A COMPLEX ADAPTIVE SYSTEMS ANALYSIS TO EXPLORE OPTIMAL SUPPLY-SIDE AND DEMAND-SIDE MANAGEMENT STRATEGIES FOR URBAN WATER RESOURCES

A Senior Scholars Thesis

by

HASSAN F ALJANABI

Submitted to the Office of Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

May 2012

Major Subject: Civil Engineering

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Approved by:

Research Advisor	Lufthansa Kanta
Associate Director, Honors and Undergraduate Research	Duncan MacKenzie

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ABSTRACT

A Complex Adaptive System Analysis to Explore Optimal Supply-side and Demand-side Management Strategies for Urban Water Resources. (May 2012)

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Urban water management specifies both supply-side and demand-side strategies to balance water supply and demands for social and environmental systems. As the sustainability of water resources depends on the dynamic interactions among the consumers and the policy makers of the water system, an optimal adaptive water management approach can be used to update utility decisions based on the feedback among these systems and may enable a more efficient use of resources. Adaptive demand-side management strategies, such as regulating water for outdoor use, can be designed with increasing restrictions corresponding to the depletion of reservoirs. Similarly, adaptive supply-side strategies can be designed to supplement supply by increasing the volume of water that is transferred among basins when reservoirs levels drop. In this study, a Complex adaptive system (CAS) framework is used to simulate the adaptive behaviors of consumers, the adaptive decisions of the water utility, and an engineering model of the water supply infrastructure. The CAS framework is coupled with an optimization methodology to evaluate a combination of supply-side and demand-side adaptive water management strategies in achieving the utilities goal of minimizing management costs. The methodology is applied to an illustrative case study of an urban water supply system to explore optimal adaptive water management strategies. The results indicate that while the management costs could be minimized through implementation of optimal supply-side and demand-side strategies, those strategies also resulted in reservoir depletion significantly below the conservation storage. Thus, a trade-off exists between the supply-side and the demand-side management of urban water resources.

DEDICATION

I lovingly dedicate this thesis to my parents, Falah Aljanabi and Weiam Alkhuzaie, who have supported me each step of way and instilled the importance of hard work and higher education.

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Lufthansa Kanta, who has been the ideal thesis supervisor, for giving me the opportunity to work on this research project. I sincerely appreciate her support, guidance, and patience throughout the period of this work. I would also like to acknowledge two senior graduate students in the Department of Civil Engineering, Marcio Giacomoni and Ehsan Shafiee, for providing me feedback and assistance to complete this research.

NOMENCLATURE

ABM	Agent-based modeling
CAS	Complex adaptive system
C	Management cost
D_t	Residential demand at current month t
GA	Genetic Algorithm
IBT_t	Inter-basin transfer volume to the reservoir at current month t
N1	Number of times *Stage1* plan is implemented
N2	Number of times *Stage2* plan is implemented
N3	Number of times *Stage3* plan is implemented
R_t	Reservoir spills at current month t
RO_t	Runoff volume from the watershed into the reservoir at current month t
S_t	Reservoir storage volume at current month t
S_{t-1}	Reservoir storage volume at previous month t-1
TRWD	Tarrant Regional Water District
WDM	Water demand management

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CHAPTER I

INTRODUCTION

The definition of sustainability of water resources has changed over time. Historically, sustainability has focused on the supply-side management of urban water resources, which simply stands for the acquisition of new resources to meet the increasing demands. This can be achieved through infrastructure expansion such as building dams and reservoirs or through inter-basin transfers. Due to population growth and urbanization, demands have increased drastically beyond the capacity of local water resources in some areas (Hardberger 2008). To bring the water resources system into balance, the water utilities may consider the demand-side management of urban water resources. The demand-side management can be defined as a set of activities initiated by water utilities for reducing demands, including promoting water use efficiency, encouraging water conservation, setting water pricing, water recycling, and leak detection (Stiles 1996).

Brooks (2006) proposed an operational definition of water demand management (WDM) which can be accomplished by meeting one or more of the following goals: (1) reducing consumers' water demand, (2) improving the capacity of existing water systems to provide consumer demand during drought, and (3) reducing water losses and changing

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This dissertation follows the style of *Journal of Water Resources Planning and Management.*

the timing of consumption from peak to off peak.

While demand management can be accomplished by either of the above mentioned goals, the availability of water supply is not a function of management decisions only; it also depends on consumers dynamic decisions, adaptive behavior, and climatic conditions. For instance, during the period of water shortage, water management officials can campaign for water conservation measures through plumbing fixture replacement rebate program and through outdoor watering restrictions. In response, if the consumers adopt water efficient technologies and comply with the restrictions, the aggregated demand will be reduced, which, in turn, will affect the water availability in the reservoir.

The research presented here explores a novel simulation-optimization approach to provide a combination of optimal supply-side and demand-side water management strategies through the influence of policy maker’s conservation campaigns and restrictions and through consumer’s adaptations on the sustainability of urban water resources. The water resources system is demonstrated here as a complex adaptive system (CAS) which is defined as a dynamic system of agents where the agents interact non-linearly and are capable of adapting to inputs from other agents in a common environment (Miller and Page 2007). To simulate a CAS, an Agent-Based Modeling (ABM) tool is used which models a group of decision-making actors, commonly known as “agents” that interact based on a set of rules for specifying adaptive behaviors (Gilbert

2007). The CAS modeling framework was designed by Kanta and Zechman (2011) to capture the dynamic interactions among water consumers, policy makers, water utilities, and hydrologic cycle. In this current investigation, the CAS framework, which is coupled with an optimization methodology, is used to evaluate a combination of optimal supply-side and demand-side water management strategies for a water utility in achieving the utilities goal of minimizing the management cost. The supply-side strategies include adaptive inter-basin transfers and the demand-side strategies deal with water conservation through plumbing fixture replacement programs that include replacing 2000 toilets, 2000 shower heads, and 2000 washing machines every year and through drought management plans which include outdoor watering restrictions based on reservoir's current storage levels.

Literature review

Several existing demand-side management models considered residential demand as a static model parameter where demand varies with price (Espey et al. 1997) or with demographic factors (Rosenberg 2007). These methods, however, may ignore important dynamics and interactions that affect the performance of the water resources system (House-Peters and Chang 2011).

Galan et al. (2009) demonstrate different water demand scenarios by combining agent-based approach and simulation to compose a Hybrid Agent-Based Model that takes into account the effect of urban dynamics such as intra-population movements, residence typology, and changes in territorial model on local water demands in the city of Valladolid (Spain). The model has two major units: the agents and the environment. The agents are the households and the environment is the geographical area where the dynamic interaction between the agents and water systems takes place. The model is composed of multiple subcomponents. Each of these subcomponents is designed to capture a range of significant socioeconomic sides of water demand in municipalities. The first subcomponent is the Urban Dynamics Model that studies, in particular, the effect of urban and territorial dynamics on domestic water consumption. The basic assumption of this model is that agents like to live in neighborhoods and dwellings according to the economic status (Galan 2009). The second subcomponent is the Opinion Diffusion Model that investigates the influence of social norms and behaviors on water consumption. The third subcomponent is the Technological Diffusion Model which explores the effect of adopting water saving products on the water use levels. The study concludes that a growing population in a city does not essentially mean a proportional increase in water use. In fact, the main factor than can increase the water use in a municipality is the movement from packed housing in the downtown (with mainly indoor use) to bigger houses in the suburbs (with mainly outdoor use).

Chu et al. (2009) develop an agent-based Residential Water Use Model (RWUM) to capture residential water use behavior and to evaluate consumers' responses to policy for Beijing city in China. Their research incorporates residential water use data obtained from water utilities, local government's planning and social survey data, and market survey data. The RWUM evaluates the responses to regulatory policies implemented by the water management agencies and also predicts the future residential water demand. The actors of the system are - regulator, households, and water appliance market. The regulator is the agent that is responsible for setting the water use policies and the level of water prices. The households represent residential consumers whose aggregated demand represents the macro water use pattern of the city. The market appliance system is the environment where the households get their water appliances such as toilets, faucets, shower heads, washing machines, and dish washers. The regulator agent imposes plumbing fixture efficiency criteria during the simulation period; based on the availability of those fixtures in the market, the household agents make decisions about replacing the existing fixtures with the more efficient ones. These high efficiency fixtures can help meet the efficiency criteria determined by the regulator and thereby can help reduce the macro level demand. Their research shows that policy decisions such as financial rebates and conservation based campaigns could promote water conservation among residential consumers in China.

