URBAN WATER SUPPLY, SALT FLUX AND WATER USE

by

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ABSTRACT

The city of Scottsdale, Arizona was selected to study urban water supply and salt flux. It is found that precipitation brought the highest amount of water to the city, followed by Central Arizona Project (CAP) supply, groundwater mining, Salt River Project (SRP) supply, and wastewater reclamation. CAP supply carried the largest salt flux into the city, followed by surface runoff, groundwater mining, domestic input to wastewater, and SRP supply. The water in Scottsdale is supplied for potable uses and golf course irrigation. The temporal variations of the municipal water usage and the salinity in golf course soil moisture were simulated. It seems that under current golf course irrigation practice the salinity in irrigation water will not damage turfgrass or soil physical properties. Although it is encouraged to cut residential landscape irrigation usage by local governments, it is found that irrigation of proper designed landscape can effectively reduce building cooling load.

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TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1. Background

Arizona has been struggling to secure water supply probably since three thousand years ago Hohokam people constructed a canal system for irrigation. Throughout last century, central Arizona relied on underground water and local surface water including Salt River, Verde River, and Gila River. In 1993, construction of Central Arizona Project (CAP) canal was finished and Colorado River water was delivered to central Arizona since then. To meet growing water demands, wastewater is utilized after treatment for golf course irrigation, agriculture irrigation, power plant cooling, and artificial recharge.

With urban development, water use has changed gradually. CAP was originally constructed to meet agriculture irrigation demand. But since its completion, it has been used more to augment urban water supply for a growing population than to apply on agriculture. Agricultural water use in Phoenix Active Management Area (AMA) has generally been decreasing, and one example is that SRP agricultural water use had decreased by 50% percent from 1984 to 2002 (Hetrick and Roberts, 2004). With electricity cooling system became dominant in newly built residential houses in early 1980s, proportion of evaporative cooling water use in municipal water supply decreased.

Salinity in water is a concern for central Arizona. Rising groundwater table and agricultural irrigation practice lead to soil salination. The increasing salinity in groundwater decreases its quality as potable water supply. The Central Arizona Salinity Study (Smith, 2005) found that water supplies brought 1.5 million ton salt into central Arizona and more than 1 million ton was accumulated in this area annually.

To better understand urban water supply, water use and salt flux, we chose Scottsdale, AZ for a case study. The reasons why Scottsdale was selected are:

- Scottsdale was delivered with all types of water supplies including importation water from Colorado River through CAP canals, local surface water supply through SRP canals, groundwater supply, and reclaimed water supply.
- Scottsdale's elevation is high in north and low in south, which makes most of its runoff go to the Indian Bend Wash in South Scottsdale. And there are six gauge stations along Indian Bend Wash which provide hourly record of precipitation and flow rate information.
- The Supervisory Control And Data Acquisition (SCADA) system of Scottsdale can provide detailed hourly data for water supplies and water uses. For example, the SCADA can provide hourly irrigation data for many specific golf courses, which is very helpful for percolation and soil salinity analysis for golf courses.

1.2. Scope of the study

This study collected varying flow-rate data from Scottsdale hydraulic infrastructures including water treatment plant, wastewater treatment plant, drainage system, reclaimed water irrigation system, and recharge sites. These data were applied to a network model in which water suppliers and water users were connected through hydraulic infrastructures. The model incorporates major water flux information of Scottsdale and could inform people where water comes and goes and how water flows in Scottsdale. In combination with salinity data of water flux, the model could inform people where salt comes and goes and how much salt is accumulated in Scottsdale. Chapter 1 gives details of the model and its application.

Water uses in Scottsdale include municipal uses and golf course irrigation. In Chapter 2, municipal uses are investigated by two categories, residential uses and commercial and institutional uses. These two categories could be further divided into sub-categories based on different end use purposes. Water demands for some end uses will vary with season, such as water for irrigation, evaporative cooling, and swimming pools. By studying the seasonal fluctuation of municipal water uses for irrigation, evaporative cooling, and swimming pools, we simulated the variation of municipal water supply. And the simulation is compared with real data.

In Chapter 3, golf course irrigation is investigated and salinity concerns during golf course irrigation are addressed. The salinity in irrigation water will concentrate in soil because of evapotranspiration. Based on the modeling of evapotranspiration and percolation, the salinity and the sodium adsorption ratio (SAR) in soil moisture of root zone are estimated.

In Chapter 4, the cost and benefit of landscape are quantified and compared. Landscape costs huge amount of water for irrigation, but it can help reducing building cooling energy consumption by providing shading and evaporative cooling.

CHAPTER 2

WATER AND SALT FLUX MODELING THROUGH URBAN HYDRAULIC INFRASTRUCTURE

2.1. Introduction

Water is recognized as a precious resource for the semi-arid area of central Arizona. Water infrastructures such as canals, wells, reservoirs, and dams have been built one after one to adapt to the urban development. The earliest water infrastructure construction in this area is the gravity-flow canal system built by Hohokam community three thousand years ago to irrigate their agriculture with water from Gila River and Salt River, the remains of which could still be seen in the Salt River valley (Artiola *et al*. 2006). In last century, hydraulic infrastructures such as the Central Arizona Project, which import water from Colorado River to the central Arizona area, have been built to sustain agriculture development, urban expansion and population growth.

Of the water conveyed through the urban infrastructure, 68% is used for irrigation (Water Resource Research Center, 2002). While irrigation salinity is a common problem for semi-arid regions (Proust, 2003; Khan *et al*., 2006), salt accumulation in soil due to increasing irrigation salinity is also a concern for the central Arizona. Water and wastewater agencies in central Arizona have launched the Central Arizona Salinity Study to address salinity issue, and the Phase One of the study has reported that 1.5 million tons of salts are imported into the region annually, 0.4 million tons leave, and more than 1 million tons of salts are added to this region (Smith, 2005).

To understand water and salt flux through urban hydraulic infrastructures, we selected Scottsdale, Arizona for a case study. In this study, information on water usage and salinity were collected, water and salt flux within the city boundary were modeled, and future water and salt flux were projected under several scenarios. The urban water flux within Scottsdale includes potable water supply, wastewater and reclaimed water, and precipitation and runoff. Real flow rate data are collected, as well as total dissolved solids (TDS) data. PowerSim, a simulation software, is used to integrate water usage and salinity information for flux modeling.

2.2. Site Description

Potable water supplies for Scottsdale include Salt River and Verde River water delivered through Salt River Project (SRP), Colorado River water delivered through Central Arizona Project (CAP), and ground water wells. Wastewater is treated and reclaimed for golf course irrigation as well as groundwater recharge. Most runoff is taken by Indian Bend Wash (IBW) south to the Salt River. There are other drainage systems such as Rawhide Wash that collect runoff, but they are negligible compared with Indian Bend Wash. Figure 2.1 shows the spatial location of these infrastructures. Water for shaded area is supplied by Salt River Project (SRP) and Central Groundwater Treatment Facility (CGTF), while water for blank area is supplied by Central Arizona Project (CAP) and supplemental groundwater. Wastewater generated north to the dash line shown in the figure is treated in Water Campus and Gainey Ranch Water Reclamation Plant (GR WRP), while wastewater generated south to the dash line is sent to 91st Ave WWTP in Phoenix. 7-mile long Indian Bend Wash (IBW) is the main collector that carries runoff from the city down to the Salt River, which is recorded by the McKellips gauge station. Table 2.1 lists these infrastructures and specifies sources for these infrastructures.

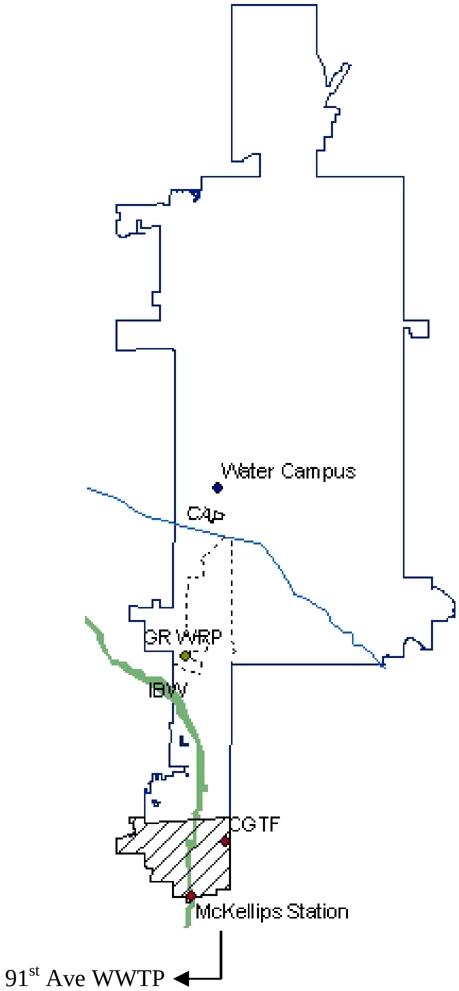


Figure 2.1 Location of water infrastructures of Scottsdale.

Table 2.1

Water Infrastructures in Scottsdale

Infrastructure	Source
Potable water	
CAP Water Treatment Plant	CAP
Verde Water Treatment Plant (in Phoenix)	SRP
Groundwater wells (including CGTF)	Groundwater
Wastewater	
Water Campus Wastewater Reclamation Plant	Wastewater north to Doubletree Ranch Rd
Gainey Ranch Wastewater Reclamation Plant	Sewer pipeline passing by

91st Ave Wastewater Treatment Plant	Wastewater south to Doubletree Ranch Rd
Reclaimed Water Irrigation	
Reclaimed Water Distribution System	Reclaimed water from Water Campus and CAP water
Irrigation Water Distribution System	Reclaimed water from Water Campus and CAP water
Gainey Ranch Golf Course Irrigation	Reclaimed water from Gainey Ranch WRP
Recharge	
Water Campus Recharge	Reclaimed water from Water Campus and CAP water
West World Golf Course Recharge	CAP water
Desert Mountain Golf Course Recharge	CAP water

2.3. Model Framework and Data Acquisition

2.3.1 Model framework

The framework of the flux model is constructed with PowerSim, a simulation software developed by Powersim Software (www.powersim.com). The software is also used at Arizona Sate University Decision Theater, and the theater supported the software use in this study. The simulations in PowerSim are based on system dynamics, a computer-based simulation methodology developed at Massachusetts Institute of Technology in the 1950s. The framework shown in Figure 2.2 conveys the basic information of water resources of Scottsdale: CAP, SRP and groundwater supply water for potable use; wastewater generated is either sent to the regional WWTP (91st Avenue WWTP) or Scottsdale Water Campus for treatment; wastewater is reclaimed in Water Campus and supplies for golf course irrigation together with CAP raw water; precipitation captured by surface soil will most likely goes to atmosphere through evaporation or evapotranspiration, and runoff collected in Indian Bend Wash either goes to Salt River or percolates into vadose zone; a significant proportion of potable water is used for landscape irrigation, through which water either evaporates or percolates into vadose zone; water percolating into vadose zone will finally reach aquifer and replenish groundwater.

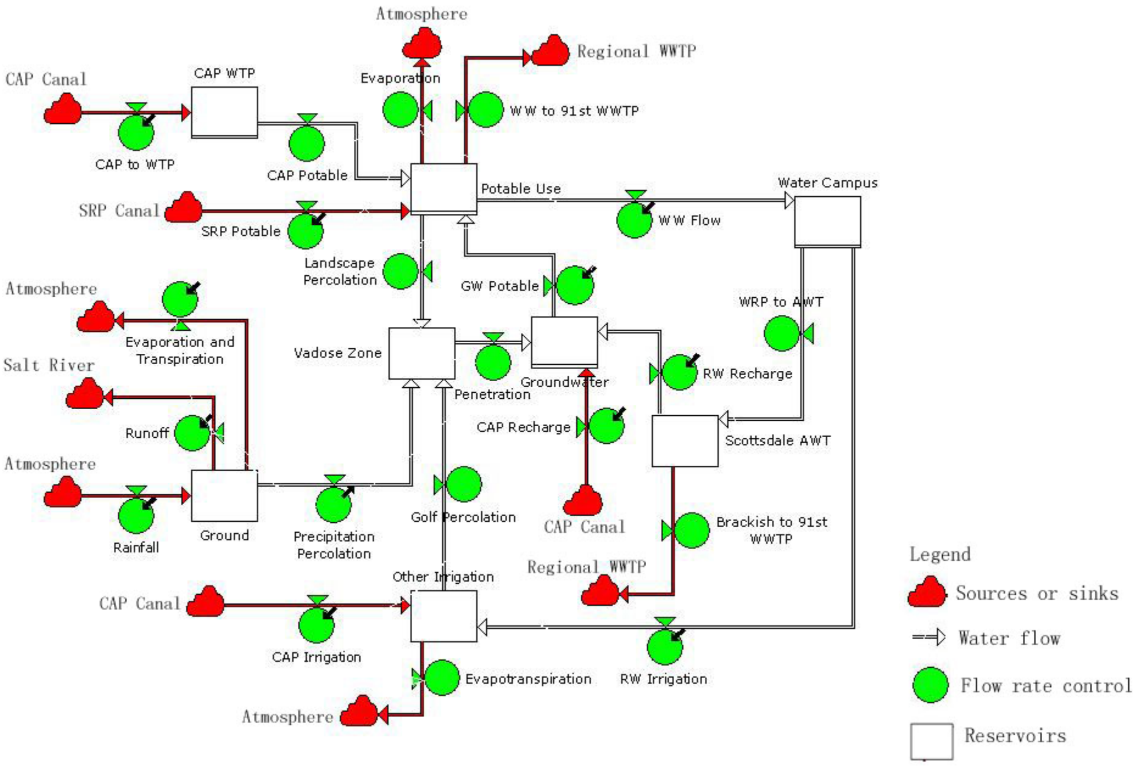


Figure 2.2. Framework of water flux model.

2.3.2 Potable water supply and wastewater data

Most of data inputs for the model are acquired from the Supervisory Control And Data Acquisition (SCADA) system in Water Campus. SCADA provided us with hourly or daily data on: (a) water pumped from CAP for potable use; (b) production of groundwater wells; (c) wastewater flowing into Water Campus WWTP and Gainey Ranch WWTP; (d) reclaimed water delivered to irrigate golf courses through IWDS and RWDS; (e) reclaimed water sent for recharge from the AWT plant; (f) CAP water for recharge; and (g) CAP water for golf course irrigation.

In 2005, Scottsdale had an entitlement of 17.8 million m^3 SRP surface water and received treated SRP water from Phoenix Verde Water Treatment Plant. This SRP supply was patterned after CAP and groundwater supply. The average daily wastewater left Scottsdale for 91st Ave WWTP was monitored to be around 65 thousand m^3 in 1999 and 2000 (Scottsdale, 2001a), and it was assumed in 2005 the same amount, i.e. 65 thousand m^3 daily, of wastewater flowing from Scottsdale to 91st Ave WWTP.

2.3.3 Rainfall-runoff data

The rain falling within the city boundary is quantified by multiplying the average precipitation of 6 stations along IBW by the area of Scottsdale, 475 square kilometers. Data of the runoff leaving from IBW to the Salt River is provided by the gauge station at McKellips.

Rainfall in excess of infiltration forms overland runoff. Guo and Urbonas (2002) used 30-year continuous rainfall data to develop a runoff capture curve for Phoenix metropolitan area. The curve could be described by following equations.

$$R = 0 \qquad P \le 2.5mm$$

$$R = 0.90(P - 2.5) \qquad P > 2.5mm$$

R – runoff capture volume, in mm;

P – precipitation, in mm.

For semi-arid area such as the central Arizona, it is most likely that the rainwater captured in soil voids during rainfall will evaporate later after the storm events. Therefore, the rain evaporation could be derived from runoff capture curve by assuming rain evaporation equal to the difference between rainfall and runoff. It is found from 2005 precipitation data that 93 mm rainfall was captured in soil and then evaporated,

$$E_R = P - R = P \qquad P \le 2.5mm$$

$$E_R = P - R = 0.1 \times P + 2.25 \qquad P > 2.5mm$$

E_R – rainfall evaporation, in mm

The difference between the runoff captured, which is calculated using capture curve equations, and the runoff leaving the city, which is provided by the McKellips gauge station, is the runoff percolation into the groundwater.

2.3.4 Evaporation and percolation of potable water

Heaney *et al* (1999) studied residential water use of 12 cities in US including Scottsdale. The study shows that 66.5% of residential water use for single-family homes in Scottsdale is for outdoor irrigation. Western Resource Advocates (2003) reported that 51% and 14% of potable water is consumed by single- and multi-family home respectively, and 35% potable water is consumed by commercial and institutional customers. In the following analysis, the assumption is adopted that multi-family homes allocate the same portion, i.e. 66.5%, of potable water for landscape irrigation as single-family homes do, and commercial and institutional customers do not irrigate landscape with potable water.

