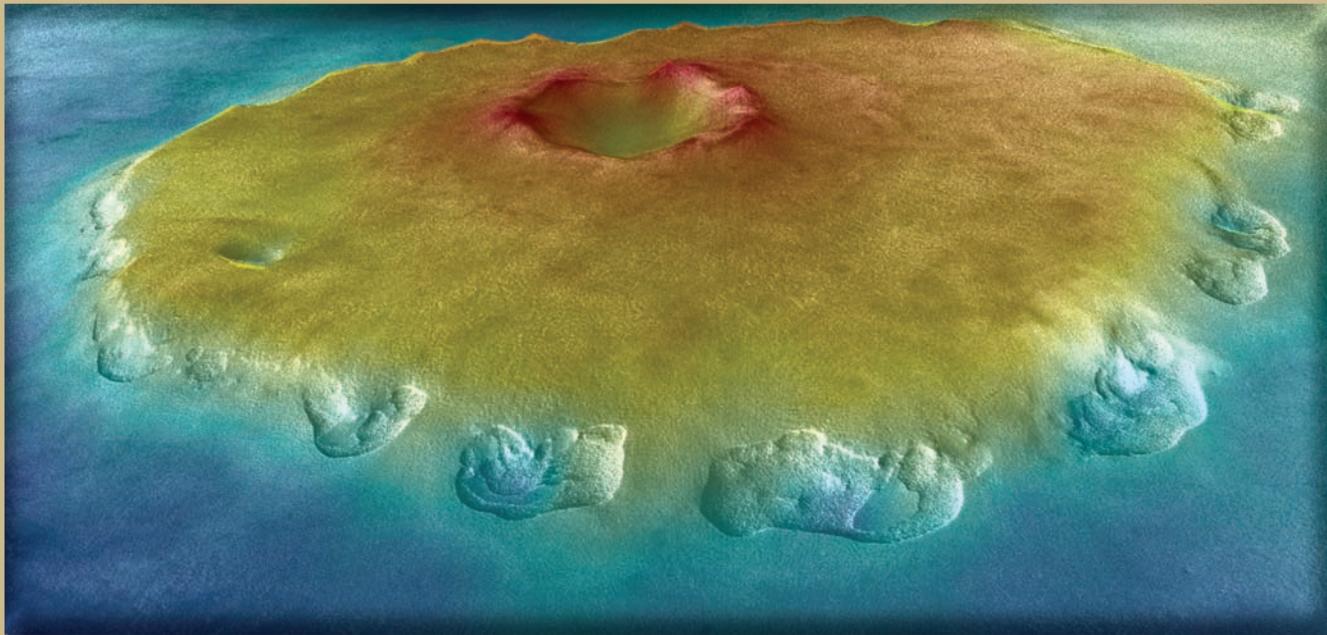


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Strange craters on Mars suggest a climate-related formation mechanism • Mantle plumes: Thin, fat, successful, or failing?
• Storage requirements in the Upper Colorado River basin



What a difference a century makes: Understanding the changing hydrologic regime and storage requirements in the Upper Colorado River basin

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[1] The changing hydrologic regime of the Upper Colorado River Basin presents a daunting challenge for water resources management. A major source of concern is that of ascertaining the nature of runoff variability and recalibrating the systemic management and planning based on a more reliable envelope of water supply variations to meet societal needs. In this letter, we examine the long-term variability and change in the Upper Colorado annual runoff volume—quantified as shifts in the mean, interannual variability, and persistence—in a recent tree-ring based reconstruction extending back to 762AD. A simple model for reservoir storage requirement shows sensitivity to the changing hydrologic regime, with episodes of abrupt shifts toward significantly higher storage requirements, often not readily evident in runoff statistics. The results also suggest that benchmarking of climate models for regional water resources assessment should focus on the runoff statistics that are most relevant for storage requirement computations.

