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ORIGINAL ARTICLE

Simulating alternative sustainable water futures

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Abstract

In the United States of America, urban areas of the arid Southwest are prone to drought risk and changing precipitation patterns; future water supplies are uncertain. A collaborative working group of researchers and practitioners developed alternative future scenarios for 2060—sustainable water futures—that incorporate standard and novel water-adaptation strategies for the Phoenix metropolitan area (hereafter "Phoenix") in central Arizona, USA. The authors adapted WaterSim-6, a water policy and planning model, to explore differences in water demand and supply for three scenarios as influenced by (1) runoff from the rivers that supply surface water to Phoenix, (2) population growth, (3) water use efficiency, (4) annual rainfall, and (5) land-cover land-use changes. Centralized water-management strategies (direct and indirect potable water reuse and reclaimed supplies) and decentralized strategies (rainwater harvesting and greywater use) were explored. We observed decreased reliance on surface water supplies, offset by increased municipal groundwater pumping in the Strategic scenario, but by alternative water supplies (non-potable water sources including greywater, reclaimed water, and rainwater harvested) in the Desert Wetland and Almost Zero Waste (AZW) scenarios. Even under modest policy implementation and service-connection adoption rates associated with our Strategic scenario, by 2060 alternative supplies from non-potable sources could offset 30% or more of outdoor water demand. Aggressive policy implementations associated with the AZW scenario suggest that up to 80% of outdoor water demand could likewise be met. The WaterSim platform combined with co-produced future scenarios illuminates tradeoffs in support of decision making for long-term sustainability of a water-limited region.

Keywords Anticipatory · Adaptation · Alternative supplies · Strategic water use

Introduction

The future portends an increasing prevalence of water scarcity in several regions globally (Vörösmarty et al. 2000), including the United States (Groffman et al. 2014). Given their generally greater wealth and concentration of political power and human capital, cities, particularly those in the developed world, have the capacity to modify water sources and delivery to ameliorate their own problems of

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water scarcity (Vörösmarty et al. 2010), which may exacerbate stresses elsewhere. Nevertheless, cities still face the threat of water scarcity under climate change, for which they need to plan and implement sustainable solutions. This is particularly true in arid and semi-arid regions, which occupy nearly one third of the terrestrial land surface and house a growing number of rapidly expanding cities (McDonald et al. 2011).

Projected increases in the duration and severity of drought in the United States desert Southwest (Cook et al. 2015), punctuated by increased frequency of extreme precipitation events (Luong et al. 2017), create complex water management challenges for urban planning. In addition, uncertain population growth and urbanization (e.g., Gammage 2016; Gober et al. 2016), coupled with the current and projected future climate challenges of arid cities of the Southwest (Garfin et al. 2014), exacerbate the planning process. To maintain and improve human well-being in the future, cities must plan for and manage the changing interactions between drought and extreme weather events, growth, their interactions, and the uncertainty associated with them.

Cities must also consider alternative water policies and adaptation measures that ensure future water security while meeting current water demands. Planners need diverse social, ecological, and technological approaches for future water management, including decentralizing water management policies, integrating green (water management that protects, restores, or mimics the natural water cycle) and gray (man-made systems designed to move urban stormwater away from the built environment) infrastructure, and promoting land use with low water requirements, and technological innovations (Marlow et al. 2013; Gober et al. 2013; Larson et al. 2016). However, transitions to more sustainable forms of urban water management also require participatory, future-oriented approaches "to explore and appraise alternative governance regimes and their impacts" (Withycomb-Keeler et al. 2015).

Sustainable water management provides increased water security by adopting policies that conserve water, utilize alternative sources, or increase the efficiency of water use. Sustainable urban water management relies on natural features of the water cycle and diverse local water sources (Marlow et al. 2013). Traditional urban stormwater systems were designed to capture and divert rain and stormwater from city centers to impoundments or natural drainage corridors as quickly and safely as possible. Conversely, more sustainable water management objectives shift from simple flood mitigation to effective use that may include enhanced ecological integrity, urban amenities, and recreational value (Thomas et al. 1997). To achieve these objectives, solutions include disconnecting waterways from impervious surfaces, harvesting and using rainwater or greywater (waste water from baths, sinks, dish- and clothes-washing machines), and maintaining natural flow regimes while still reducing flood risk (Mitchell 2006; Walsh et al. 2012).

Computer simulation models may be used to compare and reveal the outcomes and tradeoffs associated with proposed long-term water sustainability solutions. A water policy and management model for the Phoenix metropolitan area (hereafter "Phoenix"), termed WaterSim, was developed to explore water policy and management options and the impact of climate change on short- and long-term water supply (Quay 2010; Sampson et al. 2016, 2011; Gober et al. 2016). This numerical systems-dynamic model permits evaluation of various social and biophysical factors influencing the urban water balance. For example, WaterSim-5 has been used to explore the impacts of population growth, changes in water-use efficiency, and future or novel policies on the capacity of Phoenix to thrive under climate change (Sampson et al. 2016) and megadrought conditions (Gober et al. 2016). However, a key limitation of the WaterSim-5 model was its inability to incorporate water conservation strategies (e.g., rainwater harvesting or greywater use), higher spatial resolution, or land-cover land-use (LCLU) change.

The objectives of this paper were to describe the structure and function of the revised and updated model, WaterSim-6, and then apply the model for three future scenarios with varying water conservation strategies and markedly different LCLU projections. We examined the potential impact of five key variables, (1) variation in projected population growth, (2) reduction in runoff for rivers that supply Phoenix, as projected under IPPC RCP8.5 (Ballinger and Kunkel 2019), (3) variation in local rainfall, (4) embedded LCLU change, and (5) new strategies for non-potable water use, to compare and contrast urban water sustainability for the three development scenarios.