Evapotranspiration (ET), a measure of total loss of water through both soil evaporation and plant transpiration, is calculated by multiplying the reference evapotranspiration (ET_0), which could be computed using Penman-Monteith Equation and is available at the Arizona Meteorological Network (AZMET, http://ag.arizona.edu/azmet/), by adjustment factors which is known as crop coefficients (K_C) (Brown *et al*, 2000). It is found that annual ET for turf landscape in Scottsdale is around1380 mm. As discussed above, 93 mm rainfall is captured, which could offset part of the evapotranspiration demands. Therefore, only 1287 mm potable water is in need for evapotranspiration. While according to ADWR (2003)'s investigation of 33 residential landscape irrigation cases, average 1520 mm is irrigated on residential turf landscape annually. Consequently, 233 mm out of 1520 mm water is percolated into groundwater annually, and 1287 mm out of 1520 mm water is evaporated.

Based on above numbers and assumptions, following equations are developed to relate potable water evaporation and percolation to total potable water supplies.

$$E_P = \alpha_{evap}\beta_{irri}\gamma_{res}\left(CAP_P + SRP + GW\right)$$

$$P_P = \alpha_{perc}\beta_{irri}\gamma_{res}\left(CAP_P + SRP + GW\right)$$

E_P – evaporation of landscape irrigation water, in m^3;

P_P – percolation of landscape irrigation water, in m^3;

α_{evap} – ratio of evaporation to landscape irrigation, 0.85 (= 1287 mm/1520 mm);

α_{perc} – ratio of percolation to landscape irrigation, 0.15 (= 233 mm/1520 mm);

β_{irri} – percentage of irrigation usage in residential usage, 66.5%;

γ_{res} – percentage of residential usage in potable supplies, 65% (= 51%+14%);

CAP_P – potable water supply from CAP, in m^3;

SRP – potable water supply from SRP, in m^3;

GW – potable water supply from groundwater, in m^3.

2.3.5 Evapotranspiration and percolation of golf irrigation water

Brown (2006) investigated the percolation of a turf facility to evaluate the ADWR water duty regulation which caps groundwater use at 1380 and 1470 mm per year for turf grass within Tucson and Phoenix AMAs, respectively. Assuming all of rainfall is captured for evapotranspiration, Brown (2006) found average 15% percent of total water input (irrigation + precipitation) passed through root zone for deep percolation.

To estimate the evapotranspiration and percolation of golf course irrigation in Scottsdale, golf irrigation water use is assumed 1470 mm per year, as regulated by ADWR for groundwater turf facilities. And the same assumption as made by Brown (2006) is taken that all rainfall is captured by turf for evapotranspiration. As shown above, in Scottsdale, annual evapotranspiration for turf is1380 mm, and annual precipitation is235 mm. Therefore, 1145 mm irrigation water is evaporated, and 325 mm irrigation water is percolated into groundwater. The evapotranspiration and percolation are related to the golf irrigation water as following.

$$E_I = \varepsilon_{evap}\left(CAP_I + RW\right)$$

$$P_I = \varepsilon_{perc}\left(CAP_I + RW\right)$$

E_I – evapotranspiration of golf irrigation water, in m^3;

P_I – percolation of golf irrigation water, in m^3;

ε_{evap} – ratio of evaporation to golf course irrigation, 0.78 (= 1145 mm/1470 mm);

ε_{perc} – ratio of percolation to golf course irrigation, 0.22 (= 325 mm/1470 mm);

CAP_I – golf irrigation water supply from CAP, in m^3;

RW – reclaimed water from Water Campus WRP and Gainey Ranch WWTP, in m^3.

2.3.6 Salinity and salt flux

To address salt flux issue, Total Dissolved Solids (TDS) is employed as an indicator of water salinity. TDS of several types of water are listed in Table 2.2.

Table 2.2

Salinity of Water within Scottsdale

	Selected TDS (mg/L)	TDS Range (mg/L)	Data Source
CAP	650		City of Scottsdale, 2006
SRP	620		
Groundwater	620	200 - 1100	Water Campus Lab
Wastewater	1130	900 - 1300	Water Campus Lab
Reclaimed water for irrigation	1130	900 – 1300	Water Campus Lab
Reclaimed water for recharge	27		City of Scottsdale, 2006
Brackish from AWT	7380		Estimation based on the recovery of RO process
Runoff to the Salt River	350	60 - 700	USGS

With these TDS information, most salt flux can be figured out with the flux model. But to quantify the salt input from domestic to wastewater and the salt flux from landscape and golf course irrigation percolation, mass balance analysis is needed.

$$S_S = (TDS_{WW} - TDS_{DR})Q_{WW}$$

S_S – salt input from domestic to wastewater, in kg/da;

TDS_{WW} – TDS of wastewater, 1.130 kg/m^3;

TDS_{DR} –TDS of potable water, assumed to be the same as CAP water, 0.650 kg/m^3;

Q_{WW} – flow rate of wastewater to 91st Avenue WWTP, Water Campus WRP, and Gainey Ranch WWTP, in m^3/da;

The percolation water brings all the salt in irrigation water into vadose zone.

$$S_{PL} = \beta_{irri}\gamma_{res}\left(TDS_{CAP}CAP_P + TDS_{SRP}SRP + TDS_{GW}GW\right)$$

$$S_{PG} = TDS_{CAP}CAP_I + TDS_{RW}RW$$

S_{PL} – salt flux along with landscape irrigation percolation, in kg/da;

S_{PG} – salt flux along with golf course irrigation percolation, in kg/da;

TDS_i – TDS of water supply i, and i could be CAP, SRP, GW (groundwater), and RW (reclaimed wastewater), in kg/m^3.

2.4. Results and Discussion

2.4.1 Water flux

Water resources for Scottsdale include CAP supply, SRP supply, groundwater, reclaimed water, and precipitation. The 2005 accumulative supplies from these resources are shown in Figure 2.3. Surprisingly, storms especially winter and summer monsoons brought most water, about 112 million m^3, to the city. And CAP, groundwater, SRP and reclamation contributed 52, 37, 18 and 15 million m^3 water to the city respectively.

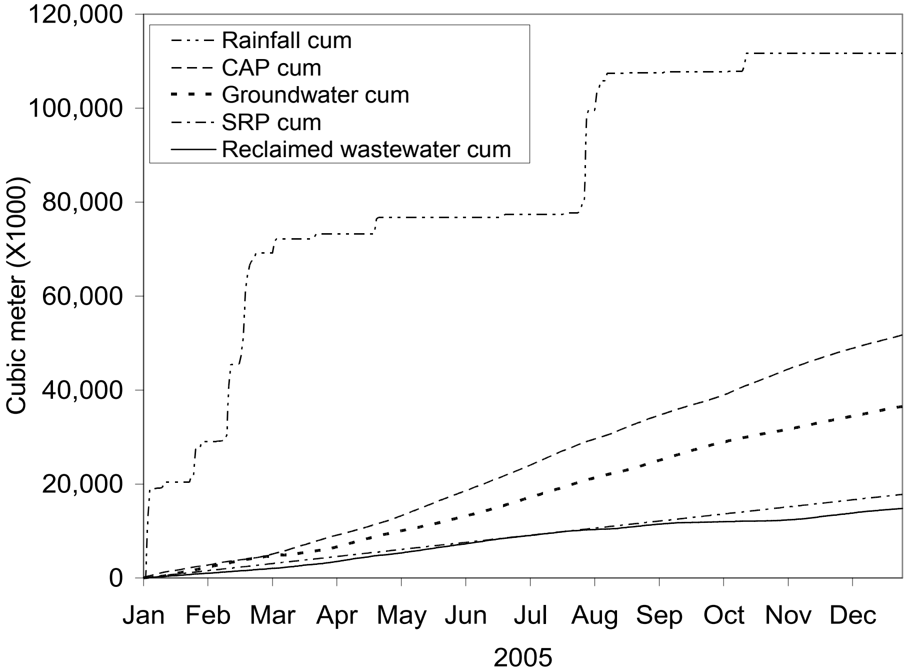


Figure 2.3. Cumulative water flux into Scottsdale from various sources during 2005 .

Water flux exit Scottsdale through evaporation, percolation, drainage to 91st Avenue WWTP, running into the Salt River, and recharging into aquifers (Figure 2.4). Annual evaporation of 2005 for Scottsdale is 95 million m^3. The accumulative percolation into vadose zone is 65 million m^3 in 2005. 24 million m^3 wastewater left Scottsdale for 91st Avenue WWTP, and 13 million m^3 runoff flowed out of Scottsdale in 2005. Annual recharge of CAP and reclaimed water was 7 million m^3. Further investigation shows that in 2005 40% of precipitation evaporated, 49% infiltrated into vadose zone, and 11% crossed the boundary of the city into Salt River.

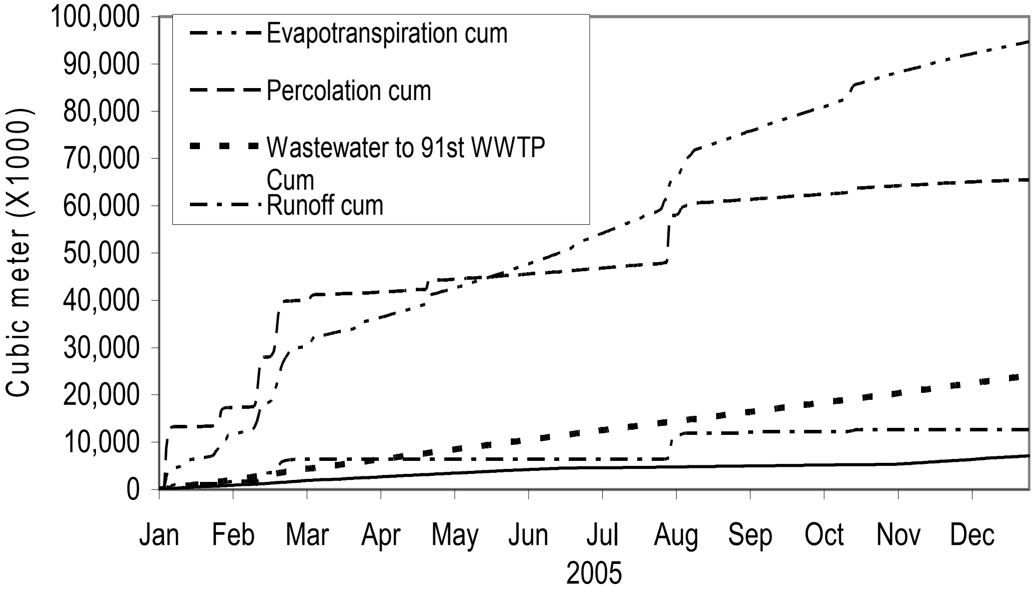


Figure 2.4. Water flux exiting Scottsdale during 2005.

2.4.2 Salt flux

The sources of salt include CAP supply, SRP supply, groundwater, human activities and residential softener use (Figure 2.5). In 2005, CAP water, surface runoff, groundwater, and SRP water brought 38, 24, 22, and 11 thousand ton salt with them respectively, and domestic released 19 thousand ton salt to wastewater. Totally 114,049 ton salt was brought into Scottsdale water infrastructure in 2005.

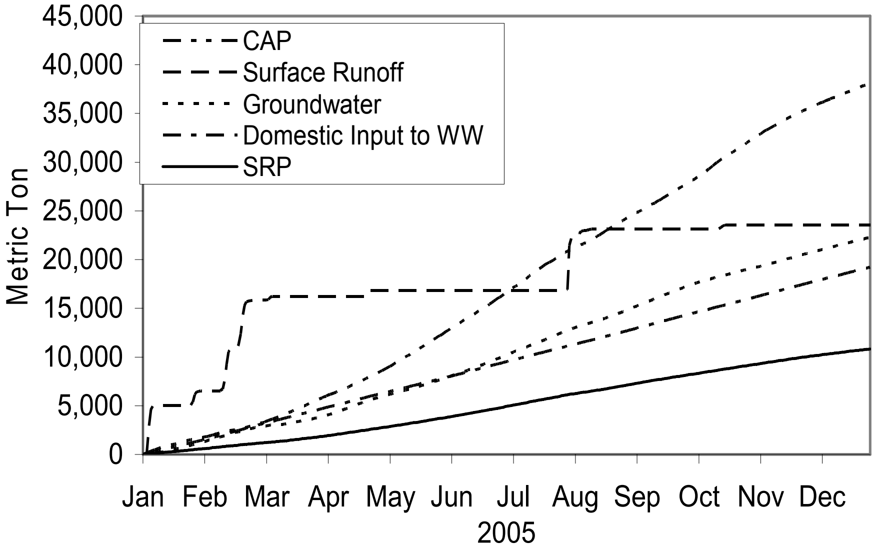


Figure 2.5. Salt flux into Scottsdale from various sources during 2005.

Of the 114 thousand ton salt brought into Scottsdale in 2005, 63 thousand ton salt in the irrigation water from CAP and reclaimed wastewater plants entered into vadose zone, 33 thousand ton salt was brought by wastewater and brackish to 91st Avenue WWTP, and 4 thousand ton salt was picked up by storm runoff from the city and brought into the Salt River (Figure 2.6). Among 63 thousand tons of salt entered into vadose zone in 2005, most came from percolation, and small portion came from recharge (Figure 2.7).

63 thousand ton salt out of 114 thousand ton salt entered vadose zone in 2005, which means 55% salt brought into Scottsdale will accumulate within the city annually. In the long run, the salt accumulation could case serious problem. The first problem is that the salt entering vadose zone will finally reach aquifer, increase groundwater salinity and reduce its quality as potable water. Nowadays, the groundwater salinity problem is aggravated by increasing groundwater table due to more and more artificial recharge practice and agriculture percolation, which makes salt meet groundwater more quickly. Another problem is soil salinity. Since golf courses are irrigated with reclaimed water whose salinity is over 1000 mg/L, the accumulated salt in soil would potentially destroy soil physic structure and make the soil unfavorable for turfgrass. The soil salinity concerns for golf courses will be addressed in Chapter 4.

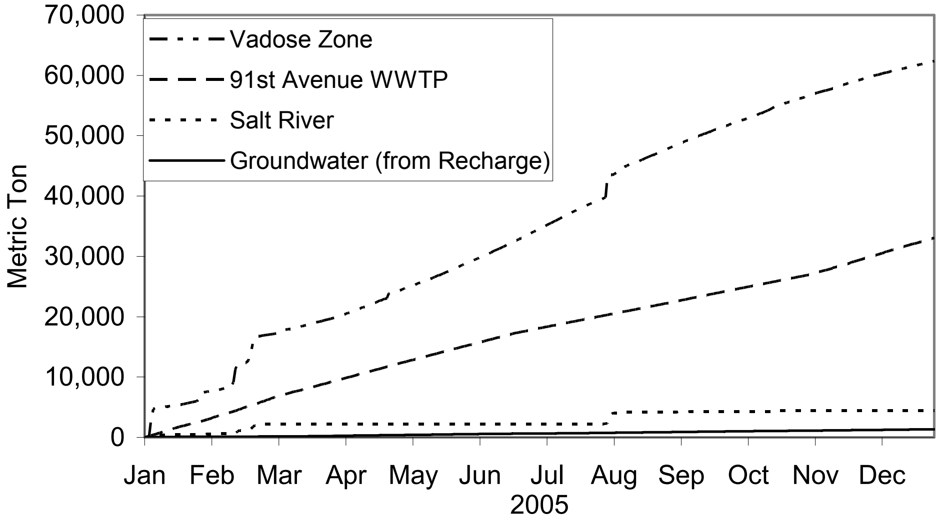


Figure 2.6. Salt flux exiting Scottsdale during 2005.

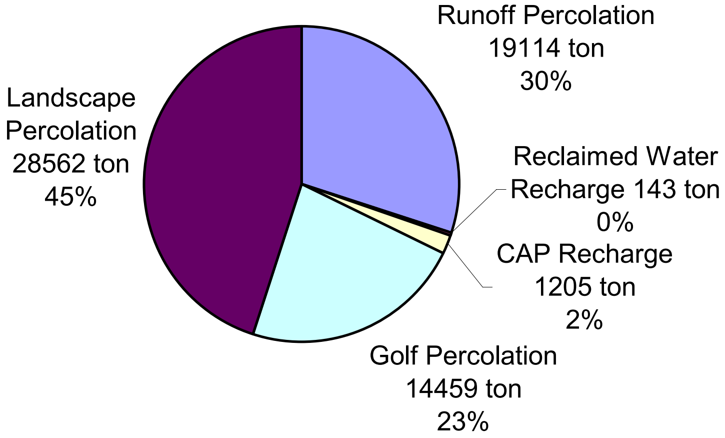


Figure 2.7. Salt flux into vadose zone and groundwater through percolation and recharge.

Among 33 thousand ton salt brought to 91st Avenue WWTP, 26 thousand ton salt was from 65000m^3/day wastewater directly discharged to 91st Avenue WWTP, and 7 thousand ton salt was from the brackish sent from Scottsdale Advanced Water Treatment Plant. During summer, all reclaimed water was sent to golf course for irrigation in stead of being sent to the Advanced Water Treatment Plant for recharge pre-treatment. Therefore, for four months in summer, the Advanced Water Treatment Plant was shut, and little brackish salt flux went to 91st Avenue WWTP, as shown in Figure 2.8.

