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An assessment of the stationarity of climate and stream flow in watersheds of the Colorado River Basin

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SUMMARY

Several studies drawing upon general circulation models have investigated the potential impacts of future climate change on precipitation and runoff to stream flow in the southwest United States, suggesting reduced runoff in response to increasing temperatures and less precipitation. With the hydroclimatic changes considered to be underway, water management professionals have been counseled to abandon historical assumptions of stationarity in the natural systems governing surface water replenishments. Stationarity is predicated upon an assumption that the generating process is in equilibrium around an underlying mean and that variance remains constant over time. The implications of a more arid future are significant for surface water resources in the semi-arid Colorado River Basin (CRB). To examine the evidence of forthcoming change, eight sub-basins were identified for this study having unregulated runoff to stream flow gages, providing a 22% spatial sampling of the CRB. Their long-term record of surface temperature and precipitation along with corresponding gage records were evaluated with time series analysis methods and testing criteria established per statistical definitions of stationarity. Statistically significant temperature increases in all sub-basins were found, with persistently non-stationary time series in the recent record relative to the earlier historical record. However, tests of precipitation and runoff did not reveal persistent reductions, indicating that they remain stationary processes. Their transitions through periods of drought and excess have been characterized, with precipitation and stream flows found to be currently close to their long-term average. The evidence also indicates that resolving precipitation and runoff trends amidst natural modes of variability will be challenging and unlikely within the next several decades. Abandonment of stationarity assumptions for the CRB is not necessarily supported by the evidence, making it premature to discard its historical record as an instrument by which to assess sustainability of water resource systems.

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1. Introduction

The semi-arid Colorado River Basin (CRB) is a critical water resource spanning parts of seven western states of the United States and portions of northwestern Mexico. The highly dammed Colorado River and its tributaries provide municipal water supply to rapidly growing populations approaching 40 million people, irrigation water to more than 4 million acres of land, and hydroelectric power generation in excess of 4200 megawatts (U.S. Department of the Interior, 2012). Dammed rivers and large surface water reservoirs are important in the basin due to the semi-arid climate of the region, the high interannual variation in precipitation and runoff, the propensity for multi-year drought, and an increasing demand for water by a rapidly growing population. These factors combined with over-allocation of Colorado River water and recent drought episodes have sensitized water management in the region to potential threats that pose a challenge to water management strategies. During the past several years indications of an increasingly arid future for the western United States from climate change modeling studies have been brought to the attention of the water community (Christensen et al., 2004; Seager et al., 2007; Christensen and Lettenmaier, 2007; Hoerling and Eischeid, 2007; Barnett et al., 2008). Two dozen general circulation models (GCMs) generally project increasing aridity driven by the poleward expansion of the subtropical dry zones, increasing lower atmosphere temperatures, and reductions in the all-important winter season precipitation (Intergovernmental Panel on Climate Change (IPCC), 2007; Seager and Vecchi, 2010). The models indicate that drying should be underway (Milly et al., 2005; Seager et al., 2007; Hoerling and Eischeid, 2007; Barnett and Pierce, 2009; Hoerling et al., 2009). But, due to the divergent findings among climate projections generated from combinations of

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different models and different greenhouse gas scenarios, substantial uncertainty exists about the consequences of climate change to precipitation. Projected precipitation trends show substantial regional variations, seasonal cycles are poorly represented, and changes are more complex and less certain than those for temperature alone (IPCC WG1, 2007; Milly et al., 2005; Dominguez et al., 2009). Once climate projections are applied to hydrologic models that are challenged to respond with accurate representations of the arid hydrology of the western United States, the range of possible outcomes enlarges as uncertainties propagate through sequential levels of modeling complexity.

Amidst these complexities and the challenge of incorporating uncertain hydroclimatic trends into water resource forecasts, the attention of the water management community was heightened by the assertions made by Milly et al. (2008). They stated that the concept of stationarity, "the idea that natural systems fluctuate within an unchanging envelope of variability – a foundational concept in water-resource engineering", should be abandoned; and that, since "it cannot be revived", only non-stationary models should henceforth be used in water resource planning. As they explained, "For a time, hydroclimate had not demonstrably exited the envelope of natural variability and/or the effective range of optimally operated infrastructure." But, that "In view of the magnitude and ubiquity of the hydroclimatic change apparently now underway, we assert that stationarity is dead"..."because substantial anthropogenic change of Earth's climate is altering the means and extremes of precipitation, evapotranspiration, and rates of discharge of rivers." "The global pattern of observed annual streamflow trends is unlikely to have arisen from unforced variability and is consistent with modeled response to climate forcing."

