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A provider-based water planning and management model – WaterSim 4.0 – For the Phoenix Metropolitan Area

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A B S T R A C T

Uncertainty in future water supplies for the Phoenix Metropolitan Area (Phoenix) are exacerbated by the near certainty of increased, future water demands; water demand may increase eightfold or more by 2030 for some communities. We developed a provider-based water management and planning model for Phoenix termed WaterSim 4.0. The model combines a FORTRAN library with Microsoft C# to simulate the spatial and temporal dynamics of current and projected future water supply and demand as influenced by population demographics, climatic uncertainty, and groundwater availability. This paper describes model development and rationale. Water providers receive surface water, groundwater, or both depending on their portfolio. Runoff from two riverine systems supplies surface water to Phoenix while three alluvial layers that underlie the area provide groundwater. Water demand was estimated using two approaches. One approach used residential density, population projections, water duties, and acreage. A second approach used per capita water consumption and separate population growth estimates. Simulated estimates of initial groundwater for each provider were obtained as outputs from the Arizona Department of Water Resources (ADWR) Salt River Valley groundwater flow model (GFM). We compared simulated estimates of water storage with empirical estimates for modeled reservoirs as a test of model performance. In simulations we modified runoff by 80%–110% of the historical estimates, in 5% intervals, to examine provider-specific responses to altered surface water availability for 33 large water providers over a 25-year period (2010–2035). Two metrics were used to differentiate their response: (1) we examined groundwater reliance (GWR; that proportion of a providers' portfolio dependent upon groundwater) from the runoff sensitivity analysis, and (2) we used 100% of the historical runoff simulations to examine the cumulative groundwater withdrawals for each provider. Four groups of water providers were identified, and discussed. Water portfolios most reliant on Colorado River water may be most sensitive to potential reductions in surface water supplies. Groundwater depletions were greatest for communities who were either 100% dependent upon groundwater (urban periphery), or nearly so, coupled with high water demand projections. On-going model development includes linking WaterSim 4.0 to the GFM in order to more precisely model provider-specific estimates of groundwater, and provider-based policy options that will enable "what-if" scenarios to examine policy trade-offs and long-term sustainability of water portfolios.

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1. Introduction

Water resource managers in desert cities of the arid Southwest of the United States face much uncertainty in population growth and in municipal water supplies (e.g., Bolin et al., 2010). These concerns are deepened by the prospect of decreased water availability as a direct result of climate change projected for this region (e.g., IPCC, 2007). Population growth (and urban development in general) in the Phoenix Metropolitan Area (hereafter "Phoenix"), an area encompassing approximately 268,000 ha (662,000 acres) in central Arizona, has long been decoupled from real or perceived

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availability of water (Gammage, 1999). Development in Phoenix has always served as the economic engine with access to water typically considered last (if at all) in the planning process (Gammage, 1999; Gober, 2006). However, because of the now real threat of future decreased water supplies, the traditional development model must be abandoned; active water planning is necessary (Gober, 2006). Uncertainty in future water resources coupled with uncertainty in population growth has sparked the development of water planning and management tools (e.g., Sehlke and Jacobson, 2005; Stave, 2003). These models permit stakeholder participation in the consideration of alternate policy decisions, in real time, for proactive (anticipatory) water planning purposes. Water management models that are sensitive to future climate projections enable policy-driven decisions in the face of increased climatic uncertainty (Gober et al., 2011).

1.1. Define the issues

Few question that climate is changing. The regional patterns of projected climate change for the United States suggest increased surface temperatures and decreased precipitation for central Arizona by 2029 (IPCC, 2000; Milly et al., 2008). Phoenix receives surface water from the Salt, Verde, and Tonto Rivers (hereafter Salt-Verde) and from the Colorado River. The Salt-Verde watershed encompasses an area of about 33,800 km^2 (13,050 mi^2), and drains a large portion of south-central Arizona. Deliveries of stored water and runoff from the Salt-Verde watershed are managed by the Salt River Project (SRP). The Colorado River watershed encompasses an area of about 640,000 km^2 (246,000 mi^2) covering parts of seven U.S. states and two Mexican States. The Central Arizona Project (CAP) administers and conveys Colorado River water to Phoenix along a 541- km (336-mile) long aqueduct which terminates south of Tucson, Arizona. Thus, local water supplies to Phoenix depend on regional to sub continental climatic conditions.

IPCC climate projections suggest that surface temperatures will increase by 1–2 °C for most of Arizona by 2029 (IPCC, 2000). Although there is greater uncertainty in the projections for precipitation, decreases are expected, with 90% of the models in agreement that rainfall in Arizona will decrease by 20%–30% by 2029 (IPCC, 2007). Projected decreases in rainfall are reflected in the regional estimates of future runoff projected for the Salt-Verde watersheds (Ellis et al., 2008). Based on down-scaled General Circulation Models (GCM s) simulations Ellis et al. (2008) project that future runoff from these watersheds may vary from 50% to 127% of historical levels; most of the model–scenario combinations indicated decreased future flow. Because the Colorado River basin is much larger it is subject to broader climate systems. Moreover, while a basin average decrease in precipitation of only 3% is expected, precipitation in northwestern Arizona is predicted to decrease by 10–15% by 2039 (Christensen et al., 2004; Seager et al., 2007). Christensen and Lettenmaier (2007) examined an ensemble of GCMs and concluded that runoff for the Colorado River may decrease by 0%–11% by 2039. By 2050, even modest climate change projections—A1B scenario—suggest a 20% reduction in runoff for the Colorado River (Overpeck and Udall, 2010). Although it may be difficult to assess how decreased precipitation projected for northwestern Arizona will be reflected in the Colorado River Basin runoff, future surface water supplies to greater Phoenix appear to be in jeopardy.

Multiple water providers manage water supplies for Phoenix; their water portfolio determines (in large part) their potential vulnerability to any one water source. A portfolio may permit access to SRP water, CAP water, groundwater, or in many cases some combination of all three depending on settlement history; “first in time of appropriation is the first in right to appropriate” dictates that communities with the longest settlement history (who have demonstrated “beneficial use upon the land”) have senior rights to surface water. The priority of right to appropriate water also determines the strength and resilience of a provider’s water portfolio. More recently established communities have to purchase rights to surface water from extant contracts or negotiate access to groundwater with the Arizona Department of Water Resources (ADWR). Today, ten water providers have access to SRP water. In 2009, 55 water providers were entitled to CAP water (http://www.cap-az.com/). In Phoenix, groundwater serves as an important component of many water providers’ portfolios and a stop-gap when surface water supplies become limiting.

The amount of groundwater available to any one provider depends not only on their legal contracts with ADWR but also on the physical availability of water which is strongly influenced by their geographical location within the Salt River Valley (SRV). Most of the SRV is underlain by three distinct alluvial layers that vary in depth and spatial extent, depending on bedrock elevation; depth to bedrock varies from 10’s to 100’s of meters within the basin (ADWR, 2006). Soil texture varies within each layer and ranges from gravel, sand, and silt in the upper alluvial layer to conglomerate, gravel, and mudstone in the lower alluvial layer (ADWR, 2006). Together, soil texture and depth determine volumetric soil water content and, thus, the water holding capacity of the alluvial layer. By 1980 the physical availability of groundwater came into serious question; groundwater mining (groundwater removals in excess of recharge) was rapidly depleting the aquifers underlying Phoenix (Hirt et al., 2008). The 1980 Groundwater Management Act (GMA) was enacted to bring the SRV into “safe yield”—a balance between groundwater recharge (natural and artificial) and pumping —by 2025 (Maguire, 2007). The GMA established regions, called Active Management Areas (AMAs), where groundwater management is required. The ADWR was created to oversee this management. There are currently 95 municipal water providers and 21 untreated water providers in the Phoenix Active Management Area (AMA); most of these providers convey water to metro Phoenix (ADWR, 1999). Current and past groundwater pumping (and recharge) in each provider area, along with underflow and sundry natural recharge has influenced the depth to the water table which, basin wide, now stands at 240 m (787 ft) to 330 m (1083 ft).

1.2. Response to stakeholders

Adaptive management of surface and groundwater resources in an uncertain, changing climate along with uncertainty in population growth demographics requires a modeling framework. A provider-based model for Phoenix can enable proactive water planning and management at a spatial resolution concomitant to stakeholder needs and can help facilitate engagement of stakeholders in the water planning process. Modelers actively engage in developing tools to explore possible outcomes in a changing world. However, effective communication of knowledge gained from these modeling exercises and active transfer of this knowledge to stakeholders often remains unrealized. Several factors explain why water managers are slow to implement policy based on modeling results. Lack of certainty in the model and (or) poor validation of the model outputs hampers widespread acceptance (Borowski and Hare, 2007; Brugnach et al., 2007). Model development without stakeholder participation has also been acknowledged as one reason why water managers are weary of using models in their water planning process (Brugnach et al., 2007; Olsson and Andersson, 2007). Often, policy makers simply do not understand the models and what they contribute. Inquiry-driven science, in this case the study of the pertinent hydrologic processes needed for planning, design, and management of water resources can, at times,

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be disengaged from the socio-economic factors that drive stakeholder relevance (Shuttleworth, 2007). Bridging modeling activities between research institutions to water managers to form water management policy can more readily be achieved by active stakeholder participation in model development, cross-disciplinary approaches in design, and increased clarity in the conveyance of how the models work, what they provide, and where their strengths and weaknesses lie (Borowski and Hare, 2007; Castelletti et al., 2008).

Gober et al. (2011) used a county-scale water management and planning model, WaterSim 3.0, to examine potential climate change impacts on consumptive use by Phoenix water users under various climate change and policy-driven scenarios. This model was developed to analyze the potential effects of future climatic conditions, population growth, land-use change, and policy options on water supply and water demand for Maricopa County, Arizona. If water demand exceeded surface water supplies, the simple difference—a "bucket" approach, where the bucket represents the county aggregate—between surface water supplies and water demand provided an estimate of the amount of annual groundwater pumping. Annual outputs generally focused on the total amount of groundwater drawdown over the simulation period —at the metro-wide scale—and liters per capita per day (LPCD) forecast for residential users.

WaterSim 3.0 was developed using a participatory process where modelers and water managers worked together in an interactive environment to modify WaterSim and make the planning tool transparent. Transparency and stakeholder participation, however, does not necessarily guarantee relevancy. A water management tool must also include capacity building (an ability to change the model as new information arises) and learning opportunities to enable successful integration of modeling and management activities (Berger et al., 2007). Although WaterSim 3.0 provided a good foundation for water modeling activities at the county level, community interest in water planning occurs at the city or, at minimum, the water provider-level. In response to stakeholder feedback we modified WaterSim 3.0 (i.e., Escobar, 2009) to create a provider-level water planning and management model for Phoenix. A diverse committee of academics from multidisciplinary fields now meets monthly to discuss how model development should proceed. To ensure that we are meeting the needs of our constituents, and to solicit feedback on our progress, we hold occasional working-group sessions for water provider managers to critically evaluate our modeling framework and direction to evaluate whether we are impacting how actual decisions are being made (e.g., White et al., 2010). This collaborative effort provides a foundation for community involvement and stakeholder participation to ensure that our work has relevancy (Wutich et al., 2010).

In this contribution we: 1) discuss model development, 2) demonstrate verification/validation of the model, 3) examine the response and sensitivity of individual water provider portfolios to imposed changes in surface water availability, and, 4) present groundwater drawdown—an estimate of the cumulative amount of groundwater pumped over a 25-year period—for 33 "large" water providers in Phoenix (Fig. 1). It is important to note that, at present, there are no formal dependencies among the water providers examined other than their individual water rights as influenced by the collective water supplies. Our framework will enable the inclusion of potential, future risk-pooling policies that will likely arise when water shortages do occur (e.g., Aktipis et al., 2011).