Materials and methods

Study context

Phoenix, a large urban agglomeration in the Sonoran Desert of Arizona, has a high risk of exposure to drought (UN 2016). Its population is ~4.5 million people and 1.6 million households (https://statisticalatlas.com/metro-area/Arizona/Phoenix/Population), covering an area of ~23,000 km^2. Phoenix has 26 individual municipalities (cities and towns, the largest being the City of Phoenix), most within Maricopa County (a map may be found in Sampson et al. 2011), and is bordered by Indian communities, state, and federal lands.

The water supply for Phoenix comes from surface water, groundwater, and reclaimed water, and the relative mix of these sources varies by municipality. Local surface water is supplied from two watersheds with headwaters in the mountainous regions of central Arizona whose rivers (Salt and

Verde) converge northeast of the metropolitan area (hereafter referred to as the Salt River). Phoenix also imports water from the seven-state area of the Colorado River Basin via the Central Arizona Project Canal. The Salt River supplies roughly 925 million m^3 annually, with an additional annual input of 1.97 billion m^3 from the Colorado River. Climate change is expected to reduce flows on the Colorado River by ~ 11% compared to an average year (based on 112 climate projections; IPCC 2007). Reductions on the Salt River due to climate change may be substantially greater (Seshadri et al. 2014). The Colorado River provides surface water to over 40 million people; it is already over-allocated (US Bureau of Reclamation 2012; Dawadi and Ajmad 2012) by as much as 1.357 billion m^3 annually and projected to be over allocated by 3.947 billion m^3 by 2060 (US Bureau of Reclamation 2012). Pumped groundwater, a third source, is mixed with Salt River deliveries, comprising anywhere from 5 to 100% of a municipalities water supply portfolio (c.f. Sampson et al. 2011). Municipality variation in groundwater use is largely due to geography and water rights and thus strongly depends on when the city or town was incorporated. Reclaimed water typically represents only a fraction (< 3%) of the water-supply portfolio for Phoenix.

Several additional stressors will affect water in the region. Climate change is projected to significantly increase the intensity (high rainfall per hour) and frequency of extreme precipitation events. Increasingly extreme monsoon precipitation has been observed for the Southwest in general (Petrie et al. 2014; Chang et al. 2015), and Phoenix in particular (Luong et al. 2017). By 2060 extreme precipitation events are likely to be even more common. If increased urban development follows historical trends, impermeable surface area will expand and exacerbate urban flooding. Finally, population is expected to increase by at least 1.1% annually (UN 2016), with the increase in Maricopa County being as high as 2.0% annually (https://population.az.gov/sites/default/files/documents/files/pop-prj-04013-2016-2050-SocioEconNum-Final.pdf). There is little indication of a slow-down in these high rates of population growth.

The Sustainable Future Scenarios project, through a collaborative participatory process with community, municipal, and academic stakeholders, has co-produced and envisioned water futures for Phoenix out to the year 2060 (https://sustainablefutures.asu.edu; Iwaniec et al. 2020). In a co-development workshop setting, participants identified distinct future visions and pathways (hereafter "scenarios"), and explored outcomes, conflicts, and trade-offs among interacting strategies for urban sustainability and resilience (Iwaniec et al. 2014; Iwaniec and Wiek 2014). The process of envisioning diverse scenarios created > 100 alternative configurations of water sustainability policy and design; here we focus on 14 (Table 1) that we were able to implement into the WaterSim-6 platform.

The WaterSim model has undergone 15 years of continual development. Accordingly, multiple versions of the model reflect various enhancements through time. Governing equations for the internal processes unique to each version, and structural changes, may be found in successive publications: for water utilities and their water rights and supplies please refer to Sampson et al. (2011); for structural changes related to modeling water demand please refer to Sampson et al. (2016). Equations relevant to this contribution are referenced, below, via the supplementary material.

Table 1 Water supply and demand management policies and water system management strategies examined under three future scenarios, and their governance mechanisms

Policies and strategies modeled	Governance
Supply management	
Augmented water	Centralized
Banked water	Centralized
Direct potable water reuse	Centralized
Effluent redistribution	Centralized
Greywater use	Decentralized
Indirect potable water reuse	Centralized
Rainwater harvested	Decentralized
Reclaimed water for direct outdoor use	Centralized
Demand management	
Density driven land-cover land-use change	Centralized
Population growth projections	Centralized
Water system leaks	Decentralized
Water use efficiency: indoor and outdoor	Centralized
Water system management	
Timing and implementation rate of non-potable water use policies	Centralized
Timing of implementation for alternate potable water supplies	Centralized

Scenario descriptions

For this study, we focused on three future scenarios for Phoenix: (1) Strategic, a type of business-as-usual scenario, (2) Desert Wetland (DW), addressing future flood resilience, and (3) Almost Zero Waste (AZW), which addresses waste reduction in all sectors. The three scenarios were selected from a suite of seven Sustainable Future Scenarios (Iwaniec et al. 2020) because they emphasize and explore distinct, alternative pathways to meet water sustainability goals through policy and design strategies. The Strategic scenario was generated to reflect a plausible future for Phoenix based on existing municipal planning goals and policies. Reflecting what is likely to occur in the future, this scenario serves as a baseline for comparison with other future scenarios. The DW and AZW scenarios reflected shared future visions from diverse stakeholders (detailed in Iwaniec et al. 2020). DW enhanced multi-scalar hydrologic connectivity to support an extensive green infrastructure network. AZW emphasized aggressive strategies for water conservation, capture, reuse, recycling, and large-scale centralized storage. Please refer to S1 for details.