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1. Introduction

[2] Sustainable water allocation and planning in the Upper Colorado River Basin (UCRB) presents a daunting challenge. Beginning in the second half of the 20th century, water resources management in UCRB has become a challenging task, largely stemming from increased water demand and an erroneously high estimate of the annual water supplies; the mean basin average runoff is based on a relatively short hydrological record from the early 20th century [*Pulwarty et al.*, 2005; *Committee on the Scientific Bases of Colorado River Basin Water Management Water Science and Technology Board, and Division on Earth and Life Studies*, 2007]. This situation is exacerbated by the recent, protracted drought that may very well be a recurring theme throughout the 21st century [*Barnett and Pierce*, 2008, and references therein]. The vicissitudes of wet and dry spells have a long history in this river basin—a multi-century dendrohydrological reconstruction reveals uncertain water supplies punctuated by droughts, sometimes lasting decades [*Meko et al.*, 2007]. Furthermore, the hydrologic

record for the early 20th century that served as the baseline for the 1922 Colorado Compact was the wettest period in the past twelve centuries [*Woodhouse et al.*, 2005]. Consequently, a major source of concern for water resources management is that of ascertaining the nature of UCRB runoff variability and *re-calibrating* the systemic management and planning based on a more reliable envelope of water supply variations. To guide and refocus efforts, much of the current body of knowledge focuses on documenting past droughts and changes in the long-term mean annual runoff.

[3] In this letter, we examine the long-term variability and change in the UCRB annual runoff volume—quantified as shifts in the mean, interannual variability, and persistence—in a recent tree-ring based reconstruction extending back to 762AD. The analysis presented here focuses on understanding the variability in runoff as it relates to reservoir storage needs in UCRB. In this context, some relevant questions are: What is the range of historical variations in UCRB runoff, and how do the dry periods differ in their character (spatial and temporal)? Finally, what is the relative impact, individually and jointly, of changes in the mean, interannual variability and persistence characteristics on storage requirements? We explore these issues using reconstructed hydrologic indices and a simplified reservoir capacity-yield-reliability model. Implications for near- and long-term water resources planning and considerations for focusing research that inspires effective use of 21st century climate projections in water resources management are discussed.

2. Data and Methods

[4] Annually-dated tree-ring based reconstruction of UCRB runoff (762–2005 period) at Lees Ferry, Arizona [*Meko et al.*, 2007] is analyzed here. *Meko et al.* [2007] provide a detailed discussion of the reconstruction procedures. Regional-to-continental scale hydrologic variability is assessed using a gridded reconstructed North American Palmer Drought Severity Index (PDSI) [*Cook et al.*, 2004]. These two datasets are excellent descriptors of the long-term variations in the western U.S. hydrologic regime. Throughout this letter, the 35-year period immediately preceding the 1922 Colorado Compact is used to compute the reference hydrology. An annual demand of 80% of the 1888–1922 period mean runoff is used in Gould-Dincer reservoir capacity-yield-reliability computations [*McMahon et al.*, 2007a] (some details are provided in the Implications for Storage Requirement section). Other methodologies, such as the Hurst's procedure, have also been used to compute reservoir storage requirements [see *McMahon and Mein*,

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1986]. Storage requirement is defined as the volume of storage needed to supply a given annual demand at a prescribed level of reliability. Here, consideration is given to the aggregate storage requirement (summed over multiple, competing objectives). Changes in water demand are not considered; consequently, a. as water demands increase, our estimates reflect the lower bound of reservoir storage requirement, and b. the analyzed runoff variations constrain the supply-end of the water resources management problem. Furthermore, the impact of evaporation on the storage requirements is not considered. The terms standard deviation and variance are used interchangeably to describe interannual variability. Similarly, we use persistence in runoff, lag-1 correlation and serial correlation synonymously. The analysis of runoff characteristics is carried out using 35-year windows, which is broadly consistent with the practice of defining climate [Guttman, 1989] and multi-decadal time horizons for infrastructure and resource management and planning.

