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## **Exploring The Robustness of Regional Scale Coupled Infrastructure Systems: Water and Landuse in Central Arizona**

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**Abstract:**

**Keywords:**

# Exploring The Robustness of Regional Scale Coupled Infrastructure Systems: Water and Landuse in Central Arizona

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## 1 Introduction

Robustness and resilience have become central ideas in Sustainability Science in general and, more specifically, the study of social-ecological systems (SESs) and their capacity to cope with change (Anderies et al., 2013; Walker et al., 2009; Janssen et al., 2007; Janssen and Anderies, 2007; Walker et al., 2006; Adger et al., 2010; Eakin and Wehbe, 2009). Much of the development of these concepts has grown out of the natural resource management literature which has traditionally focused around smaller scale social-ecological systems including rangelands (e.g., Perrings and Walker, 1997; Janssen et al., 2004) (Anderies et al., 2006b; Walker et al., 2006), small-scale irrigation systems (Cifdaloz et al., 2010; Eakin, 2003), and shallow lakes (Carpenter et al., 1999b,a). Insights generated from these studies may not be easily generalizable to more pressing problems we face today because global social, economic, and climate change is increasing the spatial scale at which social groups interact with the environment and both the temporal and spatial scales at which these coupled human-environment systems experience shocks. Further, there has been less work on resilience and robustness of larger-scale SESs where large stocks of shared, human-made infrastructure play a critical roles in structuring interactions between humans and the environment. There are some examples of studies of the resilience of larger systems, e.g. *regional-scale* systems (Anderies, 2006; Anderies et al., 2006a; Anderies, 2005), but there is a need to more systematically explore modern contexts where multiple interdependent water, energy, transportation, food, and settlement infrastructures interact. Such an exploration calls for expanding the SES concept, which does not typically incorporate large scale human-made infrastructure, to encompass the concept of *coupled infrastructure systems* (CIS) (Anderies et al., 2016; Anderies, 2014; Anderies et al., 2013).

Here, we contribute to filling this gap through an analysis of the regional-scale CIS comprised of the Phoenix and Tuscon Metropolitan areas and surrounding agricultural areas within the Central Arizona Project (CAP) service area (see below), and the water delivery infrastructure that connects these areas to the Colorado River Basin. The Colorado River extends 1,450 miles (2,334 km) with a basin size of roughly 246,000 square miles (637,137 square km), historically running from the Rocky Mountains in northern Colorado to the Gulf of California in northern Mexico. The two largest-capacity reservoirs in the United States, Lake Mead and Lake Powell, are impoundments on the Colorado River. In addition to dozens of other dams along the main stem of the river and its tributaries, a number of large canals carry water diverted from the Colorado River for

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purposes of irrigation and municipal water supply, including the CAP aqueduct. The Central Arizona Project aqueduct extends 336 miles (541 km) from Lake Havasu on the Colorado River through the metropolitan areas of Phoenix and Tucson, with a service area of roughly 24,000 square miles (62,160 square km). In central Arizona, the CAP aqueduct augments other major water supplies from Salt River Project (SRP) infrastructure in the Salt and Gila river basins (portions of hydrological subregions 1506 and 1507) as well as groundwater aquifers. In a year of normal operations, CAP delivers 1.6 million acre-feet (maf) of Arizona’s 2.8-maf allocation of Colorado River water (CAP, 2014). Total cultural water demand in Arizona is approximately 6.8 maf annually (Maupin et al., 2014), 76 percent of which is used in irrigation.

Future water supply for the Central Arizona Project is tenuous, particularly in the likely scenario of decreased precipitation in the upper Colorado River basin as a result of climate change (Bureau of Reclamation, 2012). As a condition of federal authorization for construction of the Central Arizona Project in 1968, the aqueduct has junior water rights and will bear most of the shortage if water available in the Colorado River system is insufficient to satisfy the full lower basin apportionment defined in the Law of the River (Colorado River Basin Project Act, 1968). Among Central Arizona Project contracts, agricultural water is the lowest priority. However, farmers in many irrigation districts in central Arizona have generally secure rights to ground water. Agricultural water use plays a pivotal, if incidental, role in managing the region’s water portfolio.

In the remainder of the paper we develop and analyze a dynamic model of water flow through the lower Colorado River system (Lake Powell and Lake Mead) and the Salt, Verde, Tonto, and Aqua Fria reservoir system in the face of climate change. The central question we address is how interdependencies among different classes of infrastructure (e.g., natural infrastructure in the form of aquifers, groundwater recharge basins, and river watersheds; hard infrastructure in the form of water conveyance structures and the urban built environment; and soft infrastructure in the form of water governance and land use institutions) impact the robustness and resilience of the regional CIS so defined.

We suggest that effective governance might better view these various infrastructures more flexibly, at a larger scale, and leverage capacity to mobilize multiple value streams afforded by various classes of infrastructure. We emphasize the notion of infrastructure as it is *foundational* and contributes to many potential downstream activities (Frischmann, 2005). Thus rather than conceptualizing the Central Arizona Region (by which we refer to Maricopa, Pinal, and Pima counties and will abbreviate as CAR hereafter) in terms of the agricultural sector, the urban sector, etc. we view it as a cohesive CIS that provides opportunities for wellbeing via a number of different resource streams.

## 2 The context: Water and Agriculture in Central Arizona

Though the public debate has rarely been framed this way, agricultural water users and municipal water users in the CAR have shared a strategic relationship as a result of the construction of the Central Arizona Project aqueduct and the conjunctive use of groundwater and surface water supplies in the region (for a discussion of framing, see Bausch et al., 2015). Federal funds for agricultural water development were made available for the construction of the aqueduct, which has supplied water for municipal growth. At the same time, municipal water use fees have underwritten agricultural water rates, which has given many farm operations access to more diverse water portfolios. We characterize agricultural water users as private provisioners of public goods in the CAR (Tompkins and Eakin, 2012). Institutions structuring the relationship between agricultural and municipal water users have been both accidental and intentionally designed through the public

policy process. Sometimes these uncoordinated institutions work to the same end, as in the dynamic between the reduction in agricultural groundwater withdrawals (intentionally designed) and the increase in incidental recharge of the groundwater aquifer through agricultural use of surface water from the Central Arizona Project (accidental). Dynamics like this highlight the need for a multilevel analysis of “day-to-day” operational water resource decisions concurrent with analysis of the incentive structures of public infrastructure providers (collective-choice regional water policy arena). Stakeholders at all levels might benefit from this analysis because, at present, the outcomes they face are contingent upon each others relatively uncoordinated actions.

With respect to supplying water to the CAR, local officials and policy experts have generally considered the present CIS to be quite robust (Gammage Jr et al., 2011; ADWR, 2014). The semi-arid metropolitan areas of Phoenix and Tucson have accommodated a doubling in urban population since 1990 through changes in water use patterns and through extensive infrastructure accessing three major water sources: local surface water (the Salt and Verde rivers and their tributaries), ground water, and the Colorado River. Yet, models predict water supply shortfalls will occur in within the next 20- to 45-year planning horizons unless additional supplies are developed (Bureau of Reclamation, 2012; ADWR, 2014). Critical questions for the robustness of this CIS therefore include: What types of disturbances is the system robust to? Where in the system are potential problems likely? How might institutional design affect how interdependencies in the system are mediated? Direct conflict between public infrastructure providers and resource users has been minimal in the current institutional environment, but stakeholders will need to adapt to minimize mismatches in incentives as conditions change.

### 3 The model

The model we develop here is an extension of some of the regional-scale models mentioned in the introduction. Specifically, we build on the use of minimal or stylized models for policy design at the regional scale (Anderies, 2005). For example, Anderies et al. (2006a) used a stylized model to explore the impact of policy and land use patterns on salinization in agricultural regions supplied by the Murray and Darling rivers in Australia. The model captures irrigation infrastructure (reservoirs, canals), agricultural land, and groundwater systems at the regional scale. An analogous stylized model can be made for infrastructure in Arizona, illustrating the generality of the CIS perspective. Our goal is to explore the core relationships between public infrastructure and how people (resource users) use water (the resource) and land as climate changes. In the case of the lower Colorado River system, the public infrastructure is the set of dams and reservoirs that control water flows as shown in Figure 1 (the ‘hard’ infrastructure) and the complex set of rules used to govern the flows (the ‘soft’ infrastructure), detailed in Appendix 1. A third key element of the system is natural infrastructure in the form of aquifers that underly the CAR. These aquifers are characterized by considerably more uncertainty (see, e.g., Meixner et al., 2016) than are the hard and soft infrastructures (reservoir capacities, even considering sediment backfill, are relatively well known, we can measure inflows, we know the release rules, etc.). Addressing these uncertainties is well beyond the scope of this paper. As such, consistent with our modeling approach, our results on net groundwater recharge should be understood as a rough aggregate measure only.

#### 3.1 Hard Infrastructure

The hard infrastructure is modeled as a simple network of water storages. Water moves between storages (grey trapezoids in Figure 1) based on inflows (gold trapezoids) to the top-most storages (e.g. Lake Powell, Roosevelt lake, etc.) and regulated outflows from the storages. The equations

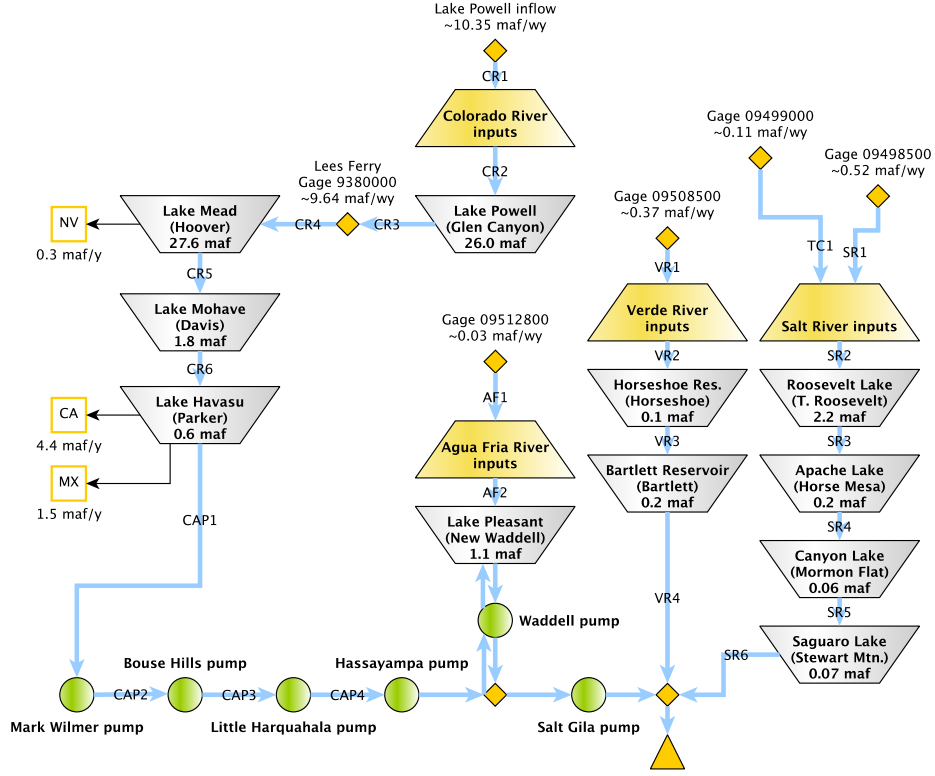


Figure 1: High-level schematic of major reservoirs and flows captured in the model.

of motion for the storages are:

$$V_p(t+1) = V_p(t) + I_p(t) - O_p(t) - r_e A_p(t) \quad (1)$$

$$V_m(t+1) = V_m(t) + I_m(t) - O_m(t) - r_e A_m(t) \quad (2)$$

$$V_s(t+1) = V_s(t) + I_s(t) - O_s(t) - r_e A_s(t) \quad (3)$$

$$V_v(t+1) = V_v(t) + I_v(t) - O_v(t) - r_e A_v(t) \quad (4)$$

$$V_{af}(t+1) = V_{af}(t) + I_{af}(t) - O_{af}(t) - r_e A_{af}(t) \quad (5)$$

where  $V$ ,  $I$ ,  $O$ ,  $A$ ,  $r_e$  are volume, inflow, outflow, area, and evaporation rate, respectively, and the subscripts refer to the (P)owell, (M)ead, (S)alt, (V)erde, and (A)gua (F)ria systems. The dynamics of the hard infrastructure are very simple: the volume of water in the next period, i.e.  $t+1$  is the volume now, i.e. at  $t$ , plus inflows, less outflows. Outflows consist of releases and evaporation. Given the granularity of the data and the multi-decadal focus of our analysis, the model runs on a monthly time scale.

