Quantifying Potential Water Savings from Conservation Practices in Northwest Houston through Local Land Use-Based Water Modeling

Harris-Galveston Subsidence District

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Project Final Report

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Prepared by

Dana N. Reed and Dr. Devin L. Shaffer

Civil and Environmental Engineering Department

University of Houston

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1. Study Objectives and Approach

The objective of this project was to quantify the potential water savings from the implementation of water conservation best management practices in a mixed land use area within the City of Houston's water service area. This land-use based water model was developed in partnership with the City of Houston Public Works Department to serve as a decision-support tool for water conservation planning. By quantifying potential water savings from various conservation efforts, the model can facilitate the prioritization and adoption of targeted water conservation measures in the City of Houston's service area.

The modeling approach was based on the use of land use, building characteristic, and business type information to predict water demand in the study area. These data were integrated into a GIS-based model along with retail water billing data and wastewater flow rates to estimate the water demand associated with various land uses and specific indoor and outdoor end uses. A conceptual framework for the model is shown in Figure 1.

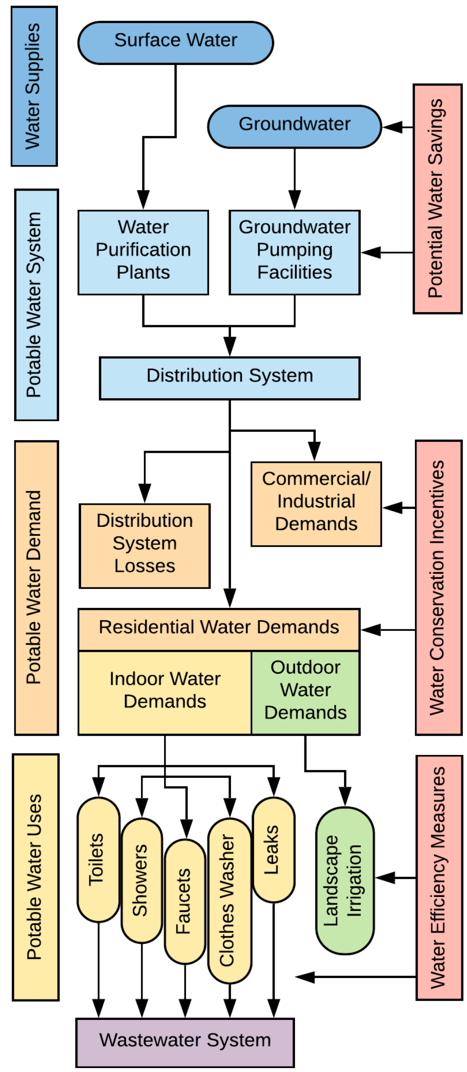

Figure 1. Conceptual Framework for Land Use-Based Water Demand Model

The water demand predictions from the model were calibrated to historic water billing data for the study area and adjusted as appropriate to accurately reflect the overall water usage in the area. The calibrated water model spatially distributes water demand within the study area on the basis of land use, including specific residential indoor and outdoor end uses and non-residential use categories.

Water conservation scenarios developed in partnership with Houston Water were implemented in the calibrated model to identify appropriate conservation measures to achieve water savings goals. These conservation scenarios consisted of water conservation best management practices that were most relevant to the study area based on the determined land use characteristics and end uses of water. The estimated water savings from "bottom-up" land use-based conservation measures were compared to a "top-down" conservation scenario that assumed per capita demand reductions and to a baseline scenario without implementation of the conservation best management practices. This information may be used to support decision making and optimize selection between various water conservation practices.

The three primary tasks for this work included:

1. Data collection and integration

2. Model development and calibration

3. Water conservation scenarios and quantification

Work performed on each task is summarized in the following sections of the report.

2. Task 1 – Data Collection and Integration

2.1 Study area boundary

A study area in Northwest Houston with mixed residential, commercial, institutional, and industrial land uses was defined for the project and is shown in Figure 2 below. The area overlaps U.S. Highway 290 and is west of W. Montgomery Road between Interstate 610 Loop and Sam Houston Parkway. It is also within both the City of Houston's water service area and the Harris-Galveston Subsidence District (HGSD) Regulatory Area 3, which is currently targeted for reduced water use from and reliance on groundwater sources. Additionally, it coincides with the boundaries of the Northwest Wastewater Treatment Plant sewage collection area, or "sewershed," which provides a potential mechanism for modeled indoor water conservation savings to be verified through measured reductions in wastewater flow. Boundary information for the Northwest Wastewater Treatment Plant service area was provided by the City of Houston.

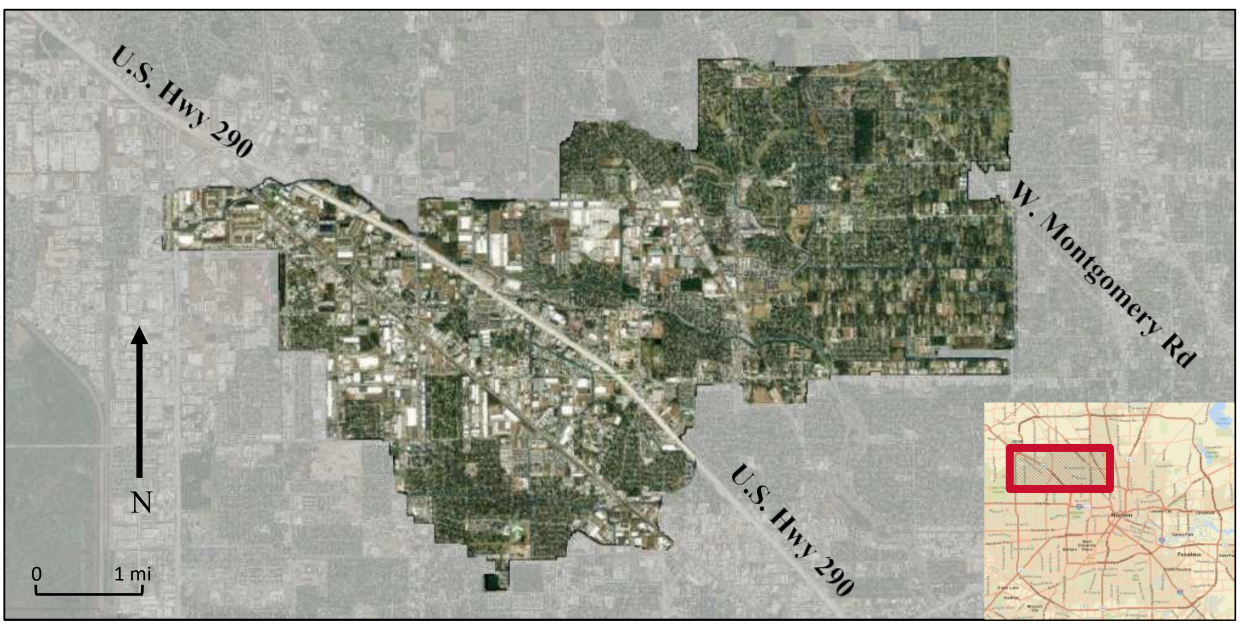

Figure 2. Northwest Houston Study Area

2.2 Data collection

For the selected study area, data sets were collected in five sub-tasks:

2.2.1 Land use and parcel characteristic data

- Source: Harris County Appraisal District (HCAD) public data
- Method: Map and tabular data downloaded from pdata.hcad.org/gis
- Purpose: Construction of geographical water model, identification of parcel properties, and prediction of end use water demand

2.2.2 Water billing data for 2018-2019

- Source: Houston Public Works- Customer Account Services
- Method: Tabular data requested from partners at Houston Public Works and downloaded
- Purpose: Calibration of water demand model

2.2.3 Population and demographic data

- Source: United States Census Bureau, IPUMS National Historical GIS (NHGIS)
- Method: Map and tabular data downloaded from www.nhgis.org
- Purpose: Comparison of bottom-up land use based water demand prediction approaches with top-down per capita approaches

2.2.4 Wastewater flow data for August 2018-February 2019

- Source: Houston Public Works- Water Planning and Geographic Information Systems
- Method: Map and tabular data for sewage lines, manholes, and flow monitoring reports requested from partners at Houston Public Works and downloaded
- Purpose: Identification of wastewater line flow directions, confirmation of variations between wet and dry weather water use, and verification of water demand model predictions for indoor and outdoor use

2.2.5 Precipitation data

- Source: Harris County Flood Warning System, Harris County Flood Control District
- Method: Sites selected within study area, tabular historical data downloaded from harriscountyfws.org
- Purpose: Identification of water demand patterns under wet and dry conditions

2.3 Determining land use categories

Using ArcGIS 10.7, a map of the study area was developed, and individual parcel boundaries were identified using GIS data from HCAD. With the Join tool in ArcGIS, parcel characteristic and land use data tables from HCAD and water billing data records from Houston Public Works were associated with the individual parcels within the study area. Once these data were spatially distributed to individual parcels, characteristics like land use and building age were identified visually on the map and compared with water demand from billing information. Figure 3 below shows a map of the aggregated land use categories for the study area. These land use categories reflect Houston Public Works practices and facilitated selection and evaluation of appropriate conservation strategies. Additionally, the inset pie graph shows the percentage of land area attributed to each land use within the study area. The aggregated land use categories are:

- Single-Family Residential
- Multi-Family Residential
- Commercial and Institutional
- Industrial
- Parks and Open Spaces
- Vacant/Undeveloped
- Other

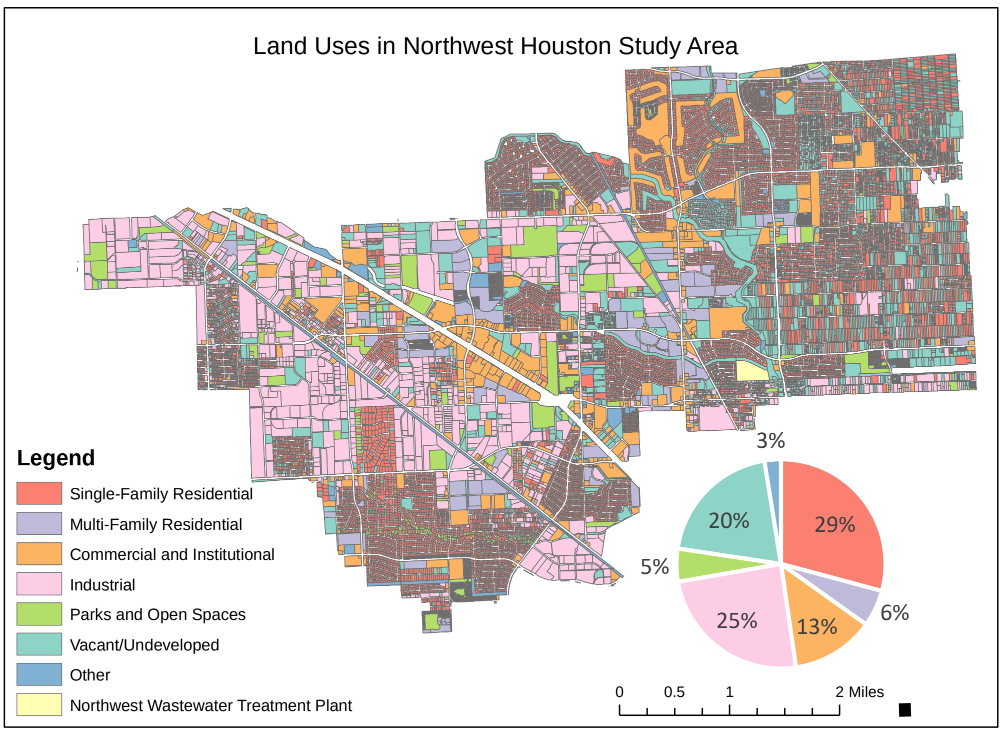

Figure 3. Land Uses in Northwest Houston Study Area

2.4 Identifying land use-dominated sub-areas

Wastewater flow monitoring data for the Northwest Wastewater Treatment Plant service area were obtained from the City of Houston for a limited time period in late 2018 through early

2019. This information was available in the format of regular flow rate measurements at selected manholes in the study area. These manhole locations are displayed in the ArcGIS map in Figure 4 below, which also contains parcel boundaries and land use characteristics.

