A Spatial Optimization Model for Water Supply Allocation

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Abstract

Climate change is likely to result in increased aridity, lower runoff, and declining water supplies for the cities of the Southwestern United States, including Phoenix. The situation in Phoenix is particularly complicated by the large number of water providers, each with its own supply portfolio, demand conditions, and conservation strategies. This paper details spatial optimization models to support water supply allocation between service provider districts, where some districts experience deficits in certain years and other districts have surpluses in various years. The approach seeks to reconcile and integrate projections derived from a complex simulation model taking into account current and future climate conditions. The formulated and applied models are designed to help better understand the expected increasingly complex interactions of providers under conditions of climate change. Preliminary results show cooperative agreements would reduce spot shortages that would occur even without climate change. In addition, they would substantially reduce deficits if climate change were to moderately reduce river flows in Phoenix's major source regions, but have little effect under the most pessimistic scenarios because there are few surpluses available for re-allocation.

Introduction

Climate change portends considerable risk of water shortage in the Southwestern United States, where supplies are already over-allocated in many places and there is growing competition for these limited supplies, both between farmers and municipalities as well as among municipalities (National Research Council, 2007). This region contains some of the fastest growing cities in the U.S., including Phoenix (Maricopa County) which grew by 28.2% between the years 2000 and 2008 (U.S. Census Bureau 2009). Water management decisions are for the most part highly fragmented and localized; they are largely decoupled from land use and growth decisions. With a few notable exceptions, the institutions that govern water do not adequately incorporate climate change into long-term planning but assume the principle of "stationarity"—the idea that environmental systems function within a known envelope of variability based on the historical record (Milly et al., 2008). This localized structure of management and decision making and the failure to consider the impacts of climate change expose the region to significant vulnerability to water shortage by the middle of this century.

Historically, the growth and economic development of Phoenix, like other cities of the arid West, have been supported by the erection of dams, reservoirs, and canals to transport water over long distances to areas of human settlement. Phoenix's large hydraulic reach includes watersheds immediately north whose rivers (the Salt and Verde) deliver an average of 1 million acre-feet of water annually. This surface water supply was augmented in the 1980s by the construction of the Central Arizona Project, a 336-mile aqueduct delivering 1.4 million acre-feet of Arizona's allocation of Colorado River water to Phoenix and Tucson. In addition to these two surface water sources, the Phoenix area has used groundwater to support both agriculture and urban development. Groundwater from large sedimentary aquifers has served as a reserve from which water could be drawn during periods when surface supplies are in deficit (Gober, 2005).

This diverse portfolio of water supply has supported growth, first during a period of large-scale agricultural development early in the 20th Century and later during rapid postwar urbanization. Future growth (Maricopa County is projected to grow from 4.2 million in 2010 to 7 million by 2040) will intensify competition for water, both between the municipal and agricultural sectors and among municipalities (Arizona Department of Commerce, 2010). While increasing population will add to the demand for water in the coming years, climate change threatens to reduce river flows from both the Colorado River Basin (Christensen et al., 2004; Seager et al., 2007; Christensen and Lettenmaier, 2007; National Research Council, 2007; Barnett and Pierce, 2008) and the upstream watersheds of the Salt and Verde (Ellis et al., 2008). The Southwest is among the many areas of the world that are in need of new tools for long-term water planning.

Complicating matters is that water policy and decision making are highly fragmented. Decisions about how to cope with rapid growth and how to manage supply portfolios are not in the hands of regional authorities, but occur at the local level by 119 public and private providers in the region with 33 accounting for more than 90 percent of current demand. Each provider has individual water rights that vary by source, based upon the seniority of historical claims and use. As a result they are unequally exposed to the effects of climate change, depending upon whether their supplies come from the Salt/Verde system, the Colorado River system, or groundwater as well as the seniority of their rights within those systems. For example, shortages on the Colorado River would differentially affect Scottsdale, which depends upon it for current and future water supplies, whereas Tempe and Phoenix rely more heavily on Salt/Verde flows. Thus, Tempe and Phoenix would suffer if climate change were to reduce river flows on the Salt and/or Verde. Moreover, providers have very different population growth trajectories, with those on the urban fringe expected to double, triple, or even quadruple in size, while landlocked older cities have leveled off in population, and hence water demand.

A future of growing uncertainty about climate conditions suggests the need for providers to engage in some type of regional cooperation. Under current arrangements, some providers will face a range of water needs that simply cannot be met independently. With the specter of climate change and uneven geographic impacts, it is possible for some providers to experience surplus while others experience deficit. One form of climate adaptation would be to develop a new set of rules for sharing in times of deficit.

This paper develops optimization modeling approaches designed to provide insights on how independent water providers might engage in regional cooperation in the management of water, particularly under various climate change and population growth scenarios. In a situation where some providers in the region have surplus water supplies while others face deficits, how can providers cooperate in a beneficial manner? What are the implications of the possible outcomes? We develop models to explore these issues under a range of climate and population scenarios. The next section discusses literature related to this research. This is followed by the mathematical specification of the developed models as well as details explaining the intent and purpose of the approach. Results of model application to the Phoenix metropolitan area are then presented. This is followed finally by a discussion of the results and concluding comments.

Literature Review

Conceptually, water resource allocation is very similar to that of economic equilibrium between spatially separated markets, a problem initially addressed by Enke (1951). A linear program oriented toward structuring this process was detailed by Samuelson (1952). While not focused on water, the modeling approach is commonly referred to as the foundation for water allocation research, as water resources can be approached as a specific example of this economic equilibrium problem (Enright and Lund 1991, Marin and Smith 1988, Vaux and Howitt 1984). Much work along these lines has followed focused on the spatial allocation of water in a region. Becker (1995) developed a spatial model for the optimization of water distribution to several consumers. This model incorporated a single limited water source controlled by a central provider and distributed according to a market system. Garrido (2000) later developed a model that was also based upon the concept of a single provider allocating water to several consumers in a market system. This model extended previous work by using transfers to fulfill demands that remained unsatisfied from initial allocation. Both provide a foundation for allocating water among several different users in a water market system, essentially adding a weight to the supply allocated. Obviously a limiting issue for our purposes is provision from a single provider, as there are instances where several sources of supply with varying allocations are encountered.

Marin and Smith (1988) explored a water allocation problem to optimize the distribution of water across a region with multiple sources and multiple providers. This model also accounted for deficits through the use of transfers to satisfy previously unmet demand in order to maximize the net social benefits to the region. Vaux and Howitt (1984) proposed a model that also distributes water across several districts from multiple sources. These models offer an extended basis for allocating water in a complex network of supply sources and varying demands in a single time period. As there are cases where water is to be allocated over time, the single period focus is necessarily a limitation in some contexts.

Much of the basis for modeling water allocation over time arises from work by Takayama and Judge (1964) that extended the economic equilibrium of spatially separated markets to include time in a mathematical programming model. Guise and Flinn (1970) develop this spatio-temporal model to optimize water allocation to several consumers in a water market. The model is framed with a single provider distributing water to individual water users. Brill et al. (1997) also developed a spatio-temporal optimization model of a water market, extending the work to include an additional source controlled by the same provider. A similar approach is taken by Barros (2008) where a single provider distributes water to a large urban area with multiple sources over time. Enright and Lund (1991) propose a model that is also based upon a single provider, but include initial allocations to several users across a district from a single source in each time period. The model determines initial allocations tied to the demand functions of each of the users, and are segregated by type of use. These models successfully incorporate multiple time periods into the optimization of water resources. A limiting feature, however, is that there is always a single provider. There are situations where multiple providers are present, and this necessitates structural changes to how supply and demand are represented. In particular, it is conceivable that multiple providers will deliver water allocations based on a variety of sources.

