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Urban Metabolism and the Energy-Water Nexus in Phoenix, Arizona

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Urban Metabolism and the Energy-Water Nexus in Phoenix, Arizona

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CEE 582/SOS 515: Industrial Ecology and Design for Sustainability

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ABSTRACT

Water is a necessary component for life and can be a constraining factor to growth when quantities are limited. This is especially true in highly populated desert regions, which must then import substantial amounts water to support the population. Finding solutions to water limitations through either conservation or additional water acquisitions will be essential to the futures of these desert communities.

This report is the culmination of a course project focused on the water use in Phoenix, Arizona. Water trends are analyzed looking at sector consumption over time, as well as through more innovative methods such as detailing imbedded water associated with urban infrastructure and calculating the co-dependence of power plants and water provisioning. Primarily, this report contains the initial water data (reported from cities) as well as basic calculations and methodologies of assessing life cycle components of water consumption. Some comparisons are drawn between different cities in the metropolitan area. Additionally, damage costs were calculated for some aspects of water use to give an idea of the consequences associated with water use that must be mitigated.

PROJECT BACKGROUND

This project is the product of a course project in the Industrial Ecology course (CEE 582 / SOS 515) taught by Mikhail Chester and Susan Spierre in Spring 2012. Through the assessment of water patterns in the city of Phoenix, the class sought to apply principles of industrial ecology methodologies to a real-world scarcity problem both because of the potential importance of research results and also to increase student understanding of course concepts and research methods. To facilitate this research experience, the students were classified into four different teams:

Buildings	**Infrastructure**	**Water-Energy**	**Impact Assessment**
Joy Edwards	Andrew Lin	David Hannigan	Michael Bernstein
Michael Sieng	Scott Unger	Abdul-Hakeem Hamdan	Chase Holton
Samuel Supowit	Edwin Williams	Liu Xiaoqian	

Synthesis: Janet Ferrell

The initial findings of this work were presented to an expert panel in April 2012. The class is extremely grateful for the insightful feedback from the audience members and the five panel participants:

Braden Allenby, ASU, Engineering
- Professor, School of Sustainable Engineering and the Built Environment
- Lincoln Professor of Engineering and Ethics
- Professor of Law

Chris Boone, ASU, School of Sustainability
- Professor and Associate Dean, School of Sustainability
- Professor, School of Human Evolution and Social Change

Edd Gibson, ASU, Engineering
- Director and Professor, School of Sustainable Engineering and the Built Environment

Rolf Halden, ASU, Engineering
- Associate Director, Swette Center for Environmental Biotechnology
- Professor, School of Sustainable Engineering and the Built Environment
- Interim Co-Director, Center for Health Information & Research (CHiR)

Stephanie Pincetl, UCLA
- Director of the Center for Sustainable Urban Systems, UCLA
- Adjunct Professor at the Institute of the Environment and Sustainability, UCLA

After receiving feedback from the panel, several revisions of the study were made. Those revisions are included in the following report.

INTRODUCTION

Water is one of the most important resources in the American Southwest, where falling water tables around regions near Las Vegas, Phoenix, and Southern California raise serious sustainability questions in light of the still-growing population of the area. This study examines the acquisition and use of municipal surface and groundwater for the basic day-to-day function of the infrastructure and population of Phoenix, Arizona.

Phoenix is the major urban center of the larger Phoenix Metropolitan Valley, a multi-city agglomeration in central Arizona. As a large urban area populated by approximately four million people, the Metro Valley of Maricopa County has experienced the growing pains associated with rapid development and population explosion, and as a result of being a highly populated region in the desert southwest, its primary sustainability concerns revolve around the most fundamental of natural resources: water. It is therefore of the utmost importance to stakeholders, policy makers, and researchers alike to understand the opportunities and limitations that are available to the people who live and work in the Phoenix metropolitan area in order to optimize planning for future growth and sustainability. The research team was divided into four groups focusing independently on the following areas:

1. Water use for buildings (residences, businesses, landscaping)
2. Infrastructure (embedded water stocks from the manufacture of roadways and buildings)
3. Water-Energy Nexus (water associated with energy production)
4. Impact Assessment (current and future economic and political implications derived from the data)

PHOENIX GROWTH

Starting around 1950 the growth in Phoenix including the population, economy, and infrastructure has increased at a rapid rate. This has had profound effects on the use of water in the valley.

Population Growth

Between 1950 and 2010, Phoenix and the surrounding suburbs have experienced a dramatic population increase (Figure 1). It should be noted that the population of neither Phoenix nor Maricopa County as a whole had not peaked as of 2010. With this, infrastructure such as roads, buildings, utilities and canals were put in place to support the growing desert population

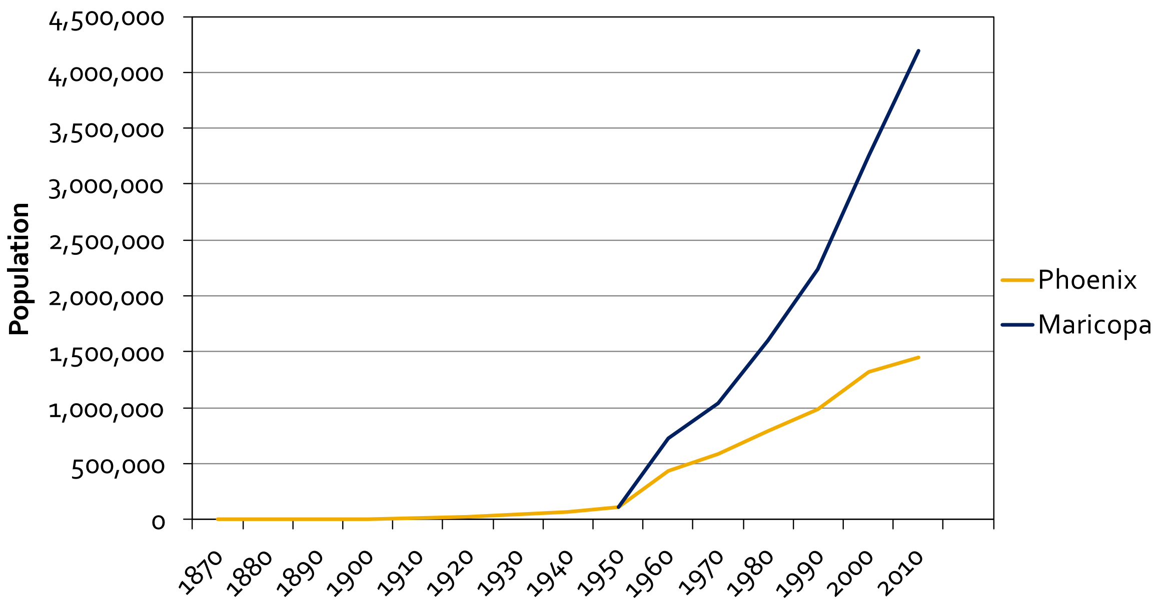


Figure 1: Historic Population Growth

Figure 2 below also indicates historic and projected urban sprawl, which has implications for the future water and energy intensity of the Phoenix Metropolitan area. As seen in the image, the city of Phoenix was located on a small plot of land in the early 1900s, but by 1950 the populations increased exponentially and subsequently caused the urban footprint of the metropolitan area to increase dramatically. With the continued increase in population and the growth of the cities in the outer-limits of the metro areas, the projections into the 2030s illustrate large land acquisitions, but hopefully this will bring a mitigated growth percentage in order to protect the urban water sources which are extremely important in the southwestern United States.

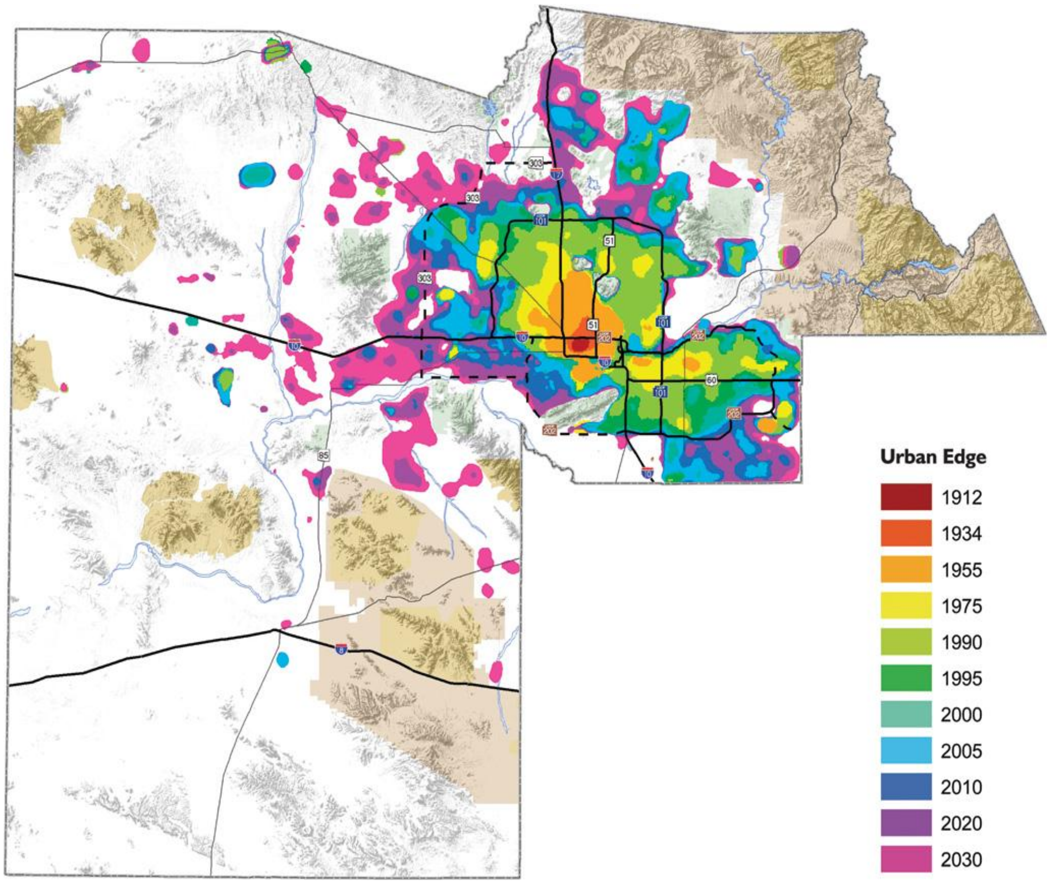


Figure 2: Urban Growth, Maricopa County, (Bagley et al, 2012)

Since the annual rainfall of Phoenix is a mere 8.3 inches (Hong Kong Observatory, 2003), water scarcity has always been a primary resource concern. Prior to the 1990's, groundwater was the valley's primary source of water. Water tables have fallen between 300 and 500 feet in the Arizona Sonoran Desert regions, resulting in a dramatic reduction in streamside vegetation, where water tables used to be high enough for the roots of plants to reach (Perlman, 2012). To supplement the diminishing groundwater sources, a complex system of canals has been put in place to provide water from far away regions.

Infrastructure Growth

The Salt River Project (SRP), the older of Phoenix's two canal networks, began in 1903 to provide water and hydroelectric power to the Metro Valley area (Salt River Project, 2012). Despite an advanced canal system which dated back to the time of the early Native American's in Arizona, at that time, Phoenix still suffered severe summer droughts and crop loss. The National Reclamation Act of 1902 helped to emphasize the need for reclamation of water in the valley area, and soon thereafter the Tonto Basin dam project began (Figure 3). The Salt and Verde Rivers now have seven dams between them, forming the Roosevelt, Apache, Canyon, and Saguaro lakes, as well as the Horseshoe and Bartlett dams and reservoirs (Salt River Project, 2012).

Figure 3: Salt River Project, (Salt River Project, 2012).

As water tables continued to fall dramatically throughout the twentieth century, it became clear that Arizona would need another source of water to support further population growth. Negotiations for a share of the Colorado River began in the early 1900's. Arizona, California, and Nevada were allotted 7.5 million acre-feet do divide amongst the three states (Central Arizona Project, 2012). The Central Arizona Project canal from Lake Havasu began in 1971 and was completed in 1993, when it connected to Tucson. Withdrawals from the canal have increased steadily since 1993, some of which is due to groundwater recharge efforts at the various dedicated facilities along the canal. These can be seen on the map below (Figure 4).