LCLU classification and trajectories

WaterSim-6 uses high-resolution LCLU data to estimate water demand. To classify LCLU in each scenario, 30-m resolution Landsat Thematic Mapper (TM) data were classified for the year 2015 using an object-based expert knowledge system (Li et al. 2014), which generated a land-cover map with an overall accuracy of 96% that accommodates the Anderson classification system. The authors then used the co-produced description of each future scenario to create LCLU maps for year 2060 (S1).

Model development

The WaterSim-6 model framework comprises a suite of models, modules, and linked languages that together create a modeling platform. Like WaterSim-5, the model uses a programmer's interface to run applications that automate the process of creating individual or multiple ensembles of "what ifs" by modifying exogenous factors that affect water supply and water demand, and/or the policy levers (controls) that reflect various water-management policies

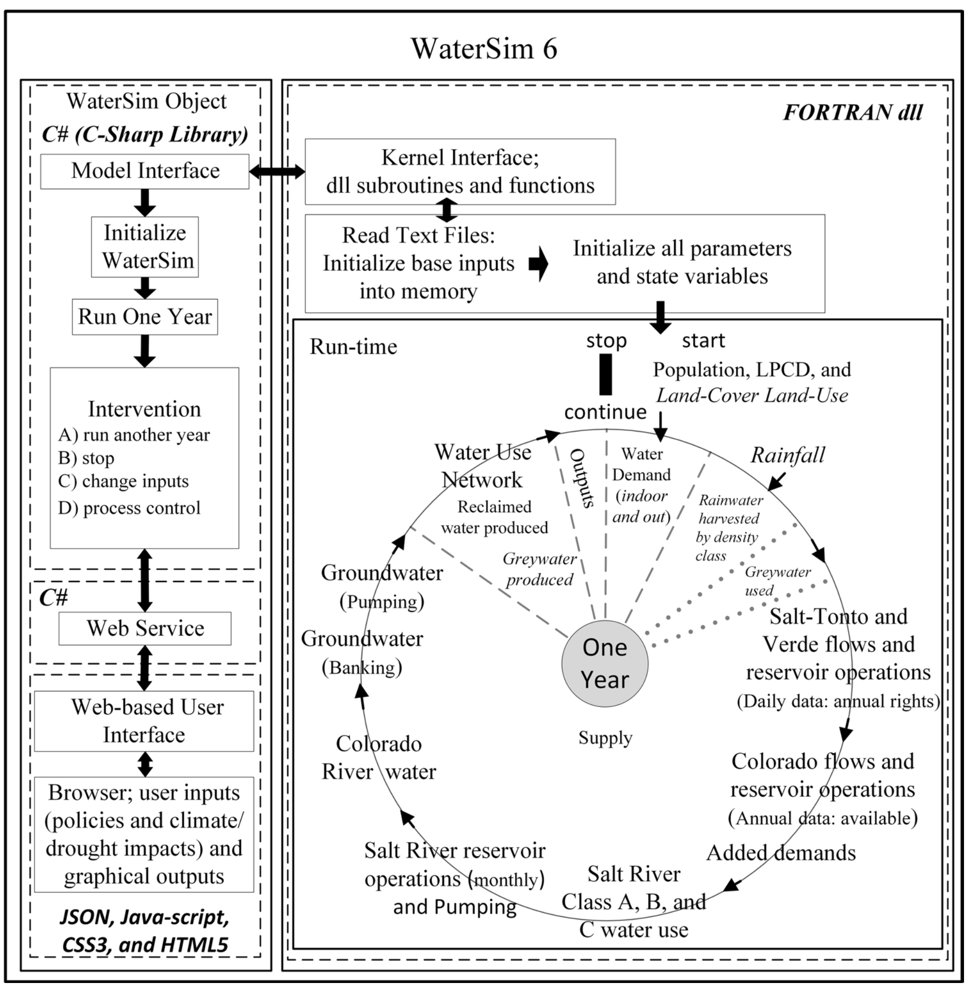

Fig. 1 The WaterSim-6 water policy and management model for the Phoenix Metropolitan Area. This framework includes the C–sharp libraries of the model interface and the overall linkage to the FORTRAN dynamic link library (dll) which contains the separate modules used to estimate water demand, water supply, and water use. Italicized text denotes new aspects of the WaterSim-6 model not found in previous versions

(Fig. 1). Here we describe the specific enhancements to WaterSim-5 for this work.

WaterSim-6 includes new water demand estimates and new supplies. From a published dataset for urban indoor and total water use for a broad sweep of municipalities across the United States (DeOreo et al., 2016), we created equations to estimate indoor and outdoor water demand (S2). We also added new water sources, including the harvesting and reuse of rainwater and greywater, in addition to reclaimed water, to meet outdoor water demand. Implementation of novel policies such as these must overcome several hurdles, including city codes and statutes, before widespread adoption by a citizenry. In Arizona it is already permissible to capture rainfall and to use greywater. Algorithms were created to mimic the temporal dynamics (and rates) for these new policies. A hierarchy in use was established based on relative cost to secure (from least costly to most costly): rainwater < greywater < reclaimed water (S3). The three urban density classes in our LCLU data (high, medium, and low urban density) translated here into multi-family, single family, and peri-urban housing units, respectively, for estimating residential water use (S2).

Simulations conducted

Simulations within WaterSim-6 start in the year 2000 using historical estimates of input drivers that run through varying intervals of time, depending on the empirical data available. However, by 2016 all simulations are projections. WaterSim uses historical estimates of river flows to project future conditions. We selected a high-, median-, and a low-flow trace (30-year segment from the historical record) for each river system (S3). To be conservative, we varied our estimates of rainfall from 70% of average to 110% of average in 10% intervals. Population projections are inherently uncertain, so we varied population growth from 80 to 120% of that projected by the Maricopa Association of Governments, in 10% intervals. And, although water-use efficiency has been increasing by about 1% per year (our default projection), we do not know if per capita water use (liters per capita per day; LPCD) will decline faster than current trends, so we varied LPCD from 70 to 100% of that projected, also in 10% intervals. Thus, each of the three future scenarios of LCLU out to 2060 resulted in 900 separate 60-year runs for a total of 54,000 records (3 * 3 * 5 * 5 * 4). These data were analyzed using SAS (2013).