Perugini et al. (2008) also conduct a study using an agent-based simulation approach to evaluate the effectiveness of urban water trading policy in conserving water during water crisis. The agents here are the households and the water authority that determines the prices and implements conservation policies. Two pricing scenarios are applied: (1) tiered pricing policy and (2) tiered pricing with tradable water allocation policy. Using this model, it is found that increasing water price only does not motivate low income water users to conserve water. This can be done by increasing the price for trading allocated water. Increasing tradable water allocation price provides incentives to the low income families to save water and thereby to resell it for a higher price than it is purchased. In addition to increasing the reselling price, the study concludes that increasing the allocation of tradable water will save more water because people now have more capacity to trade water and make profit. Last, the work recommends incorporating a buyer fee rather than a seller fee because it decreases the consumption of high water users and has no effect on those with low incomes who consume less amounts of water.

From the above literatures it can be observed that most agent-based studies have focused on evaluating demand-side management strategies through water conservation and campaign. However, none of them have included both supply-side and demand-side strategies in a same framework. In an earlier investigation Kanta and Zechman (2011) have found that supply-side policy decisions influence the demand-side management options and vice versa. Based on these previous findings, this research investigates to evaluate a combination of optimal adaptive supply-side and demand-side water management strategies. To demonstrate the proposed methodology, the CAS simulation-optimization module is applied for a realistic case study.

CHAPTER II

METHODS

Modeling water resources system as a complex adaptive system

The water resources system is a dynamic system where feedback loops emerge as the availability of water resources affects consumer's water use decisions, which subsequently affect water availability. When the water availability increases in a certain area, more people will be attracted to come and live in that area. As a result, demand will increase which might affect the water availability. As water availability decreases, conservation campaigns and outdoor water use restrictions may be implemented more frequently by the policy makers. In response, consumers may adopt water efficient technologies and comply with restrictions which may cause an improvement in water availability over the long term planning horizon. The management cost is dependent on both availability and demand. As demand increases, utility managers need to provide adequate supply to meet the demand which results in an increase in management cost. To reduce the management cost, the policy makers need to reduce additional supplies which can be achieved by demand reduction though implementation of conservations and restrictions. This cause and effect relationship between various components of a water resources system is shown in Fig.1 which includes three feedback loops. The outer most-loop represents the interactions among water availability, population growth, and water demand. The middle loop represents interactions among water availability, conservation practices, and water demand. The inner most-loop describes the relationship among management cost, conservation practices, and water demand.

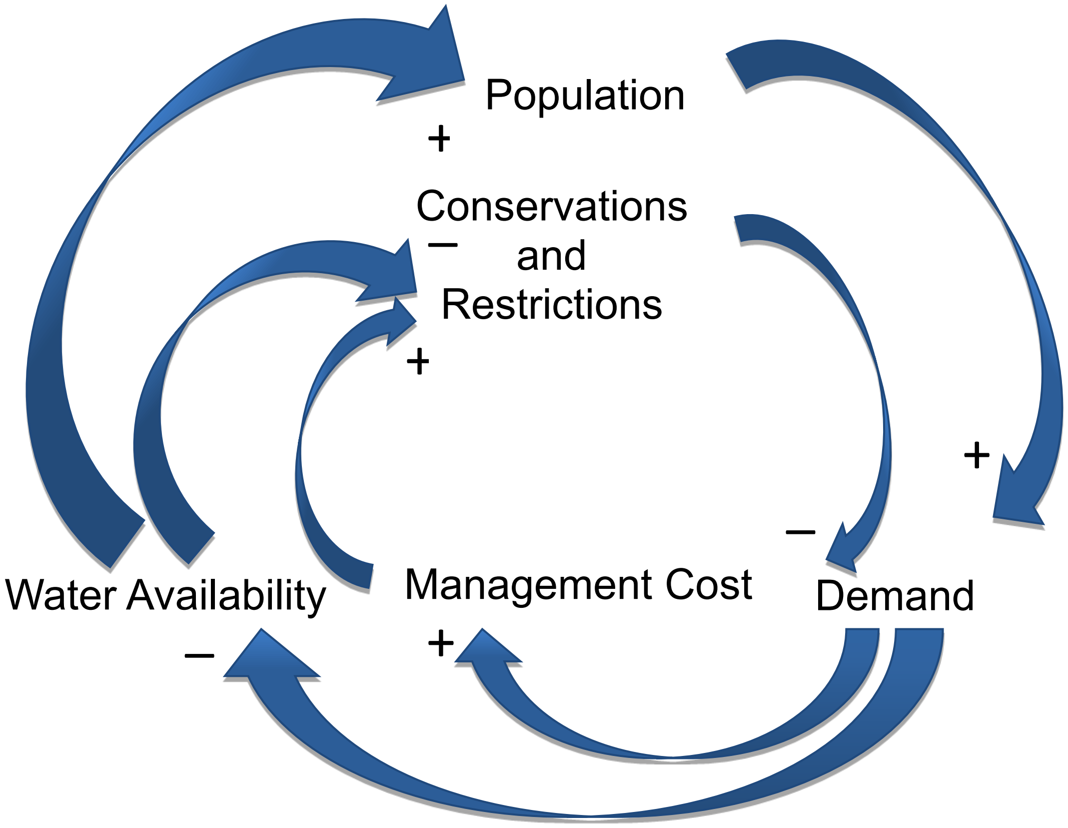

Fig.1. Cause and effect relationship between various components of a water resources system

A complex adaptive system (CAS) framework (Kanta and Zechman 2011) was used to simulate the dynamic interactions of household consumers and policy makers with the natural and engineered water resources systems. The system has two main components:

actors (agents) of the system and the water use environment. The actors of the system are residential consumers and policy makers. The environment is characterized by reservoirs, surface water systems, and watershed, representing a mechanistic water resources model. The water resources model simulates the hydrologic processes of a watershed and a reservoir. The rainfall runoff process recharges reservoirs and water is withdrawn from the reservoir and distributed to the consumers to meet their demands. Consumer demands depend on seasonal needs for watering lawns, adoption of water conservation technologies, and compliance with water use restrictions. Based on the monthly water availability and the predicted consumer demand, the policy maker imposes inter-basin transfers and outdoor water use restrictions at the beginning of each month. Policy makers can implement drought management plans which include outdoor water-use restrictions based on current water availability. The policy maker can also implement yearly plumbing fixture replacement rebate programs for the residential consumers. The residential consumers may adopt a water efficient technology based on the availability of the rebate programs. They may also comply with outdoor water use restrictions imposed by the policy maker when there is a shortage in water supplies. Due to the consumers' changed behavior, the water level in the reservoir may change accordingly and new policies may be imposed based on the changed water availability. The CAS modeling framework is shown in Fig.2 where the arrows indicate the flow of information between the modules.

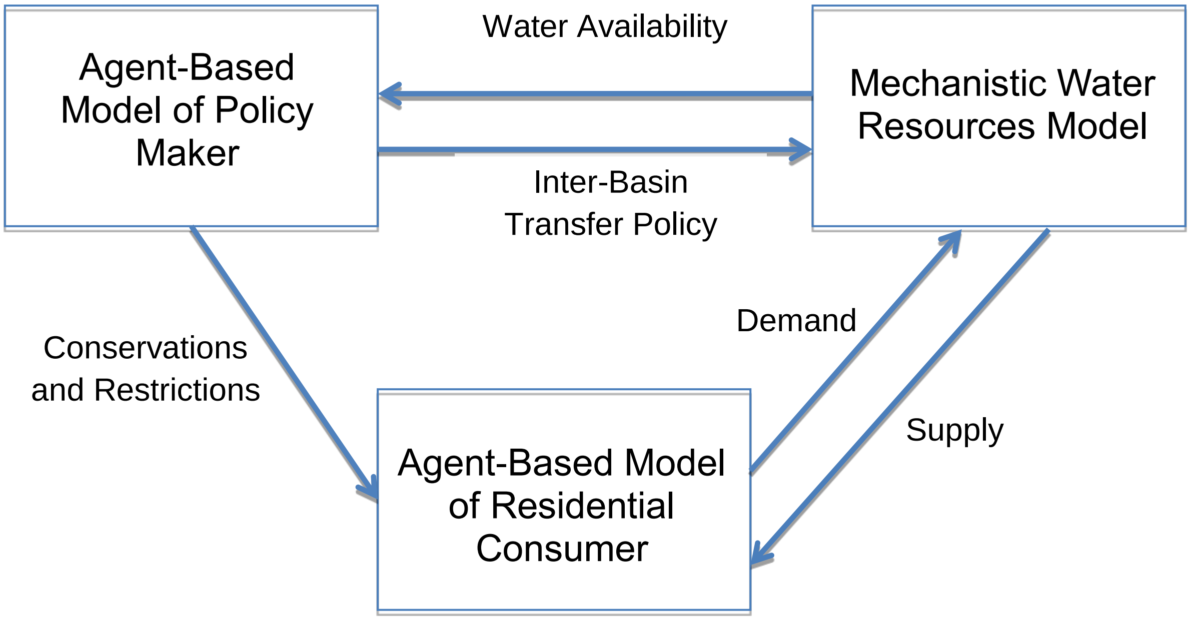

Fig.2. CAS modeling framework

Optimization model formulation

The CAS framework was coupled with an optimization methodology to minimize the management cost. The optimization model can be mathematically expressed as:

$$Minimize\ C_m = C_{inter-basin\ transfer} \tag{1}$$

subject to

$$N_1 > N_2 > N_3 \tag{2}$$

where, C_m = management cost ($); $C_{inter\text{-}basin\ transfer}$ = inter-basin transfer/pumping costs ($); N_1 = Number of times *Stage 1* water restriction is implemented; N_2 = Number of times *Stage 2* water restriction is implemented; and N_3 = Number of times *Stage 3* water restriction is implemented.

