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ABSTRACT

This paper uses 'Medieval' drought conditions from the 12th Century to simulate the implications of severe and persistent drought for the future of water resource management in metropolitan Phoenix, one of the largest and fastest growing urban areas in the southwestern USA. WaterSim 5, an anticipatory water policy and planning model, was used to explore groundwater sustainability outcomes for mega-drought conditions across a range of policies, including population growth management, water conservation, water banking, direct reuse of RO reclaimed water, and water augmentation. Results revealed that business-as-usual population growth, per capita use trends, and management strategies are not sustainable over the long term, even without mega-drought conditions as years of available groundwater supply decline over the simulation period from 2000 to 2060. Adding mega-drought increases the decline in aquifer level and increases the variability in flows and uncertainty about future groundwater supplies. Simulations that combine drought management policies return the region to levels that are more sustainable. Results demonstrate the value of long-term planning and policy analysis for anticipating and adapting to environmental and societal change. Similar anticipatory exercises can be used to assess different suites of drought management policies in other cities facing uncertainty about future conditions.

1. Introduction

Climate change is expected to increase the frequency, intensity, and duration of drought in the southwestern United States in coming decades, and questions are being raised about the sustainability of the region's water resources (Cook, Ault, & Smerdon, 2015). General Circulation Models (GCMs) have been used as the basis for projecting future climatic and hydrological conditions under varying greenhouse gas concentration scenarios (Vörösmarty, Green, Salisbury, & Lammers, 2000; Kundzewicz et al. 2008; Arnell, 2004). There is, however, low confidence about the severity, seasonality, and spatial patterns of drought conditions and their implications for regional water supply when the GCMs are combined with regional climate and hydrological models (Wilby & Dessai, 2010). Wilby (2005) and Trenberth (2010) have warned that uncertainties associated with the GCMs are unlikely to be resolved in the short- to mid-term future because models vary in the way they treat complex climate processes, and there are trial-and-error effects associated with adding more variables and feedbacks to capture system dynamics.

Water managers need to make decisions about how to adapt to climate change before the scientific uncertainties of climate modeling and hydrological impact assessment are resolved. They face classic decision making under uncertainty (DMUU) conditions where stakeholders disagree about problem definition and the probability distributions that describe critical components of the system (e.g., future streamflow and climate, per capita water use, behavioral response to policy instruments). Traditional predict-and-plan efforts in water resources management using optimization models are ill-suited to DMUU problems (Gober, Kirkwood, Ellis, & Deitrick, 2010; Quay, 2010). DMUU strategies favor scenario building, exploration of a wide range of policy options, the search for robust policies that work well across a range of climate conditions, and efforts to preserve the flexibility to respond when the unexpected occurs (Lempert, Popper, & Bankes, 2003). Such strategies often use exploratory simulation models to

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generate multiple scenarios of the future and enable assessment of the potential consequences of policy implementation on system dynamics (Bankes, 1993; Dewar, 2002).

In this paper, we employ DMUU principles to explore the potential consequences of a mega-drought for municipal water supply sustainability in metropolitan Phoenix, Arizona USA. Based on recent research using climate model projections, there is an 80 percent probability that such an extended drought will strike between 2050 and 2099 (Cook et al., 2015). We simulated mega-drought conditions in WaterSim 5, a water resources planning and policy model, to investigate what similar hydroclimate conditions would mean for water sustainability of the Phoenix Metropolitan Area (hereafter "Phoenix") in 2060. We then applied five drought-mitigation policies that have been proposed locally as possible buffers to drought and ask how sensitive groundwater availability is to each of them separately and assess their cumulative impact on long-term water availability.

2. Background

2.1. Urban water trends

The Phoenix urban region enjoys the benefit of an extensive hydraulic reach sitting at the base of large watersheds (8.4 million acres; 3.4 million hectares), including the basins of the Salt and Verde Rivers (Fig. 1). The pre-history and history of the region was based on its ability to capture, store, and use runoff from this large region. Upstream dams and reservoirs allowed 19th Century farmers to store water in wet years for use in dry ones (Gammage, 1999; Gober, 2006). Post World War II urbanization in Phoenix relied on upstream flows of approximately one million acre feet (123 cubic meters) per year and heavy use of groundwater from deep alluvial aquifers. Unsustainable water use led to the passage in 1980 of the Arizona Groundwater Management Act. This Act aimed to extend the agricultural economy for as long as possible but retain water supplies for future urbanization. The essence of the Code was to retire farmlands and shift water use to urban areas, gradually impose higher levels of urban water conservation, guarantee a 100-year assured supply of water for new development to occur, and mandate safe yield defined as a balance between the amount of groundwater pumped from the aquifer and the amount naturally or artificially recharged (Arizona Department of Water Resources, 2016). While enforcement of the Code has been uneven and controversial (Hirt, Gustafson, & Larson, 2008), overdrafts steadily declined after 2000. Reduction in groundwater use was helped by completion in 1985 of the Central Arizona Project (CAP) Canal, a 336-mile (541 km) aqueduct that diverts water from the Colorado River near Parker, AZ into central and southern regions of the state. Artificial recharge of CAP water has allowed large volumes of water to be stored in the aquifer for future use, and CAP water now provides one-third of municipal water supplies.