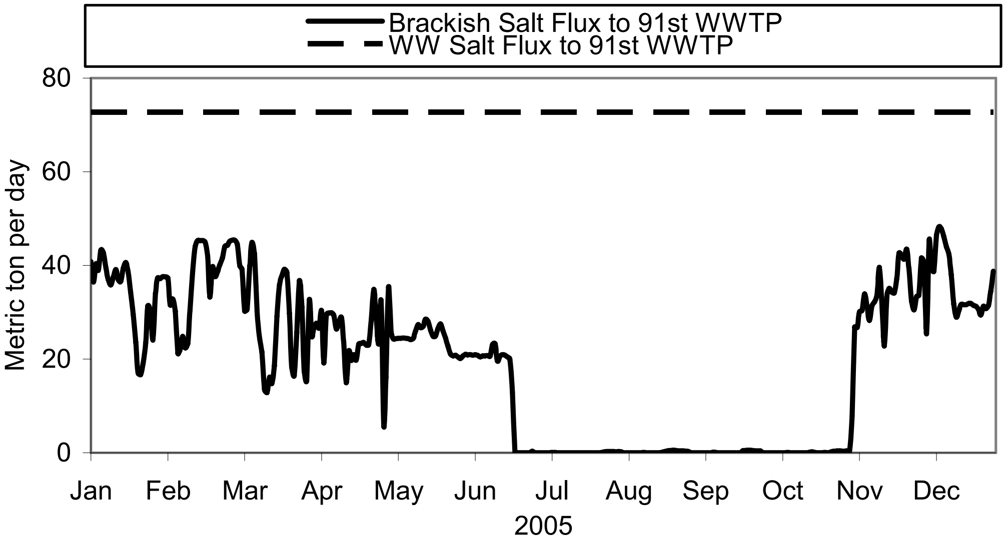


Figure 2.8. Brackish salt flux and wastewater salt flux to 91st Avenue WWTP

2.4.3 Scenario: 2005 - 2020

The potable water supply for Scottsdale was 104 million m^3 in 2005 and it was projected that the supply would increase to 127 million m^3 in 2020 (Scottsdale, 2001b). The golf course irrigation supply was 15.4 million m^3 in 2005 and it would keep the same in future (Scottsdale, 2001b). Since CAP and SRP supplies almost reached the entitlements allocated to Scottsdale in 2005. If there is no change to the CAP and SRP entitlements in the future, Scottsdale will need to pump up more groundwater to meet potable use demand in future. Groundwater will become the hugest potable water supply after 2017, and reclaimed water supply will surpass SRP supply in 2020 (Figure 2.9). CAP will keep dominant in salt contribution to potable water. Around 10% more salt will enter vadose zone and 30% more will go to 91st Ave WWTP in 2020 than in 2005 (Figure 2.10).

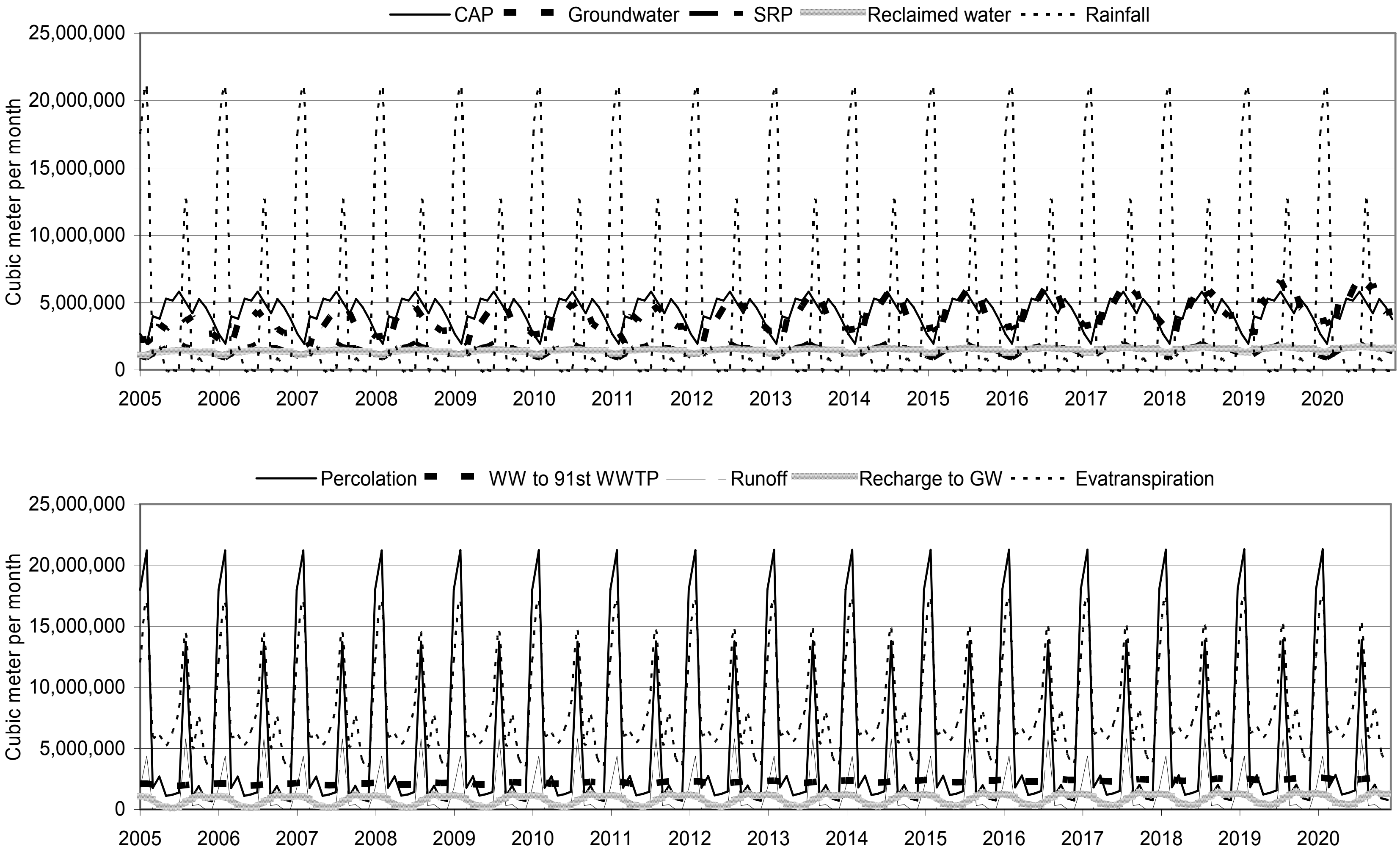
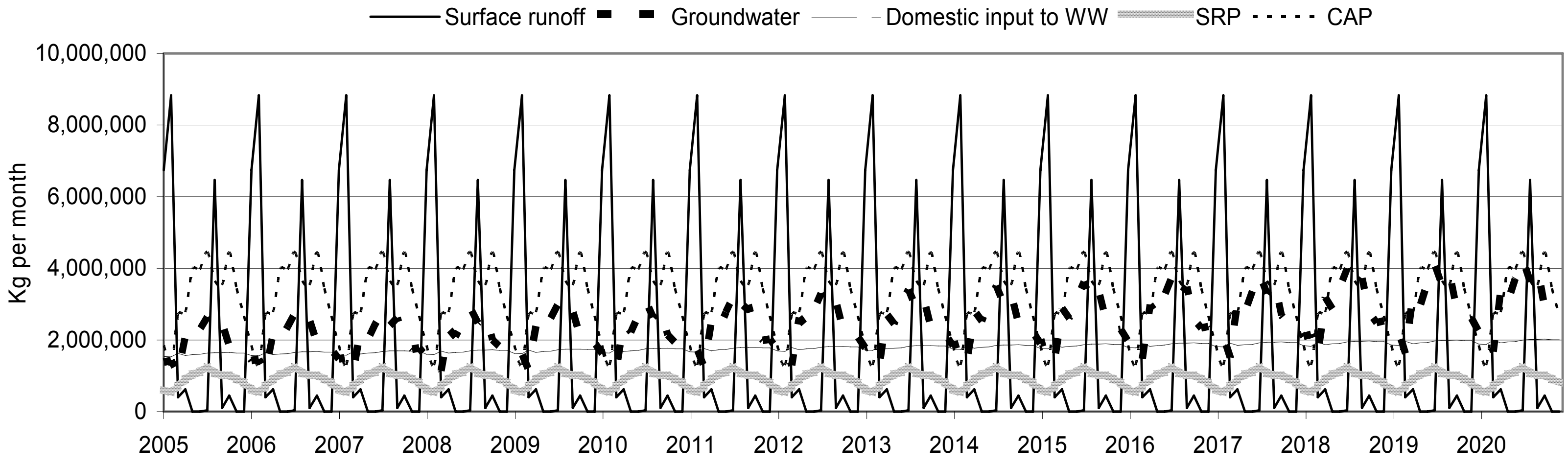


Figure 2.9. Water flux entering and exiting Scottsdale during 2005 – 2020



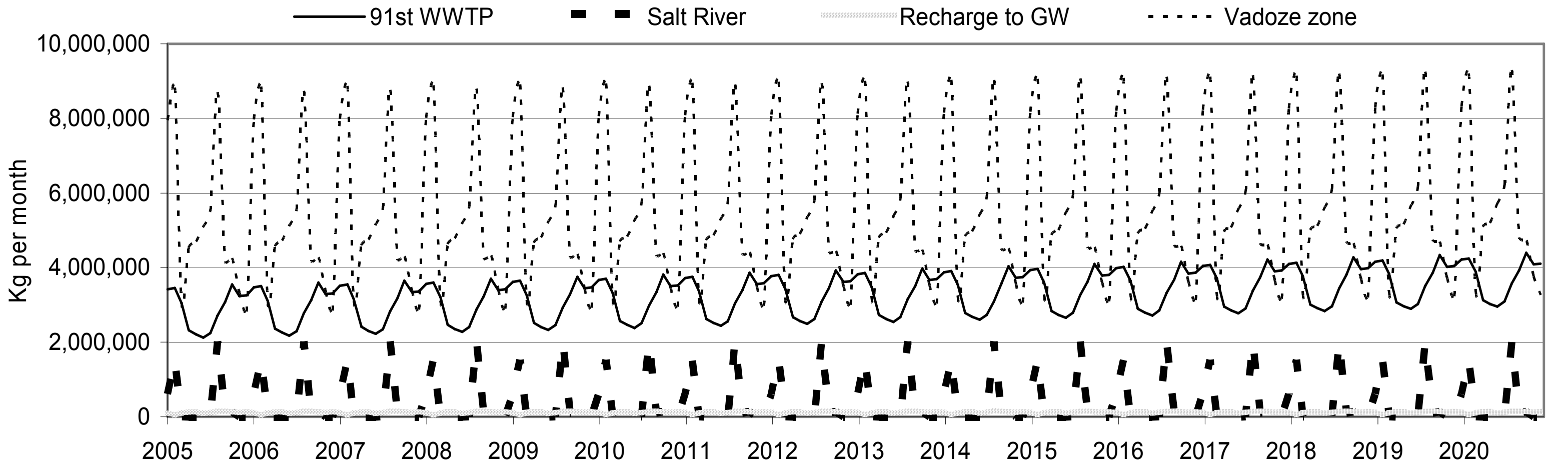


Figure 2.10. Salt flux entering and exiting Scottsdale during 2005 – 2020

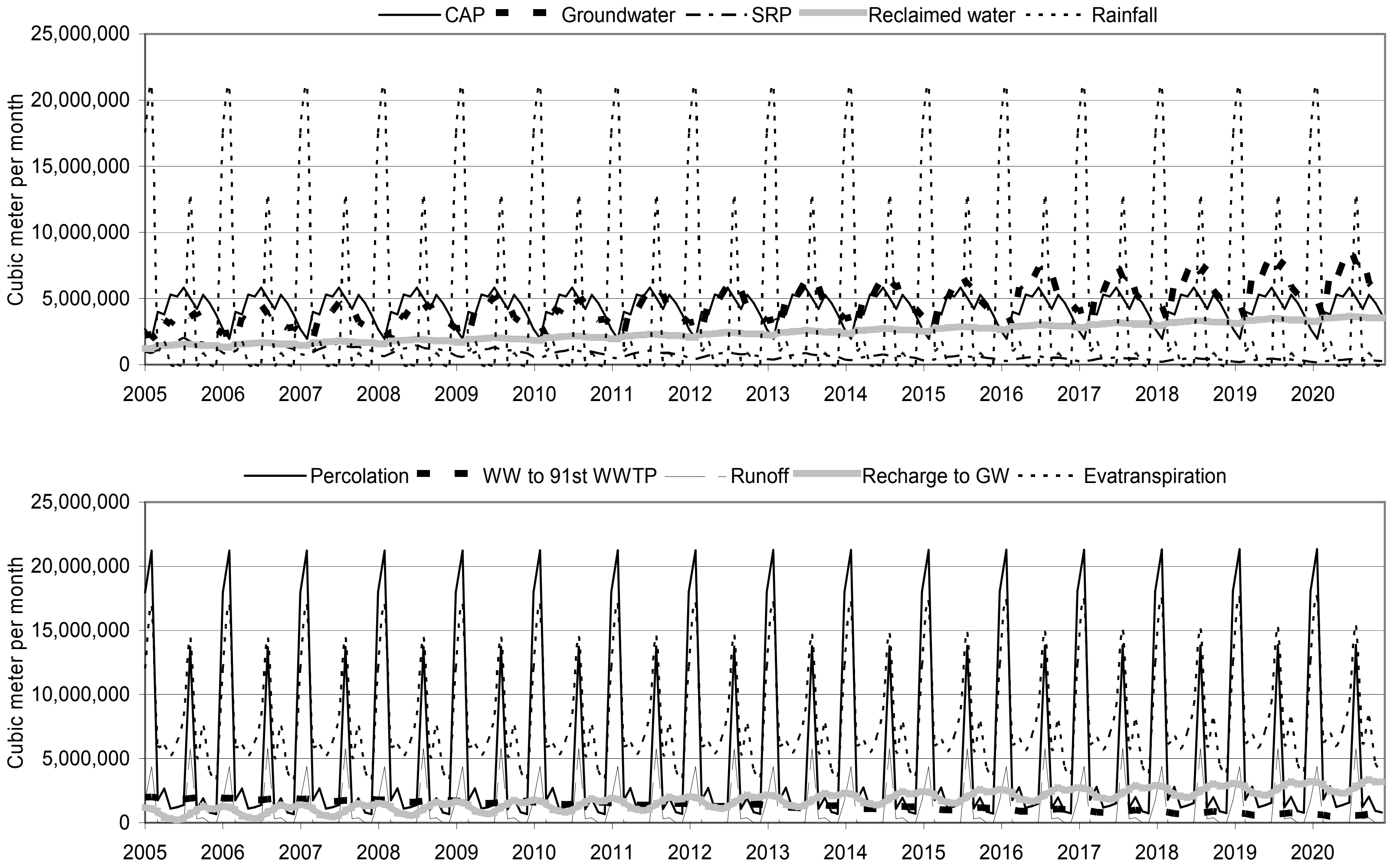


Figure 2.11. Drought scenario: Water flux entering and exiting Scottsdale during 2005 – 2020

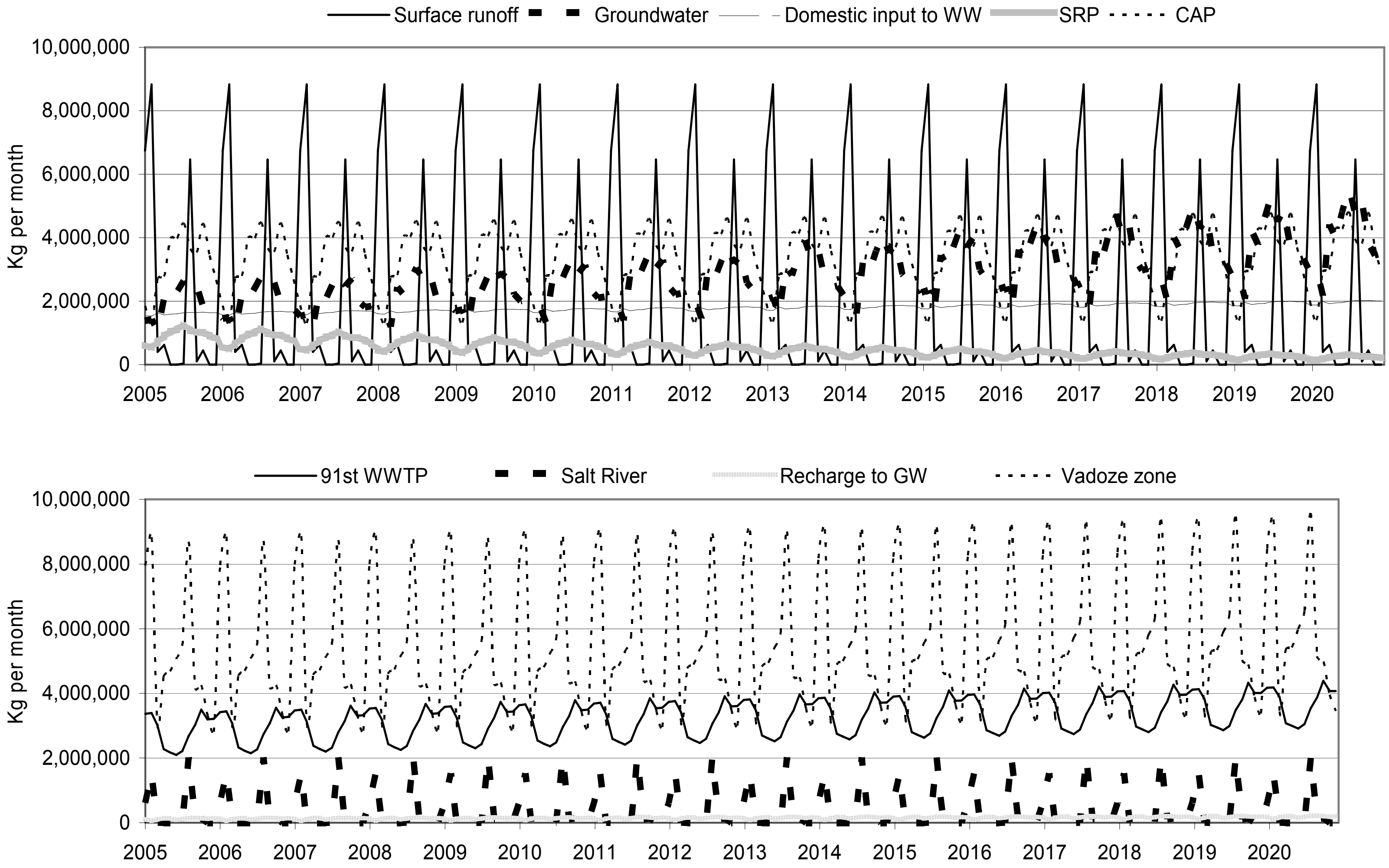


Figure 2.12. Drought scenario: Salt flux entering and exiting Scottsdale during 2005 – 2020