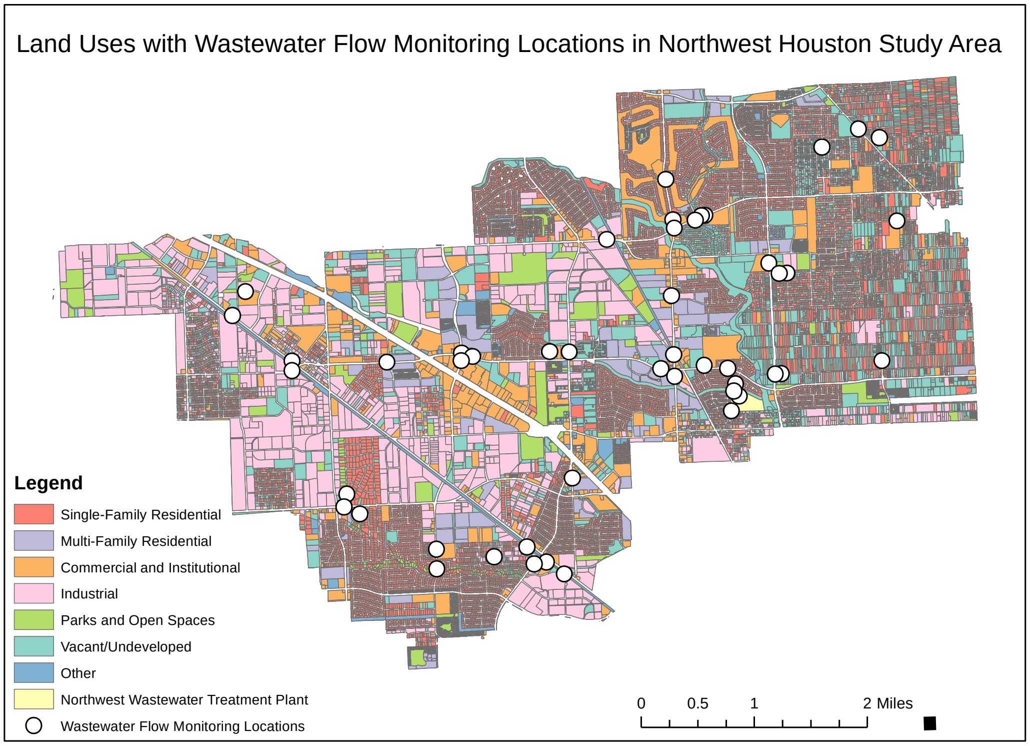

Figure 4. Land Uses with Wastewater Flow Monitoring Locations in Northwest Houston Study Area

Using this visual information, the parcels upstream of and contributing wastewater to each flow-monitoring manhole were identified based on land use. Figures 5, 6, and 7 below illustrate the selection of wastewater flow sub-basins corresponding to dominant land uses in various parts of the study area. In these figures, sub-basins within the sewershed were selected based on the primary land use contributing to wastewater flow. These sub-basins were used in Task 2 to calibrate the water demand model for water demand factors for the various land uses, isolating areas where water demand may be expected to be typical for a given land use. Further, appropriate monitoring locations were selected based on these sub-basins and identified for future monitoring of the effects of targeted water conservation approaches on wastewater flows resulting from indoor water uses.

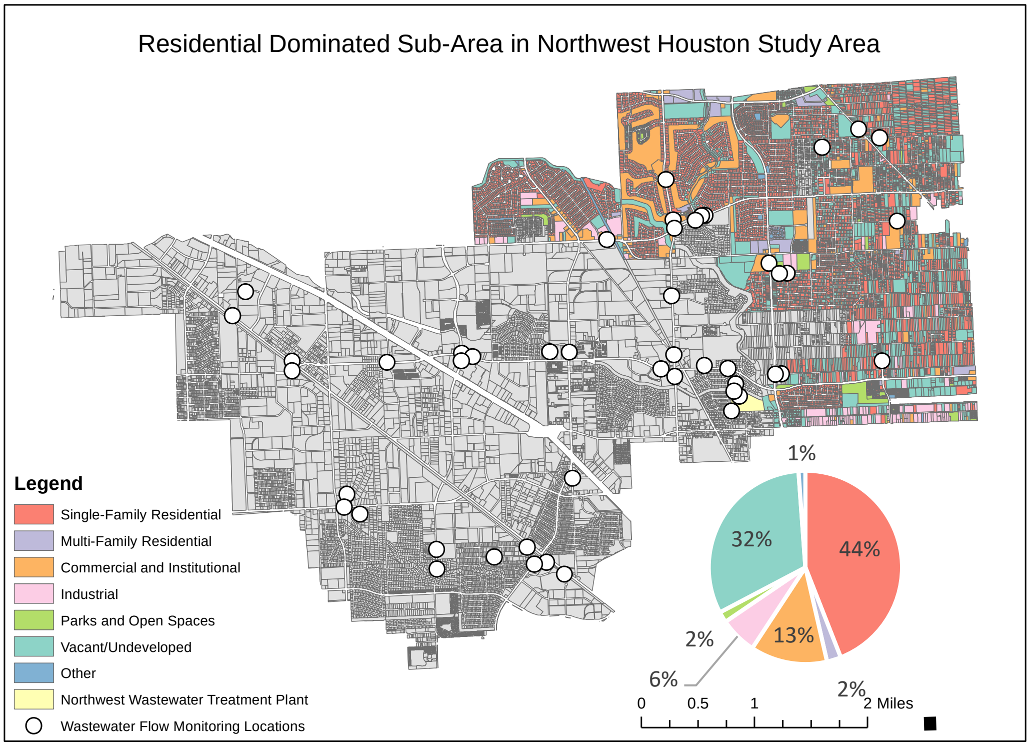

Figure 5. Residential Wastewater Flow Basin in Northwest Houston Study Area

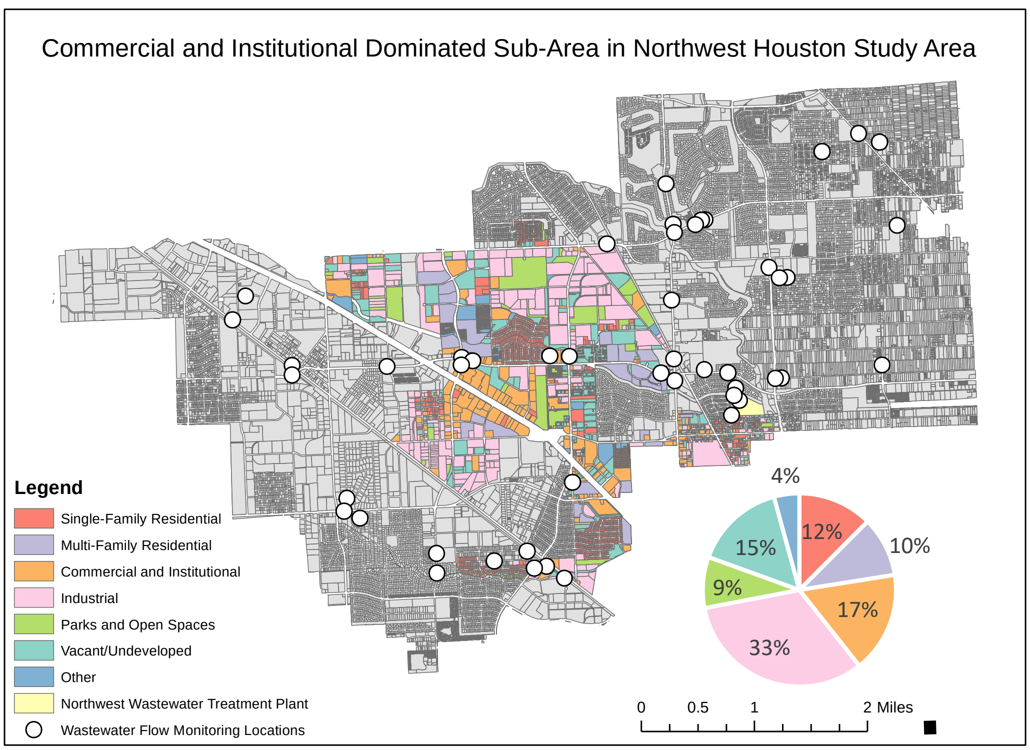

Figure 6. Commercial Wastewater Flow Basin in Northwest Houston Study Area

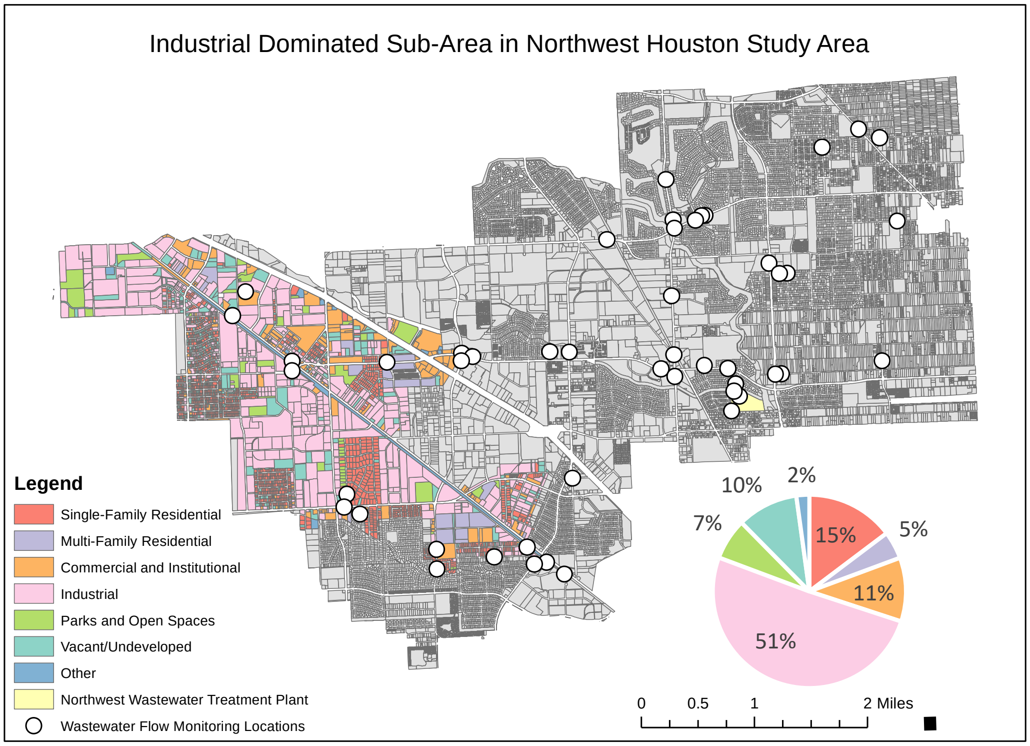

Figure 7. Industrial Wastewater Flow Basin in Northwest Houston Study Area

2.5 Spatial distribution of water demand

Monthly water billing data from the Houston Public Works for January 2018 to December 2019 were assigned to the corresponding parcels in the GIS model. The average annual use for each parcel is shown in Figure 8 below. As Figure 8 illustrates, there were many parcels in the study area for which water billing data were not available (shown in light blue). For parcels that lacked any water billing data, water demand in the model was estimated from available water billing data for similar parcels, using common land use and building characteristics to identify parcels that had similar water demand characteristics.