The inflow for Lake Powell,  $I_p(t)$  consists of a combination of natural and regulated flows from storages further upstream (e.g. Flaming Gorge). We do not model these upstream flows—we take it as a given input and explore how it affects the dynamics of flow downstream of Powell. Similarly, the inflow for Lake Mead,  $I_m(t)$  consists of a combination of natural flows between Powell and Mead plus releases from Powell. The model only accounts for the latter, as it is much larger than the former. The water ultimately delivered through the Central Arizona Project aqueduct is governed by releases from Mead. The question we address here focuses on the capacity of this system of storages combined with institutional arrangements that govern its function to meet water demands under different climate change scenarios.

### 3.2 Soft Infrastructure - The Law of the River

The soft infrastructure, consisting of the rules and organizational infrastructure that together produce the protocols for reservoir releases, is considerably more complex than the hard infrastructure. The key public infrastructure provider in our case is the the US Bureau of Reclamation, which operates reservoirs on the Colorado River according to a rolling two-year projection based each month on the previous month’s reservoir levels, inflow, and water use forecasts. Projections in August of each year are used for the operating plan of that next calendar year (CY). In 2007, responding to drought conditions that persist into the present (although the situation has begun to improve at the time of writing, see <http://droughtmonitor.unl.edu/Home/StateDroughtMonitor.aspx?AZ>), the Secretary of the Interior, Bureau of Reclamation, and the basin states agreed to guidelines for the operation of the two principle reservoirs under shortage conditions through water year (WY) 2026, the “interim” period. The lower basin states’ deliveries, and thus the operation of the two principle reservoirs, Lake Powell and Lake Mead, depend on whether the Secretary of the Interior declares the Colorado River is under normal, surplus, or shortage conditions. A declaration of shortage conditions is a determination by the Secretary that there is insufficient water supply to meet the lower basin states’ annual 7.5 maf apportionment. Historically, the water gage at Lees Ferry (below Lake Powell) has been used as a measurement of flow from the upper to the lower basin. Lake Powell has stored water to meet the upper basin states’ contractual deliveries while Lake Mead has stored water allocated to the lower basin states, and the two reservoirs have been operated in tandem with the goal of equalization of active storage between the two. During the interim period, there are four operational tiers designated for Lake Powell operations (“Interim Guidelines,” 2007). Each tier is tied to an absolute elevation, or “trigger level,” at Lake Mead and an increasing annual schedule of water surface elevations at Lake Powell. At the two highest tiers, 8.23 maf/WY is scheduled for release from Lake Powell for use in the lower basin and Mexico. Despite severe drought conditions, this scheduled release volume has been met or exceeded in most recent years. In August 2013, Bureau of Reclamation announced that scheduled releases from Lake Powell in WY2014 would be the lowest in operational history and the first significant chance of lower basin delivery shortage was projected for 2016 (USBR Lower Colorado Region, 2013, August 16).

The tabular description of if-then statements in the Appendix constitute a detailed set of rules for releases from Powell and Mead that depend simultaneously on the water levels in both reservoirs. We capture the essential features of the release protocols as a series of if-then statements in the model. For Powell, outflows are determined by four tiers, triggered by water surface elevation (a measure of the “water depth”) in the reservoir. Let  $E_p(t)$  represent the water surface elevation of lake Powell at time  $t$ , then the release is defined as follows.

1. If  $E_p(t) \geq E_{et}$  employ the Equalization Tier (ET) rules.  $E_{et}$  is the tier switching set point for ET. This tier specifies the release of at least 8.23 maf while balancing volumes in the two reservoirs, i.e.  $O_p(t) = 8.23 + V_B(t)$  where  $V_B(t)$  is the release volume for balancing (see below). There is no specified upper bound for the release volume; it is determined by physical constraints.  $E_{et}$  changes year to year.
2. If  $3575 \leq E_p(t) < E_{et}$  employ the Upper Elevation Balancing (UEB) Tier rules. The elevation of 3575 is the “Mid Elevation Release” Tier set point. UEB is then split between two tiers based on the water surface elevation in Mead. If the elevation in Mead is greater than 1075 feet, employ UEB 6B1 which dictates a release 8.23 maf, i.e.  $O_p(t) = 8.23$ . Otherwise employ UEB 6B2 which dictates a release of at least 7 maf while balancing volumes in the two reservoirs with an upper bound of 9 maf, i.e.  $O_p(t) = \min(8.23 + V_B(t), 9)$ .

3. If  $3525 < E_p(t) < 3575$  employ the Mid Elevation Release (MER) Tier. The elevation of 3525 feet is the “Lower Elevation Balancing” Tier switch point. Depending on whether the elevation of Mead is greater than or less than 1025 feet, employ MER Tier A or MER Tier B, respectively. MER Tier A specifies  $O_p(t) = 7.48$  which focuses on increasing the depth in Powell while MER Tier B specifies  $O_p(t) = 8.23$  which focuses on increasing the depth in Mead.
4. Finally, if  $E_{leb} < 3525$  employ the Lower Elevation Balancing tier and release between 7 and 9.5 maf and balance reservoir volumes, i.e.  $O_p(t) = \min(7 + V_B(t), 9.5)$

These rules specify general reservoir operations under “normal conditions.” They do not provide details regarding how flood releases and volume balancing are executed. Similarly, Mead has a set of “normal,” “surplus,” and “shortage” rules that determine release volumes that range between 7 and 7.95 maf. These are simpler than for Powell as they are governed by water elevation only in Mead. Details for Mead release conditions (and the Salt, Verde, and Agua Fria systems) can be found in the Appendix.

## 4 Analysis

Our analysis consists of a series of scenarios to investigate the function of water-related infrastructure under a range of regional climate conditions (inputs to the Colorado at Powell from the upper basin, Salt, Agua Fria, and Verde river systems). The analysis is composed of three stages: 1) model validation, 2) scenario development, and 3) scenario analysis. The first stage is self explanatory. The second involves characterizing water supply and demand scenarios used in the third stage. The third stage involves exploring how the different supply and demand scenarios developed in the second stage may impact water availability in the CAR.

### 4.1 Model Validation

First, we will illustrate the model’s behavior by validating it against actual historical water elevations in Powell. It is important to reemphasize that the model is not intended for precise prediction for short-term planning but, rather, able to robustly capture the essential features of the system (i.e., is not too sensitive to parameter choices) to explore long-term behavior of the system. Before proceeding we need to provide a few more details about Equations (1)- (5). First, because Mead is downstream of Powell,  $I_m(t) = O_p(t) + I_{mn}(t)$  where  $I_{mn}(t)$  is the natural inflow to Mead from areas of its watershed operating downstream of Powell. Because  $O_p(t) \gg I_{mn}(t)$ , in our analysis we assume  $I_{mn}(t) = 0$ . Next, some release tiers involve balancing the reservoirs via  $V_b(t)$  for which we do not have data. Thus, we assume the simplest form possible, and assume  $V_b(t) = \max(g_b(V_p(t) - V_m(t)), 0)$ . Obviously,  $V_b(t) = 0$  when the reservoirs are balanced ( $V_p(t) = V_m(t)$ ), and  $g - b$  is a constant that determines how balancing releases scale with volume differences. Finally,  $O_p(t)$  may include special flood releases not specifically included in the rules. We capture this flow as  $V_{fp}(t) = \max(g_{fp}(E_p(t) - E_{pf}), 0)$  where  $E_{pf}$  is an elevation above which flood releases begin.

The dynamics of  $V_p$  given by (1) are driven by  $I_p(t)$  for which we use actual data and  $O_p(t)$  determined by release rules such as those above. Figure 2 summarizes the validation process by showing two scenarios. The bottom panel shows the time evolution of the volume of Lake Powell when the release conditions listed above are applied starting in 1964 with default parameters. This scenario shows the “baseline” result when the model is applied naively, with no attempt to tune



parameters to fit the historical record. We have set  $E_{et} = 3650$  and  $E_{pf} = 3690$ . The left panel shows the historical water volume in Powell (thick grey) overlain with that generated by the model (thin black). The result is a reasonable fit that suggests that inputs and reservoir geometry are strong drivers of long-term dynamics and that as long as the general protocols of reservoir balancing and flood releases are observed, the model behaves well. The panel on the lower right shows the release tiers for this scenario. When Powell is empty, LEB is employed. As it fills the tier quickly switches to MER A, Then to UEB 6B1, and finally to ET. Note that the MER B and UEB 6B2 tiers are never used. This is due to the behavior of Mead - the combination depths in both reservoirs for those tiers was never realized.

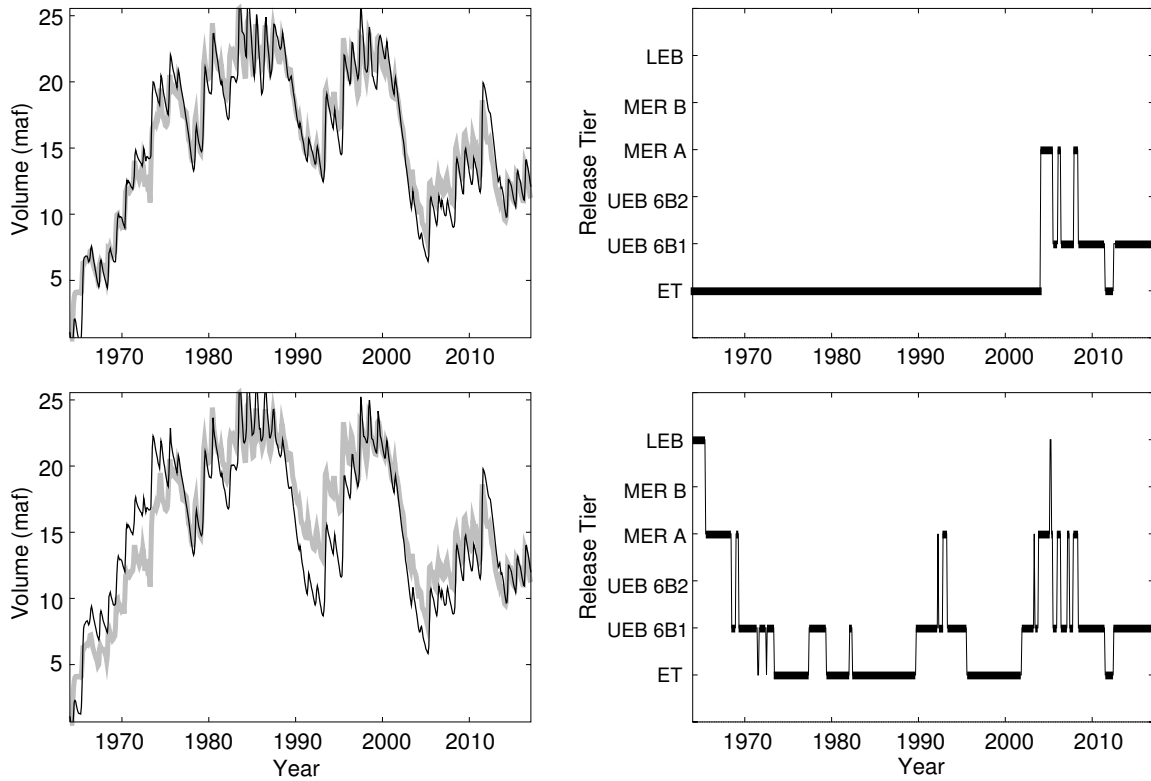


Figure 2: Powell Reservoir volumes and release tiers. Release tiers are: LEB = Lower Elevation Balancing, MER = Mid Elevation Release, UEB = Upper Elevation Balancing, and ET = Equalization Tier. See text for further discussion.