2.4.4 Drought scenario: 2005 – 2020

Six out of past seven years have seen less than normal rainfall in Phoenix area. If the Central Arizona encounters serious drought in future, SRP surface water supply will reduce. Assuming SRP surface water supply decreases by 10% annually, more ground water is pump out to meet demands, more wastewater is reclaimed to recharge for groundwater replenishment, SRP salinity increases by 1.5% annually and CAP salinity increases by 0.5% annually, we apply the flux model and get the water and salt flux of 2020 drought scenario. Under drought scenario, groundwater will become dominant supply in 2012 and recharge could triple from 2005 to 2020 (Figure 2.11). And groundwater will become dominant salt supply to potable water in 2017. The salt entering vadose zone will increase by 10% and the salt collected in 91st Avenue WWTP will increase by 30% from 2005 to 2020 (Figure 2.12).

2.5 Summary

A dynamic flux model was developed following the hydraulic network in Scottsdale, AZ. The model provides a holistic view of urban water and salt balance. With collected 2005 data, following conclusions concerning Scottsdale water and salt flux are drawn from the model.

- Although Scottsdale received only 9.2 inches precipitation, precipitation brought much more water than any other water resources to Scottsdale.
- More than 80% water left the city into atmosphere or into vadose zone through evapotranspiration or percolation.
- CAP brought more salt than any other salt sources to Scottsdale. Total salt brought into Scottsdale in 2005 was 114 thousand ton.
- Among 114 thousand ton salt brought into Scottsdale, 63 thousand ton salt was left in the vadose zone, which could potentially cause soil salination problem. The salt in vadose zone would finally reach groundwater table, which could increase salinity in groundwater and decrease groundwater quality for use.

The model could also be used to simulate future water and salt balance for given scenarios.

CHAPTER 3

MUNICIPAL WATER USE

3.1. Introduction

Scottsdale municipal water sales in 2001 were studied by Western Resource Advocates (2003), and the percentage of different uses are shown in Figure 3.1. According to daily data of CAP and SRP supplies and groundwater well pumpage, total municipal water supply of Scottsdale in 2005 was 106 million m^3. Assuming the allocation of municipal water to different sectors in 2005 was the same as it was in 2001, thus the end uses of water in 2005 were calculated and listed in Table 3.1. In this chapter, how municipal water is used for residential purpose and commercial and institutional purpose will be investigated.

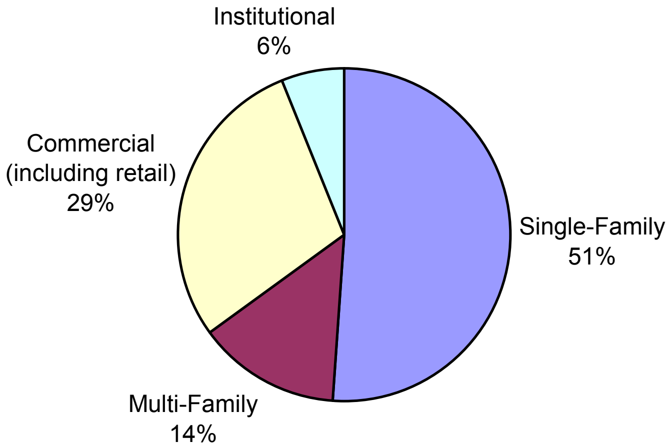


Figure 3.1. 2001 Scottsdale water sales by sectors (Source: Western Resource Advocates, 2003)

Table 3.1

Scottsdale Water End Uses in 2005

Category	Subcategory	Usage (million m^3)	Usage (million m^3)
Residential Use	Single-Family	54.1	68.9
	Multi-Family	14.8	
Commercial & Institutional Use	Commercial	30.8	37.1
	Institutional	6.3	

As we know, the water demands vary with seasons, usually high in summer and low in winter. This is because some water end uses, such as irrigation, are determined by weather. In this chapter, the varied water uses including irrigation, evaporative cooling, and swimming pools will be studied and the fluctuation of municipal water demand will be simulated and compared with real data.

3.2. Residential Use

Heaney *et al* (1999) investigated residential water usage in 12 cities including Scottsdale. 100 houses in Scottsdale were selected and water usage of these houses was monitored during two 14-day period, one warmer and one cooler. It was found that annual residential water usage was 700 m^3 per house. According to the estimation of US Census Bureau (http://factfinder.census.gov), 95,150 residential houses were occupied in Scottsdale in 2005, as shown in Table 3.2. Therefore, residential water use in 2005 is estimated to be 66.6 million m^3, pretty close to the estimation made in Table 3.1.

Table 3.2

Characteristics of House Units in Scottsdale

Selected Housing Characteristics: 2005	Estimate	Margin of Error
House Occupancy		
Total housing units	113,458	±4,855
Occupied housing units	95,150	±4,226
Vacant housing units	18,308	±3,465
Household size		
Average Household Size	2.27	
Year Structure Built		
Built 2005 or later	138	±133
Built 2000 to 2004	12,609	±2,176
Built 1990 to 1999	34,387	±2,805
Built 1980 to 1989	27,736	±3,328
Built 1970 to 1979	18,595	±2,136
Built 1960 to 1969	12,186	±1,736
Built 1950 to 1959	7,061	±1,721

Built 1940 to 1949	441	±307
Built 1939 or earlier	305	±227

Source: U.S. Census Bureau, 2005 American Community Survey

Residential water uses include indoor use and outdoor use. Of the annual residential water usage of 700 m^3 per house, 234 m^3 per house are for indoor use and 466 m^3 per house are for outdoor use. More details will be given concerning how water is used indoor and outdoor.

3.2.1 Indoor use

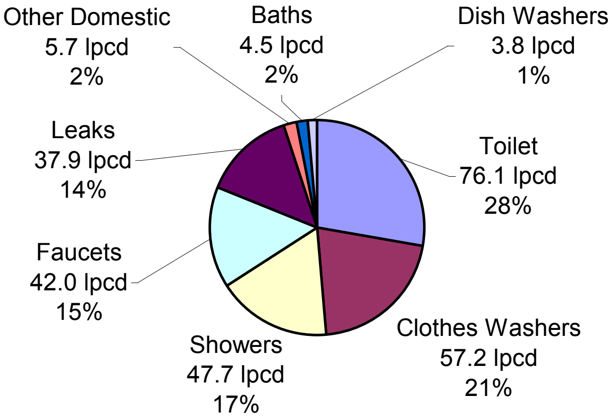


Figure 3.2. Indoor end uses for a typical single-family house (Source: Mayer *et al*., 1999)

The study of 12 cities (Mayer *et al*., 1999) provided indoor water use information for a typical single-family house as shown in Figure 3.2. Typical indoor usage is 274 liters per capita per day (lpcd). The following information is also provided in the report of the study (Mayer *et al*., 1999)

Toilet. Of all the toilet flushes recorded by the study, 14.5 percent of the flushes were less than 7.6 liters per flush, 34.7 percent of the flushes were between 7.6 and 13.2 liters per flush, and 50.8 percent were greater than 15.2 liters per flush. A typical house flushed toilet 5.05 times per capita per day. A huge amount of water could be saved by reducing the capacity of the toilet tanks. If 6.0 liters per flush toilet is used, average toilet water use will decrease from 76.1 lpcd to 30.3 lpcd assuming 5.05 flushes per capita per day.

Clothes Washers. The average loads of laundry per day per house was 0.96, the average volume per load of clothes was 155 liters, and average household size was 2.6 capita, therefore the average washer usage was 57.2 liters per capita per day.

Showers. Low-Flow (LF) shower heads are designed to restrict flow rate to 9.5 liters per minute or less. The LF shower homes used 33.3 liters per capita per day for showering, while non-LF shower homes used 50.3 liters per capita per day for showering. Average 47.7 liters per capita per day was used for showering.

Faucets. Faucets are turned on for teeth brushing, shaving, and food rinsing. 8.1 minute use per capita per day of a faucet with a flow of 5.2 liters per minute led to an average usage of 42.1 liters per capita per day.

Leaks. The variation of leaks was huge. 5.5 percent of houses leaked more than 380 liters per day, while majority of houses leaked average 38 liters or even less.

Other Domestic. Other domestic usage was for cleaning and other miscellaneous activities.

Baths. An average of 0.75 showers and baths combined per capita per day was found in the study. Baths account for a small portion of water used.

Dish Washers. Dish washer was run an average of 0.1 times per capita per day, i.e. 3.8 gliters per capita per day.

3.2.2 Outdoor use

Outdoor water uses include landscape irrigation, evaporative coolers, and swimming pools and spas.

Landscape Irrigation. Landscape irrigation consumes most of outdoor use water. The study of 12 cities (Mayer, 1999) shows that the irrigation practices have great influence on the water usage: households with in-ground sprinkler system used 35% more water than those without in-ground systems; households with automatic timers to control irrigation systems used 47% more than those without timers; households with drip-irrigation systems used 15% more than those without drip system; households that water with hand-held hoses used 33% less than other households. More surprisingly, it is found that xeriscapes received slightly more water annually than the standard landscape group because of homeowners' tendency to overwater. However, a multiyear survey of 72 households in the Phoenix metropolitan area came to a difference conclusion that the irrigation of xeriscape used less water than the irrigation of turf landscape (Chhetri, 2006). From Figure 3.3, we can find that average irrigation for xeriscape is 0.72 m per year while average irrigation for turf is 1.54 m per year.

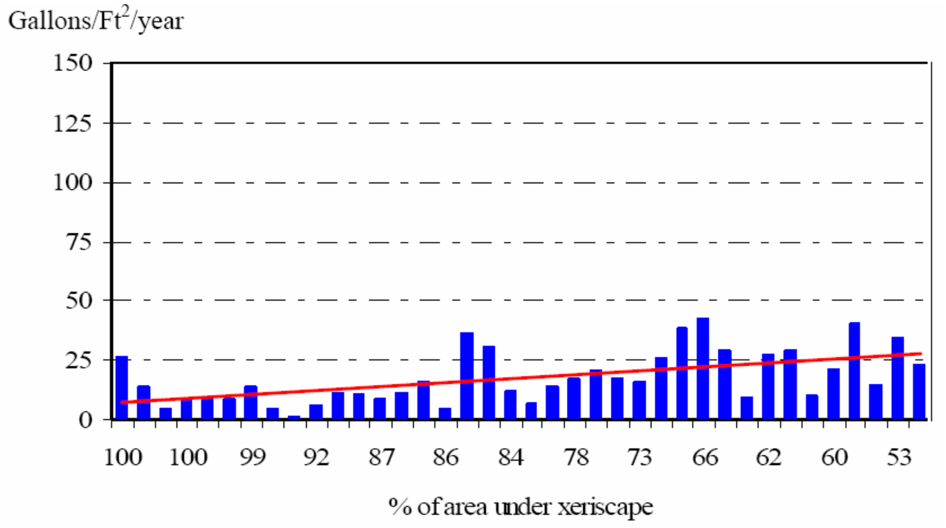


Figure 3.3(a). Irrigation water use by percent xeriscape (38 households in Phoenix area) (ADWR, 2003)

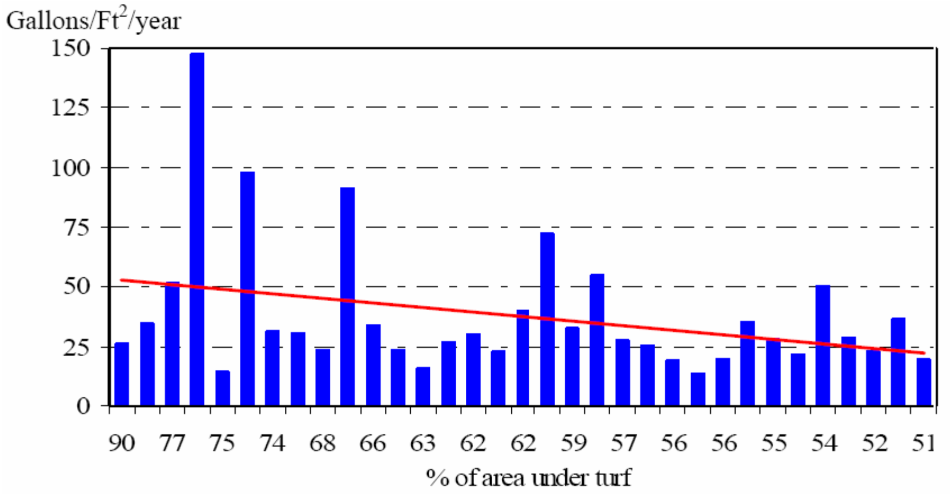


Figure 3.3(b). Irrigation water use by percent turf (33 households in Phoenix area) (ADWR, 2003)

Evaporative Cooler. A study conducted by Woodard (2003) revealed the percentage of newly built residential buildings equipped with evaporative cooler in Pima County from 1903 to 2002 (Figure 3.4). Before 1980, around 70% newly built residential houses would install evaporative coolers, but since 1981 the percentage had decreased rapidly and in 2000 few houses installed evaporative coolers.

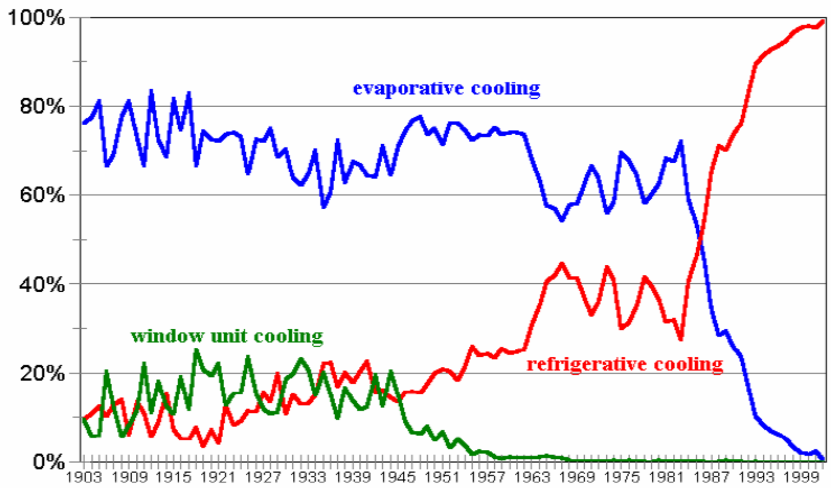


Figure 3.4. Homes with evaporative coolers vs. date of construction (Pima County, 1903 - 2002) (from Woodard, 2003)

Assuming the historic percentage of homes with evaporative coolers in Pima County applies to the City of Scottsdale, we estimate that the percentage of homes with evaporative coolers in Scottsdale in 2005 is 37% (Table 3.3). The percentage of 37% is quite reasonable since it was reported in 1998 that 43% - 46% single-family houses in Phoenix used evaporative cooling (Karpiscak, 1998) and it is easily understood the percentage would likely decrease from 43% - 46% to 37% due to abandoning evaporative cooling after 2000.