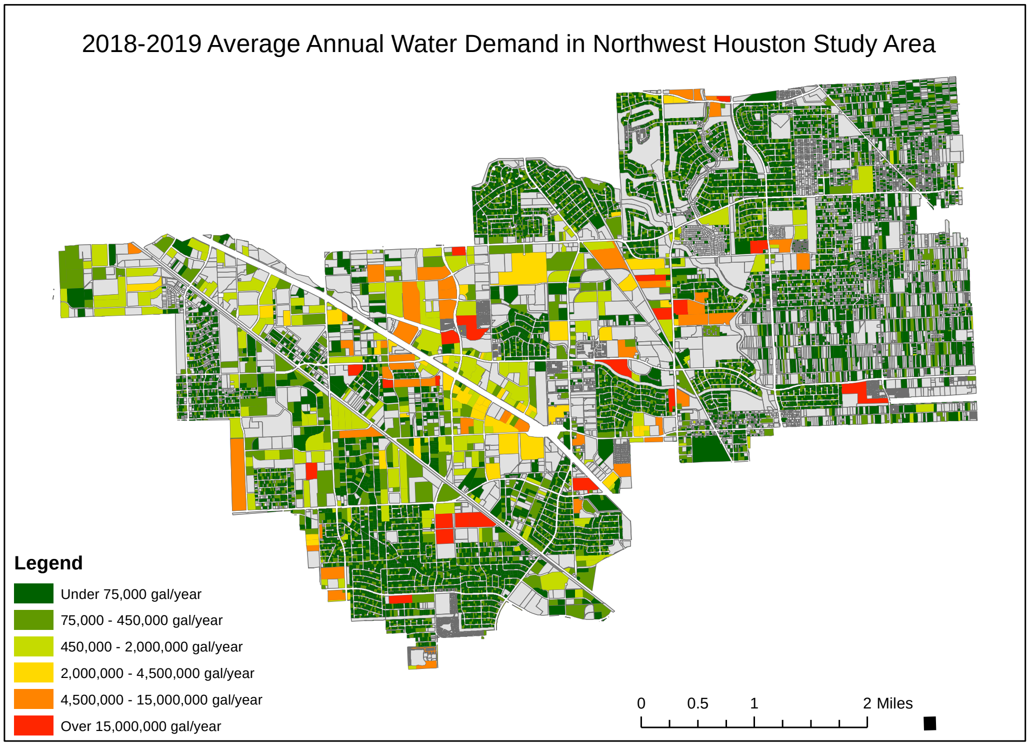

Figure 8. 2018-2019 Average Annual Water Demand in Northwest Houston Study Area

3. Task 2 – Model Development and Calibration

3.1 Calibrate land use-based water demand factors

Land use-based water demand factors were estimated from the spatially distributed water demand data and the assigned land use categories. Three distinct sub-areas within the overall study area were defined for the purpose of calibrating water demand factors. The areas are dominated by either residential, industrial, or commercial and institutional land uses and are shown in previous Figures 5-7. The total acreage and water demand data for 2018-2019 associated with each land use category in each of the sub-areas were exported from the GIS model to an Excel spreadsheet for calibrating the land use-based demand factors. Parcels without water demand data were excluded from the analysis. Residential, industrial, and commercial and institutional water demand factors were first calculated from the sub-areas dominated by these land uses by dividing the total water demand for the sub-area by the acreage for the particular land use within the sub-area. These residential, industrial, and commercial and institutional water demand factors were then applied across all three sub-areas, and a total water demand was calculated for each sub-area. Land-use based demand factors were adjusted for each land use across all three sub-areas to minimize the difference between calculated water demand based upon land use and observed water demand from monthly water billing data.

The resulting land use-based demand factors were then applied to land use categories for all parcels in the study area for which water demand data were available, including parcels in the three sub-basins dominated by particular land uses. The estimated total water demand for the study area during 2019 is 806,841,000 gallons compared to an observed demand of 891,250,000 from water billing data.

The calibrated land-use based water demand factors are summarized in Table 1 and compared to land-use based demand factors for municipalities in Texas and other large cities across the United States. Actual land use water demand factors for the three land use sub-areas are compared to calibrated demand factors for the entire study area in Appendix A.

Table 1. Land Use-Based Water Demand Factors

Community	**Units**	**Land Use Water Demand Factors**						**Reference**
		Single-Family Residential	**Multi-Family Residential**	**Industrial**	**Commercial and Institutional**	**Parks and Open Space**	**Vacant and Other**	
Los Angeles, CA	% of total water use	37.0 %	29.0 %	3.0 %	25.0 %			1
Salt Lake City, UT	% of total water use	2.4 %	60.6 %	7.9 %	23.6 %			2
San Diego, CA	% of total water use	36 %	23 %	28 %		13 %		3
Texas Municipal Water Utilities								4
- all utilities	% of metered water use	48 %	10 %	15 %	25 %			
- significant ICI utilities	% of metered water use	25 %	10 %	31 %	34 %			
Austin, TX	% of total water use	38.5 %	26.9 %		34.6 %			5
College Station, TX	% of total water use	61.0 %	26.6 %	0.0 %	5.6 %			6
Dallas, TX	% of retail water sold	38.4 %	25.4 %	7.5 %	28.8 %			7
San Antonio, TX	% of retail water sold	57.0 %	14.0 %	0.0 %	22.8 %	6.0 %		8
Houston, TX (this project)	million gallons per acre per year	.235	1.484	.138	.364	.213	.367	
	% of total water use	26.1%	32.1%	12.9 %	17.8%	4.2%	6.9%	

[1] Los Angeles Department of Water and Power, Water Conservation Potential Study (2017)
[2] P. Stoker, R. Rothfeder, Sustainable Cities and Society, 12 (2014) 1–8
[3] City of San Diego, California, Urban Water Management Plan (2016)
[4] H.W. Hoffman, Analysis of Five Years of Municipal Water Use Data to Estimate Commercial and Institutional Per Capita Use (2016)
[5] Austin Water, Austin Texas, Water Forward Integrated Water Resource Plan (2018)
[6] City of College Station, Texas, Water Demand Forecasting (2016)
[7] City of Dallas, Texas, Water Conservation Plan (2019)
[8] San Antonio Water System, San Antonio Texas, 5-Year Water Conservation Plan (2019)

3.2 Calibrate indoor versus outdoor water use

Indoor and outdoor water use were estimated based on seasonal peaks in total water use. Summertime peaks in water use were attributed to outdoor water use for landscape irrigation. Understanding the fractions of indoor versus outdoor water use informed the selection of conservation measures for the water conservation scenarios evaluated in Task 3. Figure 9 shows the billed water demand for single family residential, multi-family residential, commercial/institutional, and industrial land uses within the study area, normalized to the average demand during the billing data period. Non-normalized monthly demand data are included in Appendix B. Summer seasonal peaks in water demand (May to September) were apparent for all land uses with the exception of multi-family residential. This summer peak in water demand was attributed to seasonal outdoor use for landscape irrigation. Figure 9 demonstrates no correlation between rainfall patterns (normalized for the time period from January 2018 to December 2019) and water demand, indicating that seasonal outdoor water use in the study area was not affected by precipitation. Further wet/dry weather analysis of water demand based on wastewater flows is available in Appendix C.

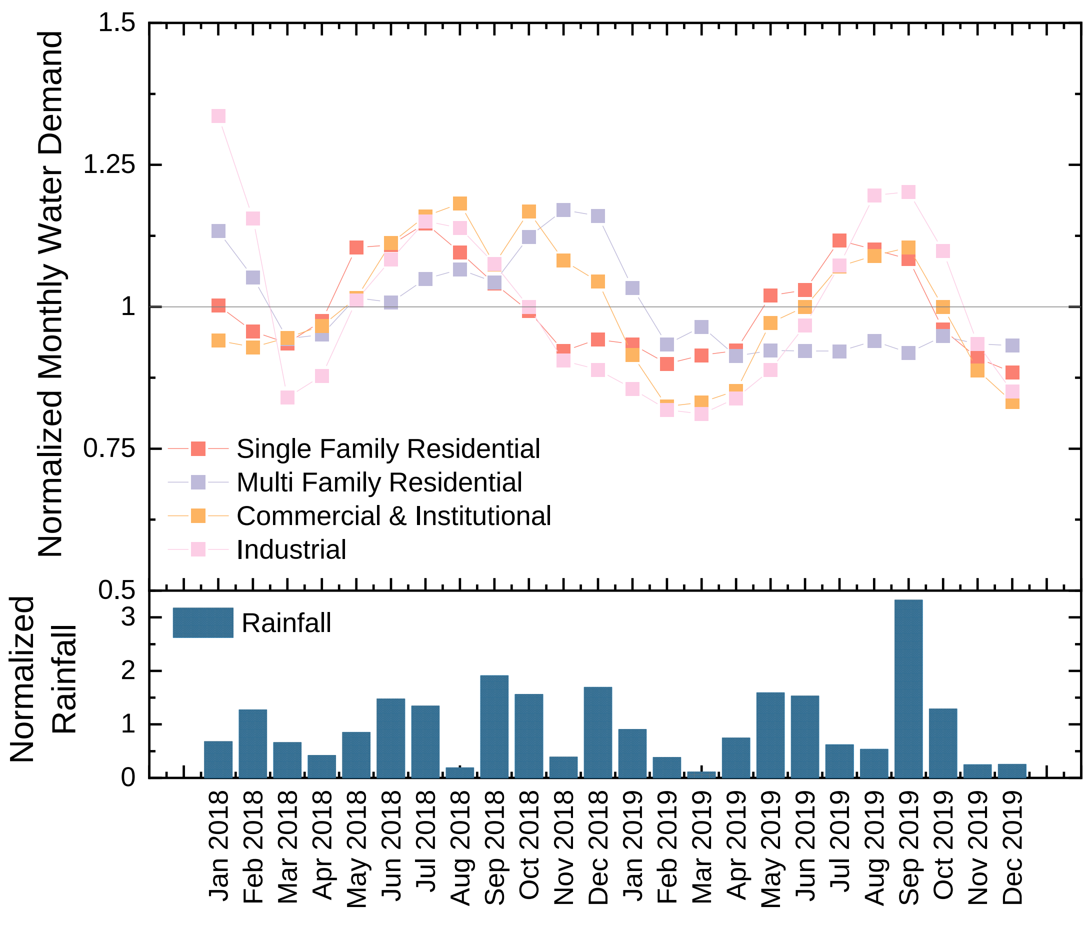

Figure 9. Normalized Monthly Billed Water Demand and Rainfall over Time for the Defined Major Land Uses within the Northwest Houston Study Area

To attribute outdoor water use for land uses within the study area, monthly billed water demand data for each land use were smoothed using an adjacent averaging approach to identify a minimum and maximum monthly demand. This approach attempted to account for the coarse billing increments (in 1000 gal/month) and rounding effects in the 2018-2019 monthly billing data from the Houston Public Works. These maximum and minimum values were divided by the average monthly demand for each year to calculate peaking factors. For single family residential parcels, the average minimum and maximum monthly demand peaking factors were 90.2% and 113.1%, respectively, for the observed time period. For multifamily residential parcels, the average minimum and monthly demand peaking factors were 92.8% and 109.8%, respectively. The minimum monthly demand peaking factor represented the ratio of the lowest monthly demand to the average monthly demand for a given land use. The percentage difference between average monthly demand and minimum monthly demand was taken to represent average outdoor use. The outdoor water use percentages of 9.8% for single family residential and 7.2% for multifamily residential land uses are consistent with analysis by Texas Living Waters, which identified outdoor water use in Region H (which contains the City of Houston) as lower than overall state averages.[9] Additionally, the older housing stock found in this study area is less likely to feature in-ground irrigation systems, which are often associated with higher outdoor water use.

3.3 Delineate end uses of water

End uses of water for residential, commercial and institutional, and industrial land uses were further delineated in the water demand model. Identifying the end uses of water for these land uses facilitated the identification of the largest water uses in the study area and the selection of appropriate water conservation measures for the water conservation scenarios in Task 3. After removing estimated outdoor use for the residential parcels using the method detailed in Section 2.3 above, the remaining indoor water use was divided among the different plumbing fixtures inside the dwelling, such as toilets, faucets, clothes washers, and dishwashers. The water demands associated with each of these indoor end uses of water were assigned using percentages identified from the Residential End Uses of Water Version 2 report[10]. The estimated end uses as a percentage of total water demand and in terms of annual demand factor (gal/acre-yr) are listed in Table 2 for each land use.