The top two panels illustrate the model behavior when historical changes in release tiers and flood control are taken into account. First, the Powell release tiers were not adopted until 2004. From 1970 to 2004, the release rule was equivalent to the Equalization Tier regardless of the depth. That is, from 1970-2004,  $E_{et} = 3370$  where 3370 is the minimum elevation of Powell. Second, it is clear that the flood control elevation of 3690 is too high (compare model to actual in the period 1980-1990). Third, the model release after flooding events is too high. This suggests that the actual flood release rule is more complex than the linear approximation in the model. To capture these facts in the model, we set  $E_{et} = 3370$  from 1964 to 2004 then switch to  $E_{et} = 3650$ . Next, we set  $E_{pf} = 3700$  during periods where flooding was not a concern (1964-1984 while Powell is filling and dry periods) and  $E_{pf} = 3670$  during the 1985-1987 and 1997-1999 wet periods. These minor changes produce an excellent fit as shown in the top left panel. The associated release tiers are shown in the top right. The point of this exercise is to demonstrate that the model can match the

Sector	Demand (use), maf/yr				Source, maf/yr	
	Maricopa	Pima	Pinal	Total	Surface	Ground
Municipal ( $D_m$ )	0.910	0.191	0.072	1.173	0.668	0.505
Industrial ( $D_I$ )	0.044	0.038	0.003	0.085	0.006	0.079
Agricultural ( $D_a$ )	1.234	0.113	1.191	2.539	1.270	1.269
Total	2.188	0.342	1.266	3.797	1.944	1.853

Table 1: Water demand (use) and supply source summary for the CAR. Sources (Maupin et al., 2014; USGS, 2017)

historical data with minimal tuning, providing confidence that it captures the basic features of the system quite well. Note that regardless of the historical trajectories, the release tiers eventually converge once the same protocol is applied for some time (compare top and bottom right panels after 2005 and top and bottom left panels after 2011).

The question to which we now turn our attention is to what extent the system can maintain flows out of Mead if the characteristics of the periodicity (major frequency modes) or amplitudes of the inflows to Powell change due to climate change. More specifically, we explore how when the CAR is viewed as a CIS comprised of urban and agricultural infrastructure systems, the robustness of the system to climate change can be increased.

## 4.2 Scenario Development

Of course, there are many scenarios of potential interest for the management and sustainability of regional-scale systems. Here, we are interested in exploring a very specific set of scenarios focused on conceptualizing such management challenges as coordinated decisions regarding investment and use of coupled infrastructures. In particular, we are interested in the interaction of water, agricultural, and urban infrastructures in the CAR. Decisions that take into account interactions between these infrastructures will necessarily perform better than those that do not. In reality, decisions regarding urban development, agricultural land use, and water infrastructure are often taken by actors who can only affect a subset of infrastructures. Here, we explore the potential of improving outcomes if decisions did take all infrastructures into account, i.e. were conceptualized as coordinated investments in a regional-scale CIS. In so doing, we may uncover potential benefits of increased coordination between governance entities at the regional scale.

To restrict our attention to a tractable problem, we will investigate how land use decisions at the CAR scale that affect urban development and agriculture impact the robustness of water availability to changes in water inputs from the upper Colorado River basin. To put this into context, consider the main water demand streams in Table 1. Total demand is around 3.8 maf/year in the CAR. We cast this demand against the backdrop of supply under normal operating conditions of the reservoir system. Specifically, of the 7.5 maf/yr apportioned from Mead, 4.4 goes to California, 2.8 maf goes to Arizona and the remainder to Nevada (Table B4 in the Appendix). Of the 2.8 maf to Arizona, 1.6 maf/yr goes to the Central Arizona Project. The local system (Salt, Verde, Agua Fria, and Tonto rivers) delivers around 0.9 maf/yr while miscellaneous local surface and reclamation sources provide around 0.4 maf/yr.

Thus, in broad terms, the total available surface water under normal conditions is  $1.6 + 0.9 + 0.4 = 2.9$  maf/yr to meet a demand of approximately 3.8 maf/yr indicating that roughly 0.9 maf/yr net groundwater withdrawals (the 1.853 maf/yr in Table 1 less 0.9 maf/yr incidental recharge primarily as a result of water used in irrigation) are required to make up the difference. Note that local water accounting practices and the fact that USGS, the source of our water use data, does not currently

Frequency Decomposition of Powell Inflow Time Series

Power	0.866	0.587	0.339	0.248	0.223	0.184	0.181
Relative Power	1	0.678	0.392	0.286	0.257	0.212	0.209
Frequency (1/mo)	0	0.083	0.166	0.00627	0.168	0.00783	0.251
Period (months)	$\infty$	12.048	6.024	159.50	5.960	127.60	3.986
Period (years)	0	$\approx 1$	0.50	13.29	0.497	10.63	0.33

Table 2: Fourier decomposition of Powell inflow time series. The time series has 638 points allowing for the Fast Fourier Transform to extract 319 frequencies ( $638/2$ ). Shown are those frequencies with the highest spectral density, with a relative power cutoff of 0.2 - i.e. powers with less than 20% of the maximum are truncated. The signal composed of these top seven frequencies is shown in Panel B of Figure 3 overlain on the raw signal.

collect consumptive-use data make it difficult to accurately categorize water use and sources, thus these numbers should be understood as rough estimates. On the time scale of our analysis, they are sufficiently accurate to provide a general picture of net groundwater use over time. Further note that the groundwater use in Table 1 is aggregated over the three counties. This allows for some areas to be experiencing recharge while others experience overdraft. We are not interested in this level of detail here. Rather, we are concerned only with the long run groundwater balance. The questions we address here are: how might changing rainfall patterns in the upper Colorado River basin and the local catchment affect this balance?, and what strategies might be employed to increase the robustness of water supplies to these changes? To address these questions, we must first clarify what we mean with rainfall patterns.

#### 4.2.1 Characterizing Changing Precipitation Patterns in the Powell Watershed

Panel A Figure 3 shows the monthly inflow to Lake Powell from January 1964 to February 2017 used to generate the volume time series in Figure 2. The mean inflow over this period is 0.8662 maf/mo or  $\approx 10.4$  maf/yr. The best straight-line fit of the data reveals a drying trend over the period with the mean declining at a rate of about 0.05 maf/yr, from around 11.73 maf/year in 1964 to 9.06 maf/yr in 2017. It is clear from the naked eye that there are annual cycles and lower frequency cycles with periods on the order of 10 years. After de-trending the data (removing the best straight-line fit) we are left with the underlying variation in the signal within the time period to which Fourier transform techniques can be applied to reveal the most dominant frequencies. Reconstructing a signal based on these frequencies allows us to systematically project different scenarios into the future.

We are interested in two specific trends associated with climate change: general drying and increased concentration of rainfall in space and time. We investigate two types of drying: reduced mean without a change in variance and reduced mean with a related reduction in variance. To create the first type, we can simply add the de-trended signal to the mean value and vary the mean, i.e. shift the entire signal downward. To investigate the second, we can simply scale the signal by a climate-change-related “drying factor,”  $d_{gc}$  where  $0 \leq d_{gc} \leq 1$  to capture and manipulate information regarding the temporal concentration of rainfall events in time. The latter involves changing the temporal patterns of dominant frequencies.

Table 2 shows the seven most dominant frequencies in the signal for inflows to Powell. The signal reconstructed from these frequencies is shown in Panel B of Figure 3 overlain on the raw signal. The most dominant frequency is 0 which corresponds to the mean inflow of 0.866 maf/mo. As we would expect, the next dominant frequency, 0.083 generates annual fluctuations (period of 1 year)

related to the seasons. The third and fifth dominant frequencies together generate fluctuations with periods of around 6 months related to intra-annual precipitation patterns. Most important for our analysis are the fourth and sixth dominant frequencies which generate fluctuations with periods of around 13 and 11 years, respectively. These may represent larger-scale climate patterns such as El Niño, La Niña and the PDO (Mo et al., 2009; Timilsena et al., 2009; Hunter et al., 2006) which may change as a result of climate change. Thus, our scenario analysis will address how the system responds to simple changes in the mean and variance in the previous paragraph, and to changes in the periods of these larger-scale climate patterns, e.g., longer periods while maintaining the mean to mimic longer drought periods between period of more intense precipitation.

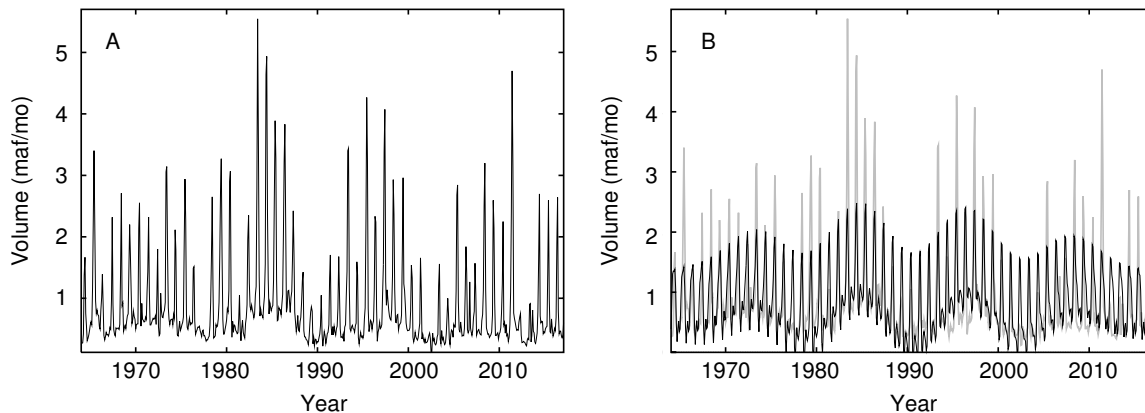


Figure 3: Powell Reservoir inflow. A: actual data. B: actual data (gray) with reconstructed signal with seven most dominant frequencies (black).

#### 4.2.2 The ‘Local’ Water System

The local water system is composed of the Aqua Fria, Verde, Salt, and Tonto watersheds and their associated dam systems (see Figure 1). The first thing to note is that lower frequency modes that drive the 12-year undulations in the Powell inflow time series are not immediately apparent (compare the low points of the signals to that of the Powell inflow data). This is likely because the watersheds for these systems are much smaller and are dominated by inter-annual dynamics. As a result, we do not attempt to extract lower frequency variation from these signals and, rather, simply explore the impact of general drying in these systems in our scenarios.

The next important point is that actual release protocols for these reservoirs are more difficult to obtain. However, because the outputs from these systems are not central to our exploration here, a rough approximation of the releases is sufficient. We assume that releases from these reservoirs are set at a constant level except for extra releases due to flood risk and the constraint that there is enough water in the reservoir to meet the constant release level. Based on the available time series for these watersheds, the maximum sustained delivery from the entire system is around 0.82 maf/year with roughly 0.55, 0.22, and 0.05 maf/yr from the Salt, Verde, and Agua Fria, respectively. That is, it is possible to deliver 0.82 maf/yr over the entire period (638 months) without the instantaneous delivery rate falling below 0.82 maf. Attempting to deliver more than this amount on a continuous basis will result in at least one month over the sequence where the release will fall below this level. Note that actual reservoir management using weather forecasts and moving water in the reservoir system could, of course, allow for improved smoothing of water supplies. As such, this number is just a rough indicator of the long run capacity of the reservoir system to dampen the variability in the incoming water signals, i.e., the maximum capacity to

capture water from higher than average flow events and store them to offset periods of below average flow events.

