to meet contractual delivery obligations to Colorado River water users (see Figure 4 for a schematic for Lake Mead Evaporation). Inflows from Lake Powell supplements the volume of beginning water storage at Lake Mead. Evaporation reduces the volume of Reclamation's available water to meet contractual delivery obligations or to place in ending storage for future years

Who bears evaporation losses? The answer is found in Reclamation's contractual obligations and the Law of the River. By impacting the volume of available water, evaporation losses impact the volume of available water apportioned by the priority system.

Regarding system delivery losses, water delivery contracts specify delivery points. For example, the U.S. Supreme Court in *Arizona v. California* recognized 2.6 million acre-feet of Present Perfected Rights for IID based on water use in the Imperial Valley. When IID agreed to a quantification of its Priority 3 right in the Quantification Settlement Agreement, the annual limit of 3.1 million acre-feet was specified at Imperial Dam. In effect, Reclamation uses available Colorado River water in Lake Mead to meet its delivery obligations of all users of Colorado River water in the Lower Basin**.** System losses is the "delivery charge" Reclamation occurs to meet its water delivery obligations.

Figure 4
Schematic of Lake Mead Evaporation



System losses means that Reclamation must release more than one acre-foot from Lake Mead to deliver one acre-foot of Colorado River water to downstream water users (see Figure 5). For example, if system losses were 5% of releases to a water user, then Reclamation must release about 1.053 (1/.95) acre feet of water from Lake Mead to deliver one acre-foot of Colorado River water to delivery points specified in the party's federal water delivery contracts. To deliver 7.5 million acre-feet of Colorado River water to the Lower Basin, Reclamation must release more than 7.5 million acre-feet of Colorado River water from Lake Mead. (The magnitude of this "overage" would reflect the findings for the "Reclamation Network" described above.)

Evaporation and system losses are real, even if they have been historically ignored. As water supplies tighten, the incentive for accurate measurement grows with the need for proper management of the Colorado River. Improving measurement of available water and understanding deliveries and system losses to meet contractual delivery obligations is indeed a very good idea.

Figure 5
Schematic of Lake Mead System Losses

Conclusion

Continuation of how we manage the Colorado River will not address the current emergency on the Colorado River. Changing management strategy and developing decentralized, transparent market platforms for voluntary trading of Colorado River Water consistent with the Law of the River including the priority system can address the challenge. Lawyerly arguing over dueling redlines of the 1922 Compact will solve nothing. The only paperwork that matters involves voluntary agreements, transactions, and Reclamation regulations that successfully navigate our challenges.

It is time for us to step up, bring creativity, imagination, and innovation to the table. It is time that we act like we believe that the Colorado River is a unique and socially valuable resource worthy of sustainable management for generations.

As I mentioned in the Prelude, I am optimistic about the future of the Colorado River Basin. I found comfort in the remarks by Tommy P. Beaudreau, Deputy Secretary, Department of the Interior last Friday before the Colorado River Water Users Association in Las Vegas. The Biden Administration's commitment to developing policy based on science, transparency and collaboration are welcome. Adding improved risk management (backed by forward-looking, fact-based understanding of the underlying risks of future hydrology and understanding of the

economic consequences of policy alternatives) will help find the pathway for a successful future in the Colorado River Basin.

Thank you for the opportunity to provide input into your SEIS planning. In the spirit of cooperation and collaboration, Stratecon stands ready to engage in any form of dialogue you find useful. Stratecon's address and phone number is in the footer of page one. My email and cell phone are, respectively, rsmith@stratwater.com and (951) 201-5603.

Respectfully,

Rodney T. Smith, Ph.D.
President

Attachment A:
Illustrative Forecast Model Based on Tree Ring Study

Tree Ring studies provide a context to examine the long-term conditions of the natural flow of the Colorado River (see Figure A-1).[4] Colorado River hydrology of the 21st Century will not replicate the hydrology of the 20th Century. The "new normal" is a long-term average of annual natural flows of 14.3 million acre-feet. Given the volatility of hydrologic conditions, risk assessment and risk management of the Colorado River challenges the "current tools" of risk management in federal guidelines (see text).