The model detailed in this paper addresses particular needs encountered in the Phoenix metropolitan area. These needs combine to reflect a complex network of independent providers, each with a different portfolio of supplies drawing from as many as three sources. Any utilized models must be capable of addressing distribution over multiple time periods. A linear programming framework is developed that extends previous efforts in this area.

Model

Water provision in the Phoenix metropolitan area is complex because of many independent agencies and municipalities that are responsible for supplying different communities in the region. Given the anticipated future conditions that will arise due to climate change, it is highly probable that there will be a need for communities to engage in various types of cooperative ventures within the region as a risk reduction strategy. In particular, it is likely that some agencies and municipalities will experience surpluses while others will see deficits associated with providing water to satisfy residential, industrial and agricultural needs. In order to address the complexities associated with the region's water distribution system, linear programming models are proposed that reflect possible collaborative ventures and enable the potential benefit of such ventures to be evaluated and understood, not to mention the supporting critical infrastructure that will be necessary.

Consider the following notation:

$i =$ index of areas (j also)

$k =$ index of water sources

$t =$ index of time periods

$u_{ikt} =$ maximum supply of water in area i by source k in period t

$d_{it} =$ demand for water in area i, period t

$\Omega_i =$ set of areas that can be supplied by surplus in area i

$p_{it} =$ population in area i, period t

$S_{ikt} =$ utilized supply of water in area i by source k in period t

$X_{it}^{+} =$ amount of water surplus in area i, period t

$X_{it}^{-} =$ amount of water deficit in area i, period t

$Y_{ijt} =$ amount of water transferred from area i to area j in period t

$Z_{it} =$ deficit after transfers in area i, period t

The general linear programming framework to optimally allocate water across multiple districts is now presented. This approach explicitly attempts to minimize the total population affected by deficits in the region.

$$\text{Minimize} \sum_{i}\sum_{t} p_{it} Z_{it} \tag{1}$$

Subject to

$$\sum_k S_{ikt} - X_{it}^{+} + X_{it}^{-} = d_{it} \quad \forall\, i,t \tag{2}$$

$$S_{ikt} \le u_{ikt} \quad \forall\, i,k,t \tag{3}$$

$$\sum_{l=1}^{t} \sum_{j=\Omega_i} Y_{ijl} \le \sum_{l=1}^{t} X_{il}^{+} \quad \forall\, i,t \tag{4}$$

$$\sum_{l=1}^{t} \sum_{j=\Omega_i} Y_{ijl} + Z_{it} = \sum_{l=1}^{t} X_{il}^{-} \quad \forall\, i,t \tag{5}$$

$$X_{it}^{+} + X_{it}^{-} \le \left| d_{it} - \sum_k S_{ikt} \right| \quad \forall\, i,t \tag{6}$$

$$\begin{aligned} &X_{it}^{+}, X_{it}^{-}, Z_{it} \ge 0 \quad \forall\, i,t \\ &Y_{ijt} \ge 0 \quad \forall\, i,j,t \\ &S_{ikt} \ge 0 \quad \forall\, i,k,t \end{aligned} \tag{7}$$

The objective (1) minimizes the population weighted deficits across the region. Constraints (2) account for the difference between supply S_{ikt} from each source k and the demand, d_{it}, with the difference as either a surplus X_{it}^{+} or a deficit X_{it}^{-} for all districts and time periods. Constraints (3) limit the water supplied to each district by source to the maximum available supply, u_{ikt}, as given by the pre-determined water allotments according to the regional water policy. Constraints (4) limit the water transferred, Y_{ijl}, from district i to another district j , to the available surplus of district i (which includes the surplus of the present period, as well as any past remaining surpluses from all past time periods l). Constraints (5) track any remaining deficits, $\mathbf{Z_{it}}$, if any, after the transfers take place. Constraints (6) ensure that the water surplus and deficit variables are positive, but not both simultaneously. Constraints (7) specify non-negativity conditions on decision variables.

This model efficiently allocates water across the districts of the Phoenix metropolitan area by taking what total supply is available and ensuring that, as long as any district has any excess water in the region during a given time period, this surplus is used to address deficits elsewhere. The total water supply in each time period is initially allocated according to historical water rights. In any given time period, some districts may have surpluses while others deficits. Those surpluses and deficits are accounted for in the model and the surpluses are distributed to any district with a deficit. Any transfer of water out of a district is limited to only what is available as a surplus, either in the current or previous periods. In period 1 the surpluses must consist only of water that was received in that period. In any subsequent time period each district has available to it the surplus in that period, plus any net surpluses that remain from past time periods (total surpluses less total transfers out). There is no limit on the amount of water stored over time as storage is theoretically possible by pumping water back into the underground aquifers and using them as storage banks. Water can be transferred between any two districts in any time period. Weighting for population ensures that if there is a year when the water supply plus past surpluses is insufficient to satisfy all demand, those districts with the largest population will be served first in order to minimize the impact on people in the region.

By effectively re-allocating water across the region in an efficient manner, and thereby making the most out of the total available water, this model addresses the uneven balance of water rights in the region and provides a framework that could be employed to examine likely cooperative arrangements that will evolve due to climate change. This specific formulation has potential to be a valuable tool in the Phoenix metropolitan area, and could also accommodate other possible objectives in light of changing demands or adaptation to another region. One factor that could be addressed in this framework is the transaction costs of transferring water, potentially varying by district. Minimizing transaction costs could be specified as follows:

$$\textit{Minimize} \ \sum_{i}\sum_{t} c_{ijt} Y_{ijt} \tag{8}$$

This objective would effectively minimize the transaction costs that are incurred while satisfying as much demand as possible across the region. Costs of transferring water from any district i to any other district j in any time period t would be minimized. Thus, the above model could incorporate two objectives, (1) and (8), as a multi-objective problem that trades off efficiency and deficit impact. Of course, other fundamental extensions could be considered as well. To this end, the developed model can be viewed as a general framework for assessing how climate change and associated decreases in water will be dealt with in a large metropolitan region.

Study Details

The linear program described above was applied in a case study of the Phoenix metropolitan area. The application of the model was based upon simulations of water supply and demand for each provider in the area for each year between 2006 and 2030. The simulation derived scenarios were provided by the Decision Center for a Desert City (DCDC), generated using the center's "WaterSim" simulation program (Gober et al., 2010). WaterSim simulates water consumption and availability in Central Arizona from the present until 2030. It relies on the Lempert et al. (2004) XLRM framework to process the analysis. Exogenous factors (X) are outside the control of regional decision makers and are concerned with climate and water supply conditions. Policy levers (L) are decisions that policy makers might take to adapt to water shortage conditions, such as groundwater policy, land-use planning, and growth management. Relationships (R) are the mathematical associations among the variables that dictate, for example, how growth is translated into changing demand or how climate change conditions are reflected in supply constraints. Measures (M) for evaluating success include whether groundwater sustainability has been achieved and whether water is available to sustain current lifestyles. Until now, WaterSim has been run at the regional scale, showing the effects of possible climate conditions and policy decisions on water supply.