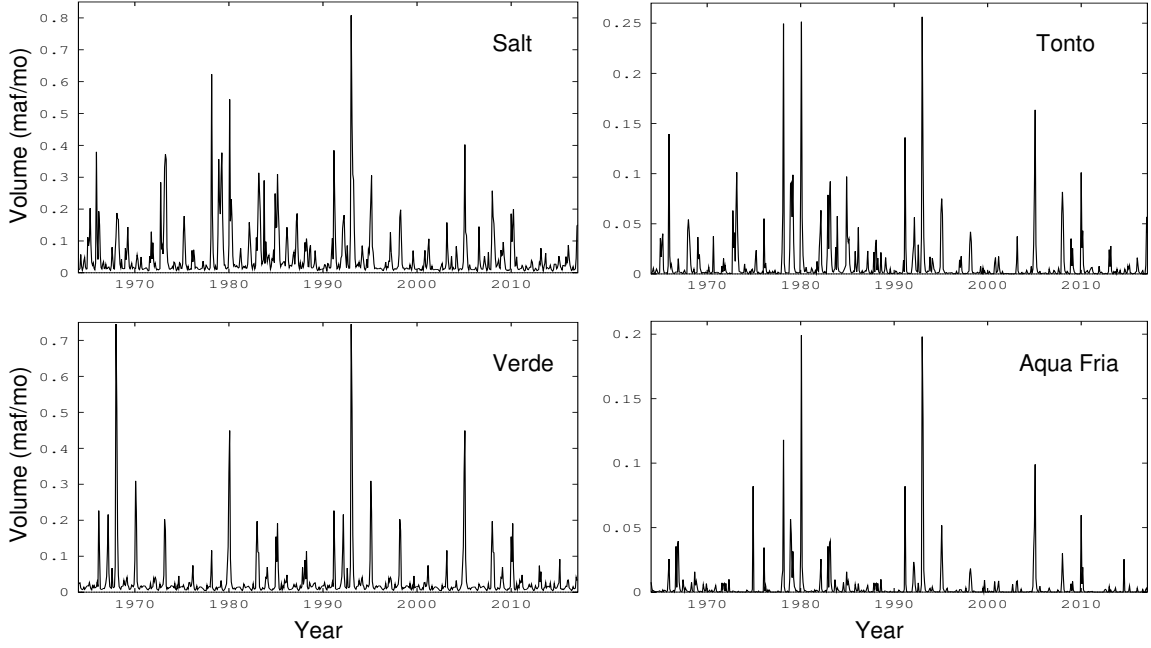


Figure 4: Local reservoir inflows for Roosevelt Lake (Salt + Tonto), Horseshoe Reservoir (Verde), Lake Pleasant (Aqua Fria). Note that in the Verde and Aqua Fria systems, data is only available beginning in 1985 and 1970, respectively. To create time series to match the length of the Powell time series, time series of the required length is simply copied from the beginning of the Verde and Aqua Fria time series to create a reasonable approximation of time series for entire period. These series are minor contributors, so this approximation has minimal effects on the model outcomes.

### 4.3 Scenario Analysis

In order to characterize the different scenarios, we must devise a way to compare them. Obviously, we are interested in the emergence of “shortage conditions”. This is notoriously difficult as “drought” is defined as a period of abnormally low rainfall but neither what constitutes the period of interest nor abnormally low is well defined. The PDSI is a rigorous measure based on soil moisture but mainly applies to agriculture and not to urban areas. Finally, a very large groundwater basin under the CAR that can be exploited in times of surface water shortage effectively eliminates water shortages for the demand streams identified in Table 1. Thus, the most sensible measure for the performance of our scenarios is their net effect on the groundwater system. We thus track net groundwater recharge over the course of our scenarios. If net groundwater recharge is less for one scenario compared to another, we say that it experiences comparatively more water stress.

Given the supply and demand outlined in Table 1, we can compute the change in the groundwater volume as

$$V_g(t + 1) = V_g(t) + (S_l + S_c + S_r)/12 - (D_m + D_I + c_r D_a + D_N + D_r)/12. \quad (6)$$

where  $c_r \in [0, 1]$  is the coefficient of recharge for agricultural water use. For example, if  $c_r = 0.7$ , 70% of each acre-foot used in agriculture is consumed, and 30% becomes incidental recharge and returns to the groundwater system. Equation (6) implies that excess supply is used for groundwater

recharge and excess demand is met with groundwater withdrawals. The essence of our analysis then boils down to studying the behavior of  $V_g(t)$ .

### 4.3.1 Scenario 1: Capturing Variance in the Local System

The central objective of reservoirs for water management is to capture variations above the mean and release them when inputs are below the mean. Reservoir size fundamentally limits this capacity. If during periods of high inflows reservoirs fill, flood releases must be made and inflows above the storage capacity threshold must be released downstream, i.e. in the Salt or Colorado Rivers downstream of storage infrastructure. Of course, the aquifers under CAR can serve as an enormous storage system given sufficient infrastructure to direct excess flows into groundwater recharge areas. The importance of this point is illustrated in Figure 5.

Panel A shows total surface supply (CAP plus the Salt, Verde, and Agua Fria systems plus local systems, reclaimed water, etc) in blue, total demand (red, about 3.85 maf), and non agricultural use (orange, about 1.7 maf). This surface supply represents the case in which the same rainfall pattern over the past 53 years is repeated in the next 53 years. Immediately obvious is that max sustainable surface delivery is below demand and this difference must be made up with groundwater. If none of the excess flood release flows can be captured and directed to recharge, the resulting groundwater deficit is shown by the red trajectory in Panel B. At the end of the 53 year sequence (i.e. in 2060), the deficit will be about 18 maf (about 70% of the total volume of Lake Powell). If infrastructure were available to direct all flood releases to groundwater recharge, the blue trajectory would result. In this case, the deficit would only be 1 maf, that is, essentially zero. The orange trajectory shows an intermediate case where infrastructure exists to capture instantaneous flows up to 5 maf and flows above that must be released into waterways.

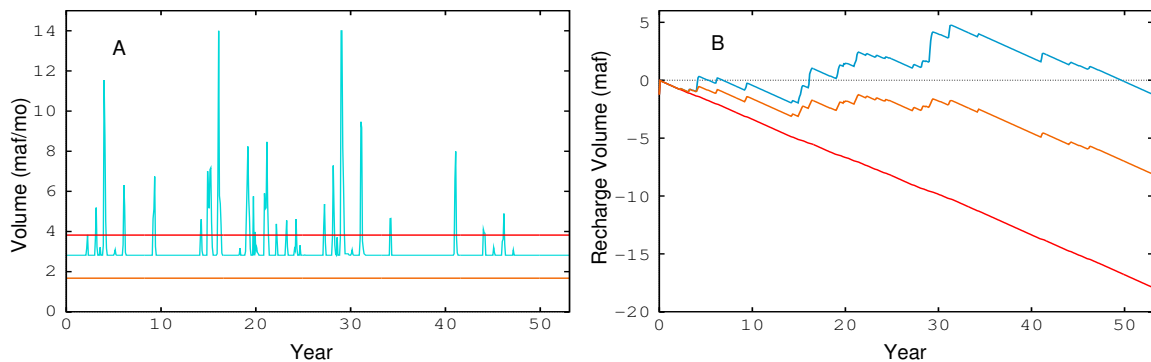


Figure 5: Panel A: surface supply (blue), total demand (red), total non-agricultural use (orange). Panel B: Net groundwater recharge. Blue, Red, Orange = all, none, and up to excess flows (flood releases) captured for recharge, Red = no excess flows captured (all released to waterways).

### 4.3.2 Scenario 2: Drying Due to Climate Change

Suppose now that the future is characterized by the same rainfall pattern as the last 53 years repeated each 53 years but experiences general drying in the sense that both the mean and variation are reduced. This scenario is captured by simply multiplying the time series by a constant, less than 1. The process by which climate change affects the amount of runoff that ends up as inflows to reservoirs depends on several factors, e.g., evapotranspiration, snow pack, precipitation. The United

States Bureau of Reclamation (Bureau of Reclamation, 2012) estimates that, on an annual basis, projected precipitation through 2080 is generally within 5 percent of historical levels. However, the report suggests that by 2080, decreases in spring precipitation range from 0 to 40 percent and winter precipitation may increase by up to 20 percent in the upper basin and decrease by 10% in the lower basin by 2080. Given this complexity, it is difficult to put a single number on runoff reduction and doing so is beyond the scope of this paper. Rather, we adopt an estimate of supply reduction generated for planning purposes of 15% (Gammage Jr et al., 2011; Vano et al., 2014) that is reasonable for our explorations here.

Panel A1 and A2 in Figure 6 shows the analogue of Panel A and B in Figure 5. In Panel A2, the red curves show the groundwater deficit for the case where there is 15% drying (we use “drying” as shorthand for “runoff supply reduction”) in the local system watersheds and no drying in the Powell watershed for the case when excess flows can be (top) and cannot be (bottom) captured for recharge. The blue curves show the same for the case in which there is 15% drying in both the local and Powell watersheds. Panels B1 and B3 show the release tiers for Powell. Panels B2 and B4 show the release tiers for Mead. Column 1 (B1, B2) shows the case for no drying in the Powell watershed and Column 2 (B3 and B4) show the case for 15% drying. Note that with no drying (B1) Powell spends most time in Tier 1 and 2 (ET and UEB, release at least 8.23 maf) and switches into the more restrictive Tier 4 (MERA, release 7.48 maf) only briefly around years 25-30 and 40-42 (equivalent to the dry periods in the mid-1990s and mid-2000s in the actual time series shown in Figure 2). Mead (B2) spends most time in Condition 1 (domestic surplus condition (DSC), release 7.9 maf) or in Condition 2 (normal condition (NC), release 7.5 maf). In this case, Arizona receives its full apportionment and Central Arizona Project apportionment of 1.6 maf. In the case with drying, Powell (B3) spends most time in tiers 3 and 4 (MERA and MERB, releasing 7.48 maf—in attempt to increase Powell depth—or 8.23 maf—in attempt to increase Mead depth, respectively). In extreme dry periods, Powell moves into Tier 6 (LEB, releasing as little as 7 maf). Likewise, Mead (B4) experiences mainly conditions 3 and 4 for the first 20 and last 10 years of the sequence (Scarcity Conditions A and B (SCA and SCB), releasing 7.167 maf and 7.083 maf, respectively). In these cases, the CAP allocation drops to 1.312 and 1.24, respectively. This is illustrated by the dark blue trajectory in Figure 6 A1 that shows CAP deliveries.

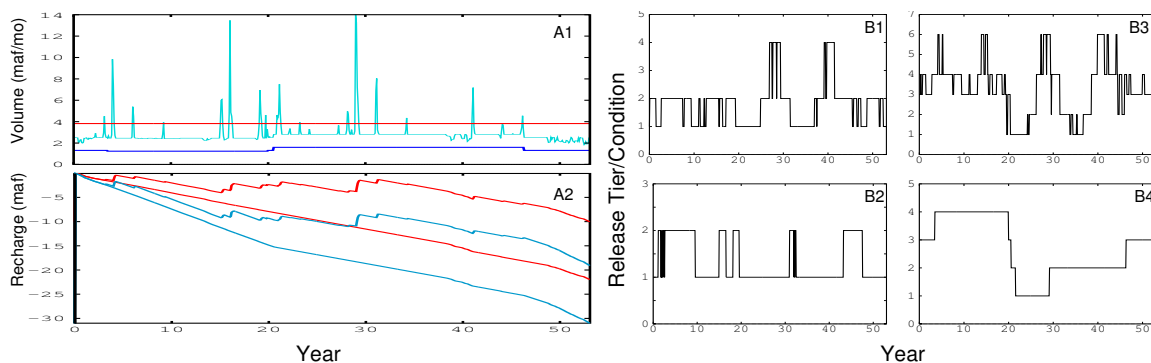


Figure 6: Panel A1: surface supply (light blue), CAP supply (dark blue) and total demand (red). Panel A2: Net groundwater recharge for two drying scenarios (see text for further discussion). B1-B4: Release tiers for Powell and Mead (see text for further discussion).