Listening to Tree-Ring Data

For the eight-hundred and ninety-nine years for the period from the year 1116 through the year 2014, estimated natural flows averaged 14.3 million acre-feet, with relatively minor fluctuations in the 100-year running average—see Figure A-1.[5] Annual flows are volatile, ranging from a minimum of 7.5 million acre-feet to a maximum of 23.0 million acre-feet.

The annual variability in natural flows shows how the risk of curtailments accelerates as water demand reaches average flows (see Figure A-2). Annual flows are a saga of a peak probability of 12% for below average flows (11.0 million acre-feet to 12.0 million acre-feet) and a peak probability of 11.8% for above average flows (17.0 million acre-feet to 18.0 million acre-feet). Natural flows near the average are less likely. From a water supply perspective, any focus on "average flows" is misleading. During periods of extreme low annual flows, water users experience curtailments and/or substantial drawdown from available water storage. During periods of extreme high flow years, such as flows above 20.0 million acre-feet, stress the ability of storage to capture water for future drier years as witnessed in the 1980s.

Runs of Dry and Wet Years

The risk of curtailment is exasperated to the extent that there are runs of dry and wet years, which is the case of estimated annual natural flow from Tree Ring studies. Table A-1 presents a statistical study of the estimated annual natural flows by Tree Ring Studies. The model's estimated long-term average of estimated natural flows is 14.3 million acre-feet, the average of the estimated natural flow of Tree Ring Study.[6] The model estimates the impact of the estimated level of natural flow in the prior year on the estimated level of natural flow of a current year. A 1 million acre-foot change in the natural flow in the prior year generates a 0.32 million acre-foot change in the

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[4] Streamflow reconstructions from tree rings, https://www.treeflow.info/ , "Longest" period, 1116-2014. Large versions of the charts are placed at the end of the attachment.

[5] Reflecting the fact that the 20th Century was unusually wet, the 100-year running average increased from 13.8 million acre-feet in 1904 peaking at 14.96 million acre-feet in 2005, which is the highest 100-year running average for the historic record in Figure A-1.

[6] Model average equals 9,687/(1-0.321) ~ 14,300 thousand acre-feet

predicted natural flow for a current year. This impact on the current year natural flows, in turn, feeds into the level of natural flows in future years.[7]

Table B-1
Statistical Model of Estimated Annual Natural Flow of Colorado River from Tree Ring Studies (one thousand acre-feet)

Variable	*Coefficient*	*Standard Error*	*T-Statistic*	*P-Value*
Intercept	9,687	462	21.0	9.38E-80
Natural Flow Prior Year	0.321	0.032	10.2	4.20E-23
R^2	0.10			
Standard Error Residual	3,035			
F-Statistic	103.6			
Significance	$4.25x10^{-23}$			

- Coefficient measures the impact of the variable on natural flow in current year
- Standard Error is a statistical measure of the variability of the estimated coefficient
- T-statistic is the ratio of the coefficient to standard error
- P-value is the probability that the true value of the coefficient is zero
- R^2 is the proportion of the variation in the natural flow in the current year is explained by the variation in natural flow in the prior year
- Standard Error Residual: the standard deviation of the difference between natural flow in a current year and the model's a prediction based on the natural flow of the prior year
- F-Statistic is a statistical measure of the ability to use natural flow in the prior year to explain variation in the natural flow of a current year
- Significance is the probability that the model's coefficients are jointly zero

[7] The impact on current year 0, and future years 1, 2, 3 . . . n equals $0.321x\ 0.321^t$, where t = 0, 1, 2, 3, . . n, which is a power series. The long-term annual impact of 1 million acre-feet in the prior year is 0.473 million acre-feet, which is substantially achieved within five years.