The water restriction stages were adapted from a study performed by TRWD where *Stage 1* water restriction means that lawn watering is reduced to twice per week, *Stage 2* water restriction means that that lawn watering is reduced to once per week, and *Stage 3* water restriction means that lawn watering is banned. The model decision variables are inter-basin transfer triggers (% of conservation storage of the reservoir), inter-basin transfer volumes, and drought triggers (% of conservation storage of the reservoir).

Since cost of inter-basin transfers depends upon the volume of pumping, a relationship between the cost and pumping volumes was found using pumping data obtained from Arlington Water utilities for a period from 2000 to 2010. First the pumping data for Lake Arlington were separated for each month for the period 2000 – 2010. Then a regression analysis was performed to determine the monthly pumping volume versus pumping cost using the data for the same period. Fig. A-1 through A-12 in Appendix A show monthly pumping volume versus pumping cost relationship for Lake Arlington.

Genetic Algorithm based optimization methodology

The optimization model was developed using Genetic Algorithm [GA] (Holland 1975). Genetic Algorithm can be defined as a heuristic method that simulates the concept of biologic evolution which was developed by Charles Darwin. This algorithm is programmed and oriented to generate solutions to optimization problems that have been hard to solve using conventional approaches (Eiben and Smith 2003).

GA has several specific operators such as: Representation, Selection, Crossover, and Mutation. The GA operators are described below.

Representation: In a typical GA, the decisions variables are encoded as an array of variables, when decoded represent a possible solution. Although several variations exist, a real representation was used for this model to initialize the GA population.

Selection: In the selection process a part of the current population is chosen to produce a new generation through cross-over and mutation. In this model a tournament selection was applied where two Individuals are chosen randomly, their fitness values (objective function values) are compared, and the winning individual of each tournament gets selected for crossover.

Crossover: The Crossover can be defined as the process of combining two individuals to generate a child solution (also called offspring). In this model, an arithmetic cross-over was used.

Mutation: In GA based search mutation operator is used to keep genetic diversity from one generation to the next by injecting new genetic material. This is achieved by randomly changing a gene with a small probability.

At the beginning of the GA process, a set of solutions (parent individuals) are created randomly. This process is called initialization. Then the process undergoes selection, crossover, and mutation to create a new generation (offspring). At the end of each generation, the parent population is replaced by offspring and the process carries out iteratively until new generation no longer yields better outcomes (Eiben and Smith 2003). A flowchart of the GA process is shown in Fig.3.

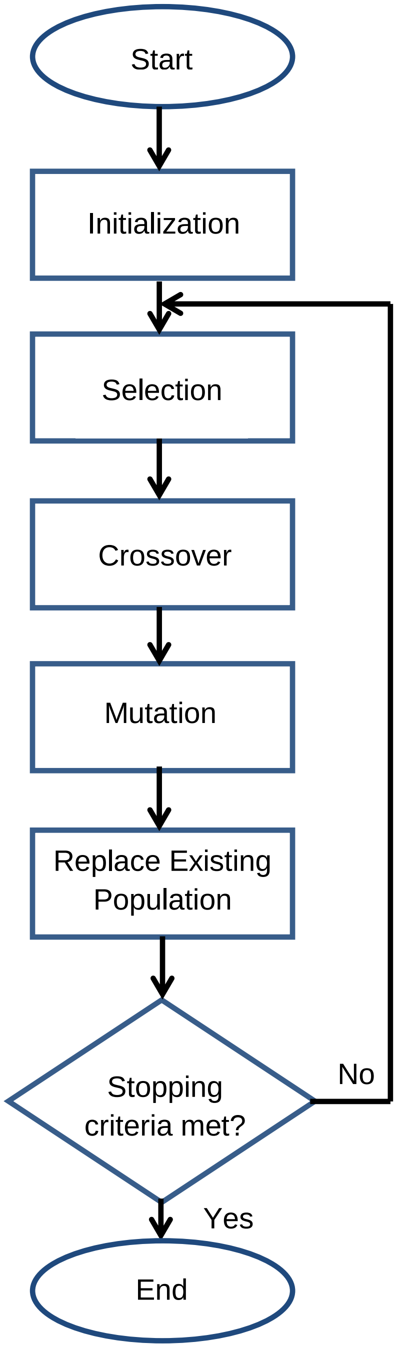

Fig 3. Flowchart of the GA process

The CAS simulation framework was coupled with the GA optimization module to evaluate a combination of supply-side and demand-side adaptive water management strategies in achieving the utilities goal of minimizing management costs. Fig.4 shows the conceptual simulation-optimization framework.

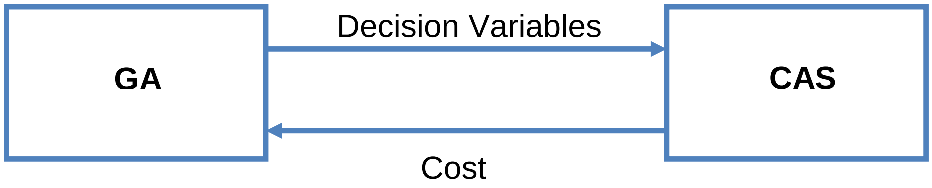

Fig.4. Conceptual simulation-optimization framework

Implementation of methodology to a case study

The modeling framework was implemented to the City of Arlington which is one of the fastest growing cities in the State of Texas. The municipality of Arlington is one of the largest customers of Tarrant Regional Water District (TRWD). The city population in 2008 was estimated to be 367,737 and is expected to increase to about 515,500 in 50 years (AWU 2009). The purchased water is transferred from Richland-Chambers and Cedar Creek reservoirs in TRWD to Lake Arlington, which has a storage capacity of 45,710 ac-ft and conservation storage capacity of 38,740 ac-ft. The current demand of the city of Arlington is 161 gallons per capita per day (National Wildlife Federation and Sierra Club 2010). Water demand rises up to 50% in this area during summer time due to lawn watering (Hardberger 2008). Therefore, saving water becomes very vital during this time of the year.

This study simulates Lake Arlington, Lake Arlington watershed, residential consumers, and the policy maker. A schematic of the case study is shown in Fig. 5. For this investigation, the Tarrant reservoirs were modeled as infinite reservoirs due to their high storage capacity. 50,600 residential customers were modeled as residential agents during the initialization process who are currently served by the Lake Arlington. At the end of each year, new residential agents were created based on the population growth rate of 2.6%, which is representative value for this area. The residential consumers' water use behaviors were evaluated based on the City of Arlington's residential customers billing data (2002 – 2010) and housing survey data for Fort Worth-Arlington Area (2002) to