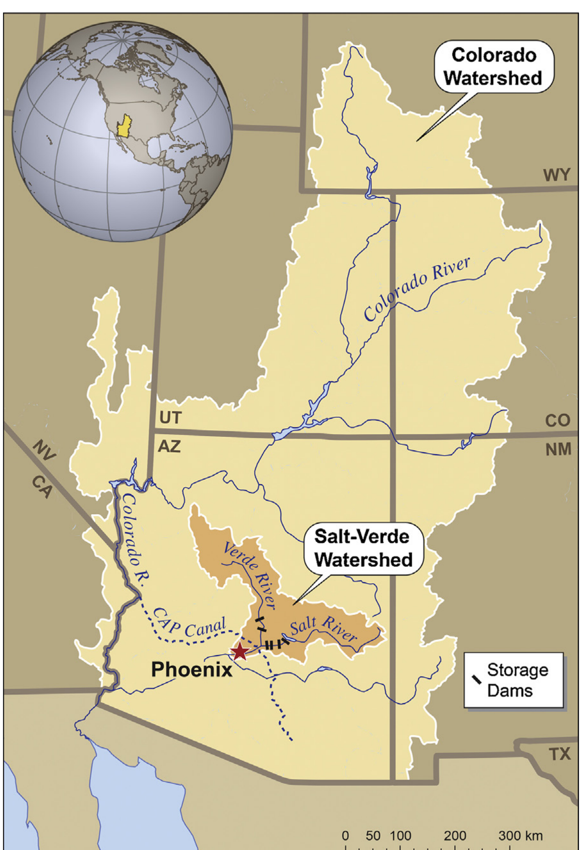

Fig. 1. Phoenix obtains water from the Salt and Verde watersheds of Central Arizona and from the Colorado River Basin via the Central Arizona Project Canal. Groundwater also play a major role in the region's water portfolio.

Water supplies to the cities that comprise metropolitan Phoenix have been robust to recent drought conditions because of the diversity of sources, steady retirement of agricultural lands and transfer of water to urban uses as mandated by the Groundwater Management Act of 1980, and water deliveries from CAP. A major concern for the future however is the potential curtailment of CAP water due to a provision in the original authorization that requires CAP to absorb the first shortages of water to the lower Basin States of California, Nevada, and Arizona. CAP holds junior priority rights to Colorado River entitlements to California, Nevada, and parts of Arizona adjacent to the Colorado River. Under current agreements, water flows to Central Arizona would dry up completely before California would suffer reductions in its allocations. The so-called Shortage Sharing Agreement among the Lower Basin states codifies the conditions that trigger reductions in CAP water. They are directly linked to levels in Lake Mead on the Colorado River. A level below 1075 ft. would trigger up to a 320,000 acre foot reduction for CAP. Lake levels have hovered between 1089 and 1075 ft. since May 2014 (US Bureau of Reclamation, 2016), increasing awareness of the potential for larger-scale regional drought impacts to affect Central Arizona's water supplies.

These increasing uncertainties about CAP water and the future of agriculture in the region occur within an urban context of rapid growth and development. Between 2010 and 2015, the region added roughly 100,000 new residents a year (Arizona Department of Administration, 2016a). Urbanized Phoenix is projected to grow from today's 4.5 million residents to 7.7 million by 2050, although there is uncertainty associated with these projections which range from 6.8 million (low series) to 8.7 million (high series) (Arizona Department of Administration, 2016b). In recent years, declines in per capita water use have buffered the effects of an increasing population, but there are limits to the potential for residential and industrial water conservation to compensate for growth (Gober, Quay, & Larson, 2016). There are also limits to the capacity for agriculture-to-urban land conversion to support urban growth. Currently, agriculture accounts for 32.5% of the region's water use (Arizona Department of Water Resources, 2015), and the traditional narrative is that agricultural land will be replaced by urban uses. This narrative of urban development, water scarcity, and agricultural obsolescence has dominated the public discourse since the 1970s (Gammage, 2011). Given that social, economic, and environmental circumstances are changing, and that priorities for development and resources have evolved, narratives of agricultural resilience and the value of agriculture have emerged in recent years to challenge the narrative that agriculture is obsolete (Bausch et al., 2015).