2. Describe the model

WaterSim 4.0 is comprised of a Microsoft C# interface, a C# library module, and a simulation model (FORTRAN) that houses the

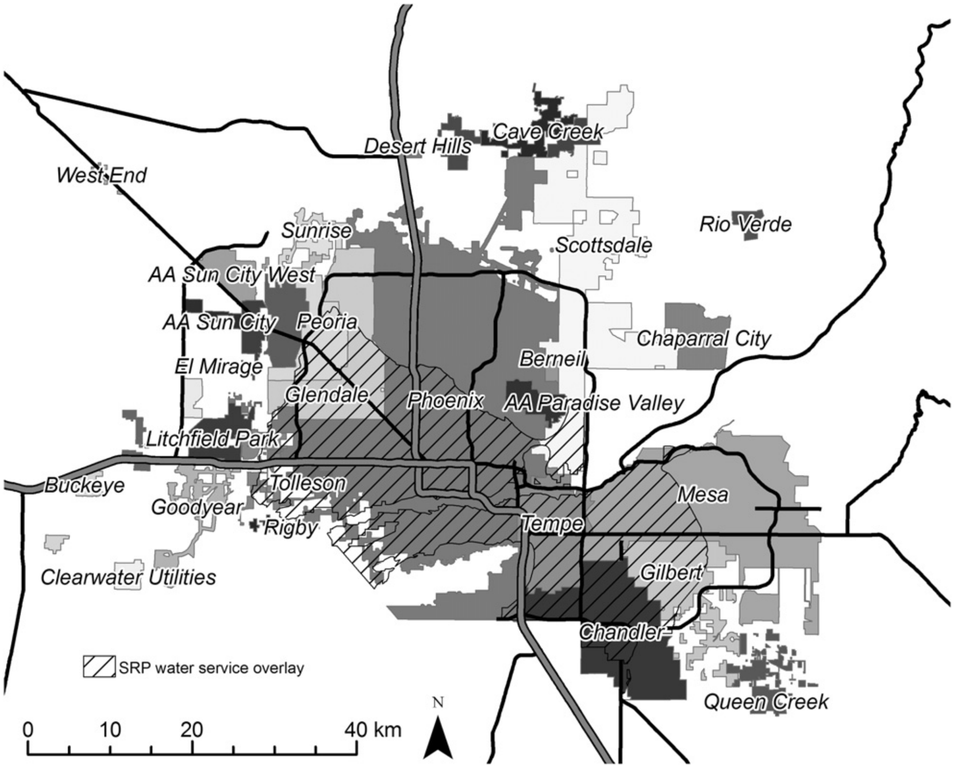

Fig. 1. Twenty-six water providers of the Phoenix Metropolitan Area. We examined 33 water providers in this study. To increase clarity, seven water provides were not depicted in this figure. Where necessary, individual provider service areas were truncated at the Maricopa County line due to data limitations.

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rules and algorithms to model water supply and demand all at the water provider-level (Fig. 2). The 33 water providers examined here are highly variable. They vary in size from small municipalities to major metropolitan communities. And, because they have distinct water portfolios, they have unique water supply and delivery challenges. Spatial and temporal aggregation of these multi-scale differences necessitates that all fine scale attributes of every water provider cannot be addressed. Moreover, processes important at one scale are frequently not important or predictive at another scale, and information is often lost as spatial and temporal data are considered at coarser scales (e.g., Turner et al., 1989). It is important in a modeling program, then, to match the data inputs with the relevant processes at biophysically and socially relevant scales in time and space. Naturally, one cannot conduct an analysis of a research question at finer spatial or temporal scales than the available data used to parameterize and verify the model. Accordingly, WaterSim 4.0 runs on an annual time-step, but monthly flux estimates of water supply and demand are generated by filtering the annual estimates through fitted models or by using Euler's approximation Method (described below). The annual time-step configuration was chosen because it best matches the time-step of the available data used to drive the model; riverine runoff (contemporary and Paleolithic estimates), groundwater designations, population and population growth rates, and the provider-level estimates of water use (liters per capita per day), for example, are only available at the annual time scale. Simulations are interrupted annually by the interface enabling run-time changes to policy levers or input specifications.

Phoenix has two principal sources of surface water, the Colorado and the Salt-Verde Rivers. Basin State Policies and the "Law of the River"—a series of legal rulings beginning in 1922—determine the amount of Colorado River water that Arizona receives. Conversely, runoff (and thus release; the water released from the storage reservoirs) from the Salt-Verde Rivers is largely influenced by inter-annual variation in climate. Both riverine systems have storage reservoirs designed to ensure an adequate supply of water during drought and to aid in flood control and hydropower generation. There are four large reservoirs located in the lower basin of the Colorado River and two, when full, can store slightly more than six and one-half years of annual CAP entitlements (USDOI, 2000). The Salt-Verde river system, when full, can store about four years of annual maximum designations (https://www.srpnet.com/Default.aspx).

2.1. Colorado River

The Colorado River Compact of 1922 apportioned 18.5 billion m^3 (15 million acre-feet [ac-ft]) to be distributed annually among seven states that are located in either the Upper or the Lower Basin of the Colorado River demarcated at Lees Ferry, Arizona. The upper Basin states include Wyoming, Colorado, New Mexico, and Utah while lower Basin states include Arizona, California, and Nevada. The Upper and Lower Basins are each "entitled" to receive 9.25 billion m^3 (7.5 million ac-ft y^{-1}) for annual consumptive use. Lower Basin allocations were established by the Boulder Canyon Project Act (BCPA) of 1928; Arizona was allotted 3.45 million m^3 y^{-1} (2.8 million ac-ft y^{-1}) under normal flow operations of the river. However, Arizona has junior rights to Colorado River water. Current law outlines three stages of shortage sharing, if a shortage was to occur, that depend on the elevation of Lake Mead (Table 1). To date, none of the seven states has experienced water shortages on the Colorado River (USDOI, 2000). However, since 2000, water storage in the Lower Colorado Basin has decreased significantly (USDOI, 2000; http://www.usbr.gov/lc/riverops.html) and, in conjunction

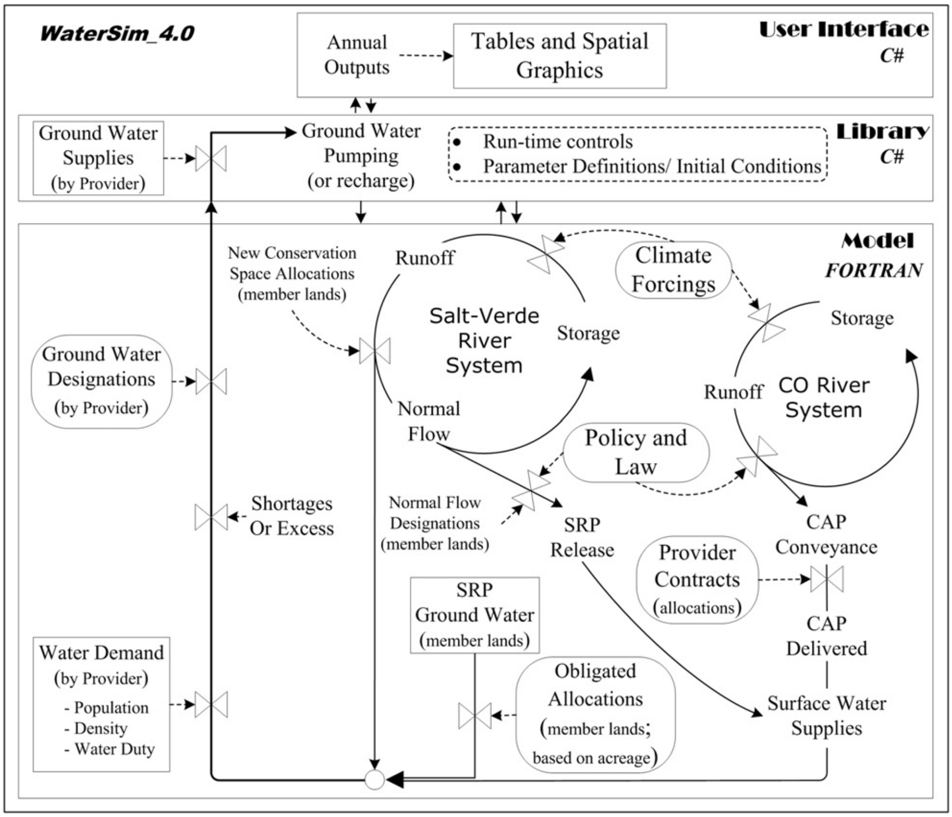

Fig. 2. A diagram of the provider-based water policy and planning simulation model WaterSim 4.0.

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Table 1
Lake Mead elevations, total lower basin shortages at each elevation, and Central Arizona Project (CAP) shortages for Arizona as a consequence of shortage sharing of Colorado River water if benchmark elevations are reached.

Elevation of Lake Mead (m)	Total CAP Shortage ($m^3\ y^{-1}$)	Arizona CAP Shortage ($m^3\ y^{-1}$)
328 (1075 ft)[a]	410,749,000 (333,000 ac-ft y^{-1})	394,714,000 (320,000 ac-ft y^{-1})
320 (1050 ft)	514,362,000 (417,000 ac-ft y^{-1})	493,393,000 (400,000 ac-ft y^{-1})
312 (1025 ft)	616,741,000 (500,000 ac-ft y^{-1})	592,071,000 (480,000 ac-ft y^{-1})

[a] USDOI, 2007.

with the projected change in climate (IPCC, 2007), water shortages on the Colorado River may soon occur.

2.1.1. Colorado runoff estimates

WaterSim uses historical estimates of riverine runoff as a proxy for future runoff availability. We recognize the climate science debate regarding this approach (i.e., that stationarity may no longer be a viable paradigm (Milly et al., 2008)). However, it is our belief that inherent uncertainties in social/political systems—particularly in response to climate change issues—and population growth (and thus water demand) would overshadow the uncertainties on model outcomes caused by unknown variability in the climate system. Moreover, by using multiple trace periods (segments of the historical record for runoff) in a simulation sequence we can incorporate some inherent variability in runoff caused by natural variation in river flows. Notwithstanding, our modeling framework supports future modifications for when new approaches become available. At present we believe that historical estimates of runoff remain viable. For these analyses we used Colorado River runoff estimates provided by the Bureau of Reclamation (http://www.usbr.gov/). Paleolithic estimates of runoff for the Colorado River, available as a user defined option, came from tree growth increment studies (http://treeflow.info/resources.html).

2.1.2. Central Arizona Project allocations

At the time the Boulder Canyon Project Act (BCPA) was enacted, average flow of the Colorado River was quite high. For the period 1906 to 1928 average flow was about 21.7 billion $m^3\ y^{-1}$ (about 17.6 million ac-ft y^{-1}) (http://treeflow.info/index.html). The basin saw several years of diminished flow immediately following the enactment of the BCPA by 1931 the flow on the Colorado River had dropped below 12 billion $m^3\ y^{-1}$ (10 million ac-ft y^{-1}). This led to a series of laws now known as “The Law of the River” which established water rights during times of drought. These shortage sharing agreements started in 1944 with the Mexican Water Treaty followed by the 1964 Arizona v. California Decree, the Colorado River Basin Project Act of 1968, and the Arizona Colorado River Shortage Sharing agreement in 1972 between the Secretary of the Interior and the Central Arizona Water Conservation District. These rulings resulted in agreements that set the annual release of water from Lake Powell and Lake Mead as determined by the storage levels in each reservoir (Table 1).