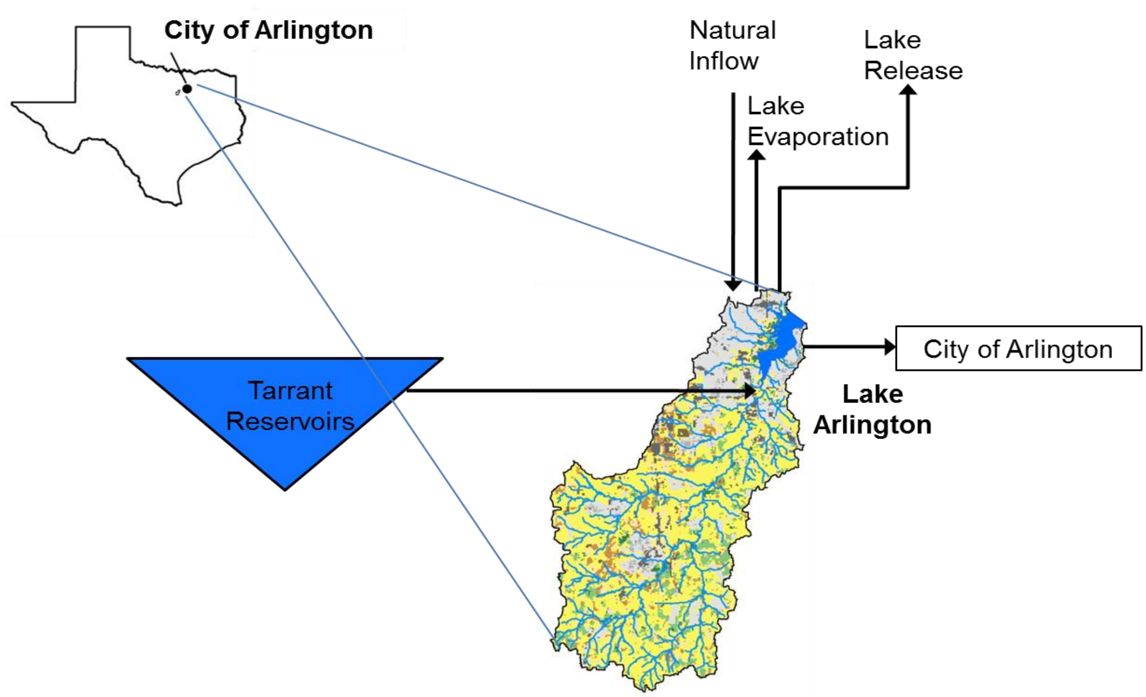

Fig.5. Lake Arlington and the watershed

simulate monthly water use. Detailed information on residential consumers monthly demand model can be found in Kanta and Zechman (2011).

The methodology was applied to evaluate optimal water management strategies during Texas drought of record (1948-1957) for the case study. It was assumed that the indoor demand is a function of type of appliances and consumer behavior whereas the outdoor demand is a function of rainfall, evaporation, lot size, and consumer behavior. Each year 2000 toilets, 2000 shower heads, and 2000 washing machines replacement rebate policy was implemented, outdoor water use restrictions were also implemented periodically based on the current month's water availability during the simulation period. A water balance equation was used to calculate water availability as follows (Kanta and Zechman 2011):

$$S_t = S_{t-1} + RO_t + IBT_t - D_t - LE_t - R_t \tag{3}$$

Where S_t = reservoir storage volume at current month t (ac-ft), S_{t-1} = reservoir storage volume at previous month t-1 (ac-ft), RO_t = runoff volume from the watershed into the reservoir at current month t (ac-ft), IBT_t = Inter-basin transfer volume to the reservoir at current month t (ac-ft), D_t = residential demand at current month t (ac-ft), LE_t = lake evaporation at current month t (ac-ft), and R_t = reservoir spills at current month t (ac-ft).

CHAPTER III

RESULTS

GA parameters and convergence

The simulation-optimization methodology was conducted for 20 independent trials to test and evaluate the robust behavior of the proposed methodology with a predefined parameter values of population size =50, crossover rate = 0.8, mutation rate = 0.01, and number of generations = 100. From all 20 trials it was observed that the objective function value decreased with the progression of generation and reached a plateau at 90 generations. The convergence of the GA from a representative trial is shown in Fig. 6.

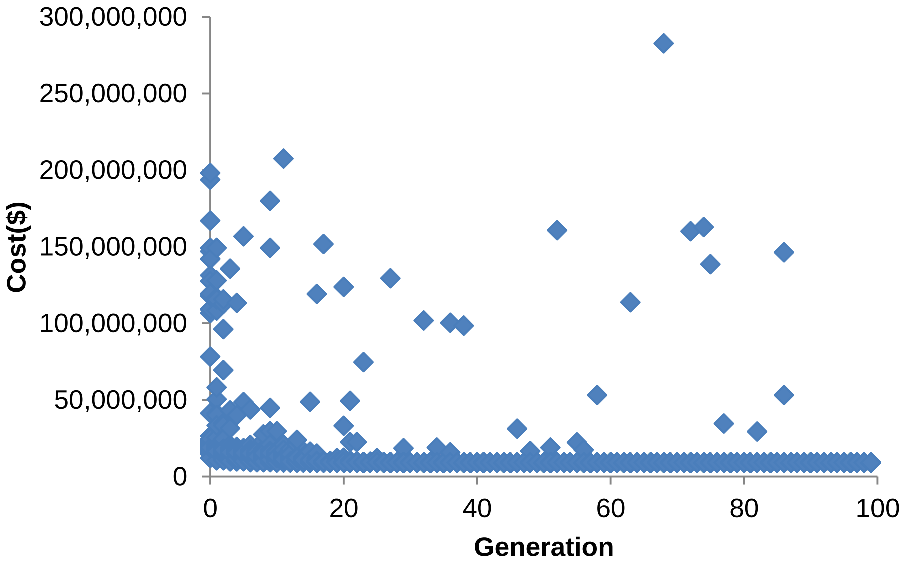

Fig.6. Convergence of the optimization algorithm

During each independent trial, a number of metrics were evaluated to compare with the objective function values. These metrics are total pumping volume and total number of days without lawn watering over the drought decade. These metrics along with the

Table 1 Model objective function values and two matrices from 20 trials

Trial	Cost ($)	Pumping Volume (ac-ft)	Number of days w/o lawn watering
1	9,009,857	153,012	2,564
2	10,546,026	178,408	2,372
3	12,441,828	244,264	2,408
4	10,802,874	183,457	2,560
5	10,863,507	185,055	2,544
6	12,259,044	208,790	2,004
7	11,621,501	198,138	1,904
8	12,110,773	238,575	2,336
9	9,828,114	167,555	2,568
10	11,707,347	244,831	2,124
11	9,122,855	155,544	2,676
12	12,015,442	244,191	2,192
13	14,712,789	256,719	2,420
14	13,799,088	244,587	948
15	10,076,462	171,610	2,504
16	10,975,304	186,094	2,580
17	11,442,794	237,099	2,280
18	12,170,816	244,913	2,232
19	12,056,501	205,174	2,524
20	9,333,674	159,192	2,576

objective function values help understanding the effectiveness of the computed policies for the study area. Table 1 shows a list of objective function values and two metrics for each trial and Table 2 shows the corresponding decision variables.

Table 2 Model decision variables from 20 trials

Trial	Pumping triggers (% conservation storage)		Pumping volumes (ac-ft)			Drought triggers (% conservation storage)		
	T1	T2	P1	P2	P3	D1	D2	D3
1	25	13	199	698	1,668	55	14	1.5
2	26	11	167	465	2,039	50	12	2.9
3	22	14	156	1,581	7,048	79	36	20
4	34	10	98	208	2,165	56	15	5
5	26	5	249	331	2,226	55	13	3
6	38	8	34	170	2,579	36	11	1
7	11	4	13	1,195	2,398	25	10	3
8	1	0	247	814	7,183	59	22	9
9	24	14	363	923	1,802	69	15	1
10	9	3	137	652	8,242	52	17	9
11	4	2	202	490	1,864	71	13	2
12	16	6	235	854	7,767	61	23	5
13	18	8	411	727	4,314	63	24	14
14	30	2	88	155	4,703	18	9	3
15	38	11	168	538	1,910	53	14	3
16	35	11	118	377	2,145	63	17	6
17	15	3	99	539	8,175	59	24	4
18	12	4	212	1,438	7,444	69	20	9
19	23	9	94	437	2,460	58	15	4
20	49	16	231	533	1,717	68	16	1

From the 20 trials, the average cost was found to be $11,344,830; the average pumping volume was 205,360 ac-ft; while the average number of days without lawn watering was 2,316. The standard deviation for cost, pumping volume, and number of days without lawn watering were computed to be 1,477,758 ($), 35,840 (ac-ft), and 384 respectively. The values of standard deviation are reasonably small for the 20 trials compared to the average values which indicate that results obtained are fairly robust. Figures 7(a), 7(b), and 7(c) shows the average pumping cost, average pumping volume, and the average number of days without lawn watering, respectively.

Simulation scenarios

From the above 20 trials, a near optimal solution (decision variables such as optimal adaptive inter-basin transfer strategy and optimal adaptive drought management strategy) from a representative trial was selected to simulate as an optimal scenario for the case study over the simulation period. The supply-side decision variables and the demand-side decision variables of the near-optimal solution from the representative trial are shown in Fig. 8(a) and Fig. 8(b), respectively.