[9] Gordon, Wendy, Texas Living Waters Project, Water Conservation by the Yard: Estimating Savings from Outdoor Watering Restrictions (2016)
[10] DeOreo et al., Water Research Foundation, Residential End Uses of Water, Version 2 (2016)

Table 2. Estimated Residential End Uses of Water

	Water End Uses			
	Single Family Residential		Multifamily Residential	
	Percent	**Demand Factor (gal/acre-yr)**	**Percent**	**Demand Factor (gal/acre-yr)**
Toilet	21.7%	50,825	22.3%	330,442
Shower	18.0%	42,354	18.6%	275,369
Faucet	17.1%	40,237	17.6%	261,600
Clothes Washer	15.3%	36,001	15.8%	234,063
Leaks	10.8%	25,413	11.1%	165,221
Outdoor Irrigation	9.8%	22,965	7.2%	106,710
Other	3.6%	8,471	3.7%	55,074
Bath	2.7%	6,353	2.8%	41,305
Dish Washer	0.9%	2,118	0.9%	13,768

For commercial, institutional, and industrial land uses, principal use categories for the study area were identified in a manner similar to the initial approach used in the Commercial and Institutional End Uses of Water report.[11] Principal use categories within these land uses were selected on the basis of water use rates and expected similarity in terms of end uses. With these principal use categories identified and their relative water use reported, a water conservation manager may more easily prioritize certain business types for targeted water use surveys and further water conservation efforts. The principal use categories for the commercial, institutional, and industrial land uses and their corresponding percentages of total water demand and annual demand factors (gal/acre-yr) are listed in Table 3 below.

Table 3. Water Demand by Principal Use Category for Non-Residential Land Uses

		Category Water Use	
		Percent	**Demand Factor (gal/acre-yr)**
Commercial and Institutional	**Retail and Shopping**	25.1%	91,275
	Office Building	22.2%	80,863
	Restaurant/Food Service	18.2%	66,131
	School and Day Care	8.9%	32,533
	Hotel and Lodging	7.8%	28,378
	Gas and Auto Service	4.5%	16,393
	Car Wash	3.4%	12,402
	Religious	3.0%	10,819
	Other	6.8%	24,877

[11] Dziegielewski et al., AWWA Research Foundation, Commercial and Institutional End Uses of Water (2000)

		Category Water Use	
		Percent	**Demand Factor (gal/acre-yr)**
Industrial	**Warehouse**	63.2%	87,056
	Food Products	12.3%	16,873
	Light Industrial	11.3%	15,576
	Cold Storage	8.3%	11,468
	Manufacturing	3.8%	5,197
	Other	1.1%	1,547

3.4 Water demand distribution for study area

Identifying the demand factors for various residential end uses and commercial, institutional, and industrial principal use categories allowed water demand to be predicted by end use for the entire study area. This water demand prediction included parcels for which billing data were not available from the Houston Public Works. Figure 10 below graphically displays the predicted relative water demands for end uses within each land use for the study area.

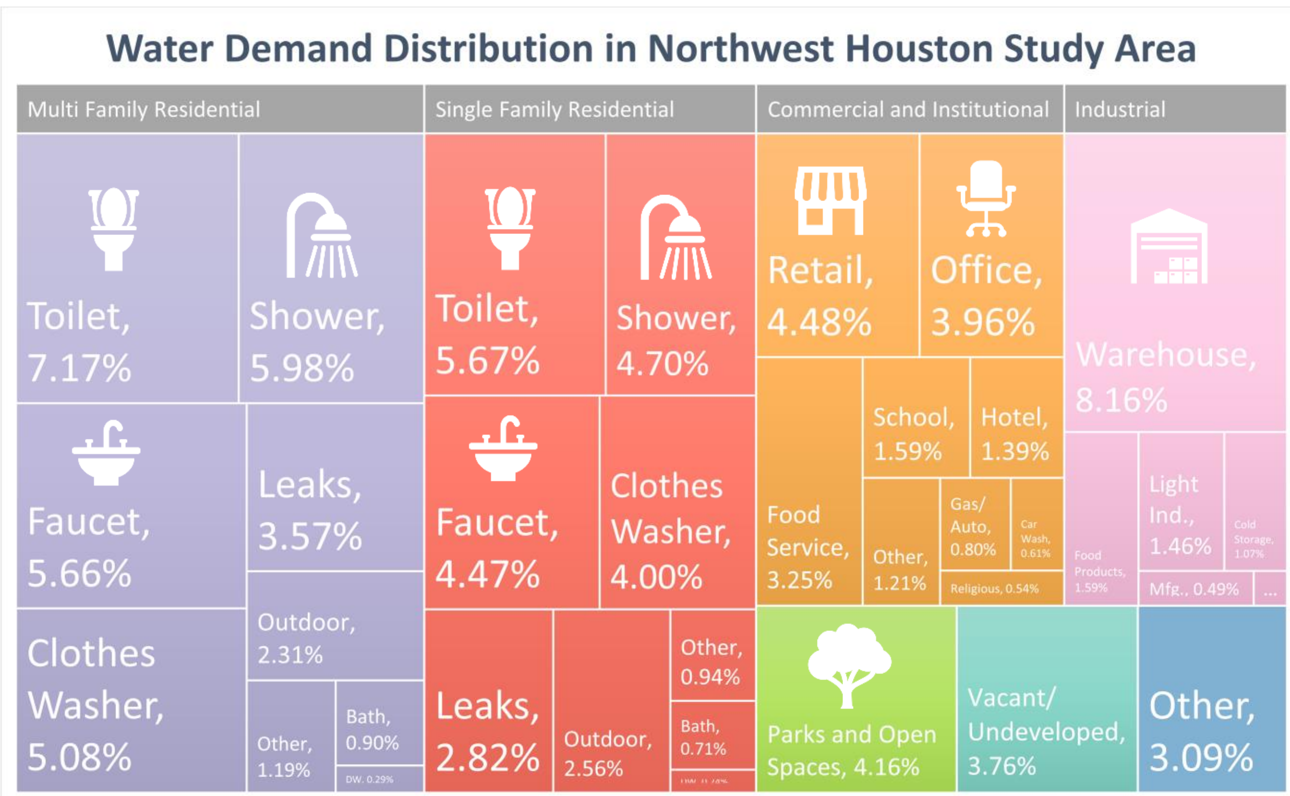

Figure 10. Water Demand Distribution in Northwest Houston Study Area

Figure 10 illustrates the significant water demand within the study area that is attributed to residential end uses, like toilet, shower, and faucet use, which are easy-to-target with water conservation measures.. Figure 10 also provides valuable information about how water demand is distributed within the commercial, institutional, and industrial sectors. This information can help water managers target certain high water demand entities in the study area, like industrial warehouses, retail stores, and offices, for further water use surveys, audits, and other water conservation measures.

3.5 Comparison between modeled indoor water demand and wastewater flow data

In order to verify the water demand modeling and end use delineation, the modeled indoor water use for the entire study area was compared to the monitored wastewater flow at the Northwest Wastewater Treatment Plant, which was assumed to be generated by indoor water uses within the study area. Based on the average wastewater flowrate of 4.04 million gallons per day (MGD) measured during the time period from September 25, 2018 to February 19, 2019, the predicted annual indoor water use for the study area was estimated to be 1,475 million gallons per year. In comparison, the water demand model predicted 2,782 million gallons per year of indoor water use when all parcels (including those with no billing data or water customer account information) were included in the estimate. This estimate excluded outdoor residential use and irrigation use for parks and open spaces, but did not eliminate any portion of commercial and institutional use that may be dedicated to outdoor irrigation. When only those parcels for which billing data were available were included, the modeled indoor use was 1,905 million gallons per year, which exceeds the estimated indoor water use from wastewater flows. This discrepancy may result from inaccurate attribution of indoor versus outdoor water use in the water demand model. The modeled indoor use may be improved in the future by auditing outdoor water use for non-residential parcels.

4. Task 3 – Water Conservation Scenarios and Quantification

Water conservation scenarios were developed through (1) discussions with Paula Paciorek, the Water Programs and Education Manager at Houston Public Works and (2) the identification of residential end uses of water and principal use categories in Task 2.4. As the manager responsible for water conservation programming, Ms. Paciorek’s current goal is to attain a water demand reduction of 0.32% per year (or 1.6% every 5 years) in accordance with Houston’s most recent Water Conservation Plan. She expressed that this goal is largely met by natural replacement of plumbing fixtures with newer more efficient fixtures and by system water loss reduction through Houston Public Works’ water main replacement program. In the future, Houston Public Works may consider more aggressive water demand reduction goals of 1% per year or 1.5% per year, corresponding to 5-year reduction goals of 5% and 7.5%, respectively. The 1% per year demand reduction goal was the basis of the “moderate” conservation scenario, and the 1.5% per year demand reduction goal was the basis of the “intermediate” conservation scenario. An “aggressive” water conservation scenario was also defined with a water demand reduction goal of 5% per year.

These goals and the selection of conservation measures in each conservation scenario were constrained on the aggressive end by the City of Houston Drought Contingency Plan. In order to avoid “double-dipping” of conservation and drought management efforts, the most aggressive conservation strategies were not more stringent than the first level of enforced drought management strategies. At present, the first enforced level of drought management for Houston is at Stage II and requires mandatory restriction of outdoor watering to no more than twice per week between the hours of 7pm and 5am.[12] Though outdoor watering restrictions are an oft-cited strategy for reducing water demand, the efforts in this work consider those to be a last resort in order to prevent overlap with mandated drought management planning.

The spatial distribution of water demand identified single family and multi-family residential toilets (12.8%), showers (10.7%), and faucets (10.1%) as the dominant end uses of water within the entire study area. Additionally, analysis of the parcel characteristics revealed that 85.6% of the residential acreage in the study area has been designated by Harris County Appraisal District as having an “improvement year” older than 1995. The Energy Policy Act of 1992 required the installation of water-conserving 1.6 gallon per flush (gpf) toilets, 2.2 gallon per minute (gpm) faucets, and 2.5 gpm showerheads on all new construction and renovation improvements nationwide beginning in 1994. Homes built prior to 1995 are more likely than those built after 1995 to have older fixtures, such as 3.5 gpf toilets and 3 gpm showerheads and faucets. These parcels could be targeted for a fixture retrofit or replacement program as part of Houston Public Works’ conservation measures. Fixture retrofit and replacement programs may include offering rebates for purchase of updated fixtures, purchasing and distributing fixtures to interested customers, purchasing and installing updated fixtures, or some combination of these measures.

Water demand modeling determined that the water conservation goals of 1% (moderate scenario) and 1.5% (intermediate scenario) annual water savings may be achieved by retrofitting or replacing faucet, shower, and toilet fixtures for residential parcels containing structures that were built or renovated before 1995. To achieve the 5% annual water savings goal (aggressive scenario) a voluntary year-round outdoor watering reduction program was determined to be necessary. Figure 11 below shows the distribution of water savings from individual conservation measures for the moderate, intermediate, and aggressive water conservation scenarios.

[12] Houston Public Works, Water Conservation Plan (2019)

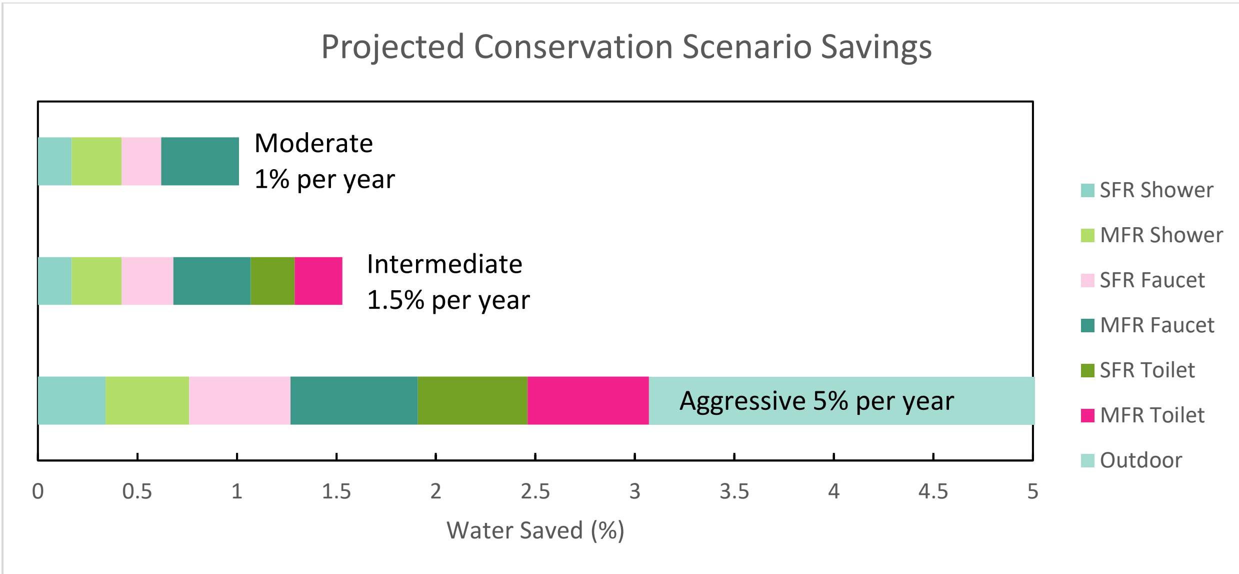

Figure 11. Projected Water Conservation Scenario Savings and Individual Conservation Measures

The suggested conservation measures for the water conservation scenarios are listed in Table 4 below. Using the water demand factors for each end use of water and the percentage of residential land area older than 1995, projected water conservation savings were estimated based on the identified adoption levels for fixture replacement programs targeting residential parcels with older, pre-1995 structures.