As evidenced by the model coefficient's P-values and the significance of the model's F-statistic, the probability is remote that the estimated natural flow in a current year is independent of the natural flow in the prior year.

There is material variation of annual natural flows from the underlying estimated run in estimated natural flows (see Figure A-3). The average variation is zero over the eight hundred and ninety-eight years of estimated natural flows. The maximum amount annual natural flows exceed estimated natural flows is 8.7 million acre-feet. The minimum amount annual natural flows are less than estimated natural flows is 6.9 million acre-feet. There is no evidence that there are any runs over consecutive years in the differences between annual natural flows and estimated natural flows from the statistical model in Table A-1.[8] Therefore, the model provides a statistically valid assessment tool for the runs in above or below average years in the natural flow of the Colorado River.

Given the low natural flow of the Colorado River in 2022, the natural flow of the Colorado River is not anticipated to return to the long-term average for five years (2028)—see Figure A-4.[9] Given the below average flows during that period, the anticipated annual running average from next year (2023) remains below the long-term average throughout the forecast period, although the discrepancy narrows over time as more years of anticipated average long-term flows are included in the running average. From a water management perspective, the running average of natural flows going forward represent the expected water supply conditions in future years.

Given the volatility in annual natural flows, even average running average flows understate the risk management facing users of Colorado River water, especially through 2025 (see Figure A-5). There is a 20% chance that the natural flow of the Colorado River in 2023 is below this year's level of 10.4 million acre-feet, although the risk that the running average remains at that level over the next three years is remote. On the upside, there is a 5% probability that the natural flow of the Colorado River exceeds 18 million acre-feet next year ("a 2023 miracle"), with the odds diminishing that the running average would remain that high over the next three years. By the end of the decade, there is a 40 percent chance that the running average of the natural flow of the Colorado River water ranges between 12 million acre-feet and 14 million acre-feet and another 40 percent chance that the running average of the natural flow ranges between 14 million acre-feet

[8] The correlation between the differences in the current year and the prior year is -0.02. The correlation between the differences in the current year and two, three, four or five prior years, respectively, 0.04, 0.01, 0.04, 0.00. There is no "statistical run" in the forecast error of the model.

[9] The Bureau of Reclamation estimates the Colorado River natural flow will be 10.4 million acre-feet in 2022 (see Figure 1). The estimated future natural flows of the Colorado River based on a Monte Carlo study using the statistical model in Table A-1 taking random draws from the historical distribution of the difference between Tree Ring estimates of natural flow of Colorado River and predictions from the statistical model (see Figure A-3). The Monte Carlo study uses the analytic tool @Risk and based on 10,000 iterations.

and 16 million acre-feet. The wide range in even the running average of natural flows reflects the underlying volatility of annual estimated natural flows of the Colorado River.