To replicate this analysis at the provider level, raw data from the simulation were imported into ESRI ArcGIS and joined to a shapefile of all water districts in the study. An initial analysis of water supplies and demands throughout the region was conducted before optimization in order to explore the status of the system under current arrangements and to better understand the potential benefits of optimizing water allocation.

Python, an open source object-oriented programming language, was used to produce the linear program as a text file, which could subsequently be read into ILOG CPLEX, a commercial optimization software package. The linear program was then solved using CPLEX, identifying optimal water allocation strategies for the various climate/growth scenarios. Once solved, the results are imported back into ArcGIS for subsequent analysis. The complexity of visualization and analysis involved with spatio-temporal data resulted in the need for several different approaches to explore results. Multiple mapping schemes and tabular displays were employed in the analysis. This process was completed for four scenarios derived using WaterSim.

The four scenarios rely on population growth rates derived by the Arizona Department of Commerce (2010) as well water flow data for the Colorado and the Salt-Verde River systems. The historical average water flow is based on a 50 year period centered on 1954. Variations among scenarios are as follows:

- Scenario 1 – Currently projected population growth rate (100 percent) and historically observed flows on both the Colorado and the Salt-Verde River systems (100 percent).
- Scenario 2 – Currently projected population growth rate (100 percent) but a reduction of flow on the Colorado system (91 percent) and a reduction on the Salt-Verde system (67 percent).
- Scenario 3 - Currently projected population growth rate (100 percent) but a reduction of flow on the Colorado system (50 percent) and a reduction on the Salt-Verde system (19 percent).
- Scenario 4 - Reduced projected population growth rate (50 percent) and a reduction of flow on the Colorado system (50 percent) and a reduction on the Salt-Verde system (19 percent).

Of course Scenario 1 represents a business-as-usual future using state projected growth estimates and no reductions in historical river flows. Scenario 2, on the other hand, reflects average conditions of what the climate models are predicting from the Colorado and Salt and

Verde systems. More harsh climatic change is reflected in Scenario 3 where the most pessimistic conditions produced by the climate models are assumed. Finally, the most pessimistic conditions are also assumed in Scenario 4, but with a responding reduction in population growth as well.

Results

The analysis of each scenario for the Phoenix metropolitan area using the optimization model indicates that overall deficits can be reduced through water resource re-allocation, although the amount of deficit reduction varies depending upon the severity of climate change and growth rate responses. With cooperation between water providers, it is possible to avert or reduce water shortages. Without cooperation, several districts would experience deficits even when the region experiences an overall surplus. The difference between cooperative strategies identified using the optimization model and what would occur under the current status quo independence suggests likely future collaborative arrangements evolving between water districts.

From our initial exploration of the data, it was found that in each of the four scenarios there would be insufficient water supplies to cover the needs of every provider over the 25 year period. In Scenario 1, which assumes climatic stationarity, the Phoenix metropolitan region would be short of cumulative water demands by over 2.6 million acre-feet between 2006 and 2030 (see Table 1). Figure 1 depicts the district by district deficits for each of five 5-year periods for Scenario 1 with status quo (non-cooperation) water management. The first 5 year period (Figure 1a) in this scenario (2006-2010) experiences the lowest level of shortages and the population continues to grow over the 25 year horizon with water levels remaining the same. Altogether there are six providers experiencing deficit (see summary in Table 1). The remaining four time periods are far less fortunate with 11, 12, 13, and 14 providers, respectively, encountering water shortages.

The population growth in the region combined with varied water rights leads to problematic situations for providers on the urban fringe, particularly in the western part of the

Phoenix region, even in this rather optimistic scenario. While the region is expected to continue growing fairly rapidly over the next 25 years, much of the growth will occur in fringe areas. Goodyear, for example, had a population of approximately 50,000 in 2006. It lies on the western fringe of the Phoenix metropolitan area, and is expected to have its population experience explosive growth between 2006 and 2030, with an increase of almost five hundred percent to just less than 300,000. This rapid growth is likely problematic when coupled with the fact that the city is allotted a certain finite share of Colorado River water under present conditions. The only way for Goodyear to increase the supply of water is to tap the heavily regulated aquifer below the region. Because use of the aquifer is so tightly controlled, there is little additional supply to be had from this source. Under the status quo system of management, Goodyear will only have access to eight percent more water in 2030, but the population is expected to increase six-fold. Other cities in the region are in the same situation, reflected in the number of providers in deficit in all of the period ranges in Table 1 for status quo management.

In contrast to the status quo operation reflected in Scenario 1, the optimization model identifies opportunities for cooperation and re-allocation of water supplies leading to an aversion of any shortages, as depicted in Figure 2. With the ability to trade water between providers in this scenario, those with surpluses are able to satisfy those deficits experienced by other providers in every period range (see also Table 1). To illustrate how this is possible, Figure 3 shows that the three providers with the largest deficits in 2030 (depicted in red), Scottsdale, Surprise and Goodyear, are able to obtain surplus water from Phoenix and Glendale. Thus, the arrows represent magnitude of water flow from one provider to another (larger arrows indicate greater flows). Therefore, in this scenario Phoenix has sufficient available surpluses to completely satisfy the water needs of Surprise and Scottsdale, and Glendale is able to fulfill the needs of Goodyear, thereby ensuring that they will not experience any projected water deficits. As a result, Table 1 indicates that there are no water provider deficits with regional cooperation. The likely benefits of regional cooperation through water trading are very clear.

In Scenario 2, where harsher climatic conditions are assumed but the projected population growth remains the same, the impacts are even more compelling. With a decrease in the availability of water in the future, the region is expected to be in deficit by more than 3.4 million acre-feet over the 25 year time span under status quo water management (see Table 2). Figure 4 summarizes the deficits associated with Scenario 2. It can be seen in Figure 4(a) that Goodyear, in the southwest corner of the region, experiences no deficit whatsoever. As mentioned previously, the city is expected to experience rapid growth which will lead to increases in deficits in each period range. Consequently, Figure 4(e) indicates that in the last period range Goodyear encounters substantial water supply deficits. Other highly populated districts, such as Gilbert, Surprise, and Scottsdale experience significant deficits across all time periods.

Using the model to re-allocate water supplies in the region based upon population finds that it is possible to reduce total deficits to about 1.6 million acre-feet (Table 2). As demonstrated in Figure 5 for the Scenario 2 case using the optimization model, Scottsdale and Gilbert are no longer in deficit during period ranges 3, 4, and 5, and Surprise is no longer lacking in period ranges 4 and 5. While Goodyear is still in deficit when water is re-allocated, the deficit in the final time period (2026-2030) is decreased by almost 85 percent. The other remaining deficits are distributed among provider districts with lower populations, thereby minimizing impacts for the greatest total population possible. Each 5-year period for this scenario is summarized in Table 2. Though not all demands can be met through water trading in this scenario, the results clearly demonstrate considerable benefits offered by cooperation.

Assuming considerably harsher climate change conditions, Scenario 3 suggests that the majority of provider districts will fall into deficit under status quo conditions in water management, and is summarized in Figure 6. Table 3 indicates that the cumulative water supply deficit will be over 15 million acre-feet by 2030. All but one of the 12 districts with a population greater than 100,000 by 2030 experience deficits, with 10 in deficit in every time period. Buckeye, in the farthest southwest corner of the region, experiences no shortages over the 25 year time span, and Tempe, in the southeast, does not go into deficit during the first two 5-year periods under status quo management.