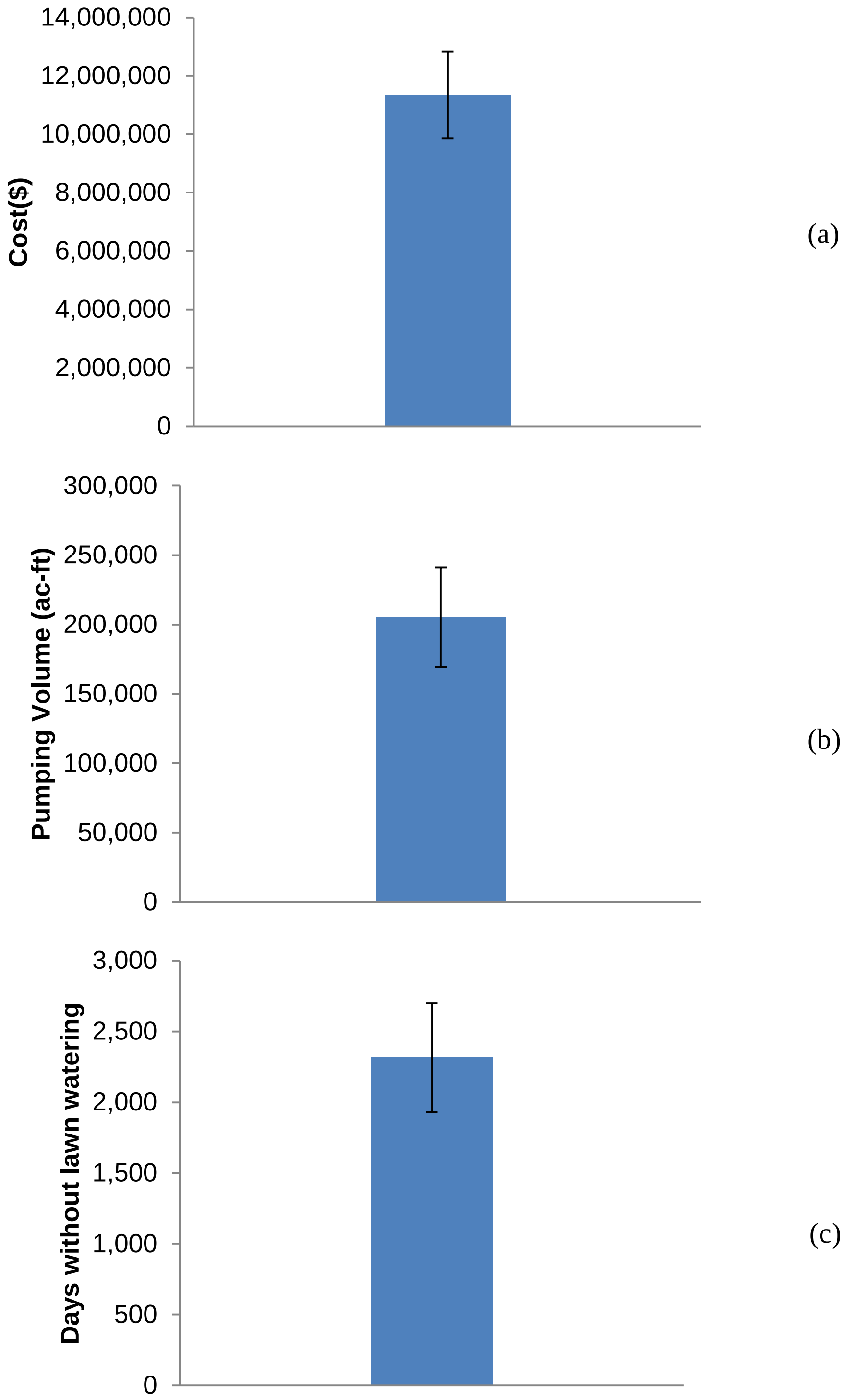

Fig. 7. Average management cost (a), average pumping volume (b), and average days without lawn watering (c) from 20 trials for the simulation period (2000-2010)

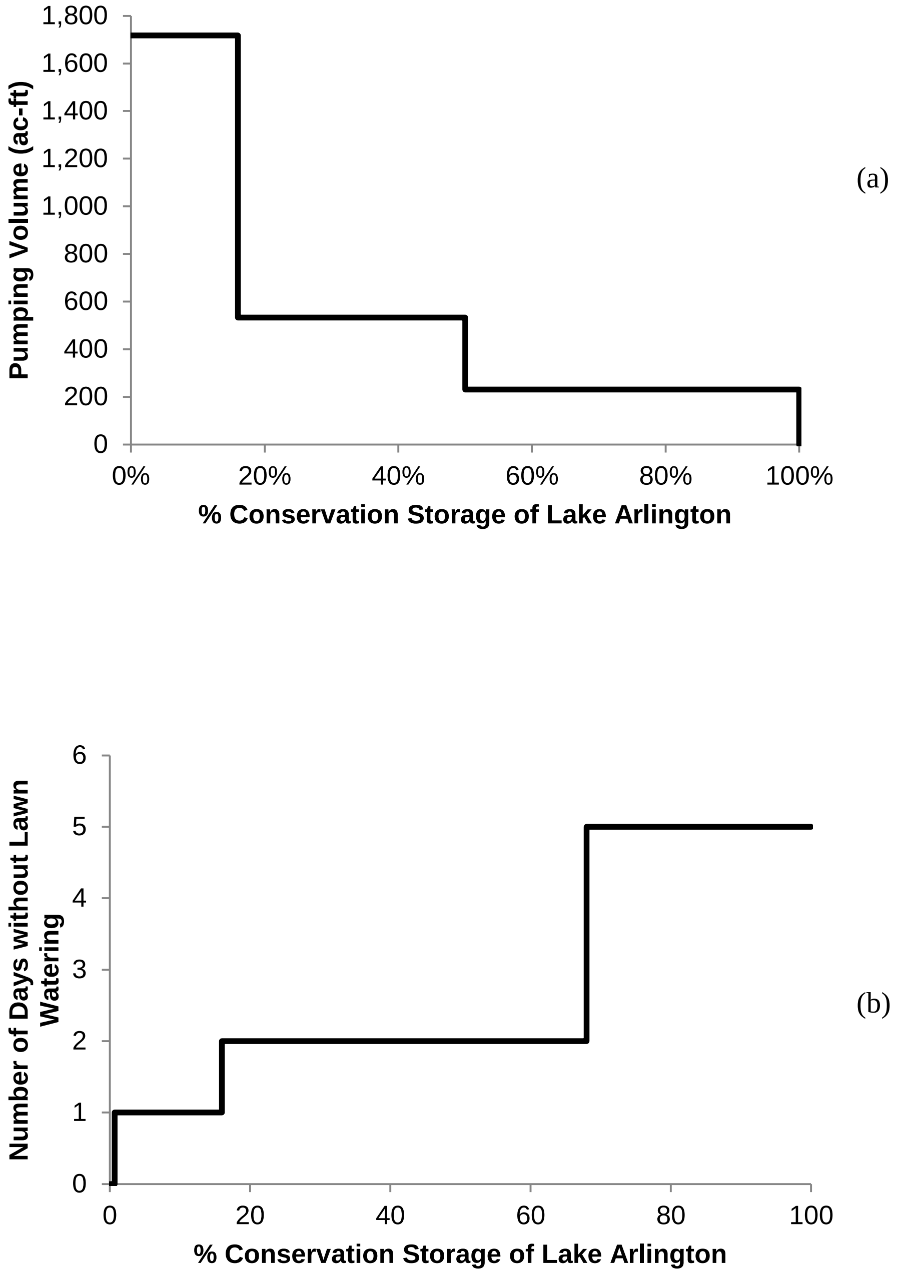

Fig. 8. Representative solution for inter-basin transfer strategy (a) and for adaptive drought plan (b)

To compare the reservoir responses for different strategies, a base case scenario, representing the current pumping strategy and no conservation scenario, was simulated and the reservoir monthly storages are plotted in Fig.9. With the base scenario, the indoor and the outdoor demands were 155.4 million gallons and 73.2 million gallons, respectively, which contributed to a total demand of 228.6 million gallons for the analysis period. While the optimal scenario was simulated, the indoor, outdoor, and total demands were 153.5 million gallons, 41.0 million gallons, and 194.5 million gallons, respectively, for the study period. Thus with optimal scenario a 15% demand reduction was achieved for the Texas drought of record. The results also indicate that with base case, the reservoir monthly storage was maintained close to the conservation storage except for few months. The outdoor water use restrictions or rebate programs were not implemented for once over the simulation period with the base case scenario which produced sufficient storage and generated greater volume of inter-basin transfers, which, in turn, resulted in higher management cost. With optimal case scenario, the reservoir storage was below the conservation storage for the most part; outdoor water use restrictions or rebate programs were implemented frequently over the simulation period. In this case, the management cost was kept minimal through less pumping, which resulted from a stringent supply-side strategy, as well as through frequent implementation of outdoor water use restrictions, which resulted from a conservative demand-side strategy.