Figure A-1
Tree Ring Estimates of Annual Natural Flow of Colorado River

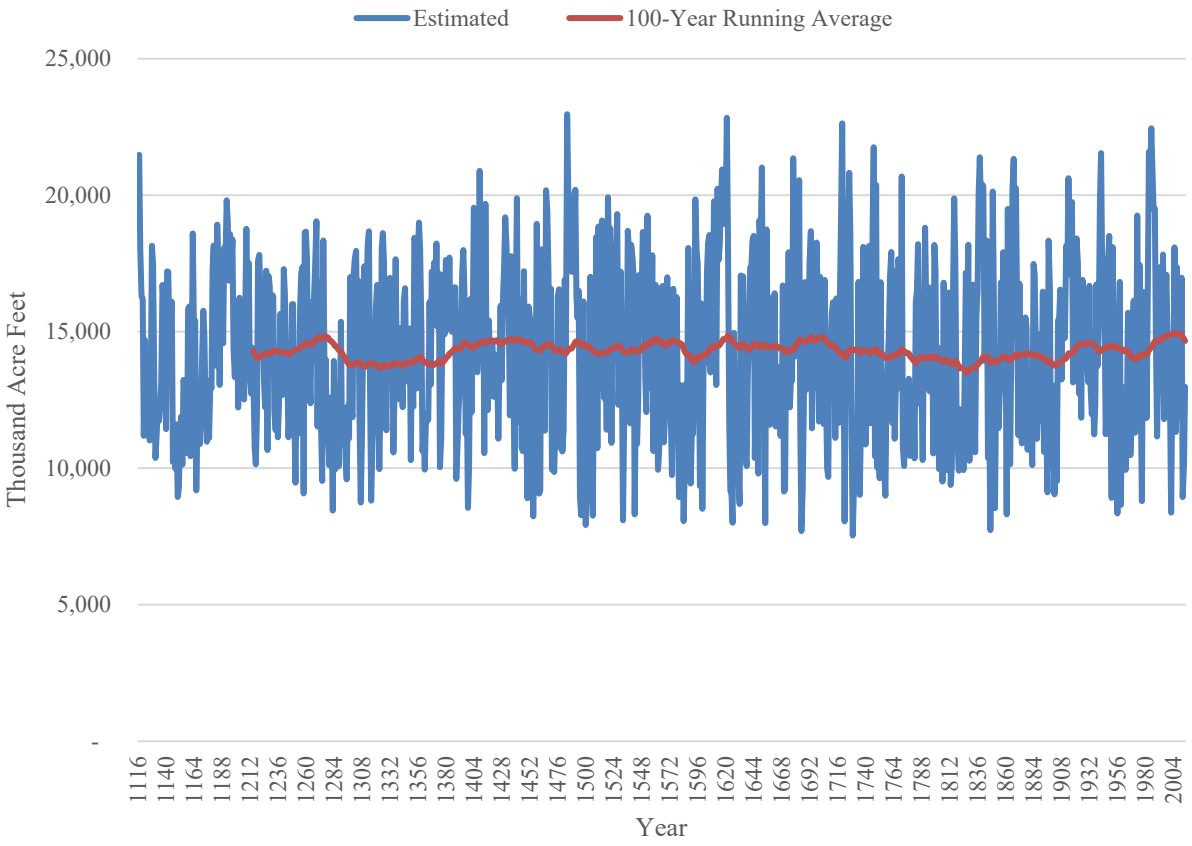

Figure A-2
Probability Distribution of Tree Ring Estimates of Natural Flow of Colorado River at Lee Ferry