Even in this most pessimistic of scenarios, regional cooperation proves to be very beneficial, although there remain significant water supply deficits (see Table 3). Because the model is weighted by population, all surpluses that occur in each year are stored for use in the last year, 2030 (Period 5 in Table 3). In 2030 all stored surpluses are transferred to the City of Phoenix, which amounts to about 140,000 acre-feet of water being transferred from several cities, and is illustrated in Figure 7. With the exception of those from Tempe, all of the surpluses later used for re-allocation originate in first three time periods (2006-2008). Tempe is projected to have periodic annual surpluses until 2021, though the city will experience several deficit years as well to that point. In 2030, with status quo management, all providers are expected to be well beyond the point of exhaustion for their allotted water supply except for the Arizona Water Company – White Tanks, which provides a small supply of water to a population peaking in 2030 at about 12,500, but accumulates surplus water when the population is less than 3,000 in 2006 and 2007. In these two years, the provider experiences a net surplus of 793 acre-feet that is not accessed throughout the remainder of the 25 year time frame. This surplus accounts for the difference between deficits under status quo management and cooperative management as it is the only water that remains unused at the end of the scenario under status quo management. While this overall difference in supply is quite small, the impact of re-allocating water in the region becomes apparent in that the population weighted average deficit decreased by more than 2,200 acre-feet over the entire scenario.

Scenario 4 presents equally harsh climatic conditions, but with slowed population growth. The situation is similar to that in Scenario 3, as there is simply such a shortage of water that surpluses that may be stored or re-allocated are very rare. Table 4 indicates that the region as a whole does experience less overall deficit, at approximately 12 million acre-feet, but it remains rather drastic nonetheless. The re-allocation of water is also similar to that which occurs in Scenario 3, as there are only a series of transfers to Phoenix in the end of the 25 year simulation. In this case, although the net gain of water in the system is only 873 acre-feet (Period 5 in Table 4), enough water becomes available from surpluses throughout the 25 years in other districts to prevent Phoenix from going into deficit after allocation in 2030, and to transfer about 7,000 acre-feet to the city in 2029, for a total of about 175,000 acre-feet transferred to Phoenix in the final two years of the 25 year span. The comparative differences in total deficit can be visualized in Figure 8, where Phoenix is able to reduce water deficits.

Further, when comparing population weighted average deficits in Scenario 4, an average savings of more than 2,700 acre-feet is possible using the regional cooperation approach.

Conclusions

The results obtained from the developed spatial optimization model reflecting regional cooperation in water supply management across the Phoenix metropolitan area demonstrate insights possible. It remains clear that the introduction of demand management strategies will be necessary in the face of future climate change, but also it is possible to significantly reduce deficits in some cases. By taking full advantage of all the water that is available and cooperation between water districts, as opposed to the practice of conserving surpluses for future use but not distributing extra water when available to those districts in need, it is possible to stretch the available supply of water to ensure that the impacts of water shortages are minimized. In every scenario, the results pointed to clear benefits of regional cooperation, whether it is the complete avoidance of deficits over a period of time (Scenarios 1 and 2), to the more equitable distribution of deficits across the region (Scenarios 3 and 4). Effective policy implementation could lead to the employment of a trading strategy that embodies the benefits demonstrated in this paper.

It is clear in each scenario presented in this paper that Phoenix and its ability to transfer water either in from or out to other districts appears inevitably. As the largest city in the region by almost four times, it clearly will be an important factor in water resource management. While it is assumed in this paper that water transfers are possible by simply recharging subsurface aquifers by one district and pumping out water by another, there may be a need for conveyance infrastructure to successfully implement an effective water sharing strategy in the region. Whether it be by manmade infrastructure or natural aquifers, in the case of the Phoenix metropolitan region, it is obvious that the city of Phoenix must be completely intertwined with the water network of the region.

The linear program presented in this paper is a foundation for effective water management and is, in the form presented, adaptable to accommodate different weighting schemes. While it may be possible to re-allocate water across the region in a more equitable manner than weighting by population of each provider district, it is evident that as it stands, this model is effective for demonstrating the potential gains of any region with multiple, independent water providers, through optimal water re-allocation. The potential to change the weighting mechanism will be important for future work, which may include a cost structure for transfer transactions, measures of social benefit achieved by water re-allocation, or economic gains related to water availability. Decision rules about who does and does not share access to relevant conveyance infrastructure may also be included in future applications. While different potential decision rules and weighting mechanisms will likely vary by application, the foundation for multi-district water re-allocation modeling presented here clearly demonstrates the potential benefits of such a system.

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References

Arizona Department of Commerce (2010). http://www.azcommerce.com/doclib/econinfo/FILES/2006MaricopaProjections.xls (Last accessed July 5, 2010).

Babayan, A., Kapelan, Z., Savic, D., and Walters, G. (2005). Least-cost design of water distribution networks under demand uncertainty. *Journal of Water Resources Planning and Management, 131*(5), 375-382.

Barnett T.P., and Pierce D.W. (2008) When will Lake Mead go dry? Water Resources Research, 44, W03201, doi:10.1029/2007WR006704.

Barros, M.T.L., Zambon, R.C., Barbosa, P.S.F., and Yeh, W.W.G. (2008). Planning and Operation of Large-Scale Water Distribution Systems with Preemptive Priorities. *Journal of Water Resources Planning and Management, 134*(3), 247-256.

Becker, N. (1995). Value of moving from central planning to a market system: lessons from the Israeli water sector. *Agricultural Economics, 12*(1), 11-21.

Booker, J. F., and Young, R.A. (1994). Modeling Intrastate and Interstate Markets for Colorado River Water Resources . *Journal of Environmental Economics and Management, 26*(1), 66-87.

Brill, E., Hochman, E., and Zilberman, D. (1997). Allocation and pricing at the water district level. *Journal of Agricultural Economics, 79*(3), 952-963.

Christensen, N.S., and Lettenmaier, D.P. (2007). A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River basin. *Hydrology and Earth System Sciences,* 11, 1417–34.

Christensen, N.S., Wood, A.W., Voisin, N., Lettenmaier, D.P., and Palmer, R.N. (2004). The effects of climate change on the hydrology and water resources of the Colorado River Basin. *Climatic Change,* 62, 337-63.

Cui, L.-J., and Kuczera, G. (2003). Optimizing Urban Water Supply Headworks. *Journal of Water Resources Planning and Management, 129*(5), 380-387.

Ellis, A.W., Hawkins, T.W., Balling, R.C., and Gober, P. (2008). Estimating future runoff levels for a semi-arid fluvial system in central Arizona, USA. *Climate Research*, 35 (3), 227-39.

Enke, S. (1951). Equilibrium among Spatially Separated Markets: Solution by Electric Analogue. *Econometrics, 19*(1), 40-47.

Enright, C., and Lund, J.R. (1991). Alternative Water-District Organization: Screening-Level Analysis. *Journal of Water Resources Planning and Management, 117*(1), 86-107.

Fullerton, T. (2006). Water Transfers in El Paso County, Texas. *Water Policy, 3*(8), 255-268.

Gammage, G. (1999). Phoenix in perspective: Reflection on developing the desert. Herberger Center for Design Excellence, Arizona State University, Tempe, Arizona, USA.