Table 4. Water Conservation Scenarios and Predicted Demand Reduction

Water Conservation Scenario		Moderate	Intermediate	Aggressive
Annual Percent Demand Reduction Goal		**1%**	**1.5%**	**5%**
Single Family Residential showerhead/ faucet replacement	Adoption Rate	25% adoption	25% adoption	50% adoption
	Demand Reduction	**0.42% reduction**	**0.42% reduction**	**0.85% reduction**
Multifamily Residential showerhead/ faucet replacement	Adoption Rate	30% adoption	30% adoption	50% adoption
	Demand Reduction	**0.64% reduction**	**0.64% reduction**	**1.06% reduction**
Single Family Residential toilet replacement	Adoption Rate	No adoption	5% adoption	25% adoption
	Demand Reduction	No reduction	**0.13% reduction**	**0.53% reduction**
Multifamily Residential toilet replacement	Adoption Rate	No adoption	10% adoption	25% adoption
	Demand Reduction	No reduction	**0.33% reduction**	**0.66% reduction**
Voluntary Outdoor Watering Reduction	Adoption Rate	No adoption	No adoption	Full adoption
	Demand Reduction	No reduction	No reduction	**2% reduction**

Predicted water demand reductions may be estimated by using the water demand model to evaluate different water conservation measures and their expected adoption rates within the study area. A user guide for the development of the land use-based water demand model and its application as a decision support tool for water conservation is included in Appendix D.

5. Discussion

Three key findings were identified from the local land use-based water modeling. (1) In this study area, residential indoor uses dominated water demand. Residential parcels demonstrated the highest water use, and the minimal variation in their seasonal water demand indicated that outdoor irrigation was less than 10% of overall residential water demand. (2) For this study area, identified conservation measures targeted indoor water use by replacing older plumbing fixtures. This approach was driven by the actual water demand distribution in the study area, which was largely for indoor use, and by the presence of older homes built before the Energy Policy Act of 1992 introduced a federal requirement for efficient fixtures. Further, these conservation measures applied an infrastructure change in study area homes to achieve water conservation savings, rather than relying on behavioral changes from water consumers. Finally, (3) this study demonstrated the benefits of using a land use-based approach rather than a per capita approach to quantify water demand and potential savings from water conservation measures.

When modeled water demand in the entire study area was normalized by the study area population from census data, the estimated water demand of 93.6 gallons per capita per day (GPCD) was significantly less than the 129 GPCD demand used by Houston Public Works based on system-wide data. This discrepancy arises from two main factors. First, actual water demand in a given area varies based on the land use characteristics, including dwelling age, residence type, parcel size, and the types of businesses and other facilities present. A top-down per capita approach was unable to account for these differences. Additionally, the 129 GPCD figure used by Houston Public Works includes 24 GPCD attributed to system water losses. While reducing these system water losses is critical for water conservation, system losses cannot be attributed to individual customer demand or addressed through consumer-focused conservation measures. In contrast, a land use-based approach allowed for identification of actual end uses of water and facilitated goal setting for water conservation scenarios and the selection of appropriate conservation measures.

Figure 12 below compares top-down per capita and bottom-up land use-based approaches for estimating water demand and potential water savings from conservation. In Figure 12, solid columns indicate water demand (orange color, left axis) and water conservation savings (green color, right axis) from land use-based water demand modeling. Patterned columns indicate water demand calculated on a system-wide per capita basis (orange color, left axis), including system water losses, and the estimated water conservation savings that would be required to achieve conservation savings goals (green color, right axis) if water demand reduction were calculated based on the system-wide water demand metric of 129 GPCD.

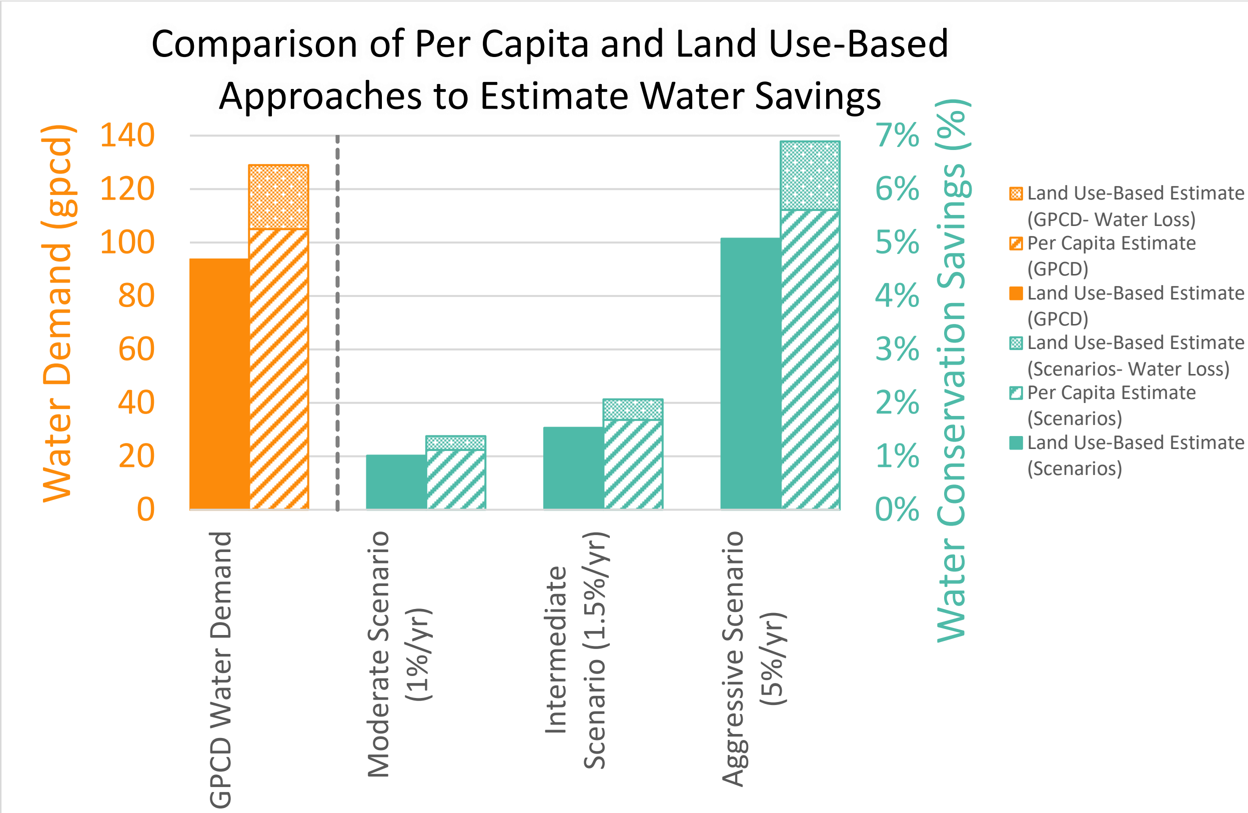

Figure 12. Estimated Per Capita Water Demand and Projected Water Conservation Scenario Savings

As discussed previously, use of the system-wide water demand estimate of 129 GPCD overestimated demand in this study area when compared to a model based on actual billing data, land use, and population data. It also includes 24 GPCD of system water loss that is not attributed to individual customers and is difficult to address through consumer-focused conservation measures. Furthermore, conservation scenario goals to reduce demand by a percentage of this 129 GPCD water demand figure will require actual water use reduction by consumers that exceeds the stated goal in order to account for reduction in the system water loss. As an example, the water demand for this study area is approximately 3.2 billion gallons per year. In order to reduce the total water demand in this study area by 1.5% (intermediate water conservation scenario), a savings of 48.2 million gallons per year would be required. If the water demand estimate and conservation scenario goal were instead calculated based on the study area population of 94,000 people and the system-wide water demand metric of 129 GPCD, a 1.5% reduction would require a savings of 66.4 million gallons per year, which corresponds to an actual water demand reduction of more than 2% per year in the study area. This example illustrates how overestimating of water demand from top-down per capita approaches can challenge water service providers to achieve conservation goals in an area with different population, land use, and water use characteristics than the system-wide average.

6. Future Directions

The results of this study for the Northwest Houston study area may serve as the basis for expanding the scope and applications of the land use-based water demand model. The following areas of potential future work were identified in this study:

- Expansion of the water demand model study area to encompass more of the City of Houston Public Works water service area.
- Further study of multi-family residential end uses to better understand the impacts of dwelling density (in terms of number of units per acre) on water demand. In this study, significant variability was observed in water demand for the multi-family residential land use.
- Implementing suggested water conservation measures (indoor residential plumbing fixture replacement) and tracking reductions in water demand via changes in water billing data and via wastewater flow monitoring as an indicator of indoor water use.
- Recalibrating the water demand model based on observed changes in water use after water conservation campaigns.
- Continued focus on minimizing system water loss.

Appendix A: Land Use-Based Water Demand Factors from Water Billing Data

Table A1. Land Use-Based Water Demand Factors for Identified Land Use-Dominated Sub-Areas

2018 - 2019	Residential-Dominated Sub-Area				Commercial- and Institutional-Dominated Sub-Area				Industrial-Dominated Sub-Area			
	Area	**Acreage**	**Water Demand**	**Demand Factor**	**Area**	**Acreage**	**Water Demand**	**Demand Factor**	**Area**	**Acreage**	**Water Demand**	**Demand Factor**
	(sq. ft)	**(acres)**	**(gal/year)**	**(gal/acre·year)**	**(sq. ft)**	**(acres)**	**(gal/year)**	**(gal/acre·year)**	**(sq. ft)**	**(acres)**	**(gal/year)**	**(gal/acre·year)**
Single Family Residential	68,581,029.0	1574.4	357,890,500	227,318	11,342,218.5	260.4	85,552,000	328,564	16,719,940.6	383.8	89570,500	233,356
Multi-Family Residential	2,953,578.3	67.8	119,516,500	1,762,655	8,138,666.5	186.8	181,458,500	971,207	4,726,861.0	108.5	186,296,000	1,716,796
Commercial and Institutional	6,538,092.0	150.1	19,665,000	131,018	13,321,940.3	305.8	111,221,000	363,670	7,830,852.6	179.8	45,472,500	252,946
Industrial	4,705,979.2	108.0	6,570,000	60,814	27,542,404.1	632.3	87,332,500	138,122	43,694,440.8	1003.1	138,140,500	137,715
Parks and Open Spaces	1,534,060.3	35.2	16,614,000	471,758	6,586,570.9	151.2	12,211,000	80,757	4,286,139.6	98.4	8,557,000	86,965
Vacant/ Undeveloped	4,746,709.8	109.0	10,696,000	98,156	1,476,166.1	33.9	8,522,000	251,475	1,757,940.0	40.4	82,521,500	2,044,800
Other	47,229.5	1.1	451,000	415,960	715,230.1	16.4	2,000	122	239,209.7	5.5	528,500	96,240
Total			531,403,000				486,299,000				551,086,500	

Table A2. Land Use-Based Water Demand Factors for Entire Northwest Houston Study Area