2.2. Climate trends

Located in the Sonoran desert, the valley city of Phoenix is sited within a hot arid subtropical desert climate regime (Köppen classification *BWh*). Mean total annual precipitation is low (177 mm), with bimodal peaks in monthly precipitation occurring in December–January and July–August. Winter temperatures are relatively mild with average daytime maximums ~18 °C/64 °F. Summer daytime temperatures in Phoenix are high, with mean maximums regularly exceeding 43 °C. Phoenix's summer climate is also notable for being subject to the North American Monsoon (Adams & Comrie, 1997), which contributes almost 40% of its total annual precipitation through brief but intense thunderstorms in July and August. However, winter storm systems that precipitate over mountain ranges surrounding Phoenix are more important in terms of regional hydrometeorology; these storms develop snowpack that are critical for spring streamflow within the Salt and Verde drainage basins. The climate is characterized by high interannual variability in precipitation and river flows.

Based on analyses of climate proxies, in the mid-12th Century, the region that now comprises the southwestern United States was subjected to a widespread, sustained and severe drought, (e.g. Salzer & Kipfmueller, 2005). These proxies suggest that above average temperatures, below average precipitation, and reduced streamflow in the Colorado River resulted from natural climate variability (Woodhouse, Meko, MacDonald, Stahle, & Cook, 2010). This historical drought's effect on hydroclimate conditions may be an analogue for future episodes resulting from climate change. Based on the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (AR5), GCM's consistently project higher temperatures for this region, but uncertainties exist in projected decreases in precipitation between results from the Coupled Model Inter-comparison Projects 3 and 5 (CMIP3 and CMIP5) for the southwestern USA (Christensen et al., 2013). More recently, Cook et al. (2015) used empirical drought reconstructions and soil moisture metrics from 17 widely used GCM's to demonstrate a robust drying response to warming across a diversity of models and metrics used. Results anticipate future drought conditions in the Southwest that will likely exceed even the driest conditions associated with the Medieval Drought anomaly. The timing of this long-term seasonal drying for the southwestern US potentially affects snowpack depth which is a major source for Phoenix's water supply and has implications for both future drought and water resource management.

3. Methods

3.1. WaterSim 5

In this paper, we use an anticipatory modeling approach designed to build capacity for sustainable water resource management decision making and climate change adaptation. Our modeling framework is comprised of a suite of separate linked modules, programs, and platforms that are collectively called WaterSim 5 (Sampson, Quay, & White, 2016). This suite of tools includes Microsoft C sharp libraries that communicate with a FORTRAN dynamic link library (dll) via a Microsoft development interface (i.e., a Windows form application; API) and, when used through a browser, a user interface built upon Javascript and HTML5. The user accesses the run library through the API that controls the specifications for the current model run. The FORTRAN dll controls the state initializations, and it houses the rules and algorithms for the model using modules that are comprised of functions and subroutines; these modules are linked components that share information and, in the process, utilize inputs and create outputs necessary for the next module in the sequential hierarchy, or as output to the API.

The water demand, supply, and use modules of this sequence are linked, in time and space, with exogenous factors that influence demand and available supplies and, together, they determine the relative use of each water source based on the individual water rights, water demand rules, and the hierarchical sequence of use. Annual water demand in conjunction with water rights are linked to the individual water sources; they determine the net delivery of surface water and groundwater to each water utility provider. Although the base model runs on an annual time-step, finer temporal resolutions (daily and monthly) are used in the simulation run-stream and in the data processing and module implementation for some of the process components. For a complete description of the model refer to Sampson et al. (2016).

3.2. Construction of simulations

We simulated business-as usual (BAU) and mega-drought (MD) conditions in modern Phoenix from 2000 to 2060. Simulations are based on river flow conditions from 40 randomly chosen 60-year trace records from the historical record of runoff for the Colorado River (1906 to present) and the Salt-Verde River record (1945 to present). These traces were then adjusted to reflect the influence of drought conditions on river flows using runoff estimates from paleo reconstruction data for the Colorado River (1121 through 1180 AD), and the Salt and Verde Rivers (1391 through 1450 AD) (Meko, Woodhouse, & Morino, 2012). This adjustment resulted in a 12%, reduction for the Colorado River and 19% reduction for the Salt-Verde (SV) Rivers. These proxy drought flow reductions were then superimposed on the BAU traces to anticipate MD conditions.

Model outputs focused on groundwater outcome metrics because of the critical role that groundwater plays as a bank from which Phoenix could draw water during periods of surface water shortage. In fact, the region has been banking groundwater for decades through the Arizona Water Banking Authority (AWBA), established in 1996. AWBA pays delivery and storage costs to bring Colorado River water into central and southern Arizona through the Central Arizona Project Canal. Water is stored underground in existing aquifers (direct recharge) or is used by regional irrigation districts in lieu of pumping groundwater (indirect or in-lieu recharge). For each acre-foot stored, the AWBA accrues credit that can be used in the future for back-up supply. The AWBA currently holds more than 1.6 million acre feet (MAF) of water in the Phoenix Active Management Area. Arizona has several state mandated goals for sustainability of groundwater in the Phoenix region. The State has a goal to achieve long-term sustained yield for groundwater use were the long term average of groundwater levels will be flat. Arizona also requires that cities and the county provide evidence that there is a 100-year "assured water supply" for every new home platted (Arizona Department of Water Resources, 2015). In WaterSim 5, levels of aquifer drawdown from the starting year in 2000 were used as proxies for assessing the region's sustainable yield goals and the number of years that groundwater pumping can continue before groundwater supply credits are depleted; our estimates of adequate groundwater supply credits were used as a proxy for the region's assured water supply goal and thus a sustainability metric for groundwater use. As discussed in Sampson et al. (2016), the groundwater outcome metrics evaluated in WaterSim 5 represent key sustainability indicators such as social-ecological systems integrity, resource efficiency and maintenance, inter-generational and intra-generational equity, and the precaution and adaptation dimensions of water sustainability.