Garrido, A. (2000). A mathematical programming model applied to the study of water markets within the Spanish agricultural sector. *Annals of Operations Research, 94*, 105-123.

Gober, P. (2009). Desert City Visions: Decision Making Under Uncertainty [Special section]. *Stockholm Water Front*, 16-17.

Gober, P. and Kirkwood, C.W. (2010) Vulnerability assessment of climate-induced water shortage in Phoenix. Proceedings of the National Academy of Sciences doi/10.1073/pnas.0911113107.

Gober, P., Kirkwood, C.W., Balling, R.C, Ellis, A.W., and Deitrick, S. (2010). Water planning under climatic uncertainty in Phoenix: Why we need a new paradigm. *Annals of the Association of American Geographers*, 100, 1-16.

Gober, P., Wentz, E.A., Lant, T., Tschudi, M.K., and Kirkwood, C. W. (2010). WaterSim: A simulation model for urban water planning in Phoenix, Arizona, USA. *Environment and Planning B*.

Guise, J.W.B., and Flinn, J.C. (1970). The allocation and pricing of water in a river basin. *American Journal of Agricultural Economics, 52*(3), 411-421.

Howe, C.W., Schurmeier, D.R., and Shaw, W.D. (1986). Innovative approaches to water allocation: the potential for water markets. *Water Resources Research, 22*(4), 439-445.

Intergovernmental Panel on Climate Change (2007). Climate Change 2007: Synthesis Report (R. K. Pachauri & A. Reisinger, Eds.).

Marin, C.M., and Smith, M.G. (1988). Water Resources Assessment: A Spatial Equilibrium Approach. *Water Resources Research, 24*(6), 793-801.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer. 2008. Stationarity is dead: Whither water management? *Science* 319:573-74.

National Resources Defense Council, and The Rocky Mountain Climate Organization (2008). Hotter and Drier: The West's Changed Climate.

Samuelson, P.A. (1952). Spatial price equilibrium and linear programming. *The American Economic Review, 42*(3), 283-303.

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

Shupe, S.J., Weatherford, G.D., and Checchio, E. (1989). Western Water Rights: The Era of Reallocation. *Journal of Natural Resources, 29*(2), 413-434.

Schoolmaster, A. (1991). Water Marketing and Water Rights Transfers in the Lower Rio Grande Valley, Texas. *Professional Geographer, 43*(3), 292-304.

Takayama, T., and Judge, G.G. (1964). Spatial Equilibrium and Quadratic Programming. *Journal of Farm Economics, 46*(1), 67-93.

Tolley, G. S., and Hastings, V.S. (1960). Optimal Water Allocation: The North Platte River. *The Quarterly Journal of Economics, 74*(2), 279-295.

U.S. Census Bureau (2008). Maricopa County Quick Facts. Washington, DC.

Vaux, H.J., and Howitt, R.E. (1984). Managing Water Scarcity: An Evaluation of Interregional Transfers. *Water Resources Research, 20*(7), 785-792.

Table 1. Comparative water deficits by five year periods for Scenario 1.

Period Range (Aggregate of 5 years)	Status Quo		Regional Cooperation (Optimization model)		Relative Water Savings (%)
	Providers in Deficit	Total Deficit	Providers in Deficit	Total Deficit	
1	6	202,512	0	0	100
2	11	355,448	0	0	100
3	12	499,416	0	0	100
4	13	679,328	0	0	100
5	14	880,972	0	0	100

Table 2. Comparative water deficits by five year periods for Scenario 2.

Period Range (Aggregate of 5 years)	Status Quo		Regional Cooperation (Optimization model)		
	Providers in Deficit	Total Deficit	Providers in Deficit	Total Deficit	Relative Water Savings (%)
1	7	233083	2	237251	-1.79%
2	13	462411	3	459406	0.65%
3	16	805659	5	471614	41.46%
4	14	788198	16	261343	66.84%
5	18	1126396	19	177624	84.23%

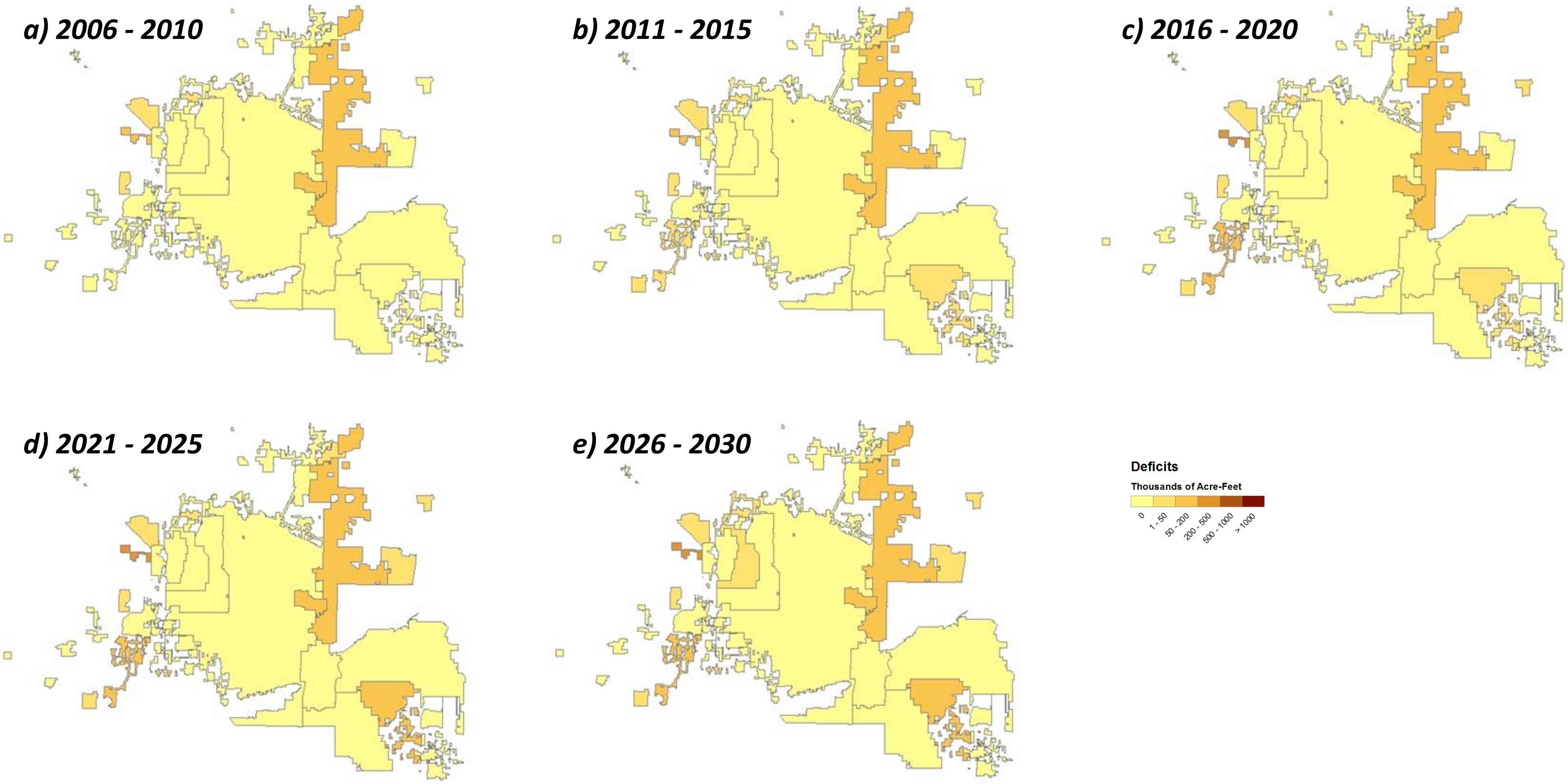
Table 3. Comparative water deficits by five year periods for Scenario 3.