Total Study Area							
	Area	**Acreage**	**Billed Water Demand**	**Predicted Demand Factor**	**Predicted Percent of Total Water Use**	**Actual Demand Factor**	**Actual Percent of Total Water Use**
	(sq. ft)	**(acres)**	**(gal/year)**	**(gal/acre·year)**	**(%)**	**(gal/acre·year)**	**(%)**
Single Family Residential	130,289,276.5	2991.0	769,542,500	227,318	32.4%	257,283	36.4%
Multi-Family Residential	22,334,402.4	512.7	710,403,000	1,366,931	33.4%	1,385,538	33.6%
Commercial and Institutional	34,438,211.6	790.6	219,476,000	363,670	13.7%	277,609	10.4%
Industrial	85,379,063.5	1960.0	258,159,500	137,712	12.9%	131,712	12.2%
Parks and Open Spaces	13,736,324.5	315.3	42,137,000	133,623	2.0%	133,623	2.0%
Vacant/ Undeveloped	8,493,051.1	195.0	106,391,000	545,669	5.0%	545,669	5.0%
Other	1,237,679.4	28.4	9,042,000	318,232	0.4%	318,232	0.4%
Total			2,115,151,000				

Appendix B: Monthly Water Demand Data by Land Use (not normalized)

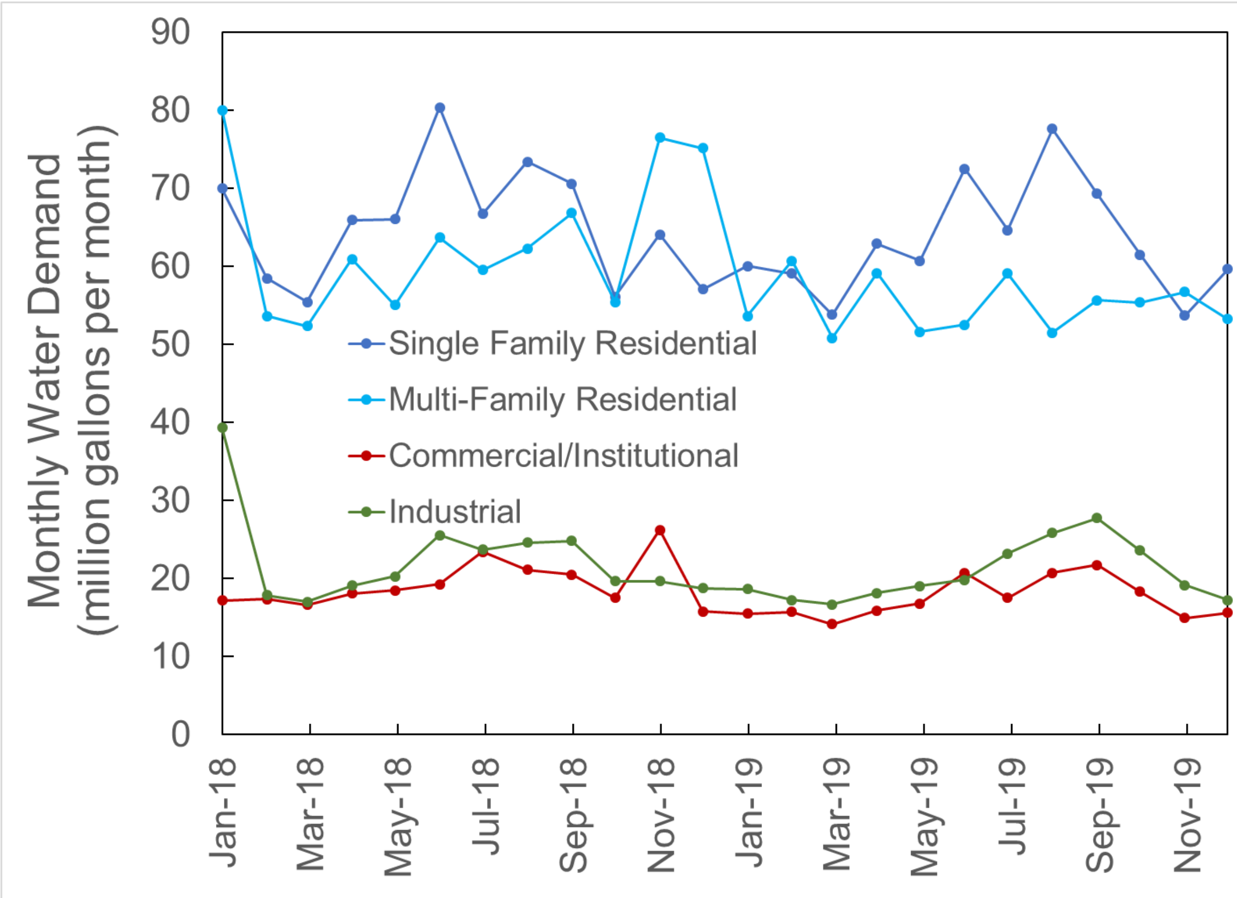

Figure B2. Raw Monthly Water Demand for Identified Land Uses

Appendix C: Wet and Dry Weather Wastewater Flow Analysis

Wet weather and dry weather periods were identified using precipitation records for six rain gauges that are maintained by the Harris County Flood Control District within the study area. The identified wet and dry weather periods are indicated in the graph of daily rainfall totals in Figure C1.

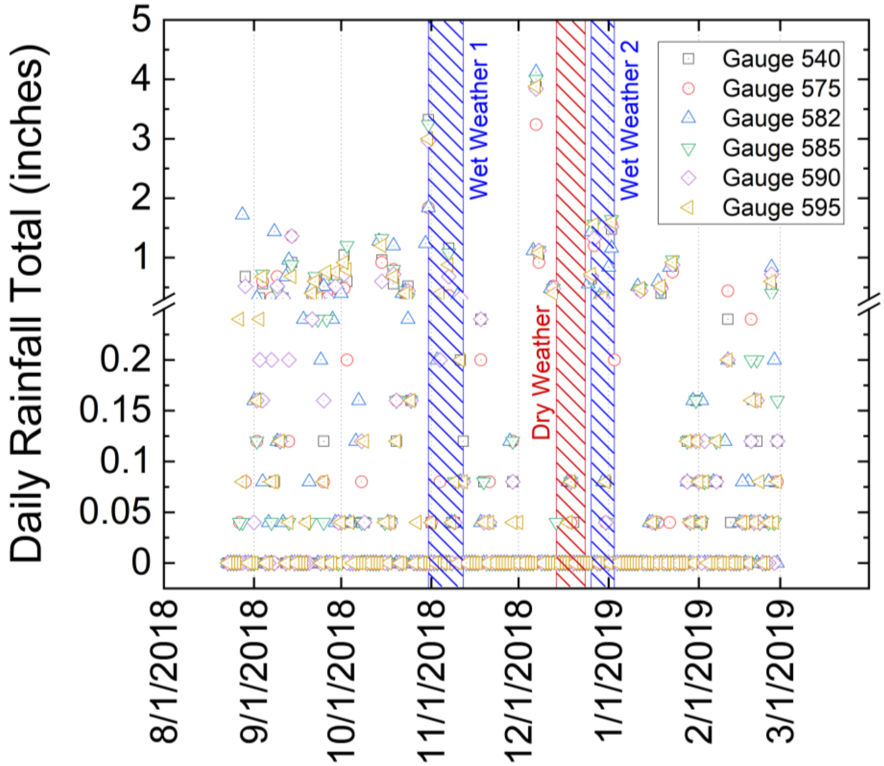

Figure C1. Daily Rainfall Totals at Six Rain Gauges across the Northwest Houston Study Area and Identified Wet Weather and Dry Weather Periods for Wastewater Flow Analysis

The wastewater flow pattern for the residential land use sub-basin, measured at monitoring location NW149003, during wet weather periods 1 and 2 is shown in Figures C2 and C3, respectively. The flow pattern at this same location during dry weather is shown in Figure C4.

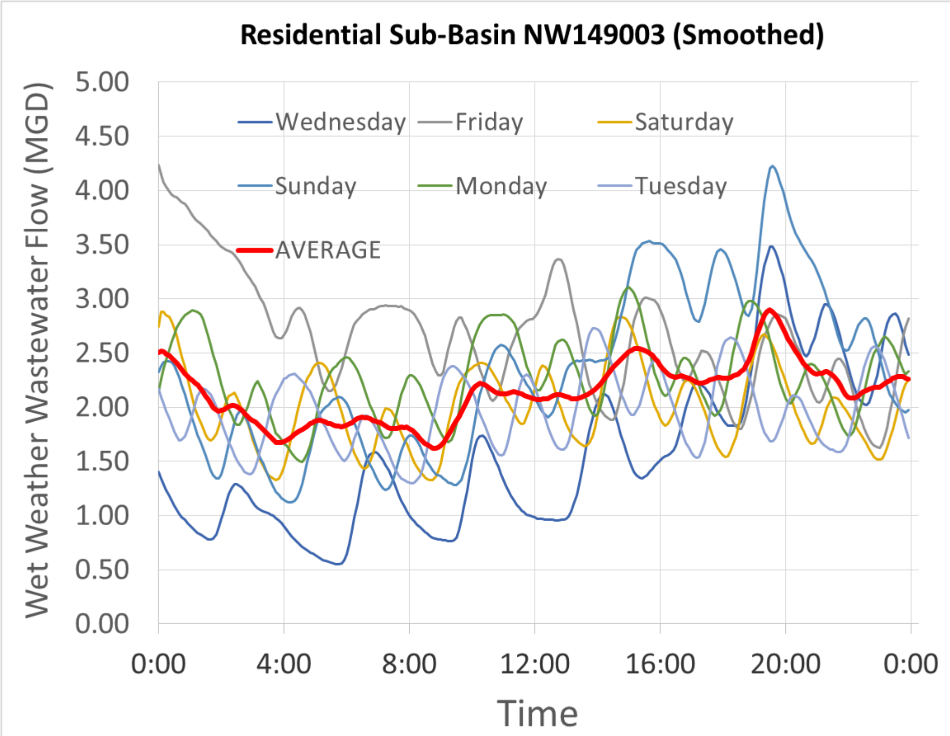

Figure C2. Smoothed Wastewater Flow of Residential Sub-Basin as Measured at Monitoring Location NW149003 during Wet Weather Event 1

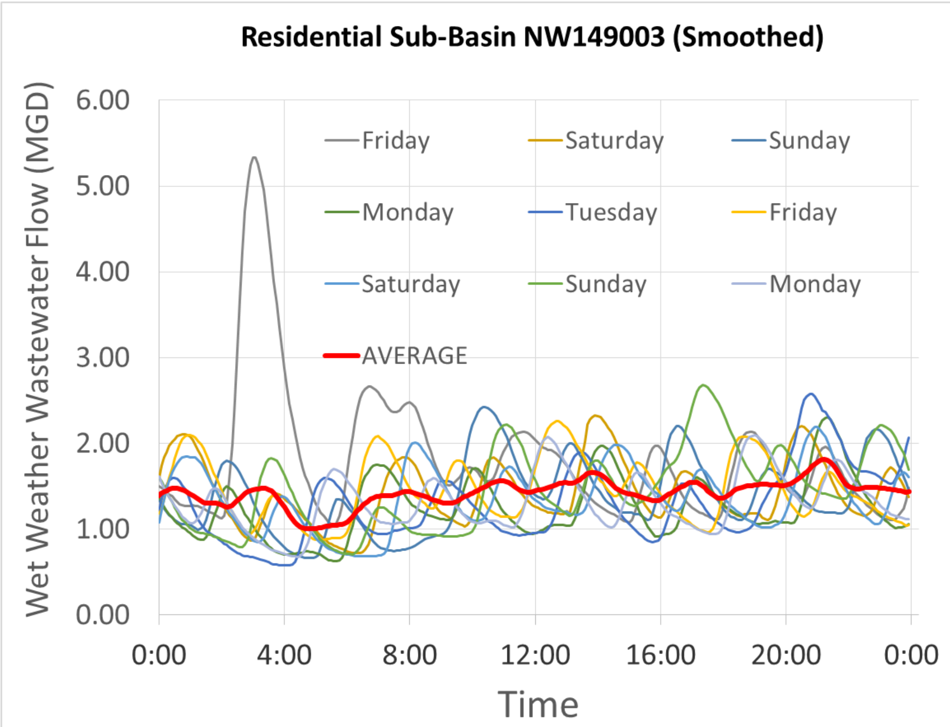

Figure C3. Smoothed Wastewater Flow of Residential Sub-Basin as Measured at Monitoring Location NW149003 during Wet Weather Event 2