Table 3.3

Homes with Evaporative Coolers in Scottsdale in 2005

Year House Built	Units	Units with evaporative cooler	Percentage with evaporative cooler
Built 2005 or later	138	0	0%
Built 2000 to 2004	12,609	0	0%
Built 1990 to 1999	34,387	3,439	10%

Built 1980 to 1989	27,736	11,094	40%
Built 1970 to 1979	18,595	13,017	70%
Built 1960 to 1969	12,186	8,530	70%
Built 1950 to 1959	7,061	4,943	70%
Built 1940 to 1949	441	309	70%
Built 1939 or earlier	305	214	70%
Total	113,458	41546	37%
Occupied	95,150	34,842	37%

Kapiscak *et al* (1998) recorded water use of 46 evaporative coolers in Phoenix in 1993 and 1994, and reported that the evaporative coolers ran average 2,100 hours in summer, coolers with no bleed-off system used an average of 13.2 liters per hour of run time, those with bleed-off system used an average of 39.7 liters per hour of run time, and average daily use by evaporative coolers was 250 liters per day. The bleed-off system of cooler reduces the salt builtup and mineral deposit inside the cooler by constantly dumping and replacing part of the water.

Swimming Pool. It was reported that 25% of single-family houses were with swimming pools in Maricopa County, the surface area of a typical in-ground swimming pool is 42 square meter, and annual evaporation rate is around 2.36 meter for swimming pools in Maricopa County (Woodard, 2004).

Outdoor water usage. As estimated in the following paragraphs on the variation of water uses, in 2005 evaporative cooling used 174 m^3 water for running 220 cooling days, and annual evaporation loss for swimming pool was 2.98 meter. Given that 37% households equipped with evaporative coolers and 25% households installed swimming pools with an average surface area of 42 square meter, the average annual water use for evaporative cooling and swimming pools are calculated to be 64.2 m^3 per house and 31.6 m^3 per house, respectively. Given the total outdoor water use of 466 m^3 per house, the landscape irrigation water use was 370 m^3 per house in 2005. The outdoor water usages are shown in Figure 3.5.

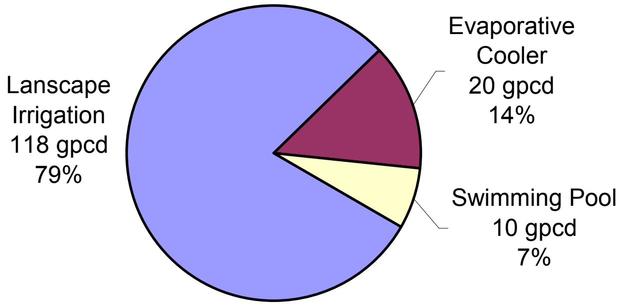


Figure 3.5. Outdoor water uses

3.3. Commercial & Institutional Use

Mayer (2003) studied water use of 25 commercial and industrial establishments in 5 urban areas including Phoenix area, and got water use information as listed in Table 3.4.

Table 3.4

Commercial and Industrial End Use of Water

ICI Category	Irriga-tion	Cool-ing	Other	Bath-rooms	Kitch-en	Laun-dry	Pro-cess	Misc-. Domestic	Total
Irrigation	96%	0%	0%	4%	0%	0%	0%	0%	100%
Retail	44%	5%	0%	31%	3%	1%	0%	17%	100%
Shopping Ctr.	36%	4%	0%	36%	6%	3%	0%	15%	100%
Office Blvd.	58%	6%	0%	29%	1%	0%	0%	6%	100%
Health Svc.	40%	4%	0%	28%	6%	6%	3%	14%	100%
Mfg./Indust.	33%	8%	0%	16%	1%	1%	29%	12%	100%
Auto Svc.	21%	1%	1%	39%	0%	0%	19%	19%	100%
Hotel/Motel	36%	4%	4%	39%	3%	8%	0%	6%	100%
Recreation	52%	0%	6%	26%	0%	2%	4%	11%	100%
Restaurant	22%	2%	0%	15%	53%	0%	0%	8%	100%
Volume of Annual	1625	89	6	609	188	28	48	248	2840

Use (AF)									
Percentage	57%	3%	0%	21%	7%	1%	2%	9%	100%

Source: Mayer (2003)

3.4. Variation of Water Use

Some types of water use will almost keep a fixed quantity for all seasons such as indoor use, while some types of water use vary a lot with seasons such as irrigation, swimming pool, and evaporative cooling. In this section, the variation of water uses will be investigated.

3.4.1 Weather

Water uses for irrigation, swimming pools, and evaporative cooling are dependent on air temperature, wind speed, and humidity. Therefore, the first step to examine the variation of water uses is to get historic weather information. The Arizona Meteorological Network (AZMET) (http://ag.arizona.edu/azmet/) provides hourly weather information including air temperature, wind velocity, relative humidity, precipitation, and solar radiation. Currently, 28 stations are available to monitor and record weather changes across Arizona. Unfortunately, the only station in Scottsdale was moved out from AZMET in 1998 and no data is available after that date. Desert Ridge Station which is located in Phoenix and close to the border of Scottsdale is selected, and the weather information it recorded is used for Scottsdale.

3.4.2 Irrigation

To study how legally binding covenants, codes, and restrictions (CC&Rs) of community associations on landscape impact residential homeowner landscape preference and practice, Martin *et al* (2003) investigate 18 communities in Phoenix area and found following landscape situation (Table 3.5). The study (Martin *et al*, 2003) also found that most people preferred a landscape design with some lawn area.

Table 3.5

Residential Community Landscape

Frequency and genera richness	CC&Rs	No CC&Rs
Total plant (no./100 m^2)	15.7	13.0

Trees (no./100 m^2)	1.8	2.3
Shrubs (no./100 m^2)	10.5	7.9
Groundcovers (no./100 m^2)	7.2	3.9
Turf (% total surface cover)	31%	44%
Genera richness (no./100 m^2)	5.8	4.9

Source: Martin *et al*., 2003

To make it simple, only turf landscape irrigation would be investigated. Water uses for turf irrigation are determined by the turf evapotranspiration, i.e. water loss due to soil evaporation and grass transpiration. Turf evapotranspiration could be estimated based on following equation (Brown *et al*., 2000).

$ET_T = K_C \times ET_O$

ET_T – turf evapotranspiration, in mm;

K_C – crop coefficient, dimensionless, the crop coefficient used by AZNET to calculate water use for turf in Phoenix area is listed in Table 3.6.;

ET_O – reference evapotranspiration, in mm.

Table 3.6

Crop Coefficients for Turf Evapotranspiration Estimation

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
K_C	0.68	0.70	0.73	0.77	0.76	0.72	0.78	0.83	0.77	0.76	0.76	0.70

Source: Brown *et al*., 2000

Reference evapotranspiration could be calculated using modified Penman-Monteith equation, which is also recommended by ASCE (ASCE, 2005) for reference evapotranspiration calculation. 2005 reference evapotranspiration estimated using Penman-Monteith equation is released by AZMET and is shown in Figure 3.6 as well as turf evapotranspiration. Annual turf evapotranspiration was 1380 mm for 2005. It is found that the during late July and early August the irrigation water use is relatively low due to summer monsoons. Water use for turf irrigation is recommended by AZMET to be equal to turf evapotranspiration. Therefore, seasonal variation of turf irrigation is the same as that of turf evapotranspiration as shown in Figure 3.6.

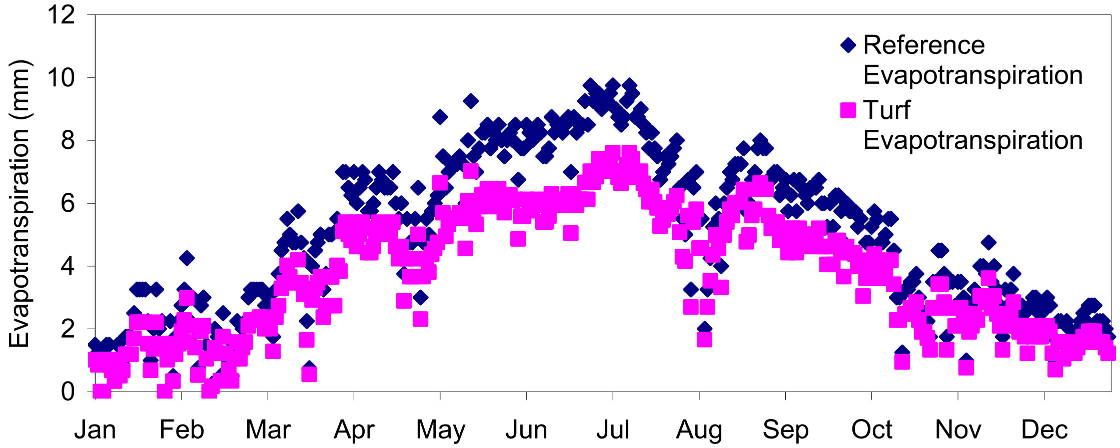


Figure 3.6. Reference evapotranspiration and turf evapotranspiration (Source: AZMET)

3.4.3 Evaporative cooling

Following equation is given by an evaporative cooler manufacture, Spec-AIR (http://www.specair.net), to estimate water use of a 50% bleed-off cooler.

$$Q = \frac{\left(T_{in} - T_{out}\right) CFM}{50}$$

Q – water use, in liter per hour;

T_{in} – temperature of air entering cooler, in Celsius;

T_{out} – desire room temperature, in Celsius;

CFM – airflow, in cubic meter per minute.

According to Karpiscak (1994), airflow of cooler (CFM) is determined by dividing the volume of house by 2. Thus, a typical single-family house with 186 square meter floor area and 2.4 meter height needs a cooler of 227 cubic meter per minute. Assuming the desire room temperature is 25 C and given the air temperature information, we can estimate the evaporative cooler water use for a typical single-family house in 2005, as shown in Figure 3.7. The running time of cooler is 220 day in 2005. And annual water consumption is 174 m^3. Figure 3.7 shows relatively low water consumption during late July and early August resulting from summer monsoons.

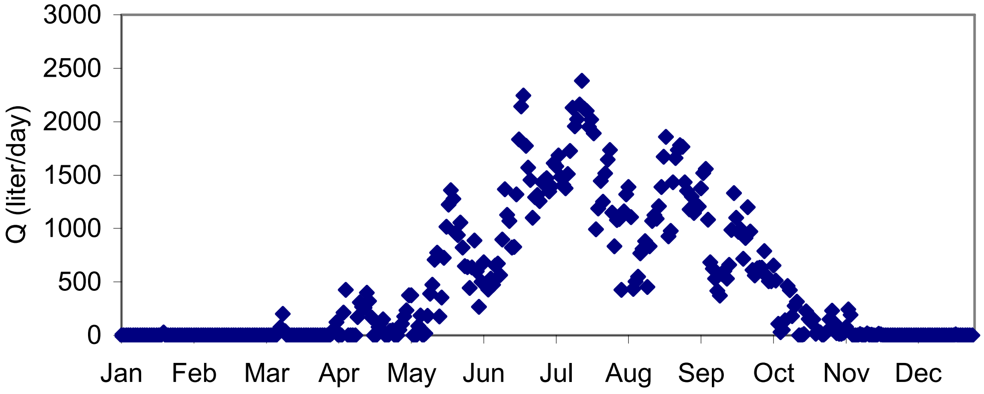


Figure 3.7. Water use of an evaporative cooler for typical single-family house

3.4.4 Swimming pool

Smith *et al* (1994) modified widely-used ASHRAE equation based on real data from experiments. The modified equation is shown as following.

$$W = \frac{(229 + 67V)(P_w - P_a)}{Y}$$

W – evaporation rate, kg/Hr-m^2;

V – air velocity over water surface, km per hour;

P_w – saturation vapor pressure at the water temperature, Pa;

P_a – saturation vapor pressure at the air dewpoint, Pa;

Y – latent heat at pool temperature, J/kg.

To make it simple, it is assumed that the water temperature keeps constant at 20C. At 20C, saturation vapor pressure of water is 2370 Pa. To heat 1 kg water from 20 C to 100 C, 334 kJ are needed. To further evaporate 1 kg water, 2251 kJ are needed. Therefore, the latent heat at pool temperature is 2585 kJ/kg. Given the hourly weather information, the evaporation loss of swimming pool could be figured out, as shown in Figure 3.8. Annual evaporation loss is 2975 mm in 2005. It is interesting to find that during July and August in 2005 the evaporation loss of swimming pool decreased due to a series of monsoons that kept the humidity relatively higher for this period.

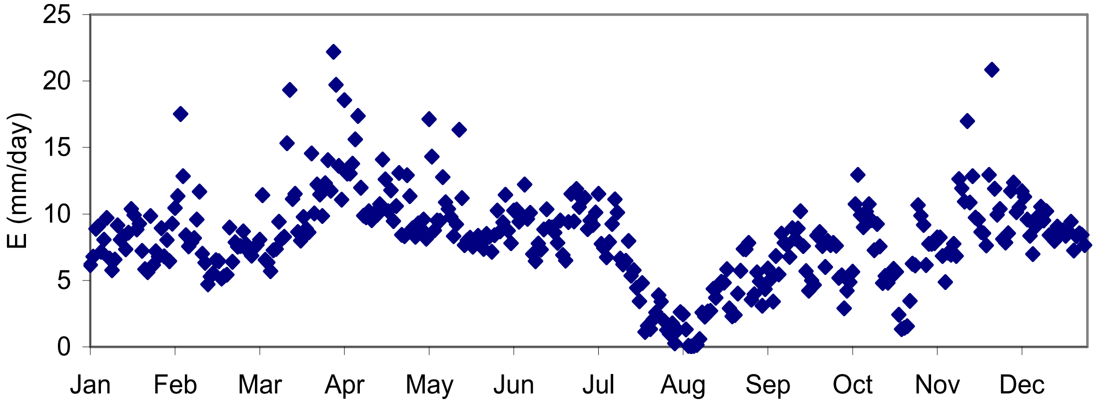


Figure 3.8. Evaporation rate of inactive swimming pool

3.4.5 Variation of municipal water use

Given above information, we can get detailed municipal water usages for Scottsdale in 2005, which is shown in Figure 3.9. The total irrigation water use was 57.4 million m^3, the total cooling water use was 7.5 million m^3, the total swimming pool water use was 3.2 million m^3, and other uses which is assumed unvaried with seasons was 37.9 million m^3.

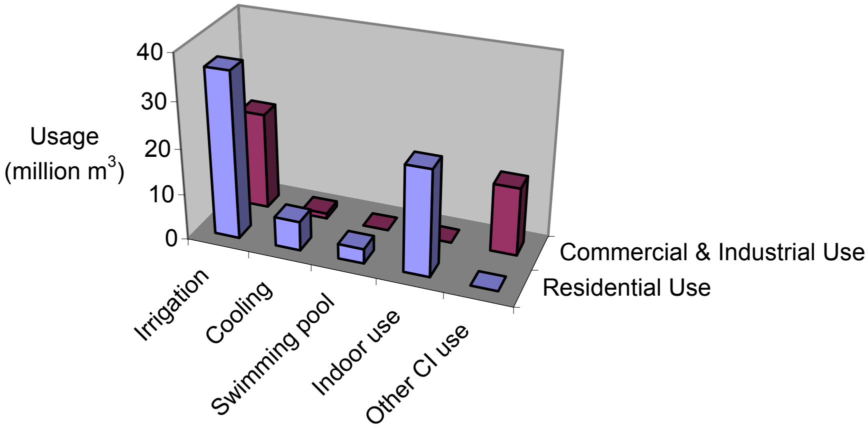


Figure 3.9. Municipal use for Scottsdale in 2005

The individual seasonal variation of landscape irrigation, evaporative cooling, and swimming pool water uses are integrated with other constant water uses (i.e. indoor uses and other commercial and industrial uses) to get seasonal variation of whole municipal water demand (Figure 3.10).

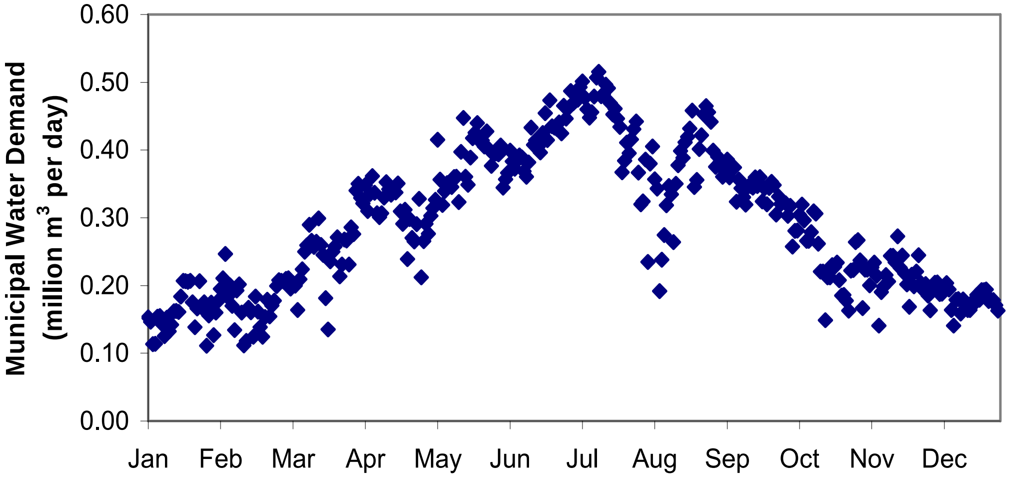


Figure 3.10. Scottsdale municipal water demand variation

3.4.6 Comparison of simulation and real data

CAP, groundwater wells and SRP provided 106 millions m^3 to Scottsdale in 2005. In Figure 3.11, the municipal water demand simulation compared with real data of water supply in 2005. The comparison shows that the curve of real data is a little flatter than that of simulation. That's to say the simulation overestimates water usage in summer and underestimates water usage in winter.