The core message from this scenario is that a 15% reduction in runoff to supply reservoirs generates groundwater depletion rates on the order of the volume of Lake Powell every half century. This is not surprising. The more interesting question we address here is what are the possible

solutions to enable sustainable groundwater management? Approaches include:

- Invest in hard infrastructure to enable extreme flow events to be redirected to groundwater recharge,
- Invest in hard infrastructure to reduce demand (water efficiency technologies) and for artificial recharge of natural infrastructure (aquifers),
- Invest in soft infrastructure (institutional arrangements for water exchange) to manage variability in water supply.

Of course, all of these options are underway to some extent. However, here we attempt to clarify some aspects of the third option. Specifically, we suggest that mechanisms to enable water exchange should be coupled with land use patterns associated with urbanization. That is, the system should be viewed as a “coupled infrastructure system” composed of water, agricultural, and urban infrastructures. More specifically, expanding the role of agricultural actors both as producers and “groundwater stewards” can be an effective mechanism to increase the robustness of the system.

This approach views land infrastructure playing 3 roles: 1) the upper 2-10 feet of the land surface as physical support for plants and nutrient delivery, 2) the upper 20-50 feet as providing a foundation for supporting the weight of built infrastructure, and 3) the upper 100-1000 feet for water storage. The key for increasing robustness to supply variation is to flexibly switch between uses 1 and 3. One approach is to allow farmers to store virtual water in the form of future claims. However, such a mechanism can only work if the supply variability is not too high. That is, farmers can only use stored virtual water so fast. This is the very same issue highlighted in Figure 5B by the difference in the blue and red curves. Any storage mechanism, whether hard or soft infrastructure has a limited “bandwidth” to cope with the frequency and amplitude of variation. Thus, to increase the robustness of the system, we need a higher-bandwidth mechanism.

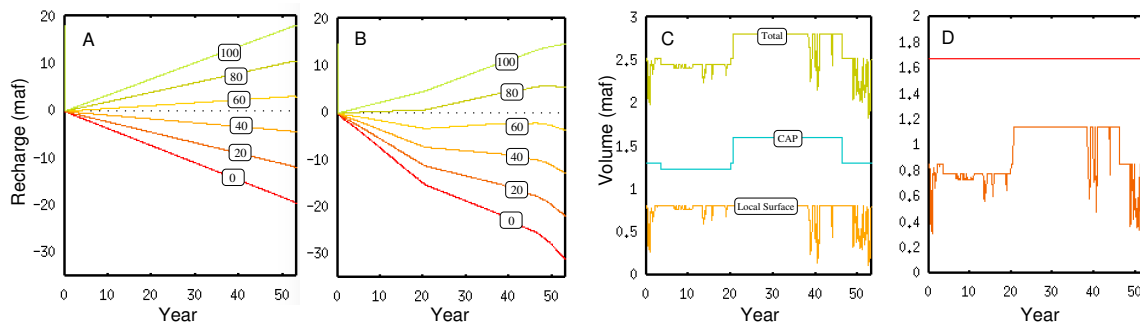


Figure 7: Panel A: Recharge trajectories, no drying. Panel B: Recharge trajectories, 15% drying in both the Powell and local watersheds. Panel C and D: Supplies and Demand (use) for 15% drying scenario, respectively. In Panel D, the red line is fixed demand while the orange is agricultural demand (use).

Figure 7 shows scenarios of groundwater recharge based on the following considerations. Instead of using natural (aquifers) or hard water-related infrastructure to cope with variation, use urban and general economic infrastructure. Right now, there is a fairly rigid demand based on municipal, industrial, and Native entitlements (mainly agricultural) of about 1.65 maf/yr. The remainder is (potentially flexible) agricultural demand of approximately 2.15 maf/yr. These together total 3.8 maf/yr (see Table 1). The latter could be made more flexible through exchange, not of virtual water, but of economic output of water users (especially urban users) in return for groundwater



stewardship from agricultural land owners. This exchange can be seen as investment by urban water users in the maintenance of natural infrastructure in the form of undeveloped land. Figure 7 shows a range of trajectories for trading system based on agricultural land owners receiving portion of their fixed entitlement and receiving the other portion only if supply allows. If there is insufficient supply, they are paid the equivalent value of the water they forgo (by the state, or municipal governments from a “groundwater stewardship” fund. Panels A and B show the no drying and 15% drying in both the Powell and local watersheds, respectively. The numbers on the curves indicate the percentage of agricultural water entitlements that are committed to the groundwater stewardship pool. Outcomes range from a 20 maf deficit to a 18 maf surplus as this percentage ranges from 0 to 100 in the no drying case. If somewhere between 40 and 60% of agricultural water entitlements are flexible (delivered only if available), the groundwater system can be stabilized. Panel B shows the analogue for the drying case, showing a range from 35 maf deficit to a 12 maf surplus, with a roughly 70% flex portion stabilizing the groundwater system. Panels C and D show the trajectories of supply and demand (actual use) for the drying scenario.

The challenge of this approach is to develop the soft infrastructure, i.e., a payment scheme such as a water insurance fund that all urban residents contribute to, perhaps linked to their property tax or city services bill. This is a standard problem of public good provisioning very similar to health care—the main challenge is, therefore, political.

### 4.3.3 Scenario 3: Concentration of Precipitation in Time

Our final scenario concerns changing the low frequency modes in regional rainfall patterns as depicted in Figure 3. To what extent can flexible demand cope with such change? Based on the The Third National Climate Assessment, the number of consecutive dry days between precipitation events may increase by 5-15% in the Powell watershed Melillo et al. (2014), which may lead to prolonged periods between more concentrated precipitation events. Such a scenario can be constructed using the Fourier decomposition shown in Table 2. Specifically by increasing the period of the mode with period of 13.29 years by 50% and increasing the spectral density contained in that mode while leaving all other modes unchanged, we can construct the signal shown in Figure 8A. The original and modified time series are shown in blue and red, respectively. Both have the same mean. Panel B shows the response of Powell and Mead volumes. In this approach, all spectral information in the original series is retained, and only one is changed.

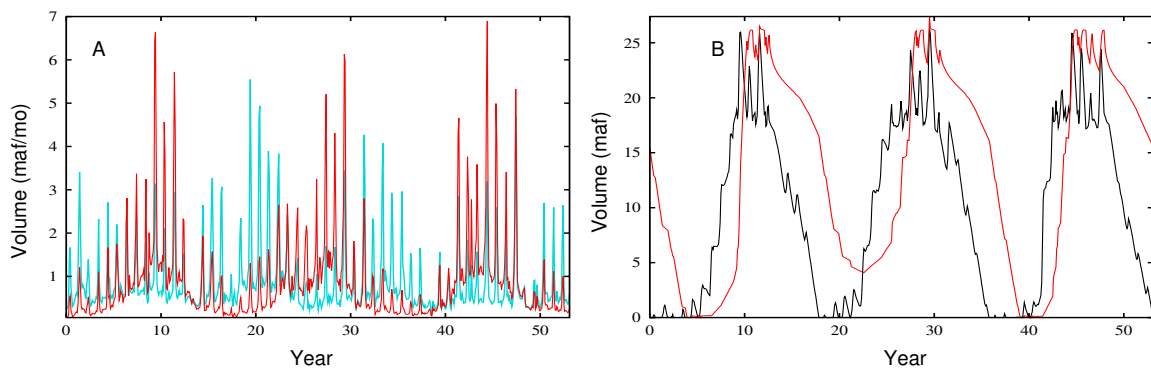


Figure 8: Panel A: Modified Powell inflows (red) and original time series (blue). Panel B: Powell and Mead volumes under the reconstructed

As mentioned earlier, the essential role of reservoirs is to capture variation. Panel B shows the limits of the capacity of Powell and Mead to do so under this new precipitation regime. During

prolonged dry periods, the reservoirs completely empty (live volume) indicating they are beyond their capacity to capture precipitation during very wet periods.

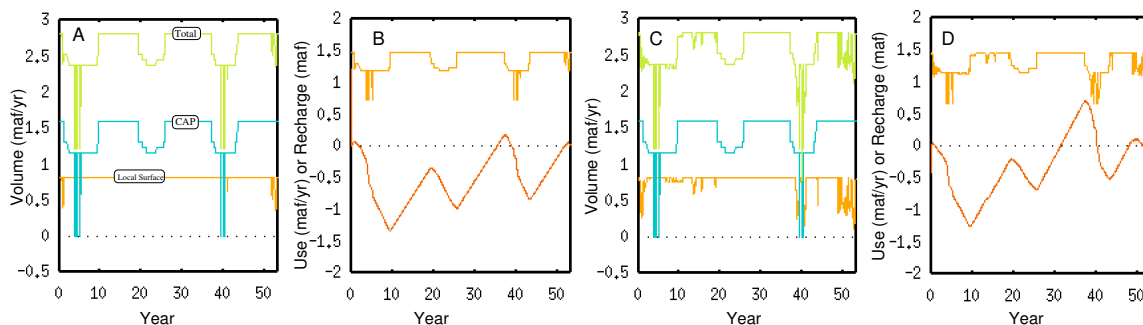


Figure 9: Panel A: Surface supply under the climate regime shown in Figure 8 A. Note extended dry periods cause total interruptions of CAP flows around years 5 and 40. Panel B: Resulting agricultural water use (orange) and associated impact on ground water (brown). Panels C and D: Analogues of Panels A and B for the case with the climate regime shown in Figure 8 A and 15% drying in the local system watersheds.

Panels A and B in Figure 9 shows the result of this change, assuming no general drying (i.e., mean of modified signal is the same as the original) in either the Powell or local system watersheds, with a 66% flexible agricultural demand to achieve groundwater neutrality. Panels C and D show the analogue with 15% drying in the local system watersheds as well. For this case, a 68.5% flexible agricultural demand is necessary to achieve groundwater neutrality. The main message from this analysis is that the system is capable of meeting fixed demands while maintaining groundwater neutrality using flexible agricultural demand. This requires that only about 30% of agricultural land be under continuous cultivation or, more accurately, that only 30% of the present 2.15 maf/yr agricultural water entitlements be continuously delivered. The remainder is only delivered when there is a surface water surplus and, under present conditions, only reaches a maximum level of about 1.5 maf/year. The demand not met (about 0.65 maf/year) is attributable to the ongoing policy of groundwater depletion in Pinal County.

## 5 Conclusions

The stylized model we present here was designed to capture the essence of the Colorado River–CAR water system. We adopted the CIS lens to highlight the importance of taking into consideration all classes of relevant infrastructures at the appropriate scale when dealing with large-scale challenges such as climate change. Our analysis provides some insight into the utility of conceptualizing the system at a regional scale, considering the interactions of groundwater, land use, and surface water infrastructures in maintaining water supply for the region, allowing us to identify policy opportunities that may be less explicit otherwise.

In particular, the modeling exercise highlights the critical role played by soft infrastructure in the hydrological resilience of the region. While the existing rules governing surface water distribution and supply have provided robustness to variation, the robustness of this existing soft infrastructure is potentially threatened by climate change. Expanding the conceptualization of the system to include the key role of agriculture in groundwater maintenance can reveal additional flexibility in the system. Here, agricultural actors can be re-conceptualized as providers of an adaptation good for the broader system through the flexible use of their land, rather than simply as a competing water use. This is not novel, but this function has been implicit rather than explicit. Municipal

users have agreed to subsidize the sector’s use of CAP water in order to alleviate pressure on groundwater resources and assure these resources are available in the future. Nevertheless, the results of our model suggest that a more explicit policy could be of benefit to the region.

Current projections for the metropolitan region imply a gradual decline in agricultural area as the urban footprint expands onto agricultural land. Our model suggests that an alternative scenario might be worth considering. Maintaining the viability of agricultural land use around and between Phoenix and Tucson may have adaptive advantages. Negotiating the development of the soft infrastructure to support such a scenario will clearly be challenging, although agriculture-urban water markets and transfers are not uncommon in the United States (see Brewer et al., 2008). While land use in crops can flexibly respond to changing water availability, the farm sector as a whole may be less flexible. Should transfers be multi-year (rather than seasonal), farmers may migrate from the area or seek other livelihood opportunities. Pressures for alternative land uses with less beneficial outcomes for water resource robustness can be substantial. Nevertheless, our prior research suggests that the current farm community in central Arizona has strong attachment to place and community, if not to specific parcels of land (Eakin et al., 2016); this attachment, in the context of strong groundwater rights, may facilitate the consideration of developing the necessary soft infrastructure to support an innovative policy that would enhance groundwater conservation and enable continued agriculture and urban vitality. Conceptualizing the role of the farm community as stewards of multifunctional natural infrastructure that provides opportunities for food production, local connection to agriculture, and aquifer maintenance rather than participants in “water markets” may further support innovative policies. However, as others have noted, the complexity of water rights, calculating consumptive use, and the number of actors involved in water distribution and access can create challenges for water market development at a minimum, and even greater challenges for the more innovative policy arrangements we discuss here.

