1 Anticipatory modeling for water supply sustainability in Phoenix, Arizona

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Abstract

City level water policy and management decisions are typically based on past experience and in-house estimates of future conditions. Naturally, this management approach relies on so-called “craft skills”—problem solving abilities that are acquired through long, place-based experience (Lach et al., 2005). Analyses using this approach depend on a limited number of socio-economic, water supply, and water demand projections, often only a single one. Increasingly, water planners are realizing that the high uncertainty associated with population projections and water use trends, as well as with future water supply estimates, greatly limit their ability to adequately predict a city’s water future. We suggest that water governance at the municipal level could benefit markedly from water planning tools that generate and analyze a large ensemble of potential future scenarios, scenarios that address population growth dynamics, water supply and demand projections, and alternative governance possibilities. For this work, we adapted our existing provider-level water supply model to create a demand-based water planning and analysis tool that can be used to explore the effects of drought, climate change, population growth, and policy options on surface water supplies, water demand, and groundwater pumping for the Phoenix Metropolitan Area. Our decision support tool (DST) framework uses numerical simulations to project future water supply and use, enabling advanced scenario analysis; quantitative or qualitative methods can be used to reveal patterns and associations among metrics for a large ensemble of scenarios. From this analysis, a smaller set of heuristics, describing the complexity and uncertainty of the scenarios, provides a basis for guiding anticipatory planning. Our DST uses population estimates in conjunction with water use to estimate water demand, and legal rights, in combination with estimates of groundwater, stream flows, and reservoir operations to estimate water supply. Policy options permit evaluation of short- and long-term alternative governance strategies. We present two examples—one regional and water provider specific—of the types of scenario analyses that are possible using this model.

Key Words: anticipatory governance, water planning, scenario generators

1. Introduction

Complexity, uncertainty, and variability are inherent properties of coupled natural and human systems, and natural resource management must consider each of these dimensions to achieve sustainability in these linked systems (Medema et al., 2008). The linkages, however, are often poorly understood and dynamics, feedbacks, and responses may be non-intuitive. For example, even though our understanding of the complex nature of atmospheric forcing has improved, uncertainty in the rainfall and runoff estimates may increase (Ghosh and Mujumdar, 2009). Moreover, evidence suggests increased variability in the range of salient meteorological forcing (e.g., ambient air temperature and rainfall) due to climate change. Stationarity, or the notion that the future climate system will operate within a known envelope of variability and periodicity, is presumed dead (Milly et al., 2008). Increased uncertainty in model predictions, and increased variability associated with the potential response of these systems over time, adds to stakeholder

skepticism regarding the usefulness of scientific information and modeling in the decision making process (Borowski and Hare, 2007). Scholars have argued for a shift in the framing of complex systems whereby scientists and decision makers are encouraged to think not only about *characterizing, quantifying, and reducing uncertainty*, but also about *managing uncertainty* and making decisions under uncertainties (Lempert et al. 2004; Quay, 2010; Gober et al., 2014).

One promising approach for incorporating complexity, uncertainty, and variability into resource management decision making is anticipatory modeling with advanced scenario analysis. The challenge is to explain the decision–space of uncertainty in an accessible, transparent manner, but without presenting all possible permutations and potential ramifications of the uncertainty itself. When framed in a context consistent with sustainable resource management and planning objectives, and within timelines consistent with decision processes, anticipatory modeling may help to assuage stakeholder concerns about the usefulness of modeling for decision making (White et al., 2010). In this paper, we describe the development and application of an anticipatory modeling framework for urban water sustainability in the Phoenix, Arizona, region.

In urban settings such as Phoenix, water resource decision making is affected by uncertainty and variability of water supplies and demands, complicated and expensive urban water system infrastructure, social trends, political events, and economic processes. These endemic challenges are now exacerbated by climate change impacts on water resource availability and use.

Anticipatory approaches to decision making take these factors into account by characterizing uncertainty (e.g., creating scenarios of water supply and demand futures); defining a problem space for complexity (e.g., systems modeling of infrastructure and institutions); and outlining political options (e.g., policy levers to explore interests of varied stakeholders).

Advanced scenario analysis is an anticipatory approach used to explore uncertainty within natural and social systems by analyzing a large ensemble of possible futures to find patterns that define a small set of strategic concepts to guide short–term tactical decisions and long–term strategic planning (Lempert et al., 2003; Quay, 2010; Chakraborty et al., 2011; Quay, 2011; Walker et al., 2013). There are multiple perspectives on uncertainty with varying implications on its source, characterization, and implications for decision making. While a comprehensive review is beyond the scope of this paper, we note here that uncertainty can be described as ontological, resulting from inherent variation that occurs within the processes of a system; or epistemic in nature, resulting from a lack of understanding about a system (van Asselt and Rotmans, 2002; Walker, 2003). Others view uncertainty from the perspective of the people involved in the decision making process, where differences of opinions about how systems work, difference in values and priorities, and the relationships between actors and perceptions can also contribute to uncertainty (Lempert et al., 2004; Brugnach et al., 2008). For urban water systems, ontological uncertainty stems primarily from weather and climate factors that affect future water supplies and water demand and the socio–economic factors that affect water demand and system delivery and collection (Quay, 2015) as well as epistemic uncertainty stemming from our limited understanding of the system and its dynamics. Social dimensions of uncertainty are derived from

social, economic, and political decision-making processes involved in water resource management.