All graphics were created using SigmaPlot® (version 10.0 Systat Software, Inc., San Jose California USA, www.sigmaplot.com). Statistical significance was evaluated at the 0.05 probability level.

Results

Simulated water demand, LCLU, population, and per capita water use

For the Strategic scenario, simulated, total water demand for residential, commercial, and industrial (i.e., municipal) water users for Phoenix peaked at 1.18 billion m^3 $year^{-1}$ in 2024 before decreasing and nearly leveling off at 0.84 billion m^3 $year^{-1}$ by 2048 (Fig. 2a). The variance in total water demand increased with time; one standard deviation of the mean resulted in ~ 0.4 billion m^3 $year^{-1}$ difference in demand in 2060. The medium-density LCLU class accounted for the dominant share of total water demand, decreasing 39% over the simulation from 0.80 to 0.39 billion m^3 $year^{-1}$. Regional water demand increased over time for the low- and high-density LCLU classes; by 2060 high-density water demand had increased by 36% while low-density increased by 19% (Fig. 2a). Regionally, our worst-case simulation set demonstrated a 30% increase in water demand by 2060 (plausible)

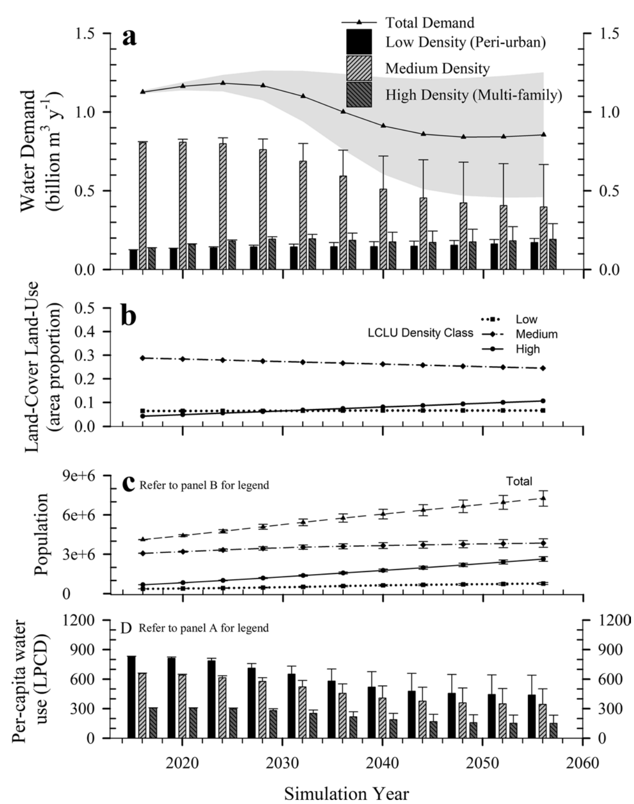

Fig. 2 Total water demand and demand by density classification (**a**), change in land-cover land-use (LCLU) over time for three density classifications (**b**), temporal estimates of population (**d**), and the liters per capita per day (LPCD) personal water use (**d**) used in simulations for the Strategic scenario. Error bars (and the area plot shaded background) denote two standard deviations of the mean

while the best case resulted in a 55% reduction in demand (highly unlikely); the mean response suggests that water demand for the region in 2060 would be 18% less than the 2015 estimate (for the Strategic scenario) while adding an additional 3 million people to the region.

The proportional area for low-, medium-, and high-density LCLU classifications for the Strategic scenario varied through time, with the regional mean value for medium-density roughly three times that of the low- and high-density classes (Fig. 2b). Medium-density LCLU decreased by 20% by 2060 while high density increased by 123%. Low density remained roughly unchanged.

Total projected population for the region (independent of the scenario examined; all three used the same water provider-specific population growth) increased from a little over 4 million people in 2016 to 7.3 million by 2060 (Fig. 2c). Uncertainty in population growth for the region resulted in ± 1 million people in 2060. For the Strategic scenario, population for the medium-density LCLU class increased slightly (15%) through time, with roughly three times the population of the low- or high-density LCLU classes in 2016. However, population for the high-density LCLU class increased sharply, nearly tripling (260%) by the year 2060, whereas population for the low-density class merely doubled (Fig. 2c).

Finally, the low-density LCLU class had significantly greater per-capita water use than the medium-density class up to about the year 2032, but low-density and medium-density classes exhibited a decrease in per-capita water use of 47% and 48%, respectively, by the year 2060 (Fig. 2d). High-density LCLU exhibited roughly one-third the per-capita water use of the low-density class, decreasing by 51% over the same period.