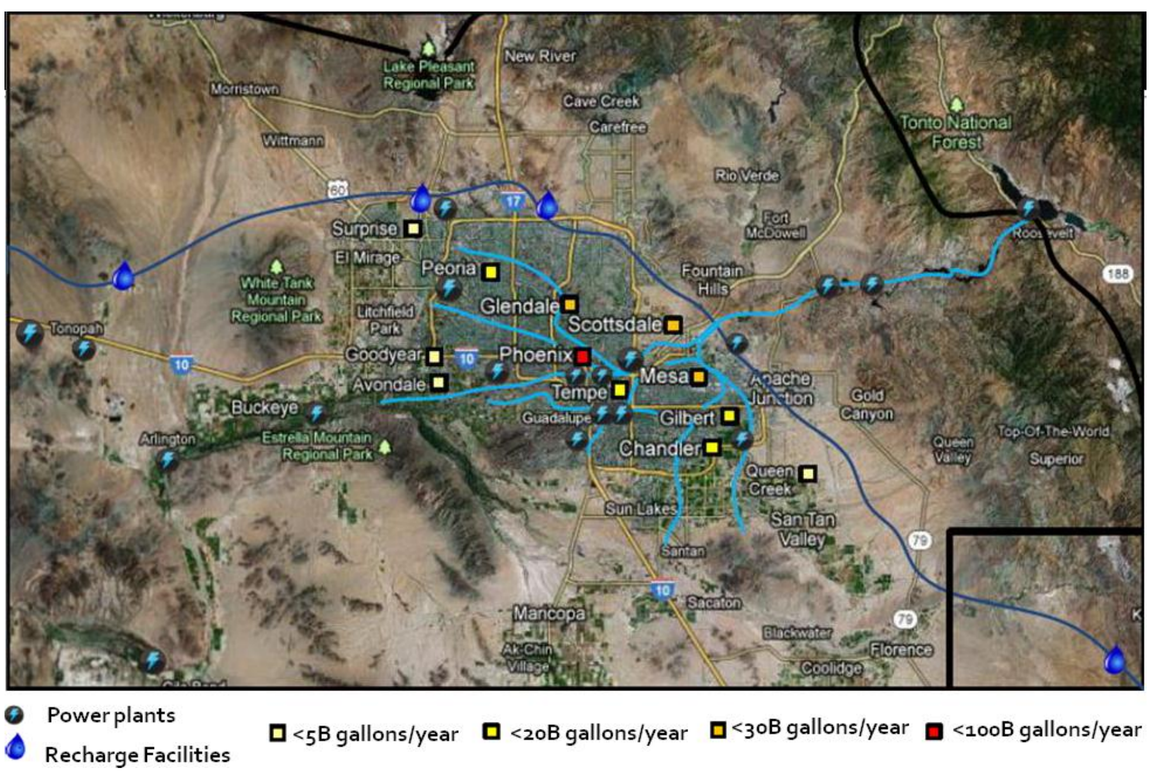


Figure 4: Maricopa Infrastructure Map, (Industrial Ecology Class Spring 2012, 2012).

As seen in the figure above, the Phoenix metropolitan area is a complex web of interconnected water sources, power plants, and recharge facilities. The black border lines represent the boundaries of Maricopa County, while the dark blue line represents the CAP canal. The light blue lines are the historic SRP canals that are still in existence today, while the lightning bolts represent power plants and the water droplets are recharge facilities. Each of the investigated cities also has a colored tile next to their name which represents the total annual water use of the city. The water infrastructure also contains varies water treatment and wastewater treatment facilities. For security purposes, the locations of these facilities have not been located on the map.

PROJECT OBJECTIVES

The main goal of this project was to provide a unique perspective on the use of water in the Phoenix Metropolitan Area, and to provide some measures of the sustainability of water use. One method of assessing sustainability is through an urban metabolism study, which is an analytical method which analogizes city material and energy stocks and flows to the metabolism of an organism. Another method is through a life cycle assessment, which looks at the cradle to grave impacts of activities which occur in Maricopa County. This study is intended to be a first step in documenting the water impacts in Maricopa County, and uses a hybrid method of material flow analysis, urban metabolism and life cycle assessment to complete an initial investigation. A full and complete study would need to be much more in-depth than could be investigated in one semester.

The following information was considered in the analysis of the metabolism of the Phoenix Metro Valley area:

- Flows
    - Residential
    - Commercial
    - Industrial
    - Power Plants
- Stocks
    - Roadways
    - Buildings (infrastructure)
    - Canals

Furthermore, the electricity associated with these water stocks and flows was also considered:

- Residential Water Appliances
- Commercial Water Appliances
- Canal Pumping
- Wastewater Treatment
- Drinking Water Treatment

SYSTEM BOUNDARY

In order to complete the research study in the period of a single semester, some boundaries were placed on the research. Therefore, the following boundaries were used and maintained throughout the investigation into the water use of the buildings in Maricopa County:

- Temporal – 1950-2010. This period of time represented a large change in Phoenix's population, invested infrastructure, and water consumption habits. Data over this period could provide meaningful patterns for the use of policy makers or other water researchers.

- Spatial: The Phoenix metropolitan statistical area (MSA) demarcates the physical extent of our study area and includes Maricopa and Pinal counties (U.S. Census Bureau, 2010). Due to data availability and limitations for the period studied, only select cities (Goodyear, Mesa, Peoria, Phoenix, Scottsdale, and Tempe) were examined in depth. Based on 2010 population levels, the cities characterized in the broader suite of 13 cities represent 79% of Maricopa County. Please refer to Table 1 for a complete list of these cities. Throughout this report, trends for the city of Phoenix are often used to represent trends for the entire Phoenix metro area due to the city's large population.

Table 1: Studied Cities, (U.S. Census Bureau, 2010)

City	Population (2010 Census)
Phoenix	1,445,632
Mesa	439,041
Glendale	226,721
Scottsdale	217,385
Gilbert	208,453
Tempe	161,719
Peoria	154,065
Surprise	117,517
Avondale	76,238
Goodyear	65,275
Fountain Hills	22,489
Paradise Valley	12,820
Tolleson	6,545

WATER CONSUMPTION

The water use in the Phoenix Metro Area was categorized into two major categories: "flows" and "stocks". The flows constitute all metered water data in combination with water used for electricity production. The "stocks" are measured of the embedded water in the Phoenix infrastructure. Note, for the purposes of this project, stocks are not stored water available for use (reservoirs, etc.), but rather they are measures of previous water commitment to infrastructure.

Water "Flows"

Water flows can be categorized into two major categories: metered water delivered to homes, businesses and industries, and water either directly from the canal system or effluent from waste water treatment plants used in power generation. The data found are discussed below.

Building Use

The goal of the building use phase assessment of the project was to find the trends in water use attributed to buildings (excluding power plants) by examining data from the years 1950, 1990, and 2010. The ultimate goal was to find data that were representative of the entire Metro Valley area with as fine a resolution as possible, be it on a city scale, or a neighborhood scale. These data were a key component to this research study, since metered water data captures the consumption patterns of the Phoenician populous. These types of data are publically available and are tabulated in annual reports from the Arizona Department of Water Resources (ADWR). Hard copy reports to the City of Phoenix were obtained for the years 1959-1990, and digital reports were obtained for the years 1991-2010 through the Arizona Department of Water Resources online at www.azwater.gov. Through interviews, the cities of Glendale, Gilbert, Tempe, Mesa, and Queen Creek provided data directly from their archives. Additionally, data for the mid 1990's to 2011 were available through ADWR. The water use data was translated into a series of graphs that were intended to illustrate the trends and changes in water use, including the shift in sources, and the magnitudes of flows in a mass balance on water. The trends observed were then each attributed to a cause, such as Central Arizona Project (CAP) completion, conservation statutes, et cetera.

Where available, the total water use was broken down by sector. In addition, stocks (not infrastructure, but rather reservoirs and groundwater) were identified, but not quantified. Although the aquifers under Maricopa County are falling at a measurable rate, it is difficult to estimate how much remains, especially considering the recharges from the SRP and CAP sources. The SRP and CAP sources themselves also are difficult to quantify as stocks because ultimately the stocks are the sources of the Colorado River, the Salt River, and Verde River, and estimations of the lifespans of these sources have already been done, although there is still much uncertainty in the assessments.

Although all of the above cities were researched, the majority of the data were focused upon Glendale, Gilbert, Queen Creek, Mesa, Tempe, Phoenix and Scottsdale as their data resolution were far superior to the other cities, and their overall water impact is higher due to their size and population.

All of the cities were chosen due to their size, or their importance in the Phoenix Metropolitan area. Each city was called individually to determine what information was available from the public record. The cities of Glendale, Tempe, Mesa and Gilbert provided some discrete data which was at a greater resolution and specificity than many other cities. Additionally, the Hayden Library at Arizona State University provided hard copies of ADWR for the City of Phoenix, as each year's annual report were available from 1959 to 1990, allowing us to look at the most populous city in Maricopa County at a temporal scale that is much larger and more resolute than the other cities in regards to water use and population change. The most beneficial source of information was the ADWR online database. This database consisted of annual reports between the years of 1985 and 2010, from a large number of the cities, although the timespan varied from city to city. Although annual reports existed before this time, these reports are not maintained on the online database. There are some cities that do not have any information listed (i.e. Paradise Valley), so it was assumed that the listed cities are representative. This information was imported into an online database owned by the research team, from which the graphical analyses were performed. .

The following assumptions were made:

- The cities listed above represent the majority of water flows in the Metro area.
- Agricultural water use was assumed to not be captured in the metered data, although it is not clear if it was actually included. Likely this varies from city to city.
- The sum of residential, commercial, and infrastructure usage should equal the total groundwater withdrawals.

Annual Reports from ADWR to the City of Phoenix have discrete numbers available for:

- Total water delivered
- Sewage flow
- Per capita use

These data were used to generate the per capita use trend graphs. The years of statute implementation and CAP completion were overlaid for the purpose of assessing the effects of these events on per capita water consumption.

As seen in Figure 5, there is a general upward trend in water use in the city of Phoenix from the years 1959 until 2010. However, it is significant to note that the rate of the population increase has decreased in recent years, and the water use for Phoenix has begun to level-off. One of the reasons for this may be some of the water conservation measures that have been implemented by Maricopa County since 1980. The first of these is the GMA, or the Groundwater Management Act which was implemented in 1980. The second possibility is the NPCCP, or the Non-Per Capita Conservation Program which was started in 1993. The other major program implemented was the MNPCCP, or the Modified Non-Per Capita Conservation Program. These are all labeled using their acronyms on Figure 5 to illustrate that the total water use began to even out at that time.

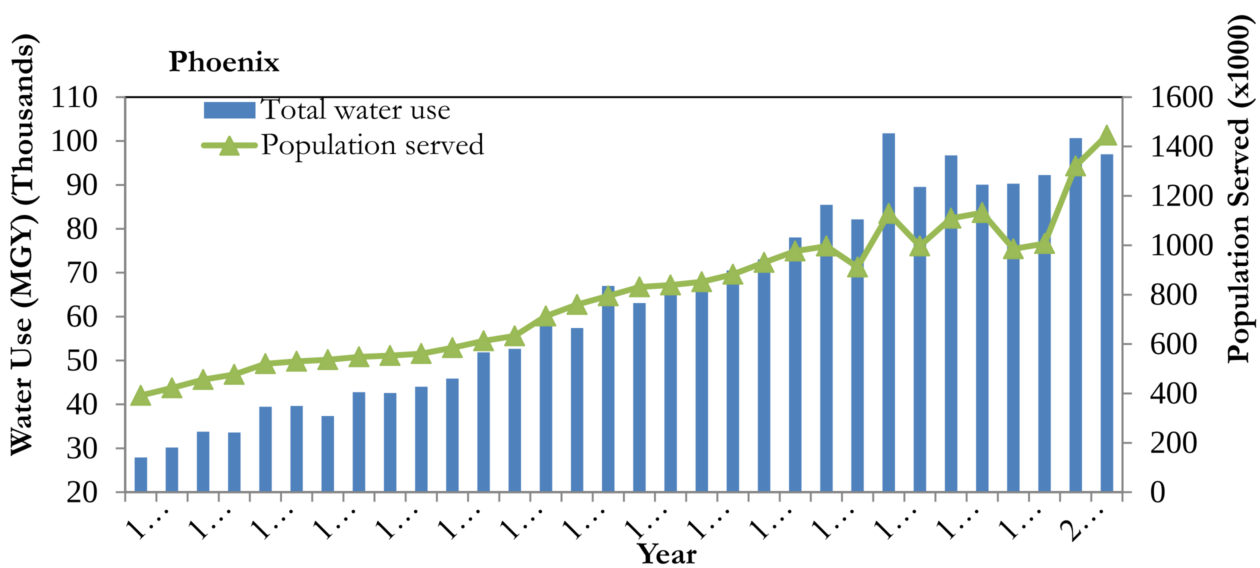


Figure 5: Phoenix Water and Population Growth (City of Phoenix, 2012)

Another method of examining water use trends in the Metropolitan Phoenix area is by looking at the per-capita water consumption. These trends can be seen in Figure 6. From 1959 until 2010, the per-capita water use has changed greatly. From 1959 until 1990, the general trend was increasing. However, by the 1990s, the per-capita water consumption evened out at an approximate maximum use. Since then, the water use has decreased greatly.

The conservation acts may have made a very large impact in the per-capita water use in Phoenix, Arizona. In 1980, the Groundwater Management Act served to establish AMAs, or Active Management Areas where groundwater was being used at a high rate which could not be sustained. The goal was to establish these areas to manage the groundwater use and to manage the supply by supplementing groundwater with other sources. This conservation measure mandated that a certain percentage of water use come from a supply other than groundwater, or if that was impossible, to abide by groundwater use caps. It is possible that this act could have contributed to the leveling of the per-capita consumption in the Figure 6. The 1992 Non-Per Capita Conservation Program served to establish conservation programs regardless of the population for residential and non-residential users for both indoor and outdoor uses. In addition, it strongly encouraged public education programs as well as programs designed to increase confidence in proper metering procedure for the major municipal sources of water. The implementation of this program may have made a large impact on the per-capita water use by causing the decrease in water use from around 250 GPCPD to 200 GPCPD. Finally, the 2008 Modified Non-Per Capita Conservation Program was designed to supplement the 1992 plans by requiring all municipal water suppliers to create and maintain a public education program, as well as to implement BMPs, or Best Management Practices. The BMPs can be found online through the Arizona Department of Water Resources. The number of BMPs that a source must implement depends upon the number of service connections, with <5,000 requiring only one BMP, while 5,001-30,000 must implement 5 BMPs, and any municipality with >30,000 connections must implement 10 BMPs. Some examples of BMPs include grey water implementation programs, leak detection information programs, and xeriscaping rebates (Western Resource Advocates).

The other temporally important event during this time period was the completion of the Central Arizona Project canal. The Canal's completion in 1993 allowed water to be transported from the Colorado River to the Phoenix metropolitan area, and may have had a large impact upon the water mix by decreasing the amount of groundwater consumed.