Urban water systems can vary from simple, with one well, storage tank, and distribution line, to complicated, with source water, facilities for storage and treatment, and infrastructure for delivery, collection, sewage treatment, and effluent reuse. Complicated systems typically rely on a large number of water resource management policies to guide management of system supply and demand under changing conditions. For example, the Phoenix Metropolitan Area (PMA) has over 50 regulated water utility systems, ranging from the simple to the complex that, together, represents a loosely coupled regional water system (Murray et al., 2012). We developed WaterSim, an urban water supply and demand model (Gober et al., 2011; Sampson et al., 2011) to explore issues of uncertainty and complexity of this system. WaterSim includes three types of modules: 1) modules to characterize the uncertainty within factors that influence water supplies and demand in the Southwest, such as climate, population and economic growth, and human behavior; 2) modules to define water flow through the urban water infrastructure and the complexity of institutions that manage local and regional water rights and systems in central Arizona; and 3) modules that integrate a wide range of policy levers for water supply and demand management options, which can be implemented to change the social, economic, and functional aspects of local and regional water systems. This model creates ensembles of future system states by varying the factors that affect supply and demand across an anticipated range of possible future values and implementing policy levers at various levels and combinations. The performance of the system for each possible future can be evaluated using metrics that characterize water flux through these complex urban systems. Together, these metrics provide very large datasets, which can be analyzed for patterns that yield insights relevant to local and regional decisions about various water management policies under conditions of uncertainty.

WaterSim is designed to explore uncertainty for certain aspects of multiple perspectives using an exploratory modeling approach (Bankes, 1993; Dewar, 2002; Lempert et al., 2003; Quay, 2010, 2011; Gober et al., 2014). One aspect of uncertainty is the inherent inter-annual variability in river flows for the Colorado, Salt-Tonto, and Verde River systems; we address this uncertainty by classifying the patterns of historic and paleo river flows (Griffin et al., 2013) as base scenario inputs into the model. And, while we recognize that there are differences of opinion among professionals and the public and, subsequently, disagreements about what constitutes a sustainable water future (White et al., 2015), WaterSim outputs provide metrics for each of these groups so that scenarios that emphasize different viewpoints of sustainability can be explored. There is also a wide range of opinions about what water management options are appropriate at different geo spatial scales (White et al., 2014). Using a participatory modeling approach WaterSim was designed to include the systems and management options that reflected this wide range of opinions which can then be explored. The current lack of knowledge about climate systems, thus uncertainty about future climate change (Lempert, et al., 2004), is addressed by using the latest global climate model results to frame a range of possible futures for precipitation and, thus, riverine flows which then can be tested using WaterSim. These

uncertainties are then analyzed across a range of possible futures for each of these inherently uncertain factors. Given the complexity of layering uncertainties, most of which have no basis for suggesting probabilities, each future is considered to have an equal probability of becoming the future.

In this paper, we describe an anticipatory modeling approach designed to build capacity for sustainable water resource management and climate change adaptation with an application to the PMA. The objectives are twofold: first, we describe the structure and function of the revised and updated version of WaterSim; and second, we present an application of advanced scenario analysis using WaterSim to examine the interactions of climate change, drought, population growth, and urban water use with implications for urban water sustainability.

2. Methodology

2.1 Study Context

The planning horizon for urban water resource management is typically several decades. Several cities in the PMA now have over a century of experience in providing water service to their customers. Water management goals in this urban desert environment are considered lofty; e.g., The City of Phoenix has a goal “to ensure the availability of safe, sustainable, reliable, and affordable water supplies in sufficient quantity to meet the needs of city customers during all foreseeable conditions” (City of Phoenix, 2011). Providing sustainable and reliable water sources to meet growing demand will prove challenging under a changing climate. Moreover, climate change, and its impact on water resources for the PMA are regional in scope; the PMA imports much of its water from the seven state area of the Colorado River Basin. Arizona transports about 1.85 billion cubic meters (m^3) (150 thousand acre–feet [kAF]) of Colorado River water into Arizona annually—41% of which stays in the PMA—along a 541 km (336 mile) man–made aqueduct that stretches from Lake Havasu on the California–Arizona border to Tucson in southeastern Arizona.

Roughly 1.11 to 1.23 billion m^3 (900 to 100 kAF) of water is also brought in from the Salt–Tonto and Verde River watersheds, an area that drains about 33,800 km^2 (13,050 mi^2), a large portion of the central Arizona highlands. These native waters are managed by the Salt River Project (SRP), a consortium of two entities that includes the Salt River Project Agricultural Improvement and Power District, a political subdivision of the State of Arizona that serves as an electrical utility for the PMA, and the Salt River Valley Water Users' Association, a private water corporation. When combined with groundwater pumping, the Phoenix Active Management Area (a water management unit that coincides roughly with the PMA) uses about 2.78 billion m^3 (225 kAF) of water annually (ADWR, 2010), roughly 53% used for municipal and industrial purposes with the remainder going to agriculture.