3. Upper Colorado River Basin: Changing Hydrologic Regime

[5] Hydroclimatic variability in the UCRB occurs on a variety of time scales, ranging from interannual, to multi-decadal and centennial periods [Woodhouse *et al.*, 2006]. The severity and extent of arid spells and pluvials exhibit a rich diversity—in PDSI reconstructions, the fraction of area in the western United States experiencing drought has varied substantially over the last millennium [Cook *et al.*, 2004]. In the context of the variability and reliability of water supplies in UCRB, the long-term changes in the mean and standard deviations in the UCRB runoff are of particular interest (see Figure 1). Together, the mean runoff estimate and standard deviation are nuanced descriptors of the low runoff regime—ones characterized by high variability and others with relatively low interannual variability (see Table 1). The moving window estimates of variance (Figure 1b) show increasing variability in UCRB runoff over the last century. Increasing variability implies a higher incidence of elevated aridity and wetness relative to the mean state and a decrease in storage reliability (discussed in detail in the next section). Two recent studies have also noted a late-20th century trend toward higher variance of streamflow across the western North American region [Pagano and Garen, 2005; Jain *et al.*, 2005].

[6] The nature of dry periods in the reconstruction is examined by selecting five, 35-year periods with some of the lowest recorded runoff (marked as triangles in Figures 1a and 1b). For these selected periods, the spatial extent and severity of PDSI confirm the persistent nature of these dry periods. It is also evident that a reduction in the UCRB runoff was accompanied by aridity on conterminous U.S.-scale (1121–1155) in some cases, west-wide (1143–1177), and interior and southwestern U.S. (1870–1904; 1558–1592) in other cases. Regionally, dry periods with large spatial extent reinforce the concern related to the regional dependence on limited water supplies, hydropower reliability and ecosystems impacts. Runoff during the five dry periods is substantially lower than the 15.2 MAF (based on the 1888–1922 period) baseline, previously considered as representative of UCRB's natural hydrologic regime. This

discrepancy has been recognized for some time, however, while having similar mean runoff volumes, these five periods show marked differences in their standard deviations (see Table 1). The recent period, 1971–2005 shows the highest interannual variability. The 35-year periods ending in 1177 and 1307 have comparable mean runoff volumes, however, the standard deviation during the latter period increased by a factor of two. This doubling of standard deviation has some dramatic impacts on the relative recurrence of extreme events—under simplifying assumptions, a Normal distribution fitted to data from these two periods would suggest that a high runoff extreme event with a 35-year return period (probability of exceedance = 1/35) during the 1143–1177 period will translate to an approximately 6-year event for the period ending in 1307. With similar mean conditions, it is evident that changes in standard deviations can dramatically alter the reliability with which water demands can be met. In general, we note that the combination of changes in the mean and variability determine the exact nature of changes in the extreme event probabilities, thus allowing a robust characterization of the storage requirements. The observations made above are also relevant and merit consideration in reservoir storage assessment using climate change projections and scenarios. Typically, nonstationarity in the mean and variability are not incorporated in stochastic models of streamflow, and for a given time horizon (here, 35-years), coupled ocean-atmospheric models must be able to not only reproduce recent trends (natural and anthropogenic) but also the multiple time scale hydroclimatic variability, embedded in the averaging window, which exert important controls on the runoff variability and mean. The next section discusses storage requirement implications from a simple model of storage computation, based on annual runoff statistics.