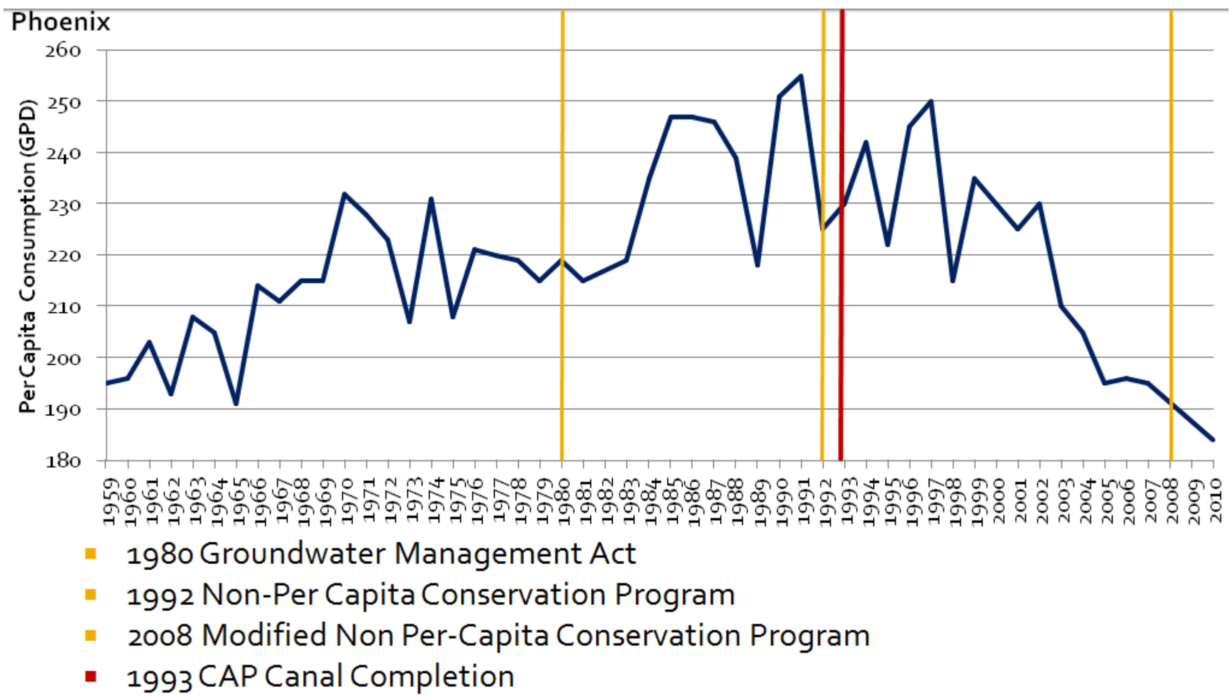
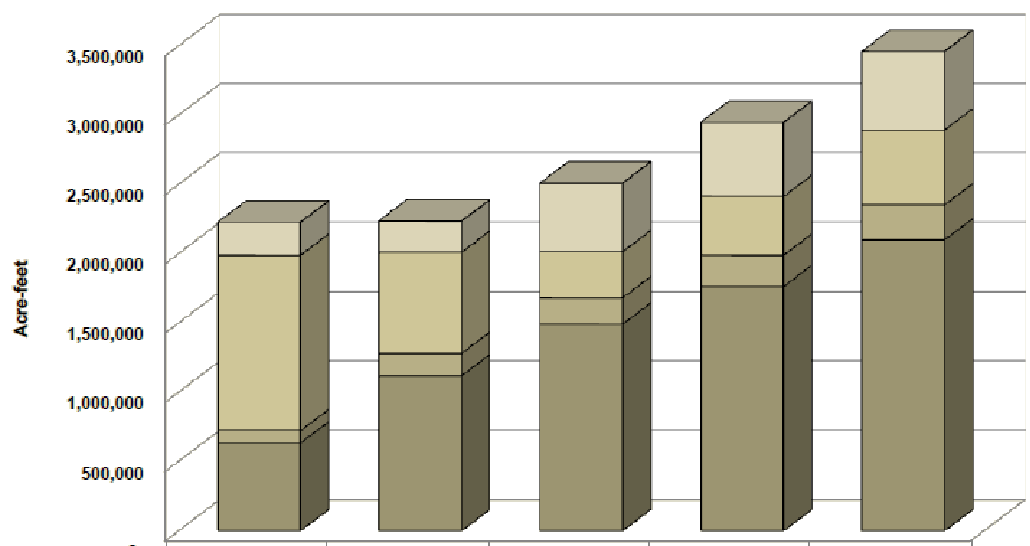


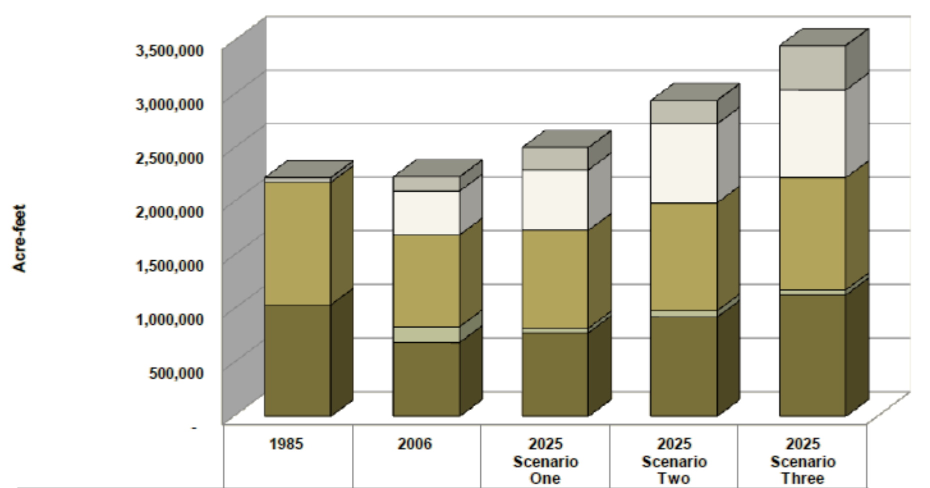
Figure 6: Phoenix Per Capita Consumption, (City of Phoenix, 2012)

It is interesting to look at the changes in projected demand by sector through 2025. This can be seen in Figure 7 and Figure 8, based on different projections made by the Arizona Department of Water Resources.



	1985 Historical	2006 Historical	2025 Scenario One	2025 Scenario Two	2025 Scenario Three
TOTAL	2,227,285	2,235,680	2,507,920	2,947,284	3,459,855
INDIAN	239,227	225,866	495,148	533,315	567,393
AGRICULTURAL	1,265,633	730,025	331,836	424,836	539,356
INDUSTRIAL	88,667	161,380	190,163	225,666	253,896
MUNICIPAL	633,757	1,118,409	1,490,773	1,763,467	2,099,210

Figure 7: Historic and Projected Water Demand, (Arizona Department of Water Resources, 2012)



	1985	2006	2025 Scenario One	2025 Scenario Two	2025 Scenario Three
TOTAL ACRE FEET	2,227,285	2,235,680	2,507,920	2,947,284	3,459,855
RECLAIMED WATER	43,766	134,060	206,603	218,223	414,295
CAP	-	408,252	565,676	737,073	818,594
SURFACE	1,142,961	856,890	912,364	1,006,885	1,046,825
IN-LIEU GROUNDWATER	-	147,149	42,281	59,530	47,181
GROUNDWATER	1,040,557	689,328	780,996	925,574	1,132,960

Figure 8: Historic and Projected Water Supply, (Arizona Department of Water Resources, 2012).

Given this overall information for the Metropolitan Area, it is clear that there is a projected increase in overall water use over the next ten to fifteen years. Therefore, groundwater tables are of a large concern to how the water systems of the area are managed. One interesting graphic for this scenario can be seen in Figure 9, as it shows the overdraft given different growth scenarios for the Phoenix Active Management Area. As seen, the overdraft was at a maximum in the late 1990s, and has decreased since that time. Each of the projected scenarios is actually expected to require less of an overdraft than was at the peak in 1998. This is good news for the Phoenix area, as planners have considered the severe implications of groundwater overdraft, and are planning scenarios where other water sources are used and where overall water use can be properly managed in the Metropolitan area.

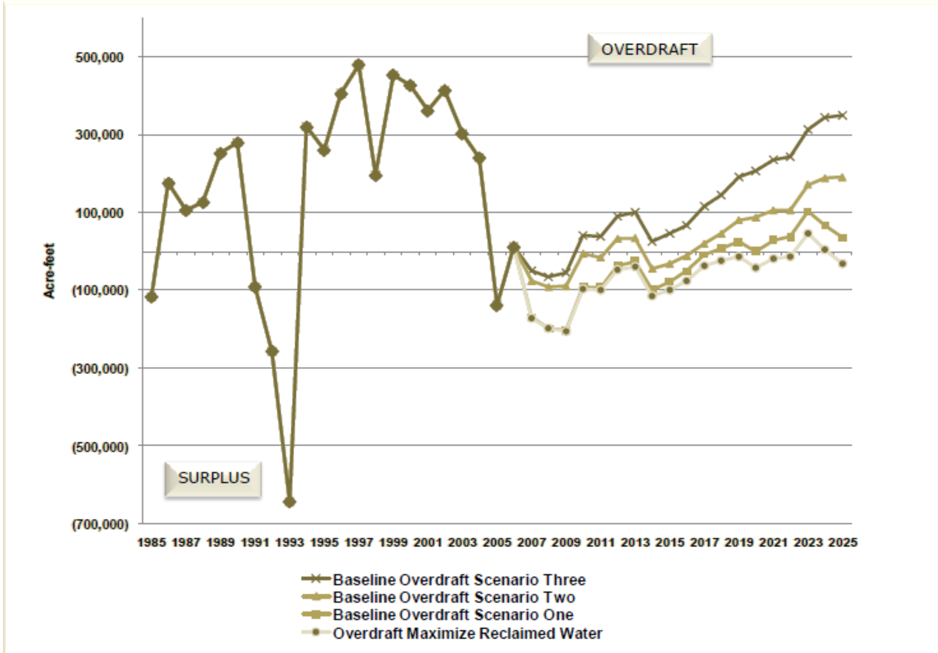


Figure 9: Historic and Projected Overdraft, (Arizona Department of Water Resources, 2012)

Power Plant Consumption

Power plants are another consumer of water in the Phoenix Metro Area that is not generally captured in metered data. The majority of the water use in power plants is for cooling the steam used in a steam-turbine power plant (ICFI, 2008). In Arizona, the majority of plants also recycle cooling water, so less water is withdrawn. However, due to the need to cool the cooling water, a larger amount of water is "consumed" due to evaporation. A map of some of the major power plants in the state is shown below (Figure 10).

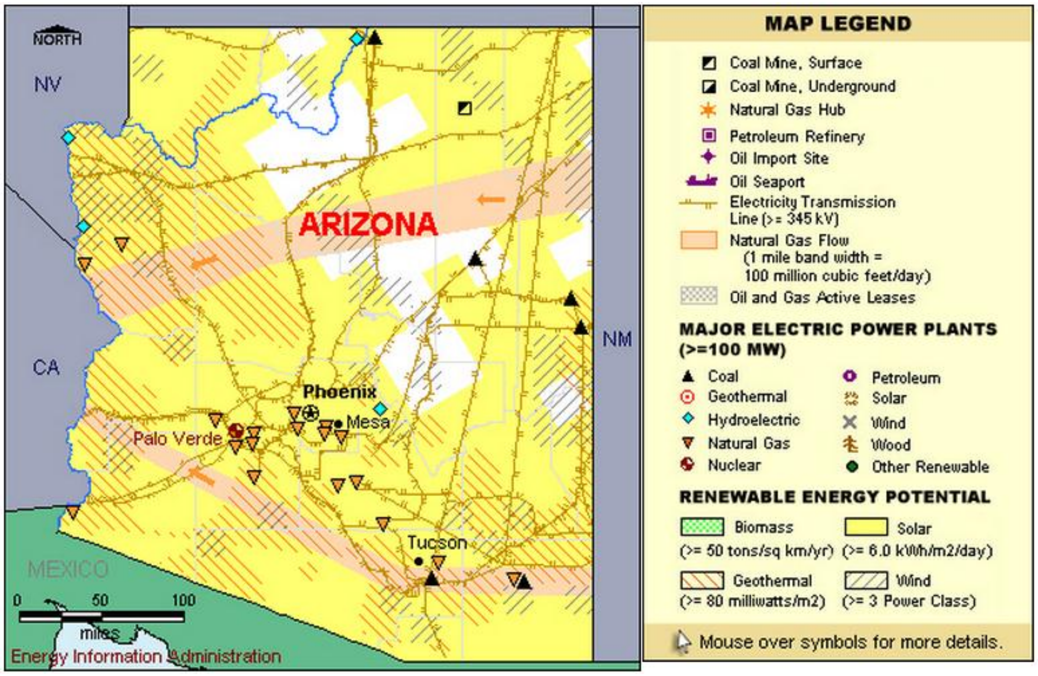


Figure 10: Arizona Power Plants Map (US Energy Information Administration, 2009)

For the purposes of this study, all power plants in Maricopa County were considered. Although these plants are not necessarily representative of the electricity *consumed* in the Phoenix Metropolitan area (this power can be consumed anywhere in the grid, even crossing state boundaries), but these plants do represent an industrial product and actual water consumption in the Phoenix area. The percent breakdown of generation by power plant type for Maricopa County is shown below (Figure 11).