Defining what a sustainable urban water system for central Arizona is complex. Because so much water is transported into the area, Phoenix has been labeled as “the world’s least sustainable city” (Ross, 2011). Others disagree, arguing that the “Sun Corridor” of Arizona, the area stretching roughly from Phoenix to Tucson, could likely accommodate several million new

residents without additional water supplies and that the region will not actually “run out of water,” as long as serious decisions regarding the balance between water use and lifestyle are made (Gammage et al., 2011). These concepts of urban water sustainability represent subsets of the more expansive concepts of sustainable resource management and sustainable development. Larson et al. (2013a) conducted a comprehensive sustainability appraisal of water governance in Phoenix, Arizona. Their appraisal evaluated water sustainability according to a set of seven principles for water governance, derived from the literature, on integrated water management: social–ecological systems integrity, resource efficiency and maintenance, livelihood sufficiency and opportunity, civil engagement and democratic governance, inter–generational and intra–generational equity, interconnectivity from local to global scales, and precaution and adaptation. It is difficult to assess sustainability in such a broad comprehensive fashion due to the challenges associated with conceptualizing, operationalizing, measuring, and modeling the full suite of sustainability principles as identified in Larson et al. (2013a). Our focus for our WaterSim research is on *social–ecological systems integrity, resource efficiency and maintenance, inter–generational and intra–generational equity, and precaution and adaptation* dimensions of urban water sustainability. These aspects of sustainable are most aligned with local water resource stakeholder’s perspective of what are the important aspects of urban water sustainability for central Arizona.

2. 2 Model Development

WaterSim 5 represents a significant modification, and broader implementation, of an earlier model developed by the Decision Center for a Desert City (DCDC), a National Science Foundation–funded research unit of the Julie Ann Wrigley Global Institute of Sustainability at Arizona State University (Larson et al., 2013b). Specifically, we updated WaterSim 4, a water supply model for 33 water providers (utilities) in the PMA (Sampson et al., 2011), to create a water policy and planning model based on urban water demand. Whereas version 4 could be used to examine changes in water supply under a changing climate, and changes in demand as influenced by population growth, version 5 permits evaluation of policy and governance on water supply, water demand, and water use as influenced by population growth, per capita water consumption, climate change and drought.

WaterSim 5 is comprised of separate linked programs that form a suite of models. The WaterSim Suite 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) (Figure 1). The user accesses the run library through the API that controls the model run specifications. The FORTRAN dll houses the rules and algorithms for the model using modules that are comprised of functions and subroutines; 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 (Figure 1).

The water demand, supply, and use modules of this sequence are linked, in time and space, with exogenous factors that influence available supplies and, with demand, determines the

relative use of each water source based on the individual water rights and the water demand rules (Figure 2). The width of the lines in Figure 2 demonstrates the relative weighting of the individual storage and flux components. Annual water demand in conjunction with water rights that are linked to the individual water sources, determine the net delivery of surface water and groundwater (Figure 2). 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 (Figure 2).

The model is utilized either through: 1) applications that automate the process of creating large ensembles of scenarios based on varying exogenous factors that affect water supply and water demand and/or policy levers that reflect varying water management policies; or 2) a web based interface that allows users to create a single scenario using visual controls to set exogenous and/or policy factors and immediately assess the scenario using urban water sustainability indicators and graphics of various water system performance factors.

In this paper, we present an overview of the design and implementation of the model suite with detailed development methods provided in the supplementary materials. These materials include the additions and/or changes to the WaterSim 4 model.

Population and water demand

We used four separate data sources to estimate population for each water provider for the period 2000 to 2085. In brief, we used summarized Transportation Analysis Zone (TAZ) data from the Maricopa Association of Governments (MAG) for the years 2010, 2020, 2030, and 2040, census data from 2000 through 2010, year 2005 population estimates from MAG, and census “QuickFacts” data. Using Esri ArcMap, the decadal estimates were joined with a Census block group shape file and then intersected with our water provider shape file. We used PROC EXPAND in SAS (SAS, 2008) to interpolate population from 2000 to 2005 and 2005 to 2010 for those cities or water providers not included in the intercensal data summary. PROC EXPAND was also used to estimate intermediate years (2010 to 2020, 2020 to 2030, etc.) for the TAZ data. We then used time series forecasting procedure in SAS[®] software, and random walk, to estimate population out to 2085 (see Appendix A for details).

Riverine water rights

Surface water rights to Colorado River water and groundwater rights were updated from those presented in Sampson et al. (2011) (Appendix B). Water rights for the Salt-Tonto and Verde Rivers are complex and, for the purpose of this model, are the same as those addressed in Sampson et al. (2011). However, we modified our approach to use daily flow data from the Salt-Tonto, and Verde Rivers (Appendix B).