3.3. Policy options

BAU conditions assumed that current water management strategies being applied in 2015 will continue with no change to 2060. We then identified a set of additional policy, planning, and management interventions that could be deployed in addition to current strategies to adapt to mega-drought in the region. The options for our anticipatory modeling were derived from prior policy research focused on central Arizona water systems, including historical analysis (Hirt et al., 2008), narrative analysis (Bausch et al., 2015), current-state sustainability appraisals (Larson, Polsky, Gober, Chang, & Chandas, 2013), and a survey of water decision makers (White, Keeler, Wiek, & Larson, 2015). We also conducted a review of existing water sustainability and climate adaptation plans, strategies, and policy proposals. Based on this evidence, we selected five policy interventions to be tested against the drought and river trace scenarios. Specifically, we examined the effects of (a) population growth management, (b) municipal and industrial water conservation, (c) groundwater banking and recharge, (d) direct potable reuse of RO reclaimed water, and (e) supply augmentation. In the simulations, we tested the sensitivity of the outcome metric to the different policy options. This metric (years of adequate groundwater supply) is one indicator of a broader set of principles for urban water sustainability (Larson et al., 2013). In selecting the policy options, we applied the plausibility quality criterion for scenarios, which allows for exploring the future with credibility and saliency (Wiek, Withycombe Keeler, Schweizer, & Lang, 2013). Plausibility means that there is sufficient evidence that the intervention could reasonably occur during the timeframe for the simulations.

For instance, in an historical policy analysis harshly critical of the region's past water management, Hirt et al. (2008) concluded: "If state and local water managers and government officials do not institute stronger mandatory conservation measures, invest in effluent reuse infrastructure, return to credible assured water supply programs, and engage in serious growth management, the region will quickly confront its widely predicted water crisis" (p. 503–504). Larson et al. (2013) highlighted a range of interventions to enhance the sustainability of the regional water governance system including enhanced efficiency in municipal and industrial conservation as well as groundwater recharge and effluent reuse programs. The White et al. (2015) survey identified decision makers' priorities for the future of the Phoenix water system in terms of supply, delivery, demand, outflow, and governance. Results revealed two distinct visions for water in central Arizona – one in which water experts and policy makers pursue supply augmentation to serve population growth and economic development, and another in which broadened public engagement is used in conjunction with policy tools to reduce water consumption, restore ecosystems, and limit population growth and metropolitan expansion.

Thus, without taking a position on the desirability, political feasibility, or cost of each option, we note here the evidence for plausibility of evaluating these interventions based on the scientific and policy discourse.

3.4. Scenarios simulated

Simulations using WaterSim 5 start in the year 2000 and are run to 2060. The period 2000 through 2012 is reserved for empirical records. This period is extended through 2013 for estimates of personal water use (liters per capita per day). Accordingly, projections of river runoff estimates start in the year 2013 and extend through the end of the simulation in 2060. Policy choices are implemented in 2016 to reflect the impact of anticipatory water policy decisions. Our scenarios encompass the impacts of the five policy options superimposed on reductions in daily flows in the SV and CO river systems. To examine the sensitivity of the system to the five drought-mitigation policies, we varied growth management conditions from "no growth" to 125% of the projected growth for the region, in 25% intervals, as estimated by the Maricopa Association of Governments (MAG) (Sampson et al., 2016). We adjusted per capita water use from default conditions (~1.0% per annum decrease in personal water use) to a maximum of 1.5% per annum reductions in personal water out to 2059, using four intervals. Water banking policy reflected a range of use in the available Colorado River water from 0 to 100% of the available to bank, also in 25% intervals. For reuse policy, we assumed that any available reclaimed water above the default estimate (17% of treated wastewater for the region) would be available for reuse as RO reclaimed water with 100% of that water used in the supply stream. There are four intervals for RO reclaimed water (17%, 50%, 75%, and 100% of available, reclaimed water). Finally, augmentation is evaluated at four levels from 0 to 21% water demand in intervals of 7% (0 is the default). Population growth rates and conservation levels are preset in the model. Next, the other policies are implemented in the following order are: direct potable reuse (RO water), water banking, and water augmentation.