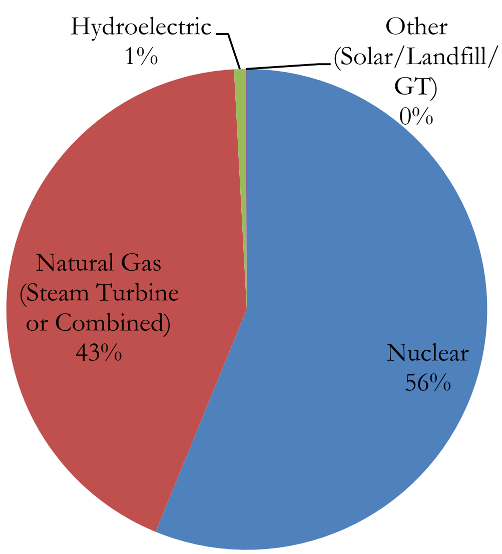


Figure 11: Maricopa County Electricity Production Mix, 2010

Annually, the US Department of Energy collects comprehensive surveys from all operating power production facilities. From these surveys, the total amount of water consumed by each plant was collected (US EIA 2010a, 2010b, 2010c). These surveys also gave monthly electricity production data. Matching this information gave a water intensity of electricity production (Table 2). Several plants reported estimated consumption as opposed to actual numbers. These numbers were not used, and the plants with estimates were assumed to have the same water intensity as other plants in the same classification.

Table 2: Water Intensity by Plant Type, Maricopa County, 2010

Plant Type	Subtype	Percent of Production	Water Consumed (Gallons)	Water Intensity (gallons / kWh)
Nuclear	Steam Turbine	56.19%	2,334,360,315	74,819
Natural Gas	Combined Cycle, Steam Part	16.12%	165,743,390	18,520
Natural Gas	Combined Cycle, Turbine Part	25.92%	258,388,623	17,953
Natural Gas	Combined Cycle, Single Shaft	0.80%	5,108,228	11,471
Natural Gas	Steam Turbine	0.12%	594,570	8,664
Natural Gas	Gas Turbine	0.02%	0	0
Hydroelectric	N/A	0.78%	0	0
Solar	PV / CSP	0.01%	0	0
Fuel Oil	Gas Turbine	0.00%	0	0
Average Water Intensity				**49,781**

Total water consumption due to electricity production was calculated and is shown relative to other annual water use (Figure 12). It is important to note that this might not be entirely representative since many power plants use recycled water from municipal water treatment plants. In these cases the water is double counted. Additionally, only the electricity production phase of each form of electricity generation was considered. For example many technologies are listed as having zero water consumption, although the construction of the facilities or generating equipment might require water. For a more realistic perspective, the water associated with the full life cycle of electricity generation technologies should be considered.

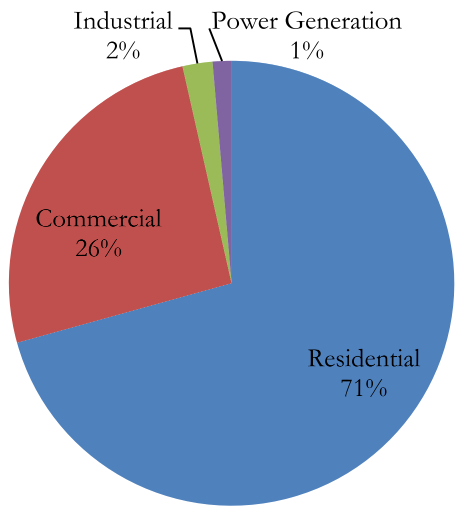


Figure 12: Maricopa County Water Use, 2010

Embedded Water

In addition to quantifying annual water flows, the class sought to calculate the "embedded" water of the Phoenix built infrastructure. The three main components considered for this were buildings, roadways, and water infrastructure (primarily the Central Arizona Project canal). According to the World Health Organization (WHO), water scarcity affects one in three people on every continent of the Globe (WHO, 2012). With water abundance already being strained significantly, water consumption that does not allow for reuse should be monitored carefully and limited when possible. This includes the "embedded water" in the construction of infrastructure.

The term "embedded water" refers not only to water that is potentially trapped in a material, but more importantly the water necessary for the production of a material. This could include things far up the supply chain, such as mining operation for retrieving a raw material, and could happen geographically far from the Phoenix area.

The primary method for calculating these stocks was by using Carnegie Mellon University's Economic Input-Output Life Cycle Assessment (EIO-LCA) tool (CMU, 2008). EIO-LCA models the entire US economy as 428 sectors and calculates the economic flows between these sectors based on survey data. These flows can then be correlated to environmental indicators, giving various emissions per dollar of economic activity within a sector.

Building Materials

Water is used in producing the materials necessary for building construction. Different building sectors use different construction materials, and thus vary in the amounts of embedded water. For example, the production of steel requires significant values of water; buildings that are constructed with high amounts of steel are considered to contain larger amounts of embedded water.

To calculate the embedded water in buildings, the first task was to compile a material inventory for an "average" building of each sector classification. These were assembled using the Athena LCA Building Software in combination with the materials suggested for average homes in the RS Means construction handbooks (RSMeans, 2008a; RSMeans, 2008b).

Table 3: 1992 EIO-LCA Factors

		Gal/kg
Steel	Total	19.81
	Direct	19.51
Concrete	Total	0.1861
	Direct	0.0931
Asphalt	Total	7.7761
	Direct	6.0481

These building estimates were then matched with EIO-LCA data (Table 3) to provide a quantity of embedded water for each building classification.

Finally these building quantities were matched with US Census data on buildings to provide temporal estimates of imbedded water. The Census provides very good data on the number of residential units in the Phoenix Metropolitan Statistical Area (US Census Bureau, 2010). The commercial and industrial facilities were estimated from the Census' reporting of the number of establishments within each NAICS classification (US Census Bureau, 2007). The total embedded water in the Phoenix building stock is shown below (Figure 13).

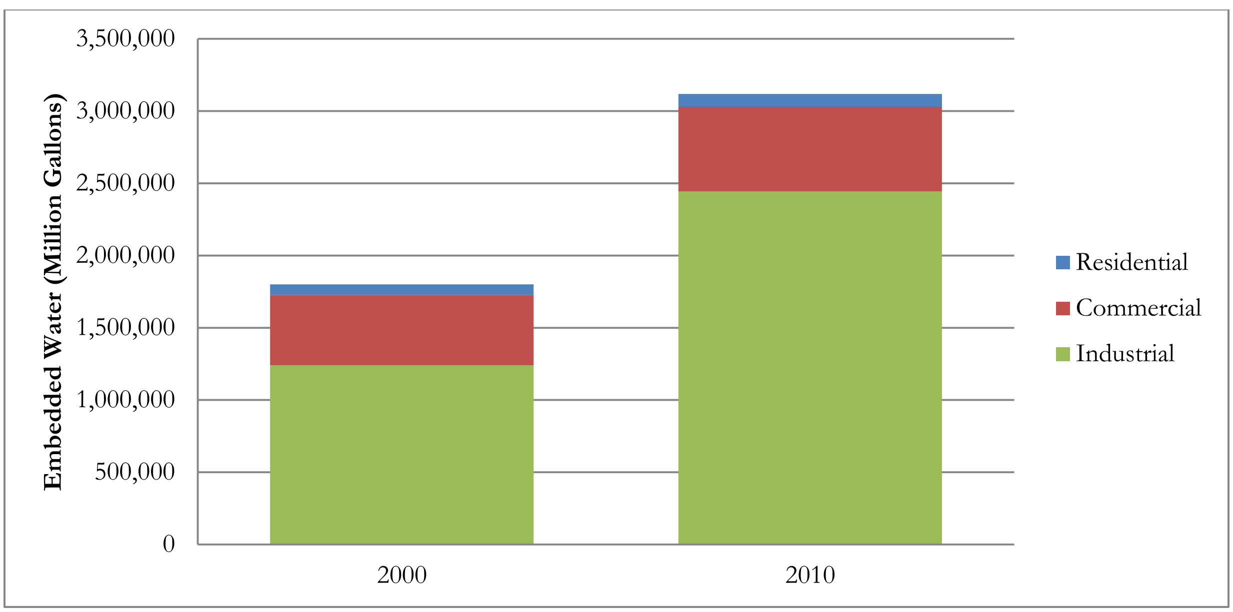


Figure 13: Cumulative Embedded Building Water

Roadway Materials
To determine the quantity of water stock embedded within roadways, roadways were divided into four categories: 2 lane roads (minor arterial and local), 4 lane roads (major collector and minor arterial), 6 lane roads (major arterial), and highways/freeways. Each of these categories was quantified based on their material usage (i.e., asphalt, concrete, and steel), and subsequently, the water usage for each material using EIO-LCA factors.

Assumptions were made for each road category and time period. In 1950, it was assumed that only two lane roads were in use, and that the only material used was asphalt with a depth of two inches (Asphalt Paving Manual, 1965). The length of the roadways was obtained from the Federal Highway Administration's Annual Highway Statistics Survey (US Department of Transportation, 1959-2012). Repair or renovation of the roadways was ignored.

To calculate the amount of used materials, two separate methods were used; a method specifically for freeways, and a method specifically for all other roads (i.e., 2 lane, 4 lane, and 6 lanes roads). For freeways and/or highways, the material usage was determined to be: 48% cement, 35% asphalt, and 6% steel (USGS, 2006). Note that the remaining materials used are natural aggregates, and do contain any inherent water. These percentages were then multiplied by the total freeway volume, which yielded total material values. The total freeway volume was calculated by multiplying the total length of freeway by the freeway's width (15 feet), and then multiplied by the average depth of highway (32 inches) (USGS, 2007).

For all other roadways (arterial, collector, and local), it was assumed that asphalt with a depth of four inches was the sole material used. This depth was multiplied by the corresponding lane width (12 feet), and then multiplied by the corresponding length of road.

Canal Materials
The US Bureau of Reclamation details the CAP and the SRP including reach length, bottom depth, side slope (channel), and internal diameter (piping) (U.S. Department of the Interior Bureau of Reclamation, 2011). In addition, information on material volumes for major detainment, spillway, and diversion structures were given. Although the quantities were for both concrete and earthen dams, the energy used in the construction of earthen dams was minimal and therefore neglected. From this, the volume of concrete used in the construction of the CAP, which provides overland flow from the Colorado River to Tucson, was calculated. Because the actual volumes of water used by Phoenix and Tucson respectively were unavailable, material investment could not be spilt by direct usage. Instead, allocation for each city was determined from a linear split, based on population. From this method, Phoenix was allocated responsibility for 76% of the CAP and 100% of the SRP system. Total concrete used in the construction of these water conveyance systems was then converted to water (and energy, discussed in the Water Provision section below) use by using the EIO LCA factors.

Embedded Water Summary
The cumulative embedded water stocks are summarized in Figure 14 below. Note that since buildings data were not available for 1990 or 1960, it is not shown on this figure. For the years shown, buildings are the major embedded water stock for the city of Phoenix. This makes sense since they are the largest volume of material stocks. Canal water stock in negligible in comparison.

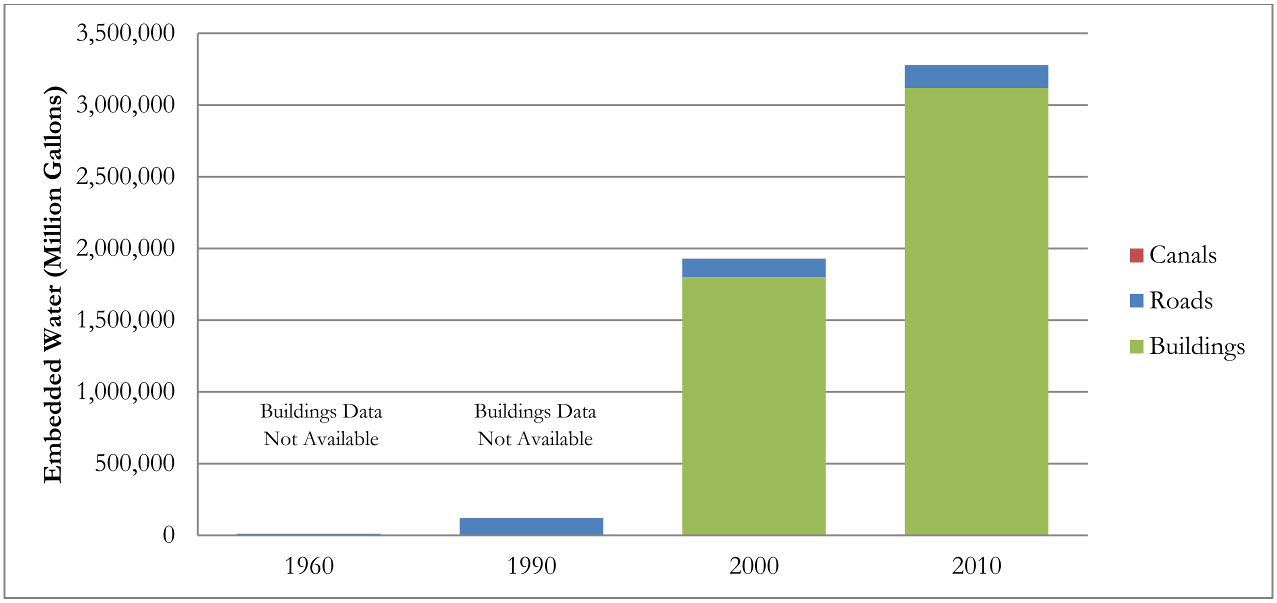


Figure 14: Cumulative Embedded Water

Comparing Stocks and Flows

It is difficult to directly compare water "stocks" and water "flows", because stocks represent a single-time investment, whereas flows represent a temporal trend of use. Still, annualizing the change in stocks can show interesting trends. For example, in 2010, the water stocks associated with the *newly added* buildings for that year accounted for 39% of the water use. It is important to note that this water consumption might fall geographically outside the Phoenix area, and not be captured in the commercial/industrial flow data. Residential use still is the dominate water consumer in the valley, even taking into account these potential indirect uses.