Confirming the role of stationarity as a foundational concept in system analysis, Nelson (1995) pointed out that, "...the concept of stationarity underlies much of stochastic modeling." Knowledge of whether or not a process generating sequential outcomes is stationary is particularly important to probabilistic representations of the process because non-stationary modeling is significantly more complex. Considering the implications of the assertions by Milly et al. (2008) this study was initiated to confirm whether, in fact, hydrologic variables in the CRB have become non-stationary in their time series. Increasing anthropogenic warming in the recent era is considered to have commenced in the late-1970s, so we are presently approaching the halfway mark towards the projected precipitation and runoff changes stipulated for mid-century. Therefore an assessment of whether nonstationary behavior in these variables has begun to emerge would be opportune. This study examines a set of sub-basins within the CRB as a platform for assessment of the assertions of hydroclimatic non-stationarity.

1.1. Definition of stationarity

Some clarification and specificity in the definition of "stationarity" is instructive for an objective and quantifiable assessment. Nelson (1995, p. 38,185) provides a statistical definition:

> "When the distribution of a process that evolves over time does not depend on time, the process is *time stationary*." "The time-stationarity property in continuous time is: $\Pr\{Y_{t+\Delta t} = j | Y_t = i\}$ is the same for all $t \geqslant 0$"

So, for any time lag, Δt, between observation intervals the probability distribution for any observation given the (same) probability distribution for another observation elsewhere in the series will be the same for all points in the time series – making a stationary probability distribution equivalent across time, t.

Characterization of stationarity is also of fundamental importance in the application of various forecasting methods, as noted by Makridakis et al. (1998, p. 136):

> "...*stationary*, meaning that the process generating the data is in equilibrium around a constant value (the underlying mean) and that the variance around the mean remains constant over time."

This is supported in a number of statistics texts, including Burt and Barber (1996, p.505): "A stochastic process is stationary if its statistical moments are invariant over time." Additionally, they state:

> "Note that varying degrees, or order, of stationarity are possible. For example, a process might be stationary in the mean, but not in the variance. ...stationarity at a given order requires stationarity at all lower orders.'

Shumway and Stoffer (2010) also distinguish between orders of stationarity, clarifying with a distinction between strictly stationary and weakly stationary time series. They define a time series as strictly stationary if all moments of its probability function are identical across time, while a weakly stationary time series is constant in just its mean and covariance functions. In general, researchers have acknowledged that in practice it is typically feasible to test just the first and second moments (mean and variance) of a series, and that this is considered sufficient in practice to evaluate whether or not a time series is stationary for most purposes. Therefore, while multiple methods are employed for the study reported below, the most rigorous assessments through hypothesis testing are focused on the mean and variance of the time series across the historical record.

2. Data

2.1. Study area

The CRB is a heavily regulated source of surface water in the western United States, posing a challenge to assessments of the purely climatological effects upon its flows. To select specific study areas the points of unregulated flow in upper tributaries were examined to identify eight sub-basins where it is feasible to obtain runoff data which directly reflect climate variability (Fig. 1, Table 1). These sub-basins represent a cross-section of climate conditions in the CRB due to their various latitudes and elevations. Each is relatively large in size to consistently capture precipitation, and they have different seasonal ranges of temperature as well as precipitation falling as both rain and snow. Each has been previously examined by the authors for hydrologic response to find that they span a range of runoff yield and efficiency, from 1% for the Little Colorado in summer to 39% for the Animas in winter. Each sub-basin drains to a maintained stream gage providing a long-term measurement record of unregulated flow, and the gridded terrain flowing to its gage can be specifically identified – both being necessary conditions to enable data sourcing for this analysis. The total area of the eight sub-basins sums to approximately 22% of the total CRB drainage area and provides a generalizable assessment of the CRB response to climate change.

2.2. Temperature and precipitation data

Fine-resolution gridded climate data sets suitable to matching the spatial boundaries of each sub-basin watershed are available from the Parameter-elevation Regressions on Independent Slopes Model (PRISM, http://prism.oregonstate.edu) (Daly et al., 1994). The resolution of PRISM grid cells is 0.0416 degrees of latitude

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