Simulated water demand difference

Differences in water demand among the three municipal LCLU classifications depended on the year and the scenario examined (Fig. 3). We observed a 37% increase in water demand for the DW scenario for the medium-density LCLU classification (Fig. 3A) when compared to the Strategic scenario, but water demand decreased for high-density classes starting in 2016 and for low-density classes starting in 2032. Because of the large decrease in water demand from low- and high-density classes, overall municipal water demand in the DW scenario decreased 10% over the simulation (compared to the Strategic scenario). Water savings from high-density development accounted for the greatest share (69%) in the overall water-demand reduction for this scenario. Conversely, the AZW scenario had an inverse response in water demand by density class, in which low- and high-density LCLU classes increased their water demand relative to the Strategic scenario (Fig. 3B) and the medium-density class

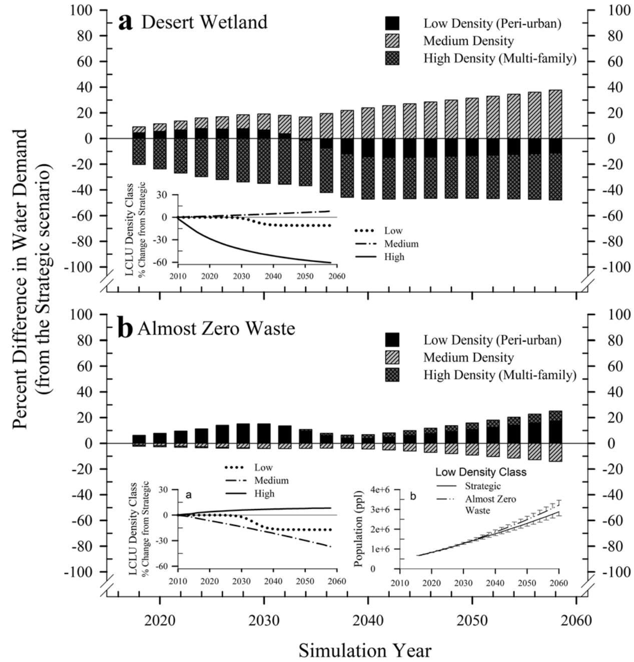

Fig. 3 The percent difference (i.e., [[response-control]/control]*100) in water demand by density class between the Strategic scenario and the Desert Wetland (**A**) and the Almost Zero Waste (**B**) scenarios over a 45-year simulation. The graph inserts for **A**, and for **B**.a depict the land-cover land-use (LCLU) change for the three density classes for each scenario. Population for the low-density class compares the Strategic to the Almost Zero Waste scenario in **B**.b, with the unidirectional error bars denoting two standard deviations of the mean

exhibited a reduction in total water demand. In the AZW scenario, water demand for low-density and high-density combined approached 25% greater than the Strategic scenario, whereas the medium-density class declined by ~ 15% by 2060 (Fig. 3B). Accordingly, overall water demand increased for the AZW scenario by ~ 10% when compared to the Strategic scenario.

Simulated water supply

Water supply sources for the three scenarios exhibited somewhat similar patterns over time (Fig. 4). We observed decreased surface-water use as a proportion of total supply over time; the use of Colorado River surface water to meet demand decreased from 39% of total water used in 2016 to about 18% by 2060 (a 54% decrease) for the Strategic scenario (Fig. 4a). About 40% of this reduction can be attributed to climate change and drought resulting in decreased riverine runoff, leading to decreased surface-water supplies (data not shown). Allocations of Salt River water decreased 41% between 2015 and 2060. Increased groundwater pumping and the availability of alternate water supplies helped to offset reductions in surface water availability and reduced water deliveries. Specifically,

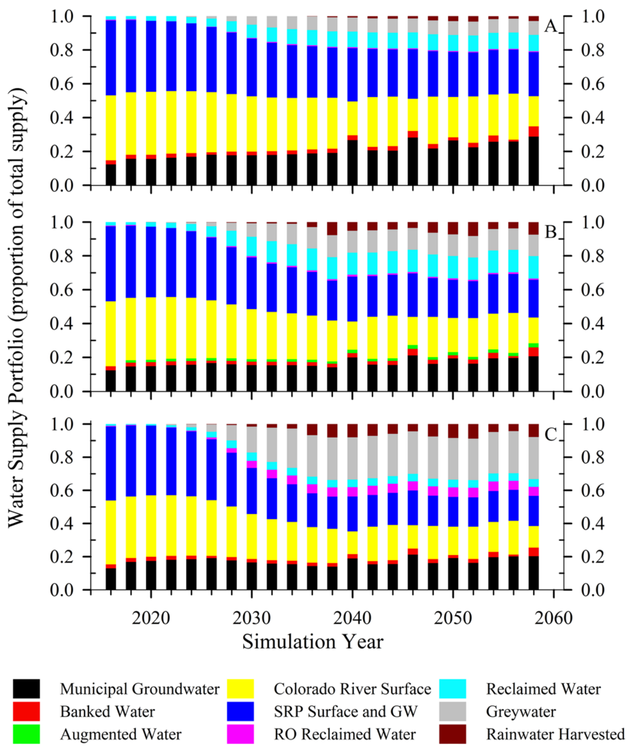

Fig. 4 The 45-year water supply portfolios as a proportion of total water delivered for the Strategic (**a**), Desert Wetland (**b**) and the Almost Zero Waste (**c**) scenarios examined in this study. The order of the arranged sources (from the top down) reflects their hierarchical use in the WaterSim-6 model

for the Strategic scenario, demand met by groundwater more than doubled (~ 12% of the supply in 2016 to 29% in 2060) over the simulation; increased use of reclaimed water (10%), greywater (8%), banked water (6%), and water supplied by rainwater harvesting (3%) made up the difference by 2060 (Fig. 4a).

The patterns in the water-supply portfolios for the DW and AZW scenarios were similar to the Strategic scenario but differed in magnitude for most of the supplies used. In the DW scenario increased use of rainwater (4%) and greywater (5%)—and a 10-year earlier start to that use— and reclaimed water (3%) by 2060 balanced out the 17% lower surface-water use and ~ 28% lower groundwater use when compared to the Strategic scenario (Fig. 4b). Over the same period Salt River water deliveries decreased by 50%. The DW scenario also had additional supplies from augmented water (2%). In contrast, our AZW simulations used 28% less surface water and 31% less groundwater in 2060 when compared to the Strategic scenario (even with a 10% increase in total demand). We saw a 60% reduction in deliveries in the AZW scenario. In this scenario, substantially more rainwater and greywater was used (100% of service connections by 2040), with non-potable water comprising almost 40% of the total water portfolio by 2060 (Fig. 4c). Potable reverse osmosis (RO) water accounted for an additional 5–6% for this scenario.