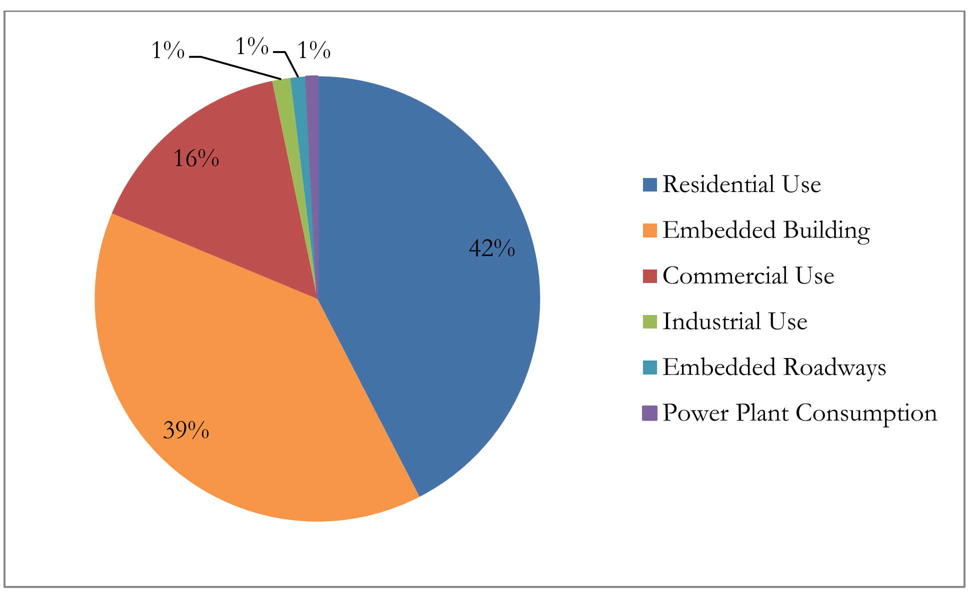


Figure 15: Flows vs. Stocks comparison, Maricopa County, 2010

THE WATER-ENERGY NEXUS

The second portion of the class project focused on understanding the codependence of water and electricity production. Due to the large inherent consumption of water by electricity producers (power plants), it is imperative that electricity production be viewed within the context of water use. Furthermore, as the processing of water for consumption and disposal requires energy, the consumption and treatment of water must be viewed in terms of the required energy to enable this consumption. A better understanding of this water-energy nexus could assist urban planners and policy makers in making informed decisions on future water management practices.

Water Acquisition

Energy is necessary in transporting and cleaning water for human use. This section of the report examines the three main energy demands for the provision of water in Phoenix.

Canal Pumping

The CAP utilizes large pumping stations throughout the canal to overcome the large elevation difference between Phoenix and the Colorado River inlet. Horsepower of these pumping stations and the volume of water conveyed was obtained from the Bureau of Reclamation (U.S. Department of the Interior Bureau of Reclamation, 2011) and was converted directly to kWh/yr.

Additionally there was an amount of energy "embedded" in the canal structure. Embedded energy was calculated using the same methodology as the embedded water, as discussed above.

Water and Wastewater Treatment

For water energy usage, data from water and wastewater treatment plants for the cities of interest were collected. Only recent flow rates could be found for water and wastewater treatment plants (2003-2010) for most cities. However, for the city of Phoenix, water treatment data from 1990 to present was available. Data were gathered either from published documents, government websites and phone interviews for the cities that did not publish any information (e.g. Avondale, Fountain Hills, etc.). The flow rates were aggregated for several key cities from multiple sources (Applied Economics, 2003; City of Goodyear, 2003; City of Mesa Utilities Department, 2004; City of Gilbert, 2006; City of Tempe, 2010; City of Phoenix, 2011; City of Avondale, 2012; City of Fountain Hills, 2012; City of Glendale, 2012; City of Phoenix, 2012; City of Scottsdale, 2012; City of Surprise, 2012) to determine energy usage for water and wastewater treatment plants. After total water usage volumes per year were collected, published values were used on energy requirements to treat water (Pacific Gas and Electric Company, 2006) and wastewater (Stokes and Horvath, 2010).

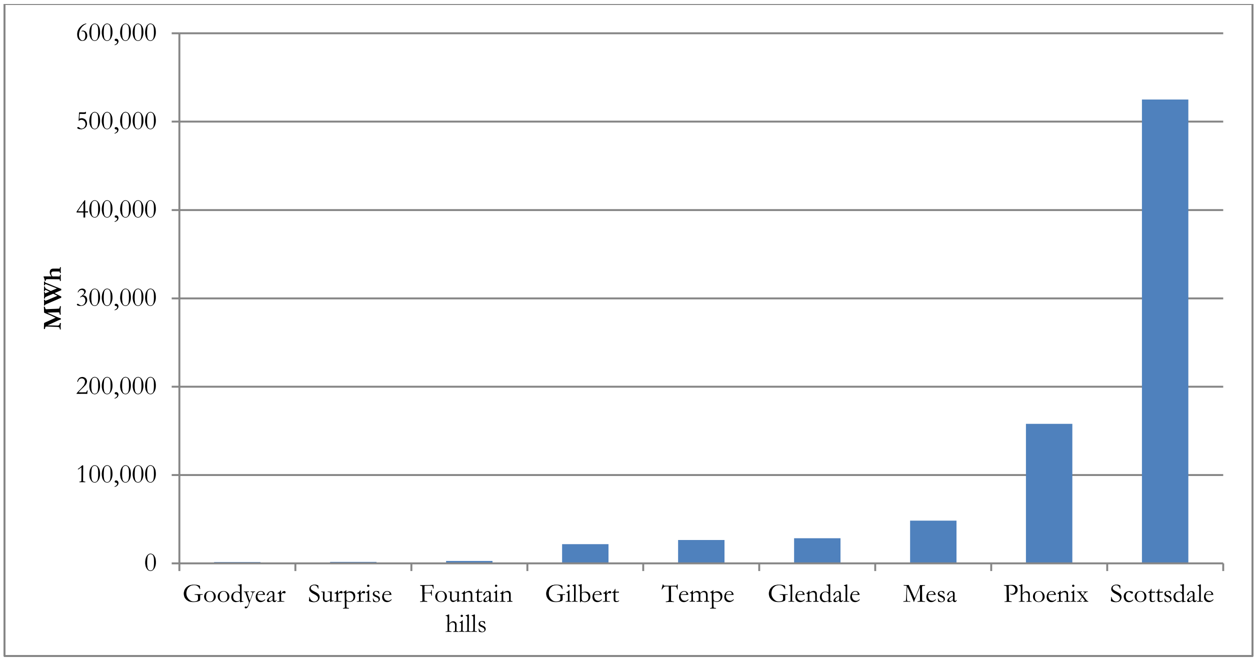


Figure 16: 2010, Water Treatment Energy

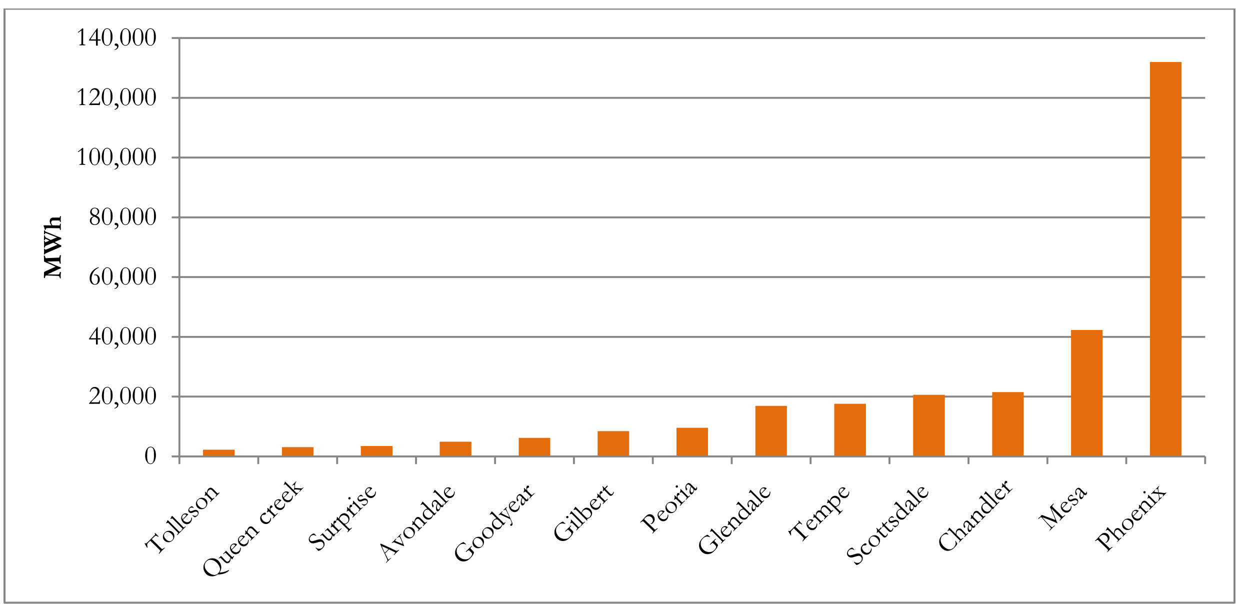


Figure 17: 2010, Wastewater Treatment Energy

Water Applications

Beyond simply the preparation of water for use, there is a significant portion of energy that is consumed in the use of water in homes and businesses for water heating, dishwashers, washing machines, etc. Although it is debated whether energy consumption associated with these applications should be attributed to the water or the energy footprint (or both), the value was calculated for this project to compare the significance to other energy and water consumers. However, policies dealing with the water-energy nexus should consider beyond this footprint, which is just a snapshot of the use-phase, to include the full life cycle of water and energy systems.

Residential and Commercial Appliances

The basic calculations was based on the assumption that the US average percentage of residential and commercial electricity devoted to water appliances was representative of the percentages in Phoenix. The data for this was obtained from the US DOE's Building Energy Data Book, which defines "water heating" for both commercial and residential sectors as well as "wet cleaning" for homes (US Department of Energy, 2000-2010).

From the percentage breakdowns, the appliance related energy use was aggregated based on the energy use in the residential and commercial sectors (USEIA, 2009b; USEIA, 2009a). Combining this information with the commercial and residential density of specific Arizona cities, water use (and the implicit energy use) could then be delineated into commercial and residential usages (US Census Bureau, 2006-2010b; US Census Bureau, 2006-2010a).

The residential and commercial energy end-use splits of 1960s and 1990s are not available in the census data. An assumption was made that the distribution has a linear trend over time, based on the linear trend from 2006-2010. Projections were then made of residential and commercial water appliance energy use ratio for the time period without data. Housing and commercial density was adjusted using previous Census data (US Census Bureau, 1990).

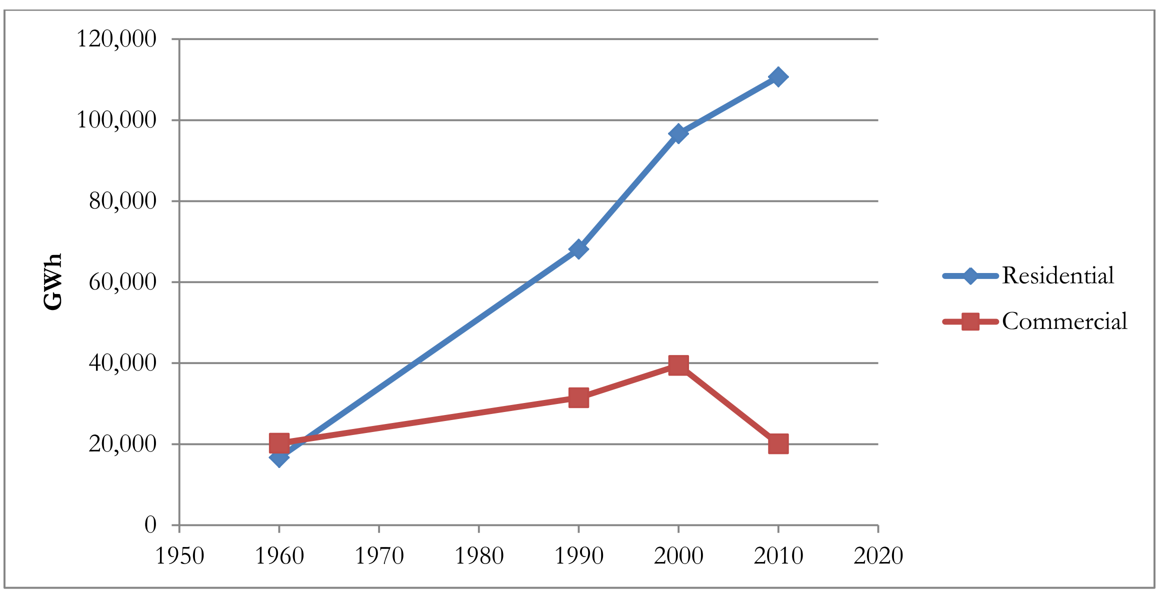


Figure 18: Total Water Appliance Energy Use, Metro Area

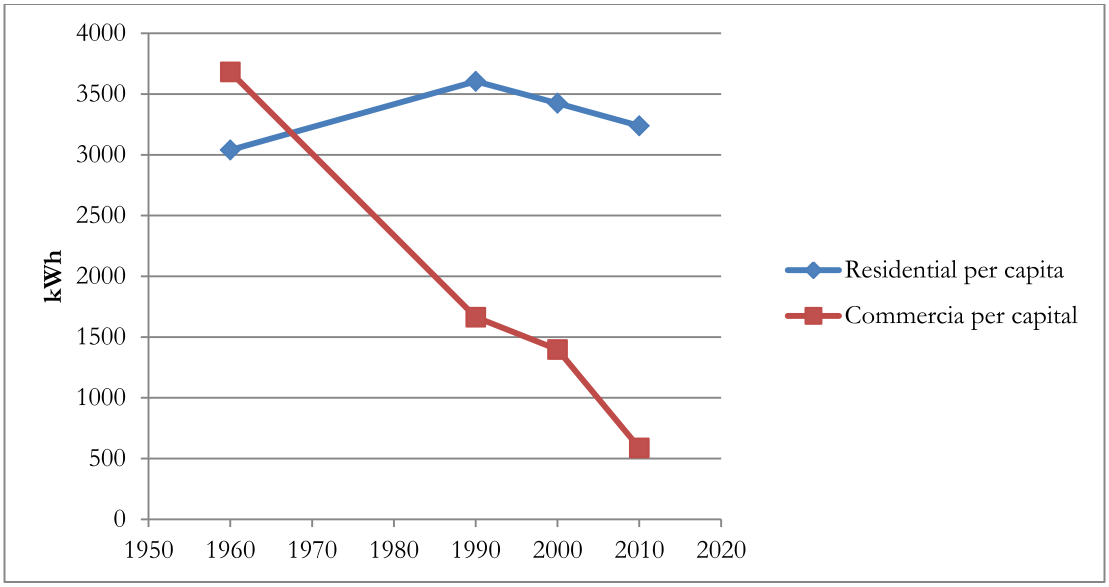


Figure 19: Per Capita Water Appliance Energy Use, Metro Area

Energy-Water Nexus Summary

The percentage of energy consumed in the provision and use of water by different categories has shifted over time (Figure 20). Home water appliances are now the dominant category of electricity consumption associated with water, and the percentage associated with commercial appliances has decreased dramatically since 1960.