3.5. Scenario outputs examined

From these scenarios, we examined the percent change in the regional groundwater over the 60-year simulation from initial volumes for BAU simulations as well as MD conditions. We also examined the change in the years of adequate groundwater supply over the simulation period for both cases. In this case we examined the mean response and the 5th and 95th percentile of the response for both scenarios. We also conducted a sensitivity analyses for individual policies to determine their effects on years of available supply, holding the other variables constant (using the default settings). For example, we looked at variation in the amount of water banking, assuming 100% of projected growth, annual conservation of 1%, per year, reuse of 17%, and augmentation at 0. Finally, we progressively added individual management policies, one at a time, at the maximum effect generated using the 75% of projected growth scenario to evaluate the step-wise changes in our groundwater metric in response with the implementation of water management policies ordered by their likely relative costs (from low to high).

4. Results

4.1. Mega-drought conditions

Analysis of the BAU scenario suggests that regional aquifer levels will decline by 7% in 2060 with a narrow range of uncertainty (Fig. 2a). Shaded areas in Fig. 2a represent the 5th and 95th percentiles around the mean response based on the 40×40 traces. Under MD conditions, the rate of decline increases to 10%, and there is a much wider band of uncertainty around the mean rate of decline. Years of adequate groundwater supply fall from ~100 in 2000 to 82 by 2060 in the BAU model and from ~100 to 77 years in the MD model (Fig. 2b). The MD model has a wider range of uncertainty around mean conditions and introduces the possibility of dipping below 50 years of available supply in half of the final 30 simulation years.

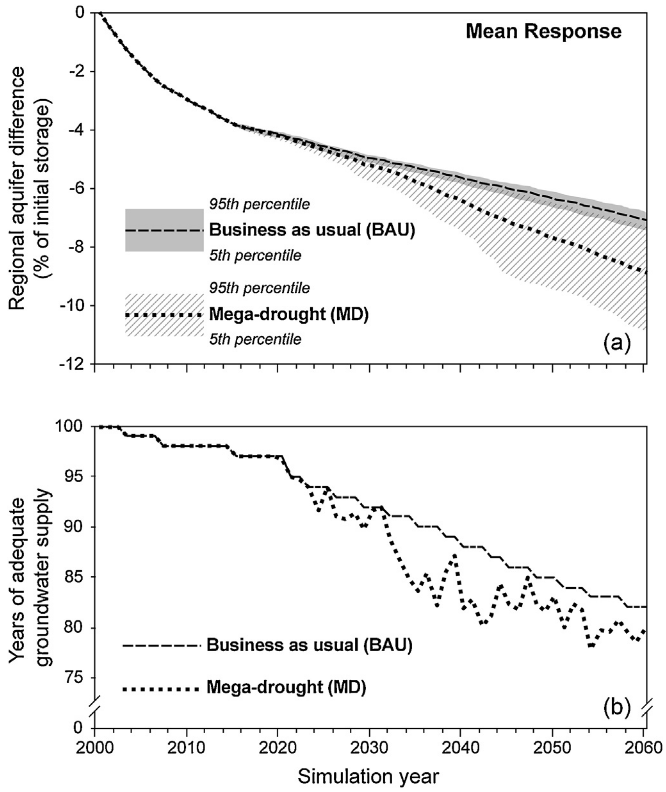

Fig. 2. Results of BAU compared to MG conditions, (a) percent decline in groundwater storage levels from levels in 2000, (b) years of adequate groundwater supply.

4.2. Sensitivity analyses

We tested the sensitivity of groundwater resources to a suite of plausible drought-management policies that could be implemented in Phoenix in time to address the potential for MD conditions to occur (Fig. 3a–d). Fig. 3a shows the sensitivity of groundwater supplies to population growth rates (growth management), with the no-growth scenario yielding close to 100 years of available groundwater supply. Phoenix could, in other words, maintain a sustainable 100 years of available supply under MD conditions, but would need to limit growth completely, assuming 1% conservation rates and current levels of policy implementation. Rapid growth, defined here as 125% of official projections, under MD conditions, lowers the years of available supply to 75 in 2060. Population growth has a linear effect on groundwater supplies due to the way it is treated in WaterSim 5. More people demand more water, and if it is not available from surface supplies (as would be the case under MD conditions), WaterSim 5 draws groundwater. Similarly, conservation reduces water demand, resulting in a linear response to groundwater supplies (Fig. 3b). At the assumed level of 75% of projected growth, even conservation rates of 1.5% per year would not be sufficient to support the 100-year standard of available supply. Years of supply would range from 80 to 85 years, depending upon the conservation rate. Reuse also extends available water supplies to ~83 years at the end of the simulation assuming 75% growth and 1% conservation (Fig. 3d). One reason for the leveling out after 2030 is that wastewater effluent, the source of RO reclaimed water, is primarily dependent on indoor water use, and thus as indoor use becomes more efficient, water available for reuse will fall. Water banking produces relatively little change in the overall trend in years of adequate groundwater, although banking moderates the inter-annual variability in available supply (Fig. 3c). This results from how water banking is operationalized. Excess water is stored