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## Supplementary Materials

The Supplementary Materials contain details of the reservoir rules and the complete code of the model.

## Reservoir operations if-then statements

Rules for the operations of major Colorado River water infrastructure originate in a number of legal proceedings collectively known as “The Law of the River”, including Section 602 of the Colorado River Basin Project Act (Public Law 90-537; 1968), the Criteria for Coordinated Long-Range Operation of Colorado River Reservoirs Pursuant to the Colorado River Basin Project Act of September 30, 1968 (“Operating Criteria;” 1970, amended 2005), Interim Surplus Guidelines (2001), and Interim Shortage Guidelines (2007).

### Operating Criteria and Interim 602(a) Storage Guideline

The Colorado River Basin Project Act, in Section 602, ranks priorities for meeting the combined provisions of the Colorado River Compact, Upper Colorado River Basin Compact, and 1944 Mexican Treaty. The quantity of stored water needed to protect the Upper Basin states from drought is referred to as 602(a) storage, and determines whether equalization releases are made between Lake Powell and Lake Mead. For at least 20 years, the 602(a) storage volume was calculated using a modeling algorithm that incorporated information about historic streamflows, critical periods of record, probabilities of water supply, and other factors.

Condition			Rule
1	either is less than the quantity of 602(a) storage for that date	or Lake Powell active storage forecast for that date is less than the Lake Mead active storage forecast for that date	release a minimum of 8.23 maf from Powell per year
2	is greater than the quantity of 602(a) storage for that date	and active storage in Lake Powell is not less than the active storage in Lake Mead	release greater than 8.23 maf from Powell per year (b) to maintain, as nearly as practicable, active storage in Lake Mead equal to the active storage in Lake Powell, and (c) to avoid anticipated spills from Lake Powell

### Interim 602(a) Storage Guideline

For WY 2005 through 2016, if projected September 30 Lake Powell storage is less than 3,630 ft., release a minimum of 8.23 maf from Powell per WY.

### B1. Determining and applying interim annual operational tiers at Lake Powell<sup>1</sup>

For 2008 through 2026, if the August “24-Month Study” projected Jan. 1 Powell elevation

<sup>1</sup> U.S. Department of the Interior (2007, December). Record of decision — Colorado River interim guidelines for lower basin shortages and coordinated operations for Lake Powell and Lake Mead. pp. 49-53.

	Powell Condition	Mead Condition	Release Rule
1	is greater than or equal to the elevation specified in Table A for that WY		apply Equalization Tier.
2	in any WY is less than 3,575 ft. and greater than or equal to 3,525 ft.	and Mead elevation is greater than or equal to 1,025 ft.	release 7.48 maf from Powell per WY (Mid-Elevation Release Tier A).
3	in any WY is less than 3,575 ft. and greater than or equal to 3,525 ft.	and Mead elevation is less than 1,025 ft.	release 8.23 maf from Powell per WY (Mid-Elevation Release Tier B).
4	is less than the elevation specified in Table A for that WY and greater than or equal to 3,575 ft.	and Mead elevation is greater than or equal to 1,075 ft.	release 8.23 maf per WY from Powell (Upper Elevation Balancing Tier 6B1).
5	is less than the elevation specified in Table A for that WY and greater than or equal to 3,575 ft.	and Mead elevation is less than 1,075 ft.	release between 7.0 and 9.0 maf per WY from Powell while equalizing reservoir storage (Upper Elevation Balancing Tier 6B2).
6	in any WY is less than 3,525 ft.		release between 7.0 and 9.5 maf per WY from Powell while equalizing reservoir storage (Lower Elevation Balancing Tier).

**B0. Table A. Lake Powell equalization elevation table<sup>3</sup>**

Each year, the Equalization Tier switch point changes according to the sequence:

Water year (WY)	Elevation (feet)	Water year (WY)	Elevation (feet)
2008	3,636	2018	3,654
2009	3,639	2019	3,655
2010	3,642	2020	3,657
2011	3,643	2021	3,659
2012	3,645	2022	3,660
2013	3,646	2023	3,662
2014	3,648	2024	3,663
2015	3,649	2025	3,664
2016	3,651	2026	3,666
2017	3,652		

In addition to water released from Lake Powell in the table above, up to 0.05 maf can be pumped directly from Lake Powell as part of Arizona’s upper basin apportionment. In recent years the state has not used the full apportionment. Most of this is used by the Navajo Generating Station, the rest is applied to irrigation and other uses within the Navajo Nation.

**B2. Further applying interim annual operational tiers at Lake Powell**

If applying Equalization Tier, release at least 8.23 maf per WY from Powell

	Powell Condition	Mead Condition	Release Rule
7	and if it will not cause Powell elevation to be less than the elevation specified in Table A for that WY	or cause Mead storage to exceed Powell storage	release additional water.
8	and if it will cause Powell elevation to be less than or equal to the elevation specified in Table A for that WY	and Sept. 30 projected Mead elevation is below 1,105 ft.	release additional water until the first of the following conditions is projected to occur on Sept. 30: (i) the reservoirs fully equalize; (ii) Mead elevation equals 1,105 feet; or (iii) Powell elevation equals 20 feet below the scheduled elevation for that WY.

If applying Upper Elevation Balancing Tier, and the April “24-Month Study” projected Sept. 30



	Condition 1	Condition 2	Condition 3	Release Rule
9		Powell elevation is greater than	the elevation specified in Table A for that WY	apply Equalization Tier for remainder of the WY.
10	Mead elevation is less than 1,075 ft. while applying Upper Elevation Balancing Tier 6B1	and Powell elevation is equal to or greater than	3,575 ft.	release not less than 8.23 maf and not more than 9.0 maf from Powell per WY while equalizing reservoir storage.

Also: “When Lake Powell is projected to be operating under Section 6.B.2. and more than 8.23 maf is projected to be released from Lake Powell during the upcoming Water Year, the Secretary shall recalculate the August 24-Month Study projection of the January 1 Lake Mead elevation to include releases above 8.23 maf that are scheduled to be released from Lake Powell during the months of October, November, and December of the upcoming Water Year, for the purposes of determining Normal or Shortage conditions pursuant to Sections 2.A. or 2.D. of these Guidelines.”

### B3. Determining annual operating conditions at Lake Mead<sup>2</sup>

If the August “24-Month Study” projected Jan. 1 Mead elevation

11	is less than 1,145 ft. and greater than 1,075 ft.	and the Secretary has not determined an ICS Surplus Condition	apply Normal Condition.
12	is less than 1,145 ft. and greater than 1,075 ft.	and a Flood Control Surplus has not been determined, and a delivery of ICS has been requested,	the Secretary may determine an ICS Surplus Condition.*
13	is greater than or equal to 1,145 ft.	and the Secretary has not determined a Quantified Surplus/70R Strategy	apply Domestic Surplus (DS) Condition.
14	is greater than or equal to 1,145 ft.	and the projected system storage space is less than the space required by the flood control criteria (assumes the 70th percentile non-exceedence flow, i.e. a natural inflow of 17.4 maf)	the Secretary may determine a Quantified Surplus/70R Strategy (QS).*
15	is less than 1,075 ft. and greater than or equal to 1,050 ft.		apply Shortage Condition A.
16	is less than 1,050 ft. and greater than or equal to 1,025 ft.		apply Shortage Condition B.
17	is less than 1,025 ft.		apply Shortage Condition C.

Note: Conditions for determining and applying a Flood Control Surplus are not defined.

<sup>2</sup> U.S. Department of the Interior (2007, December). Record of decision — Colorado River interim guidelines for lower basin shortages and coordinated operations for Lake Powell and Lake Mead. pp. 34-37.

\* ICS Surplus can be determined concurrently with Quantified Surplus or Domestic Surplus.

#### B4. Applying annual operating conditions at Lake Mead<sup>3</sup>

	Condition	Total Release	CA Portion	AZ Portion	NV Portion
18	Normal	7.50 maf /CY (basic apportionment) <sup>3</sup>	4.40 maf	2.80 maf	0.30 maf for NV.
19	Domestic Surplus (eff. 2017-2026),	7.95 maf per CY (basic apportionment plus additions)	4.40 maf plus 0.25 maf for MWD,	2.80 maf plus 0.10 for AZ Contractors,	0.30 maf for NV plus 0.10 for SNWA.
20	Quantified Surplus/70R	7.50 maf/CY plus the QS volume	4.40 maf plus 50% of the QS	2.80 maf plus 46% of the QS	0.30 maf plus 4% of the QS.
21	ICS Surplus (ICCS)	7.50 maf/CY plus QS or DS (if any) plus ICSS (if exceeds previously applied surplus)			
22	Shortage A	7.167 maf/CY	4.40 maf	2.48 maf	0.287 maf
23	Shortage B	7.083 maf/CY	4.40 maf	2.40 maf	0.283 maf
24	Shortage C	7.0 maf/CY	4.40 maf	2.32 maf	0.28 maf

In addition to the apportionment given to AZ in the table above, the state is apportioned 0.05 maf as an upper basin apportionment. In recent years it has not used the full apportionment. Most of this water is pumped directly from Lake Powell and used by the Navajo Generating Station, the rest is applied to irrigation and other uses within the Navajo Nation.

Mexico is also apportioned 1.5 maf/CY from either the surplus or from within the upper and lower basin apportionments. The agreements governing this are not represented here, and they are not directly affected by the Interim Guidelines.

#### C1. Colorado River Simulation System (CRSS) monthly modeling assumptions<sup>4</sup>

The Bureau of Reclamation uses its CRSS model to evaluate and compare operational strategies for a system of twelve reservoirs that begin in the upper basin and extend into the lower basin to Lake Havasu. In the model, each reservoir has designated minimum and maximum mean monthly release constraints specified in cubic feet per second (cfs). The user also designates a July and December target storage for each reservoir (typically, filling it in July and then drawing it down — “space building” — through to December in anticipation of the next wet season). Then, given the inflow forecast for the month, model rules compute the volume of water required to meet each reservoir’s monthly fraction of the target storage. In the case of Lake Powell and Lake Mead, additional rules attempt to equalize reservoir storage, ensure the minimum release needed to meet water delivery obligations, and simulate environmental spike flows without impeding electrical power generation objectives. The model documentation gives detail on how the respective calculations are made. As stated in the model documentation:

<sup>3</sup> Original 7.5 maf lower basin apportionment given in the Colorado River Compact (1922) Article III(A), further apportioned between lower basin states in the Boulder Canyon Project Act (1928) Section 4(A), and settled by the US Supreme Court in the Consolidated Decree in *Arizona v. California* (2006), 547 U.S. 150, Article II(B).

<sup>4</sup>U.S. Department of the Interior (2007, October). “CRSS Model Documentation.” Final environmental impact statement — Colorado River interim guidelines for lower basin shortages and coordinated operations for Lake Powell and Lake Mead. pp. A1-A34.

CRSS is used to simulate the future conditions of the system on a monthly time step. Output data include reservoir storage, releases from dams, hydroelectric generation, etc. Input data for the model includes monthly natural flow at 29 nodes throughout the Colorado River system. Input data also includes physical parameters (e.g., individual reservoir storage capacity, evaporation rates, and reservoir release capabilities), initial reservoir conditions, and the diversion and depletion schedules for entities in the Colorado River Basin States and Mexico. Operating rules for current or proposed operating policies are considered input. (p. A-33)

## C2. Approximate Lake Havasu operating rules for Arizona apportionment

Given that the Central Arizona Project (CAP) established its right to Colorado River water in 1968, on-river users with senior rights have priority during shortage. Approximately 90 percent of any Arizona apportionment shortage is borne by CAP.