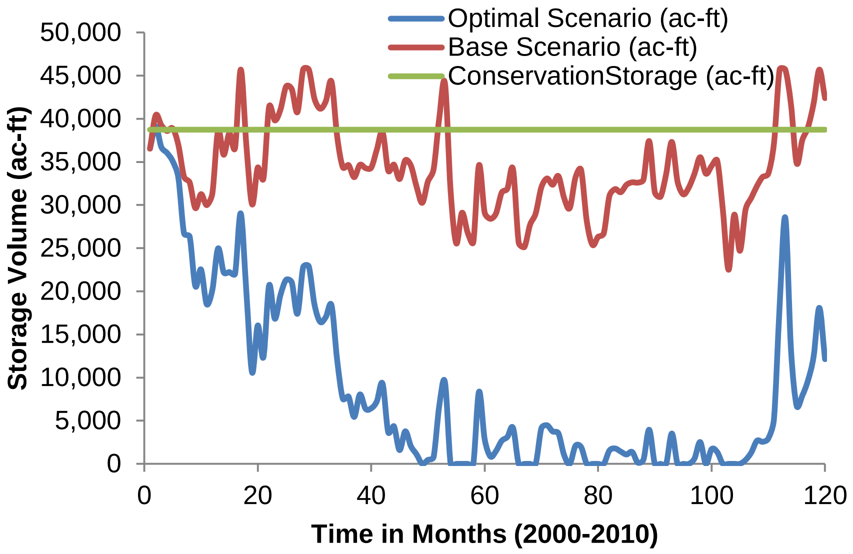

Fig.9. Reservoir monthly storage during the simulation period

The total pumping cost for both of the optimal and base case scenario were plotted and compared in Figure 10. The total pumping cost for the base case was found twice as high as that for the optimal case over the long time horizon. While the management costs were kept minimal with the optimal strategy, the total number of days without lawn watering was found to be 2,568. On the other hand, with base scenario, due to no conservation strategy, the consumers could water their lawns year round.

These results indicate that while demands could be reduced by a significant amount through implementation of optimal strategy, the reservoir depleted to a level corresponding to 1% of conservation storage. Thus, a trade-off exists between the pumping cost (or volume) and the number of days without lawn watering. This raises a key policy question that one can only optimize one of the two metrics.

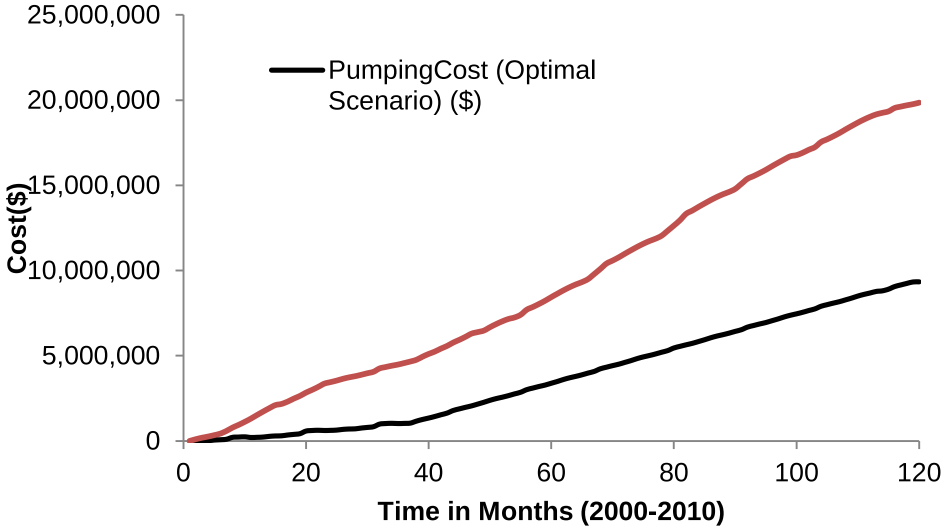

Fig.10. Total pumping cost during the simulation period

CHAPTER IV

SUMMARY AND CONCLUSIONS

Sustainability of urban water resources is an emergent property of interactions between many components such as civil infrastructures, policy makers, consumers, and the hydrologic cycle. Although few existing methodologies have addressed this dynamic interactions between the above components, those studies focused on demand-side management only. In an earlier investigation it was found that supply-side policy decisions influence the demand-side management options and vice versa (Kanta and Zechman 2011). Therefore, a novel methodology is required to address both supply-side and demand-side policy options and thereby to evaluate an optimal management strategy for urban eater resources.

This research proposed a new methodology to evaluate a combination of supply-side and demand-side adaptive water management strategies in achieving the utilities goal of minimizing management costs. A dynamic modeling framework - complex adaptive system (CAS) was applied to study the demand-side and supply-side management of an urban water system. The water resources system is dynamic and adaptive because the decision-making entities of the model such as the residential consumers and the policy makers can affect each other through their dynamic decision-making and adaptive behaviors. A simulation-optimization methodology was developed by coupling the CAS modeling framework with the Genetic Algorithm (GA) optimization module. The proposed methodology was applied to a realistic case study, City of Arlington, to identify optimal solutions that minimize the cost of inter-basin transfers in an urban water system. Regression analysis was performed to find relationships between inter-basin transfer costs and pumping volumes for the study area using historical pumping cost data. The simulation-optimization model was simulated for 20 trials to validate the robustness of the GA process. The water system's response was evaluated and compared through two metrics – pumping volume and number of days without laws watering. The average cost, average pumping volume, and average number of days without lawn watering from the 20 trials ensured that the results were consistent. Detailed analysis of results was performed with a near optimal solution from a representative trial. The optimal scenario was compared with a base case (no conservations and restrictions) and the system's responses were evaluated in terms of two metrics.

From the analysis of results it was found that with the optimal scenario, the management cost was significantly reduced and the total demand was also reduced by 15% over the ten year period. However, this caused the reservoir storage to drop below the conservation storage for a significant period of time. Frequent implementation of outdoor watering restrictions also resulted in many months without lawn watering during drought. While the utility management cost is linked to both supply-side costs such as inter-basin transfers and demand-side costs such as cost of rebates and restrictions, the current model only considered inter-basin transfer costs. Thus lower volumes of inter-basin transfers resulted in lower costs. And thus fewer inter-basin transfers resulted in more frequent implementations of outdoor water-use restrictions which resulted in higher number of days without lawn watering. Including the costs of rebates and restrictions might have reduces the number of days without lawn watering.

In future investigation, the costs of water conservation rebate programs (high efficient shower heads, toilets, and washing machines) as well as cost of compliance to outdoor water use restrictions will be added with the cost of inter-basin transfers to minimize the total management costs.

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APPENDIX A

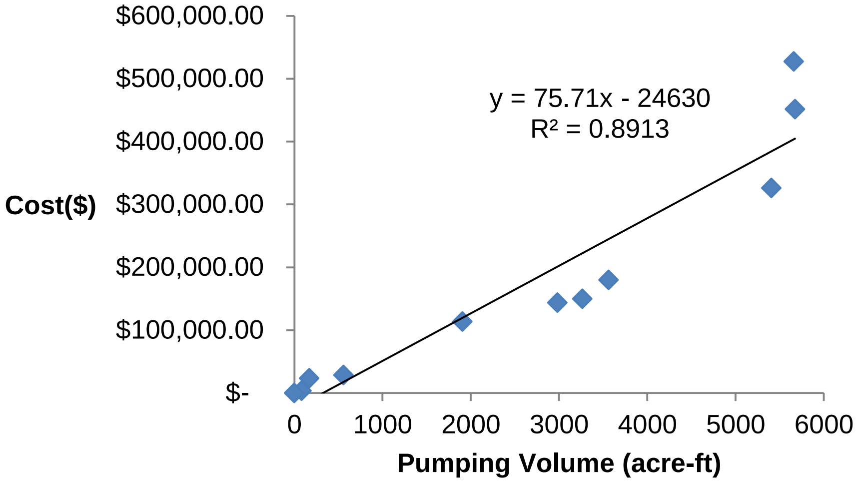

Fig. A-1. Cost vs. Pumping Volume for January (2000-2010)