A large portion of the Arizona share of Colorado River water is used on-river. This on-river use amounts to 1.48 billion $m^3\ y^{-1}$ (1.2 million ac-ft annually). Accordingly, Central Arizona Project (CAP) water makes up the difference of ca. 1.85 billion $m^3\ yr^{-1}$ (ca. 1.5 million ac-ft yr^{-1}) (CAP, 2006). However, if shortage sharing of the Colorado River water were to occur, on-river use absorbs 10% of the shortage while CAP absorbs the difference. Moreover, on-river use has a higher priority of appropriation to the Arizona share of Colorado River water than CAP. In the model we thus estimate on-river use as:

$$\begin{aligned} AZ_{\mathrm{On-River}} &= \min\Big(AZ_{\mathrm{SHARE}}, 1.48\times10^{9}\mathrm{m}^{3}a^{-1} \\ &\quad -(0.1\times AZ_{\mathrm{SHORTAGE}})\Big) \end{aligned} \tag{1}$$

Where: AZ_{SHARE} is 3.45 billion $m^3\ y^{-1}$ (2.8 million ac-ft y^{-1}) or less, if a shortage were to occur, and AZ_{SHORTAGE} varies depending on the elevation of Lake Mead (Table 1).

The CAP water deliveries along the aqueduct into Arizona are estimated using:

$$\mathrm{CAP}_{\mathrm{AZ}} = \max(\mathrm{AZ}_{\mathrm{SHARE}} - \mathrm{AZ}_{\mathrm{On-River}}, 0)\times(1-\alpha) \tag{2}$$

Where: AZ_{SHARE} and $AZ_{\mathrm{On-River}}$ were previously discussed, and α represents an estimate of the proportion lost to evaporation annually between Lake Mead and transport along the CAP canal (6%). In addition to the Colorado River shortage sharing rules there are agreements between the federal government and ten American Indian Tribes (established in 1983 by the U.S. Secretary of the Interior). These agreements established rules for the division of CAP water based on annual CAP deliveries. Twenty-two of the 33 water providers examined have CAP water entitlements (Table 2). CAP water allocation among recipients is determined by five priority levels (CAP 1 to CAP 5) as follows.

The model partitions CAP water in ascending order of priority. Priority one (CAP 1) includes Salt River Exchange Cities (25.78 million $m^3\ y^{-1}$; 20,900 ac-ft y^{-1}) and the Ak-Chin Indian community (58.59 million $m^3\ y^{-1}$; 47,500 ac-ft y^{-1}). They receive their entitlement if total CAP deliveries meet or exceed 84.37 million

Table 2
Water providers in the Phoenix Metropolitan Area that have designated Central Arizona Project (CAP) water and their entitlement under normal flow operations of the Colorado River.

Water Provider	Abbreviation	CAP annual entitlement[a]	
		$m^3\ ha^{-1}$	ac-ft y^{-1}
Adaman Mutual	ad	0	0
Arizona Water Company - White Tanks	wt	2,950,464	968
Arizona-American - Paradise Valley	pv	9,848,088	3231
Arizona-American - Sun City	su	12,768,072	4189
Arizona-American - Sun City West	sw	7,229,856	2372
Avondale	av	16,507,968	5416
Berneil	be	0	0
Buckeye	bu	76,200	25
Carefree	cf	3,962,400	1300
Cave Creek	cc	7,943,088	2606
Chandler	ch	26,377,392	8654
Chaparral City	cp	27,154,632	8909
City of Surprise	sp	31,238,952	10,249
Clearwater Utilities	cu	0	0
Desert Hills	dh	0	0
El Mirage	em	1,548,384	508
Gilbert	gi	22,052,280	7235
Glendale	gl	52,535,329	17,236
Goodyear	go	32,741,616	10,742
Litchfield Park	lp	0	0
Mesa	me	132,597,146	43,503
Peoria	pe	76,919,329	25,236
Phoenix	ph	372,221,765	122,120
Queen Creek	qk	1,060,704	348
Rigby	rg	0	0
Rio Verde	rv	2,474,976	812
Rose Valley	ry	0	0
Scottsdale	sc	160,964,882	52,810
Sunrise	sr	0	0
Tempe	te	13,152,120	4315
Tolleson	to	0	0
Valley Utilities	vu	0	0
West End	we	0	0

[a] ADWR (2009).

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$m^3\ y^{-1}$ (68,400 ac-ft y^{-1}). CAP 2 water includes deliveries above 84.37 million $m^3\ y^{-1}$ (68,400 ac-ft) but below 1.296 billion $m^3\ y^{-1}$ (1.05 million ac-ft y^{-1}). Municipal and industrial users (M&I) and "other" Indian use are considered CAP 2 priority. If annual CAP deliveries are greater than 84.37 million m^3 (68,400 ac-ft) but less than 1.05 billion m^3 (853,079 ac-ft), CAP 2 Indian use receives 36.37518% of the available CAP supply; the remainder is available for M&I. If, however, CAP supplies are greater than 1.05 billion $m^3\ y^{-1}$ (0.85 million ac-ft y^{-1}) an algorithm determines the division of water between M&I and Indian, or:

$$I = 0.115 \times 10^9 \mathrm{m}^3 + (0.2543800 \times \mathrm{CAP\ \ deliveries}) \tag{3}$$

Where: I is the CAP Indian Priority 2 allocation; CAP deliveries in excess of 1.05 billion $m^3\ y^{-1}$ (0.853 million ac-ft y^{-1}), in this equation, are in $m^3\ y^{-1}$. M&I water for CAP 2 priority is therefore the difference between CAP deliveries and I. CAP water conveyance in excess of 1.3 billion $m^3\ y^{-1}$ (1.05 million ac-ft y^{-1}) but less than 1.7 billion $m^3\ y^{-1}$ (1.415 million ac-ft y^{-1}) is considered CAP 3 water. CAP Indian Priority 3 represents 59.254506% (rounded, for brevity) of this water with M&I receiving the remaining proportion. CAP water conveyance that exceeds 1.745 billion $m^3\ y^{-1}$ (1.415 million ac-ft y^{-1}) but is less than 2.1 billion $m^3\ y^{-1}$ (1.7 million ac-ft y^{-1}) would be considered CAP 4 water (excess agricultural water). Finally, CAP deliveries would have to exceed 2.1 billion $m^3\ y^{-1}$ (1.715 million ac-ft y^{-1}) to be considered CAP 5 priority (water banking) (http://www.namwua.org/Projects/3%2520-Appendix%2520B.pdf).

2.2. Salt-Verde Rivers

Several changes were made to the Salt-Verde River module. First, we added dead-pool storage volumes for the six reservoirs that make up the Salt-Verde River system to regulate pools and overflow more accurately. We also added new initial volume estimates to enable multiple simulations start dates. Second, overflow was re-defined for WaterSim 4.0; overflow depends on the current storage, the storage in relation to either the dead-pool or to maximum storage, and the net sum of the fluxes entering or exiting storage. Third, we added a method to calculate water distributions to New Conservation Space (NCS) members. Namely, in 1995 the height of the dam at Lake Roosevelt was raised from 85.3 m (280 feet) to 108.8 m (357 feet), increasing the storage capacity of the reservoir by 336 million m^3 (272,500 ac-ft). Six water providers have additional rights to (proportional use of) the water volume in storage that exceeds the pre 1995 storage level of 1.7 billion m^3 (1.38 million ac-ft). They include Chandler (10%), Glendale (10%), Mesa (15%), Phoenix (50%), Scottsdale (10%), and Tempe (5%).

2.2.1. Salt-Verde runoff estimates

We modified the approach to estimate annual release from the Salt-Verde River storage systems. The original model estimated release using a series of equations based on current storage, expected storage, and an estimate of annual river flow. WaterSim 4.0 estimates annual release as the combined estimate of individual water provider annual designations as described below. Again, we use contemporary estimates of runoff as a proxy for current and future surface water availability. For these analyses we used runoff estimates provided by the Bureau of Reclamation (http://waterdata.usgs.gov/). Similar to the Colorado River module, paleolithic estimates of runoff for the Salt-Verde River, available as a user defined option, came from tree growth increment studies (http://treeflow.info/resources.html).

2.2.2. Salt-Verde provider allocations

The Salt River Project (SRP) —the agency that manages the Salt-Verde River water distributions—delivers surface and groundwater to its customers. Recipients of SRP water are characterized as either Class "A", "B", "C", or NCS (previously discussed) members depending on when their land was first used for continuous cultivation. Entitlements to Salt-Verde River water are defined in a legal ruling known as the Kent Decree which established that "Member and Non-Member Class A" land is entitled to "normal flow" water (river water that would have been available for irrigation in the Valley in the absence of upstream reservoirs)(Salt River Valley Water Users Association, 1910). The building of Roosevelt Dam was the impetus for a lawsuit that was settled by this decree. The Kent Decree establishes the amount and priority of use for daily flows from the Salt-Verde River. These are based on the notion that "the first in time of appropriation is the first in right to appropriate" with ownership and "reasonably continuous beneficial use" as the two criteria needed to establish rights (Salt River Valley Water Users Association, 1910). Entitlements to Salt-Verde River water are still calculated using the "Trott Table", a tabular system developed in 1910 by Frank P. Trott who was the Water Commissioner at the time.

The Trott Table was developed to estimate daily water rights for each member of the "Association" based on the weekly flow from the Salt and Verde Rivers. Because WaterSim 4.0 runs on an annual time-step an annual Trott Table equivalent was needed in order to designate water rights at the provider-level. Ten providers in metropolitan Phoenix have Class A rights to Salt-Verde River water. They are, in descending order of precedence at river maximum allocation: Phoenix, Mesa, Tempe, Glendale, Chandler, Avondale, Gilbert, Peoria, Tolleson, and Scottsdale.

Emulating the Kent Decree (and thus the Trott Table) for Class A member lands on an annual basis required several steps. First, we created digital files of the data from table 10 of the Kent Decree. Two sets of files were created. One set contained the acreage, by year, for each water provider and the associated flow from the Salt-Verde River from 1869 through 1909, inclusive, for that acreage. A second file contained the total irrigated acreage over the same period and the associated Miner's inches of water designated to that acreage. From the daily data, Miner's inches of water (flow rate of 11.2 gallons per minute) were converted to annual estimates with standard units (ac-ft y^{-1}). Proportional distribution of the water by acreage, then, provided an estimate of the total amount of water that each provider was entitled to by year. These data were then accumulated over the period 1869–1909, inclusive, to obtain the total, accumulated water rights for each provider for each flow level.

Finally, we created four digital look-up tables ranked in order of river flow. Specifically, digital table one contains the 42 flow levels (six decimal places) that correspond to the flow records in table 10 of the Kent Decree (i.e., "threshold" flow), table two contains the accumulated, annual water rights for each provider for each of the 42 levels, and table three has the accumulated proportional rights to water at the next flow level for each provider. The fourth table is discussed below.

Digital table one contains one column that corresponds to 42 ascending estimates of normal flow ($TF_{\mathrm{I}=1,42}$; let I denote the threshold level) in increments as discussed above. Digital table two consists of ten columns (one for each provider) and 42 rows that correspond to the threshold flows designated in table one. The data in table two represent the individual, cumulative, designations for Class A members for each threshold ($TR_{\mathrm{I,J}=1,10}$; let J denote the members). Because our estimate of the Salt-Verde River flow (F) (continuous variable, sixteen significant digits) cannot match any TF_{I} (continuous variable, six significant digits), annual designations for each provider must include an estimate of the water rights for the difference between F and the TF_{I}. Subsequently, digital table three is used to calculate the water rights of each provider to this difference, or $PR_{\mathrm{I,J}=1,10}$. And, because the entirety of the estimated annual flow is not allocated (the sum total of annual designations is less than the flow record itself), the fourth digital table contains the proportional amount of flow designated at each threshold level. These data were extracted from table 10 of the Kent decree.