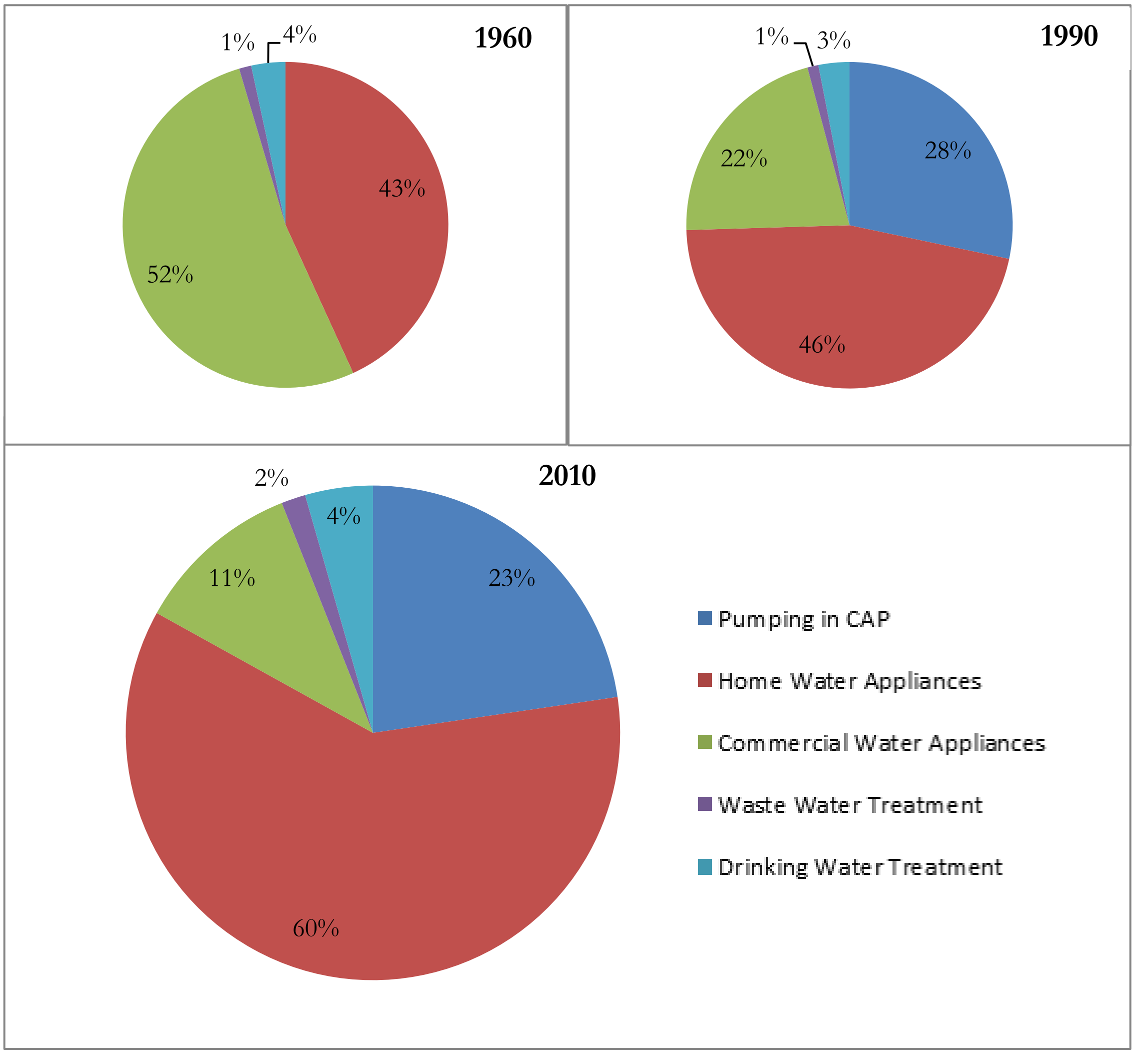


Figure 20: Change in Water Energy Use, 1960-2010

For reference, the 2010 breakdown has been shown relative to all other electricity consumption in the city (Figure 21). Although water is not the main consumer of electricity, it is a non-negligible portion.

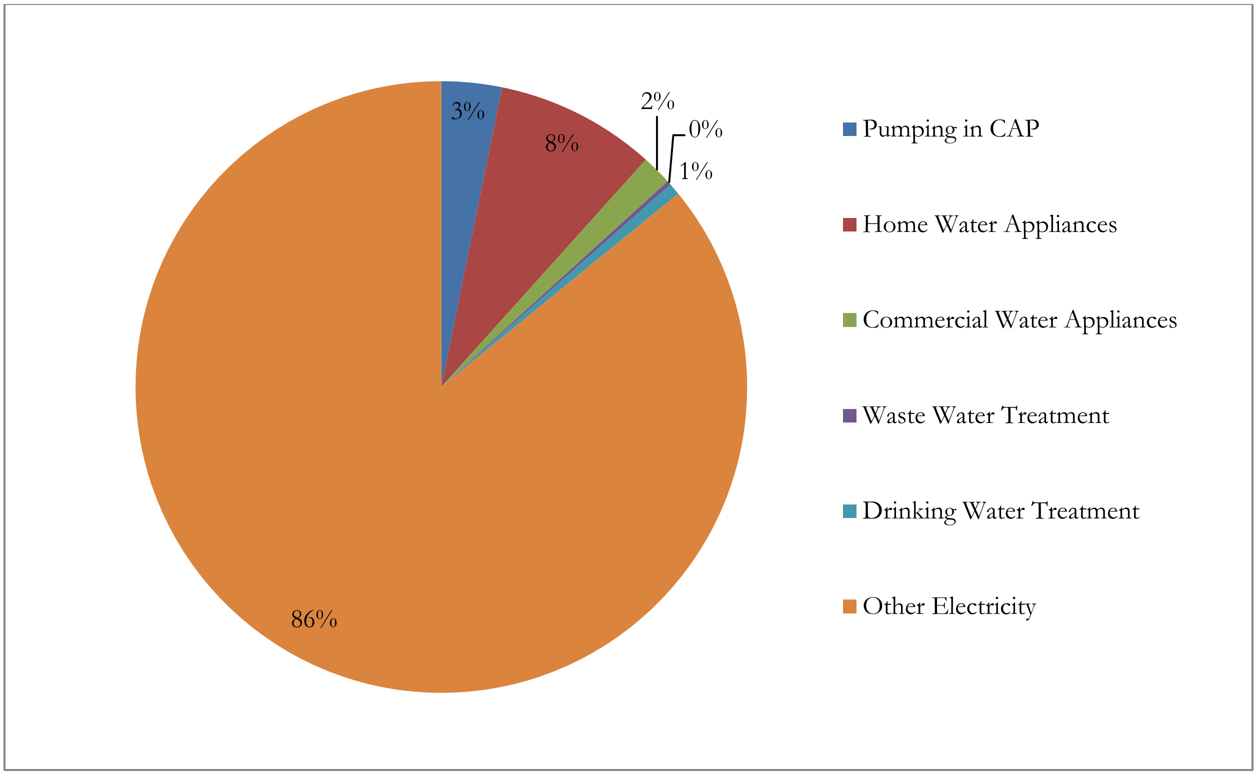


Figure 21: Water Energy to Total Electricity Consumption, 2010

IMPACT ASSESSMENT

Urban metabolism studies characterize the flow of material and energy through the city. A material flow analysis examining such stocks and flows (e.g., annual quantity/person), however, may not speak to the economic, social, or environmental impact of such an inventory. Impacts aside, few studies explore the how urban metabolisms change over time (Kennedy, Pincetl, & Bunje, 2011). The work of the Impact Analysis Team seeks to fill each of these critical gaps, expanding beyond the boundaries of a traditional urban metabolism, by a) characterizing changes in population, water use, and water use related to household electricity use over time, and b) exploring the health, environmental, and carbon dioxide equivalent emissions damage costs associated with these uses.

Initially, the impact analysis was to revolve around equity considerations of water use in the valley (e.g., how are individuals in different cities using water differently based on economic or demographic factors). This equity component was intended to augment existing literature on the distribution of environmental amenities and dismantles in Phoenix. For example, Grineski, Bolin, and Boone (2007) reported on the distribution of criteria air pollution in the Phoenix metropolitan area. Jenerette, Harlan, Stefanov, and Martin (2011) examined socio-demographic data from 1970-2000 to explore the differences in access to ecosystem cooling services that provided relief from Phoenix' urban heat island. Resolution of water-use equity could have added an additional layer, related to a vital human resource, to these perspectives. However, after characterizing the population of cities in the valley for the periods of 1990, 2000, and 2010, and incorporating data related to water and energy consumption from our peers, we determined that quintile-quintile comparisons involved in Lorenz analysis and Gini coefficient calculations were inappropriate, due to insufficiency of the data and the inappropriateness of the city as a unit for social equity analysis (Personal Communications: Dr. Joshua Abbott and Dr. Rimjhim Aggarwal). As a result of these insights, we shifted our analysis to focus on characterizing differences across cities, at different time periods, in per capita attributes related to the water energy-nexus in Phoenix, and on exploring health, environmental, and carbon dioxide equivalence emissions damage costs within the system.

Methodology

As previously discussed, city-level population data for the cities of Tempe, Phoenix, Scottsdale, Surprise, Gilbert, Queen creek, Avondale, Goodyear, Fountain hills, Mesa, Paradise valley, Ahwatukee, Laveen, Tolleson were collected from 1990, 2000, and 2010 census data (U.S. Census Bureau, 1990; U. S. Census Bureau, 2000; U.S. Census Bureau, 2010). Similarly, total electricity data were gathered from a variety of sources (e.g., EIA (2012)) by the Impact Analysis team and by peer groups.

The impact assessment selection of cities to analyze was constrained by the availability of collected data. Therefore, cities with complete data on a) population for 2010, 2000, 1990, and b) total water use (gallons) were chosen. For these select cities, total water use was resolvable by end-use sector (e.g. commercial, residential, and industrial). However, agricultural water use was not explicitly delineated in the buildings-use data, and therefore could not be teased out from total water use data for the cities included in this study. The class proposes, however, that as revenue from agricultural production may be considered part of a city's local economy, it may be reasonable to include (or at least not discount wholesale) water use data not explicitly accounting for agricultural sector end-use.

Relative Rankings

The following shows total per capita water use and household water-appliance related electricity use. Collectively, the figures provide a strong visual representation of the distribution of per capita usages in cities across the valley. In addition, the figures reveal the relationship of each city to the average per capita value, the cities with highest per capita usage, and the cities that underwent the greatest changes throughout the three time periods. On average, per capita water use was lowest in 2000; over all, household water-appliance related electricity use decreased from 1990 to 2010.

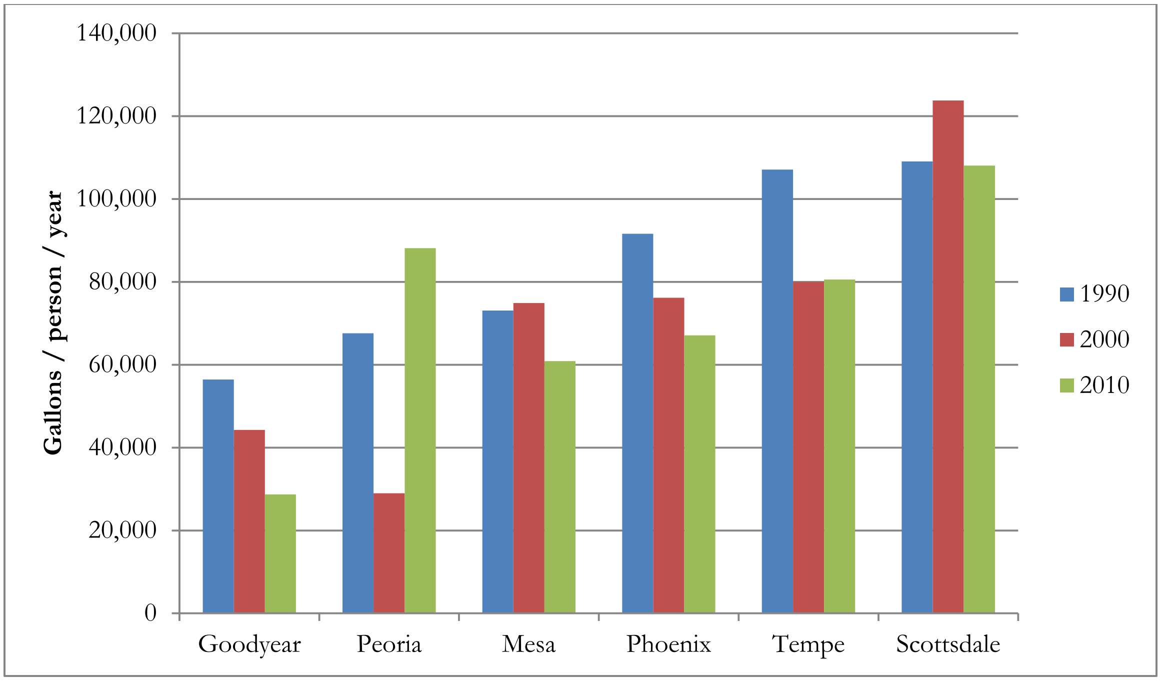


Figure 22: Per Capita Water Use by City

Relative rankings of per capita household water-appliance related electricity use by six cities in the valley reveals an overall decrease in per capita use, across cities. This result may bear out the advancing technological efficiency of water-related electricity appliances over time (see Table 4 below).