Period Range (Aggregate of 5 years)	Status Quo		Regional Cooperation (Optimization model)		Providers in Deficit
	Providers in Deficit	Total Deficit	Providers in Deficit	Period Range (Aggregate of 5 years)	
Period 1	18	1391136	19	1479537	-6.35%
Period 2	21	2852068	22	2889219	-1.30%
Period 3	22	3125477	22	3138148	-0.41%
Period 4	22	3832469	22	3833320	-0.02%
Period 5	22	3977604	22	3837737	3.52%

Table 4. Comparative water deficits by five year periods for Scenario 4.

	Status Quo		Regional Cooperation (Optimization model)		
Period Range (Aggregate of 5 years)	Providers in Deficit	Total Deficit	Providers in Deficit	Period Range (Aggregate of 5 years)	Providers in Deficit
Period 1	18	1253580	18	1348373	-7.56%
Period 2	19	2450365	21	2478096	-1.13%
Period 3	20	2500363	22	2513529	-0.53%
Period 4	22	2983856	22	3018826	-1.17%
Period 5	22	2998242	22	2826709	5.72%

Figure 1. Deficits associated with Scenario 1 under status quo (non-cooperation) water management.



a) 2006 - 2010

b) 2011 - 2015

c) 2016 - 2020

d) 2021 - 2025

e) 2026 - 2030

Figure 2. Deficits associated with Scenario 1 under regional cooperation between providers.

a) 2006 - 2010

b) 2011 - 2015

c) 2016 - 2020

d) 2021 - 2025

e) 2026 - 2030

Figure 3. Water transfers assocaited with Scenario 1 to satisfy all 2030 demand in Scottsdale, Surprise, and Goodyear.

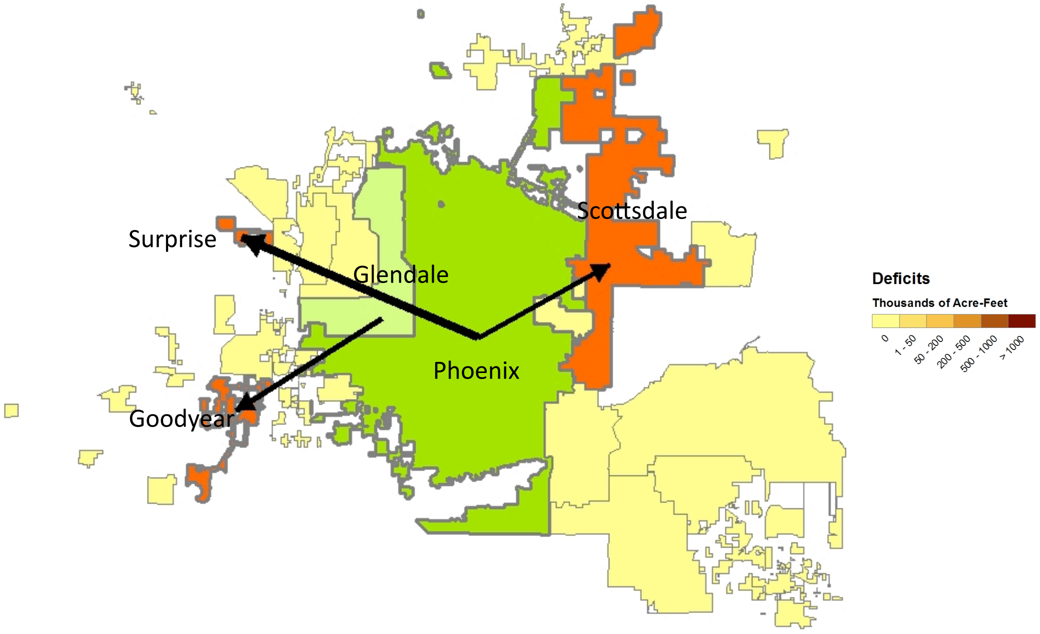
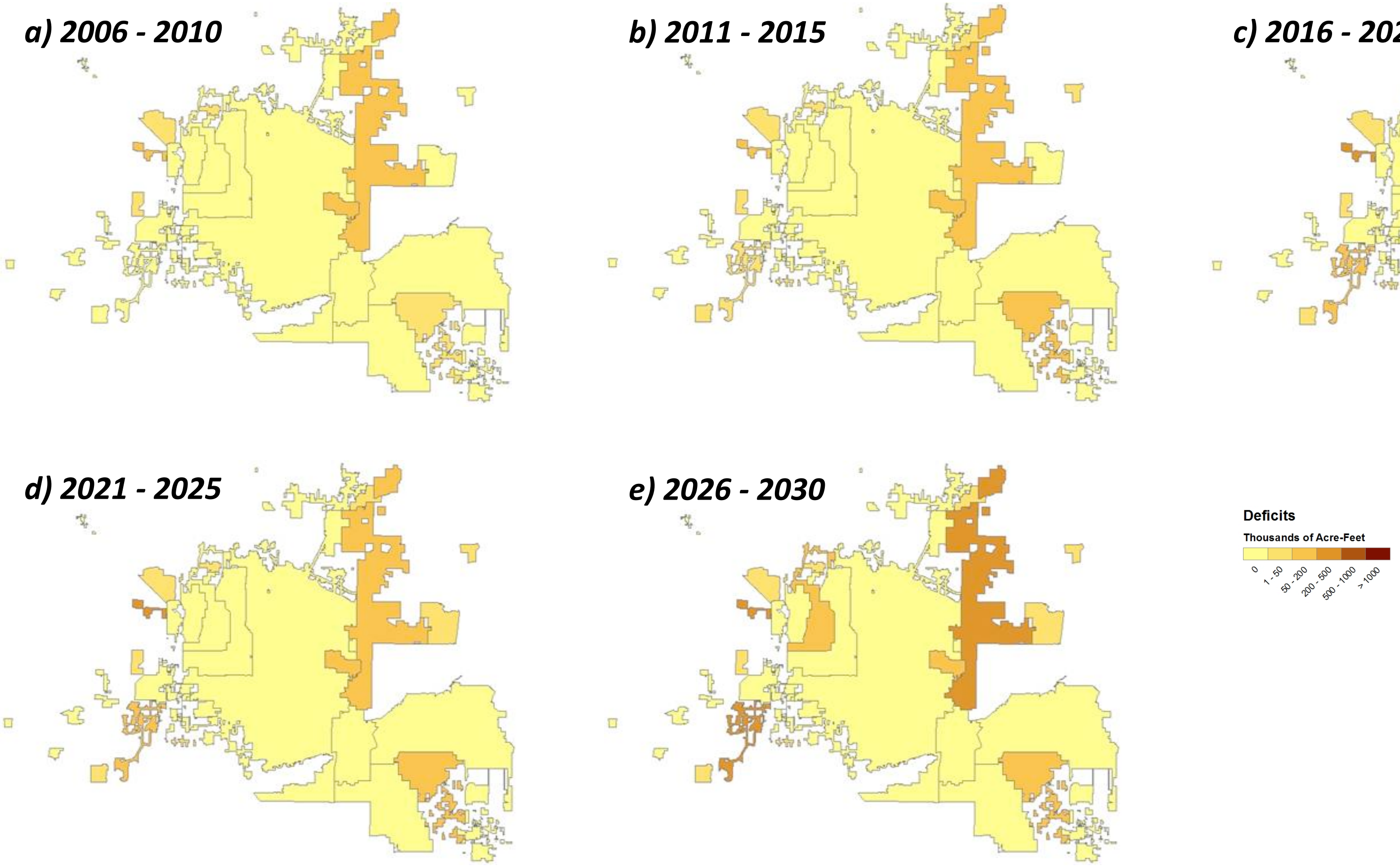