The calculation of the amount of the flow difference to be designated requires several steps. First, we calculate the difference between F and the closest threshold flow of lesser value, (TF_I). We then calculate the ratio of this value and the total difference between thresholds, or:

$$FP_{I,J} = \frac{F - TF_I}{TF_{I+1} - TF_I} \tag{4}$$

Where $FP_{\mathrm{I,J}}$ is the proportional difference on F between threshold levels. The other variables are as before.

Finally, we multiple $FP_{\mathrm{I,J}}$ by the difference in thresholds ($TF_{\mathrm{I}+1} - TF_\mathrm{I}$), by the flow-specific multiplier of normal flow use (FU_I), and by the provider-level estimate of the water rights to the next flow level from table three (i.e., $PR_{I,J}$), or

$$AR_{I,J} = FU_I \times PR_{I,J} \times FP_{I,J} \times (TF_{I+1} - TF_I) \tag{5}$$

Where $AR_{I,J}$ = additional water rights to the normal flow volume above the threshold level.

Annual water allocation for each provider, then, is calculated by matching F to the closest TF_I of lesser value in the digital table to extract $TR_{\mathrm{I,J}}$, and then adding the rights to water above that threshold but below the flow, or:

$$NFD_J = TR_{I,J} + AR_{I,J} \tag{6}$$

Where: NFD_J = normal flow designations for each provider annually. If F exceeds the maximum threshold in the table, then the maximum $TR_{I,J}$ in the table is selected and no added rights are applicable. The maximum annual designation for class A member lands is 737,670,255 $\mathrm{m}^3\ \mathrm{y}^{-1}$ (598,039 ac-ft y^{-1}) (Salt River Valley Water Users Association, 1910). Estimates of class A annual water designations (over the continuum of flow rate of the Salt-Verde River) for each of the 10 water providers in the SRP service area were extracted from the look-up tables, and graphed (as discussed below). A water demand-driven release function was added to the SRP release estimates. This formulation enables NCS water to be used if: 1) the reservoir levels meet NCS requirements, and 2) demand exceeds the Class A allocations for the year.

For illustrative purposes we extracted the annual estimates of Class A designations from the digital look-up tables to demonstrate the relationship between annual runoff and water allocation for SRP member lands (Fig. 3). These annual, normal flow designations for Class A members demonstrate the priority of appropriation among the 10 water providers that have rights to Salt-Verde River water. Precedence in access to Salt-Verde River water necessarily results in disparate rights to that water; differences in river flow determine these water provider rights. For example, Phoenix and Gilbert have increased rights as base flow increases while Tempe and Mesa exhibit only marginal changes in their water rights as river flow increase (Fig. 3). These cumulative designations are asymptotic above normal flow rates of 1.3 billion $\mathrm{m}^3\ \mathrm{y}^{-1}$ (1.06 million ac-ft y^{-1}). It is important to note that actual, real-world designations operate differently.

While Class A Members receive normal flow water designations, Class B and C members receive water based on acreage in member lands (FD_J). Their realized allocations, however, depend on the total amount of water storage on the Salt-Verde River system. If total storage in the six reservoirs exceeds $0.74 \times 10^9\ \mathrm{m}^3$ (600,000 ac-ft) then Class B and C members receive 9140 $\mathrm{m}^3\ \mathrm{ha}^{-1}$ (three ac-ft acre^{-1}). If reservoir storage drops below $0.74 \times 10^9\ \mathrm{m}^3$ (600,000 ac-ft), then allocations drop to 6096 $\mathrm{m}^3\ \mathrm{ha}^{-1}$ (two ac-ft acre^{-1}) (Phillips et al., 2008). Maximum designations for Class A, B, C, and NCS members are provided in Table 3.

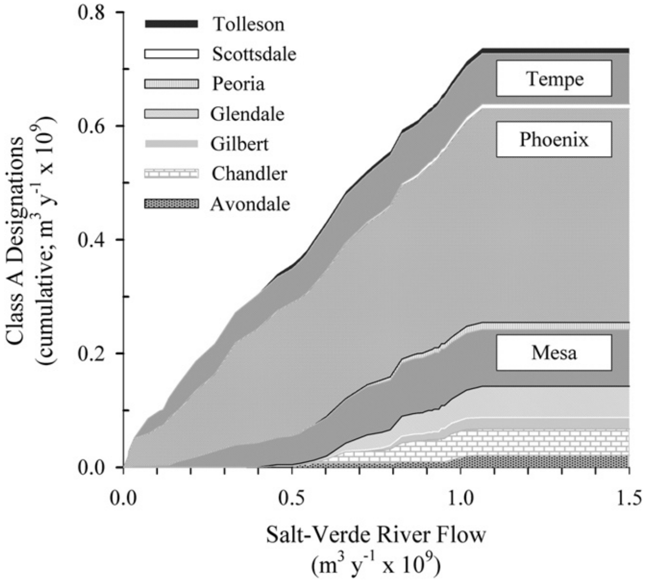

Fig. 3. Annual Class A water allocated to the 10 members that receive Salt River Project (SRP) water for different flow rates of the Salt-Verde River. Class A designations are based on "normal flow" of the river (i.e., flow that would have occurred in the absence of impoundment structures).

2.3. Groundwater

WaterSim 4.0 uses a water "bucket" approach—one for each water provider—for groundwater accounting. Under this scheme, if water demand (for water providers having surface water rights) exceeds surface water supplies then we assume that the difference comes from groundwater pumping. Pumped groundwater water reduces the amount of water in their individual "buckets." In these analyses we also assume that surface water deliveries are determined by water demand and, therefore, no groundwater recharge occurs.

We use a rigorous initial estimate of groundwater for each water provider at the start of a simulation. Specifically, we used the ADWR Regional Groundwater Flow Model of the Salt River Valley (SRV) to estimate initial groundwater for each of the water providers examined in this study. This 3-D finite-difference groundwater model uses a Valley-wide grid system and geologic information for each cell to simulate groundwater underflow, inflow, recharge, and head elevations, among other parameters, of the individual three-dimensional grid columns (Corkhill et al., 1993). The model is based on MODFLOW, a well-know and widely-used groundwater model developed by the U.S. Geological Survey in 1984. The current, revised SRV groundwater model has been calibrated for the period 1983 to 2006 and contains 9420 cells, with each cell 805 m (one-half mile) on a side (ADWR, 2009). As mentioned earlier, the SRV aquifer is comprised of three distinct alluvial layers that vary in texture and depth. The bottom of the lower alluvial layer exceeds 305 m (1000 feet) below ground level in several parts of the SRV. However, initial estimates of groundwater are based on available water to a depth of 305 m from the surface because of the allowable groundwater pumping limits outlined by the 1980 GMA. We intersected the SRV grid with our GIS layers to obtain the provider-defined cells. An estimate of

Table 3
Class A, B, C, and NCS member annual designations (m^3 per year; acre-feet y^{-1} parenthetically) for ten Salt River Project (SRP) members. Values represent maximum designations.

Water Provider	Class A maximum[a]	Class B and C maximum[a]	NCS maximum[b]	Total SRP Designations (maximum available)
Avondale	21,299,765 (17,268)	13,636,142 (11,055)	0	34,935,907 (28,323)
Chandler	46,414,689 (37,629)	73,694,373 (59,745)	33,612,381 (27,250)	153,721,443 (124,624)
Gilbert	19,720,908 (15,988)	38,195,999 (30,966)	0	57,916,907 (46,954)
Glendale	54,862,806 (44,478)	61,342,286 (49,731)	33,612,381 (27,250)	149,817,473 (121,459)
Mesa	100,068,683 (81,127)	47,180,681 (38,250)	50,418,571 (40,875)	197,667,934 (160,252)
Peoria	12,447,065 (10,091)	29,281,626 (23,739)	0	41,728,691 (33,830)
Phoenix	375,503,947 (304,426)	41,832,304 (33,914)	168,061,903 (136,250)	585,398,154 (474,590)
Scottsdale	8,552,963 (6934)	22,228,577 (18,021)	33,612,381 (27,250)	64,393,920 (52,205)
Tempe	88,200,120 (71,505)	39,513,358 (32,034)	16,806,190 (13,625)	144,519,668 (117,164)
Tolleson	10,599,310 (8593)	3,656,040 (2964)	0	14,255,350 (11,557)
Total	737,670,255 (598,039)	493,909,571 (400,419)	336,123,806 (272,500)	1,444,355,446 (1,170,958)

[a] Salt River Valley Water Users Association (1910).
[b] Pam Nagel, ADWR, personal communication (June 15th 2010).

water volume for each cell in the grid was obtained by multiplying the cell area by the saturated thickness and the specific yield of that cell using the 2006 head estimates from the SRV model (ADWR, 2009). Summing the cells in each column provided an estimate of the total water volume in each 3-D column, by provider, that was available on 1 January 2006.

We recognize the limitations of this simplified approach. For those water providers that have only groundwater rights, the amount pumped depends on their demand. In addition, all water providers are only allowed to pump an amount up to their individual groundwater designation (or permitted assurance). Although at this time we do not have at this time estimates of the later flow of groundwater nor of the natural or artificial recharge taking place, we use a water balance approach to ensure that they do not pump more water than what the bucket model suggests that they have.

2.4. *Water demand*

We have two user defined approaches to estimate water demand. One approach uses projections of land-use and water duty (an amount of water typically associated with a specified land-use category). From the Maricopa Association of Governments (MAG) (http://www.azmag.gov/) we obtained estimates of build-out land-use for Phoenix and estimates of water duty for each water provider. We estimated water demand from these data for 2000, 2010, 2020, and 2030 by scaling build-out land-use densities by the population estimate for each decade. We used PROC EXPAND, the time series interpolation procedure in SAS® software (SAS, 2008), on the digitized decadal data for each water provider to estimate water demand for the intermediate years (i.e., 2001 through 2009, 2011 through 2019, etc.).

The second approach to estimate water demand uses empirical estimates of the liters per capita per day (LPCD) reported to the ADWR (as gallons per capita per day: GPCD) by each water provider and annual population estimates (discussed below). First, we digitized the annual estimates of LPCD for each water provider for the years 2000 through 2008. We used SAS to estimate the five-year running average of the annual estimates of LPCD to give five individual LPCD values for each water provider that corresponded to the period 2002 through 2008. For simplicity we assume that the 2002 estimate of LPCD was representative of 2000 and 2001 for each water provider. Second, we incorporated Brown's simple exponential smoothing (SES) algorithm, using a fourth-order formulation (http://www.duke.edu/~rnau/411avg.htm), to estimate future LPCD as:

$$\mathrm{LPCD} = \alpha \times \mathrm{LPCD}_{t,T-1} + (1-\alpha) \times \mathrm{LPCD}_{i,T-2} + \left(1-\alpha\right)^2 \times \mathrm{LPCD}_{i,T-3} + \left(1-\alpha\right)^3 \times \mathrm{LPCD}_{i,T-4} \qquad (7)$$

Where α is the reduction (scaling) parameter, i is the water provider in question, and T is time (scaled to accommodate the 2000 through 2008 estimates of LPCD).