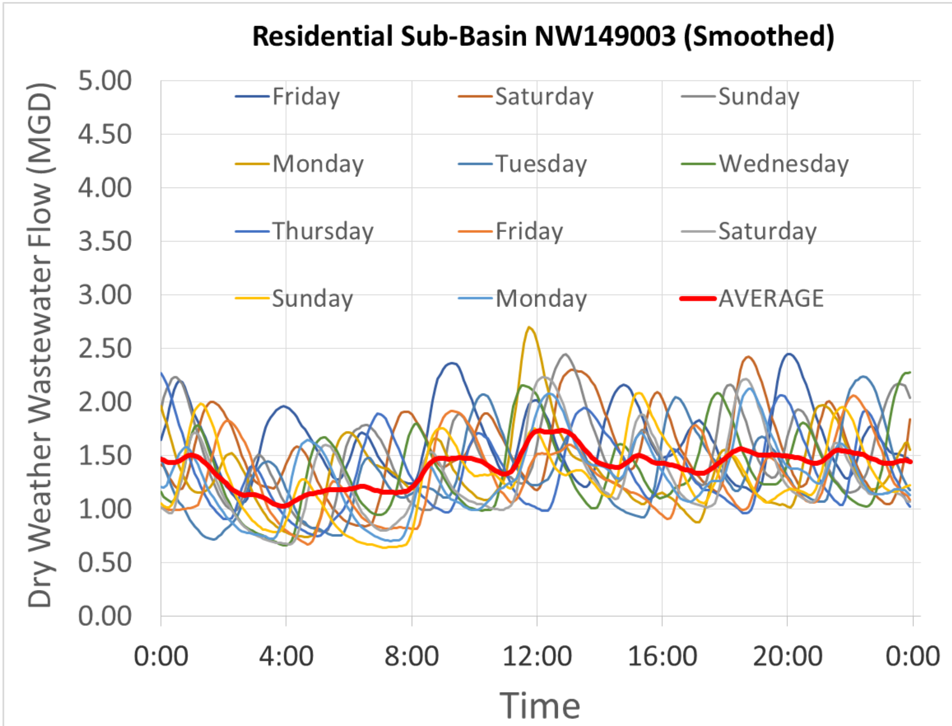

Figure C4. Smoothed Wastewater Flow of Residential Sub-Basin as Measured at Monitoring Location NW149003 during Dry Weather

The wastewater flow pattern for the industrial land use sub-basin, measured at monitoring location NW143049, during wet weather periods 1 and 2 is shown in Figures C5 and C6, respectively. The flow pattern at this same location during dry weather is shown in Figure C7.

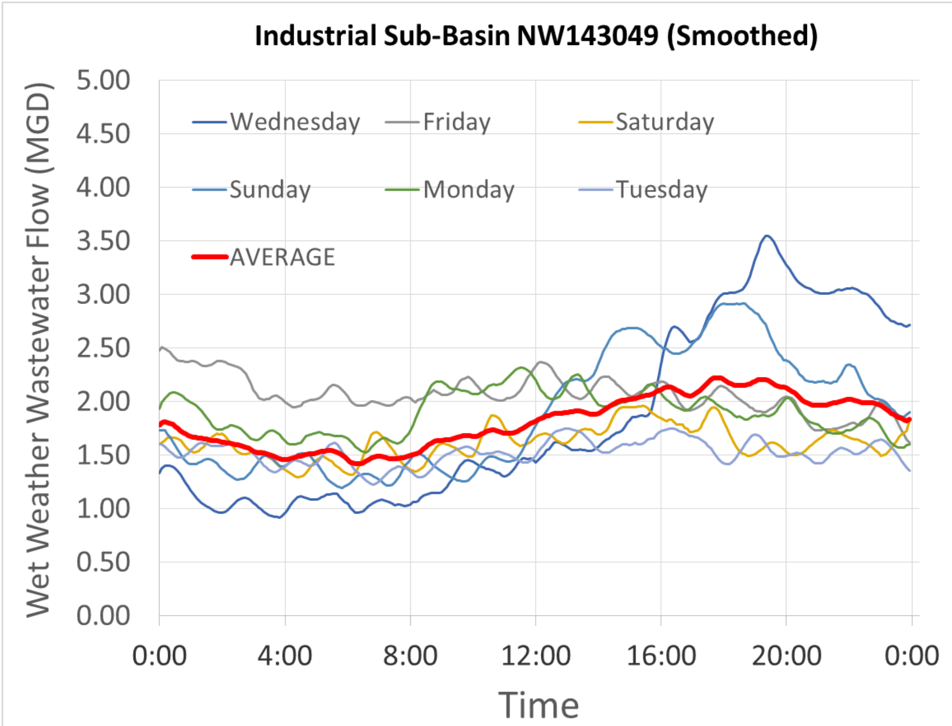

Figure C5. Smoothed Wastewater Flow of Industrial Sub-Basin as Measured at Monitoring Location NW143049 during Wet Weather Event 1

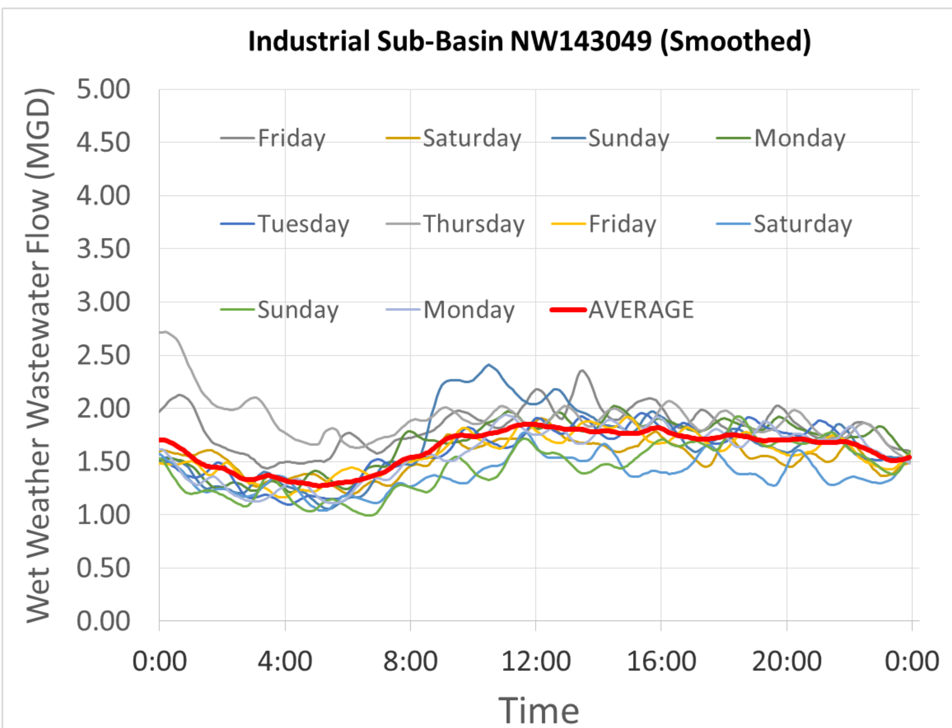

Figure C6. Smoothed Wastewater Flow of Industrial Sub-Basin as Measured at Monitoring Location NW143049 during Wet Weather Event 2

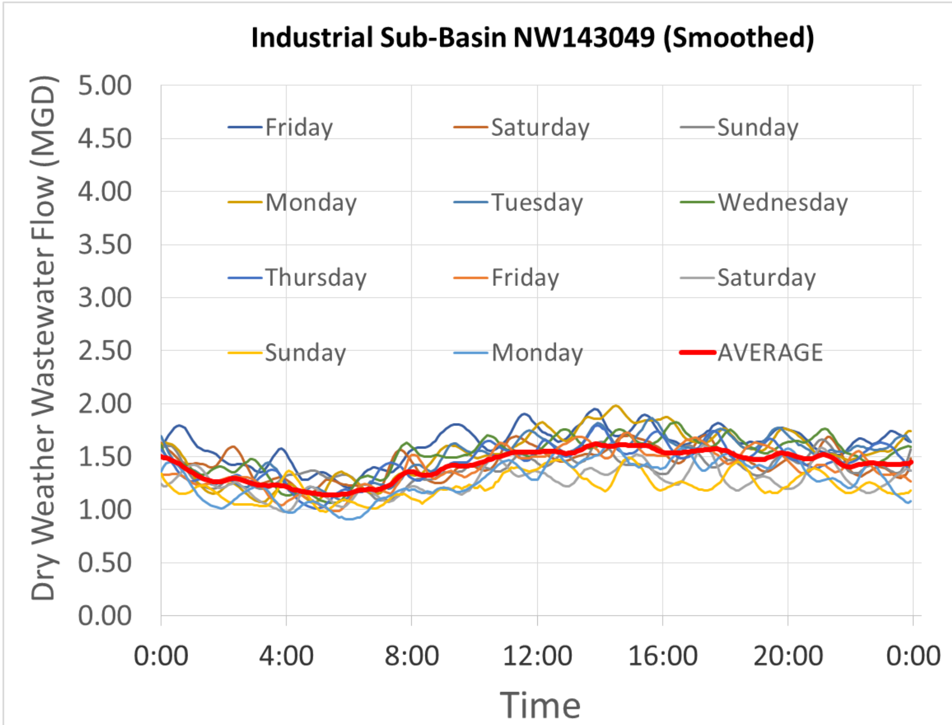

Figure C7. Smoothed Wastewater Flow of Industrial Sub-Basin as Measured at Monitoring Location NW143049 during Dry Weather

The wastewater flow pattern for the commercial and institutional land use sub-basin, measured at monitoring location NW139002, during wet and dry weather periods are shown in Figures C8 and C9, respectively.

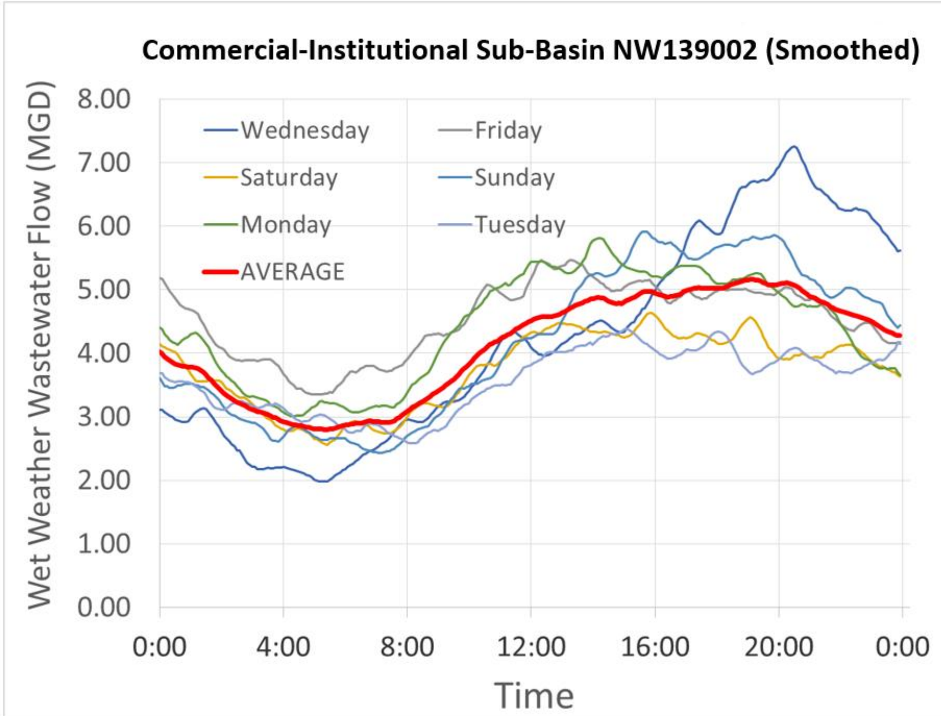

Figure C8. Smoothed Wastewater Flow of Commercial and Institutional Sub-Basin as Measured at Monitoring Location NW139002 during Wet Weather Event 1