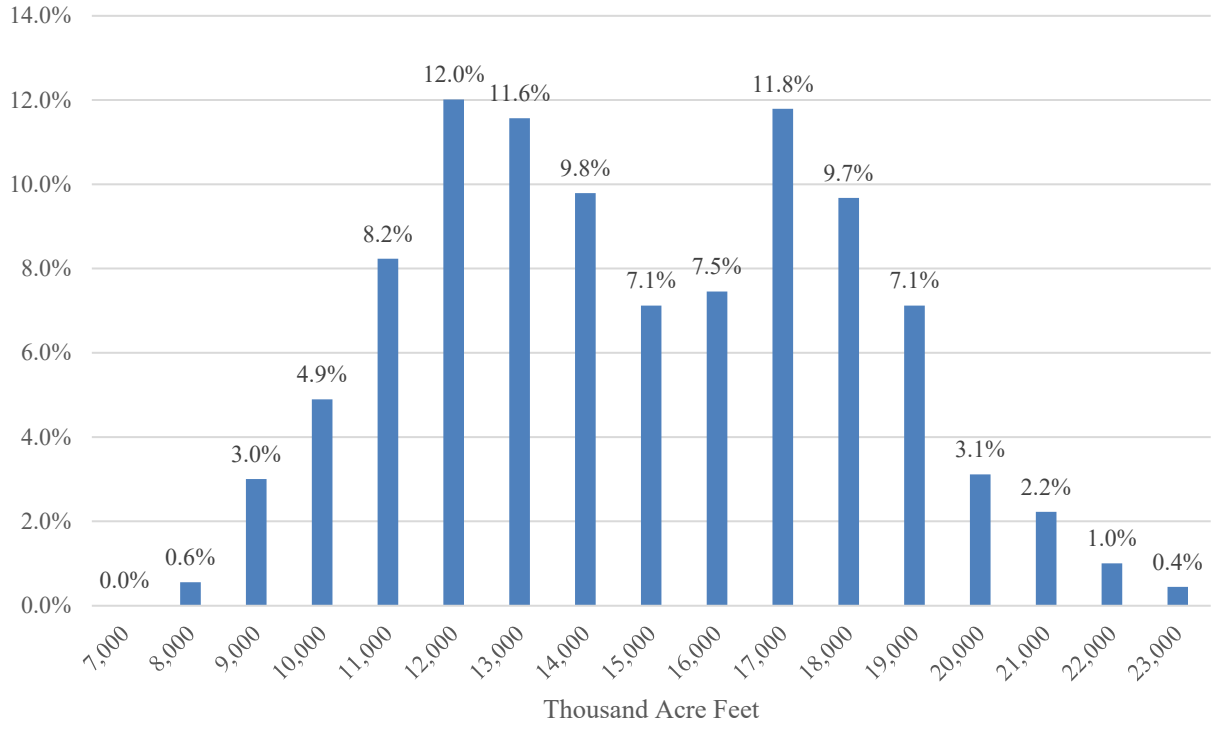

Figure A-3
Tree Rings Study Illustrates Volatility of Natural Flows of Colorado River