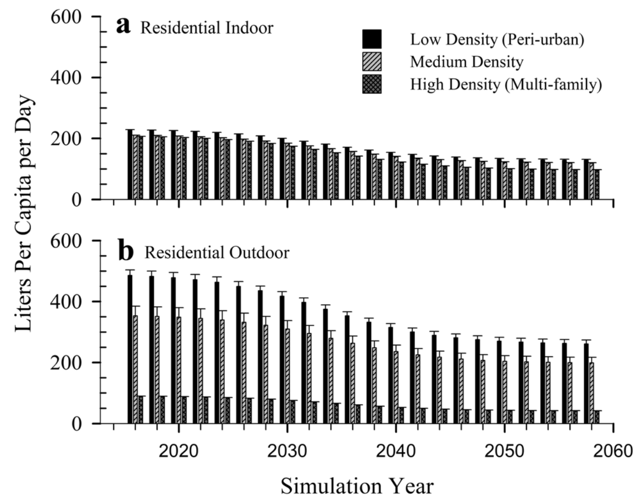

Fig. 5 Residential Indoor (**a**) and outdoor (**b**) personal water use for the three land-cover land-use classifications used in this study. Error bars denote two standard deviations of the mean

Water use differentials for the Strategic and AZW scenarios indicate divergent groundwater dependence and convergent surface-water use. We saw a slight increase in groundwater use by the Strategic scenario (1.5%) but decreased use (6%) for AZW simulations for 2060 when compared to the unconstrained scenarios. Our surface-water reliance proxy suggests that the Strategic and AZW scenarios used about 18% and 41%, respectively, less surface water by 2060 than the constrained simulations (data not shown). This difference amounted to about 4% and 9%, respectively, of the total supplies used.

Residential water use

Residential indoor and outdoor personal water use decreased over time in all three scenarios (exemplified by Strategic in Fig. 5). Indoor water use decreased to ~ 50% of 2015 per capita use by 2060 in all scenarios (Fig. 5a), whereas outdoor water use differed among classes. The peri-urban LCLU class used 50–150 L cap^{-1} day^{-1} more than the medium-density class (Fig. 5b) and, more strikingly, the high-density class used five times less outdoor water at the start of the simulation than the low-density class. However, differences in outdoor water use among LCLU classes were reduced by 2060.

Non-potable outdoor water use

For the Strategic scenario, non-potable water use met roughly 45% of total outdoor water demands for the region starting after 2040 (Fig. 6a). The error reported represents

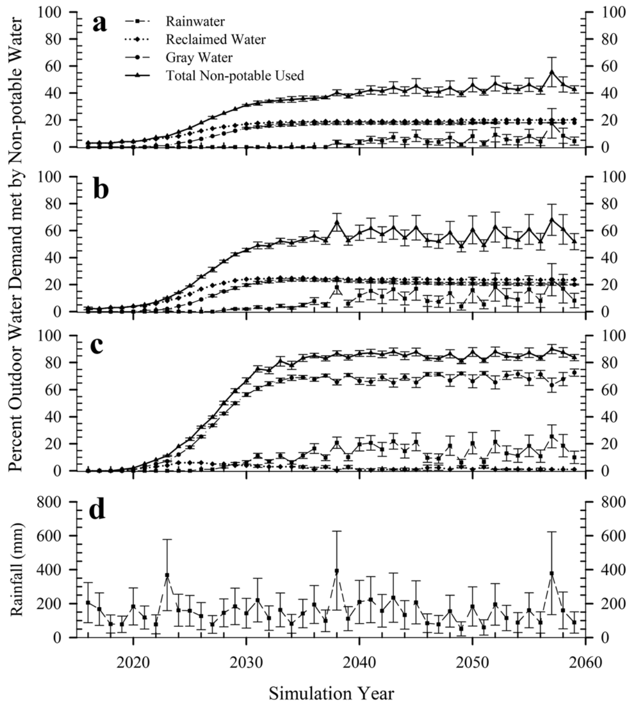

Fig. 6 Non-potable water supplies used to meet outdoor water demands for the Strategic (**a**), Desert Wetland (**b**), and the Almost Zero Waste (**c**) scenarios simulated in this study. Data represent the percent of outdoor water used by non-potable sources (solid line, solid triangle) for each source; greywater used (dashed line), rainwater harvested (dotted line with the associated 5 and 90 percent confidence interval), and reclaimed water (dash-dot line) from a water treatment plant. Error bars denote two standard deviations of the mean

the combined uncertainty associated with rainfall and future water demand, given uncertainties in population growth and per-capita water use over time. Use of greywater and reclaimed water was roughly equivalent after 2036, meeting about 20% each of total outdoor water demand; rainwater harvested added an additional 5% (after 2042). Plausible changes in inter-annual variation in rainfall over the simulation, and in potential changes in rainfall received, amounted ~ 2.5–10% of outdoor water demands being met by rainwater harvest (Fig. 6a).