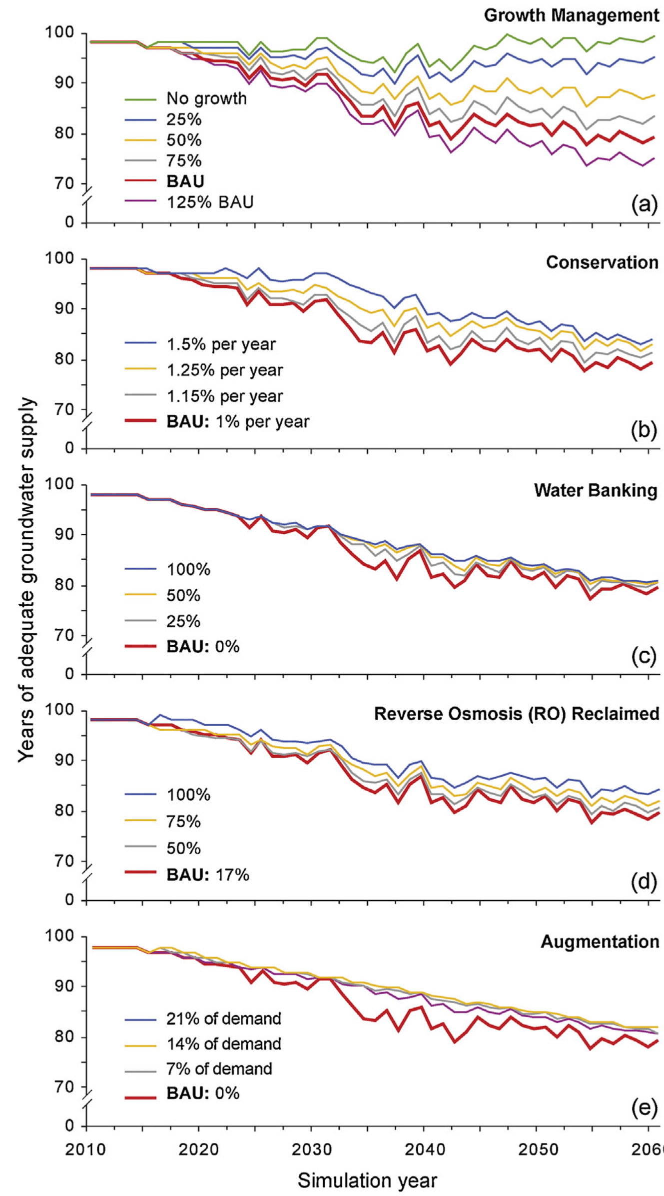

Fig. 3. Sensitivity of years of available water to drought-mitigation policies under mega-drought conditions; (a) population growth management, (b) municipal and industrial conservation, (c) water banking, 3d: Reverse Osmosis (RO) reclaimed, (e) augmentation.

or left in the ground during wetter years and withdrawn during drier years.

Augmentation (Fig. 3e) produces a non-linear response in years of adequate groundwater supplies. It takes the variability out of groundwater supplies, but does not extend years of supply to 100 years. Adding 7% of total regional demand to the available water supply from an outside source results in a much larger response than moving from 7% to 21%. It is important, however, to keep in mind that WaterSim 5 simulates supply and demand balances for 33 separate municipal water utilities, each with different supply and demand portfolios. Some providers may not need to augment their supplies; for others 7% may be optimal, and for still others 7% will not be enough. Results suggest that 7% region-wide would even out the inter-annual variations in available supply and produce 80 years of supply at the end of the simulation, again assuming population growth of 75% of projections.