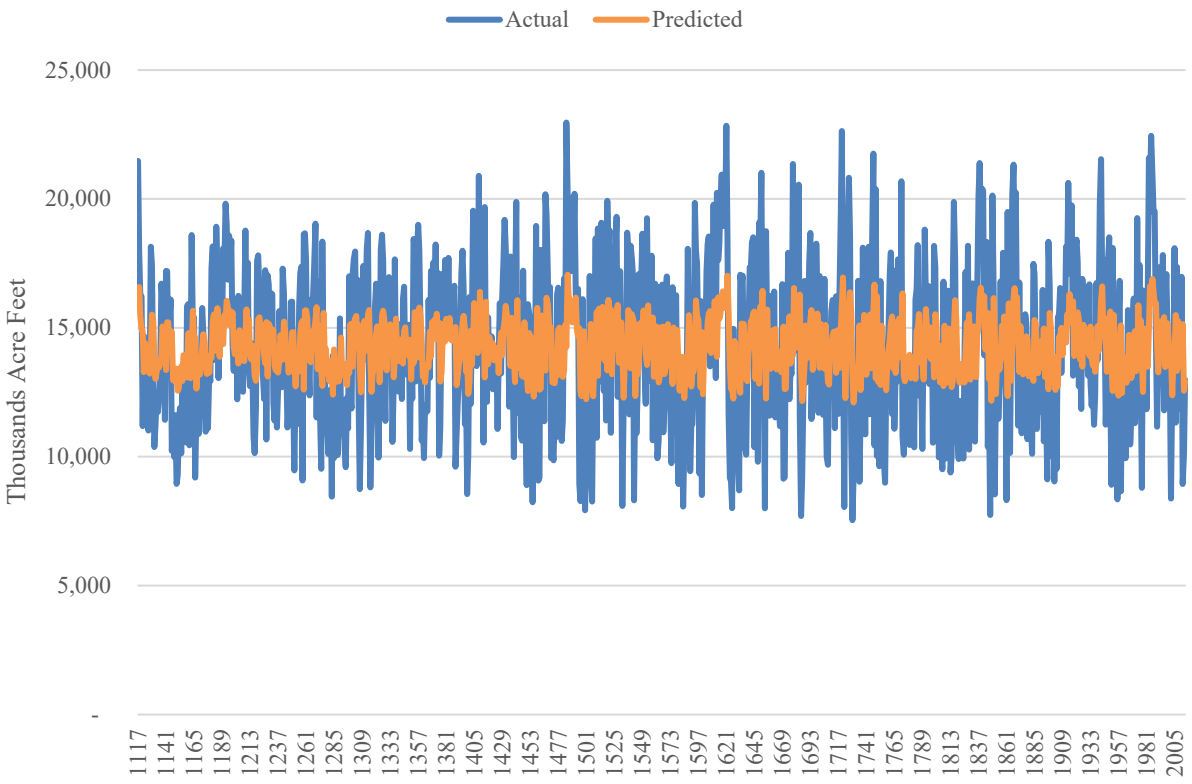

Figure A-4
Expected Natural Flow of Colorado River

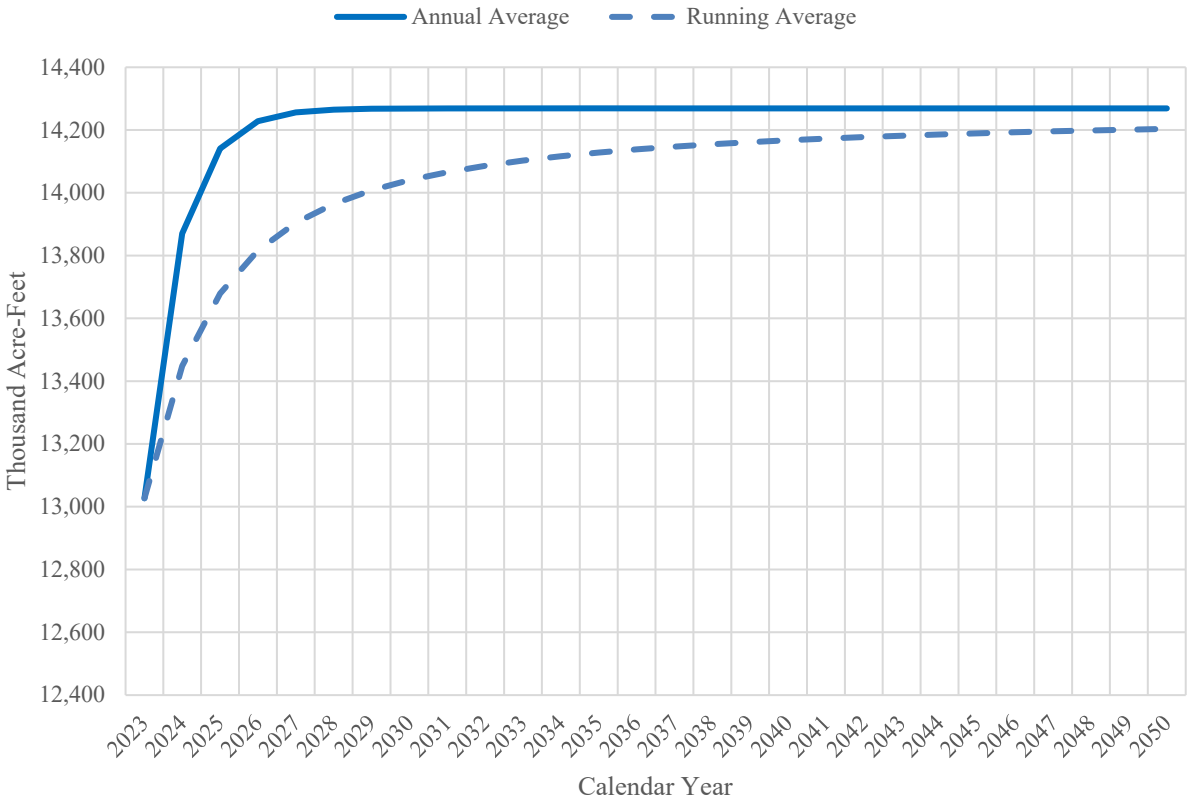

Figure A-5
Probability Distribution of Projected Running Average of Estimated Natural Flow of Colorado River