Figure 4. Deficits associated with Scenario 2 under status quo (non-cooperation) water management.



a) 2006 - 2010

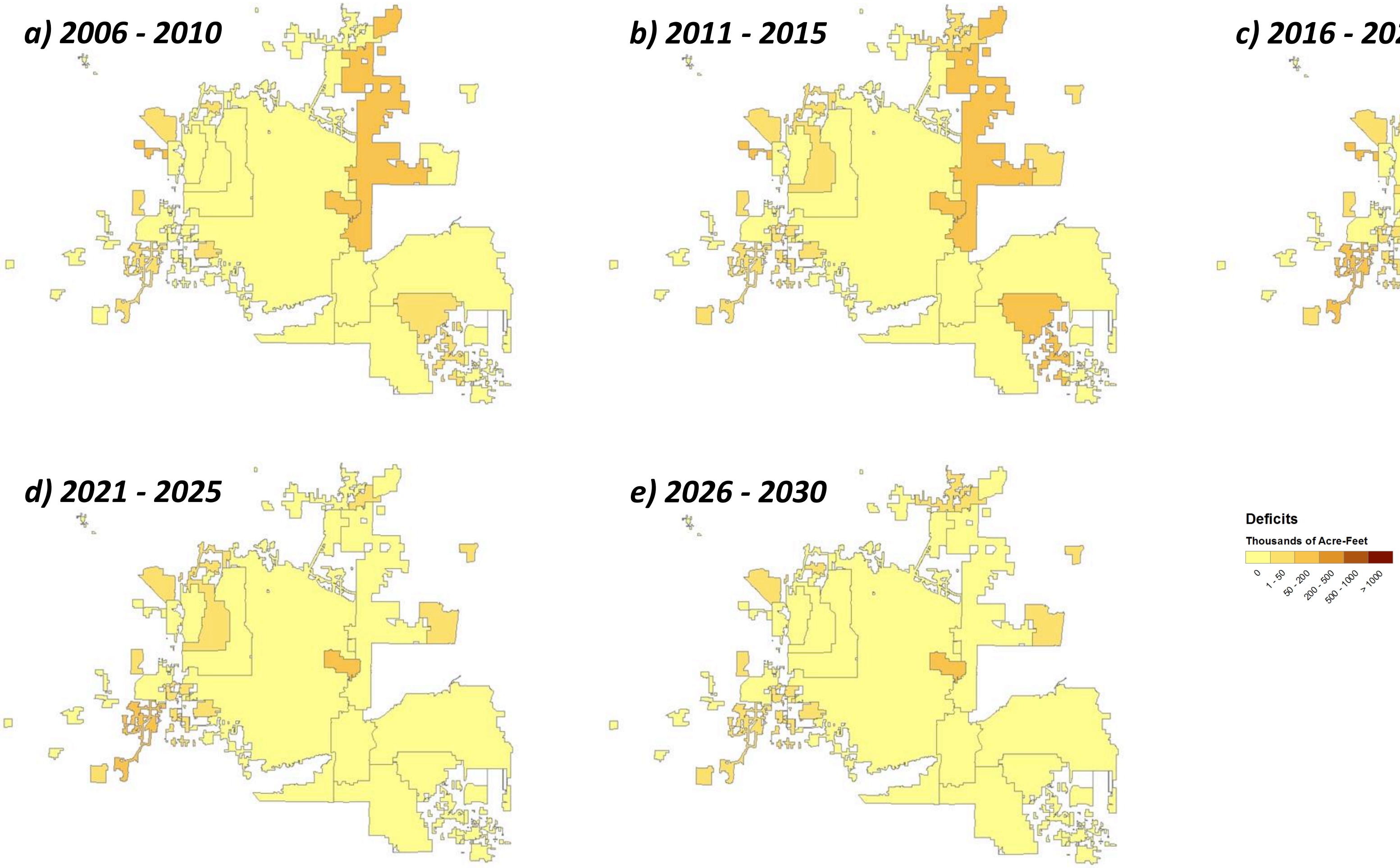
b) 2011 - 2015

c) 2016 - 2020

d) 2021 - 2025

e) 2026 - 2030

Figure 5. Deficits associated with Scenario 2 under regional cooperation between providers.