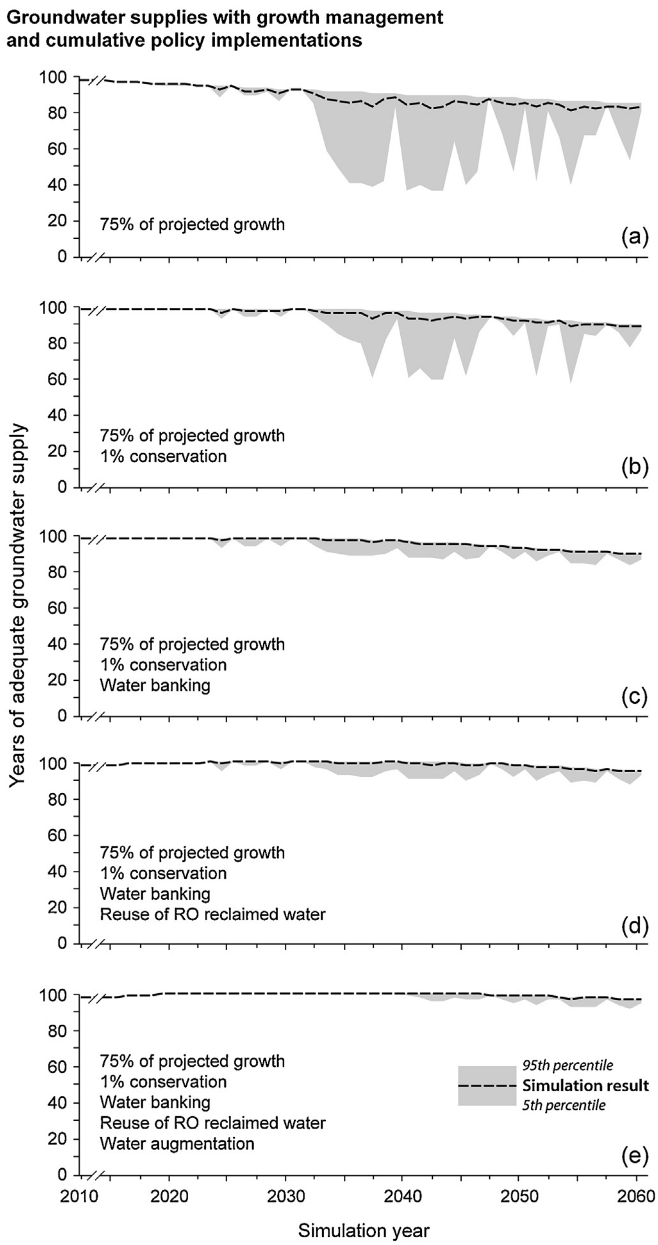

Fig. 4. Effect of drought management policies on years of available supply and risk of shortage.

4.3. Cumulative policy scenarios

It is unlikely that the proposed policies would be implemented separately but rather would be deployed as a suite of adaptation measures to mitigate shortages in anticipation of extreme drought conditions—some (growth management, conservation, and reuse) to improve the system's capacity to meet the long-term needs of growth and sustainability and others (banking and augmentation) to improve system reliability, reducing the inter-annual variations in supply (Fig. 4a–d). Assuming population growth of 75% of projected levels results in 82 years of available groundwater at the end of the MD simulation, but exposes significant risk of dipping below 60 years of available supply, especially after 2030 (Fig. 4a). Adding conservation of 1% per year reduces somewhat the uncertainty associated with the years of available supply, and it raises the mean years of available supply from 82 to 89. It is intuitive that more people living more efficiently produces a more sustainable long-term outcome, but still conservation alone does not enable 100 years of available supply over the long term with growth of 75% of projected levels.

Water banking does not add much to years of available supply, but does significantly reduce the risk of falling below 90 years of supply (Fig. 4c). It is, as mentioned previously, a mechanism for modulating the effects of inter-annual variability in surface supplies, not one for extending the years of supply. Reuse does not appear to significantly reduce the risk falling below 90 years, but it does extend end-of-simulation supply to 94 years (Fig. 4d). Augmentation adds another 3 years to available supply and reduces of risk of potential shortages in particular years. With the full complement of infrastructure and conservation policies, it is possible to support growth rates of 75% of projections and maintain a sustainable groundwater supply under MD conditions.

5. Discussion

AghaKouchak, Feldman, Hoerling, Huxman, & Lund (2015) make the point that California's recent drought has human dimensions, including rapid urbanization, and it should be recognized as "anthropogenic drought." Current shortages are not merely a function of more extreme climate conditions but the result of rapid growth, overuse, and obsolete management. They argue in favor of more proactive, structural solutions such as long-term demand management, conservation, public outreach, flexible market-based strategies, and infrastructure adaptation. They state that: "California must learn to live with its dry climate." Our modeling work was motivated by a similar goal–to be prepared for a range of climate futures, including one that mirrored the most extreme conditions in the recorded past. While we acknowledge the importance of monitoring and predictions, we assert that there is value in the "what-if" exercises of the sort we undertook here. They are anticipatory rather than a reactive and support action in the face of climate and societal uncertainty.

Results of the anticipatory modeling exercise indicate that it will be challenging, but possible, for Phoenix to continue to grow and adapt, even to mega-drought conditions, without unsustainable groundwater use. A suite of policies implemented in advance would go a long way in helping the region weather a 60-year drought period. Modest reductions in growth, coupled with continued conservation and reuse would maintain years of available supply at sustainable levels, and banking and augmentation would reduce the negative impacts of high inter-annual variability on years of supply. In order to be effective, these policies would need to be implemented before the full force of extended and extreme drought conditions affects the water system. For instance, facilities to recharge and recover banked water must be planned, financed, and constructed in advance. The Phoenix region does not currently have the physical infrastructure in place to recover all the current and planned groundwater being banked. Furthermore, reclaimed water and coastal desalination facilities require a decade or more to plan and finance. Conservation theoretically can be implemented more quickly, but as California is learning, there are psychological, behavioral, cultural, and gender-based reasons that people use water the way they do, and these behaviors and cultural patterns (especially with respect to outdoor use) take time to change (Larson, Wutich, White, Munoz-Erickson, & Harlan, 2011; Larson, Ibes, & White, 2011; Neel, Sadalla, Berlin, Ledlow, & Neufeld, 2014; Gober et al., 2016).