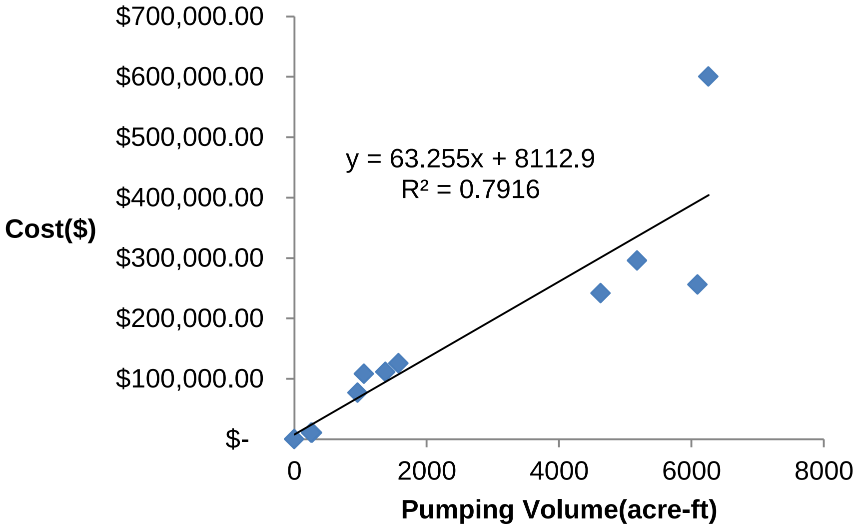

Fig. A-2. Cost vs. Pumping Volume for February (2000-2010)

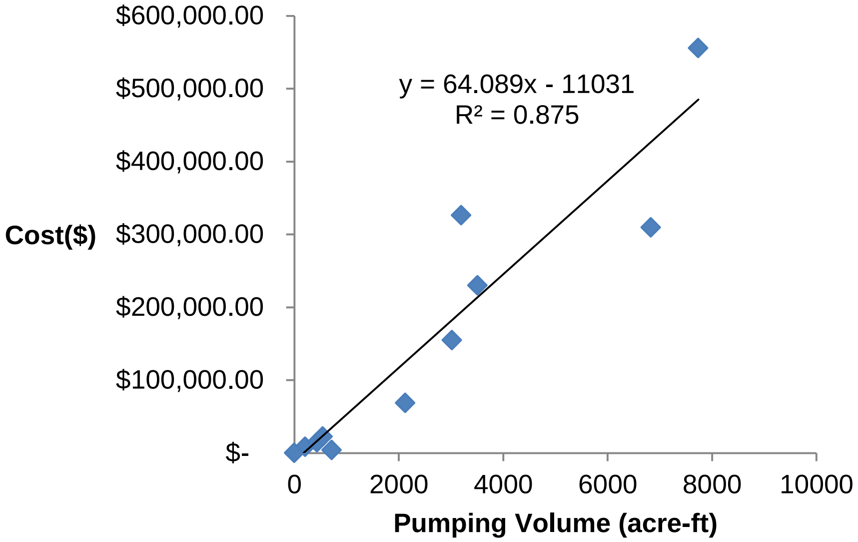

Fig. A-3. Cost vs. Pumping Volume for March (2000-2010)

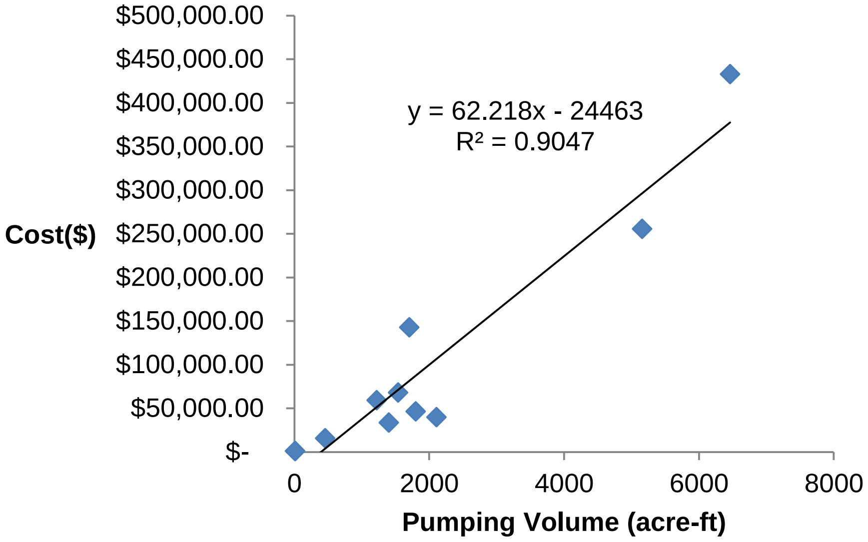

Fig. A-4. Cost vs. Pumping Volume for April (2000-2010)

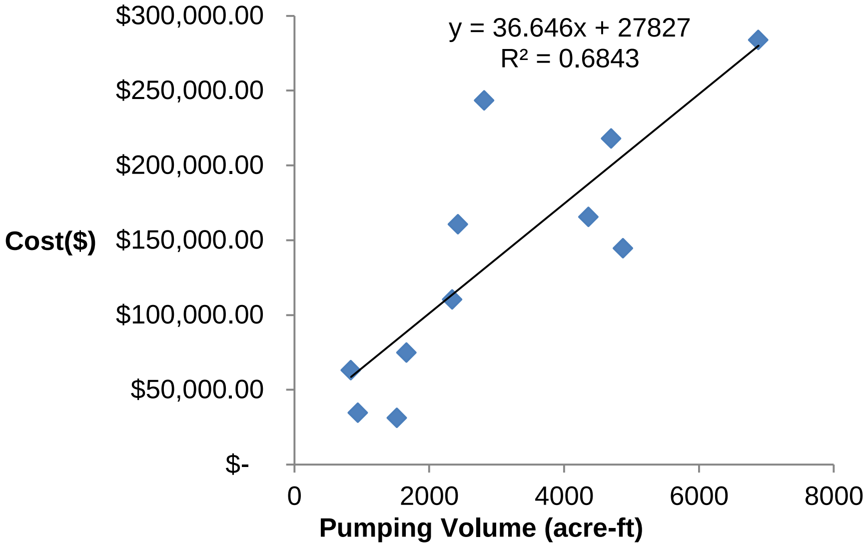

Fig. A-5. Cost vs. Pumping Volume for May (2000-2010)

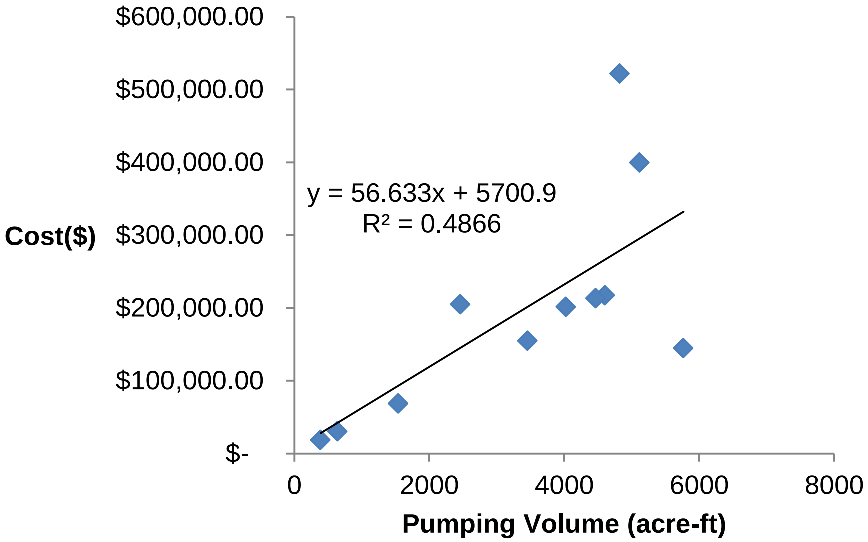

Fig.A-6. Cost vs. Pumping Volume for June (2000-2010)

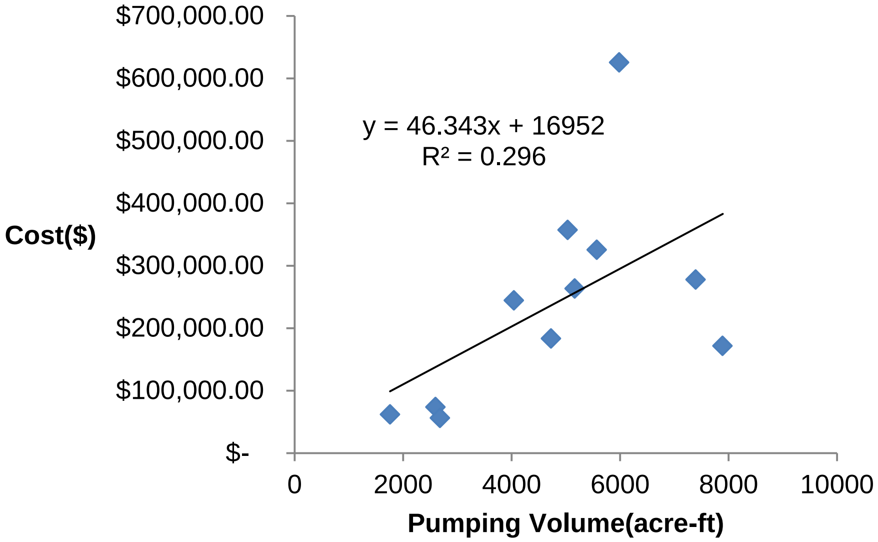

Fig. A-7. Cost vs. Pumping Volume for July (2000-2010)