If Lake Mead is operating under

	Condition	CAP Allocation	AZ On-River Users Allocation
25	Normal	release 1.6 maf per CY	and 1.2 maf per CY
26	Shortage A	release 1.312 maf per CY	and 1.168 maf per CY
27	Shortage B	release 1.24 maf per CY	and 1.16 maf per CY
28	Shortage C	release 1.168 maf per CY	and 1.152 maf per CY

## C3. Approximate CAP allocation rules

Municipal & Industrial (M&I) and Indian contracts share top priority to CAP water. If Lake Mead is operating under

	Condition	Apportionments		
29	Normal Condition,	deliver 0.925 maf per CY to M&I and Indian priority entitlements,	0.4 maf per CY to Agricultural Settlement Pool,	and 0.3 maf to other Excess Water contracts.
30	Shortage Condition A,	deliver 0.925 maf per CY to M&I and Indian priority entitlements,	and remainder to Agricultural Settlement Pool (approx. 0.39 maf?).	
31	Shortage Condition B,	deliver 0.925 maf per CY to M&I and Indian priority entitlements,	and remainder to Agricultural Settlement Pool (approx. 0.34 maf?).	
32	Shortage Condition C,	deliver 0.925 maf per CY to M&I and Indian priority entitlements,	and remainder to Agricultural Settlement Pool (approx. 0.26 maf?).	

These are very rough approximations based on presentations by CAP.

## 5.1 Model Code

Shown below is the model code. The code is written for a specialized dynamical systems numerical analysis tool called XPPaut (see <http://www.math.pitt.edu/~bard/xpp/xpp.html> for detailed information to download (runs on any operating system - even ipads and iphones) and use the software). Note, however, that the XPPaut syntax is quite general and follows conventions of other high-level scientific computing packages such as Matlab, R, Julia, etc. so can be easily translated to any language of your choice.

```
#simple model of the colorado river system

#-----
# The critical issue for this model is outflow.  If there is enough
# head then the outflow is u*(dmin-d) where u is a control variable.
# If there is too much head, then the reservoir overflows.

# In a normal year, cap attempts to deliver 1.6 maf to central arizona users.
# shortages can reduce it to as little as 1.168 maf.
#-----

### -----General Functions-----

wiener w

#=====
#=====outflow: general experessions=====
#=====

csqrt(x) = sqrt(max(0,x))
uflow(V,D1,D2) = V/(0.001 + csqrt(D1-D2))
ubal(V1,V2,g) = g*(V1-V2)
udepth(Ds,Dm,D,g) = max(0,g*((D-Ds)/(Dm-Ds))**3)
diffchck(x) = if(x > 0)then(x**2/(1+ x**2))else(0)
checktier(D1,D2,A,B) = if(D1>D2)then(A)else(B)
fg(u,D,Dm) = u*csqrt(D-Dm)
O(D,Dm,Vfr,u,ux)=if(Vfr<0)then(fg(u,D,Dm))else(max(fg(u,D,Dm),min(Vfr,fg(ux,D,Dm))))

#=====
#=====Actual and reconstructed inflow data=====
#=====

table powellu "water_data/Powell/inflow_unreg_xpp.dat"
table powella "water_data/Powell/inflow_xpp.dat"
table powellf "water_data/Powell/inflow_recon.txt"
table powelldt "water_data/Powell/inflow_detrended.txt"
table leesferry "water_data/Powell/Lees_Ferry_xpp.dat"
table tonto "water_data/Tonto/inflow_xpp.dat"
```

```

table verde "water_data/Verde/inflow_xpp.dat"
table agua_fria "water_data/Agua_Fria/inflow_xpp.dat"
table salt "water_data/Salt/inflow_xpp.dat"
table Vpactd "water_data/Powell/volume_xpp.dat"

aux powelluri=powellu(t)
aux powelli=powella(t)
aux powellr=powellf(t)
aux powellv=powelldt(t)
aux tonto_in=tonto(t)
aux verde_in=verde(t)
aux ag_fria_in=agua_fria(t)
aux salt_in=salt(t)
aux powvolact=Vpactd(t)

#=====
## -----SRP water delivery system (local water)-----
#=====

# General Function for reservoir releases-----

### because of lack of information about SRP reservoir operations
# we have a very simple model of that reservoir system. We
# have agua fria, verde, (horseshoe and bartlett), and Salt
# (four reservoirs).

# Parameters for target volumes. Ag. Fria = 1.1maf. Verde = 0.3 maf
# salt = 2.53 maf. So, simple rule - let out the minimum or the max allowable
# if you are too full. No complicated release rules.

par envStressL=1
number vMinFact=0.2

#flood release condition
Rf(V,Vs,Rm,Rx,I) = max(Rm,min(I+V-Vs,Rx))
#normal release condition with min level constraint
Rn(V,Rm,Vmin) = if(V>Vmin)then(min(V-Vmin,Rm))else(0)
#release: choose flood condition or normal condition.
R(V,Vs,I,Rn,Rf) = if((V+I)<Vs)then(Rn)else(Rf)

#=====
# agua fria system-----
#=====

number Vafs=1,Rmaf=0.004,Rxaf=0.01,Vtaf=1.1

# note Vafs is minimum target volume. Have no idea what this is in
# reality. About 80% of total volume of 1.1.??? So on average, the volume

```

```

# will be around Vafs (if enough water...)

Iaf = envStressL*agua_fria(t)
Rfaf = Rf(Vaf,Vafs,Rmaf,Rxaf,Iaf)
Rnaf = Rn(Vaf,Rmaf,vMinFact*Vtaf)
Raf = R(Vaf,Vafs,Iaf,Rnaf,Rfaf)
aux ag_fria_rel=Raf
Vaf(t+1) = Vaf + Iaf - Raf

#=====
# verde system-----
#=====

number Vvs=0.29,Rmv=0.018,Rxv=0.8,Vtv=0.3

# Vvs is set at 0.29 of total volume. Same issue as with Vvs.

Iv = envStressL*verde(t)
Rfv = Rf(Vv,Vvs,Rmv,Rxv,Iv)
Rnv = Rn(Vv,Rmv,vMinFact*Vtv)
Rv = R(Vv,Vvs,Iv,Rnv,Rfv)
aux verde_rel=Rv
Vv(t+1) = Vv + Iv - Rv

#=====
# salt system-----
#=====

number Vss=2.4,Rms=0.046,Rxs=1,Vts=2.53

# Vss is set at 2.3 - a bit larger percentage than for verde and aqua
# fria. This is becaus the volume of the salt reservoir system is larger
# relative to release volumes, so can live 'closer to the edge'.

Is = envStressL*(salt(t) + tonto(t))
Rfs = Rf(Vs,Vss,Rms,Rxs,Is)
Rns = Rn(Vs,Rms,vMinFact*Vts)
Rs = R(Vs,Vss,Is,Rns,Rfs)
aux roos_in = Is
aux salt_rel = Rs
Vs(t+1) = Vs + Is - Rs

# the sum of the three releases is the total local water flow.
# The Rma, Rmv, and Rms are the normal releases.

par wLocalMax=0.085

wLocal = min(Raf + Rv + Rs,wLocalMax)

```

```
aux local_water = 12*wLocal
```

```
init Vaf=0.5,Vv=0.17,Vs=0.45
```

```
#####  
#-----Powell and Mead Systems-----  
#####
```

```
#####  
#----General "geometric" Parameters-----  
#####
```

```
# Lake Powell is subscript p  
# Live capacity = 25.97 = 26 MAF. Average Area = 26/(3711-3370) = 0.076 MA.
```

```
# note need upmax = 0.2 to handle extreme conditions.  
# default was 0.1 which can handle historic conditions.
```

```
number gpb=0.001,upmax=0.2,efp=0
```

```
### equilization tier depth and flood control.  
# This change over time on a yearly basis.  
# over the long term - not going to make that much of a difference.  
# ad hoc regime shift just to match the data for debugging and  
# sensitivty analysis.
```

```
# note - what follows here is just an effort to match the  
# historical record. It is irrelevant in the big picture.  
# with adaptpol=0, DET and Dpfc are constants.
```

```
number DET=3650,Dpfc=3660,gpfc=0.08  
#note - for more extreme inflows, need to reduce  
#Dpfc to 3660, increase upmax to 0.2, gpfc to 0.08.  
# defaults were dpfc 3670, gpfc = 0.05
```

```
# par rse1=2004,DET1=3370,DET2=3650  
# par fc1=3700,fc2=3670,fc3=3700,fc4=3680,fc5=3700  
# par rsf1=1984,rsf2=1987,rsf3=1997,rsf4=1999  
# par adaptpol=0
```

```
# DETadapt = if(year<rse1)then(DET1)else(DET2)  
# Dpfcadapt = if(year<rsf1)then(fc1)else(if(year<rsf2)then(fc2)else(if(year<rsf3)then(fc3)else
```

```
#DET = (1-adaptpol)*3650 + adaptpol*DETadapt  
#Dpfc = (1-adaptpol)*3690 + adaptpol*Dpfcadapt
```

```
number Dpmax=3710
```

```

#note that Dp(Vp) is a tiny bit off (1 foot) when Vp
# goes to zero.  So although Dpmin=3370, flow
# will only go to zero when it is about 3371.
# this is trivial, since there is some operational depth
# > 3370 where flow goes to zero.

par Dpmin=3370

# Lake Mead is subscript m
# Live capacity = 27.62 MAF.  Average Area = 27.62/(1232-895) = 0.082 MA.

#par Imm=0,Ims=0,natflowm=0
#note, for extreme events, need to set ummax=0.15
#this is the value for scenario 3 in paper.
#default is 0.1.

number gmqs=0.05,ummax=0.15,Dmqs=1200,efm=0

number Dmmax=1230

# see the discussion for Dpmin above.  Same applies to
# Mead.  Dmmin=895

par Dmmin=895

#=====
### -----hidden variables-----
#=====

### The hidden variables are mainly flows... they are defined as
### follows:

# uimflow = minimum, institutionally defined gate setting w in the
# ith reservoir.  uidepth = gate setting directed at maintaining the
# water level at diset in the ith resevoir.  uimflow takes precedence
# over uidepth.  The outflow is limited by uimax.  Thus, the control
# variable is ui, set by the uimflow and uidepth rules, but limited
# by uimax.

###first need to compute depths for control calculations:
###equations based on fitting acutal data (very closely!).

## functions for depth (feet elevation)
## as a function of volume MAF;

###Volume/depth equations based on fitting acutal data (very closely!).