Relative rank of water-appliance related household per-capita electricity use: 1990, 2000, 2010 for the six selected cities examined.

Table 4: Relative Rank of Residential Water-Appliance Electricity

1990 Ranks	**1990 kWh per capita**	**2000 Ranks**	**2000 kWh per capita**	**2010 Ranks**	**2010 kWh per capita**
Scottsdale	4,529	Scottsdale	4,330	Scottsdale	4,161
Tempe	3,885	Tempe	3,715	Tempe	3,569
Mesa	3,696	Phoenix	3,336	Phoenix	3,206
Phoenix	3,489	Peoria	3,302	Peoria	3,173
Peoria	3,454	Goodyear	2,610	Goodyear	2,508
Goodyear	2,730	Mesa	2,214	Mesa	1,315

Figure 22 demonstrates how per capita usage of total has changed in the past twenty years. Due to data availability, these results lack the resolution to support conclusions about the causal factors driving changes in usage.

The decrease in average per capita household water-appliance related electricity and average per capita total water use from 1990 to 2010 could be an indicator of increases in technological efficiency or successful water conservation programs. However, incorporating these considerations into the decreasing per capita residential water use demonstrates that indoor water use savings are not driving decreases in consumption. Instead, the most water conservation ground seems to be covered by reducing outdoor use (Gammage Jr, Stigler, Daugherty, Clark-Johnson, & Hart, 2011). Plots of relative rank of per-capita water use and per-capita household water-appliance electricity use further demonstrate that per capita residential water use is not driven solely by water use associated with water-related appliance use for 2000 and 2010, the years when data were readily available. This finding is in line with the work of others (Wentz & Gober, 2007; Wentz, Wills, Kim, & Myint, 2010) who have indicated that household size, presence of pools, lot size and structure, and irrigation practices may be more significant and worthwhile targets for reducing per-capita residential water consumption. Although research has found that use of appliances, like washing machines, drives increases in water use in Beijing and Tianjin (Zhang & Brown, 2005) over time, on a per capita basis, our results demonstrate that these factors may not be significant for cities like Phoenix.

Urban Allometry Context

Increasingly, researchers West, Lobo, Bettencourt and others have looked into the ways in which cities are growing. L. M. Bettencourt, Lobo, Helbing, Kuhnert, and West (2007) highlighted patterns in the ways certain attributes of cities, from innovation to crime to household electricity use, scale with urban growth. Employing an urban allometry analogy, these researchers have found many of these attributes scale according to power law functions (L. M. A. Bettencourt, Lobo, & West, 2008). Allometry is a term generally employed in the life sciences to refer to the growth of the portion of an organism with regards to the growth of the organism as a whole. L. M. Bettencourt et al. (2007) identified three broad trends in the growth of city attributes as city populations increase, and these trends cluster around the ß exponent value of the corresponding power function. The first category deals with ß approximately equal to 1 (linear); the second ß approximately between 1.2 and 1 (superlinear); the third ß approximately between 0.8 and 1 (sublinear) (L. M. Bettencourt et al., 2007). These researchers identify a broad typology in which individualized attributes linked to human needs (e.g., jobs, household water consumption) scale linearly (adding another person to a city will require another job for the individual), while attributes linked to economies of scale (such as those with infrastructure) scale sublinearly, and attributes linked to social capital (like innovation or crime) demonstrate increasing returns to scale and scale superlinearly (L. M. Bettencourt et al., 2007).

Based on this urban allometry literature, the class explored how total water and total household electricity use scaled with cities of various sizes within the Phoenix MSA (Figure 23). For water use, the analysis indicates superlinear scaling consistently at each time period across the six cities selected. For energy, the results are more varied, for example considering an ill-fitting regression in 1990, however, in 2010, we see total household electricity consumption scaled linearly. According to L. M. A. Bettencourt et al. (2008), household energy and water consumption ought to display linear scaling relationship, since it is a trend associated with human needs. Water in the Phoenix MSA presents a potentially interesting case in which, as we examine cities of increasing size in the MSA, water use increases at a rate faster than population increase. This possibly could be due to the use of water for "luxury" applications, beyond the need of water for human survival.

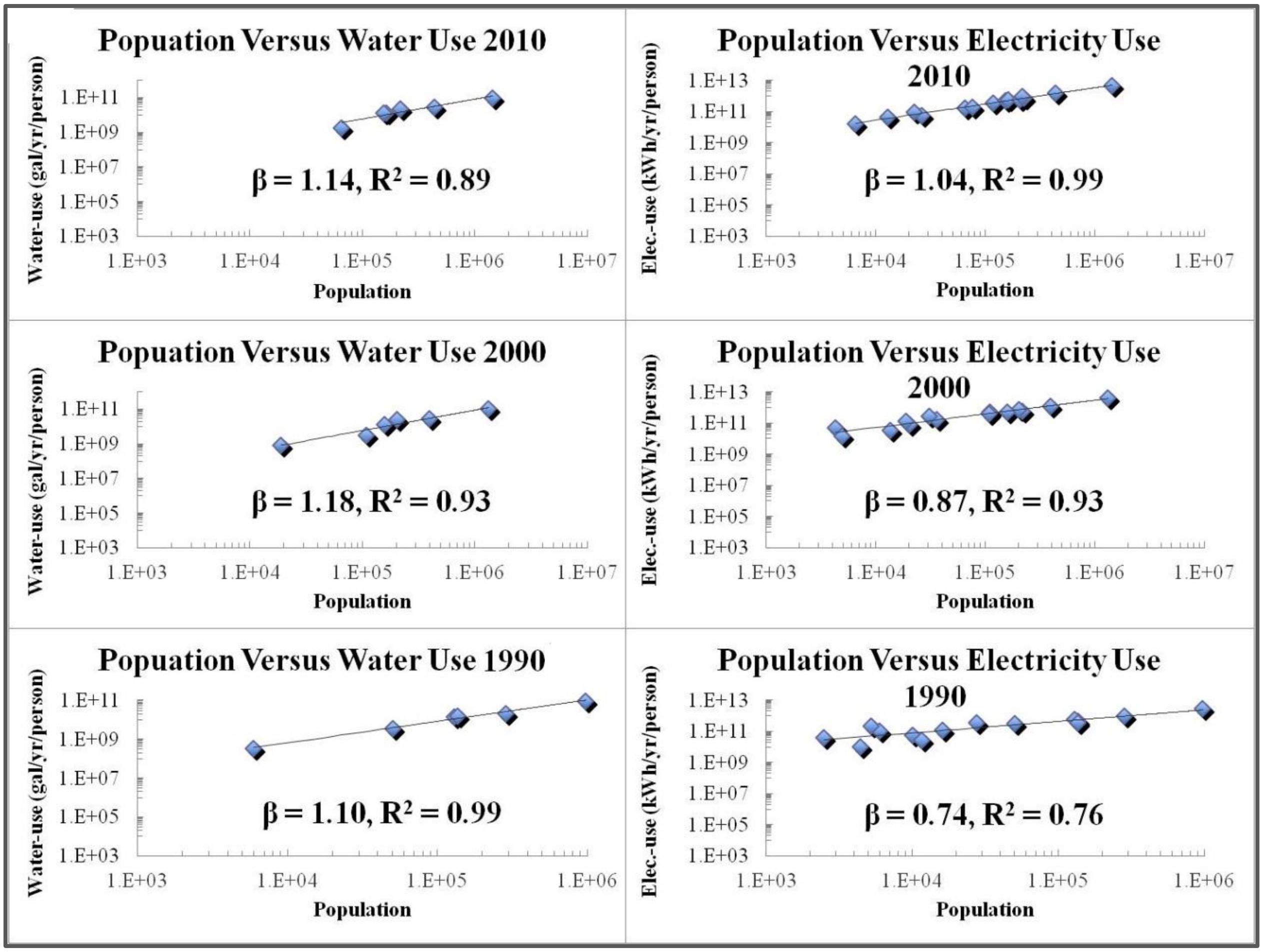


Figure 23: Urban Allometry Analogies, Phoenix Metro Area

Damage Costs

Emissions damage costs (in year 2000 dollars per short ton) were derived from the results of the Air Pollution Emissions Experiments and Policy analysis model (APEEP) developed by Muller and Mendelsohn (2007). APEEP is an integrated assessment model used for calculating the marginal costs of emissions from six common air pollutants (carbon monoxide, nitrous oxides, sulfur oxides, volatile organic compounds, and particulate matter smaller than 10 and 2.5 microns) at the county level (Muller & Mendelsohn, 2007). The model accounts for damage costs associated with agricultural yields, timber yields, outdoor recreation, visibility, man-made materials, and human health. Damages to human health made up 94 percent of total damage costs, with premature death accounting for 71 percent and illnesses for 23 percent. Determining the damages related to health was complex and required the calculation of many heath-impacted aspects, including loss of wages due to illness and differences in exposure effects based on age, gender, etc. The remaining six percent of damage costs included by APEEP were spread out among other areas, for example visibility (Muller & Mendelsohn, 2007).

Damage costs associated with CO_2-eq emissions were drawn from a review of an NRC Committee on Health (2010) report investigating the hidden costs of energy. The report indicates that marginal damage costs, based on current emissions, range from \$0-\$100 per ton CO2-eq. (\$30 as median, \$100 as max). This range was determined by the use of three widely-used impact assessment models: DICE, FUND, and PAGE and assumes there isn't greenhouse gas mitigation in place (Committee on Health, 2010). Based on this review, two instances of CO_2-eq. damage costs in $2000/short ton were explored: a median cost scenario of $30 and a maximum cost of $100 (inflation adjusted to 37.51 $2008/short ton 125.03 $2008/short ton[1]).

Emissions factors (in kg of pollutant per unit of electricity production) were derived from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model created by the Transportation Technology R&D Center of the Argonne National Laboratory, funded by the U.S. Department of Energy. The GREET model takes a life-cycle approach to calculating 1) total energy consumed from fossil fuel combustion, 2) emissions of CO_2-eq. greenhouse gases, and 3) emissions of criteria air pollutants (mentioned above) (Energy, 2011). With damage costs in dollars per short ton, and electricity use available from a variety of sources (e.g., peer groups and EIA (2012)), we used emissions factors to calculate specific health, environmental and CO_2-eq. damage costs associated with Maricopa 1) total commercial and residential electricity use in Maricopa (year 2008), 2) total residential electricity use in Maricopa county (year 2008), 3) total residential, commercial, and pumping electricity use related to water use in the study area of 79 percent of Maricopa (year 2010), and 4) total residential electricity use related to water use in the study area of 79 percent of Maricopa (year 2010) (population data from U.S. Census Bureau (2012).

In the state of Arizona, and the United States, generally, air pollutants (like carbon monoxide ammonia, nitrogen oxides, particulate matter (less than 10 and 2.5 microns), sulfur oxides, volatile organic compounds) are regulated by the 1970 Clean Air Act and any recent amendments to this law (EPA, 2011). By contrast, carbon dioxide emissions are not regulated. However, unregulated does not mean that these emissions do not have costs associated with them. Based on the National Research Council's conclusions on costs of CO_2 and how it relates to climate-related damages from coal (Committee on Health, 2010), the costs of CO_2 emissions associated with energy use, generally, and electricity use associated with the water-energy nexus, specifically, were calculated to enrich the perspective of the impact of water and energy use in this Phoenix Metabolism Study.

Figure 24, below, relates the total health, environmental, and CO_2 eq. emissions damage costs, for the three CO_2 eq. emission pricing scenarios (0, median, maximum). Total health and environmental damage costs alone, associated with criteria air pollutant emissions from total annual per-capita residential plus commercial plus pumping of electricity related to water use in Maricopa (i.e. water-energy nexus) make up more than 0.23 percent of the entire state's GDP (state GDP data from Hoffman and Rex (2009). For the median and maximum price points of CO_2 eq. emissions, total damage costs as a percentage of Arizona GDP rise to 0.41 and 0.85 percent, respectively.