The results produced in Fig. 4 are not assumed to be the definitive set and sequencing of policies for drought adaptation. Indeed, the impact of the policies on the groundwater outcome variable may differ based on the sequence of policy interventions and the underlying assumptions (e.g., levels of population growth, drought impact, etc.). This is, in fact, the goal of anticipatory modeling – to allow individuals and groups to explore varying sets of assumptions and alternative types and combinations of policies (incremental or transformative) to explore plausible impacts.

Future work may involve expanding drought management policies to include pricing and market interventions, land use and landscape regulations, and rainwater harvesting strategies. Rainwater harvesting has been used for centuries in the desert (Phoenix averages only 177 mm of precipitation per year). It reduces the need to use potable water for garden irrigation in cities where a large and increasing proportion of water use is for outdoor purposes (Gober et al., 2016). It also has the co-benefit of reducing the energy used in water treatment processes. Rainwater harvesting has been shown to have a significant impact on the water budgets in many Australian cities as it was implemented as a drought management strategy during the so-called Millennium Drought of 1997–2009. Beatty and McLindin (2012) note that it is now seen as an alternative urban water supply. In 2010, 26% of Australian households had tanks, including 43% in Brisbane and 45% in Adelaide. Preliminary simulations from Phoenix suggest that residential rainwater harvesting would account for on average 9% of residential outdoor demand, depending on the timing, duration, and amount of rainfall, the compliance rate of households establishing rainwater harvesting systems, time to adoption of the rainwater capture technologies, and outdoor water demand.

Also relevant are potential land use strategies to facilitate more water-sensitive urban designs. Askarizadeh et al. (2015) has argued in favor of "low impact development" to restore natural hydrologic connectivity, promote vegetation, and reduce run-off volume. Two large Phoenix-area suburbs, Glendale and Mesa, (together housing 700,000 residents) recently developed a *Low Impact Development Toolkit* providing specific guidelines for green streets, vegetated swales, permeable paving, green roofs, and other LID strategies (City of Mesa, 2015). It is increasingly recognized also that Homeowner Associations (HOAs) play an increasingly important role in regulating urban vegetation and thus water use as their co-called CC & R's Covenants, Conditions and Restrictions and Regulations. CCRs contain clauses that require, permit, or prohibit a certain type or amount of ground cover, particular plant species or green lawns (Cook et al., 2015; Turner & Ibes, 2011).

Also relevant to any discussion of long-term water sustainability is the spatial configuration of water governance and how we treated that spatial arrangement in the modeling and discussion of results. As mentioned earlier, metropolitan Phoenix, with some 4 million residents, is served by some 120 water providers, each with their own unique portfolio of water supplies, demographics of demand, plans for future growth, and water policies. WaterSim 5 does in fact account for the largest 33 of the region's providers and does balance supply and demand for each of them. We reported the region-wide totals to give an overview of the regional potential to achieve sustainability in the face of mega-drought. In fact, each of the 33 providers faces individual challenges with respect to both supply and demand. Regional analysis assumes that communities will coordinate and cooperate in managing both supply and demand, share the cost of infrastructure and the responsibility of conservation, and manage growth in a way that does not undermine the sustainability position of neighboring communities in terms of groundwater assets. Future research is necessary to explore the spatial dimensions of the adaptation response to understand differential vulnerabilities and adaptive capacities between the various providers.

6. Conclusions

One goal of this paper was to stress test water resources in Phoenix, using the most dire hydroclimate conditions in the pre-historical record as a analogue for the increasingly likely mega-droughts expected to hit the region in the coming decades and then introduce a set of drought management policies to see if they could prevent unsustainable groundwater use. The results are both heartening and cautionary. Simulations suggest that it is possible for the urban region to continue to grow and still withstand a 60-year period of extreme drought, but some combination of modest growth management, new expanded conservation efforts, and expensive infrastructure will likely be required to carry this off. A second goal was to demonstrate the usefulness of an anticipatory approach to mega-drought adaptation, enabling the exploration of alternative future conditions, the consequences of specific policies or clusters of them, and community discussion of ways to manage water in the face of potentially dire future climate conditions. At the end of the day, communities will decide for themselves how much risk they are willing to take to avert the negative consequences of climate change and how much they are willing to pay or change behaviors and construct infrastructure to adapt. Tools such as WaterSim 5 support these decision processes and evidence-based discussions of climate adaptation and long-term water sustainability and facilitate more anticipatory strategies for dealing with potential drought.

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