Non-potable water supplies for the DW and AZR scenarios met, on average, about 65% and 85%, respectively, of all outdoor water demands after 2036 (Fig. 6b, c); rainfall itself was highly variable (Fig. 6d). For the DW scenario, greywater and reclaimed water use were roughly identical but accounted for ~ 28% each of the non-potable water used to meet outdoor water demand (Fig. 6b). Water supplied by rainwater harvest averaged ~ 10% at the outset but reached 25% of water use. Of the three scenarios, AZW had the greatest use of non-potable water, largely greywater (Fig. 6c). In this scenario, greywater was projected to meet ≥ 70% of total non-potable outdoor water used (Fig. 6c). Rainwater harvested in the AZW scenario was somewhat similar to DW. Reclaimed water used directly for outdoor irrigation was not important as a non-potable water source in the AZW scenario. Our estimates of annual rainfall reached or exceeded 600 mm on a few occasions but were usually ≤ 150 mm, with an overall average of 155 mm year^{-1} (Fig. 6d).

Discussion

Existential threats to water systems (i.e., intensifying floods, drought, loss of snowpack, reductions in river baseflow) in an uncertain future cannot be resolved through business-as-usual policies (Gober 2018). Phoenix, like other aridland cities, will experience challenges in the future that will strain existing management, engineering, and governance systems (Gober and Kirkwood 2010) and require difficult decisions reconciling water availability and tradeoffs in water use (Gammage et al. 2011). WaterSim-6 allows exploration of such tradeoffs and the policies needed to meet upcoming water-security challenges for the region and, when coupled with future LCLU scenarios, can be used to compare alternative, density-related development pathways.

Our simulations demonstrated that exercising decentralized control over potential, available, and alternative sources of water to meet outdoor water demands holds promise (Fig. 6). However, non-potable sources offer distinctly different contributions towards meeting outdoor water demands. Rainwater, while freely available, is inconsistent in the desert Southwest. Moreover, rainwater harvesting would likely have little impact on irrigation demands for the common water-intensive outdoor landscapes (c.f. Larson et al. 2013), but may be sufficient to sustain xeric, low-water-use landscapes. While rainwater harvesting guidelines, rebates, and free workshops exist, rainwater harvesting in Phoenix remains unconventional and is not yet widely adopted.

Greywater would provide a consistent, reliable source for outdoor irrigation, but there are tradeoffs and financial costs (Oron et al. 2014). Arizona has regulations for the implementation of decentralized greywater systems, but their use for outdoor irrigation is also rare. To manage residential greywater, existing houses could be retrofitted to use greywater and new construction could be fitted with "purple pipes" for centralized control by a water utility. For example, following a prolonged drought, Australia implemented "fit-for-purpose" recycled water using third-pipe reticulation systems for new housing developments in many of their larger cities (Radcliffe 2015). After the rains returned, decentralized systems for non-drinking purposes were encouraged in Sydney and elsewhere. Water utilities have valid concerns regarding widespread use of decentralized system. Reducing the liquid fraction of a wastewater system would reduce gravity-controlled movement of solids to the wastewater treatment plants. Yet, as the prospect of prolonged drought lingers here in the Southwest, alternative water sources will receive increasing attention.

Sustainable water futures

The SFS project scenarios examined here represent three potential pathways to anticipate (cf., Quay 2015) and adapt to future challenges in water supply and demand. The scenarios integrate sustainable water strategies to address urban growth and climate change, including future extreme drought and flooding events. A sustainable Phoenix will almost certainly include both old and new strategies for the management of water demand and supply. Of course, the specific strategies employed (Gober et al. 2016), and when and to what extent they would be implemented in each community, will depend on water-system triggers (i.e., shortage sharing elevation tiers on Lake Mead, balancing releases on Lake Powell, etc.) short- and longer-term meteorological events, as well as societal changes, such as economic growth (or decline) and improved (or reduced) community resilience to drought and a changing climate.

Our simulations suggest that future reductions in surface-water supplies resulting from climate change can likely be mitigated through planned water adaptation strategies. However, effective mitigation will likely depend on incorporating decentralized alternative water supplies, and making strategic decisions about future development and LCLU change, and increasing public acceptance and, thus, adoption of water-adaptation policies. The trajectory of regional water demand out to 2060 will depend not only on future land-use change and population growth, but also on residents' willingness to live in higher-density buildings and improve water-use efficiencies (Fig. 2).

Our simulation results demonstrate two strategic insights. First, patterns of development and thus changes in outdoor water use over time will have significant impacts on future water demand for Phoenix. For example, the Strategic scenario projected a significant decrease in water demand largely as a result of a reduction in the regional extent of medium-density development coupled with a significant decrease in per-capita water use in the medium-density class, even as population increased (Fig. 2a, d). In concert, significant reductions in low-density per-capita water use bolstered total demand reductions. At the same time, water demand for the high-density class increased 36% by 2060. This increase was associated with both an increase in the proportion of high-density development for the region and an increase in population amounting to over one million new service connections by the year 2060 (Fig. 2a–c). The overall reduction in future water demand can be explained to a large extent by a reduction in outdoor water use over time (Fig. 5).

Outdoor water use depends, to a great extent, on irrigable area, which is dependent on housing density (Chang et al. 2017), vegetation type, ambient temperatures, and precipitation amounts (Ouyang et al. 2014; Kiefer et al. 2013; Polebitski and Palmer 2010; Balling et al. 2008). Thus, increasing the density of development will likely decrease per-capita outdoor water use. Likewise, income is often a significant factor when analyzing outdoor water use (Chang et al. 2017; Larson et al. 2010); our outdoor water-use estimates are spatially explicit and based, in part, on median income of a community but also on people per household and actual evapotranspiration (S2). Outdoor water use represents at least 40% and as much as 65% of total residential water use (DeOreo et al. 2016; Mini et al. 2014); simulated estimates presented here suggest that the outdoor water demand in high-density development is a quarter or less that of the medium- and low-density classes.