The SES algorithm enables the user to estimate future LPCD; the SES equation requires an expected change in LPCD, relative to the 2008 estimate, by the end of the simulation period. The SES model was not tested for expected increases in water use; the 2000 through 2008 estimates demonstrated, except in two cases, reductions in LPCD between 2000 and 2008. The alpha parameter found in the equation above reflects the reduction in LPCD expected. Alpha is estimated at run-time using a combined type four exponential and power function (Sit and Poulin-Costello, 1994). We used SAS and heuristic modeling approaches to develop this equation, expressed here as:

$$\alpha = \sigma \times \rho^x \times x^{-\gamma} \qquad (8)$$

Where σ, ρ, and γ are parameter estimates, and x is the proportional reduction in LPCD expected by the end of the simulation period. These parameters, along with the lower and upper 95% confidence limits are, as follows: $\sigma = 80.8{-}79.56 < \sigma < 82.06$, $\rho = 0.6830 {-}0.6625 < \rho < 0.7035$, and $\gamma = 0.0113{-}0.00068 < \gamma < 0.0134$. For these analyses we assume a 5% reduction in LPCD by 2030. We then compared the two estimates of water demand for the period 2005 through 2030.

Ambient air temperature influences riverine runoff (Hartmann, 2009) and urban water demand (Harlan et al., 2008). The provider-level model has a framework and algorithm suite to incorporate these important driving variables on water availability and use, but they were not implemented for these analyses.

2.5. *Population*

We used past, present, and projected population estimates for each water provider in WaterSim 4.0. The most recent data from Information Services Division (2007) covers the period 2005 to 2030 (http://www.mag.maricopa.gov/pdf/cms.resource/MAG_Projections-2007-MPA-and-RAZ-April-2007.pdf). First, we used PROC EXPAND on the digitized data for each water provider for 2005, 2010, 2020, and 2030, to estimate population for the intermediate years (i.e., 2006 through 2009, 2011 through 2019, etc.). MAG population estimates for West End, a small water provider

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that serves Wittmann Arizona, did not change for the period 2005 to 2010. For this provider we kept population constant, overriding the fit that the SAS software had performed between those dates. Second, we compared the modeled population estimate for 2009 with currently available data from the Arizona Commerce Authority. We used the proportional difference between the published 2009 estimates with that projected to adjust (in most cases, reduce) the population curves for each water provider. Third, we used Time Series Forecasting, a SAS engine available through the SAS INSIGHT software, to project the population for each water provider for the period 2031 through 2035. No fit statistics of these analyses were provided for these analyses.

2.6. Monthly estimates

We obtained five-years (2000 through 2004) of monthly water use for the city of Phoenix for residential users, and for commercial and industrial users combined. We used these data to fit a modified type five exponential equation (Sit and Poulin-Costello, 1994) to derive the regression parameter estimates for a generalized algorithm to produce monthly estimates of water demand from annual data. The equation, for both water user categories, was:

$$\text{Demand}_{\text{Monthly}} = a + \alpha \times \beta^{(x-c)^2} \tag{9}$$

Where a is an intercept parameter, α is a scaling parameter (controls the height of the response), β is the slope parameter, x is the numeric representation of month, and c is the location parameter (along the abscissa) for peak water demand (month). Heuristic principals were used to define the run-time boundary conditions for each water provider; the January estimate is calculated as 73% of the monthly average; the a and α parameter estimates are calculated as 65% and 143% of the monthly average, respectively; β is initialized as 0.81. Starting conditions for a, α, β, and c parameter estimates were obtained from the initial fit to the empirical data ($N = 60$; $r^2 = 0.85$; $p < 0.001$).

The algorithm runs in an iterative loop, summing the monthly estimates after each iteration (for each water provider for each year) to check whether their sum equals the annual estimate (closure). If there is no closure, β is incremented (or decremented, depending on the sign of the difference between the estimate and the threshold value) by 9 hundredths and the iterations continue. The loop is terminated once the final estimate is $\pm 1233.5\ \text{m}^3$ (one acre-foot) of the annual estimate. Two separate parameterizations are used, one for residential water demand and one for commercial and industrial water demand combined. A similar equation and approach, without the heuristic boundary conditions, was used to estimate monthly water supply from annual estimates of surface water supply.

Monthly deliveries of Colorado River water along the CAP aqueduct are essentially constant. Accordingly, we used Euler's first order differential approximation (http://www.physicsforums.com) to estimate the monthly supply of CAP water (from annual data) to those water providers that hold CAP designations (Table 2).

3. Simulations conducted

3.1. Model validation

Daily lake elevations for Lake Mead and Lake Powell and daily release data for Glen Canyon Dam were downloaded from the Bureau of Reclamation web site (http://www.usbr.gov/uc/crsp/GetSiteInfo). We used PROC UNIVARIATE procedures in SAS® software (SAS, 2008) to sum the release data by calendar year. We then used modeled estimates of the relationship between lake elevation and storage volume from the Bureau of Reclamation CRSS model, extracted from http://www.usbr.gov/lc/region/programs/strategies/FEIS/AppA.pdf, to estimate storage in Lake Powell and in Lake Mead for 1 January of 2000 through 2010. Storage data for the Salt and Verde River reservoirs were obtained from the Salt River Project (Mark Hubble, personal communication. 18 February). These data were used as a comparison to the simulated estimates of storage volumes from the WaterSim model for the same period for each respective reservoir system.

3.2. Sensitivity to alteration in surface water supply

We examined the sensitivity in the relationship between imposed variation in the annual runoff estimates for the Colorado River and the Salt-Verde Rivers, and groundwater reliance (GWR; the portion of a water provider's portfolio dependent upon groundwater). Because water providers differ in their water portfolio we can use GWR as a metric to examine provider-level response to altered surface water availability. Based on previously discussed studies, we adjusted our historical estimates by 80%–110%, in 5% intervals, to examine water provider differences in GWR. Similar multipliers were used for both the Colorado and the Salt-Verde River runoff estimates to simplify the analysis and interpretation of the results. Because runoff can vary considerably among years, and using one 25-year time sequence could mask inter-annual variability in river flow, we adjusted the start year of the historical data record for the 25-year simulation period (i.e., the "index year") using seven different index years: for the Salt-Verde Rivers we used 1957 through 1963 while for the Colorado River we used 1921 through 1927. These years were chosen because the median flow for each of these individual trace periods approximates the long-term median flow (as independently analyzed). Combined, the 25-year simulation period in conjunction with the runoff multipliers, index years, and providers examined resulted in a $25 \times 7 \times 7 \times 33$ matrix, or 40,425 annual simulations. Simulations for these analyses started in 2006 and ran through 2034 but only the last 25-years were retained for outputs.

3.3. Provider groundwater use

We used the historical record for surface water runoff to estimate the cumulative groundwater drawdown over the 25-year simulation period for each of the 33 water providers examined in this paper. While other metrics may also be useful, for these analyses we used the cumulative drawdown of groundwater to: 1) represent the potential sensitivity of water providers to specific water sources, and 2) demonstrate the disparate water portfolios found in the Phoenix Metropolitan Area. Initial conditions for these simulations are outlined in Table 4.

4. Statistical design

We examined the effect of reductions in surface water supply on GWR for the individual water providers. To do this we used PROC GLM procedures in SAS® and Tukey's Studentized Range Test to look for statistical differences among water providers for GWR estimates using runoff factors (the proportional multiplier on surface runoff estimates) of less than 100% of the historical estimate. We used PROC UNIVARIATE procedures in SAS® to average statistically relevant results for graphical presentation. Unless otherwise indicated, significance was evaluated at the alpha = 0.05 probability level. Error estimates, provided parenthetically, represent two standard errors of the mean (unless otherwise noted).

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Table 4
Initial conditions used in the simulations.

Parameter	Value	Units
Climate Index Year: Colorado River	1921–1927	Year
Climate Index Year: Salt-Verde River	1957–1963	Year
Climate data: Colorado River	Bureau of Reclamation[b]	n.a[a]
Climate data: Salt-Verde Rivers	Bureau of Reclamation[b]	n.a[a]
Colorado Climate Adjustment	100	Percent
Initial Storage in Lake Powell and Lake Mead (2006)	38,780,010,851 (31,439,466)	m^3 (acre-feet)
Initial Storage in the Salt-Verde watershed (2006)	1,786,322,255 (1,448,195)	m^3 (acre-feet)
Population Growth Rate Factor	100	Percent
Residential Density Path	1	Dimensionless
Salt-Verde Climate Adjustment	100	Percent
Shortage Sharing Policy	Proportional Sharing	n.a[a]
Simulation Period	2006–2034	Year
User Drought Percent (Colorado River)[a]	100	Percent
User Drought Percent (Salt-Verde River)[a]	100	Percent
User Drought Start year (Colorado River)[a]	2034	Year
User Drought Start year (Salt-Verde River)[a]	2034	Year
Water Policy	Satisfy Demand	n.a[a]
Water Policy Start Year	2006	Year

[a] Not applicable.
[b] Reference.

5. Results

5.1. Water storage and surface water availability

The annual storage estimates for the six reservoirs on the Salt-Verde River and the two largest reservoirs on the Colorado River for the period 2000 to 2010 demonstrate the correspondence between simulations and empirical observations (Fig. 4). For the Salt-Verde system, simulated estimates of storage were occasionally similar, or nearly so, but often greater than the empirical values, although the temporal patterns were relatively consistent between the two (Fig. 4A). The correspondence was least favorable for the period 2006 to 2010. However, this validation exercise used simulated estimates of release from the Salt-Verde reservoirs based on legal rights and estimates of water demand. For the Colorado River reservoirs, the model performed much better, often falling within ±10% of the actual storage estimate (Fig. 4B and C). Using actual release estimates for Lake Powell for the 2001 to 2010 period resulted in good correspondence between simulated storage and actual (estimated) storage (Fig. 4C). Simulated estimates of annual release from Lake Mead resulted in an overestimate of release for 2003, 2004, and 2005 (Fig. 4B).

For demonstrative purposes we graphed the 25-year trends in annual river runoff for the two riverine systems used in the simulations (Fig. 5). Inter-annual variability in runoff for the Salt-Verde Rivers depicts flows greater than the long-term median for the period 2020 to 2029 that correspond to the 1976 to 1985 historical period in these simulations (Fig. 5A). Intra-annual variation was greater for 2015 to 2030 caused by differences in the flow estimates from the seven different trace periods, the first of which started in 1957. For the Colorado River, runoff was more consistent over the simulation period except for lower than median flows for the period 2012 to 2019 and greater than median flows for the 2030 to 2035 period (Fig. 5B).