Reservoir operations

Reservoir operations for the Colorado River and for the Salt-Tonto and Verde Rivers were completely re-written from the prior version (Appendix C). Reservoir operations on the

Colorado River were modified to include the addition of tributary inflows, verifiable estimates of Upper Basin consumptive use, and bank storage and release estimates, to name a few. Moreover, new algorithms to estimate river and lake evaporation were developed based on surface area and pan evaporation. Also, where WaterSim 4 simulated one reservoir for the Salt–Tonto and Verde River systems, in version 5 we recognized three reservoirs: one for the Verde, and two for the Salt–Tonto, separating Lake Roosevelt from the other three reservoirs on the Salt–Tonto River system, which we combined (Appendix C). Lake Roosevelt was differentiated because of reservoir–specific management operations that differ from the other reservoirs on the system. And, we also now model monthly reservoir operations as opposed to annual operations found in version 4.

Groundwater management

Groundwater in the PMA is managed through a credit system overseen by the Arizona Department of Water Resources (ADWR). In version 5, we added the water policy option for groundwater banking and an approach to model groundwater based on groundwater credits, mimicking the ADWR management approach; although we do not, at this time, permit credit transfers (Appendix D). In addition, we manage the regional aquifer by accounting for inflows and outflows for the total basin. Initial estimates of groundwater for the aquifer were obtained from modeling estimates from the ADWR (Dale Mason, Groundwater Modeler–Hydrologist, Arizona Department of Water Resources, personal communication, 4 June, 2010). Annual estimates of groundwater pumping and recharge (and, thus the credit exchanges) permit a rough approximation of the regional aquifer balance.

New water supplies

As a policy option for exploring water supply and demand dynamics, “new water supplies” can be chosen through the model interface. These potential water sources mimic sources of water yet to be identified (e.g., desalinated ocean water). At this time they occur as a “what if” water source with no physical connection to known surface or groundwater sources, or rights.

Water use network

WaterSim 5 incorporates a water use network (Choi, 2009; Appendix E) that contains standard city infrastructure elements such as water and waste water treatment plants, and water supplies from surface and groundwater sources. Total supplies are partitioned into residential, commercial, and industrial water use (indoor and outdoor). This network incorporates rainfall, runoff, and percolation sub–models (a complete description may be found in Appendix E).

Water policy/ Scenario stories

Many endogenous and exogenous factors influence water supply and demand for a municipality. These factors (and events) can be categorized as policy scenarios (human factors that determine or influence water supply and demand) and external scenarios (abiotic controls

over water supply, i.e., climatic and hydrological controls over rainfall and river runoff). Together, these factors can be used to create a simulation scenario with relevant outputs.

Based on formal discussions with focus groups of water managers, we developed a series of water management policies to include in our modeling activities. For WaterSim 5 we are now able to test multiple policies that pertain to both demand management and supply management (Table 1). Demand management includes drought and population growth management as well as scenario implementation of programs to promote a more efficient lifestyle. Supply management includes changes in water supply through changes in use or reuse, such as the use of reclaimed water and effluent, or factors related to groundwater, including banking or collaborative swapping of surface water for groundwater.

We also examine the exogenous factors that affect water availability and use for each water provider related to drought, climate change, and the economy (Table 2). In order to compare responses across scenarios we developed standard output metrics to consistently evaluate alternative governance strategies and climate events. These metrics are grouped into one of four measures of urban water sustainability: 1) water supply, 2) groundwater withdrawal, 3) changes in population growth patterns, and 4) changes in water use efficiency (Table 3).

By either incrementally modifying the pertinent lever in the model or by using process formulations that were written in the application programmer's interface, we can generate multiple scenarios. We can now conduct hundreds or thousands of simulations and then make comparisons among them, providing an uncertainty envelope with which policy alternatives can be evaluated.

2. 3. Application Programmers Interface (API)

We have developed open source code to create an interface for general users of WaterSim 5. This includes an install program that will create the necessary structure for running the model on a desktop PC. Available code may be found on the DCDC website (<http://dcdc.asu.edu/>).

2. 4 Verification/validation procedures

Several aspects of the WaterSim model suite have the potential to be verified; to date we have conducted verification and validation procedures on reservoir storage (Salt–Tonto and Verde Rivers) and elevation (Colorado River reservoirs) (Appendix F). For the Colorado River reservoir elevation, we used empirical data of reservoir storage for the period 2000 to 2013 for Lake Powell and Lake Mead to compare against simulation projections from WaterSim (Appendix F). For the Salt–Tonto and Verde system, we had empirical estimates of reservoir storage for comparisons. In this case, we used the 2000 through 2006 estimates for model calibration and the 2007 through 2011 estimates for model verification and/or validation (Appendix F).