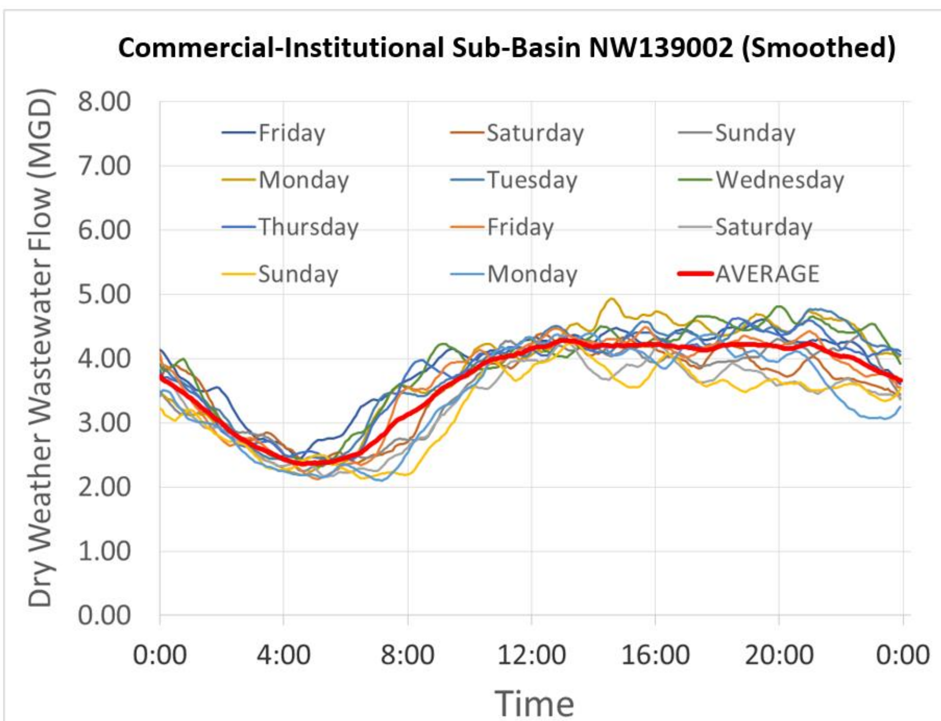

Figure C9. Smoothed Wastewater Flow of Commercial and Institutional Sub-Basin as Measured at Monitoring Location NW139002 during Dry Weather

A comparison of wastewater flows during wet and dry weather periods for the wastewater flow sub-basins dominated by residential, industrial, and commercial and institutional land uses is shown in Figure C10. Figure C10 illustrates that wastewater flows were increased during wet weather periods compared to dry weather periods, especially for the "Wet Weather 1" period in the residential land use sub-basin. Increased wastewater flows during wet weather periods may indicate stormwater inflow into the wastewater collection system. Diurnal flow patterns were evident in the industrial sub-basin and commercial and institutional sub-basin, but no clear diurnal pattern was observed in the residential sub-basin flows. These wastewater flow patterns may reflect differences in the number of flow generators and wastewater travel times within the individual sub-basins.

The observed similar wastewater flow rates during wet and dry weather periods for the residential, industrial, and commercial/institutional sub-basins indicated that indoor water uses and associated wastewater flow patterns were not significantly affected by climatic conditions. Thus, any observed differences in water demands for these land uses during dry weather and wet weather periods may be attributed to outdoor water uses like landscape irrigation.

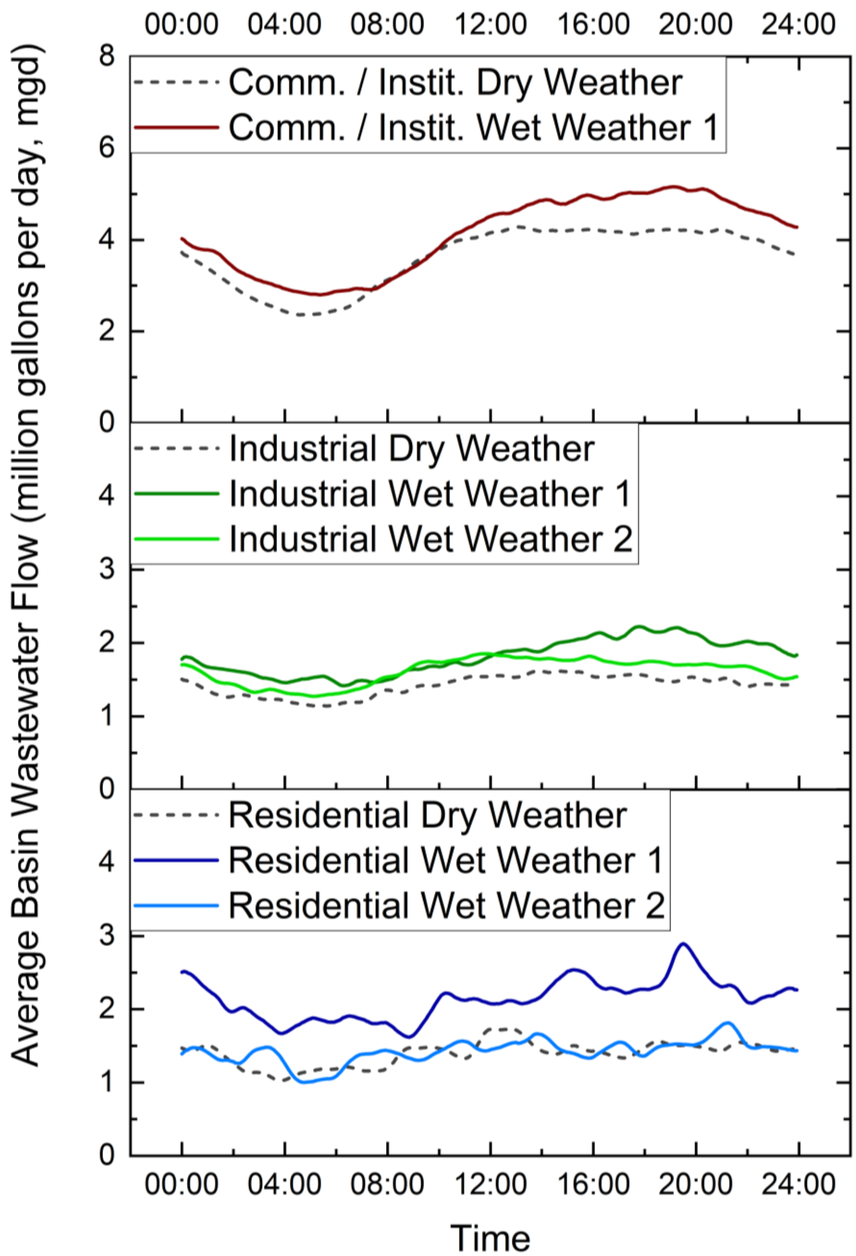

Figure C10. Comparison of Average Wastewater Flows during Wet and Dry Weather Periods for Land Use-Dominated Wastewater Monitoring Sub-Basins within the Northwest Houston Study Area

Appendix D: User Guide for the Land Use-Based Water Demand Model Development and Application of the Water Conservation Decision Support Tool

In ArcGIS:

1. Establish study area boundaries based on wastewater treatment plant service area and use these boundaries to Clip the “Tax Parcels” map from HCAD.
2. Use the Join tool to associate parcel characteristics from “Building Information (real_building_land.zip)” tabular data from HCAD and tabular Water Billing Records from Houston Public Works to individual map parcels.
3. Add an additional column with string data format to the map data table for Grouped Land Use. Use Select by Attributes to identify all parcels with land use codes corresponding to a given Grouped Land Use and Calculate Field to add the appropriate Grouped Land Use category name (i.e. Single Family Residential, Industrial, etc.) in the new column.
4. Add an additional column with numerical data format to the map data table for Cumulative Water Demand. Use Calculate Field to sum the monthly water billing records for each parcel in the new column.
5. Add an additional field with numerical data format to the map data table for identification of parcels with dwellings older than 1995. Use Select by Attributes to identify all residential parcels with “Improvement Year” prior to 1995 and Calculate Field to set the value as 1 in the new column. Use the same approach to set the value as 0 for all other parcels.
6. Import wastewater service area data and use Spatial Join to associate parcels with their respective meter basins based on physical location.
7. Add an additional column with string data format to the map data table for Land Use Dominated Sub-Basins. After identifying contiguous meter basins with similar land use (i.e. primarily residential or commercial/institutional or industrial) for model calibration, use Select by Attributes to identify all parcels in relevant meter basins corresponding to a given Land Use Dominated Sub Basin and Calculate Field to add the appropriate Land Use Dominated Sub Basin name in the new column.
8. Add Manhole Locations to the map and identify those for which flow-monitoring data are available. Export only these as a new layer. Then, identify flow-monitoring locations which are relevant to the selected Land Use Dominated Sub Basins for future use.
9. If parcel area is not already included in the Map Data Table, add an additional column with numerical data format and calculate parcel area in the field entries.
10. Use Conversion Tools to export the Map Data Table to Excel for further use.

In Excel:

1. For each land use dominated basin, select the parcel records for which water billing data are available and calculate the total land area and cumulative water demand attributed to each grouped land use.
2. For each land use, divide the average annual water demand (cumulative billed water demand divided by duration of data availability in years) by the calculated land area to determine sub-basin level demand factors by land use.
3. For the entire study area, select the parcel records for which water billing data are available, calculate the total land area attributed to each grouped land use, and multiply the area attributed to a certain land use by the relevant demand factor using the guidance below:

Land Use	**Demand Factor Source**
Single Family Residential	Residential Dominated Sub Basin
Multi-Family Residential	Average of Residential, Commercial/Institutional, and Industrial Dominated Sub Basins
Commercial and Institutional	Commercial/Institutional Dominated Sub Basin
Industrial	Industrial Dominated Sub Basin
Parks and Open Spaces	Average of Residential, Commercial/Institutional, and Industrial Dominated Sub Basins
Vacant/Undeveloped	Minimum of Residential, Commercial/Institutional, and Industrial Dominated Sub Basins
Other	Average of Residential, Commercial/Institutional, and Industrial Dominated Sub Basins

4. Compare the calculated water demand based on billed land area and land use demand factors to observed water demand from monthly water billing data for the entire study area and adjust land use demand factors, as needed.
5. Apply resulting land use demand factors to all parcels in the study area, including those for which billing data were not available, to determine estimated water demand for the entire study area.
6. To attribute outdoor water use within the study area, use an adjacent averaging approach to smooth monthly billed water demand data for each land use. This approach accounts for the rounding in and coarseness of monthly billing data. If more granular data is available, this averaging approach may not be necessary. After smoothing monthly demand numbers, normalize by the average monthly demand for the land use and identify minimum and maximum monthly demand peaking factors. Use the percentage difference between the average monthly demand and the minimum monthly demand to represent average outdoor demand for that land use in the study area.
7. Further delineate end uses of water with the following approach:
    - Residential: Beginning with the land use demand factors calculated in steps 3 and 4 for each land use, attribute the percentage calculated in step 6 to outdoor water demand. For the remaining demand, divide indoor use among different plumbing

fixtures using percentages identified from the Residential End Uses of Water Version 2 report (reference Figure 6.14), or more localized end use percentages, if available. Use these percentages to determine the gallons per acre per year attributed to each end use within a given residential land use.

- For commercial, institutional, and industrial land uses, identify Principal Use Categories based on observed water usage rates and expected similarity in terms of end uses. Calculate the water usage of each of these principal use categories as a percentage of total water usage for that category. Use these percentages to determine the gallons per acre per year attributed to each principal use category and identify future savings opportunities.

8. After identifying the demand factors for the residential end uses and the commercial, institutional, and industrial principal use categories, use these in combination with study area-wide land use to predict total water demand in each end use and category. A comparison of the water demand distribution can identify those end uses and demand categories that may be most relevant to target for future water conservation measures.
9. The model accuracy may be verified by comparing modeled indoor end uses for the entire study area to monitored wastewater flowrates at the wastewater treatment plant.
10. Once appropriate target demand reduction goals have been established for different Water Conservation Scenarios, use the Water Conservation Decision Support Tool to estimate the achievable percentage demand reduction.
    - Identify percentage water savings goal.
    - Identify expected demand reduction from water conservation measures. For example, a quantifiable reduction in flow may be expected from replacing outdated plumbing fixtures with more efficient ones.
    - Identify the portion of land area for which a given water conservation measure is applicable. For example, fixture replacements are most applicable to homes built or renovated prior to 1995.
    - Adjust expected adoption rates for each land use to achieve percentage water demand reduction goal.