5.2. Water portfolio differentiation

By modifying the historical estimates of surface water runoff in 5% increments we were able examine the provider-level sensitivities to the imposed changes in runoff from the two river systems. Groundwater reliance (GWR) provided one metric to examine the response in groundwater use, and thus the water portfolios of individual water providers, to alteration in surface water availability. The 33 water providers separated into four distinct classes, labeled here as groups A to D, based on the results from the General

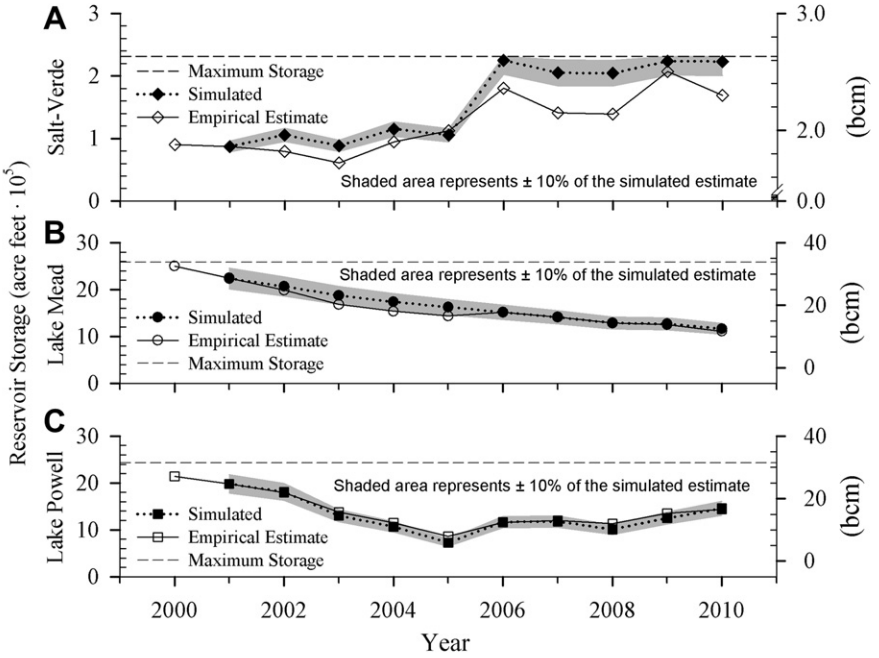

Fig. 4. Reservoir water storage in the Salt-Verde River system (A), and in Lake Mead (B) and Lake Powell (C), both on the Colorado River system, for simulated (filled symbols) and empirical (open symbols) estimates for the year 2000–2010. Maximum storage for the reservoirs, as reference, is denoted in each panel.

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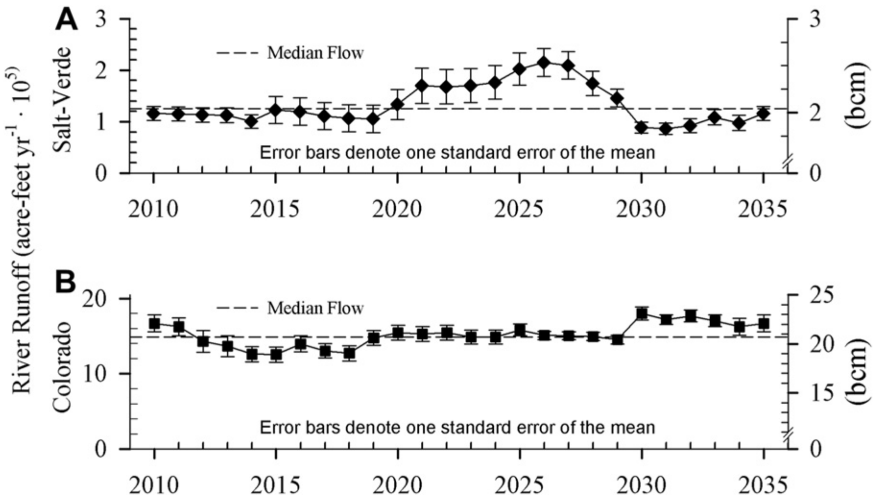

Fig. 5. Annual runoff for the Salt-Verde (A) and the Colorado (B) Rivers for the simulation period. Seven, 25-year, "trace" periods were used in these analyses each with a different start year in the historical record. The error bars, demonstrating one standard error of the annual mean, reflect annual variation in the seven trace periods.

Linear Models procedure using Tukey's Studentized Range Test to determine significance ($N = 857$; $r^2 = 0.93$; RMS error = 0.117028). Specifically, the Tukey's test associated with the GLM Procedure in SAS® outputs alpha characters matched to the class variables based on significance; water providers with similar alpha characters, or those that were not significantly different from one another, were grouped. Group A was, except in one case (and not apparent in the figure; Queen Creek), 100% reliant on groundwater showing no deviation in their portfolio as surface water supplies were increased or decreased (Fig. 6). Group B, nominally about 70% reliant on groundwater under contemporary climate conditions (100% of runoff), increased their use of groundwater as surface water supplies were reduced (Fig. 6). At 80% of the historical estimate of runoff, groundwater accounted for almost 90% of the annual water portfolio for these water providers. A third group, group C, uses groundwater for about 15% of their annual water portfolio under current climate conditions. However, these water providers markedly increased their groundwater dependence to almost 60% of their water portfolio when runoff was decreased by 20% (Fig. 6). This difference amounted to about a 300% increase in groundwater use for these water providers. Finally, group D was relatively unaffected by reductions in surface water supplies (Fig. 6), as they have little groundwater reliance.

We can differentiate the water supply sources for each of these four groups using the 100% runoff estimate of GWR as a baseline reference. As briefly mentioned above, group A exhibited a trace amount of surface water, attributed to the Queen Creek water provider (Fig. 7A). Queen Creek has a small amount of CAP water, relative to their demand, in their water portfolio (see Table 2). Group B relied on groundwater but also on Colorado River Water; CAP water accounted for ~ 32% of this groups water portfolio (Fig. 7B). Conversely, group C, the water providers that exhibited the greatest increase in groundwater use as surface water supplies

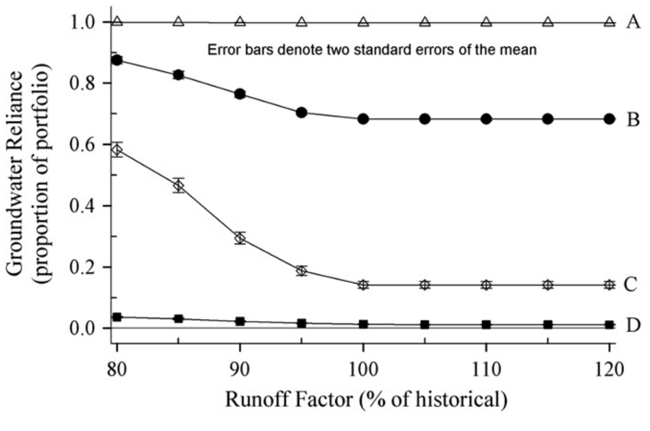

Fig. 6. Groundwater reliance (GWR; that portion of a water providers portfolio attributed to groundwater) for four groups of water providers (A–D) in response to nine runoff scenarios (runoff factor) relative to the historical record for both the Colorado River and the Salt-Verde Rivers. These four groups were delineated as a result of statistical differences found using Tukey's Studentized Range Test of GWR for estimates of less than 100% for the 33 water providers in the Phoenix Metropolitan Area.

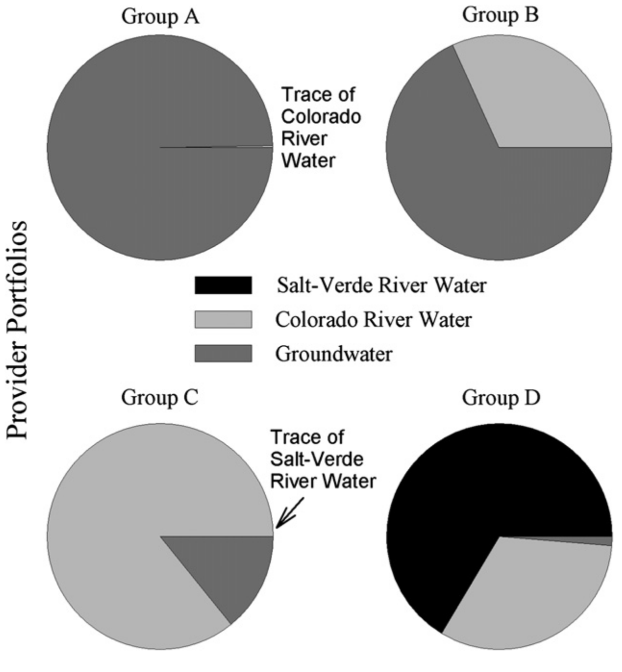

Fig. 7. The relative proportion of Salt-Verde River water, Colorado River water, or groundwater used by the four water provider groups delineated from a test of significance using Tukey's Studentized Range Test and groundwater reliance for estimates of less than 100% for 33 Phoenix water providers.

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decreased, relied on CAP water for 86% of its water portfolio with groundwater fulfilling the remaining portion. Finally, group D relied on Salt-Verde River water for 66% of their average portfolio with CAP water designations accounting, on average, for about 32% (Fig. 7). From these findings we conjecture that water providers that relied more heavily on CAP water were more susceptible (on average) to reductions in surface water supplies when compared to those that also had access to Salt-Verde River water.

5.3. *Water demand and groundwater drawdown*

The two approaches used to estimate water demand were very similar when examined by the four water provider groupings (Fig. 8). Per capita water demand was greatest for group B at nearly 1000 m^3 $year^{-1}$, with no statistical difference between the two approaches observed. This group contained two water providers (of the four present in the group) that reported water use exceeding 3800 LPCD. Groups A, C, and D were substantially lower than group B at more than one-half the estimate (Fig. 8). We observed statistically significant differences between the two water demand approaches for these groups, however in general they were fairly similar (Fig. 8).

The magnitude of groundwater pumping and, thus, the total amount of groundwater extracted over the 25-year period varied considerably across region (Fig. 9). Most of the water providers examined here relied very little upon groundwater for their water needs both now and as projected out 25-years into the future. However, a few were projected to pump greater than 10 million m^3 (8000 acre-feet) of water over the 25-year period. Several water providers may pump up to 35 million m^3 (28,000 acre-feet) of groundwater by 2034 while three may exceeded 125 million m^3 (101,000 acre-feet) by the end of the simulation period (Fig. 9). We observed a spatially-explicit pattern in groundwater use. The "outlying" or urban "fringe" providers had greater cumulative removals than more interior water providers (with the exception of Paradise Valley and, to a limited extent, Berneil) (Fig. 9). Greater groundwater removals were associated with greater dependence on groundwater for their water portfolio (Tables 2 and 3).

6. Discussion

Future (near-term) water scarcity seems inevitable. Barnett and Pierce (2009) expect shortages on the Colorado River to occur about 40% of the time by mid century with no climate change (i.e., no reduction in runoff) simply from current over allocation of the water. Climate change is projected to reduce Colorado River runoff over the next few decades, amounting to 6%–25% of historical flows (e.g., Christensen et al., 2004; Milly et al., 2008; Seager et al., 2007; Christensen and Lettenmaier, 2007). Within the last decade the water level in Lake Mead has dropped precipitously. As recently as late 2010 the elevation of Lake Mead was within 2.13 m (7 feet) of a shortage declaration (http://www.usbr.gov/lc/region/g4000/cy2010/nov10.pdf). In the event that reduced runoff levels on the Colorado River trigger shortage-sharing, reductions in CAP deliveries to Phoenix will occur with Colorado River surface water unable to satisfy present CAP contracts. This real threat of a reduction in Colorado River deliveries, to date not seen, has made relevant the need for water planning and management tools.

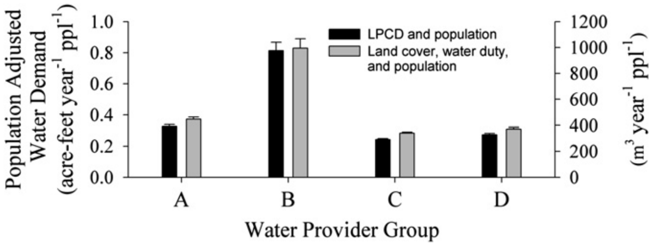

Fig. 8. Population-adjusted water demand (m^3 $year^{-1}$ ppl^{-1}) and four water provider groups that were delineated from a test of significance using Tukey's Studentized Range Test and groundwater reliance for estimates of less than 100% for 33 Phoenix water providers. Water demand was estimated using two approaches: 1) liters per capita per day (LPCD) reported to the Arizona Department of Water Resources and projected population and, 2) estimates of population and land cover change projected for the Salt River Valley, water duty, and density.