We obtained outputs from the Bureau of Reclamations' Colorado River Simulation System (CRSS; Bureau of Reclamation, 1985) using simulations provided by Arizona Department of Water Resources (Don Gross, Arizona Department of Water Resources, personal

communication, February 2013). This dataset permitted us to compare 67 years of simulated elevation estimates for Lake Mead and Lake Powell with those expected from the CRSS (Appendix F).

2.5 Simulations conducted

Simulations in WaterSim 5 start in the year 2000 but may be stopped in any year prior to 2085. Thus, the simulation run–stream may be “paused” before the start of each year for alteration in any of the water policy parameter inputs.

The analyses for this study required two sets of simulations: one related to model validation procedures, the other used to demonstrate the anticipatory approach using scenario analysis procedures available in WaterSim 5. Simulations pertaining to model parameterization, verification, and validation are found in Appendix F. Simulations pertaining to the scenario analyses were as follows. To start, we manipulated a range in factors that impact water supply and demand management and then used a metric to evaluate the relative and absolute impact of these factors on groundwater credits for both the region as a whole (i.e., the PMA; complete data set) and for the City of Phoenix (as a case example; data sub–set).

To accomplish this, we used a range of values for the driver variables that directly influence water supply and water demand, modifying: 1) the applied historical river trace (a 30–year segment from the historical record); 2) the climate factor (our surrogate for changes in riverine flow as influenced by suspected alterations in runoff over the course of decades) for the Colorado and the Salt–Tonto and Verde Rivers; 3) the length of an imposed drought (accompanied by an estimate of the corresponding reduction in flow associated with the drought); 4) the projected population growth; and, 5) a projected temporal decrease in LPCD (1 LPCD = 0.264 GPCD) (per capita water consumption). We used a total of six river traces, three separate 30–year segments for each riverine system representing a range in absolute flow from low to high (Tables 4 and 5). We varied our climate factor for the Colorado River in varying increments, from a low of 50% to a high of 110 % relative to historical flow (Christiansen and Lettenmaier, 2007). For the Salt–Tonto and Verde Rivers we varied our climate factor from a low of 40% to a high of 110 % relative to historical flow, somewhat approximating that found in Ellis et al. (2008), also in varying increments. We simulated four periods of drought, one assumed to end in 2015 (as a control), and three in 20 year intervals (ending in 2020, 2040, and 2060). For drought we reduced flows by 12% on the Colorado River and 25% on the Salt–Tonto and Verde Rivers. We also varied the projected population from 80% to 140% of the Maricopa Association of Governments (MAG) estimates, in 20% intervals. Finally, since the per capita water consumption for municipalities in the PMA has been steadily falling since the late 1980s, by about 1% per year, we varied our estimate for a reduction in LPCD from baseline (default settings) to 60% reduction in LPCD by 2085 in 20% intervals.

This scenario suite resulted in 11,520 individual scenarios (~33.6 million observations), from which we chose to evaluate 70 years (2010 to 2080) of outputs. Outputs were written to

disk using a comma separated file format. These data were then read into SAS[®] (SAS, 2008) for analysis and manipulation.

2. 6 Analysis

We used SAS (2008) to evaluate our metric of groundwater sustainability as influenced by changes in water supply and water demand; we examined the percent change in groundwater (from initial volumes) and in groundwater credits (from initial and from baseline), to evaluate the temporal change for the PMA. We also examined the percent change in groundwater credits (from initial) for the City of Phoenix. Baseline was defined by using: 1) historical flow records for the median river trace from each river system, 2) a drought ending in 2015, 3) the projected population growth rate, and 4) the default settings for the temporal trends in LPCD for each water provider.

We used the complete data set and simple area plots to examine, and plot, the temporal change in the regional groundwater aquifer from initial aquifer volume estimates for the ensemble of scenarios using SigmaPlot (version 10.0 Systat Software, Inc., San Jose California USA, www.sigmaplot.com). We then used the 3–dimensional smoothing algorithms in SigmaPlot (Loess procedures; sampling proportion = 0.15, 1st degree polynomial; reject outliers) to create “heat map” responses (three–dimensional data collapsed into two dimensions using a color–ramped contour graph) for the regional analyses. Specifically, we examined the relationships between water demand and surface water deliveries on groundwater pumping and the simulation year and groundwater pumping on the percent change in groundwater credits. Water demand, surface water deliveries, groundwater pumping, and groundwater credits were all represented as the percent change in their respective values over time from baseline.

To examine a city–level response, we used PROC UNIVARIATE in SAS[®] to calculate the median and the range of the change in groundwater credits over the 70 year period; we calculated the 50th percentile, the minimum, and the maximum for the Phoenix data set and then the 25th and 75th percentiles for the “plausible” scenario of the Phoenix data set (i.e., a 10% reduction on the Colorado River, a 30% reduction on the Salt–Tonto and Verde, a drought ending in 2015, 100% of the projected population growth, and a 20% reduction in LPCD, above and beyond the default settings, by 2085). We used a simple area graph to depict a cone of response for the percent change in groundwater credits from the initial estimates.