4. Implications for Storage Requirement

[7] The Gould-Dincer (G-D) reservoir storage-yield-reliability methodology [McMahon *et al.*, 2007a] provides a simple expression to obtain estimates of the storage requirements using annual streamflow statistics. Given the annually-resolved reconstruction of UCRB runoff variability, this method is particularly suitable for a preliminary estimate of: a. changes in the storage requirements for a given demand (here, we consider it to be 80% of the mean annual runoff computed for the 1888–1922 period), and b. the relative role of the changing mean, standard deviation and persistence characteristics of runoff on the required reservoir storage. McMahon *et al.* [2007a] pursue a comprehensive assessment of the storage requirements for rivers around the world, and also discuss the merits of this approach, as well as favorable comparisons with other storage computations methods (see McMahon *et al.* [2007b] for a brief review of these methods). Since the G-D method uses annual runoff statistics, the reservoir storage computations are limited to over-year (carryover) storage, a situation consistent with the major storage reservoirs in the UCRB. The model assumes runoff to be independent; however, serial correlation can be readily accounted for in the reservoir storage estimates. McMahon *et al.* [2007a] discuss G-D formulations based on three probability distributions as representing runoff

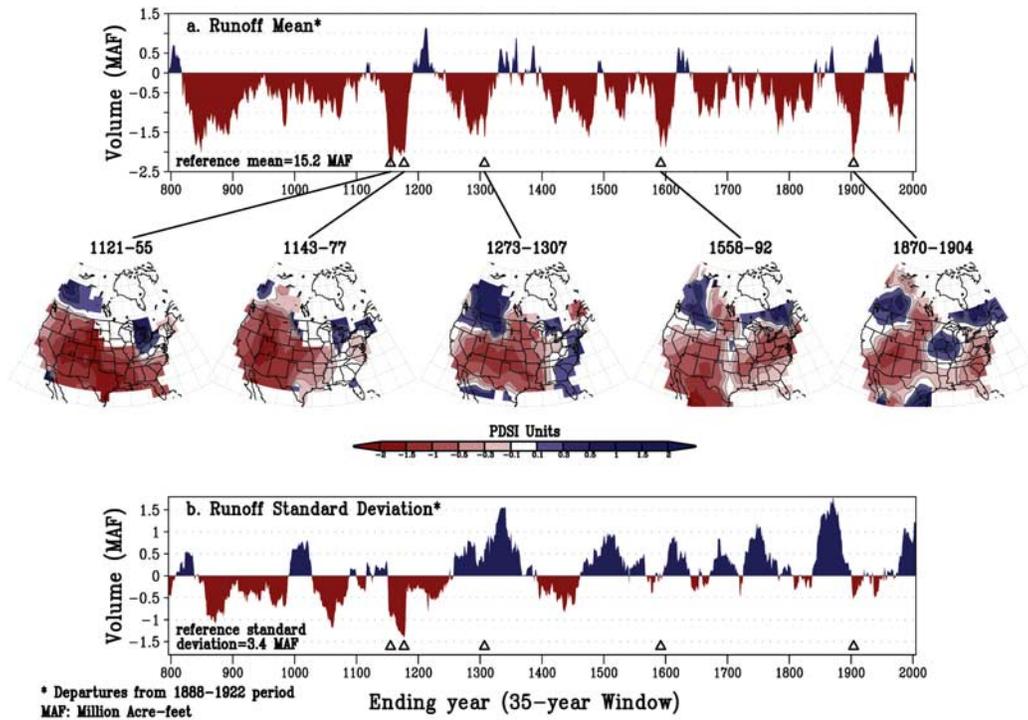


Figure 1. Long-term variations in the annual runoff for the UCRB (762–2005). (a) Variations in the mean runoff are assessed using 35-year moving averages. The results are shown as departures from a reference mean of 15.2 Million Acre-feet (MAF) from the 1888–1922 period. (b) Interannual variability of UCRB runoff is characterized based on the standard deviation. As in Figure 1a, the long-term variability is shown as a departure from a reference standard deviation of 3.4 MAF (1888–1922 period). Spatial extent and severity of aridity for five select dry periods (triangles are shown at the last year of the respective 35-year windows) is shown on the five maps of average PDSI over the focal periods.