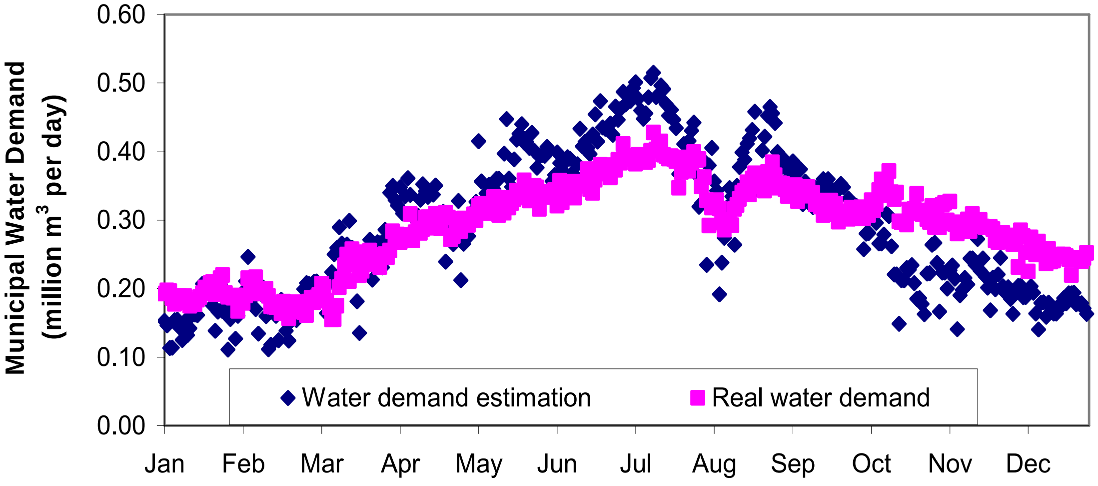


Figure 3.11. Municipal water demand: simulation vs. real data

3.5 Summary

Scottsdale municipal water uses in 2005 are investigated in this chapter. It is found that

- 65% municipal water was for residential use and 35% municipal water was for commercial and institutional use.
- 67% residential usage was for outdoor purposes including landscape irrigation, evaporative cooling, and swimming pools. 33% residential usage was for indoor purpose.
- 57% commercial and institutional usage was for irrigation, and 3% commercial and institutional usage was for evaporative cooling.
- Seasonal variation of water uses for irrigation, evaporative cooling, and swimming pools are simulated with equations. Consequently, seasonal variation of municipal water demand could be simulated.
- Simulation of municipal water demand is compared with real data, and the curve of real data is slightly flatter than the simulation, which indicates that simulation overestimate water demand in summer and underestimate water demand in winter.

CHAPTER 4

GOLF COURSE IRRIGATION

4.1. Introduction

There are 26 golf facilities in Scottsdale, accounting for 21% and 12% of the golf courses in Phoenix metro area and in Arizona respectively (City of Scottsdale, 2005). Most of these golf facilities are irrigated with reclaimed water from Water Campus through Reclaimed Water Distribution System (RWDS) and Irrigation Water Distribution System (IWDS), while Gainey Ranch Golf Course is irrigated with reclaimed water from Gainey Ranch WWTP. During summer, CAP water is also delivered through RWDS and IWDS to meet the peak irrigation demands.

There are salinity concerns arising with reclaimed water irrigation due to the relatively high concentration of total dissolved solids (TDS) in reclaimed water. The first concern is the salinity impacts on turf grass and soil. As discussed above, if reclaimed water usage for golf course irrigation is 1.49 m per year, as capped by ADWR water duty regulation for groundwater irrigation, the concentration ratio, defined as soil solution salinity divided by irrigation water salinity, could reach 4.5, and the sodium adsorption ratio (SAR) of soil solution could be higher than 12, which really poses threats to physical properties of soil. The second concern is that percolation of irrigation brings salt into aquifers and deteriorates groundwater quality.

To address the salinity concerns associated with reclaimed water irrigation, the Grayhawk Golf Course North Raptor (Figure 4.1) was selected for real-time analysis of evaporation, percolation, and TDS in percolation. The Grayhawk Golf Course locates at 33°40’50” N (latitude) and 111°54’00” W (longitude), with a slope of 2.3% to the southwest. The elevation of the golf course is around 550 m.The analysis is performed by using Simultaneous Heat and Water (SHAW) model (Flerchinger, 2000) in combination with hourly data of temperature, wind velocity, precipitation, and irrigation water use.

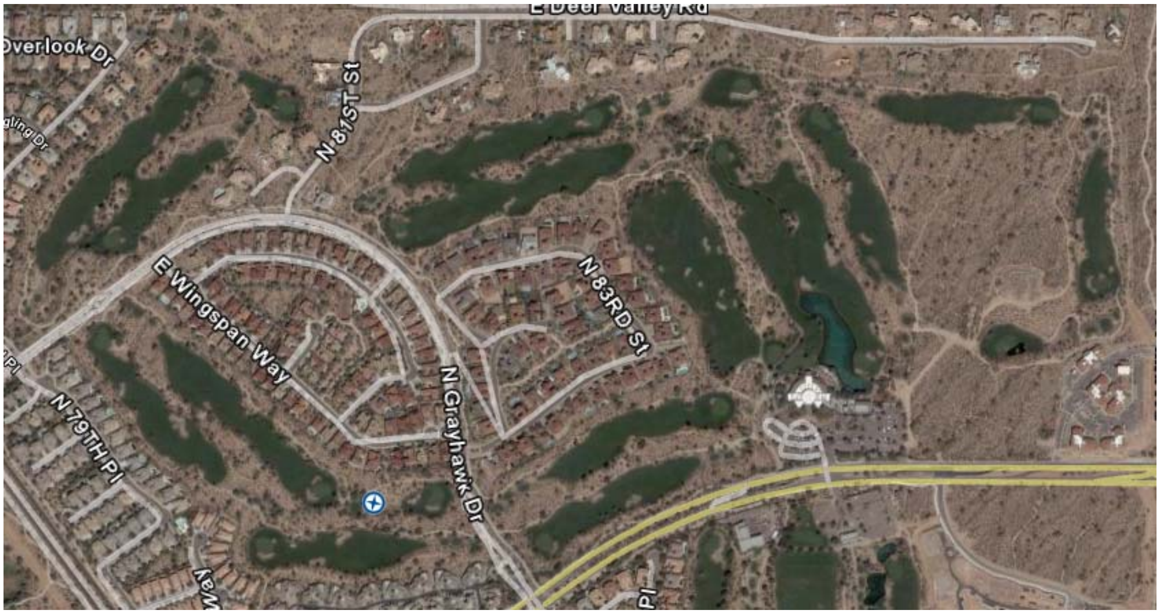


Figure 4.1. Grayhawk Golf Course North Raptor (Source: Google Earth)

4.2. SHAW Model

Developed by USDA Agricultural Research Service in Boise, Idaho, SHAW model simulates heat, water and solute transfer within a one-dimensional profile which includes canopy, residue, snow, and soil. To apply SHAW model to golf course irrigation, following simplification and assumptions are made: (1) unilayer canopy of turfgrass; (2) no residue layer between ground and canopy; (3) no snow. Thus, only two layers are left in the profile: turfgrass and soil (Figure 4.2).

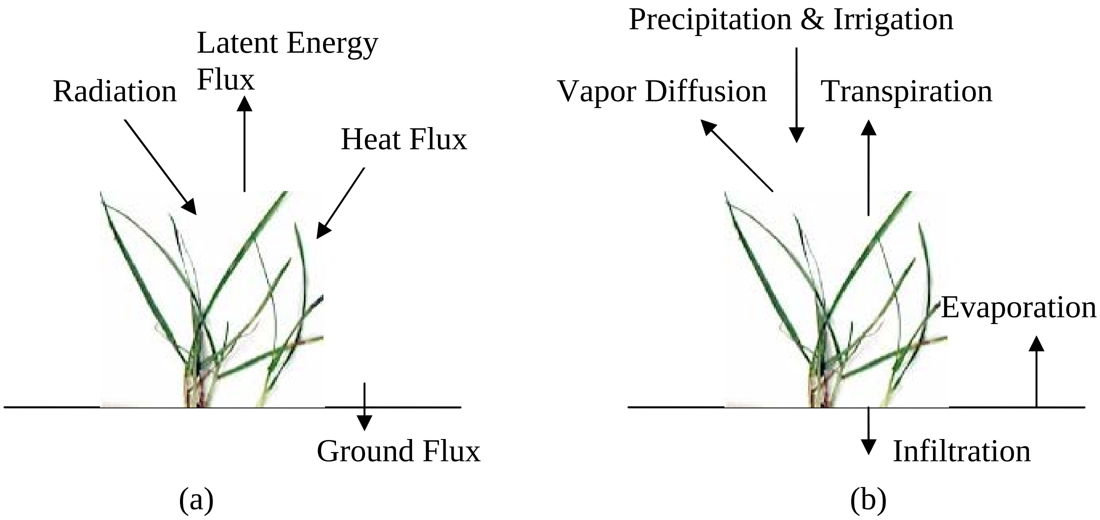


Figure 4.2. Schematic of application of SHAW to golf course irrigation: (a) Heat balance; (b) water balance

The heat balance for grass and soil is written as

$$R + H + LE + G = 0$$

where, R is net all-wave radiation (W/m^2) including direct solar radiation, diffuse solar radiation, and long-wave radiation; H is sensible heat flux (W/m^2); LE is latent energy flux (W/m^2), E is transpiration of leaves or evaporation from ground; G is soil or ground heat flux (W/m^2).

The water balance within canopy is

$$\frac{\partial \rho_v}{\partial t} = \frac{\partial q_v}{\partial z} + E$$

where, ρ_v is vapor density within canopy in kg/m^3; q_v is vapor flux into canopy, in kg/hr-m^2; and E is transpiration from leaves, in kg/hr-m^3.

The water balance in soil is

$$\frac{\partial \theta_l}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial \psi}{\partial z} + 1\right)\right] + \frac{1}{\rho_l}\frac{\partial q_v}{\partial z} + U$$

where, θ_l is volumetric moisture content, dimentionless; K is unsaturated conductivity, in m/hr; $\frac{\partial \psi}{\partial z}$ is suction water head, ψ is water potential, in m; ρ_l is moisture density, in kg/m^3; U is sink or source of water, per hr.

Infiltration is calculated using Green-Ampt approach for a multi-layered soil.

$$f = \frac{F_m / \Delta\theta_l + \psi_f + \sum \Delta z_k}{\frac{F_m}{\Delta\theta_l K_m} + \sum \frac{\Delta z_k}{K_k}}$$

Where, f is infiltration rate in layer m, in m/hr; F_m is cumulative infiltration into layer m, in m; $\Delta\theta_l$ is the change in water content as the wetting front passes, dimentionless; ψ_f is water potential at the wetting front, in m; Δz_k is the depth to the top of layer k, in m; K_m is hydraulic conductivity of layer m, in m/hr; K_k is hydraulic conductivity of layer k, in m/hr.

These equations along with other equations in Flerchinger (2000) are solved to get evapotranspiration and infiltration rate of golf course.

4.3. Input Data for SHAW Model

Information on irrigation, weather, site location, soil layer, and plant characteristics is needed for SHAW simulation. Irrigation hourly data of the Grayhawk Golf Course were pulled out from Supervisory Control And Data Acquisition (SCADA) system of Scottsdale. In 2005, 0.65 million m^3 water was irrigated on Grayhawk Golf Course North Raptor whose surface area was estimated to be 0.287 million m^2, i.e. 2.27 m/yr.

Weather hourly data including temperature, wind velocity, relative humidity, precipitation, and solar radiation were downloaded from the Arizona Meteorological Network (AZMET) (http://ag.arizona.edu/azmet/). Currently, 28 stations are available to monitor and record weather changes across Arizona. Unfortunately, the only station in Scottsdale was moved out from AZMET in 1998 and no data is available after that date. Desert Ridge Station, whose record was used for Scottsdale, is located in Phoenix and close to the border of Scottsdale.

The depth of the unilayer of soil to be simulated was set as 2 m since it is reported by USDA (1982) that Bermuda grass could even consume moisture up to 2 m deep. According to the recommendation of USGA (2004) that the root zone should contain less than 3% clay and 5% silt, the soil composition was set as 2% clay, 3% silt and 95% sand. The hydraulic conductivity was calculated by SHAW to be 15.9 cm/hr, falling into the range of 3~6 m/day for the upper alluvial unit in Phoenix area. The saturated water content was calculated to be 0.30, and the initial water content was set as 0.15 for simulation. Albedo of dry soil was 0.15 and that of wet soil was 0.30.

Plant height of turfgrass was given 5 cm, and leaf length was 10 cm. Leaf-area index LAI was 2.0 (Zhang *et al*, 1997). Dry plant biomass was 130 gram/m^2 (Dittmer, 1973). Plant albedo was 0.21 (Zhang *et al*, 1997). Minimum stomatal resistance was set as 40 s/m, the same as that of alfalfa (Todd, 1998). Leaf water potential was -10 bar, and root depth was 0.6 m (http://www.blueplanetbiomes.org/bermuda_grass.htm).

4.4. Output from SHAW

Evapotranspiration and percolation of the Grayhawk Golf Club North Raptor were generated by running SHAW with 2005 precipitation and irrigation data (Figure 4.3). Annual precipitation and irrigation was 2.62 m, annual evapotranspiration was 1.81 m, annual percolation was 0.85 m, and 0.037 m moisture in root zone was lost.

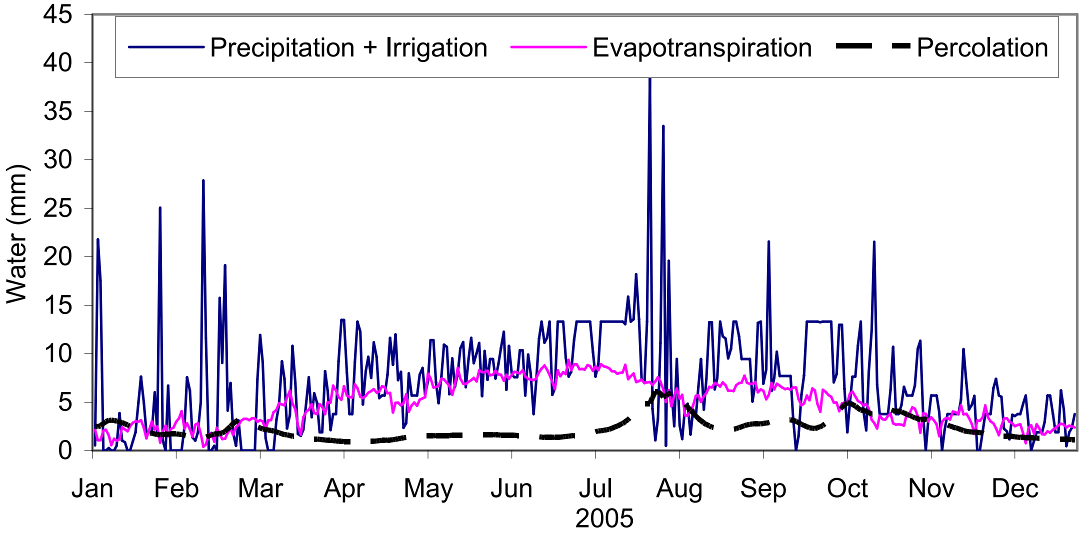


Figure 4.3. Precipitation & irrigation, evapotranspiration, and percolation of Grayhawk Golf Club North Raptor in 2005

4.5. Salinity

With water being evaporated, salts in irrigation water were concentrated in soil moisture and percolated through root zone ahead to groundwater. The mass balance of salt is written as

$$\frac{d\left(D_{moi}S_{moi}\right)}{dt} = q_{pre}S_{pre} + q_{irr}S_{irr} - q_{per}S_{per}$$

where, D_{moi} is depth of moisture, mm;

S_{moi} is salinity of moisture, mg/l;

q_{pre} is daily precipitation, mm/da;

S_{pre} is salinity of precipitation, assumed 0 mg/l;

q_{irr} is daily irrigation, mm/da;

S_{irr} is salinity of irrigation water, mg/l;

q_{per} is daily percolation, mm/da;

S_{per} is salinity of percolation, mg/l.

The salinity of percolation is assumed equal to that of soil moisture, i.e. $S_{moi} = S_{per}$=S. The salinity of irrigation water depends on the shares of CAP and reclaimed water in the irrigation water. The salinity of CAP water is 650 mg/L and that of reclaimed water is 1130 mg/L. Daily flow of CAP water and reclaimed water in RWDS and IWDS systems, as well as salinity of mixed irrigation water, are shown in Figure 4.4.