We also used PROC UNIVARIATE to calculate the temporal “variance” in the percent change in initial groundwater credits attributed to each factor examined for the City of Phoenix; we used one standard error of the mean (to correct for sample size). To do this, we let the target factor vary over the established range while holding all other factors constant (i.e., the baseline settings). We then summed the total error by year, over all factors, and divided by the individual error components to establish the relative change for each factor. We used a stacked bar chart to depict the relative standard error for each factor over time, with a subset of dates selected for clarity of presentation.

3. Results

The results from the anticipatory modeling using WaterSim 5 for advanced scenario analysis produced four key findings that provide insights into urban water sustainability challenges and solutions for the Phoenix, Arizona region. First, our regional analysis of the potential change in the aquifer groundwater credits suggests that, even at historical flows, the region will not achieve “safe–yield” by 2025¹. Rather, our simulations show that the regional groundwater aquifer below the PMA will likely decrease by about 30% by the year 2080 for the baseline scenario (Figure 3A; solid line), assuming that the water providers will pump groundwater at a rate necessary to meet total demands (supplemented by surface water and reclaimed water where applicable). Moreover, the simulations assume no other management interventions (i.e., maintaining the status quo, with no changes in a water providers’ portfolio over time and no change in groundwater management). The scenario ensemble resulted in a ~15% to 90% envelope of uncertainty in the aquifer decline projected out to 2080. Increases in water demand as a result of population growth above that projected, or decreases in surface water deliveries as a result of climate change or prolonged drought above baseline, would result in increased groundwater pumping (hatched area; Figure 3B). Thus, for reasonable reductions in riverine runoff (i.e., 10% to 15%), groundwater pumping could increase by 50% to 75% by 2080 with concomitant further declines in the regional aquifer of 30% to 40% above baseline rates (Figure 3C).

Second, scenario results focusing on the City of Phoenix demonstrate an increasing cone of uncertainty in the percent of initial groundwater credits by the year 2080, ranging from a high of 150% to a low of –100% (Figure 4). We observed a negatively skewed distribution in the response, as evident by the median response (dotted line) in relation to the overall uncertainty; at the extreme (unlikely) scenario combinations groundwater depletion (to a depth of 300 m [1000 feet]) could be expected by 2050 (Figure 4). However, these simulations depict the potential response in the absence of any policy or management intervention. Actual management practices could employ prior alternate strategies to maintain a favorable groundwater credit balance.

Third, our most plausible scenario suggests a largely positive outlook for the City of Phoenix. If we focus only on the scenarios where flows on the Colorado River are 90% of historical, flows on the Salt–Tonto and Verde Rivers are 70% of historical, population grows at the projected rate, the current drought ends in 2015, and per capita water consumption (LPCD) decreases by 20% by 2085, then we observe a substantial increase in the groundwater credits for the City of Phoenix of about 100% (dashed line) by 2080; the 25th and 74th quartiles of the likely response are depicted (Figure 4). The City of Phoenix has a robust water portfolio; however, some cities in the PMA have much more limited water rights and a different response could be expected for those water providers that have fewer rights or that rely solely on groundwater. Spatial differences in the distribution of the region’s population could develop as water becomes

¹ According to the Arizona Department of Water Resources, safe–yield is accomplished when no more groundwater is being withdrawn than is being annually replaced. The urban Active Management Areas are tasked with achieving safe–yield by 2025.

scarcer for those water providers that have only groundwater rights (e.g., newer communities on the urban fringe) and for new arrivals that settle in cities with a more robust water portfolio (Gober et al., 2014).

Fourth, each factor determining the change in groundwater credits over time for the City of Phoenix had differential effects depending on the time-frame (Figure 5). Only the Salt-Tonto and Verde River climate factor, and to a lesser extent the Colorado River trace, had an impact prior to about 2040. After 2040 all factors demonstrated variable effects on initial groundwater credits. For instance, the specific trace (30-year runoff period) chosen accounted for 1% to 20% of the variance, with the Colorado River runoff signal being substantially more prominent than the Salt-Tonto and Verde River traces. And, drought periodicity accounted for almost 20% of the response, being relatively stable over time (at least past 2040). Conversely, the effects of per capita water consumption and population growth rate increased over time.

Perhaps most notably was the decrease in the climate factor for the Salt-Tonto and Verde Rivers but the increase in the response attributed to the Colorado River climate factor (increasing to 25% by the end of the simulation) (Figure 5). Dominance of the Salt-Tonto and Verde River climate factor on the standard error, especially early on, is attributed to the heavy reliance on SRP system water by Phoenix (and including groundwater pumping by SRP to meet water provider demands). The increased proportion in the response in the Colorado River climate factor over time is attributed to decreased deliveries—and more years with no deliveries (data not shown)—as a result of increased reduction in the runoff estimates that results in a full effect achieved by 2085.

4. Discussion and Conclusion

The Phoenix Metropolitan Area will experience many challenges in the future that will strain the existing management, engineering, and governance systems (Gober and Kirkwood, 2010). Policy analysts have noted that the future will bring difficult decisions on reconciling water availability with the tradeoffs on how water is used (Gammage et al., 2011). Of these challenges, population growth and water demand, in conjunction with constrained water supply, will likely dominate. Our anticipatory modeling using WaterSim leads to two strategic insights.