Our provider-based water planning and management model provides a structure to explore the relationships between future water supply and water demand in Phoenix, incorporating relevant institutional water policy and law for 33 Phoenix Metropolitan Area water providers. Our framework can be used for scenario development (small number of scenarios with plausible descriptions of system factors) and sensitivity analyses (a large number of simulations are created from gradual variations in one single factor) (Mahmoud et al., 2009) for the anticipatory study of, and planning for, the critical social and environmental drivers that will affect future water security issues. Accordingly, users can begin to examine potential water supply challenges for individual water provider's portfolios (and thus the region as a whole) for various population growth and climate change scenarios. Missing, however, are the policy mechanisms needed to address the water insecurity issues that will undoubtedly arise when surface water shortages occur (Bolin et al., 2010).

6.1. *Groundwater management*

Reductions in surface water supply will affect all Phoenix water providers, although not evenly: Even those who are 100 percent "reliant" on groundwater will be impacted by shortages. Due to the safe yield requirement of the 1980 GMA, water providers that rely on groundwater also rely on replenishment of groundwater in other locales for their groundwater use. Specifically, the ADWR put into place several mechanisms relevant to municipal water use. The Assured Water Supply (AWS) provisions of the GMA promulgated by ADWR requires that sufficient supplies of adequate quality are physically, legally, and continuously available for 100-years (Maguire, 2007) before land may be subdivided. Two types of AWS permits are issued. Of interest here are the Designations of Assured Water Supply (DAWS) that are typically issued to cities which are older settlements established in near proximity to the Salt or Gila Rivers where, because of inherent geology and eons of hydrological processes, they overlie deep geologic groundwater basins (e.g., ADWR, 2006). Water providers that hold DAWS can "bank" excess CAP water when surface water supplies exceed water demand. Although too complex to address here fully, this conjunctive use enables temporary groundwater pumping in excess of a designation provided that recharge credits match short-term overdraft by the end of the water year.

Some communities have already reached build-out (Gober, 2006), forcing new development to the urban periphery. These recently established communities, long removed from any direct surface water rights because of "first in use, first in right" of appropriation (who cannot qualify for a designation), can join, for a fee, the Central Arizona Groundwater Replenishment District (CAGRD). The CAGRD, a subsidiary of the Central Arizona Water Conservation District (the entity that manages CAP), acquires "excess" CAP water to sell (as paper water) to members without access to renewable supplies that otherwise could not demonstrate a 100-year AWS. The CAGRD then recharges the aquifer with this excess water in hydrologically convenient locales, in exchange for groundwater pumping

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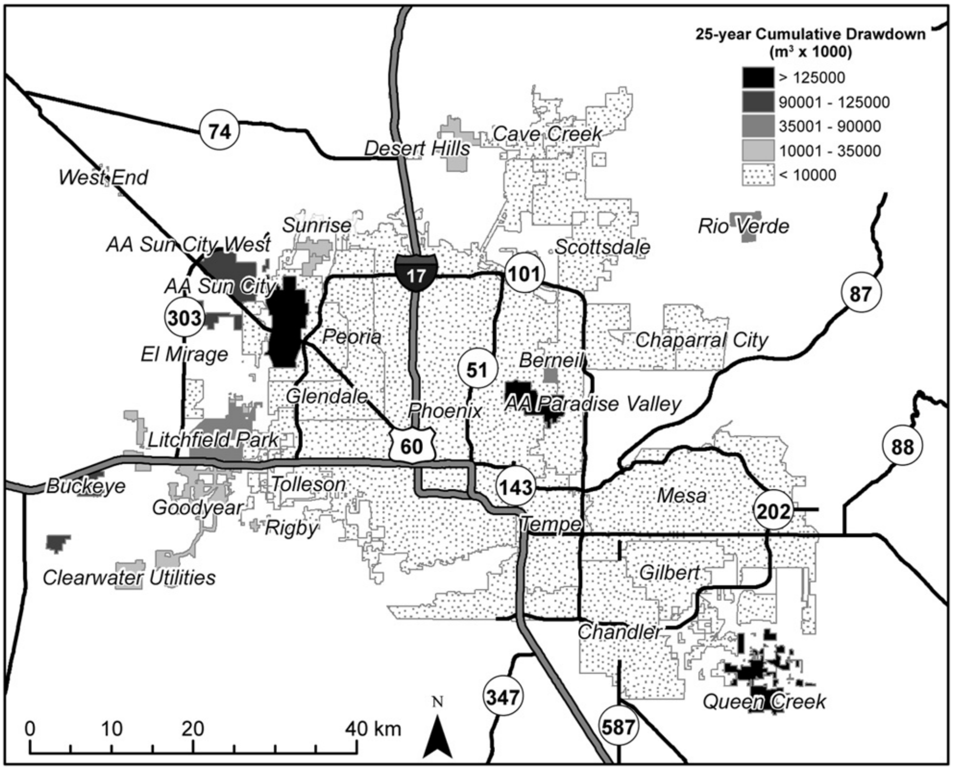

Fig. 9. Groundwater use (m^3 pumped over a 25-year period; 2009 to 2034) for 33 water providers examined in this study for the Salt River Valley model of the Phoenix Metropolitan area.

by its members often far removed from the recharge site. These member communities are typically located at the Valley edge and, because of a shallower depth to bedrock (and, thus, a more narrowly defined aquifer), they have much less (fossil) groundwater reserves to begin with compared to more centrally located communities (ADWR, 2009). Increased development pressures, heavy reliance on groundwater and, generally, shallower aquifers broaden the water supply challenges for these urban "fringe" communities.

6.2. *Portfolio response*

Many communities that lie at the urban periphery, and one located in the Valley interior, are expected to pump more than 10 million m^3 (cumulative groundwater) by the year 2035 (Fig. 9). None of these water providers have rights to Salt-Verde River water which means that they either rely solely or heavily upon groundwater; however, several have rights to Colorado River water. From our sensitivity analyses and subsequent groundwater reliance groupings (group A and B), these water providers are expected to experience the greatest growth in water demand over the next 25-years (Fig. 8) and, moreover, those that have Colorado River water rights (Table 3) are expected to increase their reliance on groundwater if surface water supplies became limiting (Fig. 6). This finding suggests that their water supply challenges are intricately linked to their groundwater rights, their available groundwater, and the future runoff patterns for the Colorado River. Currently, only two of these water providers have Designations of Assured Water Supply which means that the remaining water providers rely on surface water recharge operations of the CAGRD to recharge the aquifer in compliance with the 1980 groundwater management act (Maguire, 2007).

Those water providers that are expected to pump less than 10 million m^3 by the year 2035 showed very little response to alteration in surface water supplies (Group D, Fig. 6). These water providers appear to be buffered from reductions in surface water availability because they have a broader source of water supply (most of them have rights to Salt-Verde River water), lower water use and thus lower, projected water demand expected over the 25-year simulation period (Fig. 8), or both. They apparently face fewer water supply challenges.

6.3. *Model analysis and assumptions*

Reasonable good fit between the simulated estimates of storage and those obtained from empirical data records for the Colorado River system suggests that the model performs well for the CAP water storage (and thus deliveries) (Fig. 4). However, poorer performance was observed for the Salt-Verde River reservoirs (Fig. 4A). As stated earlier, we did not use measured estimates of water release from the reservoirs on the Salt-Verde River system in these analyses. The disagreement between measured and simulated water storage for the 2002–2006 period can be explained by greater water actually released during that time compared to simulated estimates. Water release from SRP reservoirs can occur for a variety of reasons, separate from meeting the legal obligations of member lands (Phillips et al. 2008). The relatively poor correspondence between our simulated estimates of water storage for the Salt-Verde River system and the empirical estimates suggests that improvement is needed in our Salt-Verde reservoir modeling. Notwithstanding, error in our estimates may not necessarily be critical because mis-correspondence on the order of our findings only impacts our simulations of annual designations if actual storage: 1) fell below the critical threshold of 740 million m^3 (600,000 acre-feet) that triggers reduced groundwater pumping, or 2) exceeded the upper threshold of 2.52 billion m^3 (2 million acre-feet) that triggers New Conservation Space (NCS) allocations.

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Several assumptions were necessary in order to conduct these analyses. First, our estimates of groundwater reliance (GWR), and thus changes in GWR as influenced by imposed changes to the surface water supply are strongly dependent upon our estimates of water demand at the provider-level. These estimates are based on either land-use codes, including estimates of water duty and density, or on recent estimates of the liters per capita per day typically used within a water provider boundary and projected population growth. Our estimates of water demand, based on land cover, were validated in a previous study (Gober et al., 2011). Herein we demonstrate that water demand estimated from land-use, density, and water duty are generally similar to, although a bit greater than, estimates based on current per capita water use and projected population growth. Of course, accurate estimates of future water demand remain a challenging aspect of simulation analyses.

Secondly, we have not addressed aspects of stationarity in our runoff estimates. Our historical estimates of runoff—and the inherent statistical metrics—do not represent probable future runoff. Rather, they serve as a relative proxy for changes in runoff and its effect on water provider portfolios. Actual, future changes in the variability in riverine runoff would influence our simulation results; drought periods could lengthen whereby increasing dependence on groundwater pumping and, therefore, the long-term groundwater budgets.

Finally, although we have verified our groundwater designations and assurances through the ADWR, these values are subject to change annually because of the complex water laws and the annual re-assessment of the Phoenix AMA water budget by the Department. Changes to existing contracts, and new contracts, would influence our water budgeting and accounting.

6.4. *Future directions*

To better address the influence of supply shortages as they impact provider vulnerability (e.g., Shearer et al., 2006) we are in the process of linking our provider model to Corkhill et al. (1993) Regional Groundwater Flow Model for the SRV. This spatial-temporal connection will allows us to examine provider-specific estimates of groundwater on an annual basis at the 0.8 km by 0.8 km (½ mile by ½ mile) spatial resolution. Thus, by resolving the spatial and temporal estimates of groundwater (via markedly improved estimates of groundwater pumping, recharge, and underflow), and engaging stakeholders in the application design process, we can create an anticipatory decision making framework to examine water vulnerability and management scenarios (e.g., Makropoulos et al., 2006) at finer spatial scales. An analysis of risk might include an assessment of the "adaptive capacity" for each provider in response to imminent water shortages (e.g., Mahmoud et al., 2009). Other measures might include the creation of conservation programs and anticipatory programs such as strategic planning scenarios (Shearer et al., 2006) and adaptation and mitigation strategies (Larsen and Gunnaarsson-Östling, 2009; Laukkonen et al., 2009). Adaptation to water supply challenges may also include water sharing and trading, and water markets. It's worth noting that the physical infrastructure needed to move water among Valley water providers is currently limited. In any case, models and their analyses must be based on policy-relevant research (McIntosh et al., 2007) where political, social (Shuttleworth, 2007), and economic (Ward, 2009) factors are framed within the biophysical context (Collins and Bolin, 2007).

7. Conclusion

We have developed a water management and planning model for Phoenix that examines water supply and demand at the water provider-level. This novel effort creates a spatially-explicit water management and planning tool that uses Microsoft C# to link to a FORTRAN model and we use inputs from a three-dimensional groundwater flow water, conceptually similar to Schmitz et al. (2009), for spatial and temporal analyses at the water provider-level. Adapted as a modification of a well-tested county-scale research and planning model, this new model provides a structure to begin to ask questions regarding the spatial and temporal patterns of potential, future water management challenges among Valley water providers. Missing, however, are the provider-based water policy and planning levers that will come into play as surface water supplies become limiting, such as; potential water sharing agreements; cooperative water trading via extant or newly built pipes and canals; water credits; multi-provider conjunctive use credits.