variability: Normal, Lognormal, and Gamma. In this letter, we limit our investigation of the runoff variability to G-D Normal method. A Lilliefors’ Test for Normality [Dallal and Wilkinson, 1986] indicates an overall conformance to Normality (p -value = 0.18). The G-D Normal relationship allows an exploration of the interplay of the time-varying runoff statistics in determining the reservoir capacity (C):

$$C = \frac{z_p}{4(1 - \alpha)} C_V^2 \mu \frac{1 + \rho}{1 - \rho} \quad (1)$$

where the mean (μ), variance (σ^2), coefficient of variation ($C_V = \sigma/\mu$), demand (α , as a fraction of the mean annual

runoff), serial correlation (ρ), and reliability (z_p) are the key variables. G-D method presents a simplified model of storage requirement based on the first passage time—from a full reservoir to empty condition. As a result, multiple failures are not considered here. Given the annually resolved runoff data used here, the method estimates the over-year storage requirements. Similar to the analysis of McMahon et al. [2007a], we adopt two checks to ensure that the storage estimates are consistent with the over-year storage assumption based on standardized net inflow or drift, $m = \frac{1-\alpha}{C_V} < 1$ and the time taken by the reservoir to empty from a full condition is greater than one year. Figure 2b notes

Table 1. Some Statistical Characteristics of the Selected Dry and Wet Periods in the UCRB Runoff Reconstruction^a

Selected 35-Year Period	Mean ^b (μ)	Standard Deviation ^b (σ)	Lag-1 Correlation (ρ)	Storage Ratio			
				(μ, σ, ρ)	(μ, σ)	(μ)	(σ)
1121–1155	12.9	2.44	0.42	1.91	1.35	2.59	0.52
1143–1177	13.2	1.97	0.49	1.24	0.73	2.15	0.34
1273–1307	13.6	3.99	0.13	1.85	2.43	1.75	1.39
1556–1592	13.3	3.36	0.29	2.06	1.97	2.00	0.98
1870–1904	13.0	2.85	0.00	0.96	1.66	2.33	0.71
1888–1922	15.2	3.38	0.26	1.00	1.00	1.00	1.00
1971–2005	15.0	4.59	0.37	2.47	1.95	1.06	1.84

^aStorage ratio is defined as the ratio of storage requirement for any 35-year period to the baseline storage (1888–1922 period). The storage ratio computations are based on the temporal variations in one or more of the three statistical measures (mean, standard deviation, and serial correlation) as noted in the respective column.

^bMillion Acre-feet.