First, under current climate and water resource management policies, the current regional water system would continue to deplete groundwater resources, perhaps as little as 30% but potentially much more over the next 65 years. This situation is exemplified by the response to the current drought in the West, the most extreme in over a century (Cayan et al., 2010), which affects not only surface water storage but also groundwater reserves (Castle et al., 2014). Under stressed climatic conditions that result in reductions in surface water flows of 20% or more, groundwater pumping could double with the depletion of groundwater reserves approaching 40%. Thus, in order for the water supply of the PMA to be sustainable into the next century, more aggressive water management strategies must be deployed, with the rate of these actions determined primarily by the severity in the rate of climate change impacts on runoff and storage.

Second, the capacity for the City of Phoenix to adapt to climate change–induced reductions in surface water availability suggest that the city has sufficient existing resources to adapt to moderate climate change (10% reduction Colorado River and 25% reduction in Salt–Tonto and Verde River flows). However, more severe climate impacts would require the city to deploy new, more rigorous water management strategies such as water banking; acquisition of new, senior surface water rights; even more aggressive reductions in per capita water use; or growth management strategies. Runoff from the three principal rivers that supply surface water to the PMA is expected to decline throughout the century as a result of climate change. Specifically, flows on the Colorado River may decrease, on average, by as little as 9% by 2065 (Bureau of Reclamation, 2012), but by as much as 15% to 37% following extreme drought years (Cayan et al., 2010). Mean runoff projected using an ensemble of General Circulation Models downscaled for the Salt–Tonto and Verde Rivers of central Arizona, predicts flow of the local riverine systems at about 25% of their current level by 2100 (Seshadri et al., 2014); the range in projected runoff from the ensemble varied from a high of ~ 110% of historical flow to a low of 60% of historical flow by the end of the century. Thus extreme drought remains a primary threat to the City of Phoenix’s urban water sustainability.

There are a wide variety of water policy and management strategies that could be implemented to adapt to these growth and water supply challenges. Many of these will require significant investment in infrastructure and long lead times to implement. This, combined with the uncertainty for their need, can challenge decision making. Embracing an anticipatory modeling approach to decision making by using advanced scenario analysis to explore and manage uncertainty within the coupled natural–human system can inform decision making, increasing adaptive capacity over the long–term.

Our WaterSim 5 model was created specifically for use in the Phoenix Metropolitan Area. Although the conceptual approach, systems dynamics methodology, and mathematical modeling techniques developed for WaterSim 5 are applicable and transferable to other urban water systems, WaterSim cannot be easily adapted to other locations because the surface and groundwater water rights are deeply embedded into the model design, and these rights are specific to the PMA. Thus, a majority of the code cannot now (unfortunately), as it is formulated, be simply or easily transferred.

5. Acknowledgements

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7. List of Tables

Table 1. The management approach, the objective of the policy, and the policy definitions for the water policy scenarios examined by WaterSim 5.

Table 2. External scenarios and factors tested by WaterSim 5 pertaining to drought, climate change, and factors related to the economy. The specific controls over each factor, and the event that triggers or determines the factor, are provided.

Table 3. Measures of urban water sustainability and cross–scenario standard metrics used to assess robustness of individual scenarios examined. Metrics may be used for direct comparisons among scenario alternatives. Unless otherwise noted these metrics are assessed over the entire simulation period, for each water provider, for each scenario examined.

Table 4. The 30–year trace records (years and statistics) used in these analyses for the Colorado River historical flow estimated at Lee Ferry, Arizona.

Table 5. The 30–year trace records (years and statistics) used in these analyses for the combined Salt–Tonto and Verde Rivers historical flow estimates.

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Figure 1. A diagrammatic representation of the WaterSim 5 water policy and management model for the Phoenix Metropolitan Area. This figure depicts the association between the C-sharp libraries of the model interface and the FORTRAN dynamic link library (dll) which contains the separate modules to estimate water demand, water supply, and water use.

Figure 2. A model diagram depicting the water supply structure of WaterSim 5, and the key trigger points and driver variables for exogenous and endogenous factors that affect water supply and use in the Phoenix Metropolitan Area. Line width denotes relative differences in storage and flux components.

Figure 3. The uncertainty in the percent change in the regional groundwater aquifer from initial volumes simulated for the Phoenix Metropolitan Area (PMA) projected out to 2080 for all scenarios (A), and the median response (solid line) for baseline conditions (A). The “heat maps” depict the influence of water demand and surface water deliveries on the percent change in groundwater pumping for the PMA over time (B), and the influence of groundwater pumping through time on the percent change in the regional groundwater credits (C). Note that all dependent and independent variables are represented as the percent change in their individual amounts or volumes from the baseline estimate. Here the baseline is defined as those estimates attributed to median trace flows for the Colorado River and the Salt-Tonto and Verde riverine systems, historical estimates of river flow, the projected population growth rate, a drought ending in 2015, and a 20% reduction in per capita water consumption by 2085.