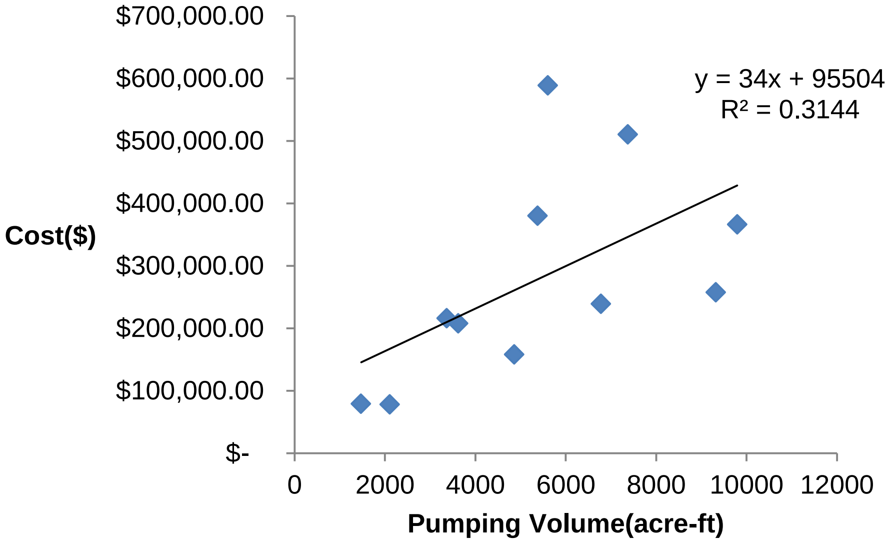

Fig. A-8. Cost vs. Pumping Volume for August (2000-2010)

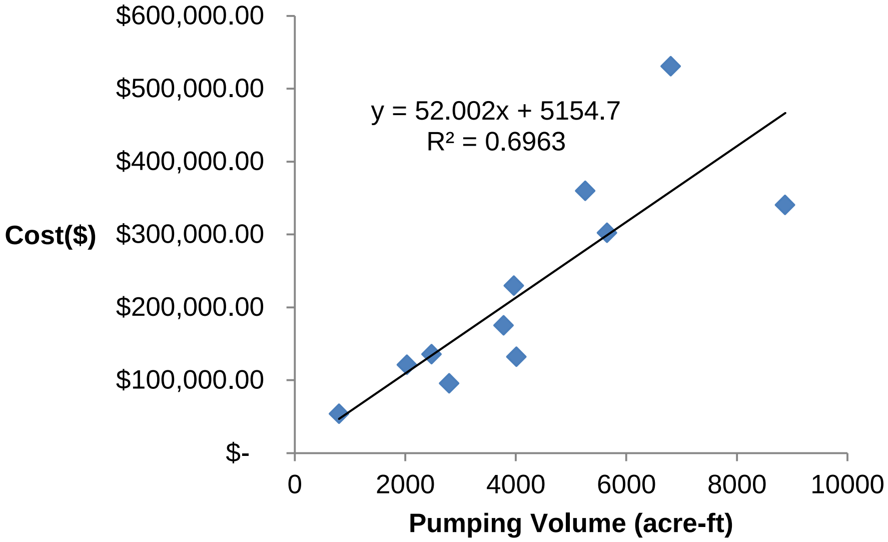

Fig. A-9. Cost vs. Pumping Volume for September (2000-2010)

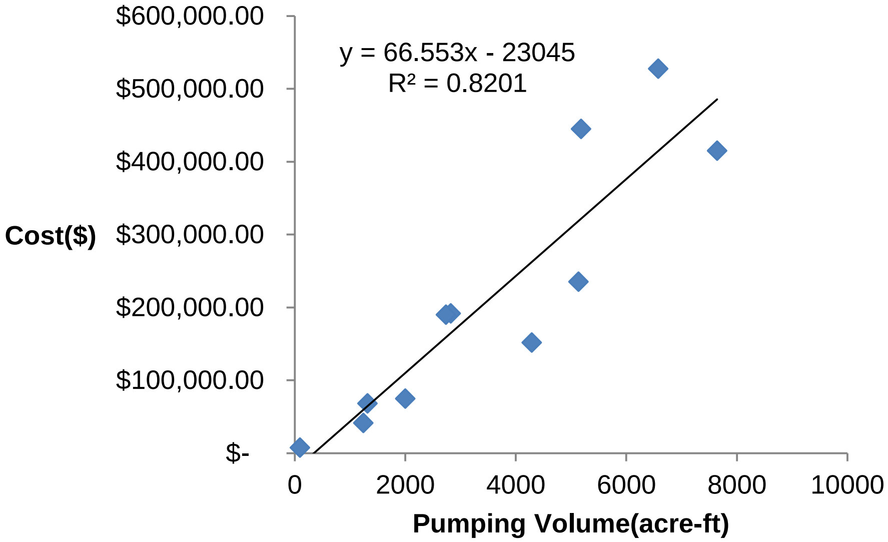

Fig. A-10. Cost vs. Pumping Volume for October (2000-2010)

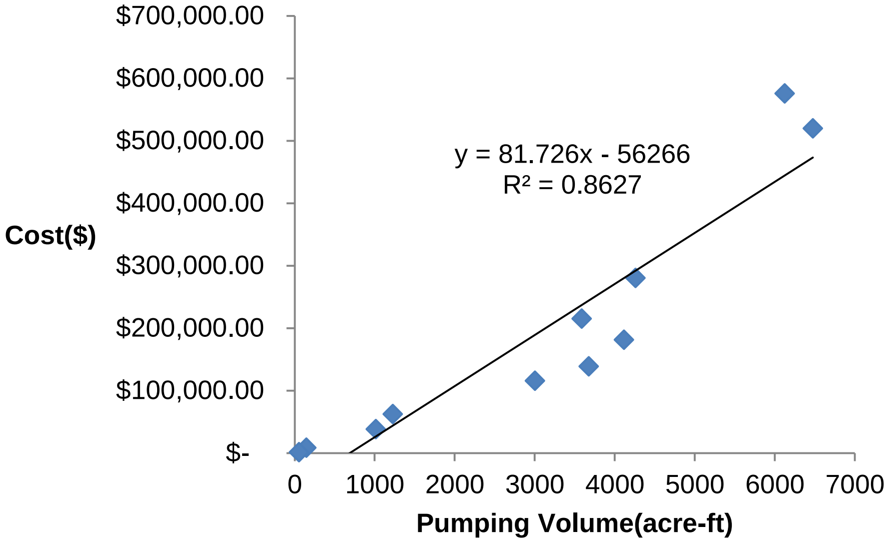

Fig. A-11. Cost vs. Pumping Volume for November (2000-2010)

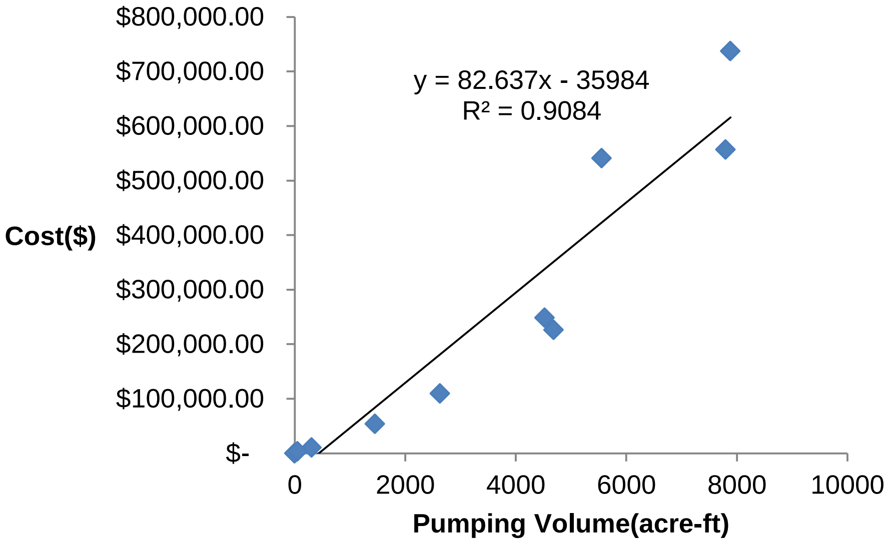

Fig. A-12. Cost vs. Pumping Volume for December (2000-2010)

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