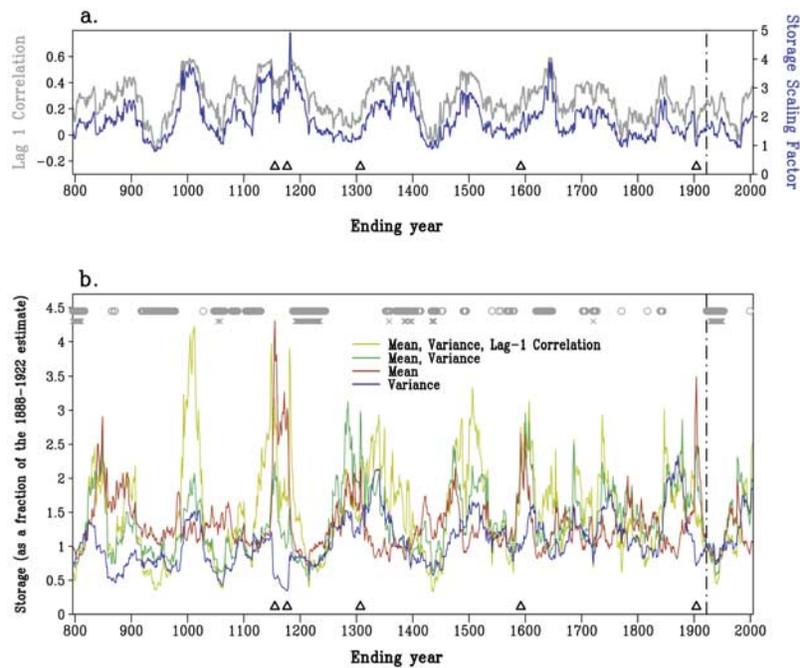


Figure 2. (a) Long-term variations in the serial correlation (ρ) of annual runoff for the UCRB (762–2005). Persistence in the runoff is based on lag-1 correlation estimates (grey) for 35-year moving windows. The impact of persistence of required storage expressed as $(1 + \rho)/(1 - \rho)$ —this Storage Scaling factor (blue) is a ratio of required storage for any 35-year window to the estimate for the shown the 1888–1922 period. A vertical dashed line highlights the serial correlation estimate for the 35-year period ending in 1922. (b) Variations in the storage requirements estimated from the Gould-Dincer procedure—35-year moving window runoff segments are used to estimate the storage requirement for a hypothetical reservoir serving a water demand of 80% of the mean annual inflow computed for the 1888–1922 period, with 95% reliability. Storage for a particular 35-year period is expressed as a fraction of the baseline storage based on the 1888–1922 period. Consequently, the ratio attains a unit value at 1922 (shown as a dashed vertical line). For each period, the relative impact of the temporal variations in the mean, standard deviation, and serial correlation is examined by selectively including the variables for storage computations, while the remainder of variables is held constant at the 1888–1922 value. The periods that are not consistent with the carryover storage and first passage time assumptions are marked (by grey circles and crosses respectively).

the periods where the assumptions of the G-D method are not met.

[8] The variability in the UCRB runoff mean and standard deviation is shown in Figure 1. Changes in mean are inversely related to storage requirement and changes in variability are directly related to storage requirements. The attendant historical variations (Figure 1) in the mean and standard deviation imply that as the shape of runoff empirical probability distribution varies over time, the storage requirement can undergo rapid or even abrupt changes. Rapid increases can have a devastating effect on the regional water resources reliability. At the same time, shifts in the mean and variability may offset each other, with a resulting storage requirement that is relatively unchanged. The variability in the persistence is shown in Figure 2a. The impact of persistence on storage requirement is, however, given by $(1 + \rho)/(1 - \rho)$.

[9] Individually, the 35-year estimates of the three key statistics (mean, variance, and serial correlation) provide a sampling distribution of these metrics for storage requirement computations. These changing statistics reflect the important role of the *local* (for example, river basin-scale antecedent soil moisture) and *remote* (atmospheric and ocean processes) drivers of hydrologic variability and change. It is important to note that the reconstruction

procedure involves a statistically fitted growth curve and removal of the low-order persistence (over the length of the tree-ring record), to account for biological aspects of tree-ring growth [Meko *et al.*, 2007]. This may cause a modest reduction in the serial correlation contributions from persistent climate anomalies and basin antecedent conditions (C. A. Woodhouse, personal communication, 2008). However, a comparison of the serial correlations over the last century (observations and reconstruction, computed on 35-year sliding windows) shows that the temporal variations in serial correlation are well-preserved in the reconstruction. Next, we examine the relative impact of these statistical measures on the storage requirement. The baseline statistics are computed for the 1888–1922 period. Based on these statistics, equation (1) is used to compute the storage requirement for a chosen level of reliability (z_p , based on the standard normal variate at $100p\%$ probability of non-exceedance). Similarly, for each 35-year window, storage requirement is computed as a ratio of storage for pre-Compact period (1888–1922). These computations facilitate: a. a quantitative assessment of the changes in storage requirements, and a retrospective view of the dynamic relationship between the past hydrologic regime on the water resources reliability, and b. an understanding the relative role played by the three runoff characteristics in

producing the changes in storage requirement, a key decision-centric variable for water resources planning and management. Time varying estimates of storage requirement (using nonstationary mean, variance, and serial correlation) show substantial variations (green line, Figure 2b), ranging from 50% of the baseline storage during the 13th, 15th, and the early 20th century to 400% in the late-10th and 12th century. This analysis also highlights a number of periods wherein the required storage is well over twice the baseline storage. Also, noteworthy is the fact that storage requirements often show a relatively rapid and near-abrupt increase over short span of a decade or longer. An understanding of this element of “hydroclimatic surprise” for a decision variable (storage requirement) is particularly important in addressing the current concern of ascertaining adequate storage in the face of a changing climate.