Our results suggest that there could be differential adaptive challenges among the major water providers that serve metropolitan Phoenix. These challenges will largely depend on their water portfolio; a provider may have flexible or constrained adaptability to climate, to groundwater reserves, or to both depending on their nominal reliance on groundwater. In addition, the geographical location of a provider within the Valley and their projected change in water demand will greatly influence their water security challenges. However, factors such as climatic uncertainty, groundwater reserves, and the "realized" population growth (or downturn) will influence how robust any particular portfolio will be regardless of its position. These challenges will be framed by their capacity to adapt (e.g., Eakin and Conley, 2002). Borrowing from traditional vulnerability assessment terminology (e.g., Polsky et al., 2007), the portfolio defines their "exposure", while their current groundwater availability and projected water demand defines their "sensitivity" (i.e., their groundwater reliance). This model provides a framework for examining water supply and demand exposure and sensitivity of Phoenix water providers.

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References

Aktipis, C.A., Cronk, L., De Aguilar, R., 2011. Risk-pooling and herd survival: an agent-based model of a Maasai gift-giving system. Hum. Ecol. doi:10.1007/s10745-010-9364-9.

Arizona Department of Water Resources (ADWR), 2009. Salt River Valley (SRV) Regional Model, Version 1. http://www.azwater.gov/dwr/content/find_by_program/-hydrology/modeling_section/SRV_Home.htm (accessed 02.02.09).

Arizona Department of Water Resources (ADWR), 2006. Arizona water Atlas, Volume 8, Section 8.1. Phoenix Active Management Area Planning Area, pp. 85–161.

Arizona Department of Water Resources (ADWR), 1999. Third Management Plan 2000–2010 for Phoenix Active Management Area.

Barnett, T.P., Pierce, D.W., 2009. Sustainable water deliveries from the Colorado River in a changing climate. PNAS 106, 7334–7338.

Berger, T., Birner, R., Di'az, J., McCarthy, N., Wittmer, H., 2007. Capturing the complexity of water uses and water users within a multi-agent framework. Water Resour. Manag. 21, 129–148.

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Bolin, B., Seetharam, M., Pompeii, B., 2010. Water resources, climate change, and urban vulnerability: a case study of Phoenix, Arizona. Local Environ. 15, 261–279.

Borowski, I., Hare, M., 2007. Exploring the gap between water managers and researchers: difficulties of model-based tools to support practical water management. Water Resour. Manag. 21, 1049–1074.

Brugnach, M., Tagg, A., Keil, F., de Lange, W.J., 2007. Uncertainty matters: computer models at the science-policy interface. Water Resour. Manag. 21, 1075–1090.

Castelletti, A., Pianosi, F., Soncini-Sessa, R., 2008. Integration, participation and optimal control in water resources planning and management. Appl. Math. Comput. 206, 21–33.

Central Arizona Project (CAP), 2006. Annual Report. – Peace in Our Time. http://www.capaz.com/financials/annual-reports/.

Christensen, N.S., Lettenmaier, D.P., 2007. A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River basin. Hydrol. Earth Syst. Sc 11, 1417–1434.

Christensen, N.S., Wood, A.W., Voisin, N., Lettenmaier, D.P., Palmer, R.N., 2004. The effects of climate change on the hydrology and water resources of the Colorado River basin. Climatic Change 62, 337–363.

Collins, T.W., Bolin, B., 2007. Characterizing vulnerability to water scarcity: the case of a groundwater-dependent, rapidly urbanizing region. Environ. Hazards 7, 399–418.

Corkhill, E.F., Corell, S., Hill, B.M., Carr, D.A., 1993. A regional groundwater flow model of the Salt River Valley – Phase I Phoenix Active Management Area hydrologic framework and basic data report. Ariz. Dept. Water Resour. Modelingreport No. 6. 170 pp.

Eakin, K., Conley, J., 2002. Climate variability and the vulnerability of ranching in southeastern Arizona: a pilot study. Clim. Res. 21, 271–281.

Ellis, A.W., Hawkins, T.W., Balling, R.C., Gober, P., 2008. Estimating future runoff levels for a semi-arid fluvial system in central Arizona, USA. Clim. Res. 35, 227–239.

Escobar, V.M., 2009. A Scenario-based Assessment of Future Groundwater Resources for Water Providers in the Phoenix Active Management Area. Unpublished Master's thesis. Arizona State University.

Gammage Jr., G., 1999. Phoenix in Perspective. Herberger Center for Design. Tempe, , AZ, p. 192.

Gober, P., 2006. Metropolitan Phoenix: Place Making and Community Building in the Desert. University of Pennsylvania Press, Philadelphia, p. 233.

Gober, P., Wentz, E.A., Lant, T., Tschudi, M.K., Kirkwood, C., 2011. WaterSim: a simulation model for urban water planning in Phoenix, Arizona, USA. Environ. Plann. B. 38, 197–215.

Harlan, S.L., Brazel, A.J., Jenerette, G.D., Jones, N.S., Larsen, L., Prashad, L., Stefanov, W.L., 2008. In the shade of affluence: the inequitable distribution of the urban heat island. In: Robert Wilkinson, C., Freudenburg, William R. (Eds.), Equity and the Environment (Research in Social Problems and Public Policy, Volume 15). Emerald Group Publishing Limited, pp. 173–202.

Hartmann, H., 2009. http://www.azwaterinstitute.org/media/EWSR/200909/200909/Hartmann.pdf. (accessed 01.02.11).

Hirt, P., Gustafson, A., Larson, K.L., 2008. The mirage in the Valley of the sun. Environ. Hist 13, 482–514.

IPCC, 2007. Summary for policymakers. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate change 2007: the physical science basis. Contribution of working group I to the Fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., pp. 7–11.

IPCC, 2000. Summary for policymakers. In: Nakicenovic, N., Davidson, O., Davis, G., Grübler, A., Kram, T., Lebre La Rovere, E., Metz, B., Morita, T., Pepper, W., Pitcher, H., Sankovski, A., Shukla, P., Swart, R., Watson, R., Dadi, Z. (Eds.), Special Report: Emission Scenarios. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Information Services Division, 2007. Socioeconomic projections of population, housing and employment by municipal planning area and regional analysis zone. Maricopa Assoc. Gov., 79 pp.

Larsen, K., Gunnaarsson-Östling, U., 2009. Climate change scenarios and citizen-participation: mitigation and adaptation perspectives in constructing sustainable futures. Habitat Int. 33, 260–266.

Laukkonen, J., Blanco, P.K., Lenhart, J., Keiner, M., Cavric, B., Kinuthia-Njenga, C., 2009. Combining climate change adaptation and mitigation measures at the local level. Habitat Int. 33, 287–292.

Maguire, R.P., 2007. Patching the holes in the bucket: safe yield and the future of water management in Arizona. Ariz. Law Rev. 49, 361–384.

Mahmoud, M., Liu, Y., Hartmann, H., Stewart, S., Wagener, T., Semmens, D., Stewart, R., Gupta, H., Dominguez, D., Dominguez, F., Hulse, D., Letcher, R., Rashleigh, B., Smith, C., Street, R., Ticehurt, J., Twery, M., van Delden, H., Waldick, R., White, D., Winter, L., 2009. A formal framework for scenario development in support of environmental decision-making. Environ. Modell. Softw 24, 798–808.

Makropoulos, C.K., Morley, M., Memon, F.A., Butller, D., Savic, D., Ashley, R.A., 2006. A decision support framework for sustainable urban water planning and management in new areas. Water Sci. Technol. 54, 451–458.

McIntosh, B.S., Seaton, R.A.F., Jeffrey, P., 2007. Tools to think with? Towards understanding the use of computer-based support tools in policy relevant research. Environ. Modell. Softw 22, 640–648.

Milly, P., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J., 2008. Climate change: stationary is dead: whither water management? Science 319, 573–574.

Olsson, J.A., Andersson, L., 2007. Possibilities and problems with the use of models as a communication tool in water resource management. Water Resour. Manag. 21, 97–110.

Overpeck, J., Udall, B., 2010. Dry times ahead. Science 328, 1642–1643.

Phillips, D.H., Reinink, Y., Skarupa, T.E., Ester, C.E., Skindlov, J.A., 2008. Water resource management at the Salt River project in Gooch, R.S., Anderson, S.S. (Eds.), In: Proceedings of the Urbanization of Irrigated Land and Water Transfers, USCID Water Management Conference, 28–31 May, Scottsdale, AZ, pp. 37–51.

Polsky, C., Neff, R., Yarnal, B., 2007. Building comparable global change vulnerability assessments: the vulnerability scoping diagram. Glob. Environ. Chang 17, 472–485.

Salt River Valley Water Users Association, 1910. Decision and decree No. 4564 from, In: The District Court of the Third Judicial District of the Territory of Arizona, in and for the County of Maricopa.

SAS, 2008. SAS/STAT User's Guide. Release 9.2 Edition. SAS Institute, Cary, N.C.

Schmitz, O., Karssenberg, D., van Deursen, W.P.A., Wesseling, C.G., 2009. Linking external components to a spatio-temporal modeling framework: coupling MODFLOW and PCRaster. Environ. Modell. Softw 24, 1088–1099.

Seager, R., Ting, M., Held, I., Kushnir, Y., Lu, J., Vecchi, G., Huang, H., Harnik, N., Leetmaa, A., Lau, N., Li, C., Velez, J., Naik, N., 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. Science 316, 1181–1184.

Sehlke, G., Jacobson, J., 2005. System dynamics modeling of transboundary systems: the Bear River basin model. Ground Water 43, 722–730.

Shearer, A.W., Mauat, D.A., Bassett, S.D., Binford, M.W., Johnson, C.W., Saarinen, J.A., 2006. Examining development-related uncertainties for environmental management: strategic planning scenarios in Southern California. Landscape Urban Plan. 77, 359–381.

Shuttleworth, W.J., 2007. Stakeholder-driven, enquiry-driven, or stakeholder-relevant, enquiry-driven science? Water Resour. Manag. 21 (63), 77.

Sit, V., Poulin-Costello, M., 1994. Catalog of curves for curve fitting Ministry of Forests Research Program Biometrics information handbook no 4 Crown Publications, Victoria, BC, Canada.

Stave, K.A., 2003. A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada. J. Environ. Manag. 67, 303–313.

Turner, M.G., Dale, V.H., Gardner, R.H., 1989. Predicting across scales: theory development and testing. Landscape Ecol 3, 245–252.

U.S. Department of Interior (USDOI), Bureau of Reclamation, 2007. Record of decision Colorado River interim guidelines for lower basin shortages and the coordinated operations for Lake Powell and Lake Mead final Environmental Impact Statement.

Bureau of Reclamation U.S. Department of Interior (USDOI), 2000. Colorado River Interim Surplus Criteria; Final Environmental Impact Statement, vol. 1. USDOI Publication.

Ward, F., 2009. Economics in integrated water management. Environ. Modell. Softw 24, 640–648.

White, D.D., Wutich, A., Larson, K.L., Gober, P., Lant, T., Senneville, C., 2010. Credibility, salience, and legitimacy of boundary objects: water managers' assessment of a simulation model in an immersive decision theater. Sci. Public Policy 37, 219–232.

Wutich, A., Lant, T., White, D., Larson, K.L., Gartin, M., 2010. Comparing focus group and individual responses on sensitive topics: a study of water decision-makers in a desert city. Field Methods 2, 88–110.

Please cite this article in press as: Sampson, D.A., et al., A provider-based water planning and management model – WaterSim 4.0 – For the Phoenix Metropolitan Area, Journal of Environmental Management (2011), doi:10.1016/j.jenvman.2011.05.032