```



```

Dp = 2940 + 370*(Vp+2)**0.22
Dm = 500 + 300*(Vm+3)**0.26

## functions for surface area (million acres) as a function
## of depth..

###equations based on fitting acutal data (very closely!).

Sap = 0.032*exp(0.0051*(Dp-3370))-0.011
Sam = 0.032*exp(0.005*(Dm-895))-0.004

## evap rate in feet/mont = cubic feet/square feet/month
## so actual evaporation is computed as this rate times
## reservoir area.

number evap_r=0.7

#=====
##-----Lake Powell IN flows-----
#=====

# The following parameter represents a drop in the mean
# of the powell inflow.
par envStress=1,userecflow=0
number pmean=0.8662

powellin = userecflow*powellf(t) + (1-userecflow)*(powelldt(t)+pmean)

Ip = envStress*powellin

#=====
##-----Lake Powell outflows-----
#=====

## outflows are determined by 4 tiers, triggered by reservoir depths:
##
## 1) Equalization tier (ET), Det = changes year to year. ET= release
## 8.23 MAF at least plus extra.....while balancing volumes.
##
## 2) Upper elevation balancing (EUB). if Dmer<Dp<Det. Dmer is the next
## tier split at 3575. Then split between
## 2 stragies based on Dub = depth in mead (1075), If Dm>Dub, employ
## 6B1 (release 8.23 maf from powell, otherwise employ 6B2
##
## 3) Mid elevation release (MER). If Dleb<Dp<Dmer (3525<Dp<3575).
## Then if Dm > 1025 employ MERA else MERB
##

```

```

## 4) Lower elevation balancing (LEB). If Dp<3525, release between
## 7 and 9 Maf and balance volumes.

## first compute release volumes for Powel through a series of checks

aux maxgatep=upmax

# Compute release volumes for different tiers, before performing next check....

#### First calculate gate positions based on depths
#### note, uefp is a minimum environmental flow,
#### and ufcf is a flood control release.

## gate position to deliver 7, 7.48, 8.23, 9, 9.5 MAF,
## given reservoir depth, respectively (MAF/month)
u7 = uflow(7/12,Dp,Dpmin)
u748 = uflow(7.48/12,Dp,Dpmin)
u823 = uflow(8.23/12,Dp,Dpmin)
u9 = uflow(9/12,Dp,Dpmin)
u95 = uflow(9.5/12,Dp,Dpmin)

##gate feedback to balance reservoir volumes
# but only if Vp > Vm
ub = max(0,ubal(Vp,Vm,gpb))

## Increase release to Mead if Powell volume exceeds Mead
## in the 'equalization tier, ET. The conditions are compelex.

# CHECK 1) Is Dp > DET?

Pd1 = diffchck(Dp - DET)

# CHECK 2) Is Powell at target depth for ET (greater than
# 20 feet below DET) for release in case Mead below 1105??

Pd2 = diffchck(Dp+20-DET)

# CHECK 3) Is Mead at target depth for ET when condition 2 holds?

Pd3 = diffchck(1105-Dm)

# combining conditions...

ubET = ub*(Pd1 + (1-Pd1)*Pd2*Pd3)
aux ubalET= ubET

## Gate position to realease environmental flow efp.
uefp = uflow(efp/12,Dp,Dpmin)

```

```

aux envfp=uefp

## Gate postion to release for flood control.
#ufcp = udepth(Dpfc,Dpmax,Dp,gpfc)
ufcp = if(Dp>Dpfc)then(gpfc)else(0)
aux floodp=ufcp

#### TIER 1: ET equalization tier - release a minimum rate of 8.23 MAF and
#### balance reservoir volumes..... Dp > DET

ET = u823 + ubET

#### TIER 2: 6B1 is just releasing 8.23 MAF - I don't get the point yet...
## 3575 < Dp < DET. Dm > 1075

6B1 = u823

#### TIER 3: 6B2 is balancing while releasing between 7 and 9 maf
## 3575 < Dp < DET. Dm < 1075. Increase release to fill Mead.
# balancing here is simpler

6B2 = min(u7+ub,u9)

#### TIER 4: MERA Focuses on increasing depth in Powell,
## i.e. releases less than 8.23

MERA = u748

#### TIER 5 MERB Focuses on increasing depth in Mead (same as 6B1)
## 3525 < Dp < 3575, Dm < 1025

MERB = 6B1

#### TIER 6: LEB is balancing while releasing between 7 and 9.5 maf

LEB = min(u7+ub,u95)

### CHECK 4) Now that we have the volume rates calculated,
### we can choose the tier.

### note, we control for the max gate posiion, umax,
### and flood control ufcfp, ie.

MER = checktier(Dp,3525,checktier(Dm,1025,MERA,MERB),LEB)
EUB = checktier(Dp,3575,checktier(Dm,1075,6B1,6B2),MER)

### final gate position

```

```

up = min(upmax,checktier(Dp,Det,ET,EUB) + ufcv + uefp)

## set of fucntions to determine which tier of 6
## possibilities is being used.
## for visualization of the controller
## ET=1,6B1=2,6B2=3,MERA=4,MERB=5,LEB=6

MERt = checktier(Dp,3525,checktier(Dm,1025,4,5),6)
EUBt = checktier(Dp,3575,checktier(Dm,1075,2,3),MERt)
tier = checktier(Dp,Det,1,EUBt)
aux reltier=tier

## Then, once up is chosen, check for flood conditions

# flood release volume, psdf=safy factor

number pfsf = 1
Vpfr = Ip + Vp - pfsf*25.97
aux PowFV=Vpfr
aux maxflowp=fg(upmax,Dp,Dpmin)*12
aux gflowp=fg(up,Dp,Dpmin)*12

Op = 0(Dp,Dpmin,Vpfr,up,upmax)

aux Outp=Op*12
aux Inp=Ip
aux Depthp=Dp
aux Depthchp=Dp-Dpmin
aux Depthpm=Dpmax
aux evapp = Sap*evap_r
aux gatep = up
#aux Powout=leesferry(t)*12

#=====
###-----Lake Mead IN flows-----
#=====

## As with Powell, this is just a place holder for inflows
## generated by the watershed below Powell that feeds Mead
## (pretty small, I would guess).. The Op bit is the output
## from Powell.

Im=Op

##-----Lake Mead out flows-----

## Just as with Powell, there are a sequence of release tiers.. Here

```

```

#they are called # "conditions" rather than tiers...

## Define some flows, for compactness of notation...and debugging...
## same interpretation as for Powell - i.e. gate positions to release
## a certain volume in MAF.

u045= uflow(0.45/12,Dm,Dmmin)
u7m = uflow(7/12,Dm,Dmmin)
u7083 = uflow(7.083/12,Dm,Dmmin)
u7167 = uflow(7.167/12,Dm,Dmmin)
u75 = uflow(7.5/12,Dm,Dmmin)
uQS70 = udepth(DmqS,Dmmax,Dm,gmqS)
uefm = uflow(efm/12,Dm,Dmmin)

## Surplus, Dm > 1,145 condition 1

DSC = u75 + u045 + uQS70

## Normal condition (NC): 1,075 < Dm < 1,145 ft.
## within this condition, there are two sub conditions:
##      1) a no ICS condition -----> apply normal condition
##      2) or a Flood Control Surplus has not been determined,
##          and a delivery of ICS has been requested,
##          -----> apply ??
## Call this condition 2

NC = u75

##shortage condition A: 1050 < Dm < 1075 - condition 3

SCA = u7167

##shortage condition B: 1025 < Dm < 1050 - condition 4

SCB = u7083

##shortage condition C: Dm < 1025 - condition 5

SCC = u7m

### CHECK Now that we have the volume rates calculated, we can choose the
### operating conditions.
### note, we control for the max gate position, umax, and flood control ie.

## Gate position to release for flood control.
number Dmfc=1180,gmfc=0.05
ufcm = udepth(Dmfc,Dmmax,Dm,gmfc)

```

```

aux floodm=ufcm

SCBch = checktier(Dm,1025,SCB,SCC)
SCAch = checktier(Dm,1050,SCA,SCBch)
NCCh = checktier(Dm,1075,NC,SCAch)
um = min(ummax,checktier(Dm,1145,DSC,NCCh) + ufc + uefm)

## set of fucntions to determine which tier of 6 possibilities is being used.
## for visualization of the controller. DSC=1, NC=2, SCA=3, SCB=4, SCC=5

SCBcond = checktier(Dm,1025,4,5)
SCAcond = checktier(Dm,1050,3,SCBcond)
NCcond = checktier(Dm,1075,2,SCAcond)
cond = checktier(Dm,1145,1,NCcond)
aux relcond=cond

## Outflows...check for flood...mfsf = flood safty factor
number mfsf=1
Vmfr = Im + Vm - mfsf*27.62

Om = O(Dm,Dmmin,Vmfr,um,ummax)

#=====
#---- AZ apportionment - function of CAP -----
#=====

AZ1 = if(cond==1)then(2.9)else(if(cond==2)then(2.8)else(100))
AZ2 = if(cond==3)then(2.48)else(if(cond==4)then(2.4)else(100))
AZ3 = if(cond==5)then(2.32)else(100)
AZ4 = min(AZ1, min(AZ2,AZ3))
AZ5 = if(Om > 0.36667)then(min(AZ4,12*Om-4.4))else(0)
QS70flow = (Om - fg(u75,Dm,Dmmin))*12
AZ = if(uQS70 > 0)then(2.8 + 0.46*QS70flow)else(AZ5)
aux QS70del = QS70flow
aux AZDeliver=AZ

#-----Cap apportionment-----

cap1 = if(cond==1)then(1.6)else(if(cond==2)then(1.6)else(100))
cap2 = if(cond==3)then(1.312)else(if(cond==4)then(1.24)else(100))
cap3 = if(cond==5)then(1.168)else(100)
cap4 = min(cap1, min(cap2,cap3))
cap = if(AZ > 2.32)then(cap4)else(0.5*AZ)
aux capDeliver=cap
aux onRiverFlow = AZ - cap

#-----difference equations for volumes

```

```

Vp(t+1) = max(0,Vp + Ip - Op - Sap*evap_r)
Vm(t+1) = max(0,Vm + Im - Om - Sam*evap_r)

#translate time scale into years

#year(t+1) = if(year < 53.084)then(year + 1/12)else(0)
#nit year=0

aux year = t/12

# for calibration/debugging

init Vp=17,Vm=16

# final operating (release) condititions at Mead
# normal condition releases 7.5 maf with 4.4, 2.8, and 0.3 to CA,
# AZ, and NV respectively.  If there is a surplus beyond the
# domestic surplus condition (DSC)

#=====
# ---- Final analysis of Phoenix basin groundwater-----
#=====

# Demand =====
# there are 5 demand streams: municipale, industrial,
# agricultural, indian, and riparian.  We assume that municipale
# and industrial demands will grow (based on data) and that ag and
# Navtive demands are constant.

#Demand data (use) is tricky to estimate.  Below are for Maricopa
#county.

#Municiple demand is on the order 1 maf.
# sources: 0.2 ground water, 0.47 local, 0.36 CAP, 0.05 reclaimed.

#Industrial is about 0.2 maf.
# sources 0.09 ground water, 0.02 local, 0.004 CAP, 0.08 reclaimed.

#Ag is about 0.75 maf
#sources 0.25 ground water, in lieu ground 0.125,
#0.262 local, 0.053 CAP, 0.05 reclaimed.

# Indian is about 0.265 maf.
# sources 0.08 ground water, 0.145 local, 0.04 CAP

#riparian is about 0.048.

```

```

#Need other numbers for Pima and Pinal counties as well.
# total estimates from USGS are below summed over counties.

#rigid demand:Md+Id+NAd+Rd for Maricopa, Pima, and Pinal.
# Md = 0.9 + 0.19 + 0.07 = 1.16.  Agd= 0.8 + 0.15 + 1.2 = 2.15

par Md=1.16,Id=0.2,Agd=2.15,NAd=0.265,Rd=0.048

# surface supply in the cap service area is cap plus local
# surface. Local surface comes from the salt, verde, and af
# systems plus about 0.25 other local sources (??) plus
# reclaimed (0.18).  So recOther = 0.25 + 0.18, but round
# to 0.4.

par recOther=0.4

surfSup = cap + wLocal*12 + recOther

rdemand = Md+Id+NAd+Rd

fdemand = max(min(Agd,surfSup-rdemand),0)

par usefagdem = 0,netAgUse=0.7

agdemand = usefagdem*fdemand + (1-usefagdem)*Agd

aux RigidDem = rdemand
aux AgDem = agdemand
aux TotDem = rdemand + agdemand
aux phxSurfSup = surfSup

netRech = surfSup/12 - rdemand/12 - netAgUse*agdemand/12

Vg(t+1) = if(t == 0)then(0)else(Vg) + netRech
init Vg=0

aux Inm=Im
aux Outm=Om*12
aux Depthm=Dm
aux Depthmm=Dmmax
aux gatem=um
#aux MeadFV=Vmfr
#aux evapm = Sam*evap_r

#-----auxiliary variables (debugging)-----

```



```
aux Pd1t=Pd1
aux Pd2t=Pd2
aux Pd3t=Pd3
aux depPET=DET
aux depPETB=DET-20
aux depbalm=1105
```

```
@ bounds=10000,xp=year,yp=Vp
@ meth=discrete,total=637,T0=0
@ xlo=0,xhi=50
```

done