Conversely, our DW and AZW scenarios had markedly different trajectories in projected water demand and use. For the DW scenario, increased water demand in the medium-density LCLU class was offset by decreased regional development in the low- and high-density classes (insert; Fig. 3A). The 10% reduction in total water demand in this scenario can largely be attributed to water savings brought about by the reduction in peri-urban and high-density housing and, thus, reduced overall outdoor water demand (Fig. 5b. Conversely, for the AZW scenario, the 10% increase in water demand can be explained by increased population movement into low-density development compared to the Strategic scenario (insert; Fig. 3B.b), and thus increased indoor and total outdoor water demand for the region (Fig. 5a, b).

Second, enhanced water supplies from non-potable sources have significant impacts on local and regional water budgets. Namely, simulations demonstrated that as surface-water supplies were curtailed as a result of climate change-driven reductions in runoff, municipal groundwater pumping increased in the Strategic scenario (Fig. 4a). Of course, these simulations assumed that only 30% of the existing and new population growth implemented rainwater harvesting and greywater use. With 60–80% or more adoption of these policies and earlier implementation, groundwater pumping in 2060 could be similar to, or even less than, the volumes currently pumped (Fig. 4b, c). Maintaining groundwater pumping at 2015 levels could be achieved, then, by continuing to increase current water-use efficiency and use of non-potable water to meet outdoor water demands, thus meeting safe-yield (the balance between the amount of groundwater pumped and the amount of water naturally and/or artificially recharged) goals for the region (ADWR 2011).

Our simulations highlight that when reductions in surface-water deliveries are realized as a result of reduced flows on any or all of the two main rivers that supply Phoenix, alternative water sources—rainwater harvesting, greywater—would gap-fill the curtailment of deliveries from the Colorado and Salt Rivers. Runoff from the three principal rivers is expected to decline throughout the century as a result of climate change with projections for reductions in flow up to 37%, but the uncertainty in these estimates is high: a 10% increase or a 60% decrease by 2100 relative to historical flows could be possible (Cayan et al. 2010; Rajagopal et al. 2014).

If the current patterns in regional development persist, that is, increasing density remains a valued objective for Phoenix communities and population growth proceeds as projected, our Strategic scenario (baseline) simulations suggest that overall water demand could diminish 27% by 2060 after peaking around 2025 (Fig. 2a). Historical data for the State of Arizona demonstrate that, while population has more than doubled, overall water use up to the present has remained stable since 1980 (ADWR 2016). Much of this response has been from the adoption of water-efficient fixtures and appliances and more efficient outdoor water systems in new housing construction, as well as increased housing density and a shift to more xeric landscapes over time. The “Sun Corridor” of Arizona, an interstate-driven development corridor that stretches from roughly Prescott to Tucson, could likely accommodate several million new residents without additional water supplies, assuming difficult decisions regarding the balance between water use and lifestyle are made (Gammage et al. 2011; Gammage 2016). Housing will likely continue to become denser as less land is available for development, communities build out (maximum development as permitted by a plan or regulations) completely, and cultural values regarding housing and lifestyle choices shift. Of course, we do not know which new policies will be broadly accepted over time.

Conclusion

The SFS process to develop participatory scenario pathways, combined with the upgraded WaterSim-6 model, is a valuable approach for exploring alternative water futures. The Phoenix scenarios integrate the knowledge, values, and visions of diverse stakeholders to examine a rich array of strategies-some known and others imagined (Iwaniec et al. 2020). Here we have focused on strategies and visions as assessed with the WaterSim model to identify potential impacts and tradeoffs. These model outcomes are then available for re-evaluation in a follow-up participatory setting, where we would expect to build capacity for future thinking, create buy-in and shared understanding of effective solutions, and support the implementation of sustainability strategies. Models that consider the socio-hydrological interactions among physical, technical, and socioeconomic factors provide and support adequate decision making processes (Gober et al. 2014).

Although we cannot predict with any certainty the future water demand and supplies for Phoenix, we can presume that to sustain Phoenix in a changing climate, both existing and new strategies for water demand and water supply management will be needed. The specific strategies that ultimately will be employed will likely depend on meteorological events but also socio-political change. Resilience to drought and other aspects of climate change in Phoenix, and communities’ willingness to adopt new policies and strategies, will also affect water-use transitions. Uncertainty in future population growth, LCLU change, increases in the efficiency of water use, and the climate system will influence the timing and adoption of policies needed to meet the water demand needs of Phoenix in the year 2060.

Assumptions accompany all modeling exercises. While inherent assumptions of the WaterSim model may be found in the referenced publications, those salient to this effort include the following: (1) indoor and outdoor water demand estimates are representative of future household water use, (2) homeowners would be both financially capable of purchasing water storage tanks and would have the requisite space on their property for installation, (3) retrofit implementation of decentralized greywater systems are financially viable, and (4) historical flows on the rivers can be used to represent potential, future flows. We recognize that the 8.5 Representative Concentration Pathway is no longer considered feasible (Hausfather and Peters 2020); this research was initiated, and finalized, several years before this new paradigm emerged. And, although we also recognize that stationary is “dead” (Milly et al. 2008), our assumed high and low flow 30-year trace periods from the historical record likely bound potential, future, flow conditions.

Two salient findings emerged from this study. First, urban development over time will have significant impacts on future water demand for Phoenix. Although population growth is expected to continue unabated, water demand will decrease because of a reduction in the regional extent of medium-density development coupled with a significant decrease in per-capita water use in medium-density housing. Nearly 3 million new residents by 2060, primarily housed in high-density areas, will increase water demand yet simulations suggest a 27% net decrease in overall water demand attributed to outdoor water savings. Second, alternative water supplies from non-potable sources could meet a significant portion of outdoor water demand, depending on early and impactful adoption of policies, such as rainwater harvesting and greywater use for outdoor irrigation. These alternative supplies could, to a large extent, help offset climate-attributed reductions in surface-water supply to Phoenix.

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