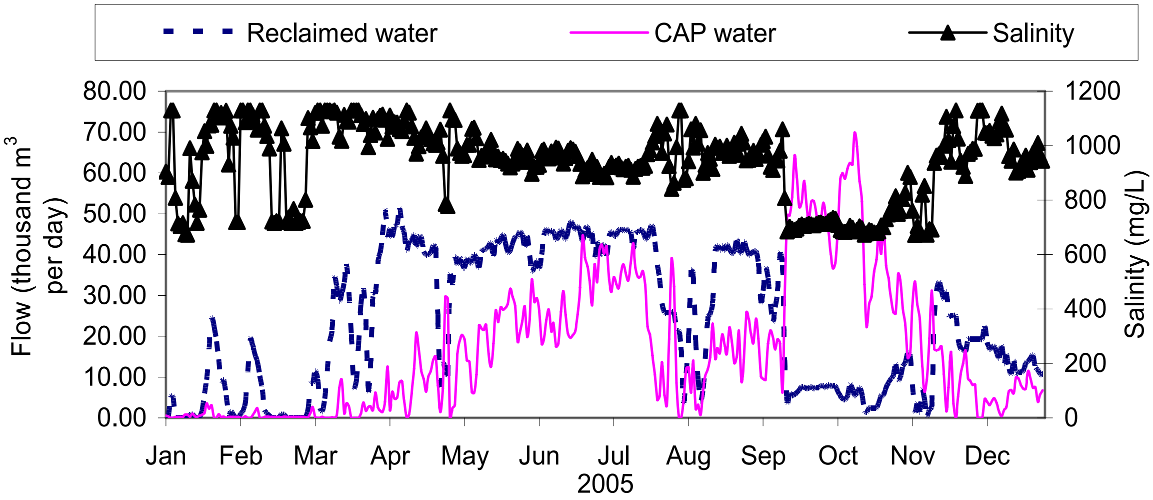


Figure 4.4. Irrigation water composition and salinity

Equation above is rewritten as

$$D_{moi}\frac{dS}{dt}+S\frac{dD_{moi}}{dt}=q_{irr}S_{irr}-q_{per}S$$

$$S_{n+1}=S_n+\frac{q_{irr}S_{irr}-q_{per}S_n-S_n\dfrac{dD_{moi}}{dt}}{D_{moi}}$$

where, S_n is the salinity of moisture and percolation in day n, in mg/l.

Since Bermuda grass can reach moisture of 2 m depth for evapotranspiration, the depth of root zone was set as 2 m. The initial moisture content was 0.15, and initial moisture salinity was assumed 3000 mg/L. Given above information, the salinity in moisture and percolation calculated from the equation is shown in Figure 4.5. From the figure, it is found that during summer high evaporation led to high salinity and monsoons in later July and August reduced the salinity. Keep in mind that the salinity analysis was made under an assumption that no fertilizer was used at the golf course. If fertilizer is counted, the salinity in soil moisture and percolation will be higher.

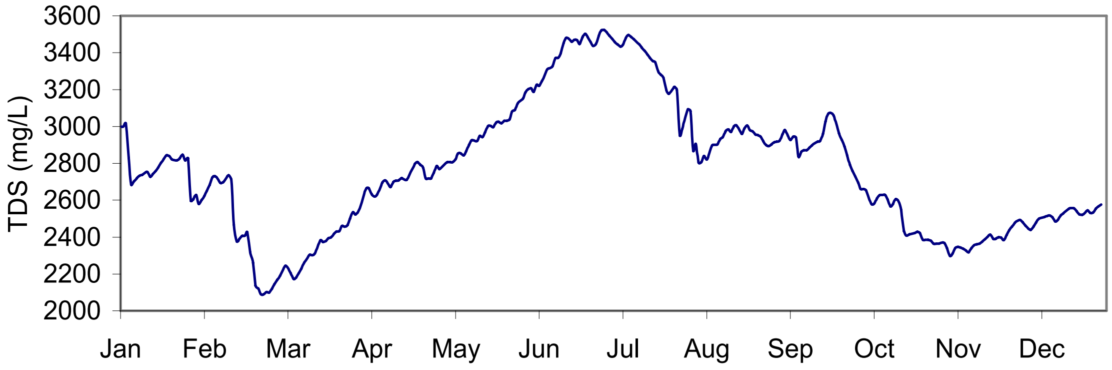


Figure 4.5. Salinity in soil moisture and percolation

Figure 4.5 shows that the salinity in soil moisture is around 3000 mg/l, which will not damage Bermuda and rye grass which are widely planted in Scottsdale for golf courses, because Bermuda grass is tolerant to salinity which is able to survive even irrigated with water of 17.8 ds/m in conductance, i.e. ~11000 mg/l in TDS (Adavi *et al*, 2006), and rye grass is moderately tolerant to salinity which shows no yield reduction irrigated with water of 3.7 ds/m in conductance, i.e. ~2300 mg/l in TDS (http://www.ricecrc.org/reader/wm-plants-waterquality/dpi389plantsalinetolerance.htm). But the salinity could be dangerous for soil, and sodium adsorption ration (SAR) is a good measure for the potential salinity damage to physical soil structure.

$$SAR = \frac{[Na^{+}]}{\sqrt{\frac{1}{2}\left([Ca^{2+}]+[Mg^{2+}]\right)}}$$

[Na+], [Ca2+], and [Mg2+] - Na+, Ca2+, and Mg2+ concentrations in meq/l

It was reported that concentrations of calcium, magnesium, and sodium ions in CAP water are 71 mg/l, 28 mg/l and 94 mg/l and in reclaimed effluent are 72 mg/l, 29 mg/l, and 225 mg/l, respectively (Scottsdale, 2006). The calcium, magnesium, and sodium concentration in soil moisture could be calculated in the same way as the salinity in soil moisture was calculated, and then SAR value could be estimated.

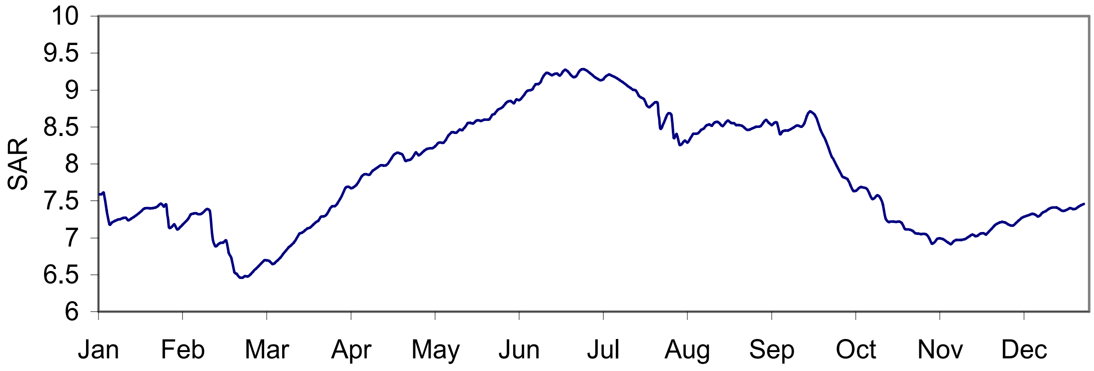


Figure 4.6. SAR of soil moisture

Figure 4.6 shows the SAR variation through 2005. Since the SAR was kept below 12, the threshold for soil particles to disperse, it seems that current golf irrigation practice will not lead to physical soil problem.

4.6 Summary

This chapter addresses salinity issues in golf course irrigation with reclaimed wastewater. Salt in irrigation water will concentrate in soil because of evapotranspiration. With quantified evapotranspiration and percolation from SHAW model, soil salinity was calculated according to mass balance. Here are some findings in this chapter.

- Under current irrigation practice, annual evapotranspiration was 1.81 m and annual percolation is 0.85 m in 2005.
- Salinity of mixed irrigation water fluctuated around 1000 mg/l (TDS), while soil salinity fluctuated around 3000 mg/l (TDS).
- SAR of soil moisture fluctuated around 8. Since 12 is the threshold above which potential soil physical problem will occur, it seems that current irrigation practice will not pose threat to soil structure.

CHAPTER 5

TRADE-OFF OF LANDSCAPE IRRIGATION AND BUILDING COOLING ENERGY

5.1. Introduction

For the central Arizona such a semi-arid area, two thirds of residential water usage is allocated to outdoor irrigation. Average annual outdoor irrigation water usage is 466 m^3 for a typical Phoenix single-family residential family. Recognizing the rapid population and urban growth and the deficit in future water supply, local governments encourage removing turf landscape or replacing current landscape and lawn with low water use plants to promote water conservation.

However, it is also recognized that well-irrigated landscape works as "evaporative coolers" and helps to reduce the heat island effects in the urban area, and trees and shrubs could provide shading to buildings, which contributes to the energy saving for building cooling. The air temperature a few centimeters or even 2 meters above turfgrass was reported to be up to 7 Celsius lower than above concrete surface or dry soil surface (Welch, 2007; Zangvil, 1982). Residential cooling loads in Sacramento, California were found to decrease by 5 to 10% per 10% increases in neighborhood tree cover (Sailor *et al*., 1992). Three ¼-scale-model residential buildings of 11 m^2 floor area were constructed on three 234 m^2 lots at University of Arizona with three types of landscapes, turfgrass, shrubs, and granite without vegetation, to examine how landscapes impacted air-conditioning electrical usage, and it was found that the turfgrass landscape and the shrub landscape could save 20%~30% cooling energy in comparison with the granite landscape (McPherson *et al*., 1989). Huang *et al*. (1987) employed building energy simulation program DOE 2 to investigate the contribution of tree canopy density increase to cooling load reduction at four cities including Phoenix, and found that 10% increase in tree canopy density leaded to 10% cooling energy use in Phoenix.

In this chapter, the cooling energy saving from landscape irrigation is simulated using a building energy simulation program, eQUEST (http://www.doe2.com/), which adopts DOE2 as engine. Then the trade-off of irrigation water usage vs. cooling electricity saving is evaluated from economic and environmental stand-point.

5.2. Prototype Building and Landscape

A typical 2-story single-family residential building design (Figure 5.1) was selected and located at a 700 m^2 lot. The livable floor areas were 87 m2 for first floor and 119 m^2 for second floor, and a garage of 38 m^2 was on the first floor. The design was a wood frame construction and had a total wall area of 254 m^2 and total window area of 12 m^2. The R values were 3.8 m^2K/W for wall, 9.4 m^2K/W for roof, and 0.9 m^2K/W for windows. The cooling temperature inside the building was set at 21 Celsius. Air-conditioning period was set as 5pm-7am for weekday, and 4pm-9am for weekend and holidays.

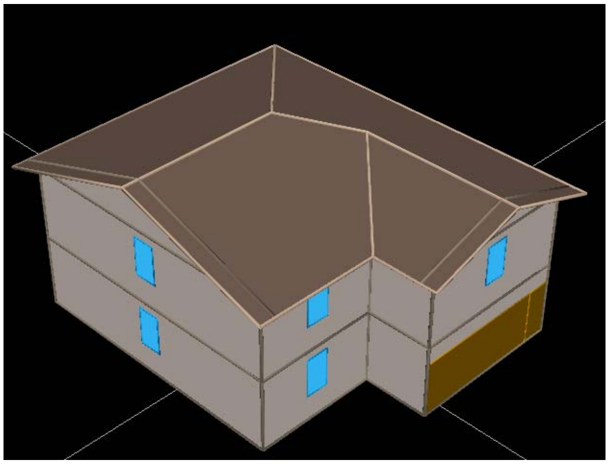


Figure 5.1. The prototype residential building design

Five landscape designs of trees and turfgrass are shown in Table 5.1. Annual irrigation water demands were calculated using following equation. The canopy of each tree is 4.5m (length)×4.5m (width)×4.5m (depth), and the covered area of each tree is 20.25 m^2. Landscape Design 1, 2, 3, and 4 were designed in this way to make the annual irrigation water demands to be 466 m^3, the amount recorded in the residential end water use study (Mayer *et al*., 1999). Landscape Design 5 comprises of 6 trees without turfgrass and its annual irrigation water demand was 111 m^3.

$$Q = A \times ET_T = A \times K_C \times ET_O$$

Q – irrigation water demand, in m^3;

A – landscape covered area, in m^2;

ET_T – evapotranspiration, in m;

K_C – crop coefficient, dimensionless, for trees 0.50, and for turfgrass 0.76 (Brown *et al*., 2000, 2001);

ET_O – reference evapotranspiration, 1.82 m for 1990, from the Arizona Meteorological Network (AZMET) (http://ag.arizona.edu/azmet/), which was calculated using Penmen-Monteith equation.

Table 5.1

Covered Area and Irrigation Demands of 4 Landscape Designs

		Trees	Turfgrass	Total
Design 1 (turfgrass)	Covered Area (m^2)	0	337	337
	Annual Irrigation (m^3)	0	466	466
Design 2 (2 trees+turfgrass)	Covered Area (m^2)	40	310	350
	Annual Irrigation (m^3)	37	429	466
Design 3 (4 trees+turfgrass)	Covered Area (m^2)	80	283	363
	Annual Irrigation (m^3)	74	392	466
Design 4 (6 trees+turfgrass)	Covered Area (m^2)	120	258	378
	Annual Irrigation (m^3)	111	355	466
Design 5 (6 trees)	Covered Area (m^2)	120	0	120
	Annual Irrigation (m^3)	111	0	111

5.3. Modeling of Cooling Load

Landscape helps reducing cooling load through two major processes: 1) reduce direct solar radiation and diffuse solar radiation on roof, windows, and walls by shading, 2) reduce conductive heat gain by lowing dry bulb temperature through evapotranspiration (Huang *et al*., 1987; McPherson *et al*., 1989; Konopacki *et al*., 2002; Akbari, 2002). Other processes, such as reduction in longwave radiation by maintaining lower surface temperature than bare soil, are less important than these two major processes.

Shade effect was simulated with building shades in eQUEST. Each set of building shades was composed of two perpendicular building shades of 4.5m (height) × 4.5m (width), representing a tree canopy. The building shades were placed 3 m above ground and 0.6 m away from walls, and its transmittance was 0.20. There is no shade modeling for Design 1 because of no tree in the design. Shade modeling for Design 2, 3, 4 and 5 are shown in Figure 5.2. For Design 2, two trees could be planted on the west, south or east of the building. For Design 3, trees were planted on the west and east. For Design 4 and 5, trees were planted on the west, south and east of the building.

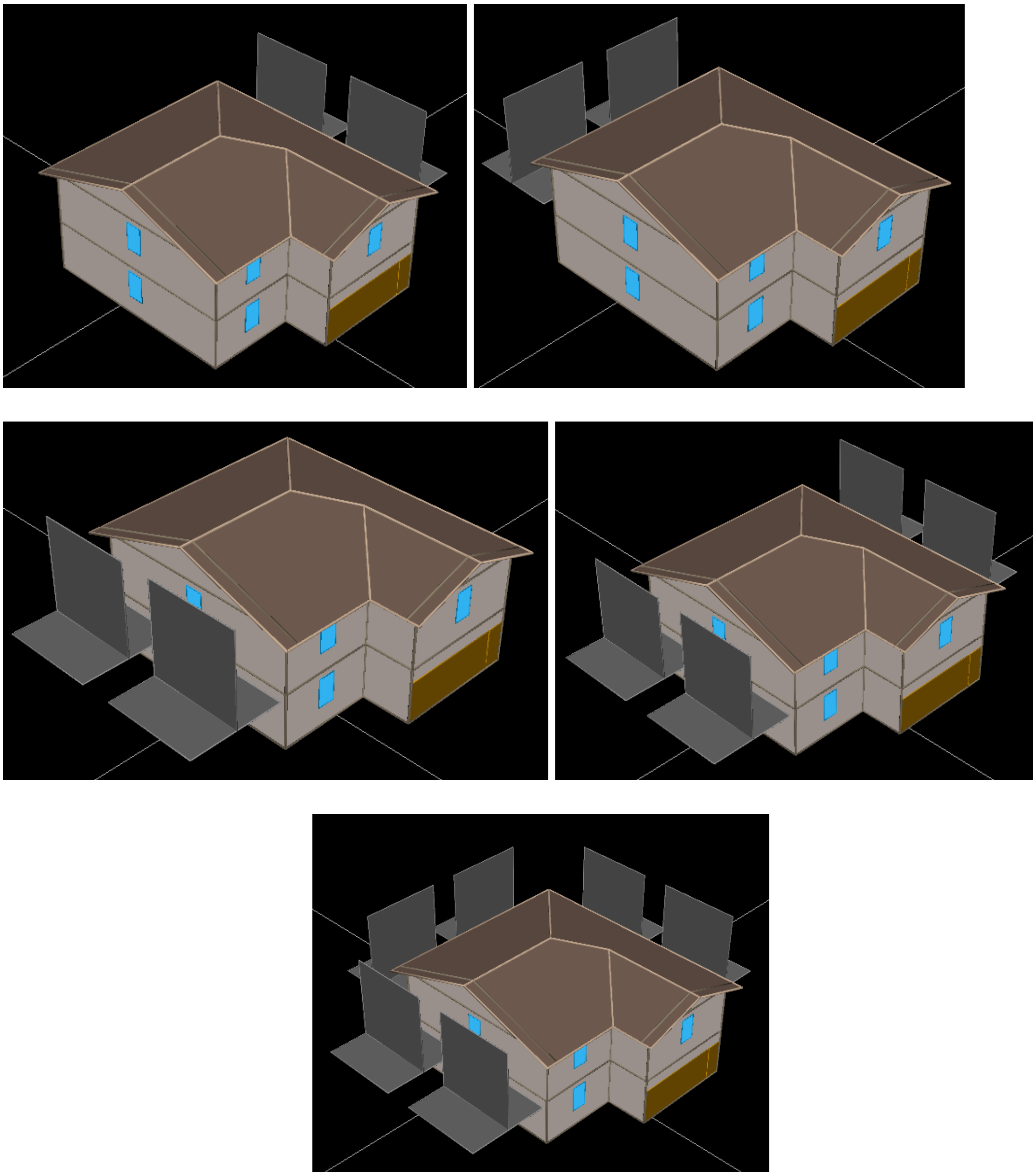


Figure 5.2. Modeling tree shade Up left: Design 2 (W) – 2 trees on the west of the building. Up right: Design 2 (S) – 2 trees on the south of the building. Middle left: 2 trees on the east of the building. Middle right: Design 3 – 4 trees on the west and east of the building. Bottom center: Design 4 and 5 – 6 trees on the west, south, and east of the building.