a) 2006 - 2010

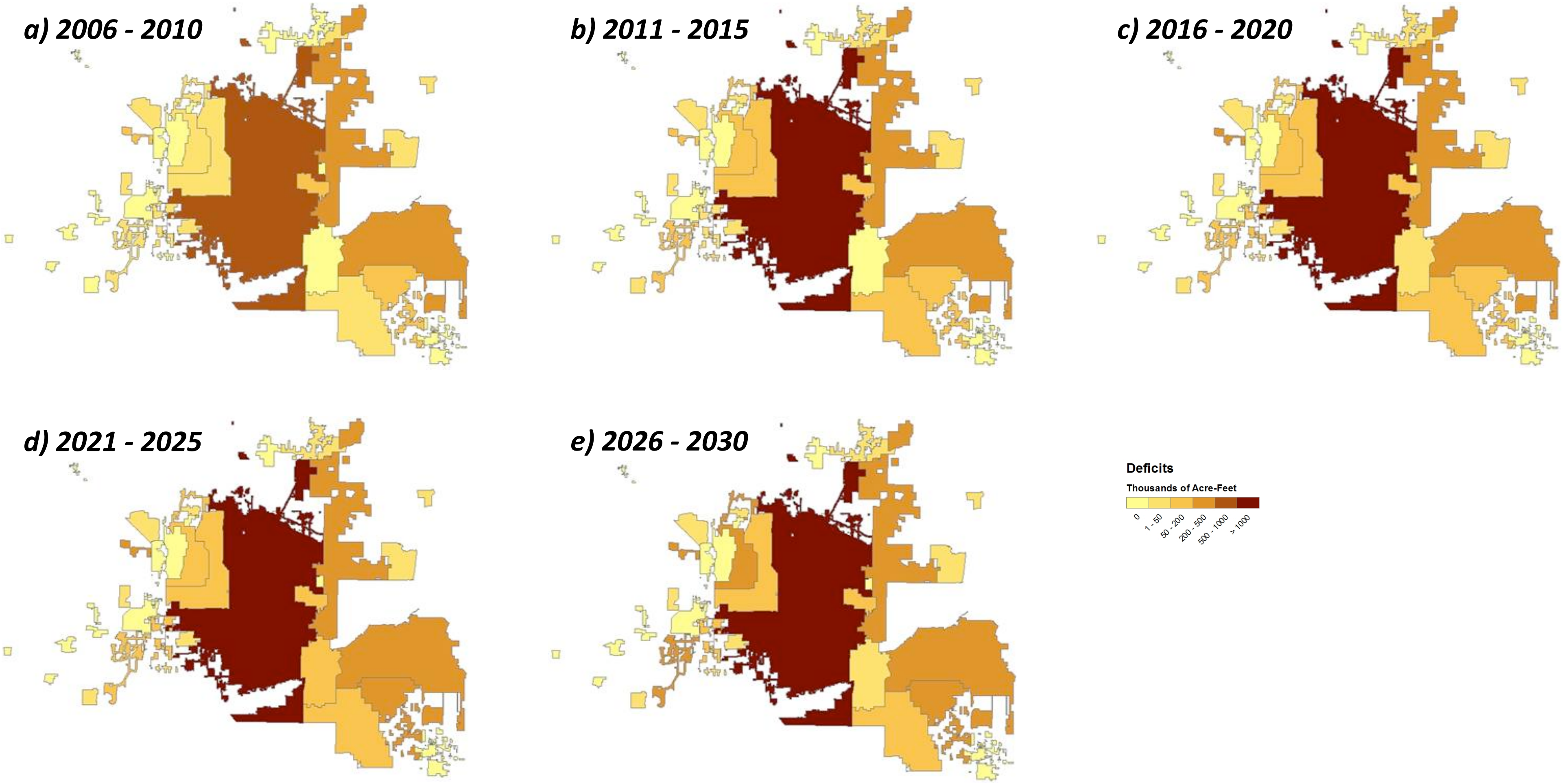
b) 2011 - 2015

c) 2016 - 2020

d) 2021 - 2025

e) 2026 - 2030

Figure 6. Deficits associated with Scenario 3 under status quo (non-cooperation) water management.



a) 2006 - 2010

b) 2011 - 2015

c) 2016 - 2020

d) 2021 - 2025

e) 2026 - 2030

Figure 7. Water transfers to minimize deficits in Phoenix in 2030 (Scenario 3).

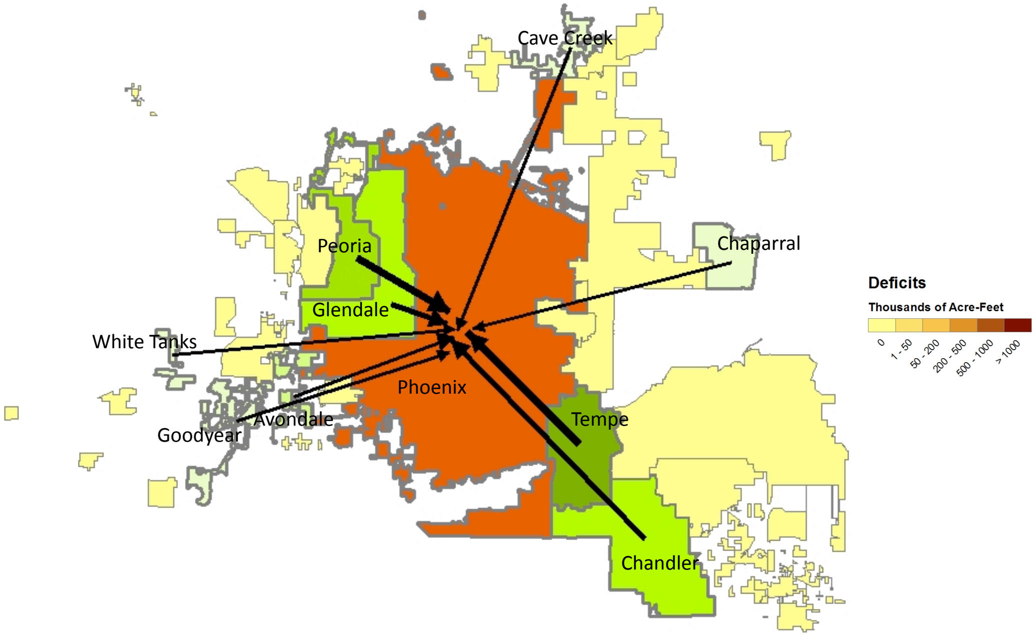
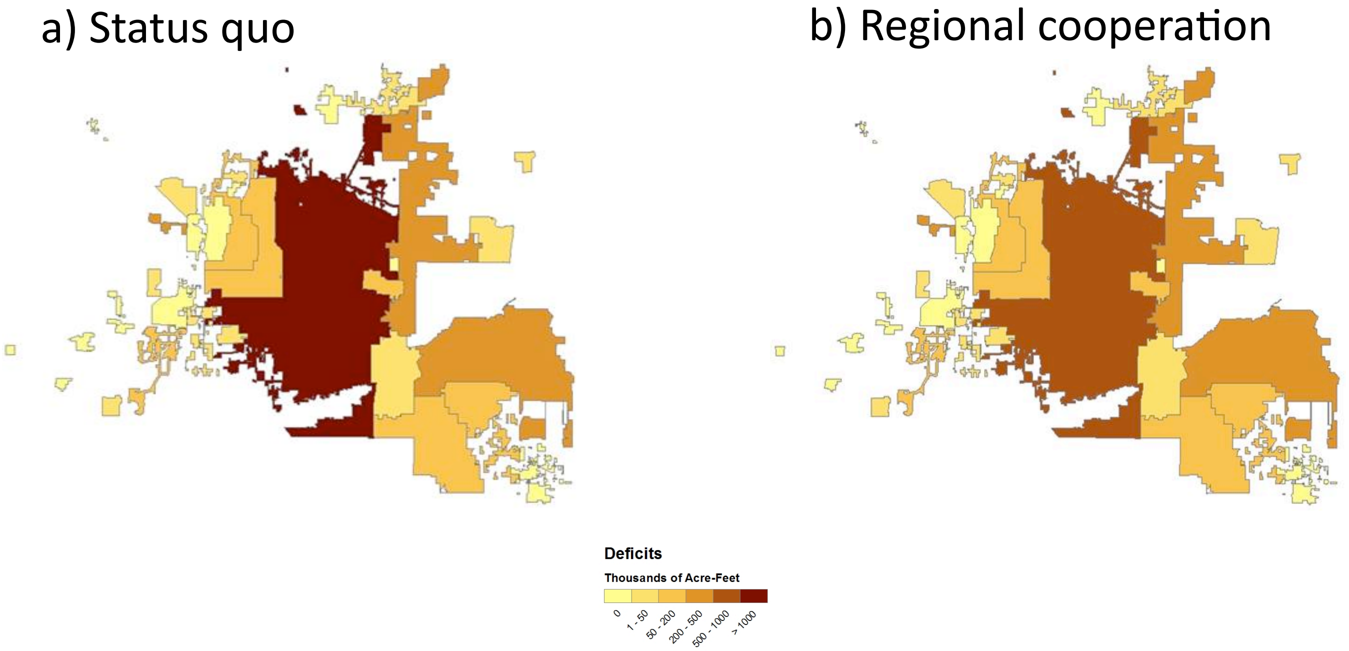


Figure 8. Deficits associated with Scenario 4 (2026-2030 period).



a) Status quo

b) Regional cooperation