Figure 4. The percent change in groundwater credits from initial volumes over the 70-year simulation for the city of Phoenix, Arizona, for the ensemble of scenarios conducted. The median response for the scenario ensemble (dotted line) and the plausible scenario (dashed line) are depicted. The dark hatched area represents the range in response between the 1st and 3rd quartiles for the plausible scenario; a 10% reduction on the Colorado River, a 30% reduction on the Salt-Tonto and Verde Rivers, the drought ending in 2015, 100% of population growth, and a 20% reduction (over year 2000 estimates) in per capita water consumption by 2085.

Figure 5. The variance (depicted using one standard error of the mean; normalized) in the percent of initial groundwater credits over the 70-year simulation period for the city of Phoenix, Arizona for the ensemble of scenarios conducted in this study. Individual factors were varied, one at a time, while holding all others constant. Please refer to the text for details.

Figure 1

Figure 2

Phoenix Metropolitan Area

Figure 3

City of Phoenix, Arizona

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773 Figure 4

Figure 5

776 Table 1.

Policy Scenarios		
Management Approach	Objective/ variable	Policy
Demand	<i>Municipal Drought Response</i>	Regulatory and voluntary reduction in water use
	<i>Growth Management</i>	Manage spatial allocation of growth based on sustainable water supplies
	<i>Other</i>	Programs to promote a more water efficient lifestyle (including indoor use versus outdoor use)
Supply	<i>Reclaimed Water: effluent</i>	Level of reclaimed water for non-potable use (outdoor) Level of reclaimed water for non-potable use (indoor) Level of reclaimed water for potable recycle Increased reclaimed and decreased effluent
	<i>Groundwater</i>	Increased groundwater recharge via local water banking Collaboration swapping of surface water for groundwater use Require/ enable physical connection between recharge and recovery
	<i>Remote water banking</i>	Amount banked and recovered
	<i>Temporary reallocation of surface water</i>	Mechanisms for using SRP water off-project
		Forced reallocation between haves and have not's

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External Scenarios		
Factor	Control	Event
Drought	<i>Surface water supply</i>	A dry cycle on the Colorado or Salt-Verde-Tonto system is long and deep enough to reduce allocations of surface water
		Extended dry cycle reduces natural recharge of aquifers
	<i>Demand</i>	A local dry cycle increases evapotranspiration and thus demand for some outdoor water use
Climate Change	<i>Supply</i>	Historical flow patterns of river systems is changed
		Historical patterns of dry cycles (length and magnitude) of river systems is changed
	<i>Demand</i>	Demand for outdoor water use changes
Economy	<i>Regional/ national population growth rate</i>	The rate of regional growth changes
		Patterns of growth and existing land use change

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Measure	Metric	Comments
Sustainable Supply	<i>Supply deficit</i>	<p>Number of years of supply deficit > 10%</p> <p>Longest length in years of continuous supply deficit > 10%</p> <p>Average number of years for events of continuous supply deficit > 10</p> <p>Average annual % supply deficit</p> <p>Largest annual % supply deficit</p>
Sustainable groundwater withdrawn	<i>Groundwater credits</i>	<p>Average % annual change in groundwater credit balance</p> <p>Lowest annual % change in groundwater credit balance (from initial simulation estimate)</p>
Population growth patterns	<i>Population patterns</i>	<p>Percent deviation in population growth from baseline scenario (no policy, market impact, drought or climate change impacts)</p> <p>Largest % annual deviation in population growth from the baseline scenario (see above)</p>
Water use efficiency	LPCD/GPCD*	<p>Average LPCD</p> <p>Percent change in LPCD from initial estimates</p> <p>Lowest annual % change in LPCD.</p>

807 *- Gallons per capita per day. Note: One GPCD = 3.785 liters per capita per day.

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813 Table 4.

Trace year	Flow characteristic	Median flow		One standard deviation	
start		(billion cubic meters annum ⁻¹)	(thousand acre- feet annum ⁻¹)	(billion cubic meters annum ⁻¹)	(thousand acre- feet annum ⁻¹)
1938	LF	15.817129*	12823.155	4.749729	3850.668
1922	MF	18.051953	14634.956	4.316591	3499.517
1906	HF	20.241605	16410.136	5.289063	4287.913

814 LF=low flow; MF=median flow; HF = high flow; * Rounded to the nearest acre-foot equivalent

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816 Table 5.

Trace year	Flow	Median flow		One standard deviation	
start	characteristic	(billion cubic meters annum ⁻¹)	(thousand acre- feet annum ⁻¹)	(billion cubic meters annum ⁻¹)	(billion cubic meters annum ⁻¹)
1946	LF	0.927702*	752.1	0.701851	0.701851
1922	MF	1.295156	1050.0	1.267156	1.267156
1965	HF	1.459579	1183.3	1.220284	1.220284

817 LF=low flow; MF=median flow; HF = high flow; * Rounded to the nearest acre-foot equivalent

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