Vegetation works as evaporative cooler by reducing dry-bulb air temperature through evapotranspiration. Under an assumption that evaporatively cooled air is well mixed vertically within defined mixed height, cooling effect could be estimated by applying following heat balance equation to dry air, moisture, and evapotranspiration.

$$(\rho_d V_{air} C_{pd} + \rho_v V_{air} C_{pv}) dT = -L_V dm_V \qquad (1)$$

ρ_d – dry air density, 1.2kg/m^3 at 20 Celsius;

V_{air} – air volume within mixed height, A·h, in m^3;

A – lot size, 700 m^2;

h – mixed height, summer mixed height for Phoenix is around 250 m (Huang *et al*, 1987);

C_{pd} – dry air heat capacity under constant pressure, 1 kJ/kg-C;

ρ_v – moisture density, $\frac{P_V M_V}{RT}$, in kg/m^3 ;

P_V – vapor pressure, in Pa;

M_V – molar weight of vapor, 0.018 kg/mole;

T – dry bulb temperature, in Celsius;

C_{pv} – vapor heat capacity under constant pressure, 1.86 kJ/kg-C at 20 Celsius;

L_V – latent heat of vapor, 2450 kJ/kg at 20 Celsius;

m_V – mass of evapotranspiration, $\rho_w \cdot A_V \cdot ET$;

ρ_w – water density, 1000 kg/m^3;

A_V – vegetation covered area, 379 m^2;

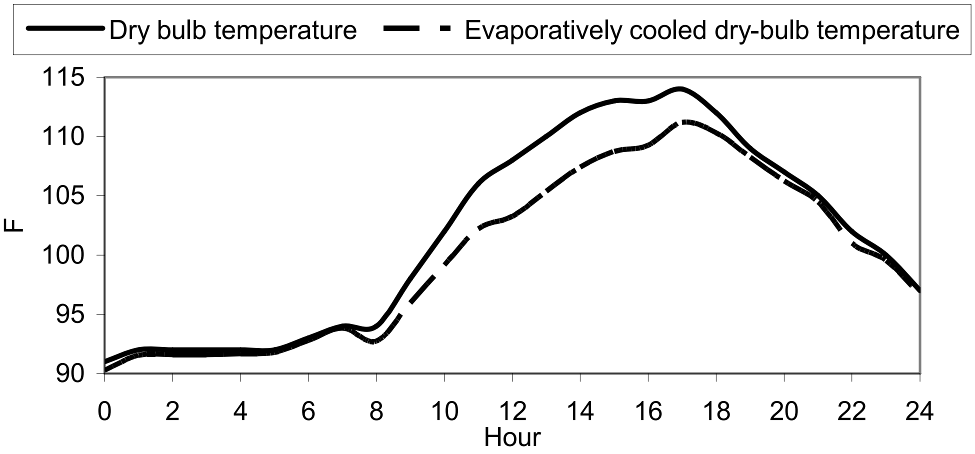
ET – evapotranspiration, in m.

1990 Phoenix hourly weather profile was got from eQUEST website (http://www.doe2.com/), which provided hourly dry bulb and wet bulb temperature and therefore vapor pressure could be calculated. Hourly evapotranspiration was estimated based on the reference evapotranspiration data from the Phoenix Encanto Station of AZMET (http://ag.arizona.edu/azmet/).

Based on the hourly dry-bulb temperature changes calculated with above equation, a new hourly weather profile was generated reflecting the cooling effect of evapotranspiration. Both the original and the new weather profiles were then put into eQUEST to estimate the reduction in building cooling load.

5.4. Cooling Load Reduction

The hourly reduction of dry-bulb air temperature by evapotranspiration was estimated by Equation (1). Figure 5.3 shows evapotranspiration cooling effect during a typical summer day, Augst 1st, 1990, for Design 1, 2, 3, and 4, whose annual evapotranspiration was 466 m^3. and Design 5, whose annual evapotranspiration was 111 m^3. At noon and early afternoon, landscape experienced the highest evapotranspiration during a day and the dry air temperature was lowered by 5 F for Design 1, 2, 3, and 4, and 1 F for Design 5.



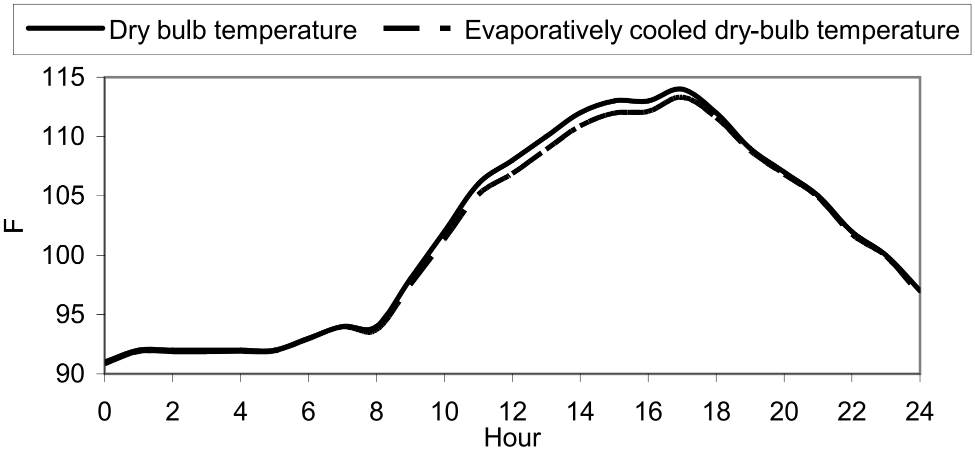


Figure 5.3. Cooling effect of evapotranspiration on August 1st, 1990 Up: Design 1, 2, 3, and 4, annual evapotranspiration of 466 m^3. Bottom: Design 5, annual evapotranspiration of 111 m^3.

The results of eQUEST simulation are shown in Table 5.2. The base case of a building without landscape was studies in order to set a baseline for the estimation of cooling energy saving. The results show that generally more cooling energy would be saved for the landscapes with more trees surrounding the building. By comparing results of Design 2 (W), Design 2 (S) and Design 2 (E), we can find that trees planted on the south of buildings are most effective in reducing cooling energy usage in Phoenix area. Two trees on the south could save more cooling energy than four trees on the west and east.

Table 5.2

Reduction of Building Cooling Load

	Annual cooling load (kWh)	Cooling energy saving (kWh)
No landscape (base case)	6300	0
Design 1	5910	390
Design 2 (W)	5840	460
Design 2 (S)	5540	760
Design 2 (E)	5780	520
Design 3	5710	590
Design 4	5340	960

Design 5	5630	670

5.5. Costs and Benefits

The simulation and analysis above gives the annually building cooling energy savings from landscape at the cost of 466 m^3 or 111 m^3 irrigation water. Although there are other costs, such as planting cost and maintenance cost, and benefits, such as aesthetic value and air quality improvement, associated with the landscape, irrigation water usage and cooling energy saving would be the only cost and benefit discussed. And the cost and benefit will be compared from economic and environmental values.

5.5.1 Economic comparison

Residential water rate in Phoenix is \$0.6 ~ 0.9/m^3, varying with months, highest in summer and lowest in winter, and a rate of \$0.75/m^3 is chose for simplification. Residential electricity rate in Phoenix is \$0.12/kWh. The costs and savings of landscape designs are shown in Table 5.3. From the table, it is found that costs of irrigation water are much higher than savings of electricity for Design 1, 2, 3, and 4, and it does not make economic sense to adopt these designs. However, for Design 5, the saving of cooling energy almost matches the cost of irrigation water. Therefore, it is cost-effective to reduce turfgrass and to plant trees around buildings when designing landscape.

Table 5.3

Costs and Savings of Landscape Designs

	Cost (\$)	Saving (\$)
No landscape (base case)	0	0
Design 1	350	11
Design 2 (W)	350	55
Design 2 (S)	350	91
Design 2 (E)	350	62
Design 3	350	71
Design 4	350	115

Design 5	83	80

5.5.2 Environmental comparison

For natural resources such as minerals and fossil fuels, the environmental impacts of resource depletion could be evaluated with “surplus energy” that is defined as the extra energy needed to extract lower-grade mineral left or to find alternative energy sources (Goedkoop *et al*, 2001). Similarly, the energy needed to make extra water available for use could be viewed as the environmental impacts associated with water use. In Phoenix area, local surface water and groundwater can not sustain long-term water demands, and water of extra demand could be acquired by importation from the Colorado River or reclamation from wastewater. Table 5.4 shows the energy demand for conveyance, treatment, and distribution for water importation and reclamation. The energy usages for conveyance and treatment are based on a previous study that collected the operation information of Central Arizona Project (CAP) canal that brings Colorado river water to the central Arizona, the CAP water treatment plant in Scottsdale, Arizona, and an advanced reclamation plant that adopts reverse osmosis separation and aquifer storage and recovery (ASR) technologies. The energy for water distribution to end use is reported to be 0.185 – 0.317 kWh/m^3 in California (DOE, 2006), and it is assumed the distribution energy in Phoenix is 0.260 kWh/m^3.

Table 5.4

Energy Use for Importation and Reclamation of 1 m^3 Water (Unit: kWh)

	Importation	Reclamation
Conveyance (CAP canal)	1.26	-
Treatment	0.16	0.95
Distribution	0.26	0.26
Total	1.68	1.21

Table 5.5

Energy Embodied in Irrigation Water vs. Energy Saving for Landscape Designs

	Embodied energy in irrigation	Cooling energy saving

	water (kWh)		
	Importation	Reclamation	
No landscape (base case)	0	0	0
Design 1	785	566	390
Design 2 (W)	785	566	460
Design 2 (S)	785	566	760
Design 2 (E)	785	566	520
Design 3	785	566	590
Design 4	785	566	960
Design 5	187	135	670

Embodied energies in irrigation water were calculated and compared with cooling energy saving for the landscape designs (Table 5.5). The result shows that Design 2 (S) and Design 3 can make net energy savings if reclamation water is chosen for irrigation, and Design 4 and Design 5 can make net energy savings no matter the irrigation water is imported or reclaimed.

What environmental benefit is associated with the 394 kWh electricity saving when Design 4 is selected and reclaimed water is used for irrigation? According to 1990 data on Energy Information Administration website (http://www.eia.doe.gov/), energy sources for Arizona electric utilities are 51.0% percent coal, 33.2% nuclear, 11.9% hydropower, 3.7% natural gas, and 0.2% petroleum. The emission inventories of each electricity category could be found in the Franklin US Life Cycle Inventory 98 database that is embedded in the life cycle analysis software, SimaPro (www.pre.nl). The environmental benefit of 394 kWh electricity saving is estimated based on the inventory database and is shown in Table 5.6.

Table 5.6

Net Environmental Benefit of Landscape Irrigation with Reclaimed Wastewater

	Electricity sources					Total
	Coal	Nuclear	Hydropower	Natural gas	Petroleum	
Electricity saving (kWh)	200.9	130.8	46.9	14.6	0.8	394
Resource savings						

Coal (kg)	100.5	1.7	0.0	0.0	0.0	102.3
Natural gas (kg)	0.2	0.4	0.0	4.3	0.0	4.8
Crude oil (kg)	0.7	0.1	0.0	0.1	0.3	1.1
Air emission reduction						
CO2 (kg)	215.2	4.7	0.0	10.1	1.0	231.1
Methane (kg)	0.5	0.0	0.0	0.0	0.0	0.5
NOx (kg)	0.8	0.0	0.0	0.0	0.0	0.9
SOx (kg)	1.4	0.1	0.0	0.1	0.0	1.6
Solid waste reduction (kg)	42.3	4.7	0.0	0.4	0.0	47.4

5.6 Summary

Cost and benefit of landscape are quantified and compared in this chapter. Residential landscape costs more than 40% of municipal water supply, but it help cutting down cooling energy consumption of residential buildings by providing shades and reducing air temperature. A typical two-story single-family residential building was designed with 5 landscape designs comprising of trees and turfgrass. Following findings of the building and landscape are presented in this chapter.

- It is more cost-effective to reduce turfgrass and to plant more trees surrounding buildings when designing a landscape.
- Trees planted on the south of buildings can save more energy than trees planted on other sides do.
- The landscape designs with annual irrigation of 466 m^3 can reduce air temperature by 5 Fahrenheit in summer noon, while the landscape design with annual irrigation of 111 m^3 can reduce air temperature by 1 Fahrenheit in summer noon.
- The landscape design with six trees and no turfgrass makes economic sense because its saving of cooling energy almost matches its cost of irrigation water, while other landscape designs are not economic sound.

- For some landscape designs (Design 2 (S), 3, 4, and 5), there are net energy savings, which means these designs are environmental cost-effective although they may be not economic sound.

CHAPTER 6

CONCLUSION

6.1 Conclusion

This study could be divided into two parts, the first part is about modeling water and salt flux, and the second part is about water uses in Scottsdale. In the fist part, a dynamic model patterned after real network of real hydraulic infrastructures was developed. The model provides a platform to incorporate flux information and it was used to study urban water and salt flux of Scottsdale.

In the second part, water uses, which include municipal water uses and golf course irrigation water uses, are discussed, and the cost and benefit of landscape irrigation is quantified and compared. Municipal water demands for residential uses and commercial/institutional uses are quantified and demands' seasonal variation is simulated. Salinity issues of golf course irrigation water use are addressed by estimating the soil salinity and soil SAR value, which shows that current golf irrigation practice will not do damage to turfgrass or soil. The landscape irrigation is justified by showing net environmental savings associated with landscape irrigation.

Major findings presented in this study include:

- In 2005, precipitation brought much more water into Scottsdale than any other water resources. Most of water left the city either into atmosphere through evapotranspiration or into vadose zone through percolation.
- In 2005, 114 thousand ton salt was brought into Scottsdale, and 63 thousand ton salt in irrigation water was left in vadose zone. Current golf course irrigation practice was analyzed and it is found that soil salinity is around 3000 mg/L (TDS), and the soil SAR value is around 8 indicating no threat to the soil physical properties.
- The seasonal variation of municipal water demands could be simulated by figuring out seasonal variation of water uses for irrigation, evaporative cooling, and swimming pools. However, compared with real data, simulation of 2005

Scottsdale water demand overestimates in summer and underestimates in winter.

- Certain landscape designs can save more energy by reducing cooling electricity usage than is needed to make irrigation water available, which means these designs are environmentally sound although they may be not economic sound.

6.2 Future work

Following work is recommended to further current study.

- Validate the soil salinity and SAR estimation in this study. In this study, the soil salinity and SAR value are estimated based on mass balance in combination with SHAW modeling of evapotranspiration and percolation. It is critical to validate the modeling result with real soil salinity and SAR value.
- Validate building cooling energy savings from landscape. In this study, cooling energy saving is estimated using eQUEST program. It is critical to validate the energy saving result with real case. CAP LTER conducted the North Desert Village experiment to study human-landscape interaction. One research question the experiment is going to address is how landscape and irrigation method affect microclimate. It is possible that outputs from that experiment could be used to validate the modeling result in this study.
- Shift the platform of flux modeling from PowerSim to GIS program (e.g. ArcGIS), and incorporate land use data. Land use could be the key for water and salt flux modeling. Land use type determines water demands and water uses, as well as salt flux. For example, golf course has higher demand for water than the residential land with the same area, and almost all salt for golf course irrigation will be left in vadose zone, while salt in potable water sent to residential land will partially goes to wastewater treatment plant. By incorporating land use data into the modeling based on a GIS platform, we can extend our capacity to integrate all results in this study into one model, and the new model would have more

features such as better visualization. Furthermore, the new model on GIS platform could possibly incorporate results and findings of CAP LTER projects related to land uses, such as the North Desert Village experiment that investigates landscape and irrigation.

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