[10] To what extent do the hydrologic variations encoded in the mean, variance and serial correlation conspire to produce the rich variety of fluctuations in storage requirement? We investigate this by selectively incorporating the temporal variations in mean, variance, and serial correlation into storage computations (equation (1)). For example, the changes in storage requirement stemming from the changing mean (red line, Figure 2b; based on equation (1)) are computed by incorporating the time-varying runoff mean for 35-year windows, however, holding the variance and serial correlation values at the baseline values (1888–1922). Similarly, we consider a combination of cases (shown in Figure 2b) for storage estimates that illustrate the relative contributions of the mean, variance, and serial correlation. In a number of cases, it is the change in variance and serial correlation that increases the storage requirement—this is particularly true during the mid-1800s, where the consideration of the temporal variations in mean resulted in a storage requirement similar to the baseline cases (storage fraction = 1.0). However, changes in the variance and serial correlation caused the storage requirement increases to 200–300% of the 1888–1922 value. The impact of serial correlation of storage requirement is also especially pronounced ca. 1000, leading to one of the highest storage requirement in this reconstruction. The storage factors for a select 35-year period are presented in Table 1. The select cases provide some useful insights toward understanding the role of various ingredients of variability and change in determining the storage requirement. For example, the 1870–1904 period presents an interesting case where relative to the baseline period, the decreased variance and absence of serial correlation offset the substantially low mean runoff, thus rendering the storage requirement nearly unchanged. The runoff variability and change during the recent 35-year period (1971–2005) has resulted in a storage factor of 247%. The increased storage requirements stem from the trend toward increased variance and persistence in runoff. While these results are sensitive to the chosen length of the averaging window, the important role of incorporating the key aspects of runoff variability and nonstationarities therein is quite evident.

5. Summary and Conclusions

[11] The UCRB hydrologic regime shows a substantial dynamic range, with arid and wet periods interspersed over

the length of the record. Based on the results presented above, it is pertinent to reiterate the importance of the variability and change encoded in the three metrics of runoff variability—mean, variance and persistence—in determining the thresholds for reliable water supply and storage requirements. Some key points from the analysis presented in this letter are:

[12] 1. Mapping large-scale hydroclimatic variability on to the decision variables (storage requirement) is critically important to regional climate change impact assessment.

[13] 2. Rapid and near-abrupt changes in the storage requirement, occurring on decadal time scales, are evident in the UCRB runoff record. The fact that moderate shifts in the three runoff statistics may conspire to produce “hydroclimatic surprises” in decision variables (such as storage requirement) must be an important consideration for current and future climate change studies and hydrologic assessment in UCRB and other river basin across the world.

[14] 3. For historical periods, where climate models and observations can be cross-checked, do the models reproduce the mean, variance and persistence characteristics at regional scales of large river basins? These results can provide a baseline for benchmarking the appropriate use of a climate model for water resources applications, as well as combining information from multiple climate models and ensembles.

[15] 4. The time-varying estimates of mean, variance, and persistence provide sampling distributions of these metrics in a nonstationary setting. Stochastic streamflow simulation and forecasting may benefit from incorporating these distributions to generate ensembles of runoff traces for water resources management and planning.

[16] 5. Finally, an exhaustive analysis of the propagation and impact of hydroclimatic change signals (their nonstationary statistics and associated uncertainty) in the coupled model representations of the hydrologic, ecological and reservoir systems can help expose systemic vulnerabilities, critical thresholds and potential for abrupt shifts at river basin scales—this is an important research task likely to best inform adaptation and mitigation efforts.

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