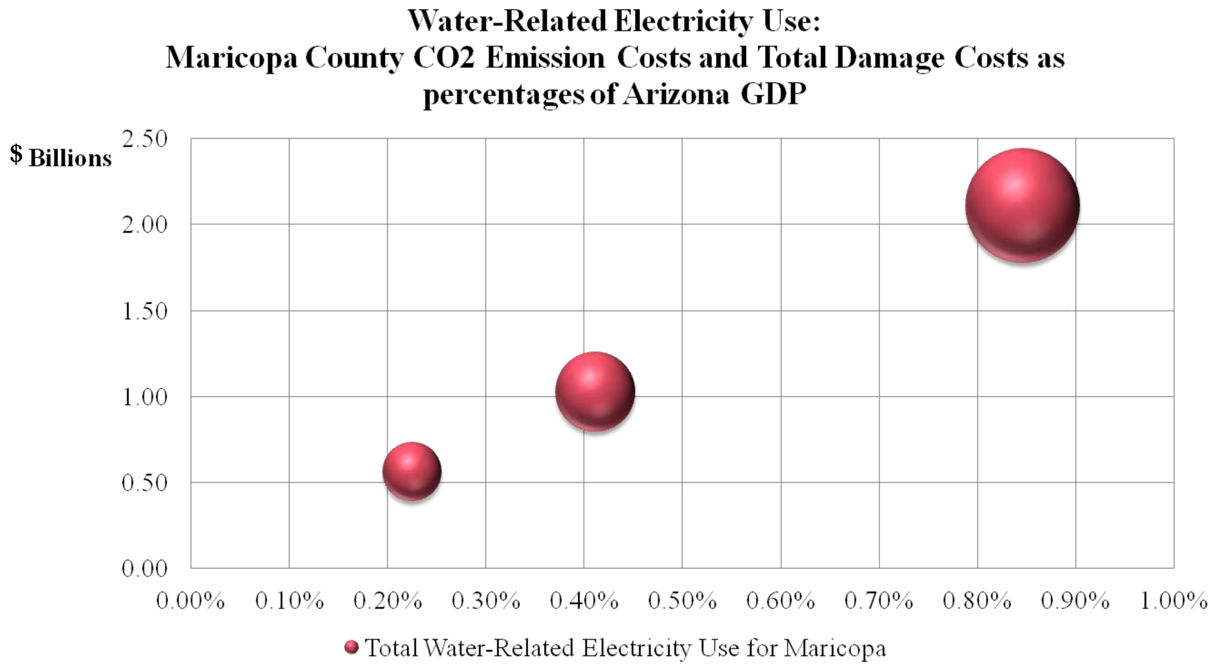


Figure 24: Emissions Damage Costs (No CO2, Median $ CO2, Max $Co2)

To discern the difference in the health, environmental, and CO_2-eq. emissions damage costs associated with the water-energy nexus, we also examined the percentage of Arizona's GDP represented by health, environmental, and CO_2-eq. emissions damage costs associated with total residential and commercial electricity use in Maricopa (Figure 25). Total health and environmental damage costs, associated with criteria air pollutant emissions from total annual per-capita residential plus commercial electricity use in Maricopa make up more than 1.3 percent of the entire state's GDP. For the median and maximum price points of CO_2-eq. emissions, this percentage of Arizona GDP rises to 2.8 and 6.4 percent, respectively. These results indicate that, at a minimum, for any given year, more than 1 percent of the state's GDP is already being paid in health and environmental damage costs from Maricopa County residential and commercial electricity use.

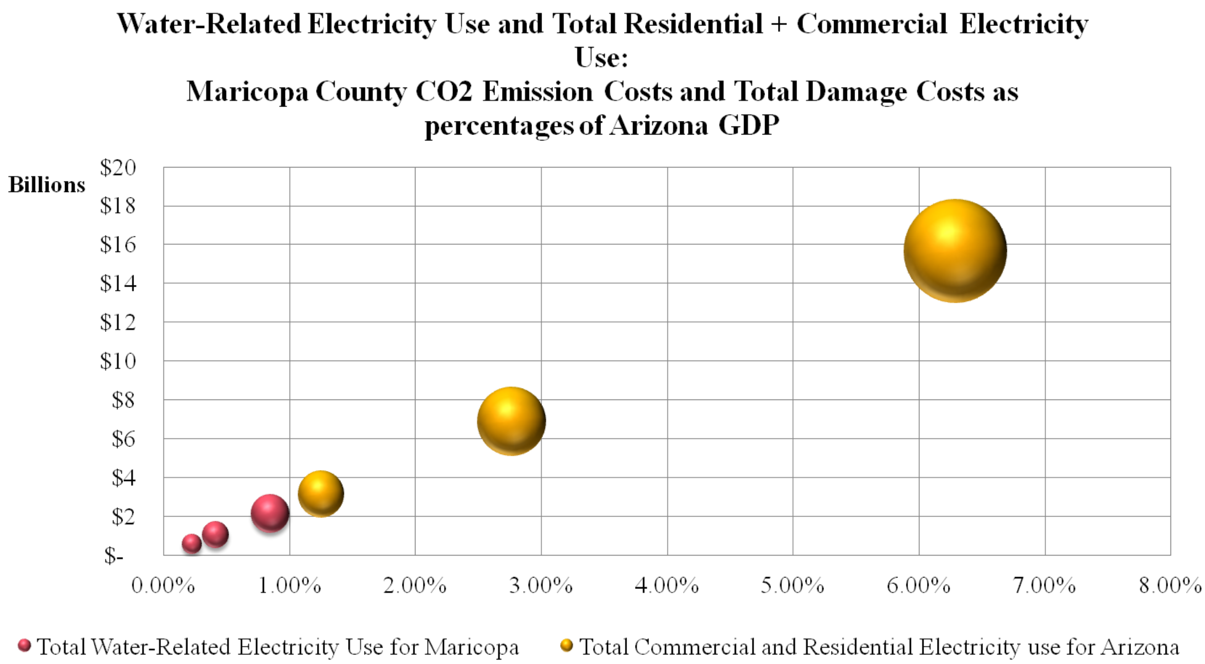


Figure 25: Water Damage Costs versus Total Electricity Damage Costs

Without understanding how individual actions impact the world, humans remain disconnected from the environmental context. Health, environmental, and CO_2 eq. emissions damage costs were calculated in order to assess the social and environmental impact of energy use, generally, and electricity use associated with the water-energy nexus, specifically. After comparing these damage costs to the GDP of the entire state, water-energy health, environmental, and CO_2-eq. emissions damage costs were examined at an individual level and linked these costs to the price of water (Figure 26).

Based on the authors' utility bills, the price of water was calculated to be 0.92 cents/gallon. The emissions damage costs value (from household water-appliance related electricity use) was divided by total (for the 79 percent of Maricopa in the study) residential water use (gallons) to estimate the necessary adjustment to the price of water. To cover health and environmental damage costs, the price of water would need to rise by 0.18 cents/gallon, or 20 percent. To internalize additional CO_2 eq. emissions damages at the median price point, the price of water would need to increase by 0.41 cents/gallon, or 44%; to internalize a maximum price of CO_2 eq. emissions damages, the increase would be 0.92 cents/gallon, a doubling in the price of water. All though this incentive for internalizing health and environmental damage costs may still not be strong enough for a Phoenix urban context, pricing health damage costs into water use in rapidly developing cities like Beijing and Tianjin—cities where households rank air pollution as a top concern (Zhang & Brown, 2005)—may provide a fruitful solution to managing water demand and decreasing air pollution.

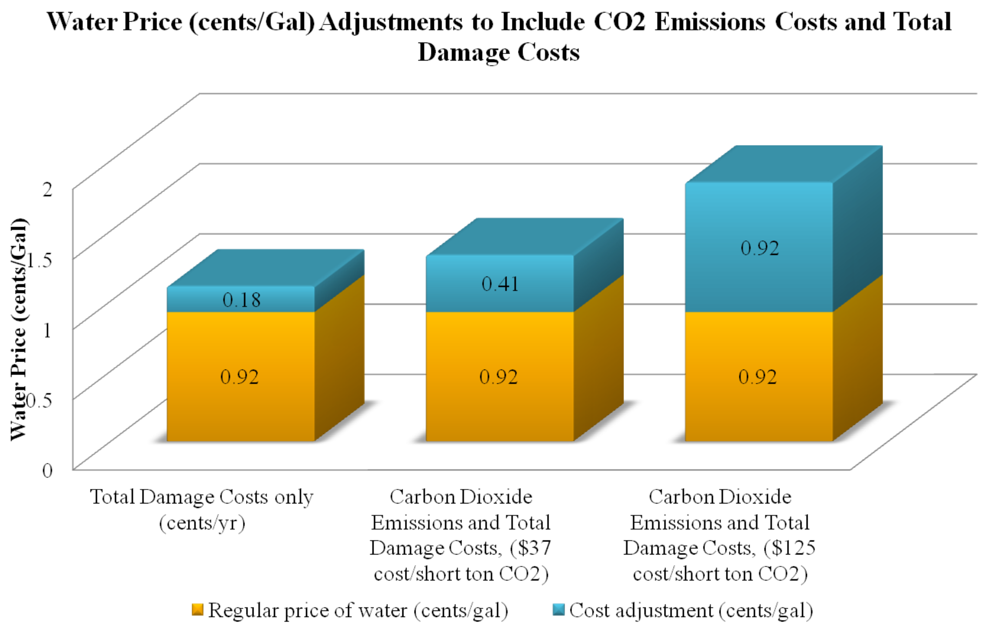


Figure 26: Water Pricing Adjustments

The Impact Assessment team set out to better understand the social impacts of the Phoenix water and energy inventory assessment conducted by our peers. These findings demonstrate that while water-appliances may be increasingly efficient, thus decreasing per capita residential water demand, by and large these efficiencies are insignificant gains compared to per capita total water use in cities within the study area. Further, by quantifying total health, environmental, and CO_2-eq. emissions damage costs associated with electricity and water-energy use in Maricopa County, a first attempt has been made at illustrating the externalities any policy solutions may need to internalize to improve the sustainability of the Phoenix study area. The question remains, for the Sustainable Urban Systems Lab specifically, and Phoenix generally, how do we position our scientific understanding to achieve positive change.

TRANSITIONAL STRATEGIES

Longitudinal metabolism studies, such as this, have the potential to identify and clarify changes in resource flows and stocks over time. Such knowledge may provide critical insight to policy makers, environmental and civil engineers, and resource managers about places to apply sustainability solutions (Meadows, 1999) in urban systems to improve urban sustainability. How do we link such critical knowledge to action (Matson, 2009): what questions do policy makers ask about an Phoenix's metabolism? How do they process information? What are effective urban re-design strategies based on water-energy nexus data? How can we engage businesses, citizens, and nonprofits to coordinate interventions? How do we best convey scientific findings to support decision makers? Investigating the answers to these questions and more will provide a rich ground for future research.

Sustainability science research may provide one such avenue for further research. Wiek, Withycombe, and Redman (2011) proposed an integrated research and problem-solving framework for sustainability. This framework provides a structure for researching and knitting together knowledge from analyses of the current state of a system with structured visions of or scenarios for future states to inform the selection of strategic leverage points (Meadows, 1999) for applying solutions (see Figure 27, below).

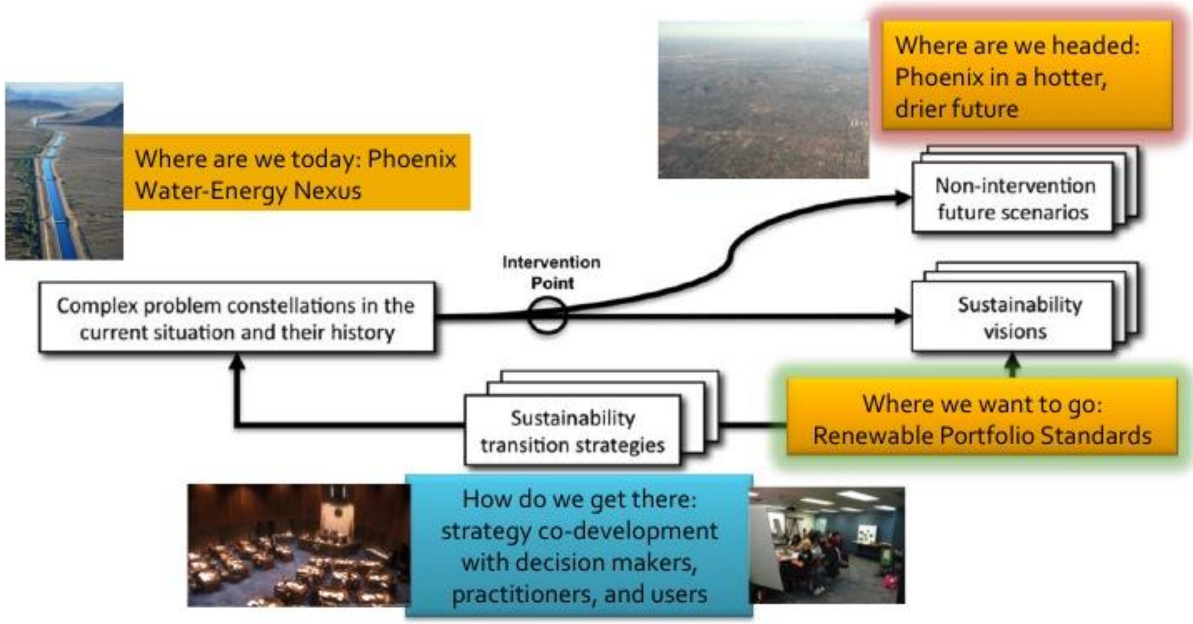


Figure 27: Sustainability Research Framework, adapted from Wiek et al. (2011)

Building on the knowledge and potential action items developed in this study, one can imagine future research undertaking spatial analysis to identify specifically who pays for health and environmental damage costs in Phoenix. Incorporating work by (Grineski et al., 2007) reported on the distribution of criteria air pollution in the Phoenix metropolitan area, could bring such current state knowledge of the water-energy nexus down to specific Phoenix populations. Future research groups picking up on these data could analyze how the hotter, drier future projected for the US Southwest (Karl et al, 2009) will alter the future of health, environmental, and CO_2-eq. emissions damage costs in the area. Students will necessarily have to engage with key community, city, and expert stakeholders to explore solutions; as scientists we can tailor knowledge for action, but are not charged with acting, directly.

Water-energy nexus damage cost issues will grow increasingly pressing as the impacts of climate change continue to accrue. The time is now to design sounds, scientifically evidenced solutions. We hope this study, as one small thread in a larger tapestry of future student work, will have contributed to this vital effort.

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